Connectivity Forecast and Performance of Urban Road Networks Using Computational Analysis

Guillermo Rodríguez López

August 25, 2023

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Resume. - Emerging computational techniques allow precision measurements of the performance of urban road networks. These measurements help analyze the levels of connectivity and intermediation of growing urban networks. Consequently, in several experiments carried out, we have managed to detect a pattern of avenues that are highly used by drivers and that are scarce in each city. Therefore, these avenues are primary candidates for having a large influx of automobiles that congest traffic. The common factor of this inconvenience is that the cities are not planned in the long term with wide avenues to meet the growth of the cities. Where, the few existing avenues built randomly and do not support the density. Also, there is the concentration of commercial, educational and other establishments, clustered in the central area of the city. This leads to the concentration of human mobility and motorized vehicles in these areas. Also, the creation of urban or rural neighborhoods that do not meet urban standards, accessibility and basic development services has been observed. Here we present techniques to identify the routes with the greatest connectivity and compare trip averages on various major routes in the city. This with the objective of proposing strategies and public policies to: reduce the flow of vehicles, reduce interruptions, optimal maintenance of these roads and recommendation to build new roads in the convenient place.

Keywords. - Planning, urban networks, congestion, travel times, mobility and accessibility.

1 Introduction

At present the cities of Ecuador are growing rapidly in a disorderly manner. At the same time, the number of automobiles that circulate through the urban network transporting citizens is also growing. This progressive increase in vehicles causes road congestion, since urban networks have not been built in a scalable way according to population growth. On the other hand, this, the lack of maintenance of the main roads and they deteriorate, preventing the normal flow of cars. If added to this, the obstacles, traffic lights, pedestrians, informal merchants and the diversity of means of transport stop more vehicular circulation. Finally, there is the low supply of wide avenues that serve as intermediaries to relieve the high traffic of vehicles. Since, these few roads are the favorites for most drivers.

These factors progressively deteriorate the circulation of transport, mobility and accessibility to areas of high human concentration. For example, shopping centers, educational, health, terminals, among others. Therefore, it is urgent to determine the morphology of cities. Identify drivers' favorite routes to reach the destination in the shortest time. Therefore, the benefit of locating these routes (avenues or highways) is to make decisions or immediate actions that guarantee their permanent maintenance. Or otherwise, the planning of new roads in strategic areas of the city to alleviate the current traffic load that generates discomfort among the population.

These antecedents make it necessary to expand urban planning studies, where areas most vulnerable to the flow of vehicles and connectivity of road networks are identified. Find indicators that reveal the shortcomings of the road network, which help to understand and interpret the behavior of urban mobility. This analysis helps to optimize the flow of vehicular traffic or the construction of new roads in the appropriate places. This to cushion congestion and improve the fluidity of roads in cities. The sectors analyzed are those that have a high density of vehicular traffic due to their commercial and social activities, such as markets, shopping centers, educational centers, land or air terminals, among others.

2 Related Works

In previous works there is a variety of research that evaluates the performance and drawbacks of urban networks, their morphological changes and the high traffic of automobiles. They analyze optimal routes through Wi-Fi networks, surveys of thousands of drivers on the choice of their favorite routes, optimization of bus routes, bicycles, even decentralized traffic simulation systems [1] [2] [3]. However, in Ecuador there are no specific studies to review the optimal routes that benefit drivers and planners to make decisions and generate new public policies. For this study based on computational technologies, the first topic to review is Dijkstra's algorithm. This is an algorithm to find the shortest paths between nodes in a weighted graph, which can represent, for example, road networks. It was conceived by computer scientist Edsger W. Dijkstra in 1956 and published three years later [4]. Basically, the algorithm starts at the node you choose (the source node) and scans the graph to find the shortest path between that node and all other nodes in the graph. The algorithm keeps track of the currently known shortest distance from each node to the source node and updates these values if it finds a shorter path [5].

Regarding the analysis of the morphology or shape of urban networks, it is a complex task that requires several approaches [6] [7]. Since, the flow of urban transport, accessibility and travel demand depends to a large extent on how the road fabric of a city is designed. This urban morphology can be evaluated using different methods, such as: graph theory, spatial analysis and fractal geometry [8]. Graph theory is used to analyze the topology of urban networks by studying the connectivity between different nodes and edges [9]. Spatial analysis is used to assess the spatial distribution of urban networks by analyzing the spatial patterns of different urban elements, such as streets, buildings, and open spaces. Fractal geometry is used to assess the complexity of urban networks by analyzing their self-similarity at different scales [10].

