

Spatial Patterns of Public Transportation Stops: A Spatial Statistical Analysis Using Hexagonal Tessellation in Culiacán, Sinaloa, Mexico

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Abstract

The spatial distribution of public transportation infrastructure is factor in assessing urban accessibility and mobility conditions in cities; however, gaps remain in identifying spatial patterns that explain its territorial organization. This study analyzes spatial autocorrelation patterns in the distribution of public transit stops in the city of Culiacán, Sinaloa, Mexico, using geospatial analysis and spatial statistics techniques. To this end, a 500-meter hexagonal tessellation was generated, with this threshold adopted as the walkable access distance. The study was restricted to hexagons containing at least one public transportation stop, prioritizing the internal structure of concentrations and excluding areas lacking service. Based on the number of stops recorded in each unit, spatial weight matrices were constructed using contiguity and proximity, and Moran's local index was applied to determine the degree of spatial autocorrelation and the presence of spatial clusters. The results show positive and statistically significant spatial autocorrelation, indicating a non-random distribution of public transit stops. Clusters of high and low concentration were identified, forming a hierarchical pattern characterized by a central core of high density and peripheral sectors with lower coverage. The main contribution lies in the characterization of a geospatial approach that integrates hexagonal tessellation and spatial statistics to characterize the territorial structure of the distribution of stops, providing a homogeneous spatial unit for identifying patterns of concentration that may be obscured by approaches based solely on point location. The findings reveal spatial differences in infrastructure concentration, which can serve as a basis for assessments of accessibility and spatial equity.

Keywords: Public transportation; Spatial autocorrelation; Geospatial analysis; Spatial clusters; Urban accessibility.

Introduction

Urban expansion and economic transformations have been closely linked to the development of transportation systems, which have played a functional role in the configuration and dynamics of cities (Figueroa, 2005). In this regard, Booth et al. (2007), note that transportation is a key factor in land-use planning, since the quality and speed of travel directly influence the areas where people can live and access goods and services. Therefore, the integration of transportation and land-use planning is essential for designing effective urban development strategies, as mobility policies must align with land-use planning objectives, while land use must take into account the characteristics and projections of existing transportation networks. In line with this perspective, Chatziioannou et al. (2020), highlight the importance of adopting urban and metropolitan planning approaches that incorporate sustainable mobility criteria, given that transportation systems contribute to the economic well-being and quality of life of territories by providing the necessary infrastructure for the movement of people and goods.

Various approaches have highlighted the need to move toward urban models that effectively integrate public transportation with the territorial structure. UN-Habitat (2020), emphasizes that investments in transportation must be accompanied by strategies that promote urban densification, pedestrian mobility, and the use of sustainable modes of transportation, in addition to strengthening connectivity for communities located far from urban centers. Likewise, this organization emphasizes that physical proximity loses its relevance when transportation systems are inadequate or lack accessibility, underscoring the importance of ensuring efficient and accessible mobility infrastructure in cities.

Foda and Osman (2010), note that bus stops constitute the primary point of contact between users and the transportation system; therefore, their location directly influences both service performance and passenger satisfaction. Similarly, Ezquerro et al. (2021), define bus stops as spaces designated for passengers to board and alight, while Moreira-Villavicencio (2022), identifies them as meeting points connecting different parts of the city. For its part, the National Human Rights Commission (2018), defines public transportation stops as designated areas located at specific distances from one another, where users of public transit are permitted to board and alight.

Based on the foregoing, it is clear that public transportation stops are fundamental elements of urban mobility systems, as they not only enable the functional operation of the service but also influence the accessibility and connectivity of the population within the city.

Talpur et al. (2024), highlight the importance of public transportation stops, as they are a key element in facilitating the population's access to destinations; therefore, pedestrian accessibility to these facilities is essential. For their part, Mavoa et al. (2012), note that access to these stops is an essential component of the travel experience, as it determines the very possibility of using public transportation. From the perspective of social justice, Harvey (1973), argues that accessibility and proximity are fundamental characteristics of any

urban system, since access to employment opportunities, resources, and services involves costs associated with distance and travel time.

In light of this, various studies have proposed distance parameters considered appropriate for accessing public transportation; for example, Celi (2018), determines that a distance of less than 350 meters represents an optimal walking distance to a transit stop, while Talavera and Valenzuela (2017), based on a review of research related to urban mobility, establish ranges between 400 and 800 meters. Given the variability of these thresholds, it is necessary to adopt operational criteria that standardize, analyze and facilitate their comparability. Therefore, this study uses a distance of 500 meters as a benchmark for accessibility, based on the guidelines established by UN-Habitat (2018), an organization that recognizes this threshold as a convenient walking distance and uses it as a benchmark for measuring urban indicators on an international scale. Adopting this threshold allows for the establishment of a standardized criterion to assess the population's proximity to public transit stops and facilitates the comparison of results. However, the fact that a stop is located within a 500-meter radius does not necessarily mean that this distance is equally accessible or easy to cover for all population groups, since the experience of walking may be influenced by physical, social, and environmental factors specific to the urban setting. In the case of the city of Culiacán, factors such as the continuity and quality of pedestrian infrastructure, safety conditions, the characteristics of public spaces, the presence of physical barriers, and weather conditions can influence how easily people travel this distance. Therefore, in this study, the 500-meter distance is considered a standardized reference threshold for the spatial analysis of accessibility, without assuming that meeting this threshold, in and of itself, represents a uniform condition of effective accessibility for the entire population.

Despite the importance of accessibility in public transportation systems, the specialized literature notes that studies analyzing this topic remain limited. Mavoa et al. (2012), refer to this situation, noting the scarcity of research that considers travel time on public transportation and the available destinations at the end of the route, and that few studies take into account all other components—notably the time it takes to reach a stop and waiting times—a fact that limits authors' ability to conduct studies on the topic.

Regarding the distribution of public transportation stops, Huang (2014), determines that the distance between bus stops is a relevant indicator for the distribution of public transportation services. Meanwhile, according to Wirasinghe and Ghoneim (1981), the spacing between stops is a key aspect of bus route operations, as it influences both service efficiency and user accessibility; therefore, planning this spacing requires striking a balance between the service's operating speed and accessibility for users. Furthermore, the authors note that the distance between stops is closely linked to the distribution of public transportation demand; consequently, various mathematical models have made it possible to optimize their location and distribution based on the mobility needs along the routes.

The information outlined above highlights the importance of analyzing the spatial distribution of public transportation stops in the city of Culiacán, as well as determining whether or not there is a statistical correlation among them. Below are some studies related to the topic addressed in this research.

