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SPATIAL REGRESSION MODEL OF URBAN WALKABILITY UNDER THE 15-MINUTE CITY APPROACH

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Abstract: The 15-minute city aims to decentralize the urban economic poles to provide local services to its entire population. The objective of this research is to geographically determine the economic poles in an intermediate Latin American city and evaluate their geospatial coverage. This research develops a geographic accessibility model to analyze the spatio-temporal distribution of the economic poles, considering the socioeconomic stratum of households in Manizales (Colombia). Moreover, we apply a spatial regression model of pedestrian trips. Results show that proximity to urban economic poles is directly correlate with pedestrian trips. In Manizales, only 35.8% of the population reaches its closest economic pole within a 15-minute walk; moreover, accessibility inequities mainly affecting lower-income families were detected. The 15-minute city approach poses a high potential to contribute to urban spatial justice to the extent that urban planners facilitate the growth of economic activities and services in neighborhoods, with special attention to the less privileged.

Key words: 15-minute city, accessibility, spatial statistics, urban mobility, pedestrian

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INTRODUCTION

In recent decades, urban environments have experienced a growth in the negative effects associated with mobility (Maltese et al., 2021). The main negative effects of mobility in cities are traffic congestion (Papageorgiou et al., 2003), traffic accidents (Escobar et al., 2021; Klanjčić et al., 2022), noise (Bao et al., 2022; Babisch et al., 2005), and pollution (Laumbach and Kipen, 2012; Wu et al., 2022). Many studies have shown that road infrastructure construction to satisfy the growing vehicular demand generates counterproductive effects associated with induced demand (Hsu and Zhang, 2014; Noland and Lem, 2002). However, this development model is still present in the urban agendas of many governments worldwide (Filippi, 2022; Volker et al., 2020), underestimating alternative strategies to structurally improve urban mobility (Antipova and Wilmot, 2012). On the other hand, once the restrictions adopted to contain the Covid-19 pandemic were eliminated, urban environments recovered their mobility conditions and, therefore, the aforementioned negative effects returned. This transition from the atypical city of quiet streets to the typical city of traffic and pollution has encouraged urban debate on the challenges of mobility planning (Aloi et al., 2020; Campisi et al., 2020). In contrast to the urban development model of the 20th century (construction of road infrastructure to meet the growing demand for vehicles), there are several alternatives to structurally improve mobility with a comprehensive approach and coordination between modes of transport. From this perspective, the 15-minute city concept emerges (Moreno et al., 2021).

The 15-minute city is a policy that promotes decentralization of urban activities, seeking that city services guarantee better population coverage. This policy implies leaving behind the model of urban activity centralized in economic poles, characterized by activities concentration and social dynamism, grouping employment, recreation, and financial services, among others. The 15-minute city aims to transform the so-called "dormitory neighborhoods" (Marín-Cots and Palomares-Pastor, 2020) into neighborhoods with more significant urban activity and better service coverage, contributing to urban spatial justice (Fainstein, 2014). Spatial justice promotes better opportunities and accessibility for people, considering the socioeconomic patterns that differentiate individuals living in a territory, that is, opportunities that respond to social diversity (Jian et al., 2020; Carroll et al., 2019). Although the foundations of the 15-minute city do not constitute a new urban policy (Patricios, 2002; Pozoukidou and Chatziyiannaki, 2021) and its implementation requires the study of social patterns related to access to services and urban forms (Moreno et al., 2021). This concept has gained importance in the

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territories' study and, gradually, has been considered in the public policies of various urban agendas in the world. Currently, some cities with specific plans for urban decentralization are Melbourne (Australia), Bogotá (Colombia), Portland (USA), and Paris (France), among others (Alcaldía Mayor de Bogotá, 2021; Pozoukidou and Chatziyiannaki, 2021).

Pedestrian trips are the focus of the 15-minute city (Abdelfattah et al., 2022). The main objective of the 15-minute city is to increase the number of trips using active modes of transport (bicycle or walking) to generate positive effects on citizens' quality of life (Maizlish et al., 2017; Pisoni et al., 2022). To this aim, it is necessary to conduct the study of services accessibility (Aultman et al., 1997; Guzman et al., 2021). Also, it is required to analyze the pedestrian transport infrastructure related to the environment and accessibility (Vallejo-Borda et al., 2020), zebra crossings (Escobar et al., 2022a; Ahmed et al., 2021), and walkability scores (Rodriguez-Valencia et al., 2022; Dalmat et al., 2021), among others.

