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Routes of Migrants Passing Through Mexico: Analysis from Graph Theory

Los caminos de migrantes que pasan por México: análisis desde la Teoría de Grafos

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ABSTRACT

The objective of this research is to update the map of migration routes in Mexico and determine the influential cities, risk zones, and the effects of the 2018 and 2019 caravans. The methodology includes the review of comprehensive documentation and the application of Graph Theory. There are 545 services for migrants (consulates, lodging places, canteens, dispensaries, religious centers, and legal support offices) with which a network of 183 nodes and 720 edges is built. Transit is ordered within a scheme of three interconnected blocks. The cities of Guadalajara, Mazatlán, Ixtepec, and Tenosique stand out as the most influential in the transit of migrants. Shorter routes to the United States always go through at least two danger zones. The results can be used for public policy design on security and information generation.

Keywords: 1. centrality, 2. migrant caravans, 3. violence, 4. Central America, 5. United States.

RESUMEN

El objetivo del artículo es actualizar el mapa de rutas migratorias en México y determinar las ciudades influyentes, las zonas de riesgo y los efectos de las caravanas de 2018 y 2019. La metodología incluye la revisión de una documentación exhaustiva y la aplicación de la Teoría de Grafos. Se localizan 545 servicios para migrantes (consulados, sitios de hospedaje, comedores, dispensarios, centros religiosos y oficinas de apoyo legal) con los que se construye una red de 183 nodos y 720 aristas. Usando la teoría de grafos, se trazan las rutas y se organizan las ciudades dentro de un esquema de tres bloques interconectados. Destacan las ciudades de Guadalajara, Mazatlán, Ixtepec y Tenosique como las más influyentes en el tránsito de migrantes. Las rutas más cortas hacia Estados Unidos siempre pasan por dos zonas de peligro como mínimo, ya sea por sus altos índices de homicidios o porque incluyen una estación migratoria. Los resultados pueden servir para el diseño de políticas públicas en materia de seguridad y generación de información.

Palabras clave: 1. centralidad, 2. caravanas migrantes, 3. violencia, 4. Centroamérica, 5. Estados Unidos.

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INTRODUCTION

Within the classical theory of migration, the discussion on currents and countercurrents proposed by Lee (1966) provides that "migration tends to occur to a large extent within well-defined paths" (p. 54), which in practice coincides with what happens in Mexico. Casillas (2008) states that "migrants do not build roads, they make existing ones their own" (p. 7). However, currently, for Central Americans who wish to reach the United States (U.S.), it is possible to better apply the neoclassical theory addressed by Sjaastad (1962) and Todaro (1976), which establishes that migrants, when selecting their route, always value security and economic risks. Now, by presenting these two phenomena, sudden changes constantly motivate migrants to adjust their itineraries (Casillas, 2008), while their perpetrators also do so in search of their resources (Foote & Small, 2013). The organization Doctors Without Borders (MSF, initials in Spanish for Médicos Sin Fronteras) identifies that due to fear, many migrants do not use shelters, soup kitchens or dedicated houses, whether public or from non-governmental organizations, but prefer to remain on the streets, regardless of whether these spaces have the capacity to support them (MSF, 2019a).

The objective of this article is to deepen the discussion with an analysis on the possible existence of a permeable network whose viability allows multiple options for the route of migrants in Mexico, and to graph these transit routes. Likewise, it is aspired to advance the discussion on the feasibility of building a barrier (The White House, 2017) or not[2] (The White House, 2021)[3] to control linear migration. In this sense, it is suggested as a research question: are there cities within the migrant route in Mexico that can be potentially controlled, due to their degree of intermediation?

Mexican and Latin American Migrants in the United States

For many decades, researchers have predicted a growing volume of migration in the world (Lee, 1966). At present, these projections continue to be confirmed. Recently, the International Organization for Migration (IOM) noted that there was an 81 percent increase in the total number of international migrants in the world. The number of international migrants in 2020 was 272 million, a figure that represents 3.5 percent of the world population (OIM, 2019).

In the case of the United States, the immigrant population has been increasing (Gaspar Olvera, 2012). Their number has quadrupled since the Immigration and Naturalization Act (*Public Law 89-236 of 1965*) came into force. Foreign born residing in the U.S. in 2018 reached 44.8 million, that is, 13.7 percent of its population (OIM, 2019). In the particular case of those born in Mexico, they

[2] The executive order signed in January 2017 by Donald Trump, ex-President of the United States, he assumes that the wall can prevent illegal immigration.

[3] The executive order signed by the President Joe Biden in January 2021 permanently suspends the construction of the wall.

represent 25%,[4] while those born in other Latin American nations represent another 25% (Budiman et al., 2020).

Migration from Latin America, and particularly from Mexico to the United States has been a permanent phenomenon where, according to the United Nations (ONU, 2009), "the multidimensional complexity of the migratory phenomenon can only be understood if it is considering Mexico as a country of origin, transit and destination" (p. 22). The Inter-American Commission on Human Rights [Comisión Interamericana de Derechos Humanos] (2013) characterizes this phenomenon as complex population movements, which include different profiles of people in search of a dignified life, work, asylum, or refuge, who "in particular come from vulnerable groups" (p. 28).

What Databases can Capture from the Movement of Migrants Passing Through Mexico

Transit to the U.S. is a process that has become intrinsic to the context of life of many families seeking the strength of the U.S. economy (Keeley, 2012; Doctors Without Borders, 2019b). In 2010, the official figures from civil organizations estimate the transit of people passing through Mexico to the US. between 400 000 and 500 000 per year (ONU, 2009; Ponces et al., 2010). For 2019, the Ministry of the Interior confessed: "That is an amount that I want to tell you that I do not know from where or how 144 thousand people passed through our country" (Delgado, 2019, p. 1).

In January 2019, the report of the National Institute of Migration (INM) stated that the Mexican territory received the first Central American foreigner to request asylum in the United States for humanitarian reasons for the year, and the report from July of that same year indicated that the applications reached 18 503 (INM, 2019). There are thousands of people seeking to enter the U.S. but not all succeed. For example, the return figures for the first half of 2018 were: 4 798 in Ciudad Juárez, Chihuahua; 4 435 in Tijuana; and 2 689 in Mexicali, Baja California (Amnistía Internacional, 2018d).

It seems that transit through Mexico is no longer temporary. The migratory population begins to benefit from the offers made by the government and the private initiative: school workshops, shelters, and health. "It has occurred both in formal jobs and in the informal sector, depending on the date of their arrival in the entity" (Ramírez Meda & Moreno Gutiérrez, 2022, p. 3), however, according to international experience, these welfare policies may not be permanent (Castles, 2004).

[4] The figures from Pew Research Center are consistent with IOM's estimates for 2020, where the migrant residents of the U.S. represent 51 million and of these 11.8 are of Mexican origin.

The Time Needed for Migrants to Traverse Mexico

The National Human Rights Commission (CNDH, initials in Spanish for Comisión Nacional de los Derechos Humanos) estimated that the time it takes to travel through Mexico, from the point of entry to the point where it is planned to cross into the United States is between one and four weeks on average (CNDH, 2018). The testimonials indicate that the travel time is variable depending on the route changes that are made along the way. Nájar (2018) identified that migrants can opt for longer journeys to be safer: "how ever long it takes, as long as it takes us to arrive but alive, the time does not matter" (p. 1). Twenty-three days was the time of the journey documented by Tucker and Tillotson (2018) from Honduras to the capital of Mexico.

