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RESEARCH ARTICLE

Merger of Network Graph Indicators to Estimate Resilience in Latin American Cities

DIEGO CORDERO[1] **AND GUILLERMO RODRIGUEZ**[2]

[1]Green IT Research Group, Administration Academic Unit, Universidad Católica de Cuenca, Cuenca 010107, Ecuador
[2]Research Unit, Academic Unit of Informatics, Computer Science and Technological Innovation, Information Technology Career, Computer Engineering Research, Universidad CatÓlica de Cuenca, La Troncal 010107, Ecuador

Corresponding author: Diego Cordero (dcordero@ucacue.edu.ec)

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ABSTRACT In Latin America, cities are characterized by uncontrolled urban growth and locations in critical geographic areas. This factor affects an individual's ability to react efficiently to an action known as resilience to disasters caused by natural phenomena or catastrophes that involve human participation. This study proposes a method for detecting vulnerabilities in urban road systems in large, intermediate, and small cities in Latin America, so that resilience can be better supported. Depending on the structural characteristics of a city, measurement techniques can be used to combine the topological, geographic, and spatiotemporal indicators. Several measurements, such as mesh and connectivity, betweenness centrality, closeness centrality, robustness of networks with interruption attacks, location of dead ends, measurement of travel times between origin and destination, elevations and fusion of indicators with clusters on the same map, were applied using network graphs from OpenStreetMap (OSM) to estimate the resilience of road networks. The results are exposed to clusters of fused geospatial maps, which show that intersections and streets tend to be classified as vulnerable, with morphological structures of growth, resistance to degradation of the urban network, marginal urban sectors with high conglomeration, and mobility. The results highlight the importance of applying resilient practices in the region and generating urban management options to strengthen the response capacity of cities in Latin America.

INDEX TERMS Resilience, road networks, indicator fusion.

I. INTRODUCTION

With the Brundtland Report of 1987, the celebration of the Earth Summit and Agenda 21 in 1992, urban planning and sustainable development have acquired greater interest in the concept of systemic or sustainable urban planning [1]. Urban planning has a long-term, systemic, and comprehensive vision [2]. However, at the beginning of the 21st century, the perspective of systemic planning lost strength due to the political and economic instability experienced by many developing countries, including some from Latin America, in the late 1990s. This has affected the entire generation of urban projects that aim to improve the physical condition of cities. Today, the importance of sustainable urban strategic planning is highlighted once again, and even though the proposed objectives are not always achieved, there is an agreement to obtain improvements [3].

The planet Earth deteriorates more rapidly [4], and the capacity to react to natural and other disasters is less efficient [5]. The Covid-19 crisis shows that no country or city has sufficient resilience to adverse events [6], especially in densely populated urban areas marked by a lack of social, governmental, communicational, and leadership capacity to respond to the crisis [7]. Therefore, it is critical to investigate the resilience and sustainability of urban networks [8], owing to their exposure to different types of risks, either individually or collectively [9], to estimate the response capacity of cities [10]. If the damage caused to the infrastructure of cities by climatic disasters, earthquakes, social phenomena, pandemics, strikes, and political disturbances [11] is added to the above, the environment exists in a context to generate various research schemes on resilience in urban centers.

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It is reasonable for humans and the environment to adapt to and recover from disasters. However, it is more likely that urban structures weaken after catastrophic events. The factors that affect cities worldwide to a greater degree are constant population growth, lack of emergency planning, increase in vehicular traffic, deficiency in basic services, conglomeration, and urban mobility [12].

According to the United Nations [13], it is estimated that by 2050, approximately 70 percent of the world's population will live in urban areas. With this concentration index, cities in poor or developing countries are subject to higher growth [14]. Consequently, it is necessary to analyze the resilience of both small and intermediate cities in advance to partially mitigate the problems that may arise in future instances if the current chaos in large cities is taken as a reference owing to disorganized urban growth and increased vehicle traffic, among others [15].

This study begins with an in-depth review of the literature on sustainability concepts that locate the mobility and transport dimensions in an urban model to sustain the relationship with resilience. To do this, the classification of cities according to the Inter-American Development Bank IDB [16], based on the number of inhabitants, is as follows: small, less than one hundred thousand; intermediate, less than 2 million; and large, more than 2 million. This is helpful in determining similarities and differences between cities, which is key to identifying the incidence of adverse factors during resilience.

This work elaborates on a proposal to determine the resilience to adverse phenomena in cities by characterizing their road networks. Emphasis is placed on the analysis through the theory of variable graphs framed in the following phases: mesh and connectivity, centrality measures, analysis of the robustness of networks, location of end nodes, travel times between origin and destination, elevation in urban networks, and fusion of indicators. These variables impact the resilience and sustainability of cities in such a way that their treatment can lead to balanced distributions of basic services and adequate management of urban mobility, among others [17].

These results add valid knowledge to the existing literature on resilience so that public policies and decisions can be stimulated [18], contributing to the integral and egalitarian development of urban areas in different regions [19]. The Latin American cities object of the study have vulnerabilities in their infrastructure, which are factors that aggravate resistance to adverse phenomena of natural or other origin. The problem becomes even more critical because of the accelerated growth of cities without adequate long-term planning. Therefore, the actors responsible for urban planning are urged to integrate aspects of resilience and sustainability into policies and instruments for managing the territory.

The remainder of this paper is organized as follows: Section 2 explains the literature, Section 3 distinguishes methodology, Section 4 presents results, followed by a discussion in Section 5, Section 6 presents the conclusions.

II. BACKGROUND

This study provides a method for detecting vulnerabilities in the urban road systems of Latin American cities that allows determining road resilience against natural or provoked catastrophic events, understanding resilience as the ability of a system to maintain functioning and overcome disturbances that affect it, or the capacity of societies, communities, or cities to resist, adapt, absorb, or recover efficiently from disasters within a reasonable period [20]. For this, a structural analysis of the cities is elaborated, which allows the determination of the state of the current road system that determines resilience capacity. Recently, there has been an accentuated increase in scientific disclosures of the resilience capacity of small, medium, and large cities that are exposed to different types of climatic [21], social [22], and health [23] risks, among others. Moreover, emphasis has been placed on sustainability, understood as the conservation of components that ensure the needs of the present without compromising future resources [24]. A thorough understanding of resilience and sustainability identifies the synergies between these concepts. Despite this, the opportunity for analysis is recruiting an increasing number of researchers enthralled by the possibility of valuing them.

The lack of methodological on this subject generates uncertainty among scientists and technicians regarding their practical applications in urban environments. Despite this, the CATMED sustainability indicators model is taken as a starting point, generated in the research program of the European framework called "Climate Change and associated natural risks," which among its edges includes the relationship between climate change and sustainable development cities [25]. In this study, the urban model was structured based on three variables: complexity, compactness, and proximity to basic services, from which the development of cities is directed towards sustainability. Compactness is directly related to construction density [26], complexity attends to urban organization, and reflects the maturity of the urban fabric and the wealth of economic, social, and biological capital [27]. Proximity is an expression of mobility [28]. The mobility and transport axes were considered using the proximity variable, which encompasses an urban road system [29].

According to Walker *et al.* [30], mobility is a fundamental axis of urban sustainability. In the case of disaster risk, the transportation system directly and indirectly influences resilience. The direct one is related to the mobility capacity of citizens after the event and has to do with the problems generated by the collapse of the infrastructure; on the other hand, the indirect one is related to the displacement habits of the population [31]. Furthermore, connectivity is vital for recovery; that is, within a city and between it and its rural surroundings [32]. Basic supplies are necessary to maintain redundancy in the infrastructure and connectivity between citizens [33]. According to Greiving *et al.* [34], the association between resilience and urban networks is determined by quantitative and qualitative indicators of the road system.

It is crucial for urban centers to be exposed to risks to ensure the correct and rapid evacuation of inhabitants into safe areas. Studies carried out on evacuations during the tsunami in Japan in 2011 showed that private vehicle congestion in the road system caused unnecessary loss of human life [35]. The lack of resilience conditioned by the capacity for adaptability, rather than its robustness, has severe consequences in crowded cities [36]. The leading cause of this problem is the misguided management of human beings in the informal expansion of urban and industrial areas [37]. According to Rodysill *et al.* [39] and Mue *et al.* [38], this factor affects a high percentage of cities in developing countries where the Latin American region is located.

In this study, the urban morphology of the cities in the sample was analyzed using network graphs, which were proposed to translate reality into geometric components to explore the topological properties, neighborhood, and connectivity, in reference to Insaurralde and Cardozo [40], in their analysis through the graph theory of the road network of the province of Corrientes in Argentina. It is also important to mention that the push for mathematical models to solve spatial problems has led to the application of graph theory in communications and transportation network studies in the United States. Kansky [41] conducted the first study, and a considerable number of theoretical-methodological references, especially on transport networks, have strengthened them. The contributions of Chorley and Haggett [42], Tinkler [43], and Potrikovsky and Taylor [44] have been strengthened by Seguí and Petrus [45], Bosque Sendra [46], and Garrido Palacios [47].

Traffic congestion is one of the most persistent problems in a city. As a solution, Zhang *et al.* [48] proposed resilience metrics based on large-scale GPS datasets to characterize and improve the adaptation and recovery of traffic in cities when problems arise. These might present disturbances, which are classified as either major or minor, and cause a considerable impact on the performance of road networks. In this research, geospatial data focused on the graph theory proposed in the literature were used [49]. Similar treatments were applied to urban road networks and transport systems to regain normality in the event of an accident [50]. In addition, studies that apply techniques to assess the impact of adverse events, such as floods or landslides, on transportation systems are considered as [51], where the urban network is modeled through a graph of N vertices (links), denoted by $G = \{V, E\}$, where V is the set of N vertices and E is the set of edges (sections of streets) that connect the vertices. Network connectivity links the E/N relationship, where E consists of ordered pairs of vertices (directed graph) and unordered pairs of vertices (undirected graph), which are represented by adjacency matrix $\{x, y\} \in E$. Here, x is the start node, and y is the end node of a side or arc (these nodes are also known as the sender and receiver.

A series of geospatial factors was analyzed to evaluate the resilience behavior in floods, such as elevation, slope, water depth, and drainage capacity of urban networks [52]. Andrade and Lucioni [53] pointed out that the presence of floods in urban spaces is determined by both anthropogenic and natural factors. The former is determined by the low capacity to capture rainwater due to physical deterioration; on the other hand, the latter is constituted by topographic aspects and hydromorphic soils with low permeability [54].

In the design of a road network without consideration of surface runoff, the construction of channels without careful consideration of the hydrological functioning of the environment is derived in urban areas that lack the need to evacuate the accumulated water product of soil waterproofing [55]. To date, in Latin America, there have been few approaches to studying this issue, based on the ravages caused by the El Niño phenomenon [56] and other geological disasters occurring in coastal cities [57].

To study elevations, publicly available digital elevation models (DEMs) have been developed, such as the Advanced Space Thermal Reflection and Emission Radiometer (ASTER) v2 and shuttle radar topography mission (SRTM) suggested by Boeing [58]. This model has been previously applied to analyze floods and sea-level loads [59]. The data provided by the ASTER DEM satellite had a spatial resolution to cover the world of 1 s from 83 °N to 83 °S, and the SRTM DEM had a resolution of 3 s from 60 °N to 56 °S. The recovery of each elevation node was performed using Google Maps API and OSMnx [60].

The main components of the study are road networks, which are considered public works because the government sponsors them to serve the entire community and belong to the economic development group according to Ortega *et al.* [61]. This infrastructure is composed of urban road networks and nearby railways [62]. The focus of the present research project is on urban transport road networks. Therefore, the measurement of resilience and sustainability of road networks is a function of congestion or interruption of vehicular traffic on roads with greater intermediation [63]. Vehicle density is directly related to population growth and is classified as a pollutant with a high degree of criticality for the environment owing to the emission of gases [64].

Another analysis corresponds to the mobility of the population as a function of travel time from the origin to the destination (OD). For optimization, the road network must be efficient, accessible, and reliable to connect specific routes in a city [65]. Studies support this by Yadav *et al.* [66], who analyzed the capacity of cities to meet the transport demand of people who need to travel to different places due to labor, commercial, educational, and entertainment needs, or tourism. For this purpose, the requirement is that the urban transport flow is robust, either at standard times or during catastrophic natural events [67].

According to Hillier [68], human settlements and road networks go hand-in-hand when establishing a cause-effect relationship. However, according to Varoudis *et al.* [69], space

TABLE 1. Comparison between the proposal and the theoretical references.