Various authors have approached the 15-minute city from a conceptual perspective. Mardones-Fernández et al. (2020) identified the action lines against urban dependence on motorized transport, addressing the concept of chrono-urbanism, one of the 15-minute city pillars. Moreno et al. (2021) studied the origin, objectives, and strategies of the 15-minute city concept. Pozoukidou and Chatziyiannaki (2021) studied three cities (Paris, Portland, and Melbourne) that have started to develop proximity urban planning. Marchigiani and Bonfantini (2022) and Pinto and Akhavan (2022) conceptually analyzed the 15-minute city, studying the particular case of Milan in Italy. Allam et al. (2022a) identified the local fiscal mechanisms for implementing the 15-Minute City, and Allam et al. (2022b) evaluated the importance of data and technology in smart cities to move toward this urban model. Analyzing the 15-Minute City from a gender perspective, Bruntlett (2022) showed that a policy of equity in land use that considers the women's mobility needs is a key element in the 15-Minute City. Some empirical research has been developed under the 15-Minute City concept but without geostatistical models. For example, Luo et al. (2022) proposed an indicator to measure exposure to green spaces (a fundamental issue for a city of proximity) with images from Google Street View and Machine Learning; subsequently, they analyzed this indicator, comparing it with rental prices in Zhengzhou (China). For his part, Kissfazekas (2022) analyzed real estate sales data in Budapest (Hungary) to identify the characteristics of urban development in city sectors planned under the concept of urban neighborhood units.

On the other hand, various authors have developed geostatistical models to analyze the 15-minute city, applying accessibility models considering the Travel Times (TT) or the Potential of Accessible Opportunities (PAO). The TT model estimates travel times without establishing a time limit, from the analysis units to a set of destination services. The PAO model determines the number of accessible services from the analysis units to a set of destination services, considering time or distance limits. For example, by applying a PAO model for 15-minute pedestrian travel times, Zhou (2019) identified residential districts that meet the 15-minute community schedule in Guangzhou, China. Marín-Cots and Palomares-Pastor (2020) studied urban density and complexity variables in Malaga (Spain); using a PAO model, they evaluated the potential for access to services in the distance ranges established for each type of service. Balletto et al. (2021) used a PAO model to establish three individual indices and their combination to assess walkability in Cagliari (Italy). Through a survey, Guzman et al. (2021) studied the changes in travel patterns in Bogotá (Colombia) at the beginning of the quarantine generated by the Covid-19 pandemic; subsequently, using a TT model, they calculated the accessibility of households to banks, neighborhood stores, educational centers, and health centers. Using PAO models, Ferrer-Ortiz et al. (2022) and Gaglione et al. (2022) analyzed the opportunities access potential in Barcelona (Spain) and Naples (Italy), respectively. To do this, they set a travel time limit of 15 minutes on foot and evaluate the potential for access to basic services. Hosford et al. (2022) used a PAO model to evaluate access to grocery stores in Vancouver (Canada) in a travel time of 15 minutes, considering two modes of transport: walking and cycling. Abdelfattah et al. (2022) analyzed indicators of population density, places of work, and services in Milan (Italy). In addition, they used the Walk Score indicator, which includes a TT accessibility model. Caselli et al. (2022) developed a TT model at the neighborhood level in Parma (Italy) to evaluate travel times from homes to two destinations: i) kindergartens and ii) points of great urban activity within the neighborhood.

Other authors have developed spatial regression models for mobility analysis from the 15-minute city approach. For example, Weng et al. (2019) applied the Walk Score in Shanghai (China) and developed a spatial regression model between socioeconomic variables (independent variables) and the Walk Score (response variable). Graells-Garrido et al. (2021) used indicators of services accessible through a PAO model in Barcelona (Spain); subsequently, they developed a spatial regression model between the different accessibility indicators and the travel flow as a response variable (number of incoming and outgoing trips to each of the neighborhoods). Finally, Calafiore et al. (2022) applied an indicator of accessibility to essential services using a PAO model in Liverpool (England); subsequently, they developed a spatial regression model between sociodemographic and environmental indicators (independent variables) and the accessibility indicator (response variable). There are three prominent aspects can be highlighted around the contributions of the 15-minute city concept: 1) few studies have been carried out using TT models, and, therefore, contributions using PAO models predominate. 2) Few studies apply spatial regression models, and an accessibility indicator is obtained to be used as a response variable (Calafiore et al., 2022; Graells-Garrido et al., 2021; Weng et al., 2019). Finally, 3) only one of the contributions has been carried out in the context of Latin American cities, characterized by socioeconomic phenomena very different from those observed in developed countries.

