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URBAN PROXIMITY UNDER ANDEAN CONSTRAINTS: SPATIAL INEQUALITIES IN 15-MINUTE PEDESTRIAN ACCESSIBILITY TO PRIMARY ACTIVITY NODES IN ARMENIA, COLOMBIA

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Abstract: This research examines pedestrian accessibility to primary urban activities in an intermediate Andean city where topography and uneven land-use distribution condition proximity. The study operationalizes the 15-min. city framework through a spatial assessment of walking access to nodes associated with education, health, recreation, commerce, and the mobility system. Using QGIS and OpenRouteService (ORS), 15-min. walking isochrones were generated from 164 centroids corresponding to normative urban sectors. These isochrones were intersected with georeferenced facility layers to compute Z(x), a cumulative-opportunity indicator representing the number of reachable nodes by category. Ordinary Kriging, was then used to transform discrete centroid-based measurements into continuous accessibility surfaces. Spatial dependence was evaluated through Moran's I, and model performance was assessed by cross-validation statistics. The results reveal a marked center–periphery gradient across all activity categories. Education and recreation show broader medium-accessibility zones and weaker polynuclear patterns, whereas health and commerce display highly concentrated structures and extensive accessibility deficits. Low-accessibility areas reach 87.1% for health and 87.7% for commerce. The mobility system presents an intermediate condition, with 48.1% of the urban area still classified as low accessibility. These findings demonstrate that urban proximity is not a homogeneous citywide attribute, but a service-specific condition shaped by functional centrality, spatial inequality, and pedestrian-network constraints. The proposed method provides operational evidence for prioritizing urban planning interventions aimed at redistributing essential services and strengthening equitable walkable access.

Keywords: 15-minute city, pedestrian accessibility, urban proximity, ordinary kriging, isochrones, spatial inequality

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INTRODUCTION

In contemporary urban planning, accessibility is recognized as a central construct for evaluating the relationship between the spatial distribution of opportunities and the frictions imposed by a mobility system. In its seminal formulation, Hansen (1959) defines it as the "potential of opportunities for interaction" derived from the location of activities, adjusted by impedances according to the transport mode; this idea remains relevant because it highlights that accessibility conditions are not reduced to simple physical proximity, but rather express the effective possibility of reaching goods and services by an individual or a community. Building on this foundation, Geurs & van Wee (2004) consolidated an analytical framework that integrates transport, land use, and individual/socioeconomic components, highlighting the utility of cumulative-opportunity measures defined by time thresholds for territorial comparison.

In this context, the proximity cities approach, and particularly the notion of the "15-minute city," operationalizes the concept of accessibility as daily access to essential services via active transport modes within said time frame, proposing a spatially and temporally explicit measurement and evaluation agenda (Bruno et al., 2024; Staricco, 2022).

The application of this paradigm, however, requires caution in intermediate cities and in Global South contexts, where the location of facilities usually responds to historical trajectories of centrality and accumulated investment inequalities (Bolay & Rabinovich, 2004). Furthermore, in Andean cities, topography and the discontinuity of the pedestrian network can significantly increase the real costs of walking, intensifying center-periphery gradients even when relatively short distances exist. Consequently, rather than normatively verifying whether a city "meets" the 15-minute ideal, it is methodologically more robust to build comparable indicators that allow for the identification of accessibility gradients, underserved sectors, and

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patterns of functional concentration with direct utility for planning and the prioritization of interventions. Within this framework, Armenia (Colombia) constitutes a relevant case study due to its status as an intermediate Andean city embedded in the Coffee Region (*Eje Cafetero*), associated with the Coffee Cultural Landscape inscribed on the World Heritage List (UNESCO, 2011). Its urban morphology is conditioned by rolling terrain with slopes that can restrict active mobility and, therefore, decisively modulate pedestrian accessibility to daily facilities. In tourist and heritage contexts, accessibility conditions, both for residents and visitors, have been increasingly addressed using spatial analysis tools; for instance, studies on routes and territories of the Coffee Cultural Landscape have employed territorial accessibility approaches to characterize connection conditions and the spatial support of tourist activity (Orjuela et al., 2020). This line of research reinforces the need for fine-grained urban diagnostics that integrate network, time, and the distribution of opportunities.

Methodologically, modeling urban accessibility conditions requires transforming discrete measurements, associated with reference points, into territorial representations capable of capturing gradients and spatial dependence. In this regard, isochrones constitute a suitable calculation tool to estimate "on-network" (rather than Euclidean) accessibility conditions, by incorporating the connectivity and the actual structure of the pedestrian mobility system. Specifically, ORS developed by the Heidelberg Institute for Geoinformation Technology (HeiGIT), allows for generating temporal accessibility polygons based on networks derived from OpenStreetMap (OSM) and routing algorithms, which are widely used for mobility and accessibility analysis in Geographic Information Systems (GIS) environments (HeiGIT, 2024, 2025; Neis et al., 2012). By intersecting isochrones with facility layers, discrete coverage indicators are obtained that express the availability of opportunities within a time threshold, consistent with the operationalization of proximity cities.