The measurement of urban network management in congested cities is a complex and broad topic. There are multiple methods to assess congestion in urban areas that consider three dimensions of congestion: intensity (severity), extent (amount of congested network) and duration (the number of congested hours)[11]. For this study, we used betweenness centrality. This is a route-based global flow measure that is a static predictor of congestion and load on networks. It is widely used to analyze social interaction networks, urban networks, biological networks and more [12]. In our case, we use it to identify the roads preferred by drivers because they have high connectivity with the rest of the nodes (intersections) of the urban network. In [13] There is talk of measuring the average travel speed of the urban network and the critical speed at the start of vehicular congestion. For this, they use the variables number of vehicles (n) and the production of trips (p).

Regarding the choice of short routes according to the travel time or the variation of the travel times from an origin to a destination, there are advances from previous studies [14]. These evaluations are carried out on roads with greater concessions and at peak hours based on free information on the Internet. Studies that recommend making detours through other non-traditional routes that are not optimal solutions either, but emotionally alleviate the situation of being stopped on a clogged route. In another study [15] describe that using public transport takes on average 1.4 to 2.6 times more time than driving a car. The study was carried out among places most visited by travelers in Sao Paulo, Stockholm, Sydney and Amsterdam.

As for identifying vulnerable neighborhoods or sectors, there are several criteria that facilitate this work reliably. The first is mapping, it can be used to identify areas that are at risk of flooding or other natural disasters and develop strategies to reduce the risk of damage. You can also analyze the infrastructure of a neighborhood with vulnerable areas by looking at the condition of buildings, roads, and other infrastructure. These criteria can be supported by data analysis from various valid information sources [16] [17].

3 Methodology

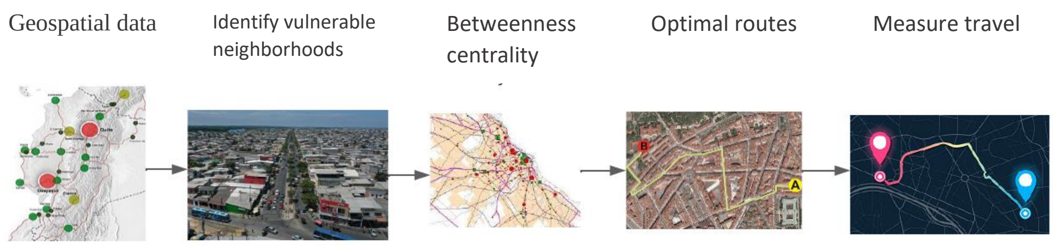


Fig. 1. Methodological phases of the study.

This research focuses on the analysis of massive data of urban networks, geospatial and temporal data. Therefore, the collected data was acquired from Web databases specifically from OpenStreetMaps OSM and Wize. For which, Networkx tools were used OSMnx and Wizeroutcalculator. The next step was to determine the measurement indicators, the same ones that are focused on the intermediation of centrality and measurement of travel time.

To achieve this, we downloaded the urban networks of the main cities of Ecuador, Quito and Cuenca in the Sierra region; Guayaquil and Machala of the Coast region. On the other hand, we downloaded the urban networks of Dubai and Barcelona, to make a comparison of the same indicators. These urban networks were selected due to their good reputation in traffic management and for being modern cities.

The next step was to extract the geospatial data from the urban networks to analyze the vulnerable sectors or neighborhoods of each urban network, markets, parks, boardwalks, educational centers.

Then, we evaluate the roads with the highest Centrality of Betweenness of the streets (Betweenness Centrality of Edges BCE) to detect the avenues prone to a higher traffic load and possible traffic jams. Based on this information, to size up this distribution and location among the cities evaluated.

Next, we calculate the most suitable routes to connect these sectors with the vulnerable neighborhoods of each city. Vulnerability is determined by its marginal location in these sectors (further away, on the outskirts of the city) and by the high risk of insecurity.