Li et al. (2021), conducted a study in which they noted that the location of transit stops can affect the efficiency of public transit services. Among other aspects, they analyzed stop densities using a kernel function and were able to identify spatial clusters, which subsequently contributed to the spatial correlation analysis they sought to perform with respect to residential areas and workplaces. During the statistical analysis, they used various Python packages and determined that spatial autocorrelation analysis based on densities is a useful tool for evaluating the relationship between public transportation demand and supply. To delve deeper into the topic, the authors analyzed the relationship between the location of residences and workplaces relative to the location of stops using statistical analysis.

Devunuri et al. (2024), address the issue of calculating the distance between bus stops, noting that, although this topic arises in discussions about stop consolidation, there are few reliable statistics and well-defined methodologies for measuring it. They also highlight that analyzing the spacing between stops involves technical and conceptual challenges stemming from the operational complexity of public transit networks. To address this, they developed a methodology based on the processing and analysis of General Transit Feed Specification (GTFS) files using Python, with the aim of obtaining statistics on stop spacing. As a result, they generated an open-source dataset on transit networks in the United States and Canada, and proposed applications for public transit research and planning.

Montero et al. (2024), analyze urban transportation planning through a study conducted in the city of A Coruña, Spain, in which they examine the relationship between the location of public transportation stops and various socioeconomic and demographic variables. To this end, they used open-access data on cadastral records, road networks, and the locations of bus stops, which was processed and refined using QGIS 3.28.3 software. The authors note that, although there is research focused on building models to estimate bus demand at the stop level, few studies have considered spatial dependence as part of the analysis. In this regard, the main objective of their research was to estimate bus demand at the stop level by developing a model based on techniques that go beyond traditional linear approaches, notably univariate and multivariate descriptive analyses. As a result, they determined the existence of spatial dependence among stops located within a distance of 1.15 kilometers, demonstrating that geographic proximity influences public transit demand behavior.

Overall, the reviewed literature shows that the distribution of public transit stops has been addressed primarily from perspectives related to spacing and accessibility; however, there is limited evidence regarding the analysis of spatial autocorrelation patterns that characterize their territorial distribution. This situation is particularly relevant in cities where the spatial configuration of stops may reflect distinct urban dynamics between central and peripheral areas. In the case of the city of Culiacán, Sinaloa, no studies were identified that statistically characterize the spatial patterns of concentration of public transit stops at the intra-urban scale; consequently, there is a lack of specific information on the spatial structure of this component of the mobility system. Given this gap, the present research represents a step forward by integrating hexagonal tessellation with spatial statistical techniques to identify patterns of concentration and autocorrelation in the distribution of stops,

generating spatial evidence that can contribute to the analysis of accessibility and to the understanding of the territorial organization of public transportation.

Given this gap, the spatial analysis of public transit stops becomes relevant as a tool to contribute to the understanding of the territorial organization of mobility systems and their implications for urban accessibility. Therefore, this article aims to identify and analyze spatial patterns in the distribution of public transit stops located in the city of Culiacán. To this end, Moran's local spatial autocorrelation analysis —expressed by the Local Indicator of Spatial Association (LISA)— is employed through a univariate analysis that determines whether the distribution of stops exhibits patterns of concentration, dispersion, or random behavior within the urban space, thereby contributing to the characterization of their territorial structure and the identification of spatial patterns in the concentration of this infrastructure.

2. Data and Methods

2.1 Study Area:

This research is conducted in the city of Culiacán, capital of the state of Sinaloa and seat of the municipality of the same name. Culiacán is located in the central region of the state and serves as its primary political, administrative, and economic hub (Fig. 1). Its level of connectivity and territorial integration has allowed it to establish itself as a major hub for investment and the exchange of goods and services in northwestern Mexico. Furthermore, its significance within the regional urban system is linked to the dynamics of supply, consumption, and distribution of products that it maintains with other cities in the country (IMPLAN, n.d.).

In demographic terms, according to the National Institute of Statistics and Geography (INEGI, 2020), the city of Culiacán has a population of 808,416 people, as documented in the 2020 Population and Housing Census. For its part, IMPLAN (n.d.), notes that Culiacán ranks among Mexico's largest cities by population size, placing it among the top thirty nationwide. The urban and economic growth experienced during the 1980s and 1990s drove the city's rapid expansion; however, between 2000 and 2005, this growth slowed, primarily due to increased migration to the United States and other Mexican cities.

Geographically, the city of Culiacán borders the administrative districts of Jesús María and Tepuche to the north; Costa Rica and Las Tapias to the south; Sanalona and Imala to the east; and Aguaruto and the municipality of Navolato to the west. It also borders the administrative district of Villa Adolfo López Mateos, also known as El Tamarindo, to the northeast. Culiacán is the most important city in the state of Sinaloa, due to its significant demographic and economic concentration. In terms of population, it is home to approximately 23% of the state's residents, while economically it accounts for 34.3% of the state's Gross Domestic Product (GDP). (National Water Commission, 2014)

Pérez and Jiménez (2020), argue that approximately two-thirds of the city's residential area consists of low-income housing developments, which coexist with gated communities, shopping malls, and developments

targeting middle- and high -income sectors. This configuration has created a fragmented urban structure, marked by physical and social barriers that limit the continuity of the urban fabric and reinforce processes of segregation and differentiation among social groups. In this sense, urban expansion has not only altered the city's physical landscape but also the forms of social interaction and the ways in which urban space is appropriated.

Taken together, Culiacán's territorial, demographic, and socioeconomic characteristics highlight the complexity of its urban dynamics and underscore its significance as an area of study within the regional context. Its status as the state's primary economic and population center, as well as the processes of urban expansion and socio-spatial fragmentation observed in recent decades, have given rise to a heterogeneous urban structure characterized by contrasts in land use, infrastructure distribution, and access to urban services. In this context, the analysis of the distribution of public transportation stops takes on special importance, as it is directly related to the city's mobility and public transportation, fundamental elements for the population's connectivity and accessibility within the city. Therefore, the urban conditions in the city of Culiacán provide a relevant context for this study, which aims to analyze the spatial patterns of public transportation stops using geospatial analysis and spatial statistics techniques, in order to understand their territorial distribution and their relationship with the urban configuration of the study area.