Proposal	Theoretical references		
	Studies	Methodology	Author
Classification of the study cities into large, medium, and small.	Classification of cities according to number of inhabitants.	Classification of cities as small less than one hundred thousand, intermediate (less than two million) and large (more than two million).	[16]
Relationship between resilience and sustainability in cities according to geographical conditions through graph theory.	Determining the impact on the resilience and sustainability of cities.	Analysis using graph theory of location, geographical elevation, connectivity, access, or lack of access to the sea of cities.	[17]
Road network analysis of cities with graphs.	Determine mobility and transportation, encompassing an urban road system.	Road network analysis using graph theory.	[28], [29]
Relationship between resilience and characteristics of road networks in cities.	Determination the association between resilience and urban networks.	Use of quantitative indicators, including those of road systems.	[34]
Mesh and connectivity analysis.	Road network analysis.	Use of graph theory in road networks.	[40] [41] - [47]
Use of proximity indicators betweenness centrality (BC), closeness centrality (CC).	Graph theory in road network studies.	Use of proximity indicators: betweenness centrality and closeness centrality.	[68] - [71]
Robustness of networks to interruption attacks.	Robustness of densely populated urban networks in relation to traffic spread.	Interaction between primary and dual transport layers through intentional attacks.	[72]
Location of end nodes.	Road network density.	Location of road network nodes.	[67]
Measurement of travel times between origin and destination ODs.	Optimization of road networks to connect specific routes in the city.	Study of the mobility of the population based on travel time origin to destination.	[65]
Measurement of elevation in urban networks	Resilience in urban planning.	Use of geospatial indicator elevation.	[52], [58], [59]
Fusion of indicators with clusters.	Centrality analysis.	Measures of centrality and eccentricity	[73]

syntax theories refer to the so-called settlement-alteration effects of mobility patterns, which merge with network science, and studies related elements through graph theory, making room for a new pattern of analysis. Centrality, which is already applied in structural sociology, finds a new field of application through nodes (people) and arcs (relationships). Freeman's investigations [70], which were taken as reference works from the 1950s, determined the first level of indicators such as betweenness centrality, closeness centrality, and degree centrality for their application in the environment of cities. Studies such as those by Mercadé *et al.* [71] use and explore the potential of centrality measures as an instrument for describing intermediate urban areas in the metropolitan region of Barcelona; references are also considered by the authors.

Thus, a robustness analysis was conducted for traffic networks based on the interaction between the primary and dual transport layers for metropolises, in which intentional attacks were conducted on self-organized and planned cities [72]. Based on a unique closeness centrality (CC) analysis in Euclidean space and the relationship between primary and dual space, it is determined that although flat graphs display very different properties, the information space induces them to converge towards systems that are similar in terms of transport properties [73].

To validate the theoretical support of the proposal, Table 1 presents, a comparison between the considerations and steps of the methodology proposed by the authors and the theoretical references.

III. METHODOLOGY

A. STUDY AREA

The cities under study are detailed in Table 2, which includes the country to which they belong, number of inhabitants, area in square kilometers, elevation above sea level, number of streets, and number of intersections. Of these with more than two million inhabitants classified as large are: Quito, Guayaquil, Bogota, Medellin, Cali, La Paz and as medium: Trujillo, Manta, Santo Domingo Tsachilas.

In BC, a vertex is more central as many low-cost routes pass through it. This was obtained by adding the shortest routes between all pairs of network nodes [75]. BC is denoted

TABLE 2. Characteristics of the cities studied.

City	Country	Population	Surface Km ^{2}	Elevation m	Lanes	Intersections
Quito	Ecuador	2,200,000	400.0	2,850	96,949	38,213
Guayaquil	Ecuador	2,366,902	344.5	4	111,715	40,310
Bogota	Colombia	7,000,000	354.0	2,640	160,193	63,504
Medellin	Colombia	2,569,424	382.0	1,495	56,916	24,056
Cali	Colombia	2,545,682	619.0	1,018	59,481	21,810
Trujillo	Peru	1,088,300	1084.0	34	40,662	13,648
La Paz	Bolivia	3,023,800	472.0	3,625	36,800	14,351
Manta	Ecuador	264,261	60.0	6	26,553	9,232
Santo Domingo Tsachilas	Ecuador	270,875	79.0	550	21,383	7,816

as a graph G (V, E), where V is a set of nodes or vertices (intersections of streets) and E is a set of edges or links (streets).

To analyze and evaluate resilience as the ability to resist, adapt, and recover from a disturbing event in a sample of Latin American cities, the urban networks were downloaded. The indicators were analyzed to measure and segment the vulnerable areas of each city with respect to: (1) Mesh and connectivity. (2) Betweenness centrality (BC), closeness centrality (CC). (3) Robustness of networks to interruption attacks. (4) Location of end nodes. (5) Measurement of travel times between origin and destination ODs. (6) Measurement of elevation in urban networks (7). Fusion of indicators with clusters on the same map.

B. INDICATORS FOR MEASUREMENT AND ANALYSIS

The seven indicators analyzed were as follows:

1) MESH AND CONNECTIVITY

The morphological structure of each city was analyzed to determine its structural formation, as it expanded over time through the calculation of mesh (MH) and connectivity (CN). The mesh parameter determines whether a city has grown in a self-organized or planned manner; if the value of the mesh is high, it implies a tendency to be planned; on the contrary, a low value represents self-organization. Connectivity considers the relationship between the number of streets vs. intersections or nodes vs. edges; if the ratio is greater than 2.5, connectivity is high.

2) BETWEENNESS CENTRALITY (BC), CLOSENESS CENTRALITY (CC)

BC and CC are evaluated to determine the segmentation or clustering of areas prone to traffic congestion and the principal agglomerations of health services, education, commerce, finance, public, and private, which affect the mobility and accessibility of urban populations [74], [80].

Betweenness centrality measures the importance of a vertex v in V to connect two edges, p and q in E, considering the shortest paths. The BC was calculated using (1) [76].

$$B_i = \sum_{j \neq g \in G} \frac{B_{jg}(i)}{B_{jg}} \tag{1}$$

where Bi is the betweenness centrality of a vertex or edge in accessibility, $\beta jg(i)$ is the number of shortest paths between vertices or edges j and g passing through vertex or edge i and βjg is the total number of shortest paths between them.

Closeness centrality, indicates the average distance of all shortest routes from vertex v to any other vertex n-1 accessible within the network [76]. CC indicates how high a node is connected in the graph, which is normalized by adding all possible minimum distances and is calculated using (2).

$$C_i = \frac{v-1}{\sum_{i \neq v \in G} d_{iv}} \tag{2}$$

where Ci is the closest centrality with respect to vertex i, d_{iv} is the shortest distance according to the Dijkstra method in graph G between vertices i and v, and vertices with a small average length towards the rest of the vertices have a high near centrality [76]. It is crucial to measure the variations in the elevation of urban networks [49], especially in coastal cities, to improve the urban analysis of the road networks of a city. This technique was used to identify lower-elevation streets prone to flooding during the winter.

The extended statistics of the study of urban networks also includes the eccentricity of the network. The eccentricity of a node is the shortest path distance from the furthest node. Where, for a node $v \epsilon V$ in a connected graph G, the eccentricity returns the maximum distance nodes v to any other node $u \epsilon V$ of the graph G. Empirically, the eccentricity measures how far a node v is from the edge furthest from the network (the perimeter of the network) [58].

3) ROBUSTNESS OF NETWORKS TO INTERRUPTION ATTACKS (RN)

Two interruption attacks are carried out on each network as follows: a random attack, where the nodes are eliminated one by one at random, and a targeted attack, where nodes are eliminated, starting with those with the greatest intermediation to those with the least intermediation. The drop in connectivity revealed by the curves of the two attacks was then analyzed to assess the resilience of the network at each growth stage [77], [78].

4) LOCATION OF END NODES

The dead-end nodes (DN) of each urban network are quantified, complementing them with nodes with three and four links (DN4), to form clusters on the map of each city and observe the distribution of the most vulnerable urban areas in the face of possible road closures.

5) MEASUREMENT OF TRAVEL TIMES BETWEEN ORIGIN AND DESTINATION (OD)

Travel times are calculated on roads with the greatest intermediation susceptibility to high demand from both vehicles and passengers at different times and on different days with the intention of detecting variations in speed and possible traffic jam routes. The geographic elevation information provided by Google Maps was used to determine the lowest sectors of cities prone to the highest risk of flooding.

6) MEASUREMENT OF ELEVATION IN URBAN NETWORKS (EM)

In this section, an analysis of geospatial data is conducted to identify the elevations or degree of slope of urban networks. That is, places with minimum slopes are prone to flooding and those highest with the risk of landslides. These data were used only for validation of some cities under study as reference points [58].

7) FUSION OF INDICATORS WITH CLUSTERS ON THE SAME MAP (IF)

Finally, BC, CC and eccentricity were used to observe groupings or clusters on a single map. This activity facilitates the global analysis of the city, both in its location, distribution, and position of each critical node. Eccentricity indicates the furthest nodes of the network from its center. It is calculated by measuring the distances from source node v to all other nodes u and taking the maximum. Instead, the smaller the eccentricity of a particular node, the closer it is to all other nodes, that is, the node is more central. Therefore, eccentricity can also be used to calculate the most central nodes when considering minima.

IV. RESULTS

A. MESH AND CONNECTIVITY

To analyze the measurements of the morphology, topology, and geography of the cities, OSM is used, and the bounding box method (bounding box) and polygon of Networkx are applied. Table 3 displays the mesh and connectivity characteristics of each city, including the number of nodes, edges, mesh index, connectivity index, and organization index. Figure 1 illustrates the urban networks of the sample cities.

B. BETWEENNESS CENTRALITY (BC) AND CLOSENESS CENTRALITY (CC)

The BC calculation is carried out for both the nodes and the links of the road network globally; this experiment is carried out to locate the streets and intersections that are candidates

TABLE 3. Mesh and connectivity.

City	Nodes	Edges	Mesh	Connectivity	Organized
Quito	38,213	96,949	0.77	2.54	0.80
Guayaquil	40,310	111,715	0.89	2.77	0.69
Bogota	63,504	160,193	0.76	2.52	0.77
Medellin	24,056	56,916	0.68	2.37	0.79
Cali	21,810	59,481	0.76	2.53	0.73
Trujillo	13,648	40,662	0.99	2.98	0.62
La Paz	14,351	36,800	0.78	2.56	0.84
Manta	9,232	26,553	0.94	2.88	0.68
Santo Domingo Tsachilas	7,816	21,383	0.87	2.74	0.72

to receive the highest vehicular traffic circulation [79]. On the other hand, the streets and intersections with the lowest average proximity to the rest of the network are highlighted with the CC analysis [80]. These sectors are generally prone to crowding, as they are shopping centers, businesses, financial entities, and health clinics.

Table 4 lists the BC and CC values for the cities studied. In this regard, BC measures the average interconnectivity of the streets, allowing the determination of those with the highest rate of vehicular traffic, the same ones that are key to connecting different points in the urban network. When the BC is higher, cities will have traffic difficulties during peak hours, as in the case of Bogota, Quito, Cali, and Guayaquil. At this point, it is convenient to ask the question: What happens to motorized traffic if the routes are blocked or interrupted by an adverse event? The most likely response is that actions, including maintenance and contingency plans, are taken to improve road resilience [81].

TABLE 4. BC and CC values.

City	BC	CC
Quito	88.32	501.30
Guayaquil	70.39	583.35
Bogotá	90.55	729.71
Medellin	67.49	436.15
Cali	74.57	351.37
Trujillo	59.7	240.60
La Paz	67.57	195.10
Manta	42.13	217.78
Santo Domingo Tsachilas	42.80	182.80

Therefore, in an adverse event, resilience decreases owing to street blockages and congestion. In the case of Trujillo and Manta City, which are coastal cities with a flat shape, a greater number of routes with a low BC index were distributed throughout the city; a similar situation occurs with Santo Domingo Tsachilas. For Medellin and La Paz, BC values had medium ranges.

The geospatial segmentation of these nodes for the cities is shown in Figure 2 which represents the BC with red points and refers to increased vehicular traffic. For each city, 200 points of higher intermediation values of the urban network were taken as a reference. This measurement makes it possible to locate the main avenues that serve as the favorite