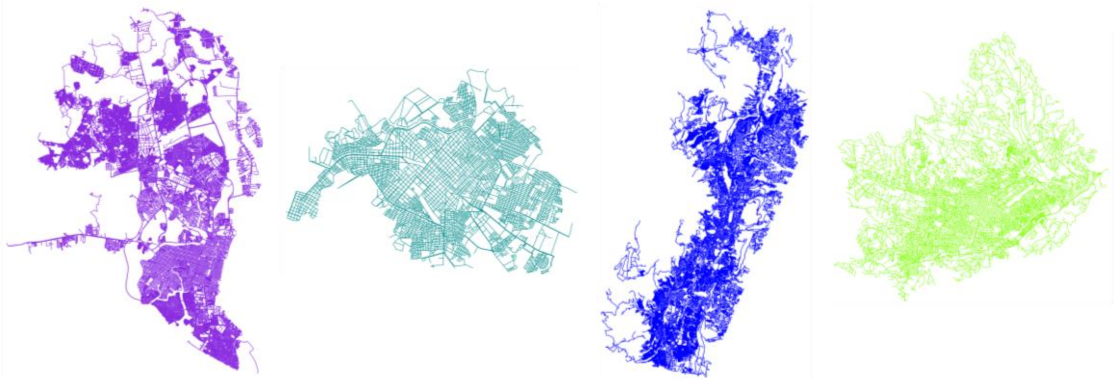
We then use Wize's WazeRouteCalculator API to measure travel times from high-mobility sectors of travelers to all nodes in a neighborhood. We take the most remote or vulnerable bus terminals and universities and neighborhoods. This in order to obtain the average time it takes to connect the origin with the destination and the distance traveled. With this information we classify the cities with the worst and best average travel time.

Finally, we present the description of the results with the most relevant conclusions and recommendations found in the investigation.

2. Results

4.1 Data acquisition

The geospatial data in the form of graphs were selected from the main cities of Ecuador according to their population and urban sectors with high vulnerability. These urban sectors were selected based on the information that they are places with poor urban planning, they are places that are difficult to access for motorized transport, they are places of high danger due to references to crime that frightens the entry of taxis, buses to transfer travelers, especially in the coastal cities of Guayaquil and Machala.



(a) Guayaquil (b) Machala (c) Quito (d) Cuenca

(e) Barcelona of Spain (f) Dubai United Arab Emirates

Fig. 2. Cities selected for morphological analysis.

The four Ecuadorian cities downloaded for the investigation were Guayaquil and Machala in the Coastal region; Quito and Cuenca of the Sierra region. In the case of Guayaquil and Quito, they are large cities with approximately 3 million inhabitants, while Machala and Cuenca are intermediate cities with approximately 500,000 inhabitants (INEC,2019). For comparison, the urban networks of Barcelona in Spain with more than 1.5 million inhabitants according to the municipal register and Dubai in the United Arab Emirates with 3.3 million inhabitants were loaded (Wikipedia,2019).

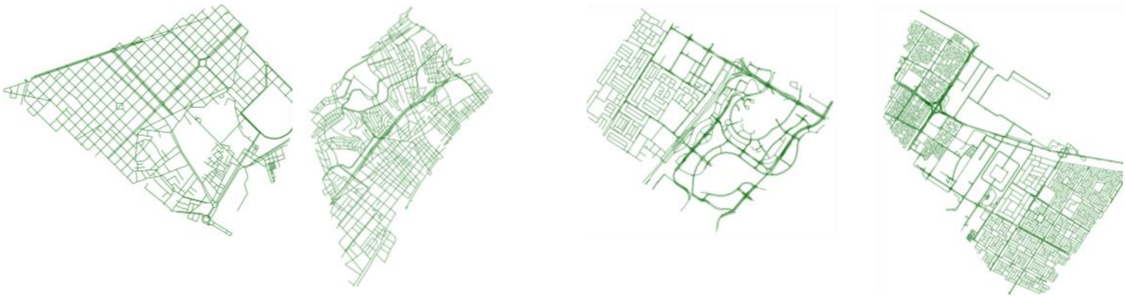
After downloading and drawing these four urban networks, the first observation made is that none of them have main roads (avenues) that connect the city nodes end-to-end in a continuous manner. This shows that there is no sustained urban growth planning for these cities since their urban expansion. Most of the avenues have been prolonged randomly and circumstantially.

To analyze urban routes, the areas with the highest concentration of people mobility and the highly vulnerable sectors were considered. For this, four neighborhoods of Guayaquil and Quito were selected because they are large cities based on the number of inhabitants. On the other hand, for the cities of Machala and Cuenca, three neighborhoods were selected because they are small cities by the number of inhabitants. The vulnerability of these neighborhoods was rated based on the following factors.

Distance: The neighborhoods located at the ends of the cities were considered for the studies, that is, those that are located to the extreme north, south, east or west. Consequently, the distances that must be traveled from the place of origin to any destination node in each neighborhood are the greatest distances traveled. The places of origin are selected for having a high concentration and mobility of people within the cities, for example, bus terminals, ports, airports, educational centers, commercial and financial centers.