Some Theories on Migration Issues

The books by De Haas et al. (2020) and Massey et al. (1998) synthesize definitions and migration theories. Nonetheless, there is no universally accepted definition for the concepts of migration or migrant, since there are several elaborated for different contexts. In the recommendations on international migration of the United Nations Department of Economic and Social Affairs (DESA), an international migrant is defined as "any person who changes their country of habitual residence," distinguished from short-term migrants who change countries for periods of up to one year (OIM, 2019, p. 27).

In relation to the issue of the paths taken by migrants, the contribution of Ravenstein (1885) when proposing that the routes are fixed and well defined is relevant. The author states that "the bulk of migrants come from short distances" and that "the number of migrants who arrive at a center decreases as the distance increases" (p. 198), depending on the existence of four factors: a) those associated with the area of origin, b) the destination area, c) intermediate obstacles, and d) personal factors such as perception, intelligence, contacts, or information. In particular, the third point is useful for this research, since intermediate obstacles, as well as violence or authority filters, seem to be the causes of the change of plans for the original route that passes through Mexico (Casillas, 2008; Foote & Small, 2013; MSF, 2019a).

Danger on the Routes

Until less than a decade ago, Central American migrants could transit through Mexico in relative safety, but as of 2007, organized crime found a stable source of income in the kidnapping of migrants (Izcara Palacios, 2015). Migrants are attacked by mafias and gang groups during their transit through Mexico (González Arias & Aikin Araluce, 2015); in addition, they are forced to participate in illegal activities by joining drug cartels, that is, they are transformed from day laborers to criminals (Izcara Palacios, 2016, 2017). Migrants lack resources and are not protected by formal organizations (Sampson, 2008), so it seems that violence and migration coexist permanently, both always looking for new routes (Ponces et al., 2010).

A second risk is experienced by migrants in migrant holding centers, due to the possibility of being deported to their countries of origin, which is accentuated by the mistreatment exerted by some agents. In this regard, the INM has a series of complaints filed about cases of abuse (Amnistía Internacional, 2017, Comisión Nacional de Derechos Humanos, 2017, 2018).[5]

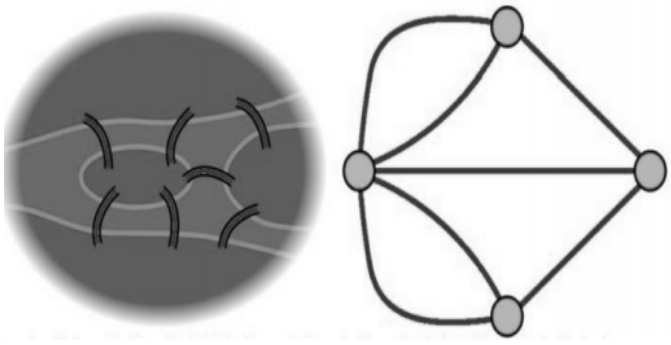
The Caravans

A recent massive protection strategy implemented by Central American migrants is the caravans (Gandini et al., Gutiérrez, 2020). Amnesty International (2018a, 2018c) estimates that the size of each of these caravans can reach up to 10 000 people. It is not clear if these movements are identified as circumstantial to the current migratory dynamics of crossings through Mexico (García Aguilar, 2020) or if it is going to be a permanent phenomenon on a smaller scale. However, these caravans use the migratory routes that pass-through Mexico.

Graph Theory for the Study of Migratory Flows

In a not very rigorous way, we can define *graphs* as schematic representations of a network of connections, whose points (nodes) are related to each other by paths (edges). These representations make it easier to visualize and interpret these problems and the study of their properties (Ortega Reyes, 2020). A first example of the application of Graph Theory is the solution of the Euler problem of the Königsberg bridges of 1736 (Núñez et al., 2004), represented in Figure 1, where the map of the site is compared with its equivalent graph.

Figure 1. Map and Graph of the Bridges of Königsberg



Source: Apple and Haken (2009).

Migration analysis has used network tools for a long time. An example is the study of the Uppsala-Näss parish in Sweden, which narrates how that at the end of the 19th century the village "resembled a train station where people come and go" (Hanagan, 2008, p. 59). However, Izquierdo

[5] In the search engine of the CNDH website, using the keyword "migrates," we found 10 records for years 2017 and 2018, filtered out of a total of 2 792 records.

Escribano and Noya (1999) propose that for the study of migration it is necessary to improve the tools to operationalize their concepts, that is, "the assumptions of the analysis techniques in empirical research must be taken into account: multilevel analysis and mathematical analysis of graphs and networks" (p. 38).

Recent studies already use Graph Theory more frequently to study migration. García Flores (2013) analyzes the patterns of internal migration in Colombia. Ramirez (2014), with a model applicable to different scales, finds that the data from a region of Chile is close to a small world network[6] with 36 nodes, 977 links, an average clustering coefficient of 0.813, and an average path length of 1 225. Lomelí Carrillo and Ybáñez Zepeda (2017) show the differences between two regions on the northwest border of Mexico, while Ruiz-Santacruz (2019) affirms that when analyzing social networks, they "provide a tool to study relationships between countries, the importance of each one within the network, and the influence of country variables on migration patterns" (p. 79).

In summary, the Graph Theory is useful to know if leaving one city you can reach another, to know the similarities between the regions and to determine the types of relationships that exist between each one of them. The contribution of this theory to migratory flows is basically that it allows us to know which cities concentrate more power in terms of traffic and which are more isolated within the network.

RESEARCH QUESTIONS AND HYPOTHESES

Based on the thesis of Lee (1966) and considering that migrants can choose long journeys because they are safer (Nájar, 2018), to answer the first research question (is there a permeable network whose viability allows multiple path options for the route of migrants in Mexico?), the first hypothesis is proposed below:

H1. The northern border can be connected by more than one road with the southern border.

If a path connecting two cities is blocked within the map of possibilities, then there is the possibility of accessing any of them by another path.

Now, regarding the second question "are there cities within the route of migrants in Mexico that can be considered control cities due to their degree of intermediation?" In principle, the theory indicates that it seems so (Ravenstein, 1885). Therefore, based on the degree of intermediation of the cities on the route, hypothesis two is proposed:

H2. There are cities in Mexico that can be considered control cities.

In case of accepting this second hypothesis, it would be possible to propose monitoring schemes in local micro-regions for the study of migration transit in Mexico.

[6] A Small World Network is a type of graph for which most nodes are not neighbors to each other, and yet most nodes can be reached from any source node through a relatively short number of hops between them.

Regarding the insecurity problems that migrants face, it is to be expected that they try to avoid danger points on their route (Nájar, 2018). Therefore, the following third hypothesis is proposed:

H3: The shortest paths between the two borders have at least one node in distress.

In case of accepting hypothesis three, useful information would be generated for the design of public policies on security.