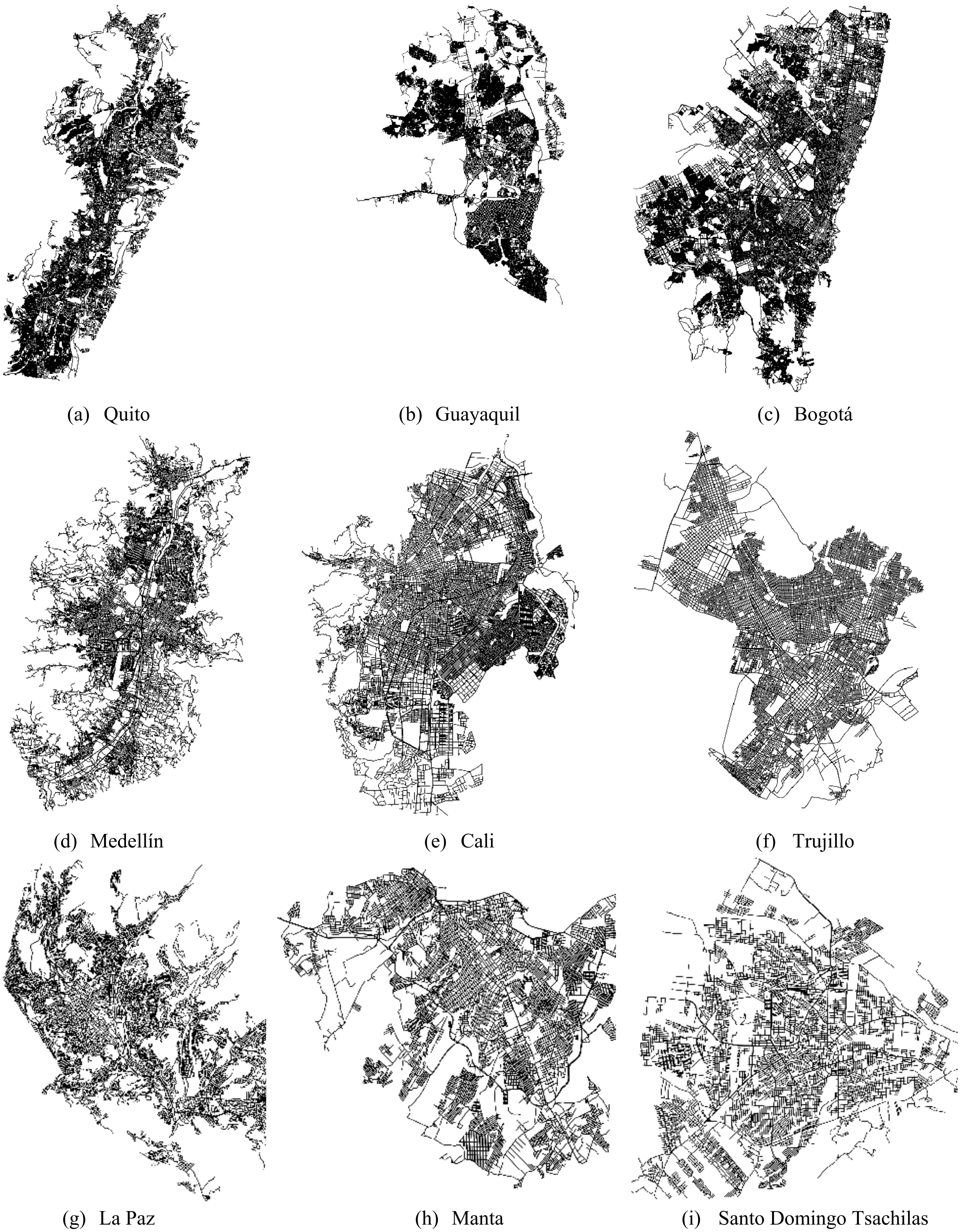
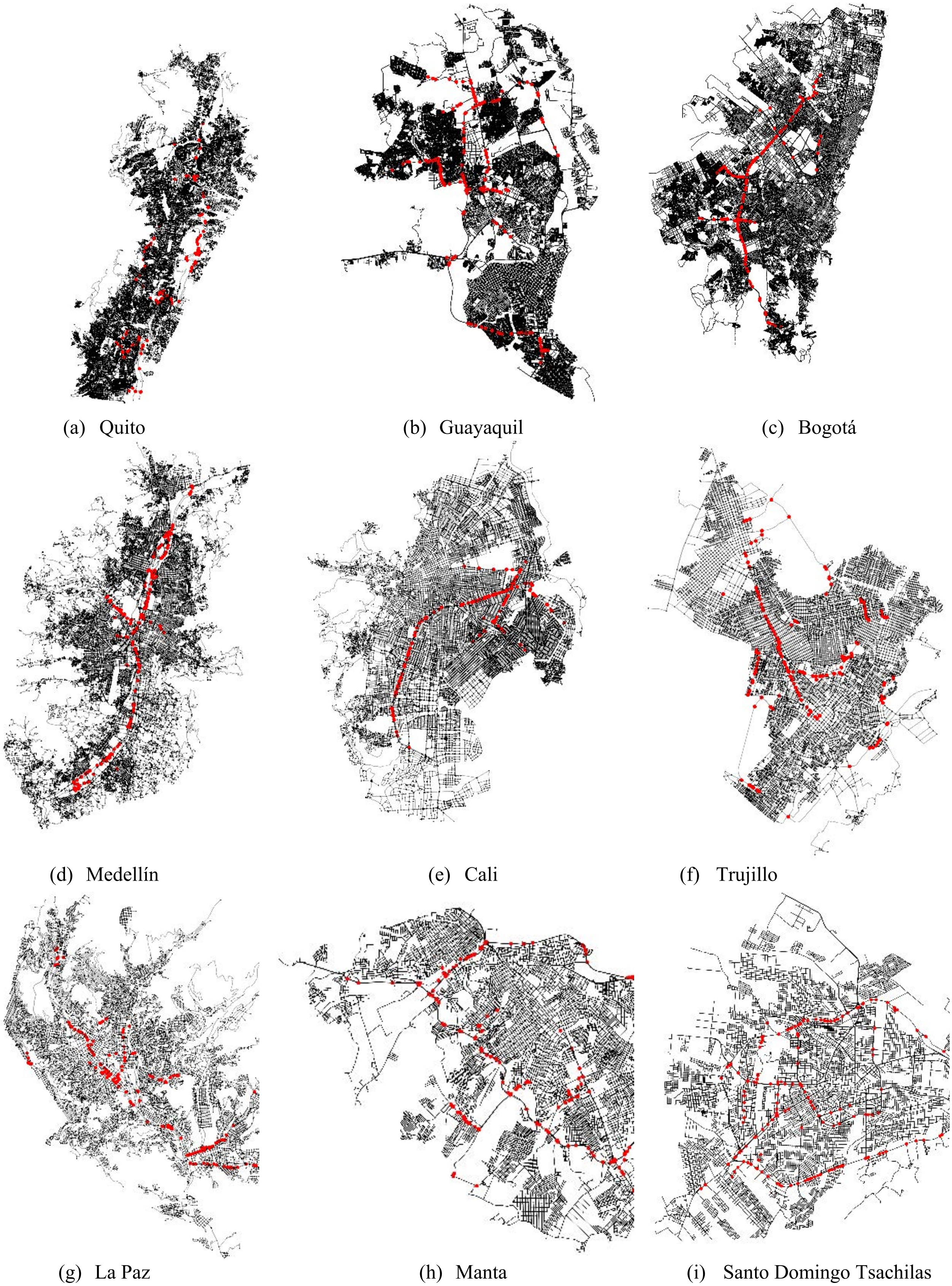


FIGURE 1. Basic urban networks of Latin American cities.



(a) Quito (b) Guayaquil (c) Bogotá

(d) Medellín (e) Cali (f) Trujillo

(g) La Paz (h) Manta (i) Santo Domingo Tsachilas

FIGURE 2. Betweenness centrality for Latin American cities.

routes for moving passengers within the city. Because the evaluation factor has the closest relationship to the calculated BC between the nodes and the edges of a route; it can be determined that in flat and open cities (without mountains), as in the case of Guayaquil, Trujillo, Cali, and Manta, it is possible to build a greater number of avenues that offer high intermediation to meet the high traffic demand of urban travelers.

CC helps determine the streets and intersections that, on average, have the shortest distance to the rest of the nodes of the urban network. If the average is low, it implies that the nodes are vulnerable or critical; generally, these areas are made up of financial and commercial entities, among others, with high vehicular traffic and agglomeration of people. An adverse event in these areas will lead to accessibility problems, making low resilience; CC values can be analyzed for each city in Table 4. The closeness centrality (CC), analysis applied to the network graphs of the cities is shown in Figure 3.

C. ROBUSTNESS OF NETWORKS WITH INTERRUPTION ATTACKS (RN)

The results of random and targeted attacks on cities showed that resilience progressively grows as the city grows (Figure 4), where the y-axis represents the number of nodes in the network, and the x-axis represents the progressive fraction of nodes in the network and nodes eliminated during the attack in each city. This indicator is understood by observing the area between the blue and orange lines that grow, because the network falls faster by interrupting nodes with a higher BC.

Robustness attacks on urban networks complement the degree of resilience of each network by progressively destroying individual nodes. The attacks were performed in a random and targeted manner based on BC analysis. In the random method, a random node is eliminated and the network connectivity is recalculated until the entire network is disconnected. For the directed method, the process is the same, except that the nodes with the highest BC which are ordered in descending order are eliminated first. The directed method causes the network to decrease faster because the main nodes that connect the entire network are removed. In the graph, the random attack is represented by the orange line, and the attack directed according to BC is represented by the blue line.

To analyze the results, the first 25% of the nodes eliminated from each city were considered, the two attacks were evaluated simultaneously, and the lost area of each network was compared. That is, the proportion of connectivity lost was calculated using the urban network by eliminating 25% of the initial nodes. As access roads are progressively interrupted, the largest cities (Bogotá, Quito, Guayaquil, Cali, and Medellín) resisted better connectivity than smaller ones (Trujillo, La Paz, Manta, and Santo Domingo de las Tsáchilas) because larger urban networks have a greater number of edges and nodes that can replace those that have been removed.

D. LOCATION OF END NODES

The indicators for dead ends (DN) and four-link nodes (N4) were calculated to assess the degree of planning or disorganization of the different road networks in each city. Dead ends correspond to terminal or return streets that are vulnerable to adverse events, because they have a minimum level of connection. If this link is interrupted, communication is impossible.

Table 5 shows the categorization according to the size of the urban network of each city, where measurements were made of dead ends and nodes with four links. The percentage of nodes without exit for the analysis indicates a weakness for the accessibility towards them in case of a disturbing event they are blocked they would be trapped without access. On the other hand, the nodes with four links are an advantage for a city; these nodes would have a better chance of access in the case of a blockage of some access, while the other three remain.

TABLE 5. Indexes of dead ends v(1) and four link intersections v(4).

City	Nodes	Dead Nodes	Nodes four links	% dead nodes	% nodes four links
Quito	38,213	7,057	7,327	19.1%	19.8%
Guayaquil	40,310	4,287	12,609	10.5%	30.9%
Bogota	63,504	13,271	8,393	22.3%	14.1%
Medellin	24,056	3,644	4,867	15.6%	20.8%
Cali	21,810	1,651	5,849	7.6%	26.9%
Trujillo	13,648	820	5,125	6.1%	38.0%
La Paz	14,351	2,296	2,230	16.1%	15.6%
Manta	9,232	1,234	2,901	13.4%	31.5%
Santo Domingo Tsachilas	7,816	1,334	2,203	16.7%	27.5%

Based on the percentage of dead nodes, the cities that lead to the connectivity problem are Bogota (22.3%), Quito (19.1%), Santo Domingo Tsachilas (16.7%) and La Paz (16. 1%). On the other hand, the best-planned cities are Trujillo (6.1%), Cali (7.6%), Guayaquil (10.5%) and Medellin and Manta (intermediate states). With respect to the percentage of nodes with four links, greater advantage of decongestion in the face of an adverse event and consequently greater resilience are found in Trujillo, Manta, and Guayaquil; with greater problems are Bogota, La Paz, and Quito.

To appreciate the degree of organization of the cities according to the distribution of dead ends and the four link nodes, Figures 5, 6, and 7 are attached.

The organic mesh analysis of dead ends and four link nodes in Figure 5, 6, and 7 and Table 5 is a technique used to assess the planning of each city in time, that is, before the population continues to expand in a disorganized manner.

E. MEASUREMENT OF TRAVEL TIMES BETWEEN ORIGIN AND DESTINATION (OD)

To complement the study of the resilience of urban networks, because the stretches of highways or avenues of Greater BC are prone to vehicular traffic congestion, three cities of