Unlike the works conducted by Calafiore et al. (2022), Graells-Garrido et al. (2021), and Weng et al. (2019), the present contribution applied a spatial regression model that uses the TT accessibility indicator as an independent variable. In addition, the socioeconomic stratum (SES) of households was involved in the analysis. On the other hand, while in the studies mentioned above, the Accessibility Score, the origin-destination flows, and the Walk Score were used as response variables, the present research has used the percentage of trips made in the pedestrian mode of transport. This variable allows us to identify the possible correlation and statistical relevance between walking as transportation means and living near an economic pole. From this perspective, the study allows us to verify whether the proximity of the services (a vital element of the 15-minute city) is related to the number of pedestrian trips. To our knowledge, this approach has not been used in previous research. In summary, the objective of this study is to assess the coverage provided by the economic poles of the city under analysis through a geographic accessibility model, and subsequently, using a spatial regression model, to evaluate the relationship between walking as a mode of transportation and various mobility and built environment variables, including an indicator derived from the accessibility model.

The study was carried out in a medium-sized city in the Andean region of Colombia. Approximately 450,000 people live in this city, characterized by a mountainous topography that poses particular challenges in mobility studies. The proposed methodology consists of four stages as follows: 1) identify the economic poles of the study area; 2) apply an accessibility model based on TT from the analysis units to the identified economic poles; 3) build a database with socioeconomic and mobility variables; and 4) develop the spatial regression model. The results indicate that 35.8% of the population living in the study area reaches its closest economic pole in a walk of no longer than 15 minutes; however, in the city analyzed, the current distribution of economic poles provides little coverage to low-income citizens. Additionally, the travel time walking to the nearest economic pole has statistical relevance and a negative correlation (-0.4034***) concerning the percentage of pedestrian trips. That means that the closer the population is to the economic poles, the greater the incentive to walk instead of using motor vehicles. In addition, the number of commercial nodes in an area is statistically significant and shows a positive correlation (0.5184***) to the percentage of pedestrian trips. The rest of this article has been structured as follows: Section 2 presents a case study description. In Section 3, the proposed methodology is explained. Then, by applying a spatial regression model in Section 4, the obtained results are shown. Section 5 addresses the discussion of the results. Finally, in Section 6, the main conclusions are presented, and some lines for future research are suggested.

Case Study Description

The geographic accessibility and spatial regression model was applied in Manizales, Colombia. This city is located in the Andean mountains at 2,150 meters above sea level and is characterized by a complex topography of inclined streets. In the Colombian context, Manizales is a medium-sized city with a population of 460,000. According to data from the Mayor's Office (Alcaldía de Manizales, 2017), walking is the most used mode of transport since it represents 29% of all urban trips. The public transportation system is made up of 64 bus routes with intermediate capacity (30 passengers), and there is a 3-km-long aerial cableway system with two lines and four boarding stations. According to the city's Master Mobility Plan (MMP), Manizales has four peak travel times (ptt): (i) ptt$_{1:}$ 6:15 am. to 7:15 am.; (ii) ppt$_{2:}$ 12:00 pm. to 1:00 pm.; (iii) ptt$_{3:}$ 1:15 pm. to 2:15 pm.; and (iv) ptt$_{4:}$ 5:45 pm. to 6:45 pm.

In ptt_1 and ptt_3 occur a higher proportion of reasons for study and work trips; in these periods, trips originate in homes, and the final destinations are the activity centers (offices, educational institutions, financial centers, factories, among others). In the opposite direction, during ptt_2 and $ptt_{4,}$ the main reason for traveling is home, and the origin places are the activity centers. Based on the above, it was established that a representative trip in Manizales shows the following sequence: leaving home in ptt$_1$, returning home in ptt_2, leaving home again in $ptt_{3,}$ and returning home in ptt_4.

METHODOLOGY

The proposed methodology to carry out the present study is summarized in Figure 1. In addition, an explanation of each stage is shown below.

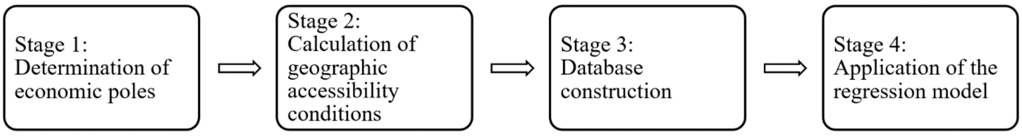

Figure 1. Proposed Methodology (Source: authors)

Stage 1 – Determination of economic poles: The information from the city government and the last Manizales Travel Survey (MTS) conducted during the diagnosis stage of the MMP was used to establish the economic poles of the study area. The MTS collects individual information regarding the mode of transport used, the number of trips and their hourly distribution, attraction and generation of trips, and reason for the trip, among other data. For each Transport Analysis Zones (TAZ), the economic poles were determined based on three binary criteria, whose values are strong-minded from the available information. The three criteria were: 1) estimation of Representative Trips (RT); 2) analysis of the Mixed-Use Area (MUA) of Manizales; and 3) service diversity analysis.

The five equations utilized in this study were an own development, aiming to provide a mathematical delineation of the process executed through the vector fields and processes calculator using Geographic Information Systems (GIS).