Poverty: The neighborhoods in the sample are considered to be poorer due to the quality of housing, basic services, and the state of access roads. For some neighborhoods, both factors were considered (Ecuador) or at least one of them, preferably distance.

(a) Mitad del Mundo Quito (b) Guasmo-Guayaquil (c) Arenal-Cuenca (d) Centro - Machala



(g) Barrio Gótico-Barcelona | (h) Badalona - Barcelona | (g) Downtown-Dubái | (h) Sarja - Dubái

Fig. 3. Neighborhoods selected to analyze the accessibility of Quito, Guayaquil, Cuenca, Machala, Dubai and Barcelona.

Calculation of the size of urban networks according to the number of nodes (street intersections) and borders (edges, each section of street). Based on this calculation, we describe in Table 1 the classification of cities according to their network size, into large cities and small cities. In addition, the size of the urban network depends on the computational time it takes to make the different measurements.

Table 1. Shows data about the size of urban networks and their computing times.

Ciudad	**# nodes**	**# edges**	**Time BCE H:M**
Quito	39526	99608	12:31
Guayaquil	40222	111272	15:50
Cuenca	11478	25593	0:49
Machala	5616	15721	0:17
Barcelona	25583	49360	2:58
Dubai	91024	193307	52:42

The computational analysis of the intermediation centralities according to the criteria of streets (edges) took a time directly proportional to the size of the network according to the number of nodes or intersections. The relationship can be seen in Fig. 4.

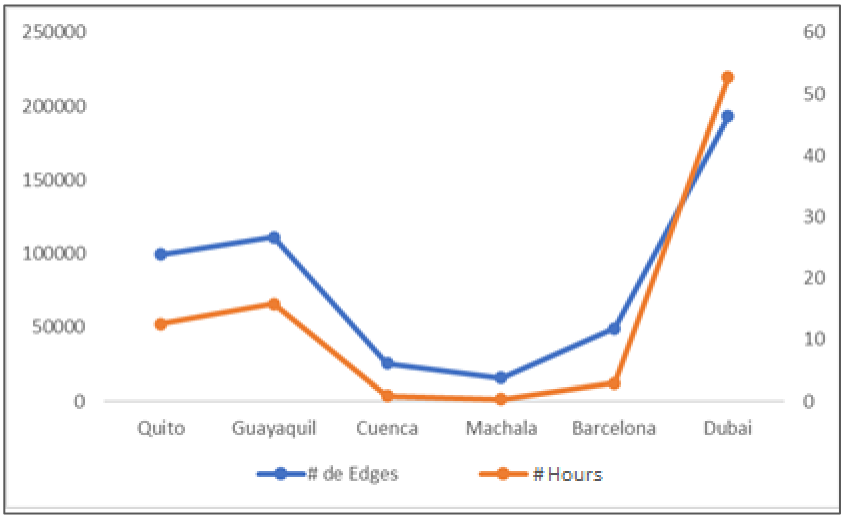


Fig. 4. Relationship between the size of each urban network and the data processing time when calculating the BCE.

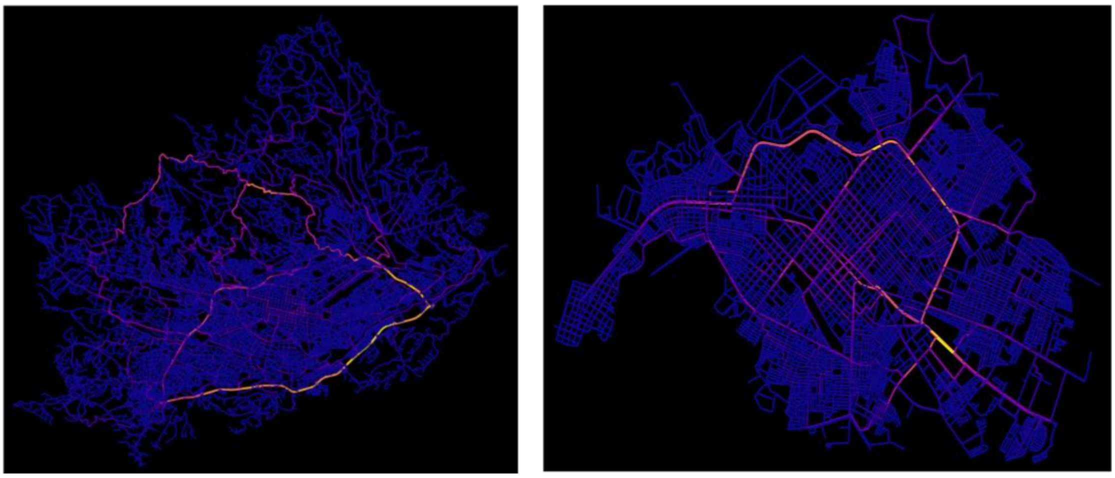
4.1 Scanning of high-traffic roads in the cities analyzed