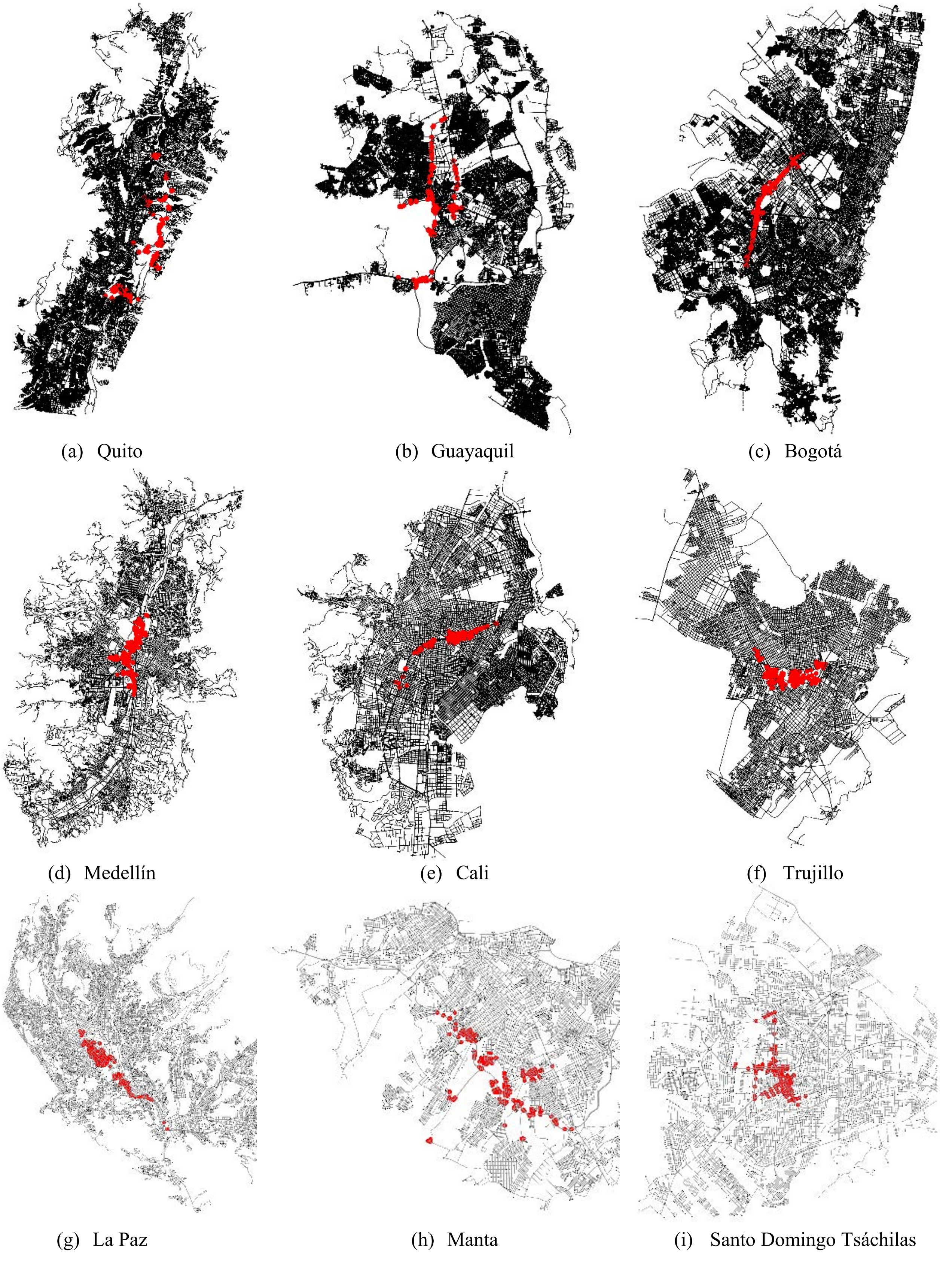
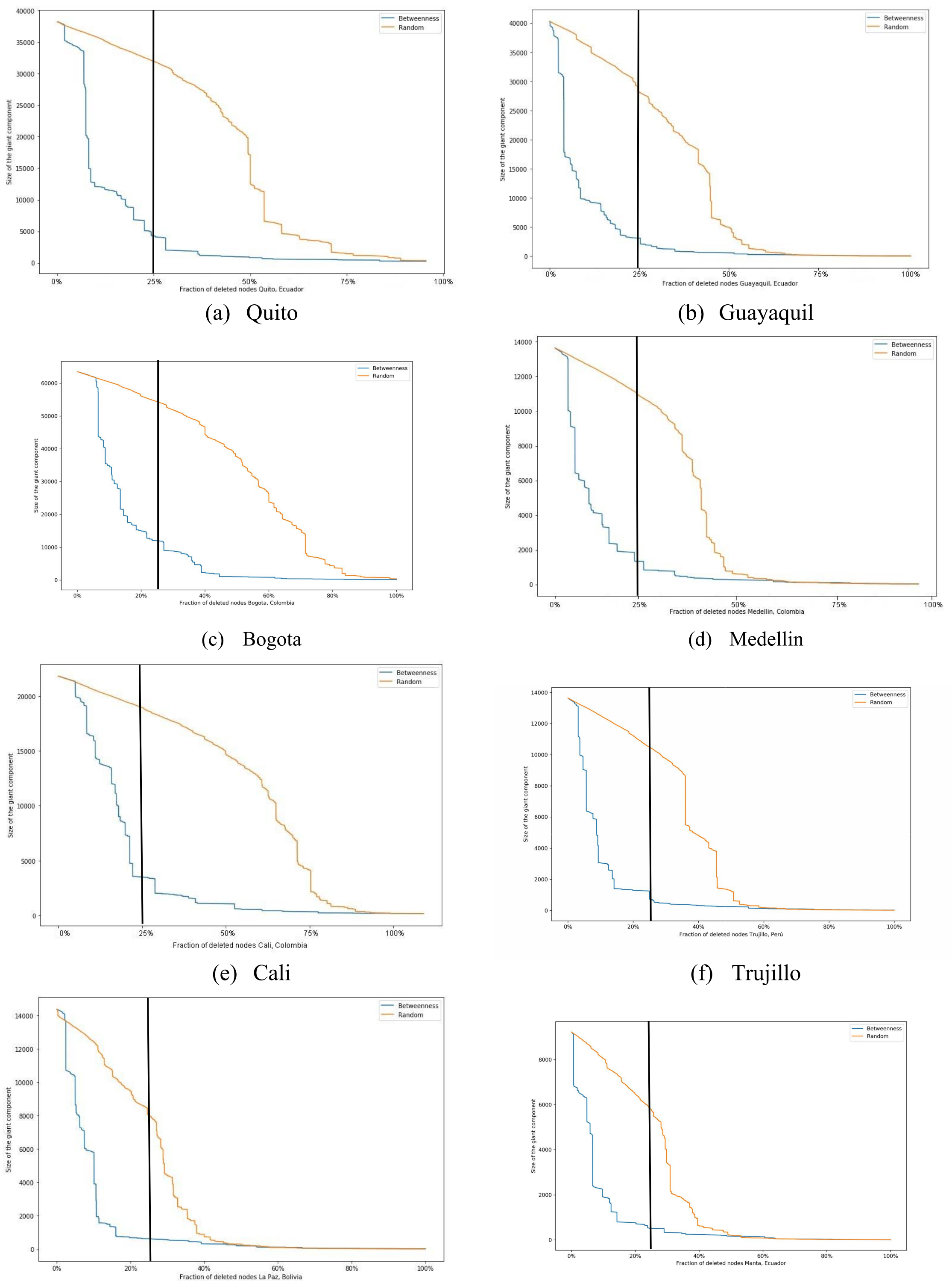


FIGURE 3. Closeness centrality for Latin American cities.



(a) Quito (b) Guayaquil (c) Bogota (d) Medellin (e) Cali (f) Trujillo (g) La Paz (h) Manta

FIGURE 4. Random and targeted attacks for Latin American cities.

the sample were taken as references: Medellin, La Paz, and Manta. The travel time (in minutes) required by a motorized vehicle (automobile) to cover a certain section of avenues in these cities was measured; the calculation was automated at thirty minute intervals; this was done every day of the week. In addition, in this process, the travel times in both directions

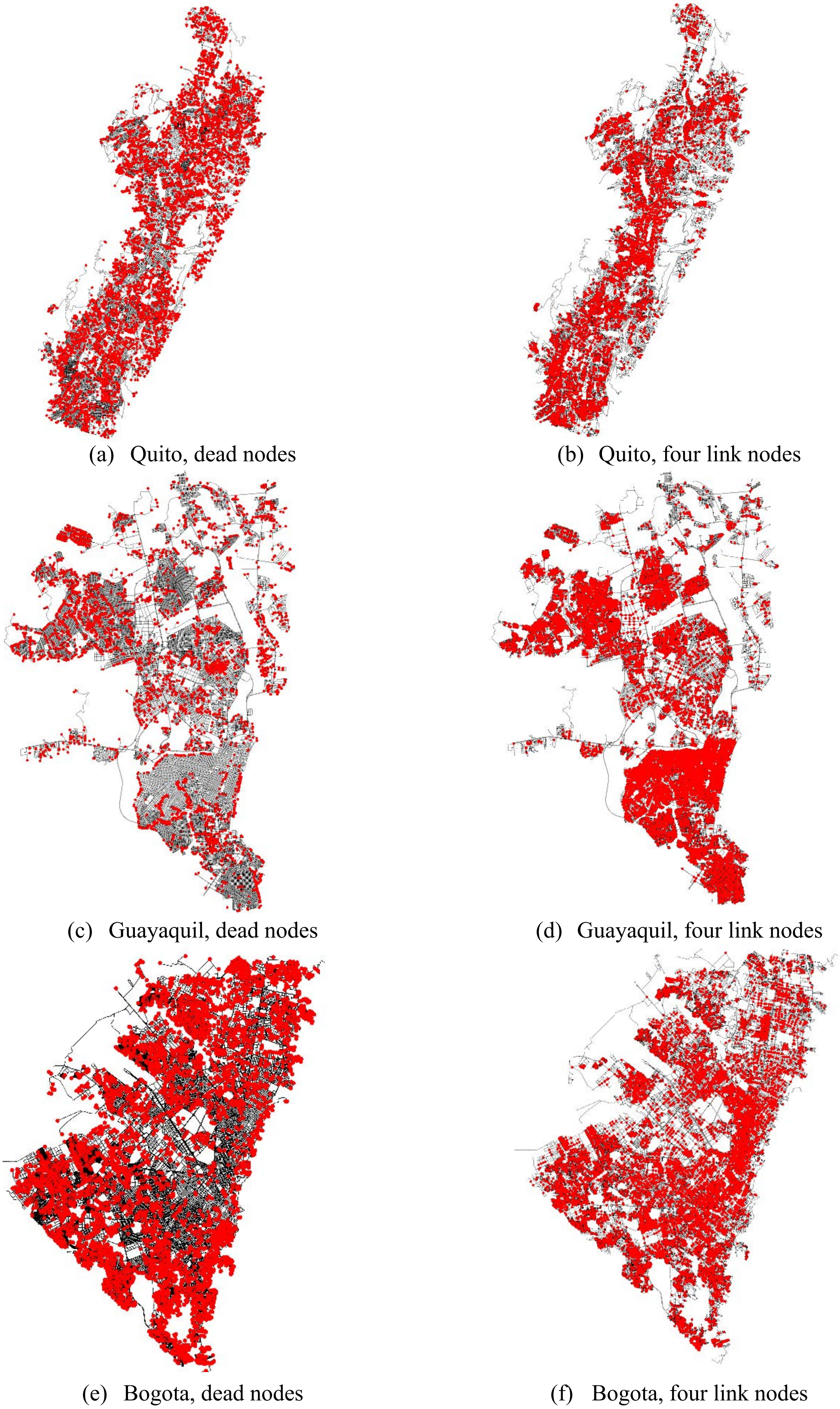


FIGURE 5. **Dead nodes and four link nodes for Quito, Guayaquil, and Bogota.**

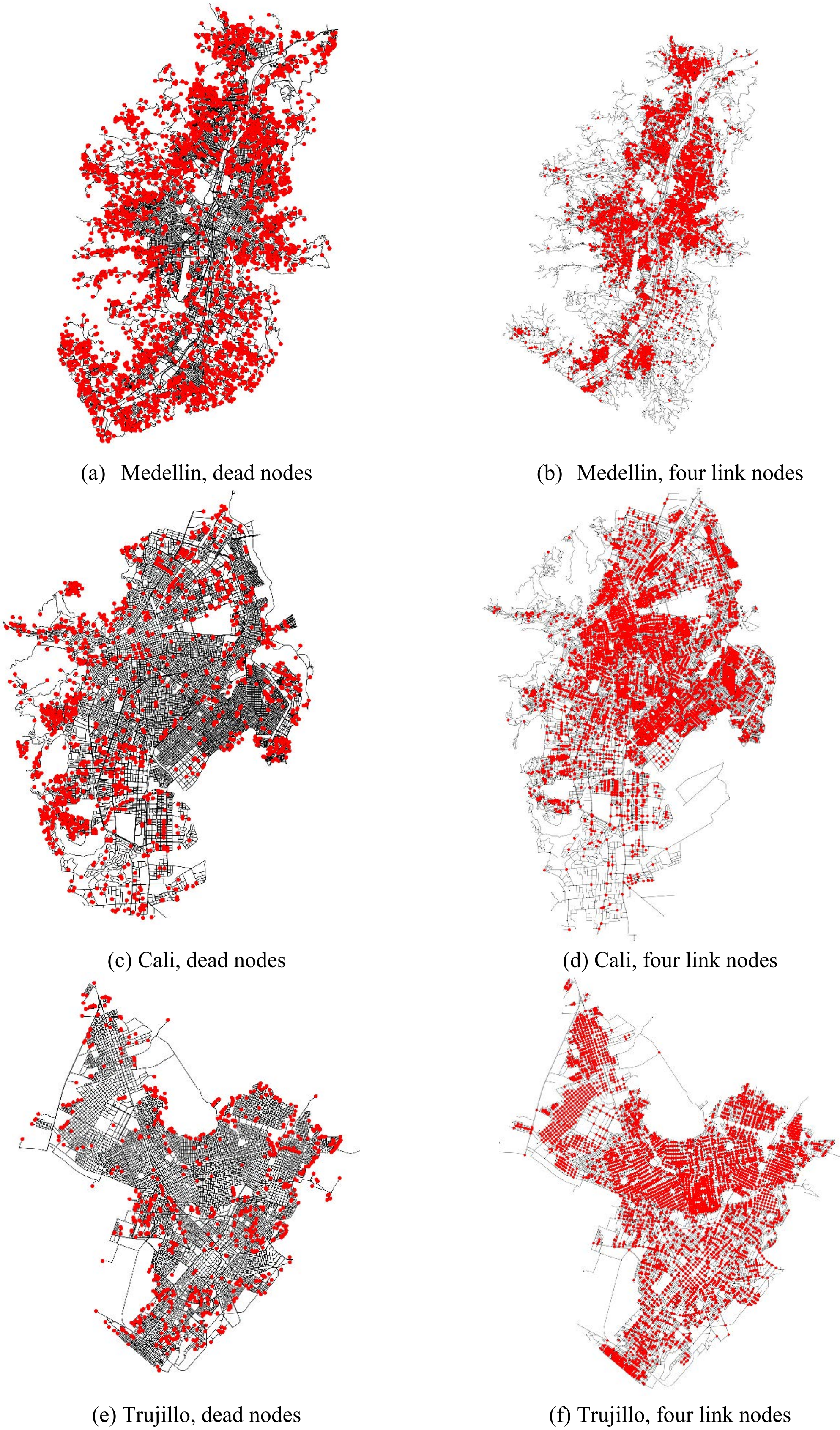
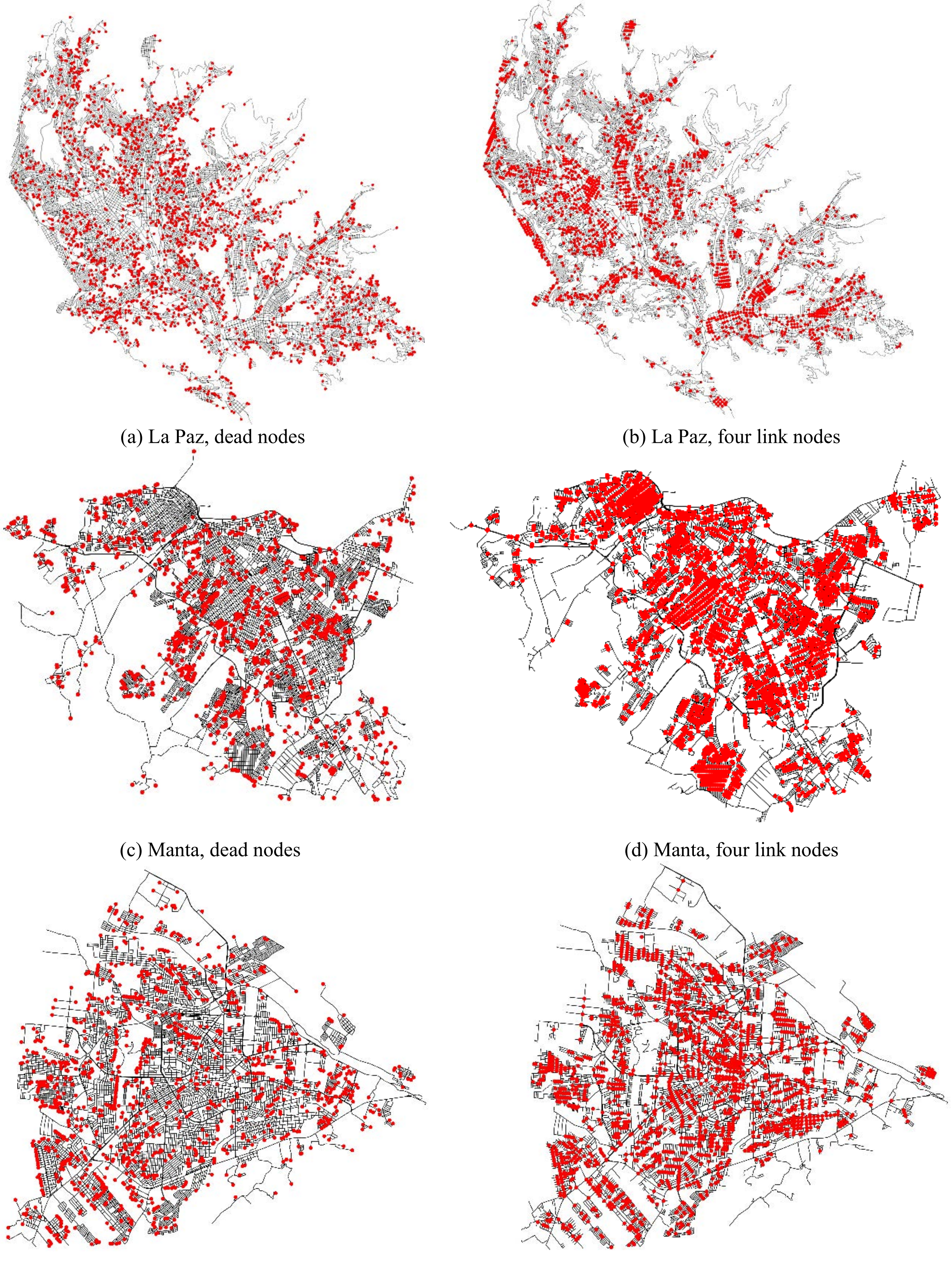