METHODOLOGICAL STRATEGIES

Problems with the Registration of Figures on the Movement of Migrants Through Mexico

One of the problems for migration studies, especially in Latin American countries, is their limited ability to collect data and provide reliable figures on the movement of people, this is basically due to geography and complicated border management. For example, in some regions it represents a challenge due to the non-existence of maritime borders, the distance from mountain passes or the control of isolated paths within tropical forests (Gallagher & McAuliffe, 2016). Also, registering the precise number of migrants presents another series of problems due to the fact that not all movements of people are counted, such as entry or exit from Mexico with a tourist, work or educational visa (OIM, 2018a).

Another phenomenon that makes the volume of the movement difficult to calculate are the caravans, since the number of people varies constantly. There are those who return to their homes, others join the journey, and others are divided to form new groups (Amnistía Internacional, 2018a, 2018c). Therefore, it is a challenge to build a specific database and has the caveats of the method used.

In particular, due to the fact that the statistics of the movements are irregular, the construction of the database of the present study is artificial since it is built based on different sources.

Sources of Information

The first methodological phase was based on an exploration whose objective was the construction of a database of the cities of Mexico through which migrants' transit. In this phase, the recommendation of the organization *Arquitectos con la Gente* (2016) [Architects with People] was followed, which proposes to trace the transit of migration based on the location of aid zones and places where people can obtain better living conditions, food, and accommodation, among other services. Along these lines, directories of shelters or support centers for migrants were obtained from government organizations, the CNDH or different civil organizations, such as Doctors Without Borders. As a complement, an exhaustive review of academic articles published in indexed journals on the subject in Mexico was made, following the suggestion of Hernández Sampieri et al. (2006).

To build the database, an Internet search was carried out based on the constructions: "migrant routes," "migrants' shelters," "migrant housing," and "migrants soup kitchens/food services." The list of public and private organizations identified that handle this information between 2010 and 2018 is presented in Table 1.

Table 1. Organizations that Have Documented Help Points for Migrants

Organization (alphabetical order)	Document
Amnistía Internacional (2010)	*Víctimas invisibles: Migrantes en movimiento* [Invisible victims: Migrants on the move].
Arquitectos con la Gente (2016)	*Mapeo: Ruta del migrante* [Mapping: Migrant route].
Instituto Nacional de Migración (INM, 2014)	*Grupos Beta de protección* [Beta protection groups]. *Consulados de México* [Consulates in Mexico].
Médicos Sin Fronteras (MSF, 2018)	*MFS en la ruta de migrantes y refugiados* [MSF on the route of migrants and refugees].
Organización Internacional para las Migraciones (OIM, 2018b)	*Directorio de casas y albergues para personas migrantes* [Directory of houses and shelters for migrants].
Organización Internacional para las Migraciones (OIM, 2015)	*Directorio de albergues para personas migrantes* [Directory of shelters for migrants].

Source: Own elaboration.

The points located in the works of Casillas (2008) and González Arias and Aikin Araluce (2015) were also included in the database. Additionally, the points identified in 26 complementary journalistic sources that responded to the search criteria indicating some of the routes taken by the migrants were integrated (Table 2).

Table 2. Articles that Documented a Route Used by Migrants

	Source (in alphabetical order)	Article title
1	Animal Político (2018a)	*Solo queremos trabajo: migrantes logran llegar…* [We just want work: migrants manage to arrive...]
2	La Prensa (2018a)	*Caravana migrante se dirige a Ciudad de México…* [Migrant caravan heads to Mexico City...]
3	Martín Pérez (2018)	*Caravana migrante llega a Oaxaca.* [Migrant caravan arrives in Oaxaca.]
4	La Prensa (2018b)	*Caravana de migrantes: hondureño muere…* [Migrant caravan: Honduran dies...]
5	Cortés (2018)	*Avanza parte de caravana migrante a Santiago…* [Part of the migrant caravan advances to Santiago…]
6	agonzalez (2018)	*Caravana migrante emprende camino a Juchitán…* [Migrant caravan sets off to Juchitán...]
7	Cabezas (2018)	*Una nueva caravana con 2.000 migrantes sale…* [A new caravan with 2 000 migrants leaves…]
8	Hernández y Campos (2018)	*Salvadoreños en caravana cruzaron hacia México.* [Salvadorans in a caravan crossed into Mexico.]

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9	Animal Político (2018b)	*Caravana migrante cambia de ruta hacia Veracruz…* [Migrant caravan changes route to Veracruz...]
10	Aristegui Noticias (2018)	*Caravana migrante, en Sayula y Acayucan, Veracruz.* [Migrant caravan, in Sayula and Acayucan, Veracruz.]
11	Animal Político (2018c)	*Caravana migrante llega a Isla, Veracruz…* [Migrant caravan arrives on Isla, Veracruz...]
12	The Economist (2018)	*Córdoba, parada del contingente mayor.* [Córdoba, stop of the largest contingent.]
13	Animal Político (2018d)	*Caravana se fragmenta: migrantes viajan de Veracruz…* [Caravan fragments: migrants travel from Veracruz...]
14	El Universal (2018)	*Mapa muestra día a día el tránsito de las caravanas.* [Map shows day by day the transit of the caravans.]
15	Licea Vélez (2018)	*Caravanas de migrantes se extienden en CDMX…* [Migrant caravans spread in CDMX...]
16	Ávila (2018)	*Caravana de migrantes sale de Puebla…* [Migrant caravan leaves Puebla...]
17	Excélsior (2018a)	*Migrantes llegan a San Juan del Río, Querétaro.* [Migrants arrive in San Juan del Río, Querétaro.]
18	Vázquez (2018)	*Migrantes se dispersan en su viaje a EU.* [Migrants disperse on their journey to the U.S.]
19	Excélsior (2018b)	*Comienza a llegar caravana migrante a Irapuato.* [The migrant caravan begins to arrive in Irapuato.]
20	Rincón (2018)	*Hidalguenses apoyan con víveres a caravana…* [Hidalguenses support the caravan with food...]
21	Santiago (2018)	*Primera ola de migrantes de la caravana llega a Tijuana.* [First wave of migrants from the caravan arrives in Tijuana.]
22	Luna (2018)	*Primer grupo de caravana migrante llega a Guadalajara.* [First group of migrant caravan arrives in Guadalajara.]
23	Morales (2018)	*Arriba a Tijuana segundo grupo de caravana…* [Second group of caravan arrives in Tijuana…]
24	Camhaji (2018)	*El delirante viaje de la caravana migrante:* [The delirious journey of the migrant caravan:] 48 horas…
25	La Prensa (2018c)	*Caravana migrante de centroamericanos se reagrupa…* [Migrant caravan of Central Americans regroups...]
26	Romero (2019)	*Crimen usa 5 rutas para traficar con migrantes…* [Crime uses 5 routes to smuggle migrants...]

Source: Own elaboration.

The second phase consisted of a concentration of data under the following process: 1) each city was assigned a node number; 2) cities were classified into three types of nodes: origin (located in Central America), transit (Mexico cities) and destination (located in the United States); 3) nodes were grouped by state for the purposes of their geographical location.

Construction of the Road Map

The third phase of the methodology consisted in the construction of the node interconnection map. For the construction of roads, the following criteria were followed: 1) if the connection between cities was declared in any of the sources consulted, the indicated path was respected; 2) if the source mentioned a city without indicating its entry or exit routes, it was connected to the closest neighboring nodes (in linear meters, following the recommendation of Kuz et al., 2016); 3) For this article, connections related to air transportation flows were excluded since they present a non-significant volume (Casillas, 2008).