Nevertheless, isochrone-based results remain tied to a finite set of origins (e.g., centroids), which can limit territorial interpretation when it is necessary to recognize spatial continuity, transitions, and functional boundaries. To overcome this limitation, geostatistics offers a consistent framework to treat the concept of accessibility as a regionalized variable and to build continuous estimation surfaces under verifiable assumptions of spatial autocorrelation. The Kriging model, based on the semivariogram, allows for obtaining unbiased linear estimations of minimum variance when the variable exhibits a spatial structure (Cressie, 1993; Matheron, 1963). Applied guides consolidate its implementation and validation through standard procedures (Johnston et al., 2001), and the methodological literature shows that spatial structure critically influences the performance and accuracy of interpolation methods (Kravchenko, 2003). In the open-source ecosystem, Smart-Map integrates these procedures into QGIS, the open-source GIS and has been documented as a reproducible tool for digital cartography based on ordinary Kriging (Pereira et al., 2022). Likewise, urban applications have demonstrated the utility of Kriging for modeling continuous surfaces of accessibility/proximity from discrete indicators and supporting territorial analysis and planning processes (González-Ruiz et al., 2019). Based on the above, this research analyzes the pedestrian accessibility conditions of the city of Armenia through an integrated approach that combines: (i) the generation of 15-minute walking isochrone curves from centroids associated with normative units defined by the current Territorial Development Plan (Plan de Ordenamiento Territorial, POT), using QGIS/ORS Tools; (ii) the calculation of discrete coverage indicators by categories of Primary Activity Nodes (PAN): Education, health, recreation, and commerce) and connection points with the mobility system; and (iii) geostatistical interpolation using ordinary Kriging to construct continuous surfaces that are comparable across categories, with verification of spatial dependence and cross-validation (Cressie, 1993; HeiGIT, 2024; Pereira et al., 2022).

This design seeks to identify territorial accessibility patterns (e.g., monocentrism, bicentrism, or functional focalization) and to recognize relative deficits in peripheral sectors, producing cartographic and metric inputs aimed at decision-making and strategies conducive to providing greater territorial equity (Geurs & Van Wee, 2004; Geurs & Van Wee, 2026).

MATERIALS AND METHODS

The research is based on a geostatistical analysis performed in QGIS, a cross-platform open-source software that allows for the creation, editing, visualization, and analysis of geographic data. It integrates plugins that act as interfaces to incorporate data, apply functions, and automate processes through algorithms within its GIS environment. In this study, the ORS Tools plugin was used, which provides routing and spatial analysis services by integrating QGIS with the ORS Application Programming Interface (API). This API, based on the OSM network, employs shortest-path algorithms on graphs representing streets, generating isochrone polygons that delimit the nodes reachable within a specific time range from a point of origin. These algorithms have been applied in recent studies to generate 15-minute isochrones for active mobility modes (pedestrians and bicycles), analyzing mobility patterns and accessibility conditions within the framework of the 15-minute city, and promoting sustainable planning in intermediate cities (Heidelberg Institute for Geoinformation Technology, 2025). To generate the isochrone curve polygons, the specific module of the plugin was used, which requires prior parameterization by the user (point of origin, transport mode, and travel time threshold). Once these parameters are defined, the plugin sends a HyperText Transfer Protocol (HTTP) request to the ORS API, which processes the information using the road and pedestrian network derived from OSM. As a result, the API returns the isochrones in GeoJSON, a geographic data interchange format based on JavaScript Object Notation (JSON), which are automatically incorporated into the QGIS project as new vector layers. The methodology is structured into 5 phases, as follows: Phase 1. Definition of spatial reference entities.

According to Staricco (2022), modeling territorial accessibility conditions requires the definition of a representative geometric barycenter for each spatial unit of analysis. The present research was conducted based on the normative sectors defined in the current POT of the city of Armenia (Figure 1), from which the centroids of each sector were calculated as an independent vector layer, thus configuring spatial reference entities for the estimation of 15-minute walking times. This structuring allowed for the definition of a point cloud with sufficient coverage for the city's accessibility study.