FIGURE 6. **Dead nodes and four link nodes for Medellin, Cali, Trujillo.**



(a) La Paz, dead nodes

(b) La Paz, four link nodes

(c) Manta, dead nodes

(d) Manta, four link nodes

(e) Santo Domingo Tsachilas, dead nodes

(f) Santo Domingo Tsachilas, four link nodes

FIGURE 7. Dead nodes and four link nodes for La Paz, Manta and Santo Domingo Tsachilas.

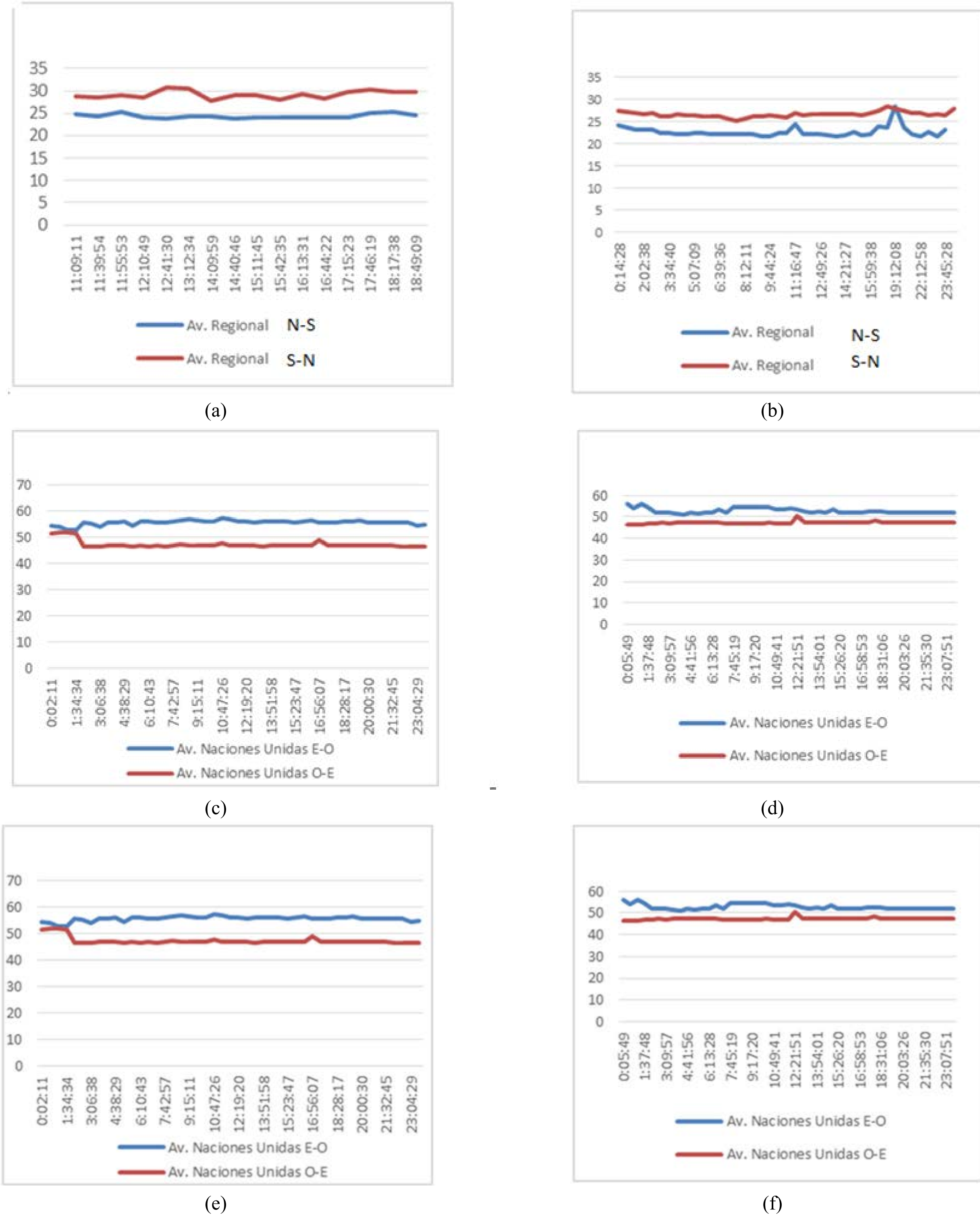


FIGURE 8. **Frequencies of travel times in minutes to move between two coordinates: origin and destination.**

(round trip) of each avenue were calculated using the Waze Route Calculator library based on Dijkstra's short-route algorithm, which uses the origin and destination coordinates as parameters.

Figure 8, illustrates the results as follows: (a), (c), and (e) represent the days that take the longest to cross the section of each avenue, and (b), (d), and (f) indicate the days with the least time consumption in the cities of the subsample.

(a) (b) (c)

FIGURE 9. Elevations of road networks: (a) Manta, (b) Santo Domingo Tsachilas, and (c) Guayaquil.

Specifically: (a) Regional Avenue of Medellin City in Colombia, with a length of 23 km on a Wednesday; (b) Regional Avenue of Medellin City in Colombia, 23 km on Sunday; (c) United Nations Avenue in La Paz City in Bolivia, with a length of 23 km on a Saturday; d) United Nations Avenue in La Paz City in Bolivia, 23 km on Sunday; (e) 4 de Noviembre Avenue in Manta City in Ecuador, 12 km long, on a Saturday; and (f) 4 de Noviembre Avenue in Manta City in Ecuador, 12 km long, on a Sunday.

F. MEASUREMENT OF ELEVATIONS IN URBAN NETWORKS (EM)

The elevation indicator was analyzed to help urban planning because it identifies the lowest sectors that are prone to flooding. The highest sites of coastal cities in Ecuador and Latin America are settlements with the poorest populations which are exposed to a more significant number of catastrophes. This measurement allows for the evaluation of the degree of importance of road networks in these sectors [82]. Therefore, these areas are vulnerable to adverse events, whether natural or social, such as heavy rains, hurricanes, or tsunamis, which affect basic services. Regardless of the case, the determination of high or low geographic elevations helps solve specific proactive or preventive planning problems. Figure 9 shows the elevations of Manta, Santo Domingo Tsachilas, and Guayaquil in Ecuador.

After evaluating the elevations of the network graphs, it was observed that the purple nodes were the sectors most vulnerable to flooding because they were located at sea level or near streams or rivers. By contrast, those in yellow represent the highest sectors in the city. However, they are at a risk of withstanding landslides or landslides during periods of intense rainfall. In addition, they are marginalized sectors with poor public work. The same type of graphical analysis is feasible for the remaining six cities of the analyzed sample, it has not been carried out because the process is considered repetitive and due to limitations in the use of the software tool.

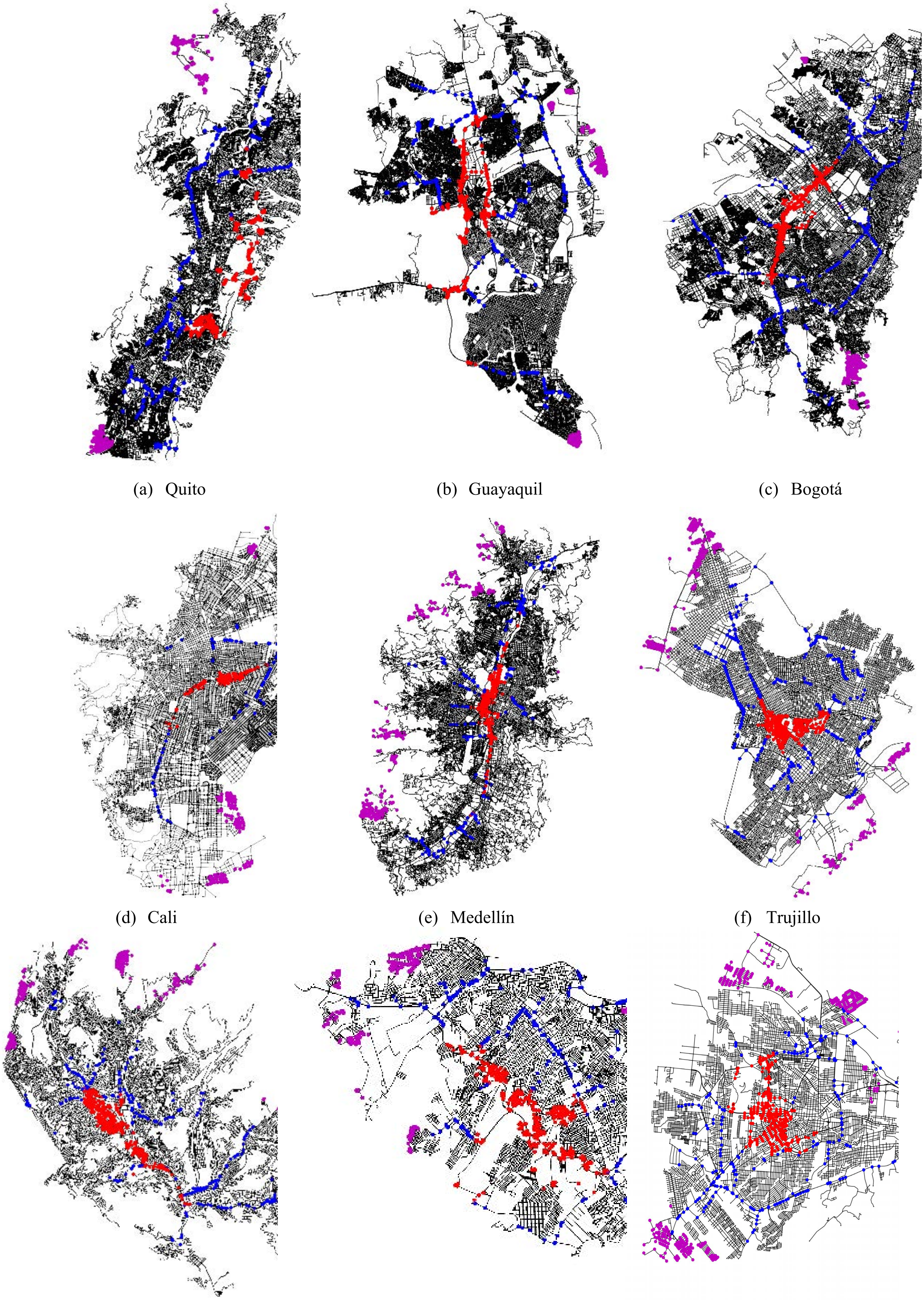
G. FUSION OF CENTRALITY INDICATORS IN URBAN NETWORK (IF)

It is possible to consolidate the indicators of betweenness centrality, closeness centrality, and eccentricity to visualize the location of the most critical sectors, streets, and intersections for each indicator on a single map.

