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Analysis of the infrastructure works on accessibility using graph theory: case study "la Línea" tunnel

David Fernando López-Patiño & Juan Pablo Londoño-Linares

Facultad de Ingeniería, Universidad de La Salle, Bogotá, Colombia. davidflopez06@unisalle.edu.co, julondono@lasalle.edu.co

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Abstract
The importance of roads in the Colombian economy is undeniable, as they condition the transport of goods, this is why a method is proposed to quantify the impact of new projects, creating an additional tool for the decision makers. In this case was analyzed the impact of "la Línea" tunnel on the departments of Quindío and Tolima, calculating accessibility indexes in two states, before and after the construction of the tunnel, this analysis was complemented with the calculation of indirect costs based on operational and costs per user time. The analysis showed that the construction of the tunnel represented an improvement of the accessibility on Quindío by 5,13% and null on Tolima due to the project's unidirectional nature, nevertheless it was obtained $932.913.194 COP (≈USD 229.141 for 2024) in daily savings.

Keywords: road network; graph theory; road user cost.

Análisis del impacto de obras de infraestructura sobre accesibilidad mediante teoría de grafos: estudio de caso túnel de la Línea

Resumen
Es innegable la importancia de las vías en la economía colombiana, condicionando el transporte de mercancías, es por esto que se plantea una metodología para cuantificar el impacto que ejercen proyectos nuevos sobre la accesibilidad regional, creando así una herramienta adicional para los tomadores de decisiones. Para este caso se analizó el impacto de la obra del Túnel de la Línea sobre los departamentos de Quindío y Tolima, calculando índices de accesibilidad en dos estados, antes y después de su construcción; este análisis se complementó con el cálculo de costos indirectos en función de los derivados por operación y por tiempo de usuarios. El análisis mostró que la construcción del túnel representó una mejora de la accesibilidad en Quindío del 5,13% y nula en el Tolima debido a que el proyecto tiene una sola dirección de tráfico, sin embargo, se obtuvieron $932.913.194 COP (≈USD 229.141 para 2024) de ahorro diario.

Palabras clave: red vial; teoría de grafos; costo de usuario.

1. Introduction

According to data of Consejo Privado de Competitividad [1], 79% of the country's cargo was transported using the road network, highlighting the importance of the terrestrial road network in Colombia.

Ospina [2] states that "[the primary road network] is basic to the country's integration and competitiveness (due to it joins the production areas with the consumption ones) because of this, the road infrastructure determines significantly regional markets, letting the transportation of goods and merchandise or the movement of passengers, Binswanger et al. [3] points out three important factors regarding the influence of the roads in the economic development:

1. The development of the road infrastructure has a significant impact on the opportunities of commercialization and the costs of transaction.
2. Markets provide higher incomes for producers and reduce the price risks.
3. Better profit margins for the producers implies a better credit access, which gives greater facilities for

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investment for banks and financial institutions.

This impact that begins at the economic transcends to other territorial dimensions Chica [4] concludes that "a better access to roads generates positive externalities, pointing in the way of being an approximation of the state presence and governance" also point out that "the interventions in tertiary roads have positives effects in the diminution of the intensity of armed conflict" which represents a positive effect in a dimension apparently unrelated as the armed conflict, this is why the knowledge and the management of road projects are crucial for the economic and social development of a territory.

From the arguments of Binswanger et al. [3], is built a methodology to measure the impact of infrastructure projects on regional accessibility and express it as an economic value easily comparable, looking for facilitate the decision-maker's tasks during the management of projects.

1.1 Study case

As an example of the proposed methodological application, it was analyzed "La Línea" tunnel, a very important project in Colombia with a cost of 1 billon Colombian pesos (≈USD 245 million for 2024) and inaugurated in 2020, "La Línea" tunnel has 8.65 km long and crosses the central mountain range joining the municipalities of Cajamarca (Tolima department) and Calarcá (Quindío department), according to Pardo [5] for BBC,

> *The ambition for the project was to open a commercial gate to Asia for a country of an enormous export potential, it would prevent part of the accidents that daily occurs caused by going up to the mountain's peak and it would save time, a lot of time, to the Colombians who travel by land to the west part of the country [5 para. 5]*

This implies a reduction in travel time and a higher ease for transportation of cargo between the port of Buenaventura and the capital, Bogotá. It is necessary to clarify that the tunnel is a unidirectional road, with two lanes, through the tunnel circulate the vehicles in the direction Calarcá-Cajamarca. In the opposite direction (Cajamarca-Calarcá.) the vehicles travel through the old road, also with two lanes.

In economic terms and according with INVIAS [6] data, "La Línea" tunnel generates an annual saving estimated of $ 250.000 million COP (≈USD 61,4 million), equal to $ 684.931.507 COP per day ($955.928.877 COP for 2024 ≈USD 234.794), while Universidad Nacional [7], publishes a number of $ 150.639 million COP per year (≈USD 37 million), equal to $ 373.542.465 COP per day ($ 521.336.844 COP for 2024 ≈USD 128.050)

For the research it was observed the economic impact of the project on the departments of Quindío and Tolima, these are the affected direct zones by the project and where the corridor is located.