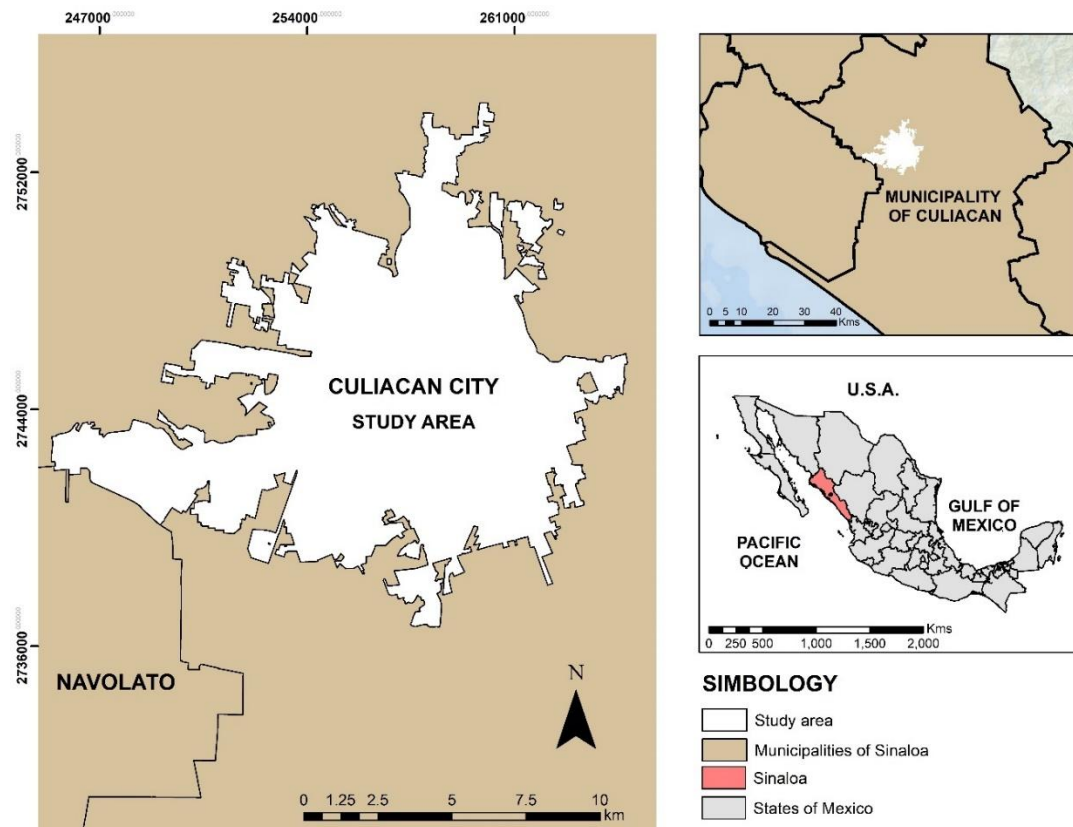


Fig. 1 Study Area

2.2 Data:

The spatial analysis was based on vector data corresponding to public transportation stops collected in 2024 and the 2020 urban Basic Geostatistical Areas (AGEB), as described in Table 1. Using these inputs, a tessellation of the study area was generated, which served as the spatial unit of analysis. Subsequently, the number of public transportation stops within each tessera was counted, and the corresponding attribute table was configured. This information constituted the spatial database used in the GeoDa software to apply the Univariate Local Moran's I (Univariate Local Moran's I), which was used to define the spatial relationship expressed in LISA. The latter is recognized by Anselin (1995), as a local indicator of spatial association with the ability to determine the degree of spatial clustering present in an observation, while Kumar et al. (2024), define it as a category capable of identifying different types of spatial patterns, which, in the case of this study, is focused on the distribution of public transportation stops.

Table 1. Information Used in the Analysis

Dataset name	Spatial unit	Data type	Reference year	Source
Urban AGEB	Polygon	Vector	2020	INEGI
Public transportation stops	Point	Vector	2024	Own
Hexagonal tiles	Polygon	Vector	2024	Own

2.3 Methodology:

The methodology employed in this research is conceived as a geospatial analysis approach designed to address the study's objective and the specific characteristics of the study area. This methodological approach allows for the integration of various tools, variables, and scales of analysis in accordance with the requirements of the research objective and the spatial conditions of the territory, thereby enabling a comprehensive and relevant analysis of the spatial distribution of public transit stops. In this regard, the proposed methodology does not aim to be a single or universal procedure but rather an analytical alternative that integrates GIS tools and spatial statistical techniques to identify spatial patterns. The combination of these elements yielded consistent and spatially coherent results, demonstrating their usefulness for understanding the case study.

Furthermore, the methodological procedure was structured sequentially, allowing for the integration, processing, and analysis of spatial information through different complementary stages. The application of this strategy facilitated the identification of spatial relationships and the generation of empirical evidence that contributes to the achievement of the research objective. The steps followed to conduct the analysis are described in detail below.

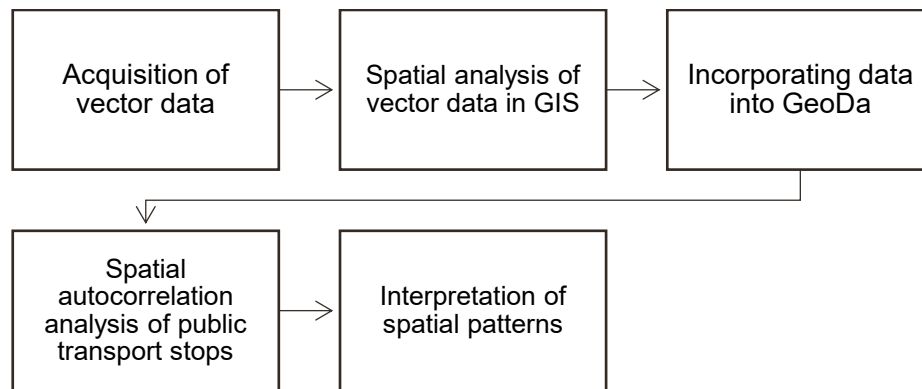


Fig. 2 Methodological proposal for spatial analysis. Own source

2.4 Acquisition of vector data:

As mentioned above, vector data is a fundamental input for conducting this spatial analysis; a description of the data used is presented in Table 1. It should be noted that the data on public transit stops in the study area are derived from the research conducted by Zazueta et al. (2025), which led to the creation of the first inventory of transit stops for the entire city of Culiacán. The authors emphasize the importance of having this type of geospatial data for the analysis and implementation of public transit system strategies. Furthermore, the urban AGEs made it possible to delimit the study area and, together with the information on public transit stops, served as the basis for configuring the regular hexagonal grid used as the unit of analysis in this study.

2.5 Spatial Analysis of Vector Data:

Once the information required for the research had been gathered, the spatial analysis was conducted. According to Longley et al. (2015), this involves a set of techniques aimed at generating new information from spatial data, in which location is a fundamental element, since the results depend on the location of the objects being analyzed. This process was carried out using QGIS Desktop 3.34.11 software, through the integration and visualization of the collected vector data.