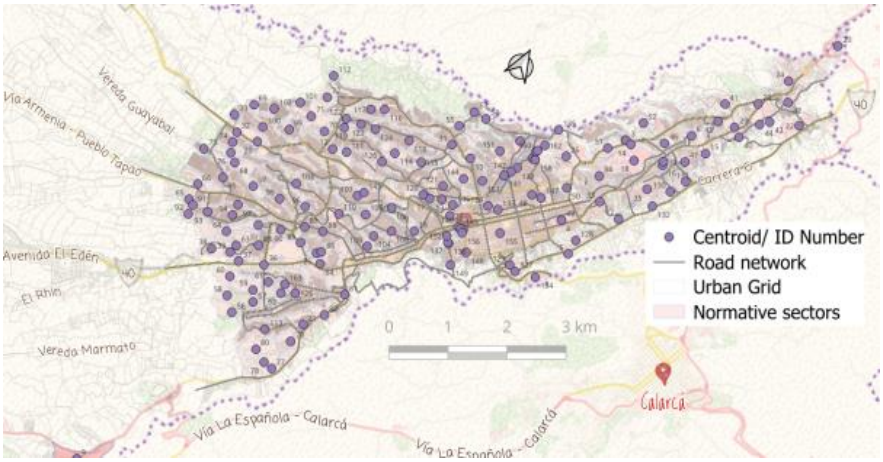


Figure 1. Normative sectors and reference centroids (Source: Authors)

Phase 2. Construction of thematic layers of urban facilities. Relevant urban public facilities are identified based on the concept of proximity cities or 15-minute cities (Moreno et al., 2021; Omwamba et al., 2021), which emphasizes the selection of PAN considered essential for meeting minimum daily needs: Education (Figure 2a), Health (Figure 2b), Recreation (Figure 2c), and Commerce (Figure 2d), alongside their relationship with the mobility system (Figure 2e).

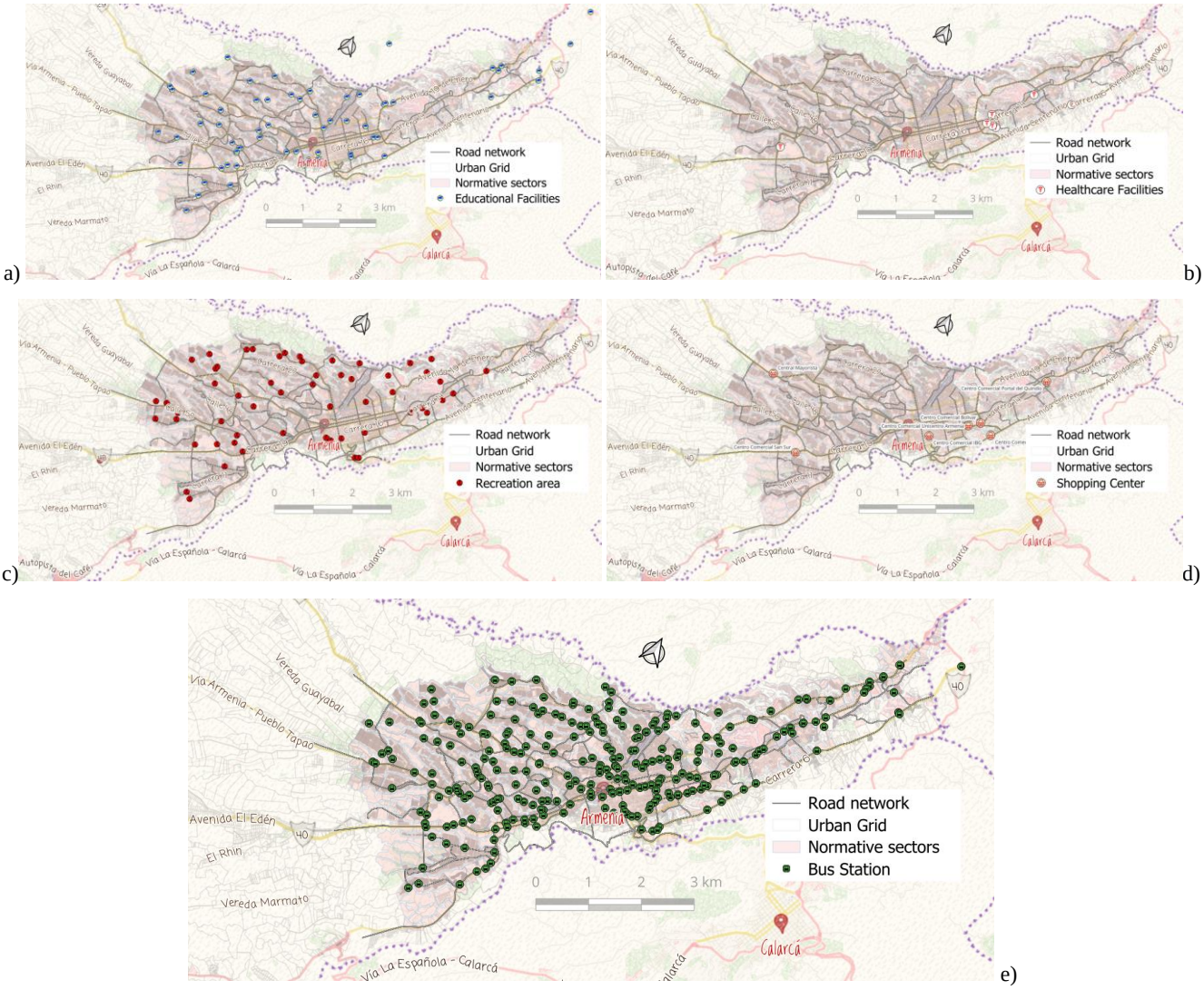


Figure 2. PAN. a) Education, b) Health, c) Recreation, d) Commerce, e) Mobility system (Source: Authors)