Criterion 1 (Representative Trips – RT). This criterion aims to estimate the representative trips in the Manizales ZAT. For this purpose, the Representative Trips (RT) indicator is proposed, whose value corresponds to the total trips attracted in the rush hours ptt1 and ptt3 and to the trips generated in the hourly peaks ptt$_2$ and ptt$_4$ at each ZAT. Then, using the information of the travel time peaks and their travel reasons, the RT for each TAZ$_j$ can be estimated using Equation (1).

$$RT_j = A_j\,(ptt_1) + A_j\,(ptt_3) + G_j\,(ptt_2) + G_j\,(ptt_4) \tag{1}$$

Where, $A_j\,(ptt_1)$ and $A_j\,(ptt_3)$ represent the total trips attracted in TAZ$_j$ during ptt_1 y ptt_3 respectively; in turn, $G_j\,(ptt_2)$ and $G_j\,(ptt_4)$ are the total trips generated in TAZ$_j$ during ptt$_2$ y ptt$_4$ respectively. For the first criterion (K$_1$), in those TAZ$_j$ whose RT$_j$ is equal to or greater than the highest decile of the data (D$_9$), K$_{1(j)}$ = 1; otherwise, K$_{1(j)}$ = 0 (Equation 2).

$$K_1(j) = \begin{cases} 0 \; if \; RT_j < D_9 \\ 1 \; if \; RT_j \geq D_9 \end{cases} \quad (2)$$

Criterion 2 (Area of Mixed Use – AMU). In this criterion, the objective is to evaluate the surface intersection between each TAZ_j and the AMU. The local government of Manizales city has spatial information categorized according to land use. The total surface of this vector layer is 28.6 km^2, and the Area of Mixed Use is equivalent to 37.6% of this surface. For the second criterion (K_2), if TAZ_j has at least 37.6% of its area within the AMU, $K_{2(j)} = 1$; otherwise, $K_{2(j)} = 0$ (Equation 3).

$$K_2(j) = \begin{cases} 0 \; if \; S_j \cap S_{AMU} < 37.6\% * S_j \\ 1 \; if \; S_j \cap S_{AMU} \geq 37.6\% * S_j \end{cases} \quad (3)$$

Where, S_j corresponds to the surface of the TAZ_j, and SAMU represents the surface of the AMU intersected by a TAZ_j.

Criterion 3 (Service diversity). The objective of the third criterion is to evaluate the diversity of services in each TAZ_j. Although according to criterion 2, if a certain TAZ_j represents a hospital and is totally contained in the AMU, this is a TAZ_j with $K_{2(j)}= 1$. However, if the land use in said TAZ_j is only destined for health, this zone lacks the diversity of services. Therefore, for the third criterion (K_3), $K_{3(j)} = 1$ if TAZ_j corresponds to an area with a diversity of services; otherwise, if TAZ_j corresponds to an area with a single service, $K_{3(j)} = 0$ (Equation 4).

$$K_3(j) = \begin{cases} 1 \; if \; in \; TAZ_j \; there \; are \; diversity \; of \; services \\ 0 \qquad if \; in \; TAZ_j \; there \; is \; a \; single \; service \end{cases} \quad (4)$$

Therefore, a particular TAZ_j is an Economic Pole (EP) if it meets the three criteria proposed above (Equation 5).

$$EP_j = K_1(j) * K_2(j) * K_3(j) = \begin{cases} 0 \; the \; TAZ_j \; is \; not \; an \; economic \; pole \\ 1 \qquad the \; TAZ_j \; is \; an \; economic \; pole \end{cases} \quad (5)$$

Stage 2 – Calculation of geographic accessibility conditions: Once the economic poles have been established, the conditions of geographic accessibility to said poles must be calculated. The sub-procedure at this stage is as follows:

- Adjust the operability and connectivity of the graph in the pedestrian transport infrastructure network through a Geographic Information System (GIS).
- Calculate the travel times in each network arc, considering speed, topographic slope, and distance.
- Obtain the travel times' vector from all pedestrian network nodes to the economic poles using the "multipath algorithm" tool of the TransCAD software.
- Obtain the vector of minimum travel times from each node of the pedestrian network to each economic pole.

Finally, and aimed to obtain a spatial estimate of isochronous curves in the territory of analysis from pedestrian travel times, the data interpolation in a GIS is carried out using the ordinary Kriging method. This geographic accessibility model calculates the population-weighted pedestrian travel time for each TAZ_j. This time becomes one of the independent variables in the regression model.