Subsequently, a grid of hexagonal cells was generated over the analysis area. According to Petersen and Middleton (1962), this type of cell offers advantages over traditional square grids because these regular polygons are more compact and cover the space with a uniform, unambiguous adjacency. The created grid shares characteristics with Voronoi tessellation, which is defined by Fleischmann et al. (2020), as a geometric partitioning method that, starting from a set of elements, generates a series of polygons known as Voronoi cells. This process was carried out with the aim of establishing homogeneous spatial units that would minimize the effects resulting from conventional administrative divisions.

The use of tesserae as units of spatial aggregation is consistent with the findings of Battersby et al. (2016), who note that spatial grouping is a method for organizing point elements within polygonal regions. These regions can correspond to both irregular administrative boundaries and tessellations composed of regular polygons.

The vertical and horizontal spacing of the tesserae was 500 meters; this value was used as a spatial reference to delimit the units of analysis. During the procedure, 481 hexagons were generated, each with an area of 216,506.35m². Subsequently, the number of public transit stops located within each spatial unit was counted. For the purposes of the analysis, only those hexagons containing at least one transit stop were retained, thus forming the spatial units of study. The exclusion of hexagons without transit stops was established as a methodological criterion consistent with the objective of identifying and characterizing the spatial patterns of concentration of the existing infrastructure, since including units without transit stops would have introduced areas lacking the phenomenon of interest into the spatial autocorrelation analysis. Thus, the analysis focused on the spatial structure of the stops actually located within the study area, allowing for an evaluation of their distribution, concentration, and spatial association among contiguous units. The number of transit stops per hexagon was subsequently added to the attribute table via a specific field, forming the database used for subsequent stages of the spatial statistical analysis.

2.6 Importing Data into GeoDa:

Once the stage of spatial processing and aggregation of the information was completed, the statistical analysis of the data was performed using GeoDa software version 1.22.0.20, incorporating the vector layer corresponding to the previously generated hexagonal tessellation. In this way, each hexagon constituted a unit of analysis and had an associated value representing the number of stops located within it.

Prior to the spatial autocorrelation analysis, the correspondence between the geometry of the spatial units and the associated attributes was verified to ensure that each hexagon was correctly assigned the corresponding number of bus stops. Subsequently, different spatial relationship schemes were defined by constructing weight matrices, which made it possible to determine which spatial units would be considered neighbors and, therefore, which proximity relationships would be used in the calculation of spatial autocorrelation.

2.7 Spatial Autocorrelation Analysis of Public Transportation Stops:

The detection of clusters in this study was based on the use of local spatial statistics, specifically Local Moran's I. According to Yildirim & Mert (2020), measures of local spatial autocorrelation are used to identify local groupings or patterns, an objective that is consistent with the purposes of this study. For his part, Chen (2023), notes that Moran's index is a valuable spatial statistical measure used to determine whether or not spatial autocorrelation exists

To assess the spatial autocorrelation of the data, the Local Indicators of Spatial Association (LISA) were used, specifically by generating significance and cluster maps. According to Kumar et al. (2024), LISA constitutes a category of spatial statistics designed to detect different types of spatial patterns, including Local Moran's I.

During the spatial analysis process, three spatial weight matrices were used to assess spatial autocorrelation under different neighborhood definition criteria. The first two were first-order contiguity matrices, using the queen and rook criteria, while the third was constructed using the k-nearest neighbors distance method, considering the four nearest neighbors. The selection of these configurations is based on the findings of Anselin (1998), who emphasizes that spatial weight matrices are a fundamental component of spatial modeling and help determine the spatial dependence among observations. In particular, the rook and queen criteria allow the neighborhood to be defined based on spatial contiguity among units of analysis. According to GeoDa (2026), the rook criterion establishes a restrictive neighborhood relationship based solely on edge contact, while the queen matrix includes units that are in contact with both vertices and edges. For its part, the k-nearest neighbors method is recognized by Ord and Getis (1995), as a traditional, globally oriented method widely used to study spatial patterns. Unlike the rook and queen criteria, k-nearest neighbors defines neighborhood based on spatial proximity, assigning each unit of analysis a fixed number of nearby neighbors, which constitutes an alternative criterion to contiguity. The combined use of these three configurations allowed us to compare results under different conceptualizations of spatial relationships and to evaluate the stability of the identified patterns. This strategy is relevant because the definition of the neighborhood structure can influence the results of spatial autocorrelation statistics; therefore, the consistency of patterns across different specifications provides stronger evidence of the consistency of the observed spatial dependence.

Once the spatial weight matrices were generated, Univariate Local Moran's I was applied. To do this, each matrix was evaluated using, as the attribute of interest, the variable corresponding to the number of public transportation stops recorded in each hexagonal cell. Subsequently, the visualizations available in GeoDa—specifically the LISA Significance Map, LISA Cluster Map, and Moran scatter plot—were generated. The study employed 999 permutations to assess the sensitivity of statistically significant locations to the number of permutations used, which allows for a p-value <0.05. According to Kumar et al. (2024), indicates that it is unlikely that the observed distribution is due to chance, suggesting the existence of a significant spatial pattern in the distribution of public transportation stops.

2.8 Interpretation of Spatial Patterns:

Once the previous steps had been completed, the results obtained in GeoDa were interpreted. This interpretation was based on the cartographic representations obtained from the application of the univariate local Moran's I statistic, specifically the LISA significance map and the LISA cluster map, as well as the Moran scatter plot.

Analysis of these visualizations made it possible to identify patterns of spatial autocorrelation and to pinpoint those tiles exhibiting statistically significant clusters in the distribution of public transit stops within the study area. Furthermore, comparing the results derived from the different spatial weight matrices allowed us to assess the consistency of the detected patterns and to support the interpretation of the observed spatial relationships. The results are shown below.

3. Results

This section presents the results obtained by applying the methodology described above. Thematic maps derived from the processing of vector data and the statistical analysis of the information are presented. Taken together, these cartographic and statistical outputs allow us to identify and characterize the patterns of spatial distribution of public transit stops in the study area, providing evidence of the presence of clustering structures, spatial dependence, and the statistical significance of the observed phenomena. Fig. 3 shows the hexagonal tessellation implemented for the spatial representation of public transit stops, while Fig. 4 graphically presents the results of the univariate analysis applied. These cartographic representations constitute the primary input for interpreting the identified spatial autocorrelation patterns, allowing us to recognize the presence of spatially significant clusters and examine the spatial relationships observed within the study area.