It was decided on a mixed network model, directed at the entry, and exit nodes of the country, and not directed at the internal nodes, since there are cases in which migrants return to previous points to change their path (Amnistía Internacional, 2018b).

Points of Danger for Migrants

To identify the nodes that represent danger for migrants, two indicators were adopted:

a) The state homicide rate, calculated from the records of the National Institute of Statistics and Geography (Inegi by its initials in Spanish), in relation to the state population estimated by the National Population Council (Conapo by its initials in Spanish). This indicator was recommended as a reliable measurement of violence because it presents the lowest black figure (Álvarez & Manzotti, 2008). Those states that had a homicide rate above the average plus one standard deviation were the selection criteria (Méndez, 2017).

b) The location of any of the INM migration stations, not only because of the risk of being deported, but also because of the violence detected (Amnistía Internacional, 2017).

Hypothesis Testing Procedure

For the analysis and testing of the hypotheses, the following definitions were used (Ortega Reyes, 2020):

Node: city or border. For example, Guadalajara and Comitán are city nodes, while the United States and Central America would be border nodes.

Edge: is the transit connection between two nodes. For example, the train route that connects Los Mochis in Sinaloa with Cuauhtemoc City in Chihuahua; the road that connects Santa Rosalía with Guerrero Negro in Baja California Sur; the sea route that connects Cancún with Progreso in the Yucatán Peninsula, or the river that connects Peñitas with Belisario Domínguez in Chiapas.

Path: is the set of edges that are required to connect any two nodes (cities); For example, a path of order 6, which connects Central America with the United States, would include: 1. Central America, 2. Tenosique, 3. Guadalajara, 4. Chihuahua, 5. Ojinaga, 6. U.S.

Graph: is the set of identified nodes and paths. The study graph includes the 183 nodes and the 720 edges of possibilities located.

Elementary path: it is that path that never passes more than once through the same node. For example, route 1. Central America, 2. Tenosique, 3. Guadalajara, 4. Chihuahua, 5. Guadalajara, 6. Hermosillo, 7. Nogales, 8. Naco, 9. United States could not be an elementary path because Guadalajara is repeated.

Shortest path: it is the one that joins two nodes with the minimum number of possible edges. For example, among the options: Celaya-Aguascalientes (by road), and Celaya-Salamanca-Irapuato-León-Aguascalientes (by train), the first path is the shortest since the second has three intermediate nodes.

To test H1 (it can connect the northern border with the southern border by more than one path), an iterative process of reduction of the total number of shortest elementary paths between both borders was used: a) the entry nodes to the United States were identified; b) all the nodes that connect by an edge to the previous nodes were identified; c) the nodes that connect to the previous nodes were iteratively identified, through an inverse tree process, until the exit nodes of Central America were located, and d) the elementary paths that were not the shortest were discarded.

To test H2 (there are cities in Mexico that can be considered as controls) the comparative analysis of nodes of the Graph Theory was used, based on two variables that measure structural centrality (Kuz et al., 2015): a) the degree of centrality, and b) the degree of intermediation (*betweenness* centrality). Both metrics are defined in Table 3. For the comparative analysis, the Gephi system version 0.9.2 (2017) was used for the analysis of social networks.

Table 3. Structural Centrality Variables in Undirected Networks

Variables	Explanation	Interpretation
Degree of centrality (*DC*)	The DC_x of node *x* is the number of edges that connect node *x* with any of the other *n-1* nodes in the network. • $DC_x = 0$ if it is an isolated node. • $DC_x = n-1$ if it is a node connected to the entire network.	The greater the degree of centrality of a city, the greater the permeability and therefore the greater number of escape routes. The DC of a city is the number of cities with which it is directly connected.
Degree of Betweenness (*DB*)	The $DB_{x,n,2}$ of node *x* is the number of times node *x* appears within the set of all shortest paths that can be constructed in a graph of size *n*.	The DB measures the probability that a city occupies an intermediate position (bridge) within the shortest path between two cities. Cities with high DB are candidates to be established as control points due to the high presence of traffic.

Source: Own elaboration based on Freeman et al. (1992).

The H2 is tested if more than one city with a statistically significant *DB* (p-val < 0.001) is identified.

To test H3 (the shortest paths between the two borders have at least one node with a dangerous situation), the database of the shortest elementary paths identified between both borders[7] was cross checked against the data base of points in danger.[8]

RESULTS

The analysis of the data reported by city and state reveals that between the Central America node and the United States node there is a road network that passes through 181 transit nodes or cities within 30 of the 32 states of the Mexican Republic. Together, the 181 cities located offer 545 services for migrants, such as consulates, lodging, food, medical care, religious, legal, or human rights guidance (Table 4). 204 main services related to food and lodging (37.43%) and 120 offering medical care (22.02%) were identified.

Table 4. Transit Cities for Migrants in Mexico

State	Border	Cities	Services
1. Aguascalientes		1	4
2. Baja California	North	7	52
3. Baja California Sur		11	0
4. Campeche	South	3	0
5. Chiapas	South	34	103
6. Chihuahua	North	6	20
7. Mexico City		1	35
8. Coahuila	North	5	25
9. Colima		1	0
10. Guanajuato		4	15
11. Guerrero		3	0
12. Hidalgo		4	6
13. Jalisco		6	14
14. Mexico State		4	12
15. Michoacán		2	4
16. Nayarit		3	4
17. Nuevo León	North	3	28
18. Oaxaca		11	28
19. Puebla		1	10
20. Querétaro		3	15
21. Quintana Roo	South	8	0
22. San Luis Potosí		1	14

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[7] The information obtained for H1 is used.

[8] Cities inside States with high homicide rates and/or presence of migrant holding centers according to the official sources of the Inegi (2019) and of Conapo (2019).

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23. Sinaloa		6	9
24. Sonora	North	19	42
25. Tabasco	South	7	14
26. Tamaulipas	North	11	38
27. Tlaxcala		1	9
28. Veracruz		12	40
29. Yucatán		2	2
30. Zacatecas		1	2
Total		181	545

Source: Own elaboration.

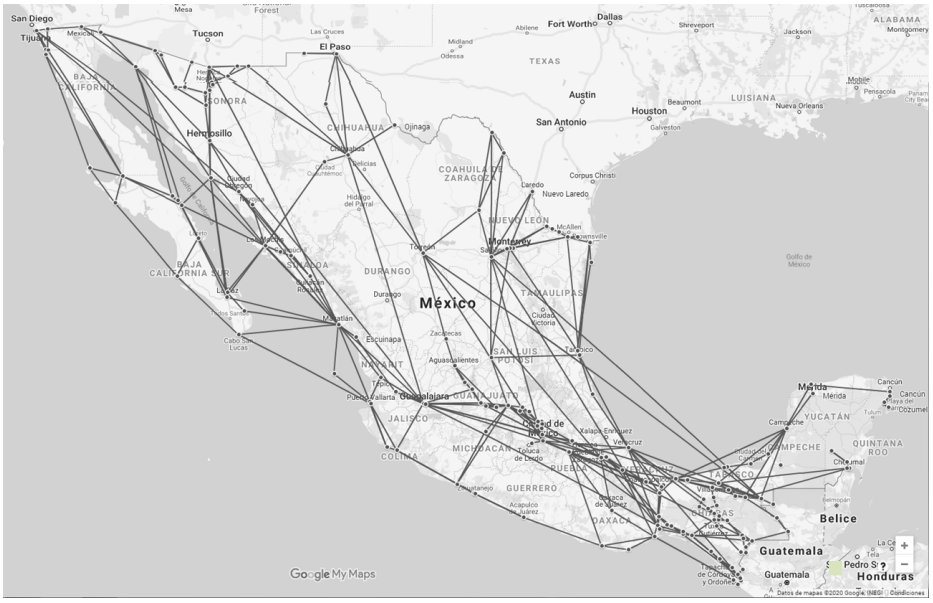
As a finding when grouping the information, 26 cities with transit and without service reports were identified. This can be a line of improvement for the care of migrants.