Stage 3 – Database Construction: To build the database for each TAZ_j, sociodemographic and mobility information was obtained from the last MTS. Information on mobility and infrastructure, such as commerce, job offers, public space, and public transport availability, was taken from the city's open databases. Based on this information, for each TAZ_j were assigned independent variables related to demography, mobility, and built environment; in turn, as the response variable, the percentage of trips using the pedestrian mode of transport was assigned. Table 1 presents a brief description of the variables considered.

Table 1. Variables of the regression model (Source: authors)

Variable	**Description**	**Type**
Percentage of pedestrian trips	Percentage of trips on foot, with respect to the total number of trips generated from the TAZ_j, excluding "to return home" trips	Dependent
Pedestrian travel time (*ptt*)	Pedestrian travel time weighted by population, from TAZ_j to the nearest economic pole	Independent
Education level	Percentage of population living in the TAZ_j with university studies completed	Independent
SES indicator*	Percentage of households in the TAZ_j belonging to low-income SES (0,1,2)	Independent
Age	Percentage of people in the TAZ_j under 30 years old	Independent
Own vehicle	Average number of vehicles per household in the TAZ_j	Independent
Driving licenses	Average number of driver's licenses per household in the TAZ_j	Independent
Jobs	Jobs number in the TAZ_j normalized according to the number of trips generated	Independent
Commerce	Number of commercial businesses located in the TAZ_j normalized according to the number of trips generated	Independent
Public space	Square meters of effective public space per inhabitant in the TAZ_j	Independent
Public transport availability	Number of public transport routes in the TAZ_j + availability of aerial cable stations in theTAZ_j	Independent

*In Colombia, the SES is an indicator associated to dwellings, which is related to the economic incomes of families. This indicator is used for subsidies allocation (Cantillo-García et al., 2019). There are 6 SES (1-6), where SES 1 corresponds to households with lower incomes and SES 6 to households with higher incomes.

There are three alternatives to define the response variable (dependent variable): i) Consider all the reasons for displacement; ii) consider only trips to return home, or iii) Consider all the trips excluding trips to return home. The last alternative was adopted in this study since the regression model aims to analyze the trips originated from the TAZ_j for purposes such as work, study, recreation, and care, among others.

On the other hand, including the pedestrian travel time in the regression model allows obtaining a measure of the pedestrian-transport-infrastructure-network conditions and including time variations created by the route topography. This last condition provides a more realistic model for cities like Manizales located in mountain regions.

Stage 4 – Application of the regression model: The spatial regression model is built based on the variables described in Table 1. Initially, an Ordinary Least Squares (OLS) regression model is used. The model's validity is determined based on the Lagrange and Robust LM statistical tests reported in the OLS regression and the spatial autocorrelation check results. If the model is invalid due to substantive and/or residual spatial autocorrelation, a spatial regression model conditioned by statistical test results should be applied. Finally, the regression coefficients and statistical significance for each independent variable can be obtained, as well as the model coefficient of determination (R^2).

RESULTS AND DISCUSSION

Result 1 – Determination of economic poles: By applying the three criteria established in the methodology, the TAZ corresponding to economic poles (EP = 1) is depicted in Figure 2 (see blue zones). As can be seen, there are TAZ (EP = 1) that limit each other. According to the Urban Development Institute of Bogotá city (IDU, 2005), if the distance between the geometric centroids of these TAZ is less than 1.1 km (15 minutes walking at 1.2 m/s), they must conform to a single economic pole; Otherwise, they represent different economic poles.

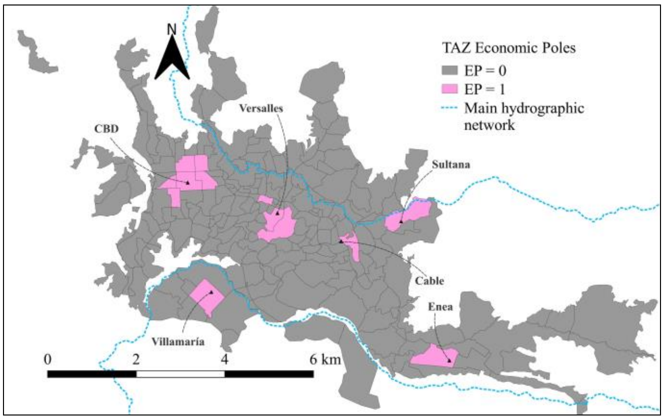

Figure 2. Result of criteria application in the TAZ of Manizales city (Source: authors)