1.2 Graph theory

The applied methodology is part of the graph theory, understanding a graph in function of the stated by Wilson [8] as a set of nodes (also called vertices) and arcs, thus the graph theory results in the study of the interaction between nodes, and how they form networks, for this purpose two basic terms are defined:

1. According to Garrido the connectivity, that "determines the grade of reciprocal communication between vertices, and it is the grade of integration or interconnection that a network has for its internal functioning" [9. p. 85], thus it can be understood as the node's capacity to form links with another node.
2. The accessibility, which "allows to analyze the network's spatial organization, this causes that the nodes form a hierarchy in function of the facility of access from each one of them to the rest of the nodes in the graph" [9. p. 85]. This represents the measure of the facility to reach a specific node from another one inside the same network.

The distinction of these two concepts results crucial because it allows the calculation of indexes that will represent different network's characteristics, the connectivity indexes are in function of the number of links (roads) and nodes from a network, thus its nature is more general, on the other hand the accessibility indexes are in function not only of the number of links but also of the position of the nodes, thus it can be obtained general measures for the entire network and also specific measures for each node.

In this context, it has been developed researches that involves graph theory in the measuring of the vulnerability of road networks for example Haldar et al. [10], who applies graph theory methods (shimbel index and connectivity indexes) in a tool for urban planning, mapping urban accessibility values and of movement from a city point to its center, reaching a map that zones the peri-urban area in scales of accessibility and connectivity in function of the movement and travel time, highlighting critical areas for intervention.

In Colombia the research of Córdoba [11] stands out, he build a comparation between two states of the road network of the municipalities Leiva, Policarpa, Los Andes, Barbacoas, Roberto Payan, Olaya Herrera y Tumaco in the department Nariño, and compares the efficiency using graph theory, the first state in the original conditions pre-intervention and the second state with the improvement of the road surface, finding that the interventions enhanced the accessibility in *veredal* zones between 36 and 38%, showing the relevance of impact measurements for improvement and construction and highlighting the importance of tertiary roads in territorial development especially in rural areas.

Another research of impact measurement is made by E. García & Escobar, [12], including this time economic variables, calculating a global accessibility index for the Armenia's valorization-funded plan for infrastructure, that includes the construction and rehabilitation of urban roads, calculating a percentage of improvement in travel times and analyzing the beneficiary population. These researches despite their different contexts and scopes, all have in

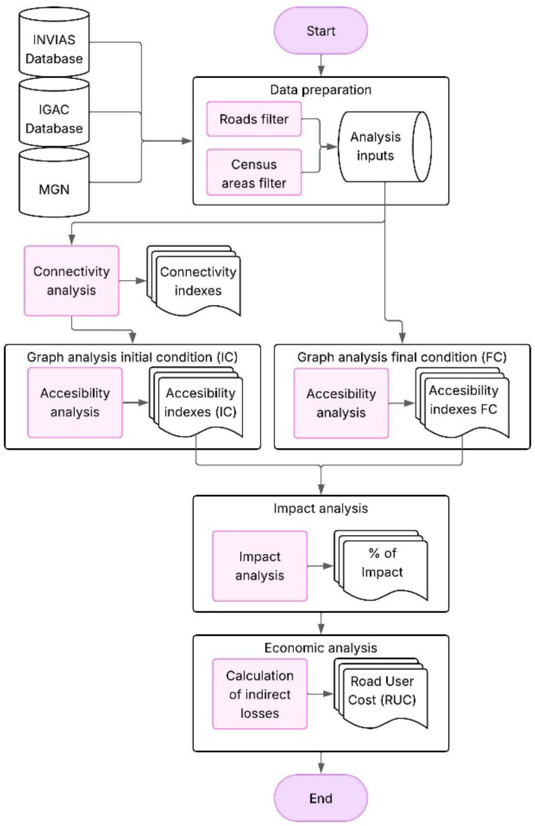


Figure 1. Methodological structure
Source: Own elaboration

common the recognition of the importance of road accessibility in economic indexes and territorial productive efficiency and the use of graph theory as a diagnostic tool for accessibility, searching in a long term its application in territorial management.

2. Materials and methods

The proposed methodology is structured in three basic processes and it is summarized in the Fig. 1.

1. Graph analysis of the initial conditions (before the construction of the "La Línea" tunnel)
2. Graph analysis of the final conditions (after the construction of "La Línea" tunnel)
3. Impact analysis and calculation of the generated savings.

2.1 Graph analysis

2.1.1 Census area filter

Due to the graph analysis uses vertices or unique points as an input, rather than polygons, is required to transform the urban areas polygons into unique points, for this the concept of *census area* is applied, defined by DANE as "the area delimitated by the census perimeter of the municipal seats and populated centers" [13. p. 21] transformed into vertices finding their geometric center.

Because of the need to obtain a coherent network (a network with fully connected nodes) and due to the smallest census areas use, unidentified or ambiguously categorized roads, a census areas filter was implemented based on the population, because of this were only considered municipalities categorized as fifth category and above, according to the categorization of the Law 1551 of 2012 [14], this means municipalities with populations exceeding 10.000 inhabitants

2.2 Road network filter

As noted, graphs are composed by nodes and arcs, the nodes in this case are equal to census areas, and the arcs to the road corridors, due to the presence in the National Geostatical Framework (Marco Geoestadístico Nacional) (MGN) [15] of ambiguous roads classifications, with unclear characteristics and where cannot be guaranteed that these accesses are suitable for populated centers connectivity, the roads; the same as the census areas; are filtered too, considering only those categorized as first, second or third order, according to the Resolution 1530 of 2017 [16].