In Mexico there are six states that border the United States and four that border Central America. The sum of nodes within the border states is 105 nodes (58.0%). On the southern border, the state of Chiapas has 34 cities with migrant transit (18.78%), which makes it the state with the most transit cities in the country. Likewise, Chiapas has 103 service points for migrants, being the entity that offers the most (18.9%) of the total services identified. While on the northern border, the state of Sonora, adjacent to the state of Arizona in the United States, is the state with the second most transit cities, having 19 (10.5%). Among the sources consulted, no transit nodes were identified in the states of Durango and Morelos.

The 181 transit nodes located in Mexico have the following configuration: a) 70 nodes (38.25%) that are cities with one entrance and one exit (DC=2), b) 110 nodes (60.11%) that have more than two connections (DC>2), and c) a single node has a single connection with another (DC=1).[9] The map of cities that can be built consists of 720 edges. The layout of roads in Mexico is presented on map 1.

[9] Oluta, Veracruz, connects only with Acayucan, Veracruz, which makes it a dead end.

Map 1. Cities and Paths of Migrants in Mexico (2008-2019)

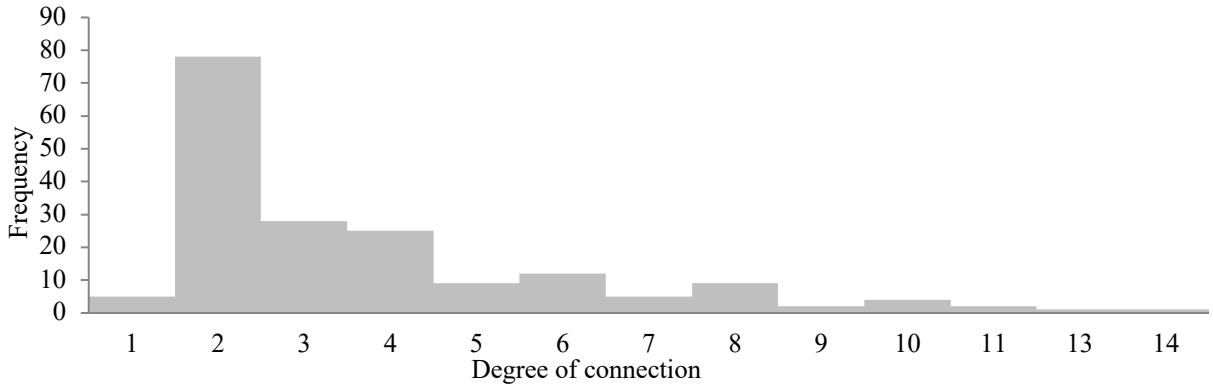


Source: Own elaboration.

The basic statistics of the graph of cities and paths are the following:

a) The average degree of centrality of the graph is $\overline{DC}$= 3.814 (with a standard deviation of 2.545), which indicates that each city on the city map has an average of 3.8 connected cities that can be used by migrants. Graph 1 shows the frequency distribution of the degree of centrality of transit cities in Mexico.

Graph 1. Degrees of centrality of cities in Mexico[10]



Source: Own elaboration.

[10] The nodes of the United States and Central America are not included in this graph.

It is worth mentioning that most of the identified cities (70 of them) only have two connections, one entrance and one exit. In particular, the cities with the most direct connections stand out: Guadalajara with 14, Mazatlán with 13, Saltillo and Querétaro with 11 and Tenosique with 10.

b) The diameter of the graph is 12 edges, which means that the longest path, within the set of all shortest paths, has 12 connections. In particular, this path connects the cities of 1. Comalapa Border; 2. Mesilla; 3. Trinitaria; 4. San Cristóbal de las Casas; 5. Tuxtla Gutiérrez; 6. Arriaga; 7. Ixtepec; 8. Guadalajara; 9. Mazatlán; 10. Cabo San Lucas; 11. Puerto San Carlos; 12. Punta Prieta; 13. Isla de Cedros.

Two examples of shortest paths with 11 edges would connect the cities of: A) 1. Soyaló, 2. Chicoasén, 3. Malpaso, 4. Peñitas, 5. Coatzacoalcos, 6. Tenosique, 7. Guadalajara, 8. Mazatlán, 9. Los Mochis, 10. Punta Chivato, 11. Guerrero Negro, 12. Isla de Cedros; and B) 1. Tecpatán, 2. Tapilula, 3. Pichucalco, 4. Reforma (Chiapas), 5. Coatzacoalcos, 6. Tenosique, 7. Guadalajara, 8. Mazatlán, 9. Los Mochis, 10. Punta Chivato, 11. Guerrero Negro, 12. Isla de Cedros.

c) The average distance between two nodes is 4.944 edges, which means that on average it is necessary to go through five edges to connect any two cities on the map of cities.

d) The density of the graph is 0.0216, which means that only 2.16 percent of the possible edges of the graph are used by migrants. The percentage is obtained by dividing the 720 identified edges by the total of 16 653 viable edges that could be built among the 183 nodes.[11]

e) The mean clustering coefficient of the nodes is 0.259. This coefficient is calculated by city and runs from 0 to 1, where a coefficient of 0 corresponds to a city whose neighboring cities are not connected to each other. For example, Loreto, which has a clustering coefficient of 0 since its only two neighbors, Punta Chivato and Puerto San Carlos, are not connected to each other. While a city with a coefficient of 1 is one whose neighboring cities are perfectly connected to each other; for example, Salamanca has a clustering coefficient of 1, since its only two neighbors, Celaya, and Irapuato, are connected to each other. A coefficient of 0.259 means that, having taken a wrong path, in only 25.9% of these situations it is possible to continue by an alternative route without having to return.

f) The shortest distance between the origin node (Central America) and the destination node (United States) is four edges, which means that migrants need to pass through at least three intermediate cities; for example, from Guatemala to Tenosique, to Saltillo, to Ciudad Acuña and then to the United States.

However, the minimum number of roads that can be built in reverse within the network of cities to connect the United States with Central America is 42, which suggests that the H1 hypothesis is accepted. Therefore, the southern border of Mexico can be connected with the northern border by

[11] The maximum number of Edges possible in a graph is given by $M_{max} = \binom{n}{2} = \frac{n(n-1)}{2}$, so if n = 183, and the maximum number is 16 653.

more than one path. Table 5 lists the 42 shortest roads that connect Central America with the United States.