In this research, Educational PANs encompass primary and secondary educational institutions, universities, and technical training centers such as the *Servicio Nacional de Aprendizaje* (SENA; National Learning Service); Health PANs comprise

Instituciones Prestadoras de Servicios de Salud (IPS; Health Service Provider Institutions) providing emergency services; Recreation PANs consist of leisure and sports areas; Commerce PANs were selected as community-scale shopping centers; and facilities belonging to the mobility system include public transport stops and regional transport terminals.

Phase 3. Generation of isochrone curves. To delimit the pedestrian accessibility areas, the ORS Tools plugin in QGIS was employed, specifically utilizing the "Isochrones from Point" tool. The ORS Tools algorithm calculated the reachable area from each centroid using a maximum temporal metric of a 15-minute walk, based on an average speed of 5 km/h established by ORS for the foot-walking mode.

The result consisted of isochrone polygons representing the accessible space on foot from each centroid, considering the actual connectivity of the urban road and pedestrian network. Using the road and pedestrian network registered in OSM as a reference, the algorithm generated an isochrone layer for each selected centroid. This procedure was systematically repeated for the 164 normative sectors, resulting in an equal number of isochrone curve polygons (See Figure 3) that represent, in a disaggregated manner, the pedestrian accessibility conditions within said time threshold, adjusted to the topological characteristics and the actual connectivity of the urban network.

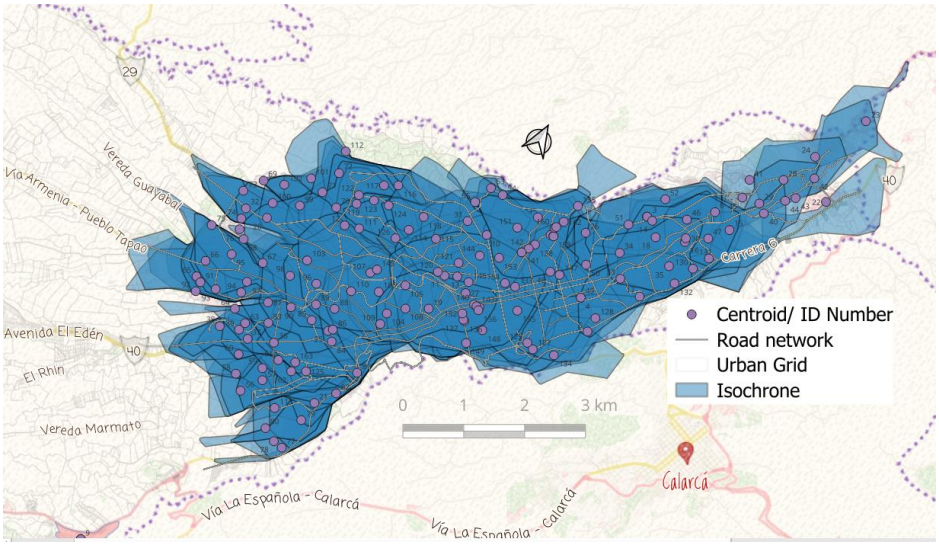


Figure 3. 15-minute isochrone curves from each normative sector centroid (Source: Authors)

Phase 4. Coverage analysis. A spatial intersection was performed between the 15-minute isochrone curves from each centroid of each normative sector, and the number of PANs located within each isochrone curve was counted. This allowed for calculating the amount of facilities available to the population within said time threshold.

Phase 5. Continuous accessibility modelling using Kriging. The procedure begins with the structuring of a spatial database associated with the centroids of the normative sectors. These centroids are assigned the accessibility values calculated in the previous phase, corresponding to the number of urban facilities contained within each 15-minute isochrone. Given that each PAN category (Education, Health, Recreation, and Commerce), as well as the connection points with the transport system, were treated as independent spatial variables, specific differentiated layers were generated for each one, allowing their spatial behavior to be modeled individually to facilitate subsequent comparison. The variable used for the interpolation will correspond to the number of PANs per category contained within the 15-minute isochrone curve (Z(x)), which is a non-negative discrete variable that can be considered a regionalized variable, as it exhibits spatial variation and potential dependence associated with PANs of the same category. Proximity-based accessibility and the indicator function will be defined as presented in Equation 1.