Finally, a planar graph (non-intersecting arcs) is obtained, which also is coherent (a network with fully connected nodes) as illustrated in the Fig. 2, for the study area.

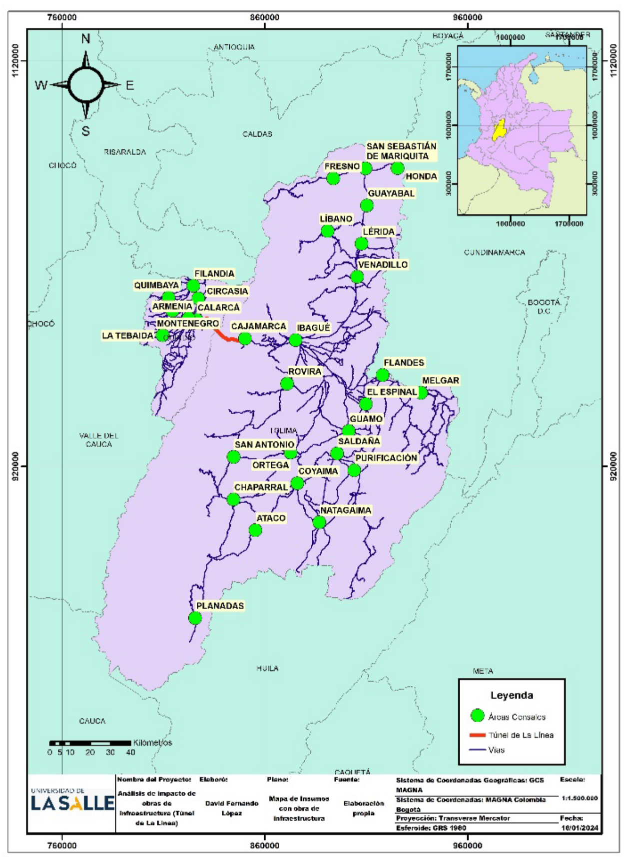
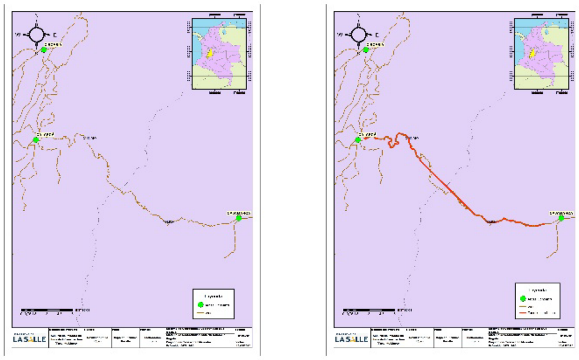


Figure 2. Road network of analysis
Source: Own elaboration



A) B)

Figure 3. Road network of analysis: A) Before the intervention; B) After the intervention
Source: Own elaboration

Additionally, in Fig. 3 is presented the detail of the road network at the initial and final conditions, pre and post incorporation of the "La Línea" tunnel.

2.3 Connectivity and cohesion metrics

As mentioned, connectivity metrics are general network measures that depend on the total number of nodes and arcs, and its calculation helps to establish the graph's general conditions, however, the analysis post intervention of connectivity metrics is not relevant, because the only change between initial and final conditions is a single link.

It is important to say that connectivity metrics were calculated taking 619 nodes, including intersections of the roads and census areas, it is necessary to include in this case the intersections because they are an indicator of the network complexity. The connectivity metrics are presented below.

2.3.1 Kansky connectivity index (β)

This connectivity index was introduced by Kansky [17] and represents the relation between the number of arcs (a) and the number of nodes (n). "Transportation networks with complicated structure will have high value of β,whereas networks with a simple structure will have low values" [17. p. 102]. It is defined by eq. (1).

$$\beta = \frac{a}{n} \quad (1)$$

"For planar graphs, however, the scale is from 0 to an upper limit of 3.0." [17. p. 102].

2.3.2 Gamma index (γmax (%))

The gamma index was developed by Garrison & Marble [18] and it is defined as "a ratio between the edges and vertices of a given transportation network" [19. p. 104]. The eq. (2) shows the value of gamma index for planar graphs:

$$\gamma_{max}\% = \frac{a}{3*(n-2)} * 100 \quad (2)$$

2.3.3 Cyclomatic number (μ)

The cyclomatic number was first introduced by Berge [20], and represent the number of circuits that exists in a graph. Insaurralde & Cardozo defined a circuit as "each one of the multiple ways that exist to travel from a node to itself, without passing the same arc twice" [21. p. 8]. For coherent networks, the expression of the cyclomatic number is shown in the eq. (3).

$$\mu = a - (n-1) \quad (3)$$

2.3.4 Complexity or Alpha index (α)

The complexity or Alpha index expressed in the eq. (6) was developed by Garrison & Marble [18] and can be defined as

> *We may interpret this formula as a ratio between the observed number of circuits and the maximum number of circuits (...) For completely interconnected networks the α index will be equal to one (the upper limit). For networks with a decreasing number of edges, the α index will approach zero (the lower limit) [17. p. 100].*

$$\alpha = \frac{\mu}{2(n-5)} * 100 \quad (4)$$

2.4 Accessibility and centrality metrics

For accessibility measures only were taken into account 30 nodes, the number of census areas, due to they represent the possible origins and destinations of the vehicles traveling through the departmental roads, from this an accessibility matrix is generated that contains the traveling distances from and to each one of the network's nodes.