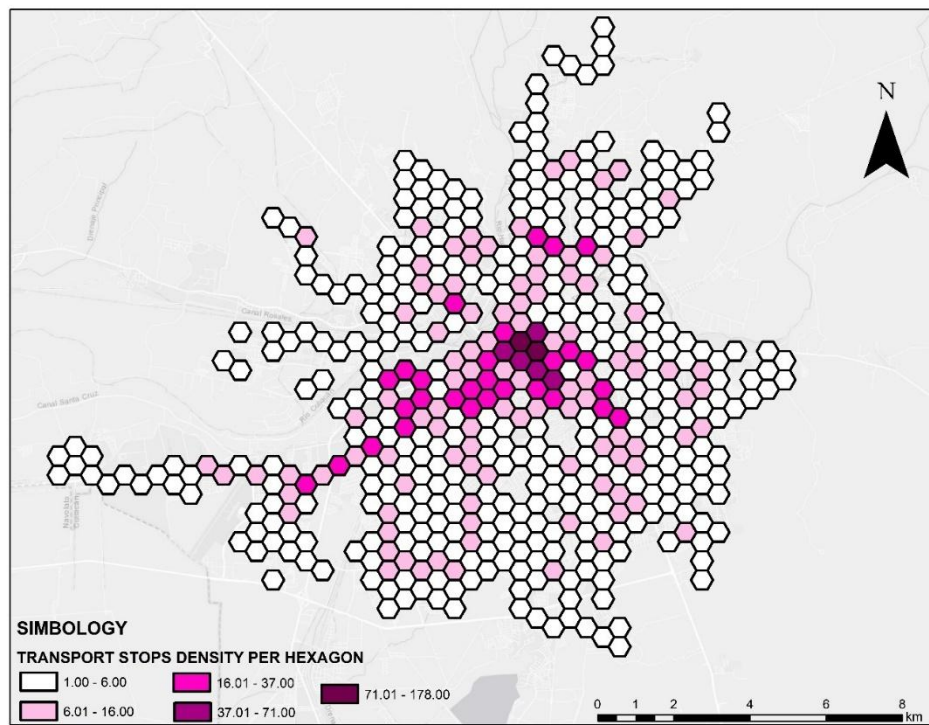


Fig. 3 Tessellation of the Study Area

Fig. 3 shows the spatial distribution of public transportation stops by hexagonal tile within the study area. The results reveal marked spatial heterogeneity in the availability of public transportation infrastructure, with a predominant concentration of hexagons containing a higher number of stops in the central sector of the urban area. It should be noted that the study population consists solely of hexagons containing at least one public transportation stop, in accordance with the objective of this research.

The hexagons classified into the public transit stop concentration intervals of 37.01 to 71.00 and 71.01 to 178.00 per polygon exhibit a continuous and relatively compact spatial distribution in the south-central and east-central portions of the study area, forming a primary core of high concentration. Adjacent to this core, hexagons with

intermediate concentrations (from 16.01 to 37.00 public transit stops) were identified, forming a transition zone that extends toward different sectors of the city.

In contrast, the hexagons corresponding to the lower concentration ranges (from 1.00 to 6.00 and from 6.01 to 16.00 public transit stops) show greater spatial dispersion and predominate in the peripheral areas of the urban area. Likewise, isolated clusters of hexagons with low and intermediate concentrations are observed, distributed toward the northern, southern, and western extremes of the study area, indicating a gradual decrease in the concentration of public transit stops as the distance from the central urban core increases.

Overall, the observed spatial pattern suggests a non-homogeneous distribution of public transit stops, characterized by the existence of a high-density core surrounded by sectors with progressively lower levels of coverage, a finding that is subsequently corroborated by statistical analysis.

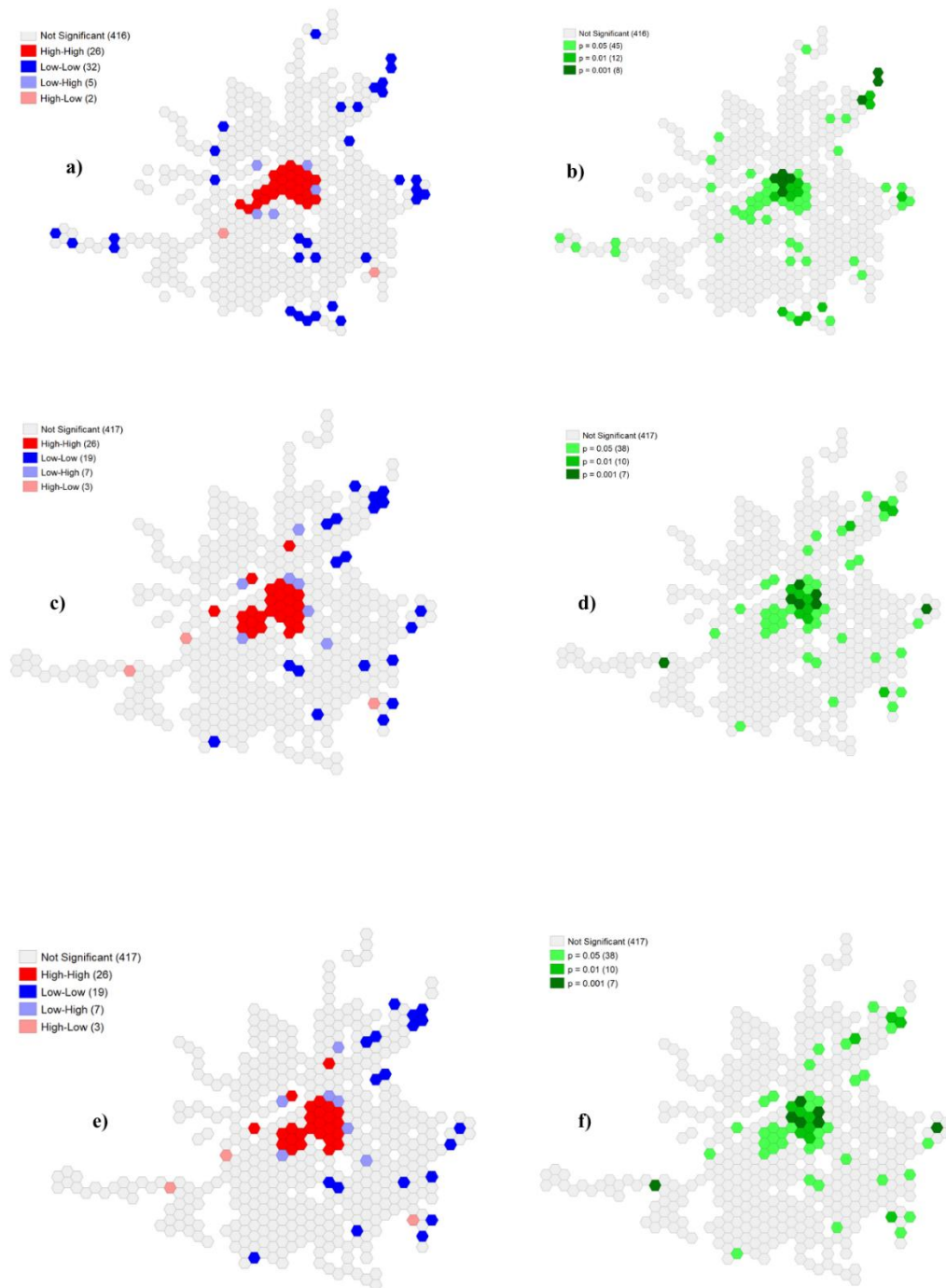


Fig. 4 Univariate analysis of the distribution of public transportation stops in the city of Culiacán, Sinaloa. **a)** LISA cluster map using k-nearest neighbors analysis. **b)** LISA significance map using k-nearest neighbors analysis. **c)** LISA cluster map in a first-order Queen's clustering analysis. **d)** LISA significance map in a first-order Queen's clustering analysis. **e)** LISA cluster map in a first-order Rook's clustering analysis. **f)** LISA significance map in a first-order Rook's clustering analysis.