Additionally, the number of intersections can be regulated according to the analysis criteria so that the distribution of these points can be located and sectors with the most significant tendency to expand and grow in cities can be identified.

The data were obtained from the Open Street Map (OSM) repository. To load the urban network graphs, bounding box and polygon techniques were used. Each road network was composed of intersections (nodes) and streets (links). Elevation data were downloaded from Google Maps and travel times were loaded using the WazeRouteCalculator API with Python from the Waze data source.

In Figure 10, the red dots represent the centrality of proximity, which is related to the greater conglomeration and centralization of the city because the main commercial and financial centers, health centers, and public entities, among others, are located in these areas. The blue dots indicate the



(a) Quito (b) Guayaquil (c) Bogotá

(d) Cali (e) Medellín (f) Trujillo

(g) La Paz (h) Manta (i) Santo Domingo Tsachilas

FIGURE 10. Fusion of indicators for BC, CC, and eccentricity of urban networks. Fusion of indicators for BC (nodes blue), CC (nodes red), and eccentricity (nodes purple) of urban networks.

TABLE 6. Proposed method vs urban resilience.

	Method Steps	Indicator	Analysis method (unit)	Urban Resilience Assessment High	Low
1	Mesh and connectivity	Mesh (MH)	Quantitative (unit)	≥ 0.83	< 0.83
		Connectivity (CN)	Quantitative (unit)	>2.5	≤ 2.5
2	Betweenness centrality closeness centrality	Betweenness centrality (BC)	Quantitative (unit)	≤ 67.06	> 67.06
		Closeness centrality (CC)	Quantitative (unit)	≥ 382.02	< 382.02
3	Robustness of networks to interruption attacks (RN)	Graphical analysis (25% removed nodes)	Qualitative	Menor area	Larger area
4	Location of end nodes	Dead nodes (DN)	Quantitative (%)	≤ 14.16	> 14.16
		Nodes four Links (N4)		≥ 25.01	< 25.01
5	Measurement of travel times between origin and destination ODs (OD)	Graphical analysis : Parameters: 1. thirty minute intervals; 2.every day of the week; 3. both directions; 4.avenue with major BC	Qualitative	Lowest number of peaks	Higher number of spikes
6	Measurement of elevation in urban networks (EM)	Graphical analysis : purple nodes (high density)	Qualitative		V
		Graphical analysis : yellow nodes (high density)		V	
7	Fusion of indicators with clusters on the same map (IF)	Graphical analysis: red nodes (high density)	Qualitative		V
		Graphical analysis: blue nodes (high density)			V
		Graphical analysis: purple nodes (high density)			V

distribution of streets and intersections with the highest BC, which is valid for locating sectors with the highest vehicular congestion. The same indicator was used to represent streets with orange-yellow lines. Finally, purple nodes were identified, representing the furthest nodes and sectors of the network. These data are of interest to the development of public policies for equality of basic services that allow the inclusion of places far from the urban network [83].

H. URBAN RESILIENCE ASSESSMENT

In this study, resilience is a city's ability to prepare and plan for, absorb, recover from, or adapt more successfully to actual or potential disturbances [84].

Empirically, the evaluating resilience in cities remains a complex issue [85]. The framework for the relationship between the proposed methodology and urban resilience is presented below.

For this, Table 6 presents the relationship between urban resilience and the seven steps of the proposed method through a synthesis of the results obtained. In the table, there are also indicators (coded with acronyms); the method of analysis, whether quantitative or qualitative (this is because in the work, some steps generate quantities and others generate graphic references); and the unit of measure.

For the quantitative part, the indicator, unit, and range of resilience (high, low) are specified; the value that corresponds to the break point is the mean between the values obtained, depending on the indicator analyzed and the results of this study (Appendix A). If the values were above or below the mean, urban resilience was assigned a high or low rating, respectively, typified as green or red. In the case of the CN indicator, the calculation of the average was not applied because, according to the theoretical reference, if the value was greater than 2.5, the connectivity was high; otherwise, it was low.

On the other hand, for the qualitative part, a visual analysis of the graph is recommended, where a high or low density of nodes with a certain color is determined, based on which a high or low urban resilience rating is determined, which is typified in green or red. In the case of the OD indicator, certain measurement parameters are recommended, such as time, interval, direction and avenue with the highest BC.

To determine the level of urban resilience of the cities that were the object of the study sample, Table 7 was generated based on the parameters in Table 6. It was determined that a city is more resilient if it has a greater number of green parameters; otherwise, it is less resilient if most of its parameters are in red. Certain cells in the table were coded as NC (not calculated) because the analyses were only applied to certain cities in the study. Despite this, the template is parametric, and any sample of cities that has all the analyses can be applied.

I. HOW TO IMPROVE RESILIENCE

From measurements in the urban networks of Latin American cities, all studies conducted must be rigorously applied to

TABLE 7. Resilience of sample cities.

City	Indicator										Urban Resilience Assessment
	MH	CN	BC	CC	RN Fig. 4	DN	N4	OD Fig. 8	EM Fig. 9	IF Fig. 10	
Quito	0.77	2.54	88.32	501.3		19.1%	19.8%	NC	NC		Low
Guayaquil	0.89	2.77	70.39	583.35		10.50%	30.90%	NC	V		High
Bogota	0.76	2.52	90.55	729.71		22.30%	14.10%	NC	NC		Low
Medellin	0.68	2.37	67.49	436.15		15.60%	20.80%	V	NC		Low
Cali	0.76	2.53	74.57	351.37		7.60%	26.90%	NC	NC		High
Trujillo	0.99	2.98	59.7	240.6		6.10%	38.00%	NC	NC		High
La Paz	0.78	2.56	67.57	195.1		16.10%	15.60%	V	NC		Low
Manta	0.94	2.88	42.13	217.78		13.40%	31.50%	V	V		High
Santo Domingo Tsachilas	0.87	2.74	42.8	182.8		16.70%	27.50%	NC	V		High

urban planning [87], avoiding monocentric and polycentric structures [86].

Cities with low resilience were Medellin, La Paz, Bogota, and Quito. Medellin has the greatest complication due to its connectivity (2.37) which is the least of all, less than 2.5, which is the average accepted in the literature [88]. To improve Medellin's resilience, there is an urgent need to build new and sufficiently wide peripheral avenues to interconnect the current urban network.

For large cities, such as Bogota and Quito, current connectivity and its strong resistance to random attacks must be used to distribute urban traffic through alternate routes. As these cities have decentralized networks (not monocentric or polycentric) that limit their connections, this has been expanded by Cats *et al.* [86].

Owing of its geographical location, La Paz makes it difficult to build new avenues. However, it is advisable to optimize current routes to redistribute the circulation of vehicular traffic and strengthen its connectivity.

For Santo Domingo de los Tsáchilas, the problem is less because they have several favorable indicators, such as connectivity, BC, and nodes with four links. However, it would be beneficial to improve these indicators by building wider avenues. It is a small city, and can better plan its urban network in the future when its population increases and the network expands.

Cali remained stable in cities with good resilience. However, it is recommended that the percentage of dead ends, BC, and CC be increased.

Guayaquil shows good resilience; however, it must improve the BC to be more resistant to interruption attacks and continue decentralizing its main CC nodes, because it has a monocentric structure that is unfavorable according to the literature [86].

The biggest problem for Trujillo and Manta is that they have low tolerance to network attacks. These cities must reinforce their connectivity of nodes (intersections) and main borders (streets), and plan the construction of wide avenues.

In general, the optimization of resilience in a constantly changing ecosystem requires building master plans in time [89]. The effective use of urban spaces is prioritized, including wide avenues that connect urban networks from end to end. Otherwise, when cities grow in a disorderly or self-organized manner, vulnerability to congestion, mobility, and accessibility increases thereby affecting the well-being of travelers.

V. DISCUSSION

With the study of resilience in Latin American urban networks, it was determined that there are vulnerabilities in their infrastructure and factors that hinder resistance to adverse phenomena such as floods, earthquakes, tsunamis, pandemics, and health crises or policies. This problem has been aggravated by the rapid growth of cities which lack adequate long-term planning. Therefore, it is imperative for responsible actors to integrate the aspects of resilience and sustainability into public policies and land management instruments, as argued by Tumini *et al.* [32]. In the sense that adaptation to changes produced by adverse events changes from sustainability to a transversal and resilient model.

After carrying out attacks to destroy small, medium, and large network nodes in each city, the resilience is inversely proportional to the size of the city. This evidence validates the fact that large cities suffer from vehicle congestion and mobility of their inhabitants, a factor of notoriety in urban centers in the Ibero-American area [91].

The results of the travel times in Figure 8, conducted in cities with high population density and in areas with the highest intermediation, confirm that they support high peaks of congestion caused by the lack of alternate avenues that distribute traffic when the demand for vehicles is high. Instead, Calvert and Snelder [92] proposed the use of an indicator called the link performance index for resilience (LPIR), which assesses the level of resilience of individual road sections to a broader road network, and is used to detect sections of roads with low resilience and determine the underlying characteristics of roads and traffic that cause this deficit.

The fusion technique of the indicators of betweenness centrality (BC), closeness centrality (CC), and eccentricity in Figure 10 summarizes the diagnosis of urban networks. It allows visualization of the current state of the critical factors of urbanization in the different areas of each city. This analysis provides findings similar to those resolved by Nogal *et al.* [93] through its restricted dynamic equilibrium allocation model to simulate the evolution of network performance, which considers the cost increase owing to the disturbance, system impedance, and user stress level. These two proposals seek to answer relevant questions that arise when a disruptive event occurs in a traffic network, such as how stressed the traffic network is How much time can the system recover a new equilibrium position if it responds to this situation?

VI. CONCLUSION

Within the cities sampled, the urban networks concentrated high rates of street and intersection intermediation on a small number of avenues to distribute the city's traffic, which increased the congestion of motorized vehicles. This pattern can be assumed to be repeated in most Latin American cities. However, it is necessary to apply resilient practices in the region and generate urban management options that strengthen the response capacity of cities in Latin America in the face of events that challenge local sustainability [90].

Assessing the resilience of unplanned road networks through the fusion of centrality, connectivity, and morphological indicators is relevant for South American cities to help improve vehicular congestion, accessibility, and urban mobility. During the study, it was found that connectivity and centrality problems as the urban network grew. Therefore, vehicular traffic congestion and the agglomeration of people in hot zones indicated by the red dots in each Figure are also complicated. This directly affects the resilience of cities, reducing their resistance and adaptability to traffic load. In the case of catastrophic events, it further aggravates resilience, complicating the recovery times of the road network to its normal state.

The increase in centralities puts the accessibility and mobility of the population within each city at risk. As a preventive measure, it is necessary to analyze the urban morphology of small-and medium-sized cities to detect centrality problems in time. These results will help reduce congestion, accessibility, and mobility in urban networks in the future, a problem that is latent in large cities in Latin America.

With the studies carried out, it is recommended that interested parties jointly analyze the indicators to plan corrective actions in the urban network. This will allow improvements in connectivity and minimize the dependency on certain roads or highways, a measure that will support the efficient distribution of traffic on all peaks.

Socio-urban investigative work is intended to provide cognitive elements for various actors and sectors, including social and civil populations, political representatives, municipalities, urbanization secretariats, city councils, and construction professionals, to reconsider ways to execute urban planning in cities. Intending to make them resilient to accelerated demographic growth in such a way that they can better cope with future habitat conditions.

APPENDIX A

Values break point. See Tables 8–13.

TABLE 8. Mesh values (MH).

City	Mesh
Trujillo	0.99
Manta	0.94
Guayaquil	0.89
Santo Domingo Tsachilas	0.87
La Paz	0.78
Quito	0.77
Cali	0.76
Bogota	0.76
Medellin	0.68
Average	0.83

TABLE 9. Conectivity values (CN).

City	Connectivity
Trujillo	2.98
Manta	2.88
Guayaquil	2.77
Santo Domingo Tsachilas	2.74
La Paz	2.56
Quito	2.54
Cali	2.53
Bogota	2.52
Medellin	2.37

TABLE 10. Betweenness centrality values (BC).

City	BC
Bogota	90.55
Quito	88.32
Cali	74.57
Guayaquil	70.39
La Paz	67.57
Medellin	67.49
Trujillo	59.7
Santo Domingo Tsachilas	42.8
Manta	42.13
Average	67.06

TABLE 11. Closeness centrality values (CC).