Table 5. Shortest Routes Connecting Central America with the United States

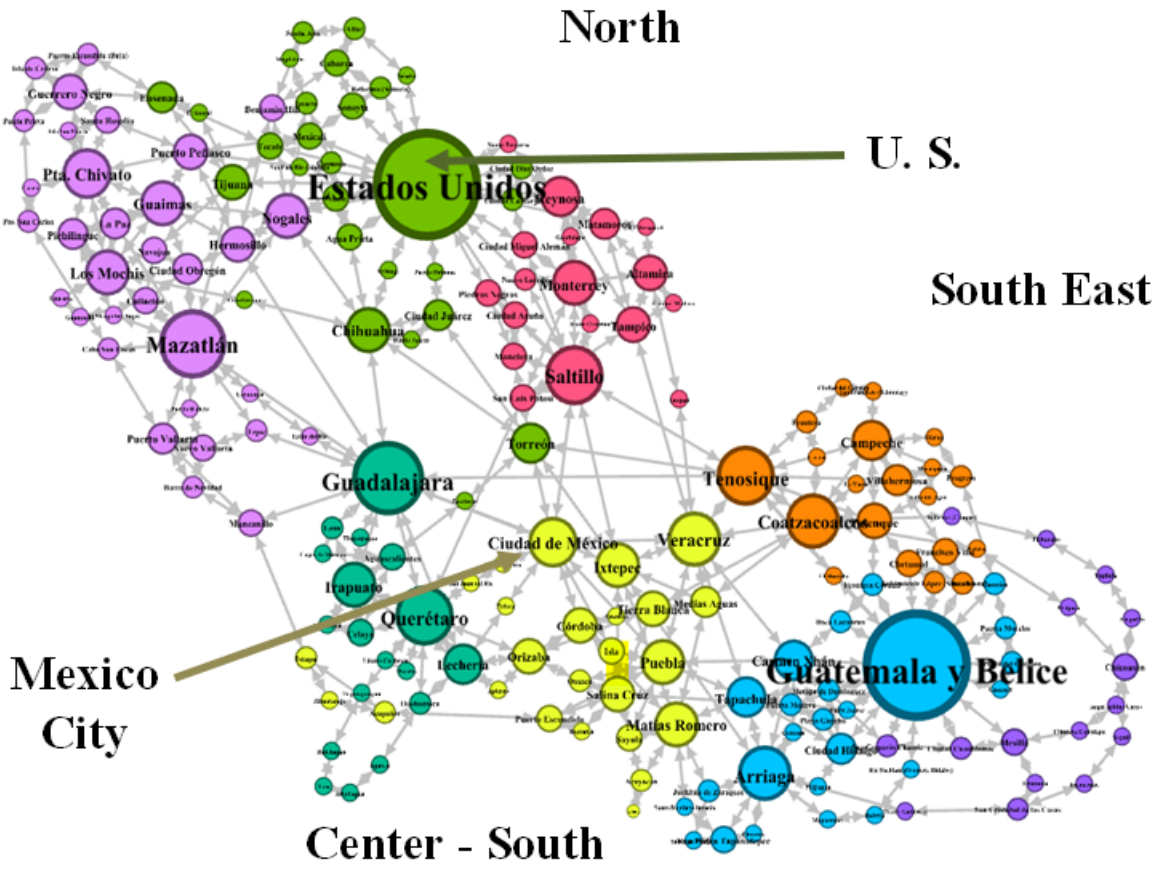
Output Node	Node 1	Node 2	Node 3	Node 4	Node 5	Node 6
Sásabe	Altar	Caborca	B. Hill	Hermosillo	Guadalajara	Tenosique
Sásabe	Altar	Santa Ana	B. Hill	Hermosillo	Guadalajara	Tenosique
Reforma Son.	Caborca	B. Hill	Hermosillo	Guadalajara	Tenosique	
Sonoyta	Caborca	B. Hill	Hermosillo	Guadalajara	Tenosique	
Sonoyta	Mexicali	P. Peñasco	Hermosillo	Guadalajara	Tenosique	
C. Díaz Ordaz	C. Camargo	C. Alemán	Saltillo	Tenosique		
C. Díaz Ordaz	Reynosa	Monterrey	Saltillo	Tenosique		
C. Díaz Ordaz	Reynosa	Tampico	Veracruz	Carmen Xhán		
C. Díaz Ordaz	Reynosa	Tampico	Veracruz	Tenosique		
Mexicali	P. Peñasco	Hermosillo	Guadalajara	Tenosique		
Naco	Agua Prieta	Chihuahua	Guadalajara	Tenosique		
Naco	Agua Prieta	Chihuahua	Torreón	Tenosique		
Naco	Nogales	Chihuahua	Guadalajara	Tenosique		
Naco	Nogales	Chihuahua	Torreón	Tenosique		
Naco	Nogales	Hermosillo	Guadalajara	Tenosique		
Naco	Nogales	Mazatlán	Guadalajara	Tenosique		
Nvo. Progreso	Reynosa	Monterrey	Saltillo	Tenosique		
Nvo. Progreso	Reynosa	Tampico	Veracruz	Carmen Xhán		
Nvo. Progreso	Reynosa	Tampico	Veracruz	Tenosique		
S. L. R.Colorado	P. Peñasco	Hermosillo	Guadalajara	Tenosique		
Tecate	Tijuana	Mazatlán	Guadalajara	Tenosique		
Agua Prieta	Chihuahua	Guadalajara	Tenosique			
Agua Prieta	Chihuahua	Torreón	Tenosique			
C. Camargo	C. Alemán	Saltillo	Tenosique			
Matamoros	Tampico	Veracruz	Carmen Xhán			
Matamoros	Tampico	Veracruz	Tenosique			
Nogales	Chihuahua	Guadalajara	Tenosique			
Nogales	Chihuahua	Torreón	Tenosique			
Nogales	Hermosillo	Guadalajara	Tenosique			
Nogales	Mazatlán	Guadalajara	Tenosique			
Ojinaga	Chihuahua	Guadalajara	Tenosique			
Ojinaga	Chihuahua	Torreón	Tenosique			
P. Palomas	C. Juárez	Torreón	Tenosique			
Reynosa	Monterrey	Saltillo	Tenosique			
Reynosa	Tampico	Veracruz	Carmen Xhán			
Reynosa	Tampico	Veracruz	Tenosique			
Tijuana	Mazatlán	Guadalajara	Tenosique			
C. Acuña	Saltillo	Tenosique				
C. Juárez	Torreón	Tenosique				
C. Alemán	Saltillo	Tenosique				
Nuevo Laredo	Saltillo	Tenosique				
Piedras Negras	Saltillo	Tenosique				

Source: Own elaboration with the support of Gephi software, version 0.9.2.

The Diagram of Cities and Paths

The diagram of cities and paths (nodes and edges) built with the Gephi software, from the *Force Atlas* distribution (Figure 4), was created from an algorithm that arranges the nodes on a plane based on two iterative rules: the nodes attract each other based on their geometric distance[12] and repel each other based on the number of connected neighbors[13] (Jacomy et al., 2014). As a result, the software calculates an optimal partition of clusters, which concluded in 8 regions, which are presented in the diagram of Figure 2.

Figure 2. Diagram of Cities and Roads of Migrants[14]



Source: Own elaboration with the support of Gephi software, version 0.9.2 (Force Atlas distribution).

[12] The force of attraction F_a between two connected nodes x, y Depended linearly on distance $d(x - y)$.