The results obtained using the different contiguity specifications employed in GeoDa show remarkable convergence in the identification of the main spatial patterns, which lends robustness to the inferences made.

In the three neighborhood schemes shown in Fig. 4, a High-High spatial cluster is observed, located predominantly in the central area of the urban area. This pattern indicates that hexagons with a high concentration of public transit stops tend to be surrounded by other spatial units with similar characteristics, forming a core of high stop concentration associated with greater availability of public transit infrastructure. The persistence of this clustering regardless of the spatial weight matrix used suggests that this behavior constitutes a well-established structural feature of the urban transit system in the study area.

Complementarily, Low-Low clusters are identified, distributed primarily in the city's peripheral sectors. The presence of these clusters highlights areas where the sparse distribution of public transit stops is spatially associated with neighboring tiles that also exhibit low levels of coverage, reflecting potential areas with poorer accessibility to public transit services.

Likewise, some spatial outliers corresponding to the High-Low and Low-High categories are detected. Although their frequency is considerably lower than that of the main clusters, these configurations allow for the identification of territorial units whose behavior differs significantly from the immediate spatial context. In particular, tiles classified as High-Low represent specific areas with a relatively high number of transit stops located within environments of low availability, while the Low-High categories indicate units with a lower presence of infrastructure situated in areas with a higher concentration of transit facilities.

The statistical significance maps confirm that a significant proportion of the identified spatial associations exhibit high levels of confidence, with the central cluster of high concentrations standing out in particular.

From a territorial perspective, the identified patterns reveal a marked concentration of public transit stops in the central area of Culiacán. The High-High clusters observed across the different spatial weight configurations are located primarily in the central zone, where a significant portion of the city's commercial, administrative, and service activities has historically been concentrated. This concentration of activities generates greater demand for travel and, consequently, a greater presence of public transportation infrastructure. Therefore, the identified central pattern can be linked to this area's role as a space of high activity and connectivity within the urban structure.

In contrast, Low-Low clusters are found primarily in peripheral sectors and areas farther from the central core. These results indicate the presence of tiles with a low number of transit stops that are also surrounded by other units with similarly low values. This pattern may be associated with the city's gradual expansion toward the periphery, where urban growth has incorporated new residential areas that have a lower concentration of activities and, consequently, a lower density of public transportation infrastructure compared to the central area. In this regard, the results of the spatial analysis not only demonstrate the existence of spatial dependence but also allow for the identification of a differentiated territorial organization of public transit stops between the urban core and its peripheral areas.

Overall, the persistence of High-High clusters in the central zone and of Low-Low patterns primarily in peripheral sectors—regardless of the spatial weighting configuration used—reinforces the interpretation that the distribution of public transit stops reflects structural characteristics of the urban territory. Therefore, the results can be considered representative of a spatial pattern associated with the concentration of activities and urban expansion in the study area, rather than with a particular definition of neighborhood.

To complement the analysis of local spatial autocorrelation and evaluate the distribution pattern of public transportation stops, we examined the scatter plots of Moran's I and the histograms derived from Monte Carlo permutation simulations for each of the spatial weight matrices used. According to Andronov et al. (2016), Monte Carlo simulations are a useful procedure for determining whether a dataset differs significantly from a spatially random distribution. In this regard, their application provided complementary evidence regarding the statistical significance of the clustering patterns identified in the distribution of public transportation stops.