2.4.1 Associated König Number (KON)

It was proposed by Konig [22] and represent the distance needed to travel from a node till the furthest node, through the shortest path, it is extracted from the accessibility matrix, being the maximum value of each row, higher values indicate less accessible nodes.

2.4.2 Shimbel number (Shim) and dispersion index (G index)

Both indexes were proposed by Shimbel [23], and they are obtained from the accessibility matrix. To find the accessibility index also known as Shimbel number, the distances of each row in the accessibility matrix are summarized, obtaining a different value for each one of the network's nodes, a higher value indicates a less accessible node, and vice versa. The Maximum Shimbel number (Shim max) represents the most inaccessible node of the entire network, while the Minimum Shimbel number (Shim min) the most accessible.

The G index or dispersion index is obtained summarizing all the shimbel from the matrix, higher values indicate a less accessible network.

> *We can characterize the measure of dispersion as an index expressing an over-all property of the network whereas the index of accessibility is a measure indicating the spatial relation between a given element of the structure and the remainder of the network [17. p. 116]*

2.4.3 Average Accessibility Index (IAM)

The Average Accessibility Index (IAM) is calculated using the eq. (5), according to Muñoz et al.

> *It determines an average value of the network's accessibility from the ratio between the G index and the total number of existing nodes. This network's mean can be used to compare different graphs, or for analyses inside a single graph, each node's accessibility (Shimbel number) respect to the mean (G index); those indexes above the mean are the less accessible [24. p. 78].*

$$IAM = \frac{G}{n} \tag{5}$$

2.4.4 Mean centrality (C)

The mean centrality is the ratio between each node's Shimbel number and the total number of nodes minus one, this value represents each element's topological position, a higher value indicates a less central node and a lower value indicates a central node. Its expression is shown in the eq. (6)

$$C = \frac{Shim_i}{n-1} \tag{6}$$

2.4.5 Impact analysis

Once obtained the results for the two network's states, a comparison was conducted using eight accessibility indexes, as mentioned the analysis of the connectivity metrics was made only for the initial conditions. The calculated accessibility indexes were G index, Average Accessibility Index (IAM), Maximum Shimbel number (Shim max), Minimum Shimbel number (Shim min), Maximum Associated König Number (KON max), Minimum Associated König Number (KON min), Average path length, Maximum Mean centrality (Cmax), Minimum Mean centrality (Cmin)

Table 1.
Inputs for the savings calculation

Input	Unit	Source
Average wage	$COP/h/user	Decree 1572 of 2024 [27]
Climb+ Descent	m*km	Calculated from ALOS PALSAR L1.5., 2015 [28]
Horizontal Curvature	Degrees*km	Calculated from Road Information System [29]
Average speed	km/h	Law 1239 of 2008 [30] and INVIAS [6]
Average Daily Trafic (TPD)	veh/day	Historical traffic Series (TPD) [31]
Operating cost	$COP/km/veh	Vehicle operating costs [32]

Source: Own elaboration

The impact is calculated using the eq. (7) and represents the relative percentage change:

$$\%\text{ of impact} = \frac{Index_{Initial\ condition} - Index_{Final\ condition}}{Index_{Initial\ condition}} * \mathbf{100} \tag{7}$$

2.5 Economic analysis

The final step is the saving calculation generated by the tunnel construction, based on the methodology developed by Dos Santos et al. [25, 26], who initially describes indirect losses, but in this investigation, it had a conceptual difference from the original. This calculation is made for the initial condition, using only the old road (OR) and the final condition, using in one direction the old road (OR) and in the opposite direction the road with the tunnel (RWT), for this calculation are used the eq (8) and the eq (9)

$$RUC = VOC + VOT \tag{8}$$

$$\Delta RUC = RUC_{IC} - RUC_{FC} \tag{9}$$

VOC= Vehicle operating cost
VOT= Value of time
RUC= Road User Cost
ΔRUC= Saving due to the incorporation of the project

Initially, for the calculation of the RUC, the inputs related in the Table 1 are required.

Finally, the calculation is performed factor by factor applying certain modifications to the formulas presented by Dos Santos et al. [25, 26], due to it can be reach more exactitude using the real number of vehicles from the TPD reported by INVIAS [31] instead of using a proportion for each type of vehicle.

2.5.1 VOC-vehicle operating cost

For the calculation of the Vehicle operating cost, is used the eq. (10). The value of the Distance is obtained from the accessibility analysis.

$$VOC = Distance * \sum(Operating\ cost_i * TPD_i) \quad (10)$$

To appropriately determine the road operating cost, are calculated the curvature factors of the road. INVIAS [32] stablishes a classification of the road alignment using the value of Climb+Descent and the Horizontal Curvature.