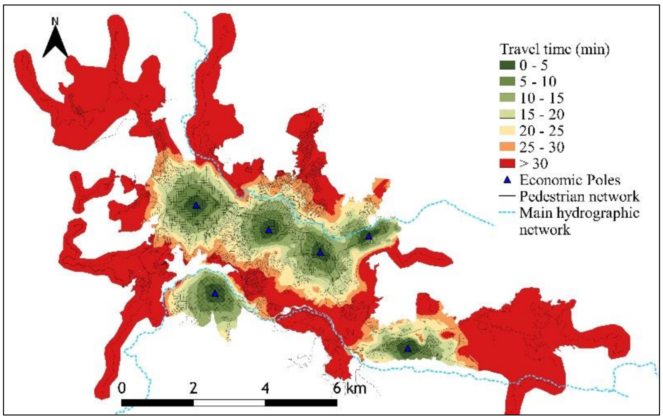

Figure 3. Pedestrian isochronous curves towards the economic poles (Source: authors)

As established in the methodology of this study, the economic poles are those TAZ with a high number of representative trips (RT) located in Areas of Mixed Use (AMU) where there is a diversity of services. These poles are: La Enea neighborhood, La Sultana neighborhood, El Cable sector, Versalles neighborhood, Villamaría center, and historic center.

Result 2 – Calculation of geographic accessibility conditions: As a result of the travel time model application, the map of pedestrian isochronous curves toward the economic poles was obtained (Figure 3); That is to say, the time required to reach the nearest economic pole from any point in the city. Figure 4a shows the coverage by general population and by area. As can be seen, 6% of the population reaches one of the six economic poles in a travel time equal to or less than 5 minutes; 19% of the population achieves it in a travel time of 10 minutes; 35.8% need up to 15 minutes.

Figure 4a shows the coverage by SES. For any travel time, SES 1 and 2 present the lowest population coverage of walking towards an economic pole. For travel times less than or equal to 10 minutes, strata 1, 2, and 4 show the lowest coverage. For instance, in 5 minutes, only 0.15% of the population living in strata 1 and 2 is covered. In contrast, in 5 minutes, strata 3, 5, and 6 reach population coverage of 12%, 10%, and 14%, respectively. From a travel time of 10 minutes, stratum four considerably increases its population coverage. For a travel time of 15 minutes, strata 1 and 2 only reach a population coverage of approximately 15%, while in strata 4, 3, 6, and 5, the coverage reaches 35%, 53%, 56%, and 72%, respectively.

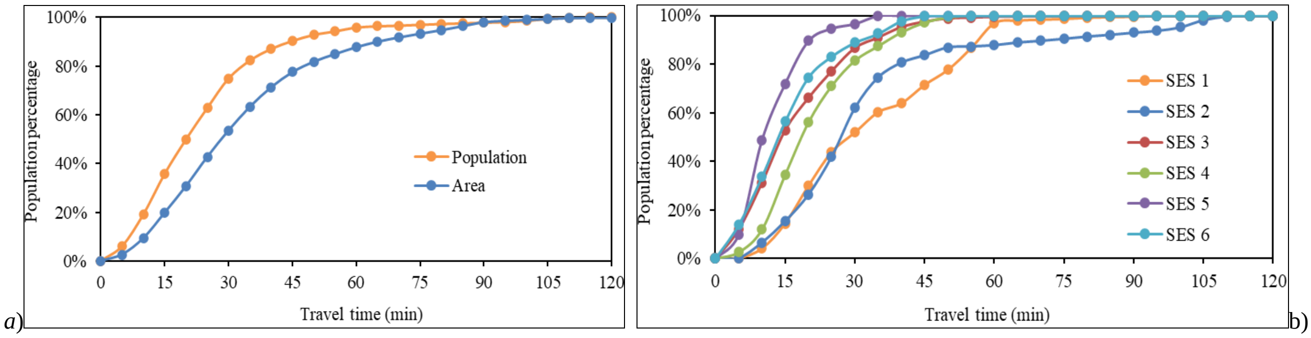

Figure 4. a) Coverage by general population and by area; b) coverage by SES (Source: authors)

Result 3 – Database Construction: Table 2 presents the statistical summary of the variables associated with each TAZ_j for the regression model.

Result 4 – Application of the regression model: Table 3 shows the results of the two regression models addressed: OLS and spatial regression. Based on the significance level observed in the Lagrange and Robust LM tests in OLS model, it is established that, due to the statistical significance of the Lagrange Multiplier error and delay tests, a Spatial Lag model should be used.