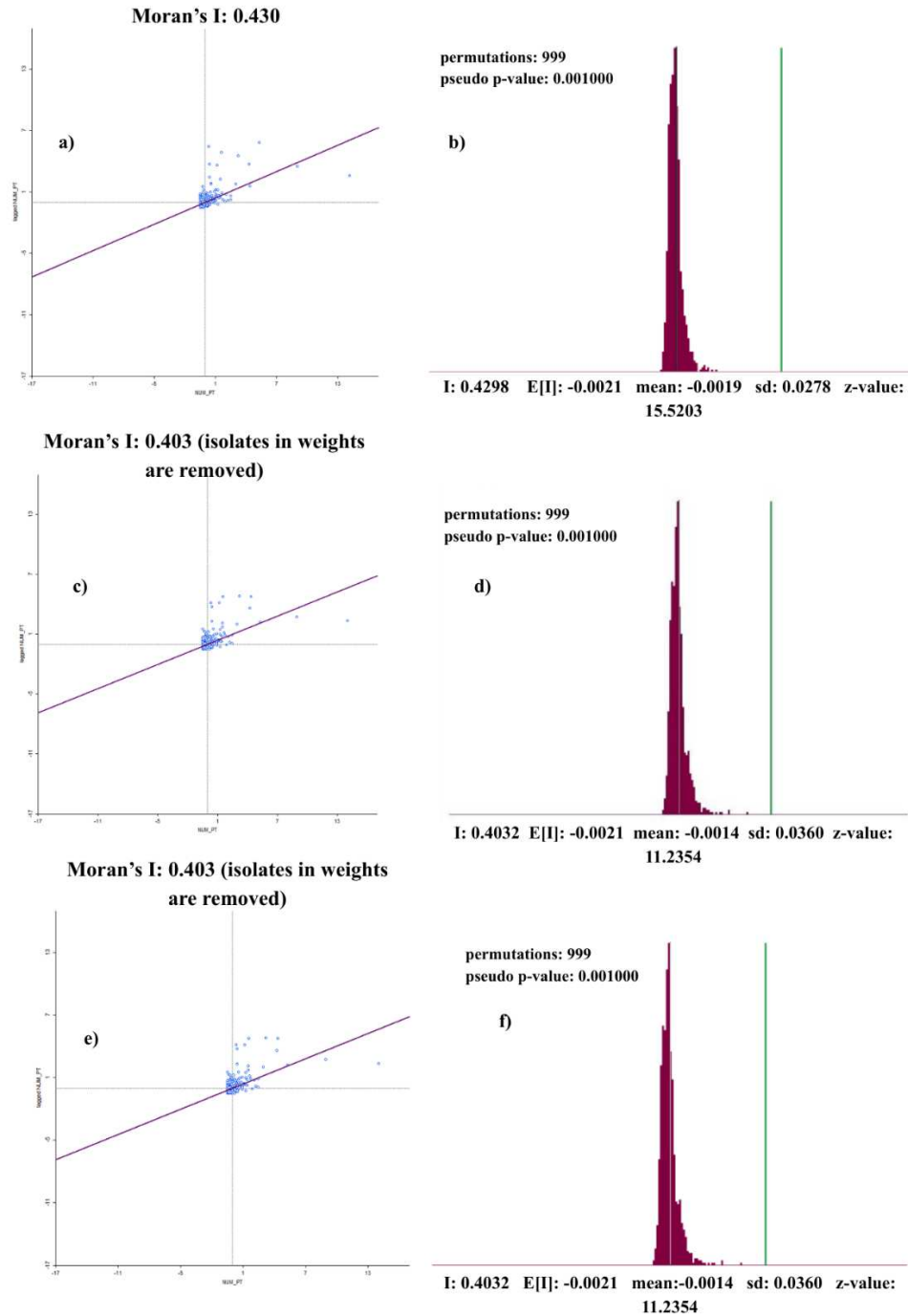


Fig. 5 Statistical analysis of the distribution of public transportation stops in the city of Culiacán, Sinaloa. **a)** Moran's index for k-nearest neighbors. **b)** Monte Carlo simulation for k-nearest neighbors. **c)** Moran's index for Queen of order 1. **d)** Monte Carlo simulation for Queen of order 1. **e)** Moran's index for Rook of order 1. **f)** Monte Carlo simulation for Rook of order 1.

The results in Fig. 5 show the presence of positive and statistically significant spatial autocorrelation in the three schemes analyzed. In the case of k-nearest neighbors, a Moran's index of 0.430 was obtained, a value considerably higher than that expected under a random distribution ($E[I] = -0.0021$). The significance test based on 999 Monte Carlo permutations yielded a pseudo p-value of 0.001 and a z-statistic of 15.5203, indicating that the probability of obtaining a spatial pattern of similar magnitude under the null hypothesis of spatial randomness is less than 0.1%.

Similarly, analyses conducted using first-order Queen and Rock contiguity matrices produced identical values for the Moran's I index ($I = 0.4032$), accompanied by pseudo p-values of 0.001 and z-statistics of 11.2354. These results confirm the existence of a spatial structure characterized by the clustering of hexagons with similar numbers of public transit stops, showing that spatial units with high values tend to be located near others with similar characteristics, while hexagons with low infrastructure availability also exhibit a tendency toward spatial clustering. This equivalence is explained by the spatial configuration of the tessera used, which does not represent a completely continuous hexagonal grid, but rather a subset of hexagons selected based on the presence of public transportation stops. By excluding empty spatial units, the resulting structure exhibits spatial discontinuities; however, the results confirm that effective neighborhood relationships are strictly maintained through shared edge adjacencies.

The consistency in statistical significance and in the magnitude of the statistics obtained using different spatial weight configurations suggests that the identified spatial dependence constitutes a consistent property in the territorial distribution of public transportation stops in the city of Culiacán, and is not a result associated with a particular specification of neighborhood relationships.

Discussions

This study is relevant to the city of Culiacán, Sinaloa, due to the limited availability of research focused on the spatial analysis of public transportation infrastructure and, in particular, knowledge regarding the current state of the territorial distribution of its stops. Although public transportation is an essential component of urban mobility, information regarding the location, concentration, and spatial organization of its boarding and alighting points is often scarce or scattered, making it difficult to identify coverage patterns and potential inequalities in service provision. In this context, this research provides evidence that allows for the identification of areas of concentration and clustering, as well as territorial differences in the distribution of this infrastructure. Furthermore, the incorporation of spatial analysis and spatial statistics techniques—particularly those aimed at measuring spatial autocorrelation—helps strengthen the methodological rigor and validity of the results by making it possible to determine whether the observed patterns result from statistically significant spatial processes or from random distributions.

The use of these analytical procedures provides an objective basis for interpreting the territorial structure of the public transportation system and facilitates the generation of scientifically grounded knowledge about its spatial behavior. Consequently, the results serve as a benchmark for future research on urban mobility and provide

information for decision-making aimed at promoting a more equitable and efficient distribution of public transportation facilities in the city.

The spatial analysis depicted in Fig. 3 identified a clear concentration of public transit stops in specific areas of the study area, revealing non-random clustering patterns. This spatial clustering suggests a hierarchical configuration of the transportation system, where the location of stops corresponds to the city's functional structure—particularly the concentration of urban activities, road connectivity, and potential mobility demand. From this perspective, the results confirm the existence of spatial inequalities in service distribution, with greater concentration in central zones and lower coverage in peripheral areas, which is consistent with spatial organization processes typical of complex urban systems.

Similar results have been documented in other urban contexts. Karly et al. (2026), found that Jakarta's highest public transportation density is concentrated in central areas, which serve as hubs of economic and social activity that generate greater demand for and supply of mobility services. In contrast, these authors demonstrate a significant decrease in density in peripheral areas, reflecting an uneven pattern in the distribution of the transportation system. In this regard, the convergence between the two studies reinforces the idea that the spatial distribution of public transportation tends to be structured around urban centers, creating accessibility gradients between central and peripheral areas.

A comparable trend was identified by Huynh et al. (2018), when analyzing the spatial distribution of public transit stops in U.S. cities based on information provided by the transit agencies themselves. The authors observed that clustered and dispersed configurations are typically associated with monocentric urban structures, while regular patterns correspond to cities that lack clearly defined centers. Although the scale of analysis and methodological procedures differ from those used in this study, both works agree that the distribution of stops reflects the functional organization of urban space and the way in which mobility systems are structured. This convergence highlights the ability of different spatial analysis methodologies to identify similar trends in the territorial structure of urban mobility systems, which lends greater robustness and support to the findings of this study.

