GENERAL GUIDELINES FOR THE DESIGN OF BRT ROUTES IN THE PUBLIC TRANSPORT INTEGRATED SYSTEM OF BOGOTÁ

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ABSTRACT

The objective was to establish general guidelines for the design of the BRT route network in Bogotá's Public Transport Integrated System – SITP – in terms of geographical layouts, stop points, and frequencies. The demand for the morning rush hour in a typical business day before COVID-19 was contemplated.

The research methodology had three phases. 1) Establish several sets of preliminary guidelines for route network design in the Bogotá BRT System – TransMilenio –. 2) Development of a methodology – based on a transport model implemented in PTV-Visum – to assess different routes scenarios designed following those sets of preliminary guidelines. 3) Application of this assessment methodology to quantify the impact of each set of preliminary guidelines for route network design, thus choosing the best alternatives.

The outputs can be divided into two categories. 1) Heuristic processes for the systematic design of routes in the BRT system. 2) Selected guidelines for the design of route network in TransMilenio. This report will be focused on the second category of outputs. Among the conclusions, the BRT services in Bogotá should be designed with a multi-criteria approach, which implies a relatively complex route network. A very simplified route network has proven to be inconvenient. On the other hand, in the short term, it is recommended to maintain diametrical routes to avoid the collapse of central stations due to increased transfers. However, in the medium term, the paradigm must evolve to radial routes design. This approach would make it possible to significantly reduce the minimum required fleet, improving headways, increasing comfort within buses, and/or reducing investment in rolling stock. Furthermore, it has been shown that the radial routes approach would require four new central interchange stations in Bogotá.

1. INTRODUCTION

Bogotá's BRT - TransMilenio - constitutes the backbone of mobility in the city (TransMilenio, 2019). Beyond its qualities or problems, the sustainability of this transport system is essential to guarantee the correct development of urban activities on a day-to-day basis. This sustainability is the result of a combination of many factors related to various areas of knowledge, and among them, transportation planning is one of the branches that can contribute the most to the success of a transit system.

1.1 Background

The design of the route network in transit systems, as part of the transportation planning process, is a problem whose solution can significantly affect some aspects of the service (Ceder, 2001). In this way, the research problem to be solved was the determination of guidelines for route network design in BRT systems, specifically for TransMilenio in Bogotá.

The main objective of the research was "To establish general guidelines for the design of the BRT route network in the Integrated Public Transport System -SITP- of Bogotá, at least in terms of geographical layouts, stop points, and frequencies." Its importance lies in the fact that it is necessary to seek innovative solutions that optimize, even more, the use of available resources to improve the service level offered to the user. This becomes even more relevant considering that, before the COVID-19 pandemic, TransMilenio supported over 45,000 passengers per hour in a single direction (TransMilenio, 2020), and therefore, historically high levels of overcrowding have been notorious.

1.2 State of the art

As defined in the main objective, this research has covered three aspects of the route network design in a BRT system: the design of geographical layouts, the choice of stop points, and the assignment of frequencies. Thus, in this review, literature has been grouped according to its relevance in each of these three items.

According to Kepaptsoglou and Karlaftis (2009), the literature on geographical layouts for route network design can be classified into three levels:

- Design objectives: maximization of the benefit to the user (Lee and Vuchic, 2005; Zhao and Zeng, 2006); minimization of operating cost (Ceder and Israeli, 1997); maximization of total well-being (Fan and Machemehl, 2006); maximization of transport capacity (Morlok and Viton, 1984); energy conservation / environmental protection (Delle and Filippi, 2001).
- Operational parameters: priority decision variables (Van Nes, 2003); network structure (Chang and Schonfeld, 1993); demand patterns and characteristics (Zhao and Zeng, 2007; Tom and Mohan, 2003; Chakroborty and Dwivedi, 2002).
- Methodology used: conventional methods vs. heuristic methods.

As regards methodologies, it is worth digging a little deeper. Conventional methods (Morlok and Viton, 1984; Van Nes et al., 1988; Delle and Filippi, 2001; Chang and Schonfeld, 1993; Van Nes, 2003) include analytical methods and those that involve some type of mathematical programming. However, due to their high complexity and combinatorial and multi-objective nature, these methods are only suitable for problems where it is necessary to generate general policies but not complete detailed designs. In general, they are only theoretical interests, according to Kepaptsoglou and Karlaftis (2009).

Thus, the heuristic approach becomes the dominant methodology for dealing with real-life problems using reasonable computational power. There are at least two heuristic paths to be followed. The main of these, and that has been adopted in this research, consists of the following steps:

- Previous processes for consolidating demand data, road network information, and setting restrictions.
- Generation of a set of candidate routes through heuristic processes based on algorithms. (Lee and Vuchic, 2005; Ceder and Israeli, 1997; Tom and Mohan, 2003; Chakroborty and Dwivedi, 2002).
- Configuration of routes through processes in which frequencies are iteratively determined and demand is assigned, the best routes are selected according to previously defined indicators, these selected routes are improved, and the iterative cycle is resumed. (Zhao and Zeng, 2007; Fan and Machemehl, 2006; Cipriani et al., 2005).
- Final selection of the optimal set of routes and their associated frequencies.

The other possible path starts with the direct construction of the set of routes through a heuristic process that considers operational restrictions and that can be based on geographical considerations, and travel demand flows (Carrese and Gori, 2002). It can also be based on "ant colony algorithms" (Hu et al., 2005; Yu and Yang, 2006; Yang et al., 2007).

Turning to the literature on the choice of stop points, a problem that has received a little more attention than geographic layouts design, it is possible to cite studies based on mathematical optimization models on the design of express services in corridors with capacity restrictions (Leiva et al., 2010; Larraín et al., 2010; Larraín and Muñoz, 2019). Likewise, also notable publications are Scorcia (2010), with a work of design and evaluation of BRT express services in Chicago. Hart (2016) with a methodology to evaluate the potential of express services in corridors where regular services also operate. Ghaderi et al. (2017), which method focused on reducing users’ travel times through the spatial analysis of the stop points and their locations. Luo et al. (2017) with a heuristic for the design of express services at rush hour with a fixed-size fleet; and (García and Jaramillo, 2019) where it has been sought to maximize the users' comfort within buses through an improvement of express services.