First, we perform the scanning of the urban networks of Ecuador using the Centrality of Intermediation of streets or edges (BCE) algorithm. Using Networkx and OSMnx libraries BCE = nx.betweenness_centrality(nx.line_graph(G1)) [18].

This scan allows us to observe the avenues with the highest intermediation within each urban network. These avenues are highlighted in intense yellow and as it decreases, they change and those in blue are those with less intermediation. This means that high intermediation streets allow to better connect each node or point of the urban network. Therefore, these avenues are recommended for drivers to use. Consequently, these avenues support a high load of vehicular traffic and are easily congested. This analysis is shown in Fig. 5.

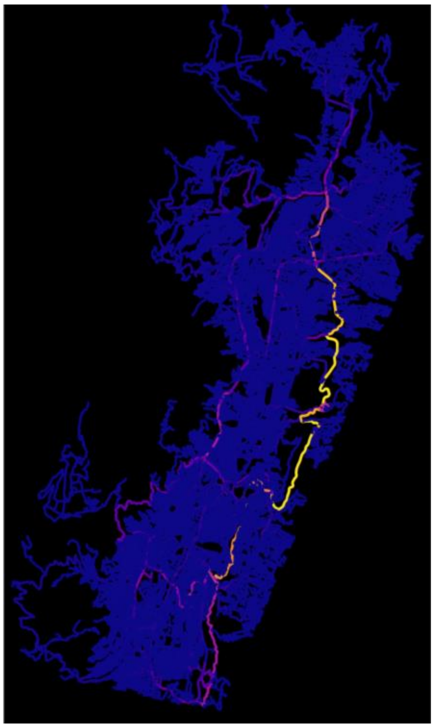
In the case of the city of Cuenca, the high BC avenue is the one that crosses from east-west through the south of the city. Another important stretch is the one between the main avenue and heading towards the northwest of the city, forming a ring road. However, there are other avenues, which are acquiring high BC through the northern part of the city. This is because the city has expanded in this sector, but it can be seen that these avenues are irregular, that is, without prior planning. Therefore, these avenues do not ensure a fast flow of traffic in the present and even worse in the future. This is because the city continues to grow and will have more drivers using these roads that do not offer good circulation. In addition, it is observed that there are no alternatives to expand these roads in such a way that the entire city runs from east to west and from north to south.

In the case of the city of Machala, we observe that the east-west access has high intermediation. Then, this access is divided into three branches, one to the north, the one with the largest BC, another to the center and the last to the south, all heading west (Pacific Ocean). However, there are no new avenues that connect the ends of the city through the growth sectors.



(a) Cuenca-BCE urban network (b) Machala-BCE urban network

(c) Guayaquil-BCE urban network



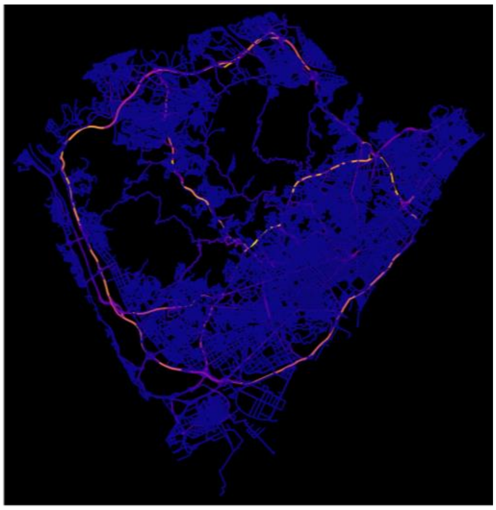
(d) Quito-BCE urban network

Fig. 5. Shows the urban networks of high intermediation centrality of the most populated cities in Ecuador.