City	CC
Bogota	729.71
Guayaquil	583.35
Quito	501.3
Medellin	436.15
Cali	351.37
Trujillo	240.6
Manta	217.78
La Paz	195.1
Santo Domingo Tsachilas	182.8
Media	382.02

TABLE 12. Dead nodes values (DN).

City	% dead nodes
Bogota	22.30%
Quito	19.10%
Santo Domingo Tsachilas	16.70%
La Paz	16.10%
Medellin	15.60%
Manta	13.40%
Guayaquil	10.50%
Cali	7.60%
Trujillo	6.10%
Media	14.16%

TABLE 13. Nodes four (4N).

City	% nodes four
Trujillo	38.00%
Manta	31.50%
Guayaquil	30.90%
Santo Domingo Tsachilas	27.50%
Cali	26.90%
Medellin	20.80%
Quito	19.80%
La Paz	15.60%
Bogota	14.10%
Average	25.01%

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REFERENCES

[1] D. Tamayo, "Hacia una planificación urbana sistémica: Una experiencia universitaria de aprendizaje y aplicación de nuevos instrumentos técnicos en La planificación urbana tradicional," *Espacio y Desarrollo*, vol. 20, pp. 69–86, 2008.

[2] R. Babilonia and R. Sánchez, "Planificación urbana estratégica a través de macroproyectos urbanos: Percepción ciudadana sobre el parque lineal 'La ronda del Sinú' en la ciudad de montería, Colombia," *Revista de Urbanismo*, vol. 39, pp. 1–12, 2018, doi: 10.5354/0717-5051.2018.48727.

[3] A. P. Ledo, J. J. O. González, and A. M. Iglesias, "De La planificación estratégica al marketing urbano: Hacia La ciudad inmaterial," *EURE Santiago*, vol. 36, no. 108, pp. 5–27, Aug. 2010, doi: 10.4067/s0250-71612010000200001.

[4] F. A. Canaza-Choque, "DE La educación ambiental al desarrollo sostenible: Desafíos y tensiones en los tiempos del cambio climático," *Revista de Ciencias Sociales*, vol. 165, pp. 155–172, Dec. 2019.

[5] D. G. Couret, "Sobre resiliencia de ciudades del arte ante catástrofes naturales," *Arquitectura y Urbanismo*, vol. 38, no. 1, pp. 96–102, 2017.

[6] M. Salanova, "How to survive COVID-19? Notes from organisational resilience (?' Cómo sobrevivir Al COVID-19? apuntes desde La resiliencia organizacional)," *Int. J. Social Psychol.*, vol. 35, no. 3, pp. 670–676, Sep. 2020, doi: 10.1080/02134748.2020.1795397.

[7] C. Oltra and A. Boso, "Lecciones aprendidas de La crisis del coronavirus: Preparación y resiliencia social," *Revista Española de Sociología*, vol. 29, no. 3, pp. 769–775, 2020, doi: 10.22325/fes/res.2020.50.

[8] H. Khreis and M. Nieuwenhuijsen, "The health impacts of urban transport: Linkages, tools and research needs," *Measuring Transp. Equity*, pp. 131–142, 2019, doi: 10.1016/B978-0-12-814818-1.000081.

[9] X. Basagaña, "Heat islands/temperature in cities: Urban and transport planning determinants and health in cities," *Integrating Hum. Health Urban Transp. Planning*, pp. 483–497, 2019.

[10] C. R. Freitas, A. L. D.-A. D'Vignon, and A. C. Castro, "Urban social vulnerability and climate change in rio de janeiro city associated with population mobility," *J. Environ. Policy Planning*, vol. 21, no. 6, pp. 797–810, Nov. 2019, doi: 10.1080/1523908X.2019.1674135.

[11] D. Koren and K. Rus, "The potential of open space for enhancing urban seismic resilience: A literature review," *Sustainability*, vol. 11, no. 21, p. 5942, Oct. 2019, doi: 10.3390/su11215942.

[12] L. J. Vale, "The politics of resilient cities: Whose resilience and whose city?" *Building Res. Inf.*, vol. 42, no. 2, pp. 191–201, Mar. 2014, doi: 10.1080/09613218.2014.850602.

[13] ONU. (Sep. 9, 2020). *Perspectivas de La Población Mundial 2019*. Access: Jan. 10, 2021. [Online]. Available: https://www.cepal.org/es/notas/perspectivas-la-poblacion-mundial-2019-metodologia-naciones-unidas-estimaciones-proyecciones

[14] ONU. Jul. 10, 2014. *UN News*. Access: Jan. 10, 2021. [Online]. Available: https://news.un.org/en/story/2014/07/472752-more-half-worlds-population-now-living-urban-areas-un-survey-finds

[15] F. Moraci, M. Errigo, C. Fazia, G. Burgio, and S. Foresta, "Making less vulnerable cities: Resilience as a new paradigm of smart planning," *Sustainability*, vol. 10, no. 3, p. 755, Mar. 2018, doi: 10.3390/su10030755.

[16] G. Á. De la Torre, "Estructura y temporalidad urbana de las ciudades intermedias en México," *Frontera Norte*, vol. 23, no. 46, pp. 91–124, 2011.

[17] G. Michaels and F. Rauch, "Resetting the urban network: 117–2012," *Econ. J.*, vol. 128, no. 608, pp. 378–412, Feb. 2018, doi: 10.1111/ecoj.12424.

[18] P. Chauvet and A. Baptiste, "Transporte de carretera en América latina: Evolución de La infraestructura y de sus impactos entre 2007 y 2015," *Comisión Económica Para América Latina y el Caribe*, p. 15, 2019.

[19] J. M. Cariolet, M. Vuillet, and Y. Diab, "Mapping urban resilience to disasters—A review," *Sustain. Cities Soc.*, vol. 51, Nov. 2019, Art. no. 101746, doi: 10.1016/j.scs.2019.101746.

[20] Y. Jabareen, "Planning the resilient city: Concepts and strategies for coping with climate change and environmental risk," *Cities*, vol. 31, pp. 220–229, Apr. 2013, doi: 10.1016/j.cities.2012.05.004.

[21] M. Batty, "Resilient cities, networks, and disruption," *Environ. Planning B, Planning Des.*, vol. 40, no. 4, pp. 571–573, Aug. 2013, doi: 10.1068/b4004ed.

[22] M. S. Golan, L. H. Jernegan, and I. Linkov, "Trends and applications of resilience analytics in supply chain modeling: Systematic literature review in the context of the COVID-19 pandemic," *Environ. Syst. Decisions*, vol. 40, no. 2, pp. 222–243, Jun. 2020, doi: 10.1007/s10669-020-09777-w.

[23] A. Sharifi, "Urban resilience assessment: Mapping knowledge structure and trends," *Sustainability*, vol. 12, no. 15, p. 5918, Jul. 2020, doi: 10.3390/su12155918.

[24] L. Huang, J. Wu, and L. Yan, "Defining and measuring urban sustainability: A review of indicators," *Landscape Ecol.*, vol. 30, no. 7, pp. 1175–1193, Aug. 2015, doi: 10.1007/s10980-015-0208-2.

[25] I. Tumini, "Acercamiento teórico para La integración de los conceptos de resiliencia en los indicadores de sostenibilidad urbana," *Revista de Urbanismo*, vol. 34, pp. 4–19, 2016, doi: 10.5354/0717-5051.2016.40056.

[26] F. García, "Compacidad y densidad de las ciudades españolas," *EURE Santiago*, vol. 42, no. 127, pp. 5–27, 2016, doi: 10.4067/S0250-71612016000300001.

[27] G. B. Gutiérrez, "Ciudad digital: Paradigma de La globalización urbana," *Bitácora Urbano Territorial*, vol. 27, no. 1, pp. 79–88, 2017, doi: 10.15446/bitacora.v27n1.51349.

[28] Y. C. Gatica, "La recuperación urbana y residencial del centro de Santiago: Nuevos habitantes, cambios socioespaciales significativos," *Eure Santiago*, vol. 37, no. 112, pp. 89–113, Sep. 2011, doi: 10.4067/S0250-71612011000300005.

[29] J. Blanco, L. Bosoer, and R. Apaolaza, "Gentrificación, movilidad y transporte: Aproximaciones conceptuales y ejes de indagación," *Revista de Geografía Norte Grande*, vol. 58, pp. 41–53, Sep. 2014, doi: 10.4067/S0718-34022014000200003.

[30] B. Walker, N. Abel, F. Andreoni, J. Cape, H. Murdock, and C. Norman, "General resilience: A discussion paper based on insights from a catchment management area workshop in south eastern Australia," Resilience Alliance, Decatur, GA, USA, Tech. Rep., 2015.

[31] J. R. Quintero-González, "Del concepto de ingeniería de tránsito al de movilidad urbana sostenible," *Ambiente y Desarrollo*, vol. 21, no. 40, pp. 57–72, 2017, doi: 10.11144/Javeriana.ayd21-40.citm.