The value of Climb+ Descent is calculated using the eq (11) while the value of Horizontal Curvature is calculated using the eq (12).

$$Climb + \ Descent \ = \frac{\sum|z_{i+1} - z_i|}{L_T} \quad (11)$$

$$Horizontal\ Curvature \ = \frac{\sum \theta_i}{L_T} \quad (12)$$

z= Elevation for every segment

Lt= Total length of the road

θ_i= Angle between two segments of the road

These two factors are calculated for the old road and for the road with the tunnel. For the old road, the elevation information is extracted from the Alaska Satellite Facility Service, for the road with the tunnel are considered the INVIAS et al., 2021 [33] requirements for tunnel slopes, specifically for tunnels with a length superior to 3.000 m with a maximum slope of 3%.

Using these values, the road alignment can be classified in one of the next types: 1) Flat and straight, 2) Undulating and straight, 3) Gently curved and undulating, 4) Mountainous, 5) Curved and slightly undulating and 6) Steep. The terrain for the old road was classified as Steep, and for the road with the tunnel as Mountainous.

To obtain the Vehicle Operating Cost, the information related to the vehicle operating costs on paved roads ($/km) for hdm IV (December 2016) [32] was used as an input, this information is based on market prices but does not correspond to the date of analysis, so it is needed to perform an inflation adjustment, using the eq. ((13), where the IPC values were obtained from Ministerio del Trabajo [34]:

$$Cost_{Final} = Cost_{initial} * (1 + IPC_{initial\ year}) * (1 + IPC_{initial\ year+1}) * \ldots (1 + IPC_{Final\ year}) \quad (13)$$

The result for 2024 prices, good pavement and a mountainous and steep road alignment are presented in the Table 2

Table 2.
Vehicle operating costs (2024 prices)

Type of vehicle	Type of road alignment	
	Mountainous	Steep
Cars	$ 1.957,98	$ 1.984,30
Buses	$ 3.994,94	$ 4.526,38
Trucks	$ 5.951,27	$ 6.999,36

Source: Own elaboration

2.5.2 VOT-Value of time

The users' time value is calculated using the eq. (14) the average wage per hour was $ 5.416,00 corresponding to the minimum salary per hour for the 2024.

$$VOT = Distance * \sum(Average\ wage_i * \text{Average number of users}_i * Average\ speed_i * TPD_i) \quad (14)$$

The average number of users per vehicle for cars corresponds to the average use capacity of the most common car models, for the busses the data is based on the data from the vehicle operating costs [32], while for trucks it is assumed that the only user is the driver.

At this point is necessary to stablish that exists an increase in the average speed of the vehicles, which may travel faster in the final conditions because there are two lanes in the old road and two lanes in the road with the tunnel, INVIAS 2020 [6] stablish an increase in the speed from 18 km/h to 60 km/h for cars, and using a proportionality based on the Law 1239 of 2008 [30], from 12 km/h to 40 km/h for trucks.

3. *Results*

3.1 *Connectivity metrics*

Initially, connectivity metrics are calculated as presented in the Table 3, to assess the general graph conditions in the initial conditions and metrics related to its complexity, the analysis was performed using a graph with 619 nodes (census areas and intersections) and 650 arcs (road links)

The obtained value of β was 1,05, which means that the number of nodes and arcs are similar, characteristic of a low complexity network.

For the γmax (%) the result was of 35,12% which is equivalent to 32 circuits correspondent to the μ index, significantly lower than the ideal of 100%, that can be reach with the inclusion of 1201 additional arcs, which would give an ideal index of road network linkage

Table 3.
Connectivity metrics

Index	Result
β	1,05
γmax (%)	35,12%
μ	32
α	2,61%

Source: Own elaboration

Table 4.
Accessibility metrics and percentage of impact

Accessibility Index	Pre-Intervention	Post-Intervention	Difference	% of impact
G Index	122980353	121416953	1563401	1,27%
IAM	4099345	4047232	52113	1,27%
Shim min (Ibagué)	2780196	2780196	0	0,00%
Shim max (Planadas)	6828342	6828342	0	0,00%
KON min (Espinal)	171447	171447	0	0,00%
KON max (Fresno)	335293	335293	0	0,00%
Cmin (Ibagué)	95869	95869	0	0,00%
Cmax (Planadas)	235460	235460	0	0,00%

Source: Own elaboration

Additionally, the value of α was 2.61%, a relatively low value, which means that the road network in Tolima and Quindío is highly dependent on specific critical links, characteristic of a fragile network. Notably the Cajamarca-Calarcá Road, stands out as a vital connection, this emphasizes the strategic importance of “La Línea” tunnel, as it is the only direct access between these two departments.

3.2 Accessibility metrics

In the Table 4 are presented the accessibility metrics for the network analysis, which includes the maximum and minimum Shimbel and Konig numbers and C index, with the comparison between the two scenarios with and without the project, as well as the difference and the percentage of impact obtained for each calculation.

The project improved the IAM, this indicates that with the tunnel is easier to access from any network’s point to another one in an average of 1,27%, this value corresponds to the change of distance travel, approximately 9.7 km, between the 23 Tolima’s nodes and the 7 Quindío’s nodes,

The G Index improved as well, indicating that it is easier to travel to the remotest parts of the network or at least to the Quindío region, due to the direction of the tunnel.

For the maximum and minimum values of the Shimbel number there were no change, this occurs because of the unidirectional operation of the tunnel, the old road Cajamarca-Calarcá direction (East-West), has no distance change, and the points that represents maximum (Ibagué) and minimum (Planadas) accessibility are part of Tolima (East side), region that obtained no benefit in the distance factor because of the tunnel.