Regarding the literature on the assignment of frequencies to services, Campos (2016) proposes a "Lego" type heuristic that would allow obtaining a reasonable frequency assignment for the BRT system in Bogotá. Meanwhile, Peña et al. (2016) present a mathematical model adapted to TransMilenio's case to optimize its operation by adjusting frequencies and variations in the scheduled departure times for the different routes. Additionally, a heuristic methodology based on an evolutionary algorithm to simultaneously undertake the design of routes and the assignment of their frequencies is developed by Martínez et al. (2017), with a case of theoretical application to various BRT systems in Colombia.

Finally, two books have been vital to the development of this research. One of these books (Ceder, 2007) constitutes a whole compendium that anyone designing and operating public transport systems should review. The other reference text (Norambuena, 2002) has as its main objective the formulation of a heuristic that allows obtaining an efficient route structure for a public transport system, with application case for transit corridors in Santiago, Chile.

From the above, it has been possible to conclude that although there is a certain amount of literature that addresses the route network design problem from a theoretical perspective, it is not so common to find studies applied to real-life transport systems, particularly regarding the sup-topic of geographical layouts. It is even less frequent to find works that covers simultaneously all the relevant sub-topics – geographical layouts, stop points and frequencies – related to route design in BRT systems. Thus, the present research aims to fill this gap, offering comprehensive guidelines for route network design in BRT systems, with an application case focused on TransMilenio.

2. METHODOLOGY

The methodology implemented was of the hypothetical-deductive type, as shown in the diagram in Figure 1:

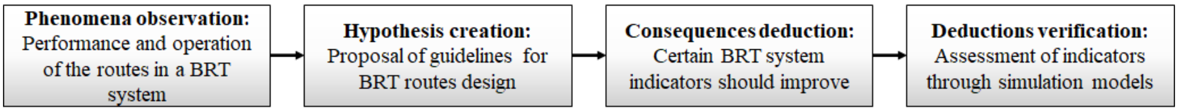

Figure 1: Hypothetical-deductive scheme of the research.

2.1 Experimental design

The phases of the research methodology are shown in Figure 2. In its first phase, the research had a qualitative design. Through a review of the existing literature, international study cases, and interviews with experts in the area, several candidate sets of guidelines for route network design were established. This process will not be covered in this document, but it can be consulted here (Moreno, Unpublished results).

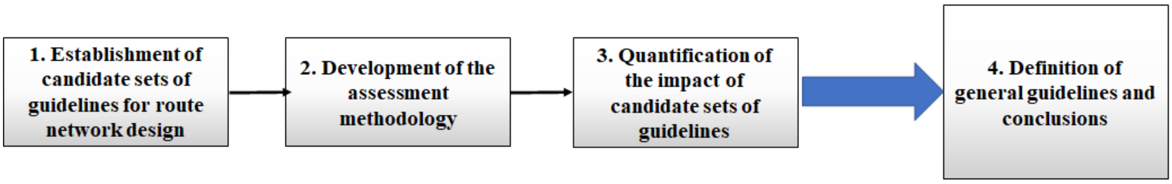

Figure 2: Phases of the research methodology.

Once the candidate sets were established, a quantitative approach was adopted: the impact of the various sets of proposed guidelines was quantified numerically to select the best solution alternatives to the research problem. All this through experimentation with a PTV-Visum simulation model.

2.1.1 Population and sample

The object of the study is to create design guidelines for Bogotá's BRT route network and their impact. However, as these guidelines have an intrinsically abstract nature, it is necessary to generate a transport model that simulates the behaviour of different variables that adequately describe the system's performance. Regarding the population and sample data for this transport model, the demand of internal trips in the BRT system has been considered:

- Population: trips, or trip segments, of the morning rush hour on Bogotá's BRT, establishing their origin and destination as stations in the system.
- Sample: a statistically representative collection of trips belonging to the previously defined population and presented in the form of a travel matrix.

The 2019 Bogotá Mobility Survey (SDM, 2020), the input and output records from the stations' turnstiles (TransMilenio, 2020), the seed matrix – calibrated to 2019 – of internal trips of the BRT system, and the study with the evasion baseline in TransMilenio (UNAL, 2019) have been used for the elaboration of the travel matrix.

The aforementioned data sources have been combined to generate a travel matrix updated to February 2020 – before the pandemic – by implementing a generation and attraction sub-model, and a distribution sub-model by Fratar. The final matrix estimated for the morning peak hour - 06:15 to 07:15 - contains 265,000 internal trips - for Bogotá's BRT. Additional details on the construction of the travel matrix can be found in (Moreno, Unpublished results).

2.1.2 Operational variables and objective function

These are the operational variables defined to characterize the transport model:

- t_{wait}: first boarding wait time (min)
- t_{travel}: onboard travel time (min)
- t_{trans}: transfer time (min)

- $\boldsymbol{N_{seats}}$: total number of seats (size of the minimum required fleet – bus seats)

The access time has not been considered since it has been assumed that users are already inside the stations in the internal transport model. The user fare cost has not been taken into account either because there is a flat fee to access any of the stations in Bogotá's BRT. Thus, the total fare does not depend on the number of transfers within the BRT system, or the distance travelled: it is the same for every individual in the BRT system.

