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Improving BRT route design through code: the case of Bogotá's BRT system, TransMilenio

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Abstract

This study presents the methodology used by TRANSMILENIO S.A. –the company in charge of managing the BRT lines in Bogotá, Colombia– to renew its operational design. TRANSMILENIO S.A. is increasing its bus fleet by acquiring higher capacity bi-articulated buses. This process demanded a redefinition of the frequencies, stops, and type of bus for all routes in the system. Therefore, a line scheme was selected based on the number of trips between corridors. A non-linear optimization model was then used to establish an initial route design that could satisfy passenger demand in the morning rush hour. Five algorithms were implemented to adjust the initial route design to the actual restrictions, namely, fleet and bus capacity at stops. The algorithms modified the type of bus employed, the defined stops of routes, and eliminated low demand routes. Different alternatives were tested for the execution order of algorithms. The alternative to implement was selected based on compliance of the defined restrictions. Algorithms were iteratively run. Between iterations, a trip assignment model was used to adjust route frequencies based on demand. The execution order of algorithms, its impact on the level of service indicators, and compliance of restrictions are part of this study's discussion. Particular relevance and effects of each algorithm are also analyzed. Both methodology and results might be tested, adapted, and improved in further studies by other BRT systems as a reference or input for their own route design process.

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1. Introduction

Bus Rapid Transit systems have proven to reduces the use of private cars, improves air quality, mitigates traffic accident rates, and generates employability (WRI, 2013). TransMilenio is the name of Bogotá´s BRT system, one of the largest BRT systems in the world (WRI Brasil, 2021). TRANSMILENIO S.A. on the other hand is a company owned by several public authorities of the city and is in charge of planning and managing the public transport system in Bogotá (which also includes regular bus routes and cable cars). Furthermore, this company does not own or operate buses but assigns routes to private transport operators. TRANSMILENIO S.A. recently performed two priority public bids (TMSA, 2018) which incremented the number of buses in the system.

The new fleet was divided into 67% bi-articulated and 33% articulated buses. The entity set off the design of a renovated operational design which apart from establishing the operable conditions for the new fleet, must guarantee general attention of Bogotá's BRT demanded trips. Likewise, BRT systems, unlike rail schemes, have a set of operational parameters that must be defined for service coverage. Particularly, BRT system has higher flexibility since its infrastructure can be adapted to the existing needs of a given space (CEPAL, 2012). Therefore, when planning the scheme of routes for this type of system, the followed variables must be considered:

- Number of routes offered per corridor or line.
- Defined path and stops for each route (vehicles in BRT systems can skip stops).
- Frequencies and type of bus to be used for each route.

These variables highlight the requirement to generate a process in which all are analyzed in a holistic and coordinated methodology. A methodology that leads to the execution of the process called Operational Design.

2. Initial solution

2.1. Existing methodologies

Planning public transport has been widely analyzed in the literature. In this section, two types of methodologies are presented: the first one related to a regular bus routes design, and general guidelines specifically for a BRT system.

In the first case, the principal process to evaluate a design is based on three main steps according to (Ceder, 2007): Initially, a feasible solution is proposed based on the different OD pairs with higher demand. This will result in a first approximation of the model. Then, these groups of routes are evaluated based on the attended demand. Subsequently, an evaluation of frequencies and network performance is executed according to selected indicators such as fleet size, rules for insertion or elimination of nodes in existing routes, among others. Finally, it is obtained an improved solution after removing, dividing, or interchanging the routes.

The second one comprises a BRT Planning guide (ITDP, 2017) which shows the guidelines for executing the service planning. In the document, mainly in chapter 6, the different indicators and considerations for basic service planning are presented. Some of these are saturation, speed, travel time, service frequency and headways, direct and express services. However, these guidelines are presented from a general strategic perspective. In the present document, it is presented a combination of both methodologies.

2.2. Line selection and preliminary design

Since vehicles in a BRT system can easily change from one trunk line to another, a "line" is defined as an itinerary connecting two or more trunk lines. Transfers therefore occur in many stations and not only at the intersection of two trunk lines.

An initial set of routes and lines was selected, by analysing trip demand between the existing trunk lines, following a line selection process as mentioned by Ceder (2007). The trip demand used was the morning peak hour (6:30 to 7:30) estimated in a study for the integral structuring of the trunk component operation of TransMilenio System" (Temporary Union SDG-PHR-KPMG, 2018). 22 lines were considered as main lines.

For each selected line, a simple optimization model was developed in Excel to create an initial set of around five routes per line. The model maximized the number of principal O-D pairs covered with no need for transfers while avoiding leaving stations without service.