This formulation will make Z(x) the sum of discrete presences within each isochrone curve, constituting a direct indicator of effective accessibility (Johnston et al., 2001).

$$z_{(x)} = \sum_{j=1}^{k} f\left(d(xj)\right); \qquad f(d) = \begin{cases} 1, if\ d(x,j) \le 15\ min \\ o" \\ 0, if\ d(x,j) > 15\ min \end{cases} \tag{1}$$

Where: j = index representing each individual PAN of the evaluated category; k = total number of PANs of said category in the study area; d(x, j) = travel time between location x and PANj; f(d) = indicator function that determines whether or not PANj will contribute to the accessibility value of point x.

It should be noted that, although many categories of urban PANs tend to show spatial organization patterns consistent with the functional structure of the city, in cases where the supply is scarce or highly specialized, as can occur with hospitals or other complex facilities, the variable Z(x) might not exhibit a clearly structured spatial distribution. Therefore, the existence of spatial dependence will not be assumed beforehand; instead, it will be empirically verified through the calculation of the semivariogram, in order to determine whether or not the accessibility values present any similarity between nearby locations. The spatial dependence of Z(x) will be examined using the empirical semivariogram, which will

be calculated with Smart Map. In geostatistical terms, such dependence will imply that accessibility values at nearby locations will tend to present greater similarity to each other than to more distant points, configuring a spatial autocorrelation pattern. Based on the identified spatial structure, the Ordinary Kriging model will be applied, defined as a minimum variance unbiased linear estimator, where the weights λ_i are automatically determined by the Smart Map plugin from the selected semivariogram model. This allows the estimator to incorporate the modeled spatial structure and generate continuous accessibility surfaces by PAN category, as presented in Equation 2 (Matheron, 1963).

$$Z^*(x_0) = \sum_{i=1}^{n} \lambda_i Z(x_i) \quad (2)$$

Where: $Z^*(x_0)$ = estimated value at the unsampled location; x_0 = point where accessibility is to be interpolated; x_i = locations with observed data; n = number of observations used in the estimation; λ_i = interpolation weights assigned to each observation $Z(x_i)$, derived from the defined semivariogram model.

The procedure will generate a series of independent raster surfaces, each corresponding to the continuous spatial distribution of the pedestrian accessibility level towards a specific category of PANs. These surfaces are compared across categories, allowing for the identification of areas with a higher intensity of PANs and sectors presenting relative deficits within the 15-minute walking threshold. Additionally, a cross-validation process is performed between the observed values and the values estimated by the model, in order to evaluate its internal consistency and predictive capacity. This procedure allows for the continuous representation of the spatial behavior of urban accessibility and will serve as the basis for the comparative analysis among the different PAN categories in the city of Armenia.

RESULTS AND DISCUSSION

The prospective raster surfaces obtained using the ordinary Kriging model (Figure 4 to Figure 8) for each analyzed PAN allow for comparing the spatial structure of pedestrian accessibility conditions for the 15-minute threshold, measured as the number of accessible PANs, Z(x), where the green sectors indicate high accessibility, yellow sectors indicate medium accessibility, and red sectors indicate low accessibility. In general terms, all PAN categories present a centre-periphery gradient pattern, with accessibility maximums concentrated along the central urban axis and a progressive decrease towards the edges. However, the categories differ markedly in (i) the territorial extent of high and medium accessibility zones, (ii) the abrupt change in transitions between accessibility conditions, and (iii) the degree of functional concentration (monocentrism vs. presence of secondary focus).

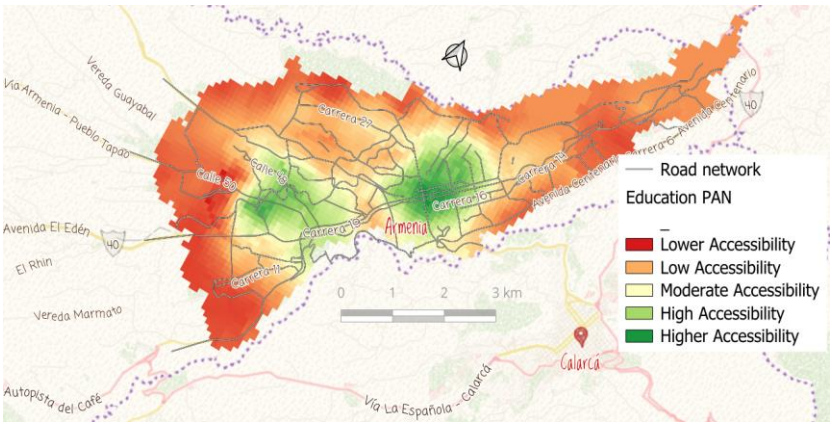


Figure 4. Prospective raster for Education PAN (Source: Authors)