The same situation happens to the Mean centrality (C), as the minimum and maximum values correspond to the same census areas.

The Köning number did not changed, due to the longest route (San Sebastián de Mariquita- Planadas) is made from north to south, not from east to west, because of this the tunnel has no relevance in this indicator.

The results for the Shimbel number were spatialized using the Inverse Distance Weighted (IDW) interpolation method, which assigns greater weight to areas closer to each point, IDW is used pre and post the intervention, the results are shown in the Fig. 4 and Fig. 5, respectively.

The most inaccessible node of the road network is Planadas, Tolima, point that obtained the higher Shimbel number, in the same way the municipality Fresno, also in Tolima, obtained the highest Köning number, which indicates that is a low accessible node, for the network analysis.

On the other hand, the best indexes were obtained for the municipalities of Ibagué in the case of the Shimbel number, and Espinal for the Köning number.

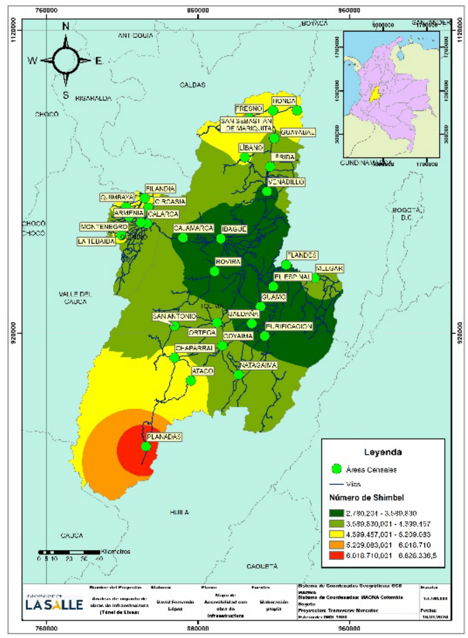


Figure 4. Accessibility map before construction of the tunnel
Source: Own elaboration

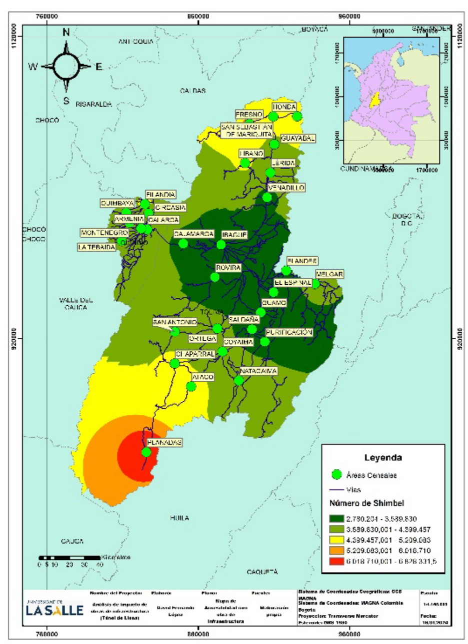


Figure 5. Accessibility map after construction of the tunnel
Source: Own elaboration

Table 5.
Percentage of impact for the Shimbel number for each node

Departament	Municipality	Census area	% of impact
Quindío	Calarcá	Calarcá	5,66%
Quindío	Armenia	Armenia	5,47%
Quindío	Montenegro	Montenegro	5,16%
Quindío	Circasia	Circasia	5,09%
Quindío	La Tebaida	La Tebaida	4,98%
Quindío	Quimbaya	Quimbaya	4,88%
Quindío	Filandia	Filandia	4,63%
Tolima	Ibagué	Ibagué	0,00%
Tolima	Espinal	El espinal	0,00%
Tolima	Guamo	Guamo	0,00%
Tolima	Rovira	Rovira	0,00%
Tolima	Saldaña	Saldaña	0,00%
Tolima	Flandes	Flandes	0,00%
Tolima	Cajamarca	Cajamarca	0,00%
Tolima	Venadillo	Venadillo	0,00%
Tolima	Purificación	Purificación	0,00%
Tolima	Coyaima	Coyaima	0,00%
Tolima	Lérida	Lérida	0,00%
Tolima	Ortega	Ortega	0,00%
Tolima	Melgar	Melgar	0,00%
Tolima	Natagaima	Natagaima	0,00%
Tolima	San Antonio	San Antonio	0,00%
Tolima	Armero	Guayabal	0,00%
Tolima	Líbano	Líbano	0,00%
Tolima	Chaparral	Chaparral	0,00%
Tolima	San Sebastián de Mariquita	San Sebastián de Mariquita	0,00%
Tolima	Ataco	Ataco	0,00%
Tolima	Honda	Honda	0,00%
Tolima	Fresno	Fresno	0,00%
Tolima	Planadas	Planadas	0,00%

Source: Own elaboration

The Table 5 presents the changes for the accessibility expressed in percentages for each census area.

Comparing the graphs in the initial and final states, the results clearly demonstrate the greater influence of the project on the department of Quindío, where can be noticed an average accessibility improvement of 5,13% compare with a null improvement in the department of Tolima, caused by the unidirectionality of the tunnel, this characteristic of the project reduces notably the impact on the east side of the network.

Also due to the longest routes are from north to south without crossing the tunnel, this also reduces the importance in Tolima.Despite this, in Quindío (West Side) accessibility improves for all the census areas, with all of them showing an improvement, higher in the closest zones to the project.