3. Additional restrictions

The preliminary design, which resulted from the initial optimization model required to be adjusted to the following restrictions:

- The resulting operational design should require no more buses than the available fleet (736 articulated and 1263 bi-articulated buses)
- Bi-articulated bus require larger stations, stop points, and doors, and not every station in the system is adequate to operate with this vehicle type. There must be no bi-articulated bus routes designed to stop in stations without the adequations required.
- The number of buses per hour that can stop in each station is limited to a previously defined capacity value. Stations with more buses stopping that the capacity value are considered saturated.
- To avoid long waiting times, TRANSMILENIO S.A. has established a seven (7) minute limit for the maximum headway allowed. This limit must be observed even when route demand is low. A limit of two (2) minutes for the minimum headway allowed has also been established to avoid bus bunching.

4. Developed algorithms

To adjust the preliminary operational design to the current restrictions, four algorithms were developed that iteratively modified the initial scenario. A transit assignment model was used to evaluate different supply scenarios. The model used was previously developed for TRANSMILENIO S.A. as part of the consultancy by Temporary Union SDG-PHR-KPMG (2018) and uses EMME transport planning software. Algorithms were implemented using python scripts. For more information on transit assignment models refer to Ortúzar and Willumsen (2011), chapter 10.6.

Algorithms are presented in the execution order decided after different iterations described in section 5.

4.1. Relevant OD pairs inclusion

The first algorithm searched OD pairs with the highest number of trips in the origin-destination matrix (those that fell within a defined percentile). For those pairs that were not directly connected, a route that passed through the corresponding origin and destination stations (without stopping), was used to connect the OD pair (by making it stop). If no routes were found, the OD pair remained without direct connection.

4.2. Capacity adjustment in stations

This algorithm was developed adjust to the hourly bus capacity of the stations. The algorithm searches for stations that are saturated (as defined in section 3) in any of the two directions, then eliminates the stop of the route with the least number of total movements (ascents and descents in both directions). Therefore, the selected route will no longer stop at this station. The stop elimination process is repeated, continuing iteratively until the percentage of saturated stations falls below a defined threshold, or when the maximum iteration defined number is reached.

4.3. Change to biarticulated type

After capacity adjustment is completed, if the design requires more articulated buses than those available, and less bi-articulated than those available. This algorithm looks for those routes that are being served by articulated buses and stop only in stations equipped for bi-articulated buses. The algorithm then modifies the type of bus of all the routes found to bi-articulated. This is not an iterative process, and all the routes found are modified at once.

4.4. Fleet adjustment

For the other cases in which the available fleet restriction is breached (even after executing the algorithm for changing to bi-articulated bus type), *Change to articulated type* and *Route elimination* algorithms were developed.

Change to articulated type: this algorithm is executed if there are more bi-articulated buses than those available. In each iteration, it looks for the route of bi-articulated buses with the lowest demand (fewer total boardings) and modifies it to articulated bus type. The algorithm continues to iterate until the design meets the available fleet of bi-articulated buses.

Route elimination: After completing the first algorithm, and if the available articulated bus fleet restriction unfulfilled, the second algorithm will search for the articulated bus route with the least demand (least number of total boardings) and eliminate it. The algorithm continues to iterate until the design meets the available fleet of articulated buses. After each iteration, an assignment and headway adjustment (as described in 4.5) is carried out.

4.5. Assignment and headway adjustment

As stated above, between the iterations of the algorithms, headways from all routes were equaled to a reference value. Then a transit assignment using EMME's optimal strategies (Spiess and Florian 1989) was executed. And finally, headway was adjusted to all routes by calculating the frequency required for each route to be able to transport the passenger demand at the segment with the higher load.

A relatively simple methodology for transit assignment was used, as the effects of vehicle capacity, parallel lines, and overlapping routes were not addressed. An alternative for the future improvement of this methodology is the use of more sophisticated assignment models, such as those developed by Verbas and Mahmassani (2016), or Schmöcker and Fonzone (2011).

4.6. Route protection and performance indicators

In addition to all system routes, it exists a set of routes that stop in all stations along their path. To prevent any of the algorithms to erase or modify these routes, a functionality was implemented to "protect routes" by marking them using a dummy variable in the software. As planning process progressed, this functionality proved to be useful and was extended to other routes. The reason is briefly explained in section 7.

To evaluate the performance of the developed algorithms, the overall design, and the resulting routes, the following indicators were calculated between every iteration:

- Bus fleet (articulated and bi-articulated buses).
- In-vehicle time.
- Waiting time.
- Average boardings (including initial and transfer boardings).
- Saturated stations (percentage from total stations as defined in section 3).
- Generalized cost (average sum of waiting times, and in-vehicle times considering perception factors).