[13] The force of repulsion F_r is proportional to the product of the plus one degrees (DC+1) of the two nodes, where the coefficient K_r is defined by the configuration: $F_r(x,y)=K_r\,(DC_x+1)(DC_y+1) / d(x - y)$.

[14] Node size is defined relatively from degree (number of edges).

The eight resulting regions (clustering process) are identified with the name of the city with the highest degree of centrality: 1) Mazatlán Region; 2) Northern border region; 3) Saltillo Region; 4) Guadalajara Region; 5) Veracruz Region; 6) Tenosique Region; 7) Southern border region; and 8) Chicoasén Region.

Structural Holes

Six articulation points are identified in the graph, that is, nodes that when removed divide the map into two disconnected maps. Such are the cases of the cities of Campeche[15] and Progreso in the Yucatan peninsula, as well as Reynosa, Chihuahua, El Paso, and Altar in the north. If these nodes are removed, an isolated set of cities from the general map tree type *treer*[16] occurs. These types of nodes are also known as structural holes, since, if a check point is established, it can break the transit of a sector of the network (Borgatti, 2005; Jimeng & Jie, 2011).

Control Cities Due to Their Degree of Intermediation

By calculating the degree of intermediation—the number of times the city in question appears within all the shortest paths—of each of the cities in the migrant network in Mexico,[17] its degree of influence on transit to the interior of the graph is identified. On the other hand, if BD is divided by the total possibilities of edges, the probability of control of the transit of the graph is calculated. Table 6 shows the most influential cities.

Table 6. Most Influential Cities Within the Migrant Network in Mexico

City	Intermediation degree	Traffic control probability (%)
Guadalajara	15 679.34	94.2
Tenosique	8 164	49
Ixtepec	6 675.39	40.1
Mazatlán	6 383.17	38.3
Veracruz	4 510.38	27.1
Coatzacoalcos	4 345.22	26.1
Arriaga	4 330.98	26
Hermosillo	4 324.40	26
Querétaro	3 511.28	21.1
Saltillo	3 192.72	19.2

Source: Own elaboration based on the data obtained from the authors indicated in tables 1 and 2.

[15] Campeche is the most relevant case, since, if controlled, it would separate from the main graph to the cities of Merida, Progreso, Cancún, Puerto Morelos, Playa del Carmen, and Cozumel.
[16] A type graph tree that represents a structural connection hierarchy where a main node can be connected to many subordinate nodes; resembling the connection of branches to the trunk of a tree.
[17] See definition of DB within the Table 3.

In other words, Guadalajara, Tenosique, Ixtepec, and Mazatlán are the cities through which the greatest number of minimal interconnections can pass within the network.[18]

With the location of control cities, whose probability of traffic control > 0 (p-val < 0.001) H2 is approved, therefore, there are cities in Mexico that can be considered control due to their degree of intermediation.

However, the average degree of intermediation of the graph is *DB* = 709.91 (DSM[19] =120.92), which rejects the idea that the network of migrants in Mexico is a perfectly connected network (p-val < 0.001), which would happen if *DB* were equal to zero (as it happens in a complete graph).

Network of "Negative" Factors that Affect the Migrant's Decision

To test the hypothesis, a database of cities with a dangerous situation was built.

a) The homicide rate was calculated for each of the states in Mexico with information from the Inegi (2019) and Conapo (2019) on the number of homicides committed per state and the number of people per state during 2017, 2018 and 2019. The national average was 30.9 homicides per 100 000 inhabitants (with a standard deviation of 23.7). Table 7 presents the homicide rate in descending order.

Table 7. Average State Homicide Rate in Mexico (2017-2019)

State	TPH	State	TPH
Colima	106.3	Tabasco	22.5
Baja California	74.1	Veracruz	19.2
Chihuahua	72.6	S. L. P.	18.7
Guerrero	63.6	Puebla	18.5
Guanajuato	53.2	Mexico State	18.4
Baja California Sur	45.7	Nuevo León	15.1
Zacatecas	43.8	Mexico City	15.1
Michoacán	43.7	Hidalgo	12.4
Sinaloa	42.7	Tlaxcala	11.5
Morelos	42.0	Chiapas	11.1
Quintana Roo	40.8	Querétaro	10.1
Sonora	33.9	Durango	10.0
Tamaulipas	32.6	Coahuila	8.7
Nayarit	28.9	Campeche	8.2
Jalisco	28.3	Aguascalientes	6.8
Oaxaca	26.8	Yucatán	2.4

Source: Own elaboration with information from Inegi (2019) and Conapo (2019).

[18] Nodes with a higher DB within a graph can be thought of as *Broker* or guardian, since they can control the flow of information and transit, as is the case of the city of Guadalajara.

[19] DSM = Standard Deviation of the Mean.

b) The location of the migrant holding centers and the Beta Groups were obtained from the INM directory and are detailed in Table 8.

Table 8. Location of Migrant Holding Centers and Beta Groups by State

State	Authority	State	Authority
Aguascalientes	• Aguascalientes	Morelos	• Cuernavaca
Baja California	• Mexicali • Tecate • Tijuana	Nayarit	• Nuevo Vallarta
Baja California Sur	• Cabo San Lucas	Nuevo León	• Monterrey
Campeche	• Campeche	Oaxaca	• Ixtepec • Oaxaca
Chiapas	• Arriaga • Comitán • Palenque • Tapachula • Tuxtla Gutiérrez	Puebla	• Puebla
Chihuahua	• Ciudad Juárez • Ojinaga • Puerto Palomas	Querétaro	• Querétaro
Coahuila	• Acuña City • Piedras Negras • Saltillo	Quintana Roo	• Cancún
Colima	• Manzanillo	Sinaloa	• Mazatlán
Mexico City	• Mexico City	S.L.P.	• S. L. P.
Durango	• Durango	Sonora	• Agua Prieta • Hermosillo • Nogales • S. L. Río Colorado • Sásabe • Sonoyta
Mexico State	• Toluca	Tabasco	• Tenosique • Villa Hermosa
Guanajuato	• León	Tamaulipas	• Matamoros • Nuevo Laredo
Guerrero	• Acapulco	Tlaxcala	• Tlaxcala
Hidalgo	• Pachuca	Veracruz	• Acayucan • Veracruz
Jalisco	• Guadalajara	Yucatán	• Mérida
Michoacán	• Morelia	Zacatecas	• Zacatecas

Source: Directory of the National Institute of Migration (2021).