Based on the first 3 operational variables, the objective function that allowed the assessment of the candidate sets of guidelines has been defined as the sum of perceived travel times for **n** trips:

$$F_U = a_{wait} \sum_{i=0}^{n} t_{wait} + a_{travel} \sum_{i=0}^{n} t_{travel} + \sum_{i=0}^{n} t_{trans} \quad (1)$$

For the first two time-weighting coefficients, these values were used (Ortuza and Willumsen, 2001):

$$a_{wait} = 2 \quad (2)$$

$$a_{travel} = 1 \quad (3)$$

Meanwhile, the transfer time was broken down into three components, as allowed by PTV-Visum:

$$t_{trans} = a_{walk\ trans} * t_{walk\ trans} + a_{wait\ trans} * t_{wait\ trans} + P_{trans} * N_{trans} \quad (4)$$

where:

- $\boldsymbol{t_{walk\ trans}}$: walking time during transfers (min)
- $\boldsymbol{t_{wait\ trans}}$: waiting time during transfers (min)
- $\boldsymbol{P_{trans}}$: penalty for each transfer (min)
- $\boldsymbol{N_{trans}}$: total number of transfers (dimensionless)

For the coefficient of walking time during transfers, again a classic value suggested by the literature is taken (Ortuza and Willumsen, 2001):

$$\boldsymbol{a_{walk\ trans} = 2} \quad (5)$$

On the other hand, for the two remaining coefficients, three simulation cases were defined:

- Low penalty transfers:

$$a_{wait\ trans} = 2 \ \cap \ P_{trans} = 2{,}5_{min/trans} \quad (6)$$

- Medium penalty transfers:

$$a_{wait\ trans} = 3 \ \cap \ P_{trans} = 5_{min/trans} \quad (7)$$

- High penalty transfers:

$$a_{wait\ trans} = 4 \ \cap \ P_{trans} = 7{,}5_{min/trans} \quad (8)$$

Additionally, for the assessment of the various scenarios, the minimum fleet required was also taken into account, estimated as the total number of seats:

$$N_{seats} = N_{f\ dual} * 80 + \ N_{f\ art} * 160 \ + \ N_{f\ biart} * 240 \quad (9)$$

where:

- $\boldsymbol{N_{f\ dual}}$ corresponds to the required number of 80-seats dual buses.
- $\boldsymbol{N_{f\ art}}$ corresponds to the required number of 160-seats articulated buses.
- $\boldsymbol{N_{f\ biart}}$ corresponds to the required number of 240-seats bi-articulated buses.

2.2 Assessment methodology

From the elaboration of state of the art, four groups of guidelines were defined. Namely:

- Simple design: this group of guidelines refers to the design of the route network must be as simple as possible.
- Multi-criteria design: this group of guidelines seeks that the route network design adopts multiple strategies and criteria that are necessary to optimize transport operation, even if this implies generating a complex route network.
- Radial design: this group of guidelines refers to the geometry of the routes layouts. Specifically, it is suggested that the routes should start from trip-generating areas, travel to a trip-attracting zone in the downtown, and then return to the initial point of origin.
- Diametrical design: in this case, it is suggested that the routes should start from a trip generating area and make their tour to another trip generating area, at the opposite side of the city, passing through the downtown.

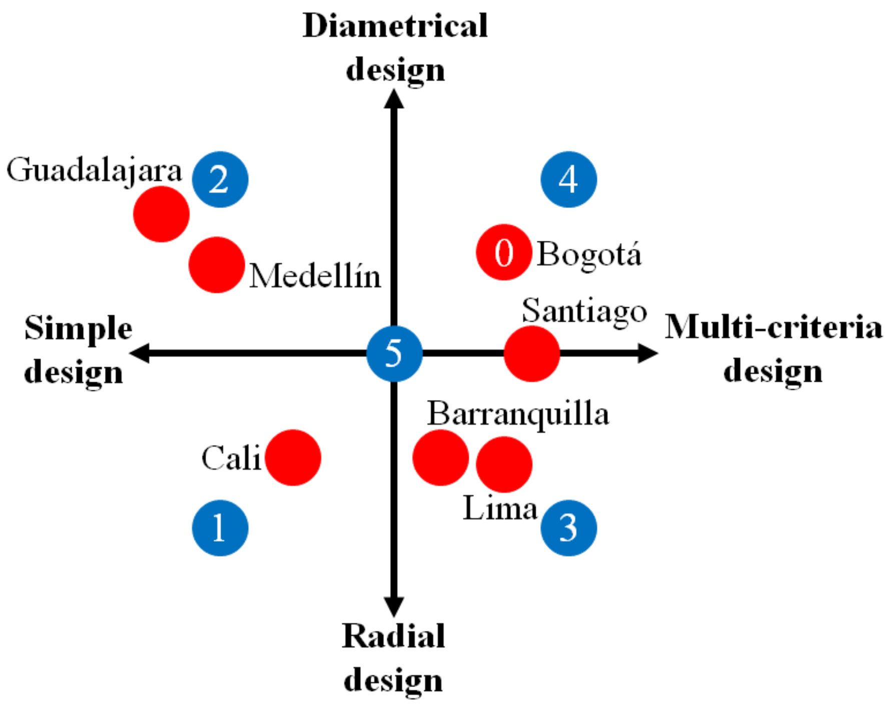

Figure 3: Cartesian plane of candidate sets of guidelines for route network design.

Combining these guidelines groups, as shown in Figure 3, five candidate sets of guidelines were obtained for the route network design. From each of these candidate sets, a route network scenario was generated by implementing a heuristic process. A route network scenario 0 (zero) was added, containing the actual services – February 2020 – of Bogotá's BRT. Therefore, it was possible to compare the solution given by the current route network vs. the solutions given by the new candidate sets of guidelines. The following are the route network scenarios generated:

- Scenario 0: 2020 route network.
- Scenario 1: radial routes with a simple design approach.
- Scenario 2: diametrical routes with a simple design approach.
- Scenario 3: radial routes with a multi-criteria design approach.
- Scenario 4: diametrical routes with a multi-criteria design approach.
- Scenario 5: routes based on different guidelines sets (radial + diametrical + multi-criteria design approach).