5. Development process and execution order

Initially, only Fleet Adjustment (FA) algorithm (section 4.4) and Capacity Adjustment in Stations (CAS) algorithm (section 4.2) were developed. FA was intended to precede CAS, but this intended execution order proved inadequate. As a result, the execution order was inverted and further issues were identified, which lead to the development of the other two algorithms.

Scenarios 351 and 361 were both built using the preliminary design as the starting point (section 2.2). For scenario 351, FA was executed before CAS. When issues with scenario 351 were identified, scenario 361 was created with the execution order inverted. Issues with the first scenario are evident when compared to the second one, as is shown below. For scenario 351, Change to Articulated Type (CAT) algorithm (section 4.4) was performed from iterations 1 to 8, when the bi-articulated fleet restriction was fulfilled. Route elimination (RE) algorithm (section 4.4) was subsequently performed until iteration 22, and CAS was then executed until iteration 42. At iteration 42 CAS maximum iteration number was reached without achieving convergence.

Fig. 1. Required number of articulated buses throughout algorithm execution, scenarios 361 and 351.

For scenario 361, CAS was executed from iterations 1 to 21, when the desired convergence was reached (5% of stations saturated). CAT was performed until iteration 30 when the bi-articulated fleet restriction was fulfilled. RE was then executed until iteration 50 when the maximum iteration number was reached (20 iterations). CAT had the desired effect by reducing the number of required bi-articulated buses. However, required buses also varied when CAS was executed. Figure 1 shows the required number of articulated buses along algorithm execution. This figure shows the desired effect of RE algorithm in reducing the number of required articulated buses. It can be observed that required articulated buses also vary when CAS is executed.

Fig. 2. Percentage of saturated stations throughout algorithm execution, scenarios 361 and 351.

By comparing both scenarios it was clear that progress obtained by FA algorithm could easily be undone by CAS. On the other hand, the inverse relation was not true. As shown in figure 2, the Percentage of saturated stations was effectively reduced by CAS and it was not significantly increased when executing FA. It was then decided to execute FA after CAS.

FA and CAS algorithms were effective at complying with system restrictions. However, since both eliminated routes and routes stops, more transfers were required in the system. Even though for some stations the number of transfers diminished, for others, it augmented dramatically. "Calle 100" station, for example, went from nearly 2.350 transfers to 26.250; more than 11 times the initial value.

To address this problem, Relevant OD Pairs Inclusion (RPI), and Change to Biarticulated Type (CBT) algorithms (sections 4.1 and 4.3) were developed. CBT was executed between CAS and FA and two options were evaluated for the execution of RPI. RPI was run immediately after CAS in scenario 403, and before CAS (at the beginning of the whole process) in scenario 413.
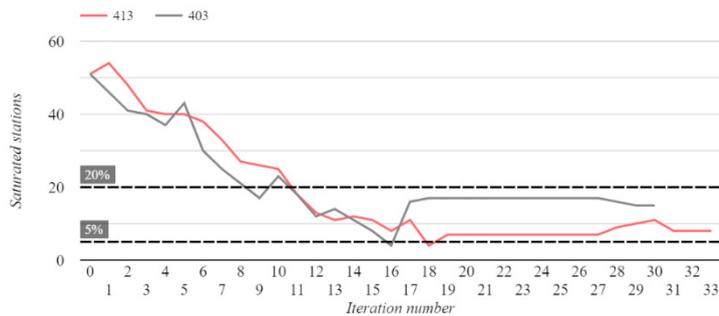

Fig. 3. Percentage of saturated stations throughout algorithm execution, scenarios 413 and 403.

Except for the percentage of saturated stations, there were no significant differences in performance indicators between scenarios 403 and 413. Figure 3 shows that some of the progress achieved by CAS was undone by RPI in scenario 403 (Iteration 16 to 17). It was then decided to execute RPI before CAS.

5.1. Capacity adjustment in stations algorithm convergence

CAS algorithm was completed when the percentage of saturated stations was 5% or less. This value was selected as a convergence threshold because complete compliance of station capacity restriction (0% saturated stations) could not be achieved. In the scenarios when CAS was executed beyond reaching 5% of saturated stations, it continued to eliminate route stops increasing the number of transfers and deteriorating the overall route design.