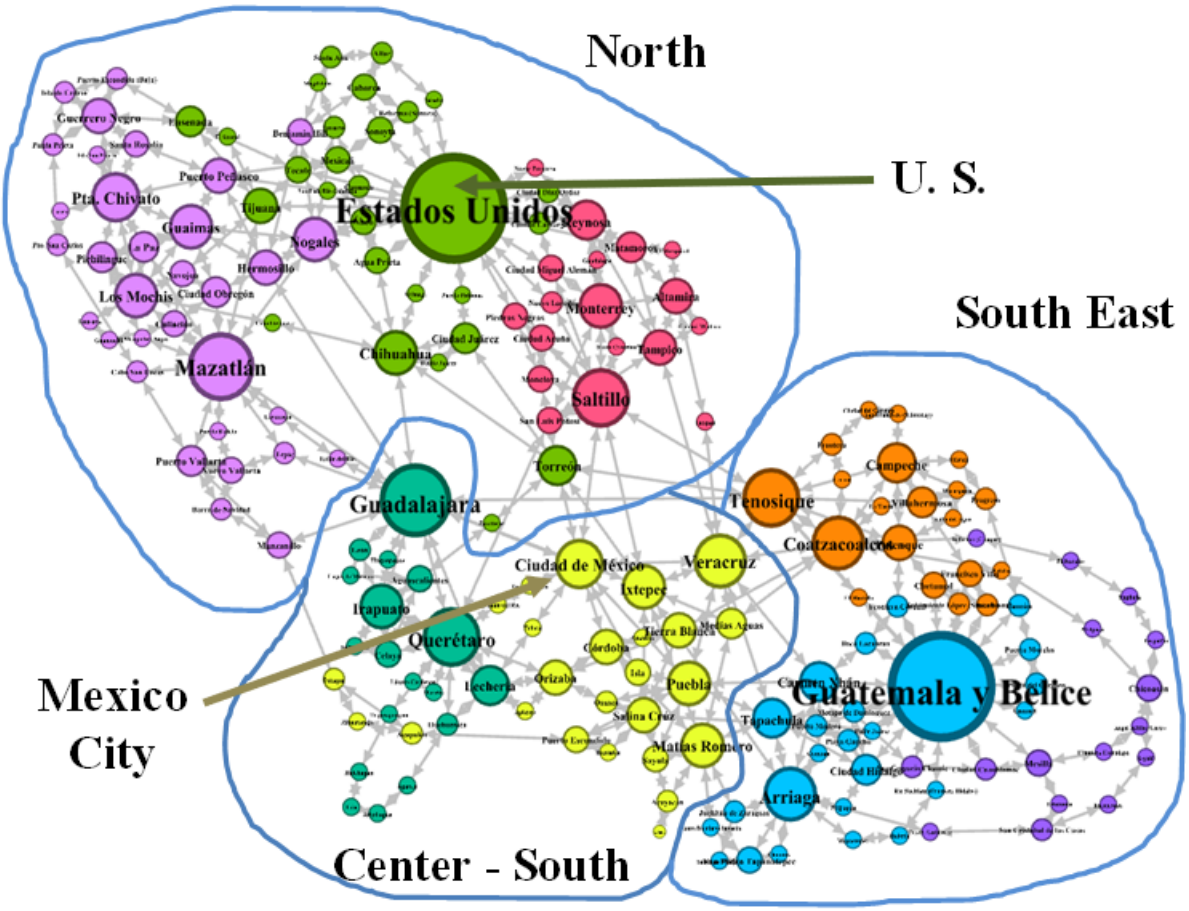
If it is considered that the dangerous cities are those that belong to the states whose homicide rate is higher than the national average, plus one standard deviation (>54.6), such as Colima, Baja

California, Chihuahua, Guerrero, and those that have some INM office, it can be verified that all the shortest paths identified in Table 5 pass through at least two such cities with a dangerous situation. This confirms the H3 hypothesis since the shortest routes between both borders include at least one node with a dangerous situation. For example, a route was identified that passes through four danger points: Central America, Tenosique, Guadalajara, Chihuahua, Ojinaga, United States.

Pragmatic Distribution

A finding was presented regarding the possibility of subdividing the map of cities and routes of migrants into a hypergraph of order 3 from a construction of three mutually exclusive and collectively exhaustive blocks. The Venn diagram is presented in Figure 3.

Figure 3. Diagram of the Three Identified Blocks



Source: Own elaboration.

A particularity of this scheme of partition into three blocks or clusters is that a series of tangent borders can be distinguished between them. However, within each block there is an extensive interconnection network. The northern block has three regions, the central south two and the southeast three regions. There are 14 edges between the north block and the south center, 14 between the south center and the southeast, and only two between the north and the southeast.

DISCUSSION AND CONCLUSIONS

The present research is based on the application of the Graph Theory which has been widely used for the study of migration since its first application in the problem of the Königsberg bridges in Prussia. In this regard, in Mexico there are recent studies such as those by Lomelí Carrillo and Ybáñez Zepeda (2017) or in Latin America that of Ruiz-Santacruz (2019), however, one of the biggest challenges of this theory is the operationalization of its concepts; for example, defining what a node, a path, or a graph is (Ortega Reyes, 2020). In this sense, one of the methodological contributions of this research is the exhaustive documentary review and the application of Graph Theory to exemplify these concepts in terms of migration.

On the one hand, it was verified that there is a permeable network whose viability allows multiple path options for the route of migrants in Mexico, on their journey from Central America to the United States, thus verifying Lee's thesis (1966), provided that they do not present intermediate obstacles, such as those identified by Casillas (2008): 1) the operation of migration stations, 2) the installation of National Guard checkpoints, 3) natural disasters, 4) changes of migration agents in controls that imply the renegotiation of protection, and, in particular, 5) the violence of organized crime. On the other hand, the identified permeability gives formality to the observations of the reported rates of violence (MSF, 2019a) and to the conclusions of permeability (CNDH, 2018); These institutions identify that 20 percent of the migrants do not have a planned path and 30 percent change their route according to the circumstances that arise in their transit through Mexico.

On the other hand, it was identified that cities such as Guadalajara, Mazatlán, Ixtepec, and Tenosique are candidates to be control points due to their degree of intermediation, as well as the cities of Campeche, Progreso, Reynosa, Chihuahua, El Paso, and Altar, which have the quality of isolating and cutting off the traffic within some subregions (structural holes), confirming the theory of Ravenstein (1885).

Based on the findings, the following conclusions are presented:

1) There is an inherent complexity to the migratory phenomenon that makes it difficult to build maps of the roads they use, basically because they do not want to be detected, which makes both public and private databases questionable, which are the foundation of the geographic studies. However, it is possible to work with approximations.

2) There is a permanent mutation effect of the routes used by migrants, since while they adjust their travel itineraries in order to have greater security, their perpetrators—organized crime and/or

some other types of operation—are also constantly dispersing and/or relocating in the same geographic space. Therefore, it is foreseeable that the definitive path used by migrants will be defined in their walk.

3) Due to the connectivity of the routes that can be built in Mexico, from the 16 653 possible sections (or edges) that link the 183 identified cities (or nodes), it is impossible to think of a wall within the national territory that hinders the existing permeability of migration.

4) Negative factors mean that the shortest routes between Central America and the United States pass through at least two points of danger, so it is to be expected that migrants prefer to opt for longer but safer journeys (Nájar, 2018).

As a contribution, it is worth mentioning that the 545 help points identified within the migrants' paths (lodging, food, toilets and sanitation, medical care, among others) favor mobility and influence their trajectories. However, if you want to monitor the migratory flow, it is suggested to set up observation stations and security posts in the cities of Guadalajara, Mazatlán, Ixtepec, Tenosique, Campeche, Progreso, Reynosa, Chihuahua, El Paso, and Altar.

Based on the annual figures of cases of violence reported by Doctors Without Borders (MSF, 2019b), future lines of research could study the transit (volume of migrants) of the 181 cities identified on the paths of migrants and their relationship with the indices of violence of each one, in order to deepen the discussion of whether migration is a source or recipient of cases of violence and human rights abuses.

Translation: Berenice Martínez.

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