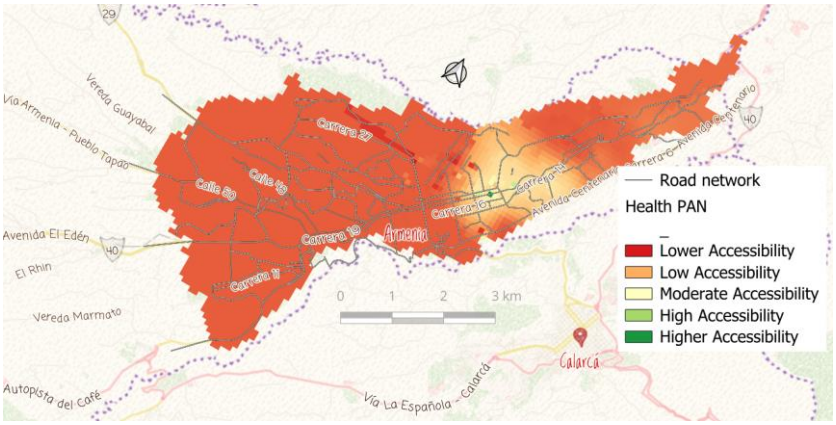


Figure 5. Prospective raster for Health PAN (Source: Authors)

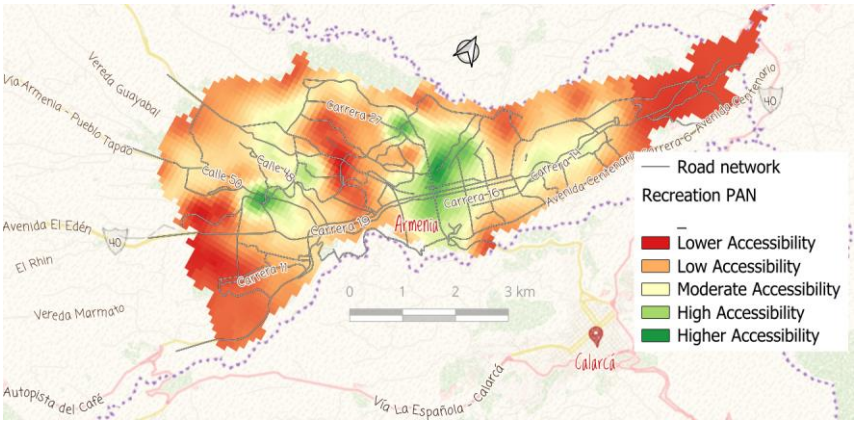


Figure 6. Prospective raster for Recreation PAN (Source: Authors)

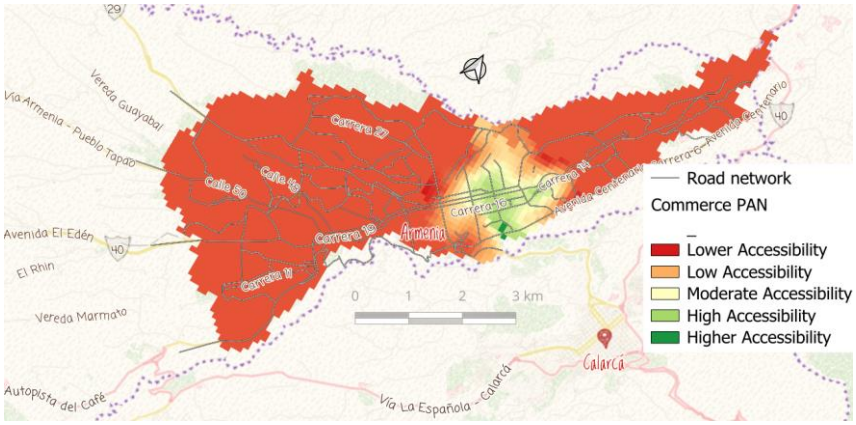


Figure 7. Prospective raster for Commerce PAN (Source: Authors)

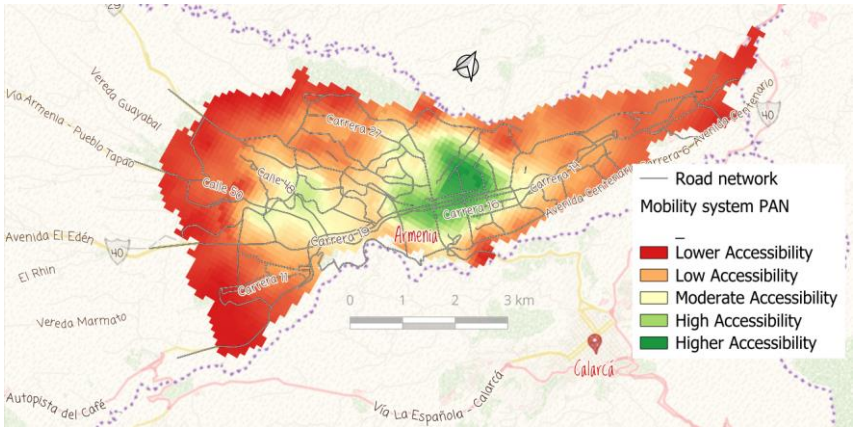


Figure 8. Prospective raster for Mobility system PAN (Source: Authors)