6. Results

A side effect of these algorithms was an increase in transfer rate at some stations. Manual adjustments were made to the initial solution to reduce transfers. Adjustments included adding stops to routes, and protecting routes from modification as described in section 4.6. This process was repeated iteratively for all stations with more than 4000 transfers/hour generating several scenarios until a stable point was reached. Consequently, this section presents the results for scenario 744, which satisfied system restrictions and had reasonable amounts of transfers at most stations.
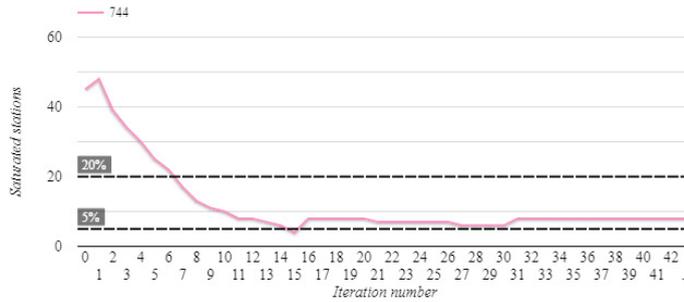
Fig. 4. Percentage of saturated stations throughout algorithm execution, scenario 744.

CAS algorithm ran from iteration 1 to 15 and stopped when the proportion of saturated stations was under 5%. As shown in figure 4, this percentage was relatively stable for the remaining of the process, never exceeding 10%.
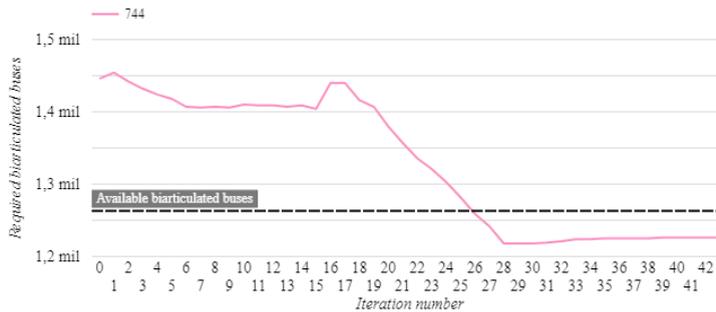

Fig. 5. Required number of articulated buses throughout algorithm execution, scenario 744.

After CAS and CBT were completed, CAT algorithm was initiated at iteration 16. Figure 5 shows a drop in the required number of bi-articulated buses during CAT, and figure 6 shows an increase in the required number of articulated buses. CAT ended at iteration 28 when the target value was met.
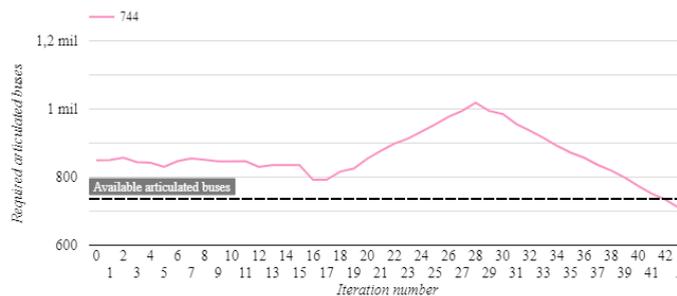

Fig. 6. Required number of articulated buses throughout algorithm execution, scenario 744.

Figure 6 shows that the required number of articulated buses decreased as RE algorithm ran from iterations 28 to 43. The required number of bi-articulated buses and the percentage of saturated stations remained under acceptable ranges. For the other indicators described in section 4.3 their value improved between base scenario and the preliminary design, and there were no significant variations when the algorithm was executed.

7. Conclusions

CAS and FA algorithms were designed to achieve target values for saturated stations and bus fleets. The two are effective in this matter. Therefore, process automation aids to create an operational route design proposal for a BRT system by considering a broader set of restrictions when compared with traditional methodologies.

The developed algorithms have an impact on system direct connectivity. In this case, planners had to manually resolve high transfer rates at some stations.

The execution of the described algorithms was not sufficient to achieve a fully applicable operational design. In the case studied, the attained percentage of saturated stations was 8%, meaning that 12 stations were to be analyzed manually to avoid sending more buses than their capacity.

Based on the iterations carried out with the CAS algorithm, it was reasonable to infer that a convergence scenario with 0% of saturated stations was not reliable, regarding the current conditions of the system. Since the saturation values in stations did not exceed the threshold of 5% in the iterations process, regardless of the elimination of service stops. Thus, in this research, it was necessary to manually restrict the algorithm to avoid undesired exclusion of several routes per station that can bring detrimental effects (stations or OD pairs not attended) so it must stop once the threshold is reached.

Despite the existence of international methodologies to generate an operational design for BRT systems, these methodologies are not definitive and do not include specific guidelines for addressing the station capacity and available fleet restrictions. The planning process for a BRT system is still open for improvement and debate.

Vehicle capacity, parallel lines, and overlapping routes can affect the results of transit assignment. Using an assignment model that takes these factors into account could improve the assignment results, and therefore the overall operational design. Based on this research, process automation aids to create an operational design proposal for a BRT system by considering a broader set of restrictions compared with additional manual methodologies.

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