The Table 6 presents results of the analysis for the direct route from Calarcá to Cajamarca.

Table 6.
Results Calarcá-Cajamarca route

Parameter	Result
Old Route (OR) distance (m)	43.730
Road With Tunnel (RWT) distance (m)	34.019
Difference (m)	9.711
% of impact	22,21%

Source: Own elaboration

Table 7.
Inputs by type of vehicle for initial conditions (2024 prices)

Type of vehicle	Average speed (km/h)	Average number of users (users /veh)	TPD (veh/day)	Operating cost ($COP/km/veh)
Car	18	3	3.252	$ 1.984
Bus	18	28	2.140	$ 4.526
Truck	12	1	2.326	$ 6.999

Source: Own elaboration

Table 8.
Inputs by type of vehicle for final conditions (2024 prices)

Type of vehicle	Average speed (km/h)	Average number of users (users /veh)	TPD (veh/day)		Operating cost ($COP/km/veh)	
			OR	RWT	OR	RWT
Car	60	3	1.606	1.646	$ 1.984	$ 1.958
Bus	60	28	1.041	1.099	$ 4.526	$ 3.995
Truck	40	1	1.121	1.205	$ 6.999	$ 5.951

Source: Own elaboration

The analysis confirms a reduction of 22,21% in the travel distance in the direction Calarcá-Cajamarca (West-East), but the distance keeps being the same in the opposite direction.

3.3 Economic analysis

As mentioned, the terrain for the old road was classified as Steep, and for the road with the tunnel as Mountainous. Based on this, the inputs by type of vehicle are presented in the Table 7 for the initial conditions and in the Table 8 for the final conditions considering the old road (OR) for the East-West direction and the road with tunnel (RWT) for the West-East direction.

3.3.1 VOC-vehicle operating cost

The Table 9 presents the results for the Vehicle Operating Cost expressed in function of the distance which is variable to every route.

Largest vehicles require more operating costs, making the truck sector the most benefited from the project because the savings for this item, the daily savings were of $124.881.937/day (≈USD 30.673) equivalent to an improvement of 17,54% for the operation costs. Cars and busses also show significant reductions in operating costs of 11,76% and 16,09% respectively.

Table 9.
VOC-vehicle operating cost (2024 prices)

Type of vehicle	Total VOC Initial Conditions ($COP/day)	Total VOC Final Conditions ($COP /day)	Difference ($COP /day)	% of impact
Car	$ 282.197.186	$ 249.003.887	$ 33.193.299	11,76%
Bus	$ 423.525.285	$ 355.369.933	$ 68.155.352	16,09%
Truck	$ 711.875.634	$ 586.993.697	$ 124.881.937	17,54%
TOTAL	**$ 1.417.598.104**	**$ 1.191.367.517**	**$ 226.230.587**	**15,96%**

Source: Own elaboration

Table 10.
VOT-Value of time (2024 prices)

Type of vehicle	Total VOT Initial Conditions ($COP /day)	Total VOT Final Conditions ($COP /day)	Difference ($COP /day)	% of impact
Car	$ 128.372.523	$ 34.183.005	$ 94.189.518	73,37%
Bus	$ 788.301.288	$ 209.525.023	$ 578.776.265	73,42%
Truck	$ 45.903.241	$ 12.186.417	$ 33.716.824	73,45%
TOTAL	**$ 962.577.053**	**$ 255.894.446**	**$ 706.682.607**	**73,42%**

Source: Own elaboration

Table 11.
RUC-Road User Costs (2024 prices)

Type of vehicle	RUC Initial conditions ($COP /día)	RUC Final Conditions ($COP /día)	Difference ($COP /día)	% of impact
Car	$ 410.569.709	$ 283.186.892	$ 127.382.816	31,03%
Bus	$ 1.211.826.574	$ 564.894.957	$ 646.931.617	53,38%
Truck	$ 757.778.875	$ 599.180.114	$ 158.598.761	20,93%
TOTAL	**$ 2.380.175.157**	**$ 1.447.261.963**	**$ 932.913.194**	**39,20%**

Source: Own elaboration

3.3.2 VOT-Value of time

The results for the value of time are presented in the Table 10.

Because of the higher number of users from busses this sector is the most benefited, but in proportion all sector presents significant reduction in the Value of time, an improvement higher to 73% equivalent to $706.682.607 (≈USD 173.574) in total.

3.3.3 Road User Costs (RUC)

The final RUC for the initial and final conditions is present in the Table 11:

The results show an economic impact of 39.20% for the vehicles in general equivalent to a daily saving of $932.913.194 (≈USD 229.141), after the intervention.

The proportion of the saving by item is shown in the Fig. 6.

The majority of savings (75,75%) were obtained from the time of the users, while 24,25% corresponds to the saving due to the value of the operation costs.

The Fig. 7 shows the savings by each type of vehicle.