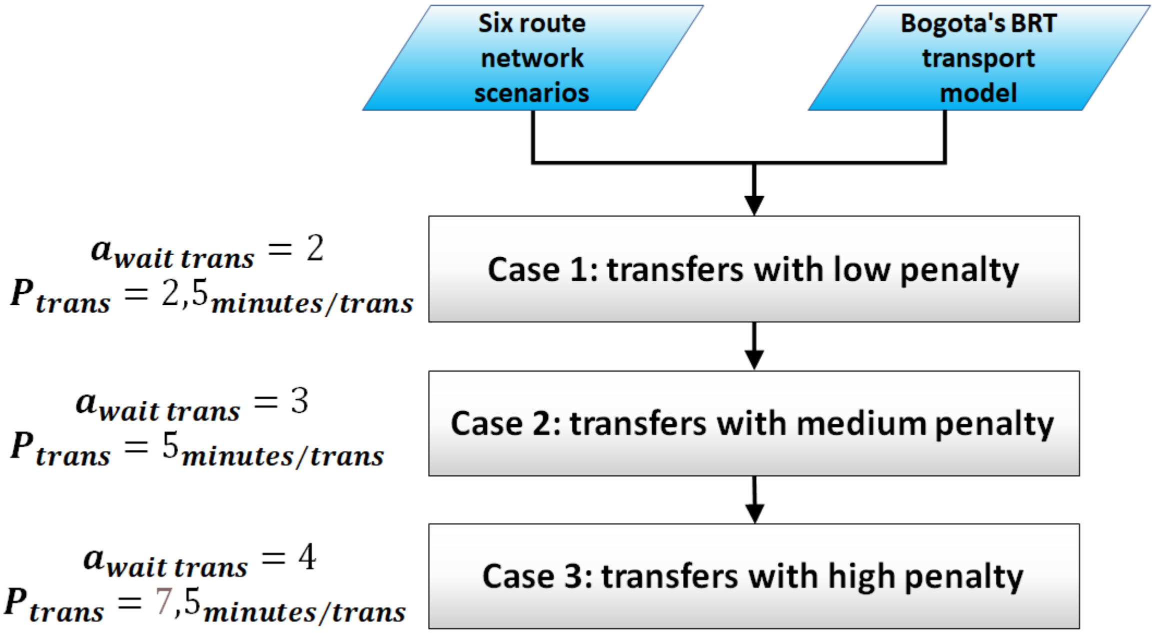

Figure 4: Structure of simulation cases.

Details of the heuristic processes developed for the generation of the route network for each candidate set of guidelines will not be covered in this document. They are widely explained in the thesis book generated for this research (Moreno, Unpublished results). Meanwhile, Figure 4 illustrates the simulation cases that were run to assess the different route network scenarios.

3. RESULTS

Table 1 summarizes the route network scenarios that were generated. In this table, the corresponding roundtrip services are counted as a single route. The total number of routes per scenario corresponds to the sum of its number of radial and diametrical routes.

Esc.	Geographical Guidelines	Design Approach	# Radial Routes	# Diametrical Routes	# Regular Routes	# Express Routes	# Super Express Routes	# Partial Routes
0	Actual	Actual	27	38	9	50	6	8
1	Radial	Simple	46	0	9	37	0	0
2	Diametrical	Simple	5	20	6	19	0	0
3	Radial	Multi-criteria	85	0	9	54	22	14
4	Diametrical	Multi-criteria	9	45	6	32	16	10
5	Rad/Diam.	Multi-criteria	34	32	6	40	20	11

Table 1: Synthesis of the six simulated route network scenarios.

Furthermore, Table 2 shows the results obtained for the six route network scenarios in each of the three simulation cases.

Scenario		Typology (Seats/Bus)			Fleet Size		F_U = Travel Time (min)		% Trips by required transfers			
Caso	**Esc.**	**80**	**160**	**240**	**Buses**	**Seats**	**Perc.**	**Net**	**0**	**1**	**2**	**3**
1	**0**	422	678	1245	2345	441040	46,7	41,7	14,1%	38,6%	33,2%	14,0%
1	**1**	330	554	1321	2205	432080	48,3	41,9	6,2%	21,5%	30,4%	42,0%
1	**2**	743	620	1369	2732	487200	47,8	41,8	6,6%	21,7%	31,5%	40,1%
1	**3**	367	644	1164	2175	411760	47,9	41,9	9,6%	31,6%	35,4%	23,5%
1	**4**	511	766	1157	2434	441120	46,9	41,5	11,6%	36,9%	34,0%	17,5%
1	**5**	361	617	1249	2227	427360	47,0	41,6	10,5%	37,2%	34,6%	17,7%
2	**0**	341	755	1182	2278	431760	48,2	42,2	29,1%	48,7%	19,8%	2,4%
2	**1**	264	625	1219	2108	413680	50,6	42,3	12,2%	39,5%	36,3%	12,0%
2	**2**	585	587	1289	2461	450080	49,4	42,2	15,6%	43,0%	32,7%	8,7%
2	**3**	334	654	1083	2071	391280	50,7	42,5	16,5%	46,5%	31,1%	5,8%
2	**4**	446	644	1116	2206	406560	48,8	42,0	22,8%	49,9%	24,2%	3,2%
2	**5**	311	614	1117	2042	391300	49,4	42,3	20,6%	52,9%	23,9%	2,5%
3	**0**	343	683	1223	2249	430240	49,2	42,6	39,5%	48,4%	11,4%	0,7%
3	**1**	264	624	1190	2078	406560	52,6	42,7	16,5%	48,7%	30,7%	4,0%
3	**2**	544	574	1254	2372	436320	50,8	42,7	23,0%	52,1%	22,8%	2,1%
3	**3**	341	555	1117	2013	384160	52,9	43,1	21,4%	57,3%	20,5%	0,8%
3	**4**	426	642	1070	2138	393600	50,3	42,5	32,4%	54,7%	12,3%	0,5%
3	**5**	304	614	1128	2046	393280	50,9	42,7	28,0%	59,3%	12,4%	0,3%

Table 2: Quantified results of the simulation cases per scenario.