In the case of Guayaquil, it is observed that the city has only one avenue of high intermediation BC, which is the Perimetral that connects the west side from north to south. For what makes this avenue of vital importance for the daily circulation of vehicles and drivers. There are other avenues of less interconnectivity BC that go from the center of the city to the north. This implies that Guayaquil depends to a large extent on an efficient maintenance plan that is given to this road. Since it does not have other avenues that connect the ends of the city, especially from north to south or vice versa, nor east-west accesses.

In the case of the city of Quito, it is observed that the avenue with the greatest intermediation is the eastern one (Av. Simón Bolívar). This avenue that despite being very irregular (winding), connects from south to north and vice versa and supports the largest amount of traffic in the city. Therefore, this avenue is exposed to permanent congestion. In other words, if this road is interrupted, great confusion is expected that it would cause the city and drivers. Since, interruptions are highly probable due to adverse events such as floods, landslides, poor road conditions or earthquakes. Other avenues such as the western avenue and one or two central avenues offer important intermediaries but do not fully connect the city from end to end. For this reason, these avenues are not preferred by drivers for daily trips, see Fig. 6

(e) Barcelona-BCE urban network

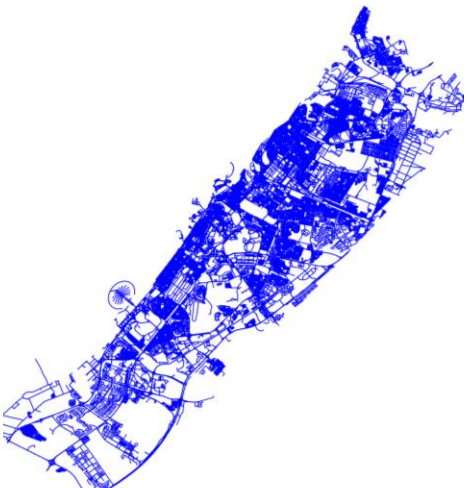


(f) Barcelona-BCE urban network

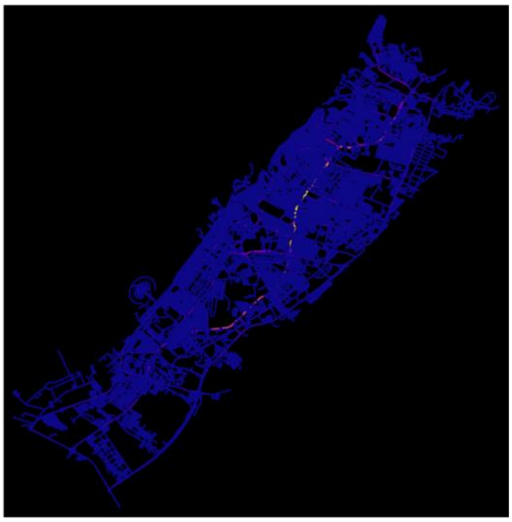
Fig. 6. Shows the urban networks with high intermediation centrality in Barcelona.

On the other hand, we take the urban networks of the City of Barcelona (Spain), to make a comparison of the intermediation of its avenues and how they are distributed. Since, according to the literature, Barcelona is among the large cities that offer the best intermediation due to its low cost of time in transporting travelers from the origin to the destination. Indeed, Barcelona has a greater offer of highly intermediated avenues in which the daily traffic flow of vehicles and drivers is distributed. This means that the average travel time is one of the lowest compared to other cities with similar characteristics in the world.

We made the same analysis to the city of Dubai (United Arab Emirates), where we appreciate that this city also has several avenues that connect the ends of the city from east to west and from north to south, see Fig. 7.



(a) Dubai-BCE urban network



(b) Dubai-BCE urban network

Fig. 7. Shows Dubai's high betweenness centrality urban networks.

4.3 Detection of carriers' favorite routes

In this experimentation, the short routes, favorites of carriers to travel from one end of the city to the other, were detected. The routes were calculated from the sectors with the greatest mobility and concentration of the urban population, to the most remote and vulnerable neighborhoods of the cities. However, these routes found are also prone to a high load of vehicular traffic causing congestion and delays in the transfer during the trip. Below, we show these trends, evidencing which roads are most affected by this behavior.

First, we take the city of Guayaquil, to calculate the shortest, preferred or drivers' favorite routes. Taking as origin four points of high concentration of travelers such as: the Bus Terminal of Guayaquil (center-east), Forestal Park, Maritime Port, Agrarian University, the latter to the South of the city. On the other hand, for the destinations, we take all the nodes of the furthest north neighborhoods of the city, such as Pascuales and Monte Sinaí-El Fortín, see Fig. 8.

(a) Origin: Guayaquil Bus Terminal and Forest Park. Destination: Barrio Pascuales, north.