From a comparative perspective of accessibility conditions, the Education (Figure 4) and Recreation (Figure 6) categories show the greatest relative extent of medium to high accessibility.

In Education, the area classified as high accessibility (green) represents approximately 7.7% of the urban area, while medium-high (yellow) and medium-low (orange) accessibility conditions reach 14.3% and 45.8%, respectively, leaving low accessibility conditions (red) at 32.1%. This result demonstrates a surface with a predominance of intermediate zones (yellow + orange ≈ 60.1%) and suggests a weak polynuclear pattern, where the central core is complemented by secondary foci towards the west, expanding the accessibility field beyond the consolidated center.

In Recreation, the behavior is even more widespread in terms of medium accessibility conditions; although the green area is smaller (3.8%), the yellow class reaches 16.4% and the orange 51.7%, with a relatively reduced red area (28.1%).

This distribution (yellow + orange ≈ 68.1%) indicates that accessibility conditions to Recreation PANs are expressed as a more heterogeneous and fragmented surface, with medium accessibility sectors and transition corridors that partially connect with the central core.

In urban terms, this morphology is consistent with a more dispersed recreational provision than that of Health and Commerce PANs, but it is still incapable of eliminating peripheral deficits, which persist as extensive red areas.

The Mobility System (Figure 8) exhibits a more monocentric pattern with relatively gradual transitions around the urban center. For this PAN, high accessibility conditions represent around 5.9%, medium accessibility represents 45.9% of the area (yellow 10.4%, orange 35.5%), and low accessibility conditions (red color) rise to 48.1%; that is, nearly half of the territory maintains low accessibility conditions to the system. This result suggests greater spatial "capillarity" around the urban centrality compared to Health and Commerce PANs, but it confirms that the coverage of the mobility system alone does not neutralize the accessibility deficit in urban edges, which remain structurally lagging.

In contrast, the results for Health (Figure 5) and Commerce (Figure 7) PANs show poorer and more concentrated accessibility conditions. For Health, low accessibility conditions represent approximately 87.1% of the urban area, with a practically non-existent presence of high accessibility (green area ≈ 0.2%) and a marginal fraction of the urban area with medium accessibility conditions reaching 12.7% (yellow 0.4% + orange 12.3%). The spatial structure corresponds to a focalized pattern (high concentration in a central-eastern core), with abrupt transitions towards low accessibility, which is consistent with higher-complexity healthcare facilities and a lower number of units. Similarly, the Commerce PAN presents a dominance of low accessibility conditions at 87.7%, with a minimal share of high accessibility (0.5%), and a marginal share of medium accessibility conditions at 11.8% (yellow 4.0% + orange 7.8%). This reflects that commercial accessibility is anchored in a reduced centrality, while vast peripheral areas remain outside effective proximity thresholds.

Overall, the comparative reading presented in Table 1 confirms that the inequality in accessibility conditions in Armenia is not homogeneously distributed across various PAN categories and, consequently, urban functions. Recreation and Education PANs present more extensive surfaces with medium accessibility conditions, suggesting relatively more distributed coverage; the Mobility System PAN has a broad core but with persistent deficient peripheries; and the Health and Commerce PANs extremely concentrate the high values of Z(x), leaving most of the territory in low accessibility conditions. These differences are relevant for urban planning, as they indicate that territorial prioritization should not be uniform: while Health and Commerce demand strategies for the redistribution/strengthening of supply in the peripheries, Education and Recreation require finer interventions aimed at closing local "gaps" and improving pedestrian continuity in transition zones.