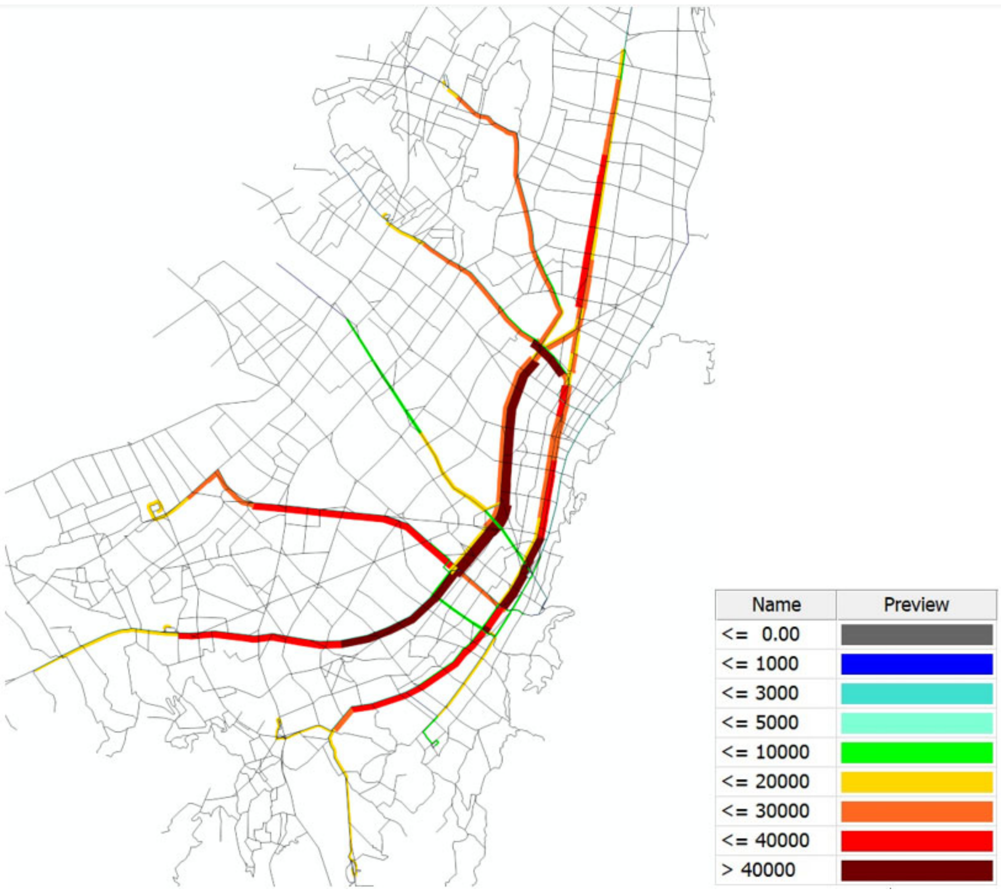

Figure 5: Passenger volume per arc in Case 2, Scenario 0 - Route network 2020 -.

Meanwhile, Figure 5 shows an example of the result of a trip assignment process. This example corresponds to Case 2: medium transfer penalty – Scenario 0: 2020 route network. In the whole exercise, a total of 18 trip-assignment processes were executed: 3 simulation cases x 6 route network scenarios.

4. DISCUSSION

Figures 6 and 7 show the results related to the average perceived travel time ($\boldsymbol{F_U}$) and the total number of seats ($\boldsymbol{N_{seats}}$). The figures compare the data obtained for the real route network (in gray tones), route networks with simple design (green tones), and route networks with multi-criteria design (in golden tones). These tones get darker as the transfers are penalized more in the transport model.

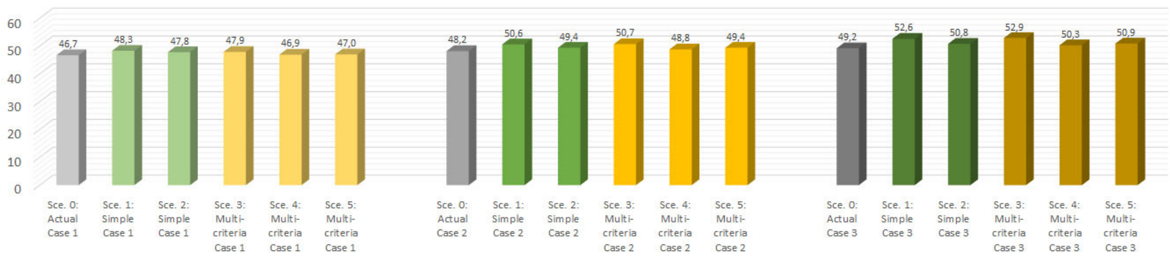

Figure 6: Average perceived travel times – F_U – per case and scenario (min).

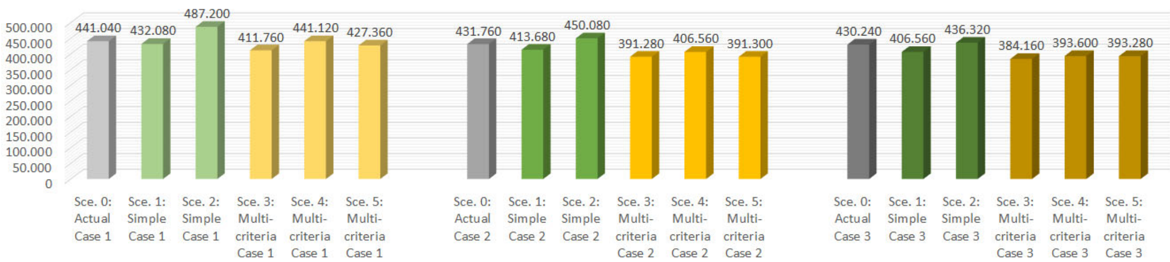

Figure 7: Minimum Required Fleet – N_{seats} – per case and scenario (seats).

At this point, it is convenient to explain that the reason why three simulation cases with different transfer penalties - low, medium, and high - have been defined is that the weighting of the transfer time from the users point of view depends, to a great extent measure, of the installed infrastructure: it is not the same to make a transfer within a comfortable station, with shops and restaurants, than to do it in a station in the most dangerous zone of the city, without a roof that covers the head and under unfavourable weather conditions. Thus, the proposed scheme of the three simulation cases allows to analyse the results for different infrastructure situations.

4.1 Simple design vs. multi-criteria design

There is no appreciable difference between route networks designed with a simple approach and those designed with a multi-criteria approach in terms of perceived travel times.