(b) Origin: Maritime Port and Agrarian University. Destination: Barrio Pascuales, north.

(c) Origin: Guayaquil Bus Terminal and Forest Park. Destination: Monte Sinai neighborhood - Fortín, north.

(d) Origin: Maritime Port and Agrarian University. Destination: Monte Sinai neighborhood - Fortín, north.

Fig. 8. Geographic sample of the favorite short routes of the city of Guayaquil from South to North.

For the following sample of favorite routes, instead, we present the results for four other important nodes from the north to two populous neighborhoods in the south of Guayaquil. The important nodes: Pascuales land terminal, El Dorado Shopping Center, Comercial Plaza and José Joaquín de Olmedo Airport and the southern neighborhoods are: Isla Trinitaria and Guasmo Sur. See Fig. 9.

(a) Origin: Terminal Terrestre Pascuales and CC Mall El Dorado. Destination: Isla Trinitaria neighborhood, South.

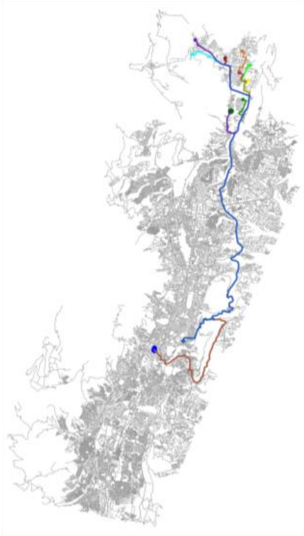
(b) Origin: Comercial Plaza and J.J. Airport. de Olmedo Destination: Isla Trinitaria neighborhood, South.

(c) Origin: Terminal Terrestre Pascuales and CC Mall El Dorado. Destination: Isla Guasmo neighborhood, South.

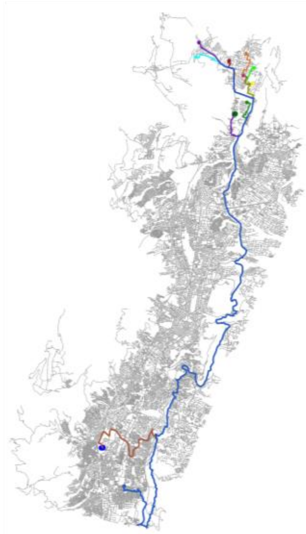
(d) Origin: Comercial Plaza and J.J. Airport. de Olmedo Destination: Barrio Isla, Sur.

Fig. 9. Geographic sample of the favorite short routes of the city of Guayaquil from North to South.

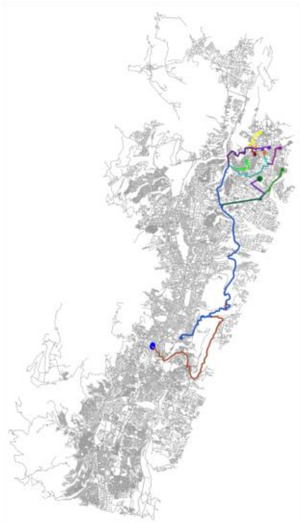
For the city of Quito, following the same format, first the trips from South to North were analyzed. The nodes of origin with the highest concentration of people mobility were: Carondelet (Presidency of Ecuador), Coliseo Rumiñahui (these two centers south), Terminal Terrestre Quitumbe and Terminal Beaterio de Combustibles (these two to the south). On the other hand, the selected neighborhoods in the extreme north of the city are: San Antonio – Mitad del Mundo and Carapungo. The results were the following, see Fig. 10.



(a) Origin: Historic Center and destination: Middle of the World.



(b) Origin: Quitumbe Bus Terminal, Destination: Middle of the World.



(c) Origin: Historic Center and destination: Barrio Calderón.

(d) Origin: Terminal Quitumbre and destination: Barrio Calderón.

Figure 10. Geographic sample of the favorite short routes of the city of Quito South-North.

For the measurement from North to South, the following routes of origin and destination were evaluated. The points of origin were taken, Terminal Terrestre Carcelén, El Portal Shopping, Hospital Pablo Arturo Suarez and Parque Bicentenario to the north and the most extreme neighborhoods to the south of Quito were Quitumbe and Guamaní.