Table 2. Database used in the regression model (Source: authors)

Variable	Minimum	Quartile 1	Median	Average	Quartile 3	Maximum	Standard deviation
Percentage of pedestrian trips	0.00	6.15	21.54	25.82	39.79	100.00	22.85
Pedestrian travel time	3.27	12.41	18.89	22.45	28.84	105.48	14.41
Education level	0.00	3.64	11.28	17.52	25.46	100.00	18.63
SES indicator	0.00	2.97	13.32	36.21	82.60	100.00	39.10
Age	0.00	33.52	39.04	35.66	42.98	56.25	13.06
Own vehicle	0.00	0.43	0.62	0.69	0.90	2.33	0.39
Driving licenses	0.00	0.64	0.90	1.02	1.33	3.25	0.53
Jobs	0.00	0.03	0.23	0.91	0.63	14.58	2.21
Commerce	0.00	0.01	0.02	0.68	0.04	127.72	8.96
Public space	0.00	0.01	1.00	4.32	3.59	71.92	10.18
Public transport availability	0.00	4.00	10.00	14.36	20.00	75.00	13.88

Considering a statistical significance level of $p < 0.05$, the independent variables of the model are the pedestrian travel times (-0.4034***) and the number of commercial businesses located in the TAZ_j (0.5184***). The negative correlation of the pedestrian travel time variable suggests that those TAZ farthest from the economic poles generate the lowest percentage of pedestrian trips. According to the regression model, for each minute of variation in pedestrian travel time, the pedestrian trips inversely vary by 0.4%. On the other hand, the positive correlation observed in the number of commercial businesses located in the TAZ_j indicates that the greater the number of trips generated by a TAZ_j, the higher the percentage of pedestrian trips generated. In this way, when the commercial indicator in the TAZ_j differs by one unit, the pedestrian trips vary directly by 0.52%. The independent variable related to vehicle ownership shows a negative correlation (-10.4795), which suggests that those TAZ with a higher average number of vehicles per household generate a lower percentage of pedestrian trips. However, the null hypothesis test for this variable (0.0807) is not low enough to be considered statistically significant.

Table 3. Results of the OLS and Spatial Lag regression models (Source: authors) Response variable: percentage of pedestrian trips. Statistical significance: ***<0.001, **<0.01, *<0.05, °<0.10

	Indicators and variables	Regression models	
		OLS	Spatial Lag
	R^2	0.3026	0.3450
	I de Moran	0.2280	0.2280
	Log likelihood	-886.0870	-881.0880
	Akaike info criterion (AIC)	1,794.1700	1,786.1800
Regression coefficient + statistical significance	Pedestrian travel time	-0.5427***	-0.4034***
	Education level	-0.0582	-0.0066
	SES indicator	0.0653	0.0537
	Age	-0.0315	-0.0909
	Own vehicle	-10.4402	-10.4795°
	Driving licenses	-4.0500	-3.8867
	Jobs	-0.6579	-0.4939
	Commerce	0.5495***	0.5184***
	Public space	-0.0111	0.0241
	Public transport availability	0.1427	0.0611
p-value	Lagrange Multiplier (lag)	0.0106	---
	Robust LM (lag)	0.0561	---
	Lagrange Multiplier (error)	0.0496	---
	Robust LM (error)	0.3256	---

Based on the Representative Trips (RT), Area of Mixed Use (AMU), and Service Diversity criteria, the economic poles of Manizales city were identified. These areas generally concentrate most of the urban activity and are essential to the city's services and opportunities. For example, the Versalles neighborhood generates a high flow of RTs due to various services such as hospitals, universities, parks, and sports venues. In turn, the Historic Center concentrates the most significant number of financial institutions and various health, education, recreation, and security services (Escobar et al., 2015). The analyzed city covers an area of approximately 36 km2. The six economic poles identified suggest that in this city, there is an economic pole for every 6 km2. Due to the proximity between the economic poles of the Versalles neighborhood, the Cable sector, and the La Sultana neighborhood, in Figure 3, we observe that the 15-minute isochronal curve associated with these sectors is geographically connected. The preceding suggests that, in this area of the city, its inhabitants have access to at least two economic poles in less than a 15-minute walk.

The results indicate that 38% of the population can walk to one of the economic poles of the city in a maximum time of 15 minutes, indicating that the city still faces challenges in its urban planning processes and more significant efforts to stimulate pedestrian mobility. That is, a decentralized city where smaller-scale economic poles abound, providing various services for its inhabitants. On the other hand, under the current urban configuration, the lower socioeconomic strata (SES 1 and 2) have less walking access to the economic poles of the city. In contrast, the highest socioeconomic strata (SES 5 and 6) present better possibilities of accessing the economic poles on foot in a travel time of 15 minutes.

Although no work has been carried out in other urban contexts applying a methodology similar to the one used in this work, some studies based on regression models offer similar results in some socioeconomic variables. In particular, the identified contributions have demonstrated the inequity of accessing areas of urban activity, especially for lower-income households. For example, Weng et al. (2019) found that the most walkable environments with the most significant access to services in the city of Shanghai were located in the city's central areas, while much lower walkability indicators were observed in rural areas. Although these authors did not use socioeconomic variables such as income, socioeconomic status, or housing cost, they found that due to the high cost of housing in central areas, medium- and low-incomes populations tend to move towards rural areas in where walkability is less. In the spatial regression model of Calafiore et al. (2022) applied in the city of Liverpool, it was found that although the housing cost (socioeconomic indicator) presented a weak relationship with service access, in higher costs zones, less access to services was observed due to a lower urban density.