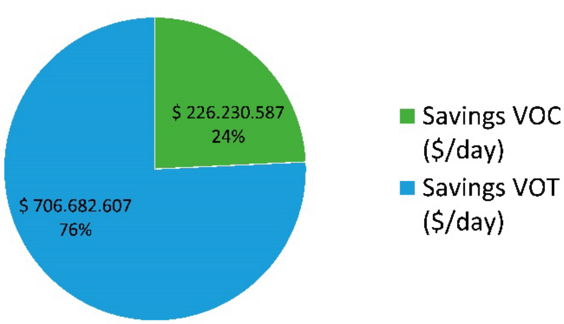


Figure 6. Saving by item
Source: Own elaboration

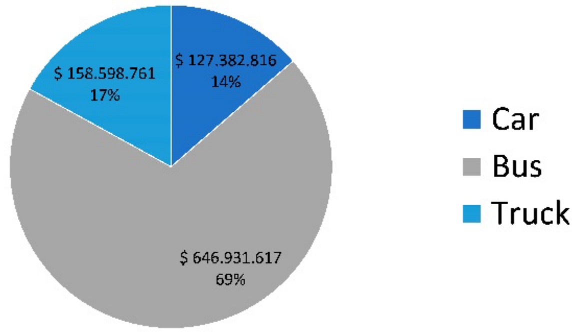


Figure 7. Saving by each type of vehicle
Source: Own elaboration

The bus sector is the most benefited, with a 69,35% of all the savings, followed by a 17,00% for trucks and last 13,65% for cars.

4. Discussion

The analysis highlights a particularity, due to the country's geography, the network has a low redundancy in corridors connecting the west with the east, as a result the majority of efforts are focused in projects that facilitated this crossing, which is not large in euclidean distance, but represents great challenges caused by the mountainous terrain, this has conditioned historically the Colombia's economic and productive development.

The impact analysis resulted in a clear diagnosis which can be compared with multiples states and projects, being the economic analysis a key point, allowing to measure the influence of the infrastructure projects, the resulting data in $/day is an ideal number to quantifying benefits. On the other hand, the impact analysis revealed that the relevance of the project diminishes with the distance from the implementation location, Calarcá and Armenia the nearest census areas from the project get a higher impact in comparison with census areas as Filandia, Quimbaya and La Tebaida.

Due to the unidirectional characteristic of the project, in terms of graph analysis, Tolima received no impact by the "La Línea" tunnel project, accessibility indexes did not change at all. In comparison the department of Quindío received an average improvement of 5.13%, this value is obtained from the sum of the travel distance improvements from each node of Quindío to any census area of the network, it is clear then that projects like a second tunnel in the opposite direction would be a key factor to improve the accessibility to Tolima and to the East part of the country.

Regardless the null impact on the Tolima's accessibility the economic analysis revealed substantial benefits of road investments that applies for the entire users of the road, reaching $ 932.913.194 COP/day (≈USD 229.141 for 2024) of saving with the construction of "La Línea" tunnel, this represents a justification for the execution of the project and highlight its importance.

The changes in the slope of the road alignment have a significant economic impact especially on the truck sector, which could represent significant reductions in the cost of goods transport and a possible reduction in overall prices, but the largest savings were found in the value of time, mainly due to the great reduction in time travel and the improvement in average speed representing an improvement higher to 73%.

5. Conclusion

"La Línea" tunnel caused no improvement in the accessibility of Tolima but was relevant to Quindío's accessibility, this result is a reason to say that the project is relevant and represents an economic benefit for the entire region, the daily savings were $ 932.913.194 COP/day (≈USD 229.141 for 2024), causing significant savings in operational costs particularly because of the slope changes and largest savings in the time of the users increasing average speed and reducing time travel.

The calculated daily savings follow the same order of magnitude as calculated by INVIAS [6] of $ 684.931.507 COP per day ($955.928.877 COP for 2024 ≈USD 234.794) and by Universidad Nacional [7] of $ 373.542.465 COP per day ($ 521.336.844 COP for 2024 ≈USD 128.050), closer to the report of INVIAS [6] than the Universidad Nacional [7] calculation.

The methodology combined GIS with graph theory techniques, and resulted adequate and very useful, because it quantified the possible saving to the users of the regional roads, which is easily comparable with other sources and quantify the relevance of the project in the region.

Additionally, the methodology is systematic and follows a logical sequence of sub-processes, which is applicable to multiple scales and allows the comparison of projects and investment for road infrastructure projects.

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D.F. López-Patiño, received the BSc. Eng in Civil Engineering in 2021, MSc. in Territorial Planning and Management in 2024, both from the University of La Salle, Colombia. He has worked in geotechnical engineering and public space projects, and as an investigator in the methodological application and development of risk management for road corridors in cooperation with the University of La Salle and the INVIAS. His research interest includes risk management, topological analysis, graph theory, landslide hazard and urban planning.
ORCID: 0009-0001-2545-1348

J.P. Londoño-Linares, is a BSc. Eng in Civil Engineer with MSc. and Dr. and 20 years of professional experience. He earned his undergraduate and MSc. from the Universidad Nacional de Colombia, and his PhD. from the Polytechnic University of Catalonia (UPC) in Barcelona, Spain. As part of the Risk Assessment Group at the International Center for Numerical Methods in Engineering (CIMNE) and the UNESCO Chair on Sustainability at UPC, he developed models for analyzing susceptibility, hazard, and disaster risk—particularly landslides—as well as methodologies for probabilistic risk analysis. These models have been validated through various projects led by Universidad Nacional of Colombia. He has recently directed several projects focusing on infrastructure analysis and adaptation to climate change.
ORCID: 0000-0002-0830-2981