The difference is only 1.0% on average in favour of the multi-criteria approach, which is negligible.

On the side of the minimum required fleet, the differences are noticeable. It is noteworthy that route networks designed with a multi-criteria approach require fewer seats than the real route network (-7.4% on average) and fewer seats than route networks with a simple design approach (-8.2% on average). In terms of investment or user comfort level, this savings in required fleet is highly important.

The percentages provided in this comparison exercise correspond to the average of all simulation cases - low, medium, and high penalty for transfers - assessing the modelled indicators of real routes, simple approach, or multi-criteria approach scenarios, grouped according to their type.

4.2 Radial design vs. diametrical design

From the previous discussion, it is possible to conclude that the multi-criteria design approach is desirable over the simple design approach. Therefore, the performance of radial routes vs. diametrical routes will be compared, considering only the multi-criteria route network scenarios 3 and 4. The visualization of the modelled indicators from real route network is maintained, to have an additional point of comparison.

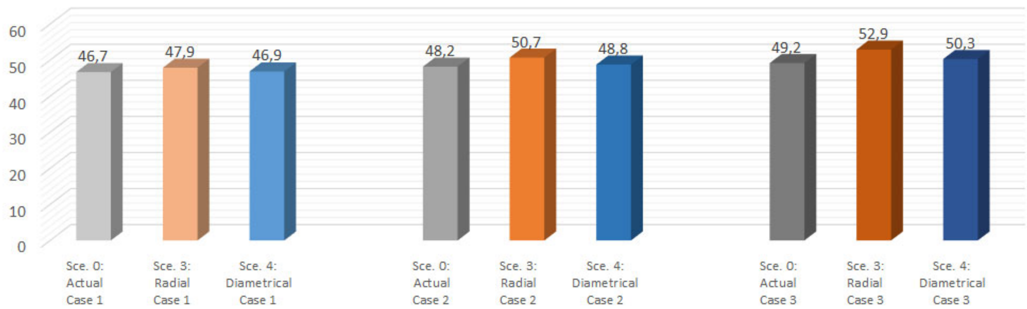

Figure 8: Average perceived travel times – F_U – per case and scenario (min).

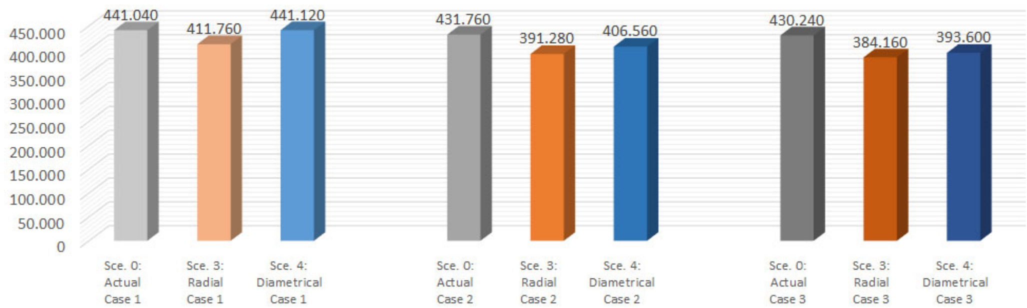

Figure 9: Minimum Required Fleet – N_{seats} – per case and scenario (Seats).

Figures 8 and 9 show the results for scenarios 0, 3, and 4, related to the average perceived travel time ($\boldsymbol{F}_{\boldsymbol{U}}$) and the total number of seats ($\boldsymbol{N}_{\boldsymbol{seats}}$). Note that real routes scenarios are kept in gray tones, while the radial routes scenarios are shown in orange tones, and the diametrical routes scenarios are depicted in blue tones. Again, these tones get darker as transfers are more penalized.

Regarding perceived travel times, the route network with radial multi-criteria design has perceived travel times 5.2% greater than those of the real route network, on average. While the increase is 3.8%, on average, when compared to the route network with diametrical multi-criteria design. This is undoubtedly a product of the increase in the number of required transfers in a radial route scheme, in which a significant number of people are expected to make additional transfers at central interchange stations. Nevertheless, if the general results in Table 2 are considered, and if the net travel times are compared (net travel times without time weighting coefficients), the differences between the three assessed scenarios are reduced to the order of 1,0%. In other words, radial routes implementation does not significantly impact the net travel times, but it does on the times perceived by the user.

On the side of the minimum required fleet, the radial route network offers a savings of 8.9% in the number of seats concerning the real route network and 4.4% of savings compared to the network of diametrical routes. Again, this is highly significant in terms of investments in rolling stock, as fewer buses are required to meet demand; or in terms of user comfort, as it would be possible to schedule services with higher frequencies.

5. GUIDELINES FOR ROUTES DESIGN IN TRANSMILENIO

The foregoing discussion leads to the conclusion that the most recommended approach is to implement routes with radial and multi-criteria design guidelines: scenario 3. To give an explicit answer to the research question, the specific guidelines - radial and multi-criteria - that were applied to the design of the selected scenario are listed below:

- Geographical layouts:
    - Taking into account the current infrastructure of TransMilenio, today's day it is recommended to maintain a route network in which the diametrical design predominates. This is because the current infrastructure would not support the higher number of transfers at the central stations in the case of implementing radial routes, there is not enough space.
    - In the short term, a broader implementation of partial routes – routes starting and ending at intermediate stations, other than main portals – is recommended.

  - In the medium term, Bogotá's BRT system should migrate towards a radial route network that allows reducing the minimum required fleet to serve demand. This will require the construction of central interchange stations.

- Stop points:

  - In the medium term, central interchange stations must be implemented in certain geographical locations identified in this research. These stations must have capacity enough to serve passengers who make a transfer and allow buses operational return, in the case of implementing radial routes. Figure 10, on the next page, shows the identified places for this central stations and their passengers demand.
  - In the short term, it is recommended to expand the implementation of super-express services, both from main portals and from the intermediate stations with the highest demand.
  - In the short term, it is suggested to implement routes with asymmetric stop points for each direction, according to actual passenger flows.
  - In the short term, it would be convenient to test routes whose stops points are assigned to serve specific destination areas in the central corridors.