The results associated with the Moran's index are consistent with the findings presented by Zhang et al. (2008), who indicate that a high positive value of the local Moran's index reflects the presence of similar values (high or low) in neighboring units, which demonstrates the existence of significant spatial clustering in the analyzed distribution. Furthermore, these findings align with the arguments put forward by Leitner and Brecht (2007), who state that this index is positive when the values of nearby locations show greater similarity than would be expected under a random pattern, thereby confirming the spatial dependence in the data. Similarly, Yildirim & Mert (2020), reinforce this interpretation by noting that positive spatial autocorrelation occurs when high values of a variable at one location are associated with high values at a neighboring location. The above interpretations also find methodological support in the work of Anselin (2005), who notes that calculating Moran's index first requires defining neighborhood relationships using a spatial weighting matrix. Furthermore, the author explains that the statistical significance of the index is determined through a random permutation procedure that

generates a reference distribution of the statistic, from which a pseudo p-value is obtained. This procedure provides a statistical basis for establishing that the observed patterns of spatial autocorrelation are not the result of chance but rather reflect a significant spatial structure in the distribution of the analyzed data.

Overall, the consistency between the results and the specialized literature confirms the presence of positive spatial autocorrelation in the analyzed distribution, demonstrating that the location of public transit stops does not follow a random pattern but rather an organized spatial structure in the form of clusters. This behavior reinforces the existence of territorial concentration processes associated with underlying urban dynamics, providing solid empirical support for the spatial interpretation of the phenomenon under study and strengthening the validity of the inferences derived from the applied statistical analysis.

The main contribution of this research lies not only in identifying spatial clusters, but also in demonstrating that the distribution of stops constitutes a territorial expression of urban processes related to the concentration of activities, accessibility, and the functional organization of the city. The application of local indicators of spatial association made it possible to recognize patterns that would be difficult to identify using conventional descriptive procedures. As Anselin (1995), points out, LISA indicators make it possible to detect local spatial clusters and anomalies that remain hidden when only global measures are considered. The results provide evidence for understanding how transportation infrastructure contributes to the formation of differentiated patterns of accessibility within the urban space and reinforce the potential of spatial statistics as a tool for evaluating the territorial organization of mobility systems. From an applied perspective, the identification of these patterns provides spatial information that can support decision-making regarding urban mobility and transportation planning, particularly in identifying sectors with a concentration of infrastructure, areas with fewer transit stops, and potential imbalances in territorial distribution. In this regard, the results can serve as input to guide the evaluation of service coverage, the planning of new transit stops, or the review of the existing distribution, contributing to transportation planning grounded in spatial evidence and the distinct characteristics of the territory.

From a planning perspective, the identified spatial patterns can serve as a basis for guiding differentiated actions regarding public transportation infrastructure. The concentration of transit stops in certain areas suggests the need to review the existing distribution to identify potential areas of infrastructure overrepresentation, while areas with lower concentrations may be considered priorities for conducting complementary assessments of coverage and accessibility. Thus, the results can support planning processes aimed at reviewing the location of new transit stops, assessing the relevance of maintaining or redistributing existing infrastructure, and identifying areas that require a more detailed analysis of access conditions to the city's transit system.

Conclusions

The results demonstrate that the spatial distribution of public transit stops in the city of Culiacán exhibits an organized and statistically significant spatial structure, characterized by the presence of territorial clusters that do not follow a random pattern. The persistence of positive spatial autocorrelation patterns and the identification

of clusters with high and low concentrations indicate that the location of this infrastructure is closely related to the city's functional and organization. Consequently, the distribution of stops can be understood as a spatial manifestation of urban processes associated with centrality, connectivity, and the concentration of activities within the territory.

From a scientific perspective, the main contribution of this research is to generate empirical evidence on the spatial structure of public transportation infrastructure through the application of spatial statistical techniques and local spatial association analysis. The use of a hexagonal tessellation as the unit of analysis made it possible to systematically represent the territorial distribution of transit stops and, by comparing different spatial weight configurations, to demonstrate that the identified autocorrelation patterns retain their significance and magnitude under various neighborhood definition criteria. This consistency strengthens the interpretation of the results by showing that the observed spatial dependence is not an effect associated exclusively with a particular configuration of the analysis, but rather represents a consistent spatial characteristic of the distribution of transit stops in the study area. In this regard, the study makes a methodological contribution by demonstrating the utility of integrating spatial tessellations and spatial statistics to analyze the territorial configuration of urban mobility infrastructure.

From a practical perspective, the findings provide spatial information that can be used as input for territorial planning and public transportation management. Identifying areas with high and low concentrations of transit stops allows for the recognition of differences in the territorial distribution of infrastructure and can support diagnostic processes, coverage assessments, and the prioritization of interventions. In particular, this information can help guide the review of stop locations, identify areas requiring greater attention in terms of infrastructure, and provide spatial evidence to support future strategies for reorganizing or expanding the network. Therefore, the analysis conducted is not limited to describing the existing spatial configuration but provides a quantitative basis to support decision-making processes related to mobility and urban planning.

Complementarily, the results provide insights for a deeper study of the city's functional organization by showing that the distribution of public transportation infrastructure exhibits spatial patterns associated with the territorial configuration of urban activities. This perspective allows us to consider public transit stops not only as physical elements of the mobility network but also as components whose distribution can contribute to the analysis of the relationships between transportation, urban structure, and territorial accessibility. In this regard, the proposed approach can be replicated and adapted in other cities to compare spatial configurations, identify common patterns, and explore the territorial characteristics that influence the distribution of public transportation infrastructure.

The results should be interpreted with an awareness of the limitations inherent in the scope of the research. In particular, the analysis focused on the spatial distribution and location of public transportation stops; therefore, while the identified patterns describe the territorial configuration of the infrastructure supply, they do not, on their own, explain the conditions of access or the actual use of the service. In this regard, the analysis did not incorporate variables related to user demand, service frequency, travel times, service quality, and operational

characteristics, nor did it include socioeconomic and demographic variables that would allow for an analysis of the diverse conditions of the user population. The absence of these components limits the ability to establish direct relationships between the spatial distribution of transit stops and aspects such as intensity of use, service efficiency, or accessibility conditions for different population groups.

Therefore, future research could expand the analysis through a multidimensional approach that combines the spatial structure of the infrastructure with information on demand, operations, travel times, service quality, and the socioeconomic characteristics of the population. Among the main lines of research are the analysis of multimodal accessibility, considering the interaction of public transit with other modes of travel; the evaluation of population coverage, with the aim of determining what proportion and what characteristics of the population are effectively served by the infrastructure; and the estimation of potential demand, incorporating territorial and demographic variables that allow for an approximation of the population's mobility needs. Furthermore, the use of explanatory spatial models would allow us to move beyond the exploratory identification of patterns toward an analysis of the factors that help explain the spatial distribution of transit stops and their relationship to the characteristics of the territory. Applying these approaches to other cities would also make it possible to compare the identified patterns and determine to what extent the observed relationships reflect specific characteristics of the study area or constitute recurring patterns in the spatial organization of public transit systems. In this way, we could move toward more comprehensive analyses of urban mobility, capable of linking the territorial configuration of the infrastructure to the actual conditions of service provision and use.

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