[32] I. Tumini, C. Arriagada, and R. Baeriswyl, ''Modelo para La integración de La resiliencia y La sosteniblidad en La planificación urbana,'' in *Proc. 3rd Int. Congr. Sustain. Construction Eco-Efficient Solutions*, 2017, pp. 926–938.
[33] S. T. Pickett and W. Zhou, ''Global urbanization as a shifting context for applying ecological science toward the sustainable city,'' *Ecosystem Health Sustainability*, vol. 1, no. 1, pp. 505–515, 2015, doi: 10.1890/ehs14-0014.1.
[34] S. Greiving, L. Schödl, K.-H. Gaudry, M. Quintana, K. Iris, B. Prado-Larraín, M. Fleischhauer, M. M. Jácome-Guerra, and J. Tobar, ''Multi-risk assessment and management—A comparative study of the current state of affairs in Chile and Ecuador,'' *Sustainability*, vol. 13, no. 3, p. 1366, 2020, doi: 10.3390/su13031366.
[35] H. Murakami, K. Takimoto, and A. Pomonis, ''Tsunami evacuation process and human loss distribution in the 2011 great east Japan Earthquake—A case study of Natori city, Miyagi prefecture,'' in *Proc. 15th World Conf. Earthq. Eng.*, 2011, pp. 1–11.
[36] K. Goh, ''Flows in formation: The global-urban networks of climate change adaptation,'' *Urban Stud.*, vol. 57, no. 11, pp. 2222–2240, Aug. 2020, doi: 10.1177/0042098018807306.
[37] N. Chen, S. Yao, C. Wang, and W. Du, ''A method for urban flood risk assessment and zoning considering road environments and terrain,'' *Sustainability*, vol. 11, no. 10, p. 2734, May 2019, doi: 10.3390/su11102734.
[38] D. Mu, P. Luo, J. Lyu, M. Zhou, A. Huo, W. Duan, D. Nover, B. He, and X. Zhao, ''Impact of temporal rainfall patterns on flash floods in Hue city, Vietnam,'' *J. Flood Risk Manage.*, vol. 14, no. 1, pp. 1–15, Mar. 2021, doi: 10.1111/jfr3.12668.
[39] J. R. Rodysill, J. M. Russell, M. Vuille, S. Dee, B. Lunghino, and S. Bijaksana, ''La niña-driven flooding in the Indo-Pacific warm pool during the past millennium,'' *Quaternary Sci. Rev.*, vol. 225, Dec. 2019, Art. no. 106020, doi: 10.1016/j.quascirev.2019.106020.
[40] J. A. Insaurralde and O. D. Cardozo, ''Análisis de La red vial de la provincia de corrientes por medio de La teoría de grafos,'' *Geográfica Digit.*, vol. 7, no. 13, pp. 1–15, 2010.
[41] K. Kansky, ''Structure of transportation networks: Relationships between network geometry and regional characteristics,'' Dept. Geography, Univ. Michigan, Ann Arbor, MICH, USA, Tech. Rep., 1963.
[42] R. J. Chorley and P. Haggett, ''Trend-surface mapping in geographical research,'' *Trans. Inst. Brit. Geographers*, no. 37, pp. 47–67, 1965.
[43] K. J. Tinkler, *An Introduction to Graph Theoretical Methods in Geography*. Catharines, ON, Canada: Brock University, 1977.
[44] M. Potrykowsky and Z. Taylor, ''Geografía del transporte,'' Editorial Ariel, Barcelona, Spain, Tech. Rep., 1984.
[45] J. Seguí and J. Petrus, ''Geografía de redes y sistemas de transporte,'' Editorial Síntesis, Madrid, Spain, Tech. Rep., 1991.
[46] J. B. Sendra, ''Sistema de información geográfica,'' Rialp Editorial, Madrid, Spain, Tech. Rep., 1992.
[47] J. Garrido Palacios, ''La organización espacial de La red de carretera en aragón. Aplicación de La metodología de la teoría de grafos,'' *Geographicalia*, vol. 32, pp. 83–101, 1995.
[48] L. Zhang, ''Scale-free resilience of real traffic jams,'' *Proc. Nat. Acad. Sci. USA*, vol. 116, no. 18, pp. 8673–8678, 2019, doi: 10.1073/pnas.1814982116.
[49] G. Boeing, ''OSMnx: New methods for acquiring, constructing, analyzing, and visualizing complex street networks,'' *Comput. Environ. Urban Syst.*, vol. 65, pp. 126–139, Sep. 2016, doi: 1016/j.compenvurbsys.2017.05.004.
[50] J. Tang and H. R. Heinimann, ''A resilience-oriented approach for quantitatively assessing recurrent spatial-temporal congestion on urban roads,'' *PLoS ONE*, vol. 13, no. 1, Jan. 2018, Art. no. e0190616, doi: 10.1371/journal.pone.0190616.
[51] B. S. Dees, A. G. Constantinides, and D. P. Mandic, ''Graph theory and metro traffic modelling,'' 2019, *arXiv:1912.05964v1*.
[52] L. F. Molina-Prieto, ''Resiliencia a inundaciones: Nuevo paradigma para el diseño urbano,'' *Revista de Arquitectura*, vol. 8, no. 2, pp. 82–94, 2016, doi: 10.14718/RevArq.2016.18.2.8.
[53] M. Andrade and N. Lucioni, ''Factores de riesgo hídrico en el gran La plata, Argentina,'' *IX Jornadas Nacionales de Geografía Física Bahía Blanca*, pp. 14–24, 2012.
[54] G. Furdada, M. Guinau, and G. B. Subiela, ''Las cuencas de portainé y romadriu: Susceptibilidad al cambio y factores de control antrópicos y naturales. Geomorfología del antropoceno. Efectos del cambio global sobre los procesos geomorfológicos,'' *UIB-SEG*, pp. 335–338, 2018.
[55] J. C. Meza, M. L. Ramirez, and F. I. Contreras, ''Cartografía de áreas de riesgo a inundaciones y anegamientos a partir de modelos digitales de elevación de general José de San Martín,'' *Contribuciones Científicas G/EA*, vol. 29, pp. 149–164, 2017.
[56] H. A. Pacheco and A. D. Montilla, ''Causas y consecuencias de las lluvias extraordinarias de 2017 en La Costa ecuatoriana: El caso de La provincia manabí'' *Boletín de Investigaciones Marinas y Costeras*, vol. 48, no. 2, pp. 45–70, Nov. 2019, doi: 10.25268/bimc.inveMar.2019.48.2.766.
[57] M. Jácome, ''Planificación urbana y resiliencia socio-ecológica en un contexto territorial con riesgos de amenazas naturales. El caso del cantón manta, Ecuador,'' *Recercat*, 2019.
[58] G. Boeing, ''Street network models and indicators for every urban area in the world,'' 2020, *arXiv:2009.09106*.
[59] S. A. Kulp and B. H. Strauss, ''New elevation data triple estimates of global vulnerability to sea-level rise and coastal flooding,'' *Nature Commun.*, vol. 10, no. 1, pp. 1–12, 2019, doi: 10.1038/s41467-019-12808-z.
[60] A. E. Dingil, J. Schweizer, and F. Rupi, ''Road network extraction with OSMNx and SUMOPy,'' *EPiC Eng.*, vol. 2, pp. 111–117, Jun. 2018.
[61] J. L. Ortega, J. López-Sauceda, J. Carrillo, and J. Sandoval, ''Método de construcción de dígrafos a partir de redes viales reales en mapas digitales con aplicaciones en La búsqueda de rutas óptimas,'' *Informes de la Construcción*, vol. 71, no. 556, p. e320, 2019, doi: 10.3989/ic.65988.
[62] R. J. Sánchez, ''Provisión de infraestructura de transporte en América latina: Experiencia reciente y problemas observado,'' *Cepal*, 2005.
[63] S. M. Boccolini, ''Regulación urbana,?' Hacia una Córdoba sostenible e inclusiva? Urbe,'' *Revista Brasileira de Gestão Urbana*, vol. 10, pp. 96–117, 2018, doi: 10.1590/2175-3369.010.supl1.ao06.
[64] A. Solé-Ribalta, S. Gómez, and A. Arenas, ''Decongestion of urban areas with hotspot-pricing,'' *Netw Spat Econ*, vol. 18, no. 1, pp. 33–50, 2018, doi: 1007/s11067-017-9349-y.
[65] D. Hernández, ''Activos y estructuras de oportunidades de movilidad: Una propuesta analítica para el estudio de La accesibilidad por transporte público, el bienestar y La equidad,'' *EURE Santiago*, vol. 38, no. 115, pp. 117–135, 2018, doi: 10.4067/S0250-71612012000300006.
[66] N. Yadav, S. Chatterjee, and A. Ganguly, ''Resilience of urban transport network-of-networks under intense flood hazards exacerbated by targeted attacks,'' *Sci. Rep.*, vol. 10, no. 1, p. 10350, 2020, doi: 1038/s41598-020-66049-y.
[67] M. S. Nelson, ''Integración de herramientas para La toma de decisiones en La congestion vehicular,'' *Dyna*, vol. 85, no. 205, pp. 363–370, 2018, doi: 10.15446/dyna.v85n205.67745.
[68] B. Hillier and S. Iida, ''Network effects and psychological effects: A theory of urban movement,'' in *Proc. 5th Int. Symp. Space Syntax*, 2005, pp. 475–490, doi: 10.1007/11556114_30.
[69] T. Varoudis, S. Law, K. Karimi, B. Hillier, and A. Penn, ''Space syntax angular betweenness centrality revisited,'' in *Proc. 9th Int. Space Syntax Symp.*, Seoul, South Korea, Oct. 2013.
[70] L. C. Freeman, ''A set of measures of centrality based on betweenness,'' *Sociometry*, vol. 40, no. 1, pp. 35–41, Mar. 1977, doi: 10.2307/3033543.
[71] J. Mercadé, F. Magrinyá, and M. C. A. de Medina, ''Medidas de centralidad y escala intermedia: El potencial estructurante de La red viaria en el vallés oriental,'' *ACE. Arquitectura, Ciudad y Entorno*, vol. 11, no. 36, pp. 13–39, 2019, doi: 10.5821/ace.13.39.5302.
[72] H. Alatrista, M. Prado, and M. Rodríguez, ''Robustness of densely populated urban networks in relation to the spread of traffic. Techno review. International technology,'' *Sci. Soc. Rev.*, vol. 8, no. 1, pp. 1–10, 2019, doi: 10.37467/gka-revtechno.v8.2042.
[73] A. P. Masucci and C. Molinero, ''Robustness and closeness centrality for self-organized and planned cities,'' *Eur. Phys. J. B*, vol. 89, no. 2, pp. 1–8, Feb. 2016.
[74] Z. Wang, J. Zheng, Y. Wu, and N. Mitton, ''A centrality-based RSU deployment approach for vehicular Ad hoc networks,'' in *Proc. IEEE Int. Conf. Commun. (ICC)*, May 2017, pp. 1–5.
[75] R. A. Batista and A. L. C. Bazzan, ''Identification of central points in road networks using betweenness centrality combined,'' *Polibits*, vol. 52, pp. 85–91, Jul. 2015, doi: 10.17562/PB-52-9.
[76] J. Wang, ''Resilience of self-organised and top-down planned cities—A case study on London and Beijing street networks,'' *PLoS ONE*, vol. 10, no. 12, 2015, Art. no. e0141736, doi: 10.1371/journal.pone.0141736.
[77] J. Shi, S. Wen, X. Zhao, and G. Wu, ''Sustainable development of urban rail transit networks: A vulnerability perspective,'' *Sustainability*, vol. 11, no. 5, p. 1335, Mar. 2019.

[78] L.-N. Wang, K. Wang, and J.-L. Shen, ''Weighted complex networks in urban public transportation: Modeling and testing,'' *Phys. A, Stat. Mech. Appl.*, vol. 545, May 2020, Art. no. 123498.

[79] B.-H. Lee and W.-S. Jung, ''Analysis on the urban street network of korea: Connections between topology and meta-information,'' *Environ. Planning B Planning Des.*, vol. 497, pp. 15–25, May 2018, doi: 10.1016/j.physa.2017.12.131.

[80] T. Shanmukhappa, I. W.-H. Ho, and C. H. Tse, ''Spatial analysis of bus transport networks using network theory,'' *Phys. A, Stat. Mech. Appl.*, vol. 502, pp. 295–314, Jul. 2018, doi: 10.1016/j.physa.2018.02.111.

[81] R. Zimmerman, ''New York City panel on climate change 2019 report chapter 7: Resilience strategies for critical infrastructures and their interdependencies,'' *Ann. New York Acad. Sci.*, vol. 1439, no. 1, pp. 174–229, 2019.

[82] B. Abdulla, A. Mostafavi, and B. Birgisson, ''Characterization of the vulnerability of road networks to fluvial flooding using network percolation approach,'' *De Comput. Civil Eng.*, vol. 2019, pp. 428–435, 2019, doi: 10.1061/9780784482445.055.

[83] Y. C. Gatica and C. A. Sickinger, ''Reconstrucción exclusionaria. Lo comunitario y las políticas públicas en ciudades menores e intermedias chilenas afectadas por el terremoto y tsunami del 27F 2010: Los casos de constitución y dichato,'' *Revista de Geografía Norte Grande*, vol. 64, pp. 83–107, 2016, doi: 10.4067/S0718-34022016000200007.

[84] J. Tang, H. Heinimann, K. Han, H. Luo, and B. Zhong, ''Evaluating resilience in urban transportation systems for sustainability: A systems-based Bayesian network model,'' *Transp. Res. C, Emerg. Technol.*, vol. 121, Dec. 2020, Art. no. 102840.

[85] Z. Liu, H. Chen, E. Liu, and W. Hu, ''Exploring the resilience assessment framework of urban road network for sustainable cities,'' *Phys. A, Stat. Mech. Appl.*, vol. 586, Jan. 2022, Art. no. 126465.

[86] O. Cats and K. Y. T. P. Krissada, ''Rail network robustness: The role of rapid development and a polycentric structure in withstanding random and targeted attacks,'' in *Proc. Transp. Res. Board 98th Annu. Meeting*, Washington, DC, USA, 2019, pp. 13–17.

[87] C. Heinzlef, B. Robert, Y. Hémond, and D. Serre, ''Operating urban resilience strategies to face climate change and associated risks: Some advances from theory to application in Canada and France,'' *Cities*, vol. 104, Sep. 2020, Art. no. 102762.

[88] E. J. Meijers, M. J. Burger, and M. M. Hoogerbrugge, ''Borrowing size in networks of cities: City size, network connectivity and metropolitan functions in Europe,'' *Papers Regional Sci.*, vol. 95, no. 1, pp. 181–198, Mar. 2016.

[89] A. Sharifi, ''Urban form resilience: A meso-scale analysis,'' *Cities*, vol. 93, pp. 238–252, Oct. 2019.

[90] M. Carrizosa, *Enfrentar el Riesgo. Nuevas Prácticas de Resiliencia Urbana en América Latina*. Caracas, Venezuela: CAF, 2019.

[91] V. Moreno and J. Luis, ''Las ciudades iberoamericanas: Perfiles de sostenibilidad y resiliencia,'' *Una Mirada en Perspectiva*, vol. 39, pp. 23–56, 2019.

[92] S. C. Calvert and M. Snelder, ''A methodology for road traffic resilience analysis and review of related concepts,'' *Transportmetrica A, Transp. Sci.*, vol. 14, nos. 1–2, pp. 130–154, Jan. 2018, doi: 10.1080/23249935.2017.1363315.

[93] M. Nogal, A. O'Connor, B. Caulfield, and B. Martinez-Pastor, ''Resilience of traffic networks: From perturbation to recovery via a dynamic restricted equilibrium model,'' *Rel. Eng. Syst. Saf.*, vol. 156, pp. 84–96, Dec. 2016, doi: 10.1016/j.ress.2016.07.020.

DIEGO CORDERO was born in Azogues, Ecuador, in 1966. He received the Graduate degree in computer and informatics systems engineering from the Escuela Politécnica Nacional, Quito, Ecuador, in 1993, the master's degree in management information systems from the Escuela Politécnica del Ejército, Guayaquil, Ecuador, in 2008, and the Ph.D. degree in sciences administration from the Universidad Nacional Autónoma de México (UNAM), Mexico, in 2017.

He was a Postdoctoral Researcher in ''Latin America and its Insertion in the Global Order,'' Ecuador, in 2018. He was a System Manager, a Strategic Manager, the Dean, the Director of Research, the Academic Director, and the Director of Innovation Processes. He is currently a Research Professor with the Universidad Católica de Cuenca (UCACUE). He leads research projects. He is the author of two books, ten chapters of book, more than 40 articles, and has participated as a speaker in more than 15 international conference. His research interests include technology governance and inclusion, green IT, data analytics, and educational innovation.

Dr. Cordero is a member of the Green IT Research Group. He is an Accredited Researcher of the Secretary of Higher Education, Science, Technology, and Innovation of the Republic of Ecuador and an Ecuador Node Coordinator of TIC Latin America. He is an Associate Editor of the *UDA Journal* (Academ).

GUILLERMO RODRIGUEZ was born in Paute, Azuay, Ecuador, in 1973. He received the Graduate degree in systems engineering from the Catholic University of Cuenca, in 2001, and the master's degree in information technology management from the State University of Milagro, in 2015. He is currently pursuing the Ph.D. degree in computer engineering with Pontificia Universidad Católica (PUCP), Lima, Peru.

Since 2010, he has been working with the Catholic University of Cuenca as a Research Professor. He is the author of a book, more than ten articles, and four book chapters. His research interests include business intelligence, business data analytics, urban mobility and accessibility, and resilience of urban infrastructures. He works with machine learning, deep learning, and artificial intelligence using Python.

Prof. Rodriguez has participated in IEEE LA-CCI congresses in Guadalajara Mexico 2018 and in ETCM Ecuador 2021.