In the research by Hosford et al. (2022) carried out in Vancouver, the urban areas with a higher population of children, older adults, and minority groups showed less access to product stores; in contrast, areas with a larger population of employed people and higher educational levels showed better coverage. Although the socioeconomic analysis included a measure of the population's income, this variable did not affect access to services. Guzman et al. (2021) calculated access to banks, neighborhood stores, educational centers, and health centers in Bogotá. Their results show that the low SES presented better access to neighborhood stores, while the middle and high SES showed better access to educational centers, banking, and health services. The results obtained in the accessibility model of this research are consistent with other studies carried out in the context of Manizales city. In particular, the current distribution of the different urban services provides poor coverage for the lower SES. In this line, the work of Escobar et al. (2022b) identified social inequity in access to the aerial cableway because the lowest socioeconomic stratum (SES 1) showed the lowest population coverage compared to other SES. Zuluaga et al. (2021) analyzed access to the public bicycle service in Manizales, concluding that the current distribution of stations provides poor access to the lowest socioeconomic strata (SES 1 and 2). Gómez et al. (2022) analyzed the Spatio-temporal distribution of educational centers in Manizales, observing better coverage for high SES.

The socio-spatial analysis offered by the travel time variable in geographic accessibility highlights the importance of promoting a decentralized urban development model to facilitate the implementation of the 15-minute city concept. Although deeper statistical analyses are required to determine causality between the variables, a negative correlation between pedestrian travel time and the percentage of pedestrian trips suggests a statistical association between living near to an economic pole and making trips on foot. This outcome highlights the importance of redistributing employment in the city to facilitate accessibility relegating other transportation means. The city decentralization brings the population closer to the economic poles and creates positive effects on the number of pedestrian trips. On the other hand, the statistical significance shown by the number of commercial businesses recognizes the importance of this variable in the 15-minute city model. Therefore, increasing the commercial offer in the neighborhoods increases the job offer and the number of services, which in turn encourages the mobility of people in the public space.

CONCLUSIONS

The 15-Minute City promotes the decentralization of urban activities to guarantee better coverage of services to the population. Under this approach, urban planning should promote the transformation of the so-called “dormitory neighborhoods” into neighborhoods with more significant urban activity (economic poles), offering better opportunities to the citizens. In this context, the main objective of the 15-minute city is to facilitate pedestrian trips and, in this way, avoid using other transport means that increase pollution and urban congestion.

Although various research works have been conducted under this approach, three main gaps that encourage our research were detected. 1) research using TT models is scarce; 2) few studies apply spatial regression models and, in all of them, an accessibility indicator is obtained to be used as a response variable; and 3) only one contribution has been carried out in the context of Latin American cities, which are characterized by particular socioeconomic and geographic conditions. To respond to these gaps, the methodology proposed in this paper applies a spatial regression model that involves the TT accessibility indicator as an independent variable. In addition, the SES of households was considered in the analysis. Moreover, unlike previous contributions, in our model, the percentage of pedestrian trips was used as a response variable to identify the correlation between walking as a means of transportation and living near to an economic pole.

When applying the proposed methodology in the city of Manizales (Colombia), it was found that only 35.8% of the population reaches its closest economic pole in a walk of no more than 15 minutes, showing conditions that are more favorable for residents of higher economic income. In other words, in the context of the analyzed city, the current distribution of the economic poles provides little coverage to the areas inhabited by lower-income families. This situation indicates that in the analyzed city, more efforts must be made to improve urban justice. From a statistical point of view, the spatial regression model used in this research made it possible to characterize behaviors and patterns of pedestrian travel in the different activity areas of the city. In particular, it was found that the travel time walking to the nearest economic pole has statistical relevance and a negative correlation (-0.4034***) with respect to the pedestrian trips. It was also found that the level of business activity in an area is statistically significant showing a positive correlation (0.5184***) respect to the number of pedestrian trips.

Therefore, the proximity of urban services correlates with the number of pedestrian trips. On the other hand, since families with lower economic incomes showed poor access to the economic poles in the analyzed city, the 15-minute city approach poses a high potential to contribute to urban spatial justice to the extent that urban planners facilitate the growth of economic activities and services in neighborhoods, with special attention to the less privileged. However, this study shows some limitations related to the geographic accessibility model because other variables affecting the speed and intensity of pedestrian transportation, such as age, gender, and health conditions, were not considered. It is also necessary to develop models involving the urban relevance of the economic poles. Therefore, future works could analyze individual access to services through a POA model. In addition, more variables could be explored affecting the speed and intensity of pedestrian transport in different areas of the city or on different days of the week.

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