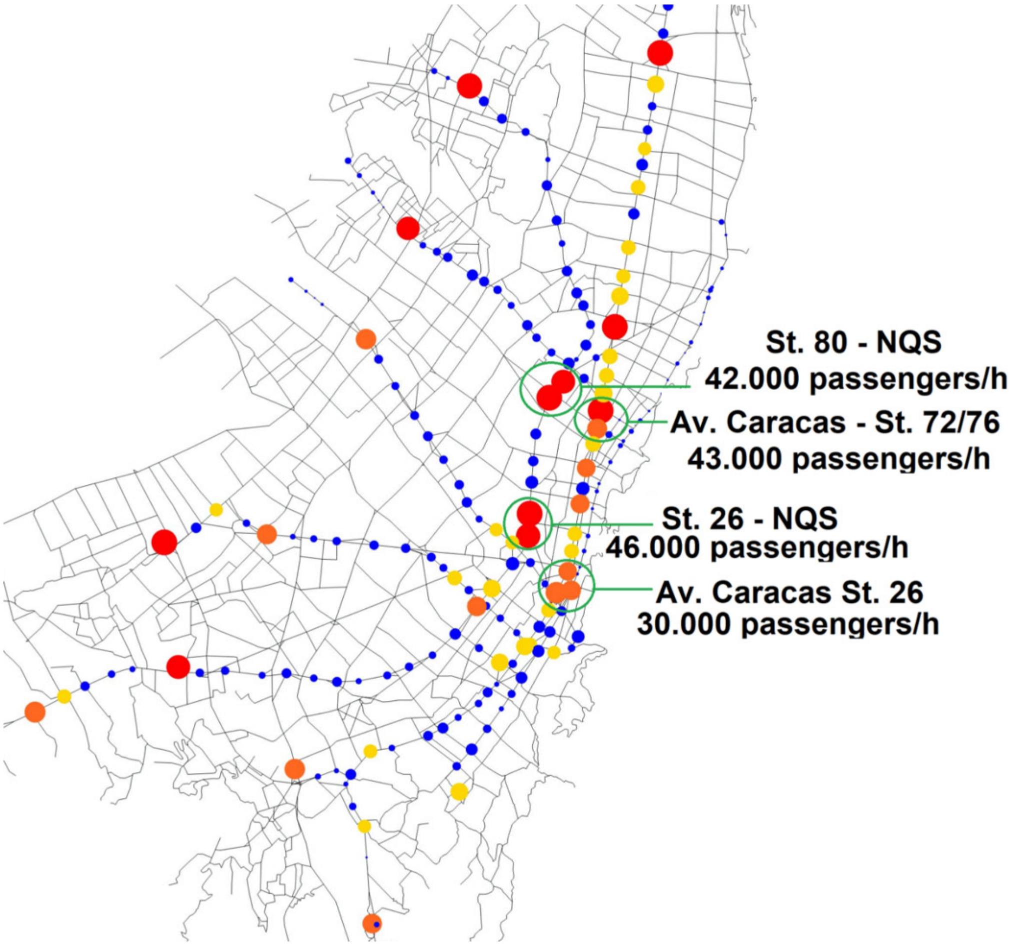

Figure 10: Location and stopping passengers of proposed central interchange stations.

- Frequencies:
    - It is not recommended to implement a route network that is too simple in Bogotá's BRT, since this would imply too short step intervals for the services, with its consequent effects on convoys formation and long lines of buses waiting at the stations. Scheduled intervals shorter than two minutes may be not suitable for actual operation.
    - The implementation of route networks designed with multi-criteria guidelines is recommended, so that the scheduled intervals are within reasonable limits – 2 to 7,5 minutes – for the rush hour operation of a BRT system such as TransMilenio. See Figure 11 at the end of the next page.

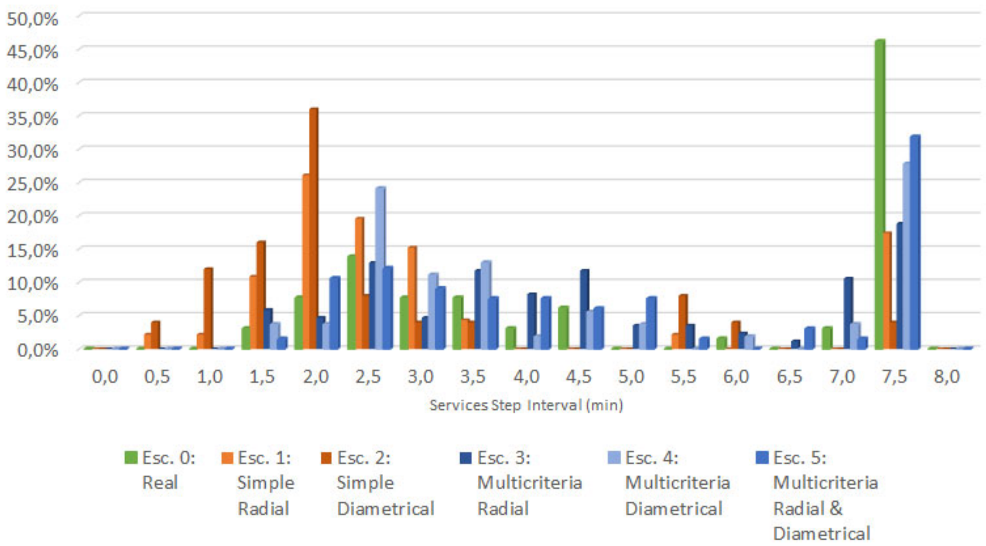

Figure 11: Percentual distribution of services scheduled intervals per scenario.

Finally, and as a reference, Figure 12 shows the route network scenario 3, which would be the most recommended: radial routes plus a multi-criteria design approach.