4.4 Travel times in kilometers per hour

For this analysis, we measure the travel time from a source of high agglomeration of people such as ground transportation terminals or airports. Instead, for the destination we take all the nodes (street intersections) of two (2) neighborhoods of each evaluated city. The first neighborhood located in the peripheral sector with faster access and the second neighborhood located in the center of the city with more delayed access. The data was then averaged to obtain an average travel speed for the city. This measurement allows estimating the level of delay in travel time that each city has relating to each other. The results are detailed in Fig. 11 and Table 2.

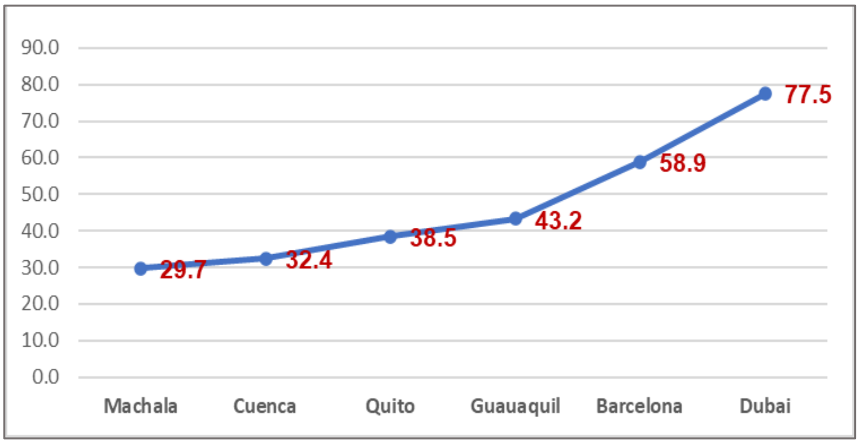


Fig. 11. Shows the average speed of motor vehicles in cities

Figure 11. Shows the average speed of motor vehicles in cities.

Ciudad	Origin-Fixed	Destination/Neighborhood	Nodes	km/h	Average
Machala	Terminal Terrestre	Neighborhood: Puerto Bolívar	317	30.02	
		Neighborhood: Centro	300	29.4	**29.7**
Cuenca	Terminal Terrestre	Neighborhood: Arenal	1048	37.99	**32.4**
		Neighborhood: Centro Histórico	1503	26.72	
Quito	Terminal Terrestre	Neighborhood: Mitad del Mundo	899	39.5	**38.5**
		Neighborhood: Parque Carolina	1093	37.48	
Guayaquil	Terminal Terrestre	Neighborhood: Guasmo Sur	1842	40.73	**43.2**
		Neighborhood: Monte Sinaí - Fortín	1737	45.74	
Barcelona	Aeropuerto	Neighborhood: Gótico	839	51.95	**58.9**
		Neighborhood: Badalona	2386	65.92	
Dubái	Aeropuerto	Neighborhood: Sarja	3884	84.7	**77.5**
		Neighborhood: Downtown	1049	70.19	

In summary, the travel time data shows that Machala is the Ecuadorian city with the lowest average mobilization of motorized vehicles with an average of 29.7 km/h. On the other hand, Guayaquil is slightly better than the other cities in Ecuador with a travel time of 43.2 km/h on average. For its part, Barcelona in Spain has an average speed of 58.9 km/h, significantly higher than the average for Ecuadorian cities. Finally, Dubai, far exceeds all the cities evaluated with 77.5 km / h average travel. This is an indicator that the lower the average trip, the longer it takes vehicles and people to move from a place of origin with a high concentration of passengers to their destinations in the respective neighborhoods. This causes costs, whether due to loss of time on the roads or highway, fuel consumption, pollution, among other factors that directly affect travel delays.

5 Conclusions

The morphology of the urban networks of the cities of Ecuador is very irregular and disorderly. It is observed that they have had a random growth without planning and this has directly affected the severe transport congestion in the main cities, analyzed in Fig. 5.

This can be appreciated when reviewing the travel times, which are very high compared to cities with better urban morphology such as Barcelona and Dubai in Fig. 11 and Table 2. Therefore, it has been possible to classify from highest to lowest the cities most vulnerable to transport congestion, especially at rush hour. Being this classification Machala, Cuenca, Quito and Guayaquil. Where, Machala has the lowest average speed in km/h, therefore, it is the city that spends the most time moving around. On the other hand, Guayaquil has the highest average, therefore being the one that loses the least time to mobilize. On the other hand, when compared to Barcelona and Dubai, Guayaquil is well below the average for these cities.

In summary, Ecuadorian cities must work hard to compensate for this loss of time that they have in urban mobilization. Which in turn is the loss of monetary and environmental resources that affects citizens.

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