Table 1. Comparison of Accessibility Conditions by PAN (Source: Authors)

PAN	Accesibility Conditions				
	High (green)	**Medium high (yellow)**	**Medium low (orange)**	**Low (red)**	**Medium (yellow+orange)**
Education	7.7%	14.3%	45.8%	32.1%	60.1%
Health	0.2%	0.4%	12.3%	87.1%	12.7%
Recreation	3.8%	16.4%	51.7%	28.1%	68.1%
Commerce	0.5%	4.0%	7.8%	87.7%	11.8%
Mobility system	5.9%	10.4%	35.5%	48.1%	45.9%

These patterns are consistent with evidence of significant spatial dependence reported in the inferential analysis. In particular, Moran's index confirms positive autocorrelation for Education ($I = 0.823$; $p = 0.001$), Health ($I = 0.688$; $p = 0.001$), and transport system stops ($I = 0.737$; $p = 0.001$), which implies the presence of high and low accessibility clusters and supports the geostatistical assumption of spatial continuity. Complementarily, the internal consistency of the Kriging model, evaluated through cross-validation, shows strong fits for Health ($R^2 = 0.883$) and the Mobility System ($R^2 = 0.837$), and a satisfactory fit for Education ($R^2 = 0.815$), validating the use of continuous surfaces as a basis for comparison across categories. In terms of spatial interpretation, where high accessibility conditions occupy a reduced territorial fraction and the predominance of low accessibility conditions is greater (Health/Commerce), transitions tend to be more abrupt, and the peripheral deficit acquires a structural character.

In contrast, in categories with a greater presence of medium accessibility conditions and secondary foci (Education/Recreation), the gradient softens and more complex spatial configurations emerge (e.g., bicentrism or weak polynuclearity), although without completely eliminating the deficient areas at the urban edges.

CONCLUSION

The results confirm that urban proximity, understood as the possibility of walking to essential services within a fixed time threshold (15 minutes), does not materialize homogeneously in the city of Armenia. Even though all analyzed categories present a center-periphery gradient, with accessibility maximums concentrated in the central axis and decreases towards the edges, the ability to fulfill the proximity paradigm varies substantially depending on the type of PAN.

This evidences an unequal urban functional structure that is highly dependent on consolidated centralities.

This differentiation by function is key: the "15-minute city" is not a global attribute of the urban system, but a service-specific condition and, therefore, susceptible to failing in some components even when others show relatively better performances. In comparative terms, Education and Recreation PANs present the best relative conditions of pedestrian proximity, which tends to be sustained over a broader portion of the urban fabric and with more gradual transitions towards the periphery. This suggests more complex spatial configurations (e.g., weak polynuclearity) and a higher probability for the population to find opportunities within the time threshold compared to other PANs.

In contrast, Health and Commerce exhibit the greatest proximity deficits, with an extreme dominance of low accessibility conditions: Health registers 87.1% of the area in red and Commerce 87.7%. This indicates that pedestrian access to emergency healthcare services and community-scale commercial nodes does not adequately meet the 15-

minute threshold for most of the urban territory, especially in the peripheries. The focalized spatial organization and abrupt transitions observed in these surfaces suggest that the supply is anchored in a reduced centrality, generating extensive "shadow zones" where daily life depends on longer commutes or the use of motorized modes.

The Mobility System of PANs is situated in an intermediate condition because, although it presents a relatively broad central core and a relevant proportion of medium accessibility conditions (45.9%), low accessibility still represents 48.1% of the urban area. This indicates that the connectivity associated with stops/terminals, even while being more "capillary" than Health and Commerce PANs, does not by itself compensate for the low functional provision in the urban periphery, and that effective proximity depends simultaneously on pedestrian connectivity and the spatial distribution of opportunities. In terms of urban policy, this finding suggests that solely reinforcing the mobility system without intervening in the location/coverage of critical PANs may improve relative accessibility, but does not guarantee the fulfillment of the proximity paradigm.

In summary, the results lead to a central implication for urban planning: territorial prioritization must be differentiated by function according to the PAN. The evidence suggests that Health and Commerce PANs require explicit strategies for the redistribution or strengthening of supply in the peripheries (new facilities, coverage expansion, or satellite services), while Education and Recreation PANs demand finer interventions aimed at closing identified local gaps and improving the continuity of the pedestrian network in transition zones.

In the same vein, the methodological approach based on isochrones (ORS Tools) and interpolation (Smart-Map/Kriging) allows for translating the proximity concept into operational metrics and surfaces to guide POT decisions, by moving from discrete measurements by centroids to continuous accessibility fields comparable across PAN categories.

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

Use of Generative AI: Not applicable.

Abbreviations: API: Application Programming Interface; GIS: Geographic Information System; GIMS: Grupo de Investigación en Movilidad Sostenible (Sustainable Mobility Research Group); HeiGIT: Heidelberg Institute for Geoinformation Technology; HTTP: Hypertext Transfer Protocol; IPS: Instituciones Prestadoras de Servicios de Salud (Health Service Provider Institutions); ORS: OpenRouteService; OSM: OpenStreetMap; PAN: Primary Activity Nodes; POT: Plan de Ordenamiento Territorial (Territorial Development Plan); QGIS: Open-source Geographic Information System software; SENA: Servicio Nacional de Aprendizaje (National Learning Service); UNESCO: United Nations Educational, Scientific and Cultural Organization.

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