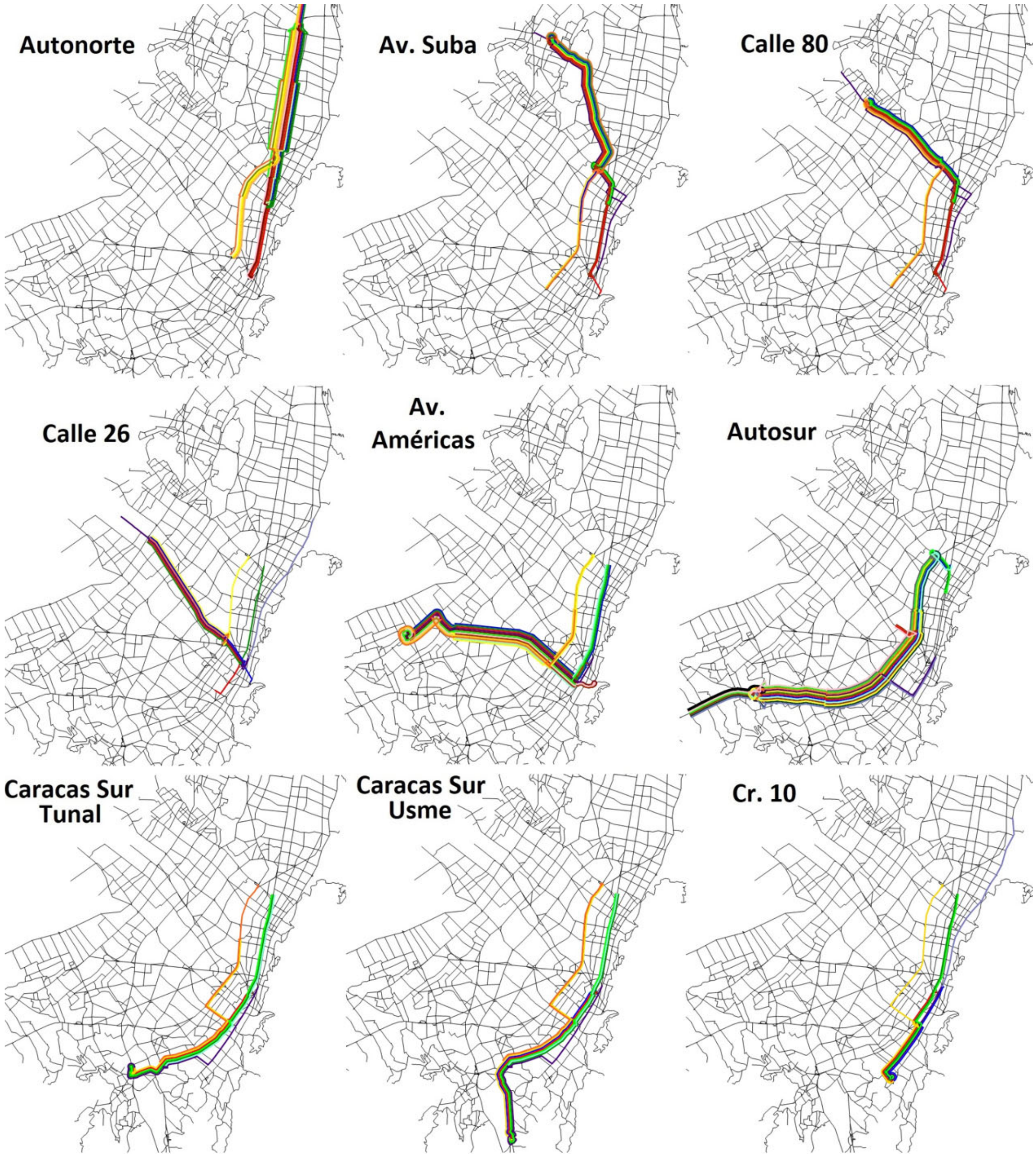

Figure 12: Scenario 3: radial route network with multi-criteria design approach.

6. CONCLUSIONS

Regarding the average perceived travel times, it has been shown that the multi-criteria design approach does not present significant advantages over the simple design approach. However, if the minimum required fleet is considered, the difference is more noticeable, with the multi-criteria approach achieving valuable seats savings. Compared to the scenario of the real route network of Bogotá's BRT, the multi-criteria approach results in slightly higher average perceived travel times. However, in terms of the average net travel times (without time weighting coefficients) the difference is negligible. As for the required fleet, the multi-criteria approach would allow, according to the simulations, significant savings in the number of seats compared to the real routes.

On the side of the comparison between multi-criteria radial routes vs. multi-criteria diametrical routes, the latter provide a slight improvement in average perceived travel times compared to their radial equivalents. However, the real route network would have slightly shorter perceived travel times than those on the multi-criteria diametrical route network. In any case, if the average net travel times are compared, again the difference between the real, radial multi-criteria, and diametrical multi-criteria route network scenarios is negligible. In addition, if the minimum required fleet is considered, the radial routes with a multi-criteria approach offer seats savings of 8.9% with respect to TransMilenio real routes, and 4.4% compared to the scenario of diametrical multi-criteria routes.

Considering the above, the main conclusion is that the scenario of radial multi-criteria routes would offer the best response to TransMilenio's needs. However, today’s day it would not be possible to implement these radial routes without first building four central interchange stations that allow handling the higher flows of transferring passengers and returning buses in the expanded centre of the city.

6.1 Scope, limitations, and next steps

With respect to the research scope, these results are valid for Bogotá's BRT and its passengers demand before the pandemic. However, the developed methodology can be reproduced in any other BRT system around the world and can be scaled to cover the entire transportation system of Bogotá metropolitan area.

Among research limitations and next steps is the fact that possibly, once the pandemic ends, it will be necessary to re-evaluate the route network scenarios according to the new passenger demand after COVID-19. In addition, given that research results have been obtained through transport model simulations, these results are subject to the possible deviations of a model that merely emulates the real world. Thus, a real-life pilot in some BRT corridor would be convenient. It is also necessary to say that the transport model developed does not consider micro-simulation details of a traffic model, which development would be too helpful to assess the impact on BRT traffic due to the proposed guidelines.

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