ANALYSIS AND EVALUATION OF DIFFERENT HEADWAY CONTROL STRATEGIES FOR BRT: SIMULATED WITH REAL DATA

Felipe Ortiz[1], Ricardo Giesen[2], Juan Carlos Muñoz[3], Luis Antonio Lindau[4,5], Felipe Delgado[6].

E-mails: fortizr@uc.cl, giesen@ing.puc.cl, jcm@ing.puc.cl, lindau@producao.ufrgs.br, fdb@ing.puc.cl

[1,2,3,6] Departamento de ingeniería de Transporte y Logística, Pontifica Universidad Católica de Chile, Av. Vicuña Mackenna 4860, Macul, Santiago, Chile.

[4]EMBARQ Brasil

[5]Laboratório de Sistemas de Transporte, Universidad Federal do Rio Grande do Sul, Brazil

ABSTRACT

Real-time control of headways between buses has demonstrated to help increasing the level of service on transit systems. This paper evaluates adapted versions for large-scale real systems of the control strategies proposed by Delgado et al. (2012). These strategies were implemented and simulated on the EMBARQ BRT Simulator using real data from the Insurgentes BRT corridor in Mexico City. Several scenarios were evaluated to establish the benefits of implementing different control schemes. Results showed that the proposed holding strategy, optimizing every 2 minutes and considering a planning horizon of 12 of the 72 stops, reduces the perceived waiting time by users in 21% and the variability in 39%. In addition, this strategy allows the operator savings of 5% of the vehicle fleet. The proposed control strategy seems feasible to apply in practice and we recommend its implementation for the Insurgentes corridor.

Keywords: bus bunching, headway control, holding, boarding limits, transit operation, BRT.

1 INTRODUCTION

The level of service in transit systems has demonstrated a big role in attracting passenger to the system. This level of service is associated to several aspects that are perceived by users such as: waiting and travel time, comfort, cost, reliability, regularity, security, etc.

In Delgado et al. (2012) it is described how the headway regularity helps to improve the level of service in most of its aspect. The main effects are on reducing the variability of the waiting times, balancing the load of buses, thus improving the comfort, and additionally allowing to reduce the operational costs through the reduction of cycle time.

Delgado et al (2012) proposes control strategies that allow adjusting the headway between buses in order to regulate the system and to avoid the bus bunching. Two of the proposed strategies are: (i) holding buses on bus stops and (ii) limiting the number of passengers who are allowed to board a bus at a stop or boarding limits. Additionally, capacity restrictions are included in the model, an important characteristic for transit systems in developing countries where full buses are common.

The results obtained by Delgado et al. (2012) showed the efficiency of the two control strategies, compared to the non-control or simple threshold rules. Given the reported benefits, this paper evaluates those control strategies through their implementation in a simulator that allows a better representation of a BRT corridor and using real data, with more random components and bigger size scenarios. In addition, practical considerations are taken into account and restricted strategies are also considered. To evaluate these strategies The EMBARQ BRT Simulator was used (Lindau et al., 2011).

The structure of this paper is compounded first by a literature review on real-time control strategies and the model of Delgado et al. (2012). Section 3 includes the methodology followed to accomplish the objectives, including the new formulation proposed for the optimization problem. In section 4 the simulation experiment is described and the results obtained are presented. Finally, section 5 presents a summary of conclusions regarding the results of simulations and some recommendations about the control strategies and their implementation.

2 LITERATURE REVIEW

Problems that occur during operation of transit systems can be counteracted by the design of real-time strategies. Control at stations is one of the most popular and frequently used to reduce passenger waiting time or prevent the bus bunching. This includes the use of holding, stop-skipping and short-turn as strategies. Holding strategies has turned to be very popular among practitioners in public transit systems; two types of holding strategies could be identified: (i) threshold-base control where buses are held at stops in order to correct the headway between consecutive buses; (ii) mathematical programming models with holding times as decision variables and passengers' waiting time as the objective function to minimize (Zolfaghari, Azizi & Jaber, 2004).

The latter type has been the focus of several recent studies (Daganzo, 2009; Daganzo & Pilachowski, 2011). In all these studies real time information is considered for decision making. Those studies showed improvement in regularity, although did not consider operations where capacity of buses is reached

Part of the studies in this subject is Delgado et al. (2012), model of interest for this paper. It is considered that this model has advantages above the previous in several aspects. Among them are the inclusion of boarding limits as a measured stop-skipping and the fact of considering bus capacity as a constraint that affects considerably the waiting time of passengers. The model proposed by Delgado et al. (2012) has two versions: Holding and Boarding Limits with Real Time information (HBLRT) and Holding with Real Time information (HRT). The second one is a restricted version of the latter, since it discards the application of boarding limits.

This model consists on an approach of re-planning with a rolling horizon where every time a bus reaches a stop it solves a deterministic mathematical programing problem. The decision variables are each of the two control strategies, and the objective function is to minimize both the waiting time in bus stops and vehicles for passengers. For a detailed description of the mathematical formulation refer to Delgado et al. (2012).

The model considers real time information regarding passenger waiting at bus stops, passengers on board buses, buses location, among others; the authors remark that it is information feasible to collect. The transit system underlying the model is a single line in a unidirectional corridor, with N bus stops and a constant fleet of K buses that circulate in a loop. The scheme for this system is presented in Figure 1.

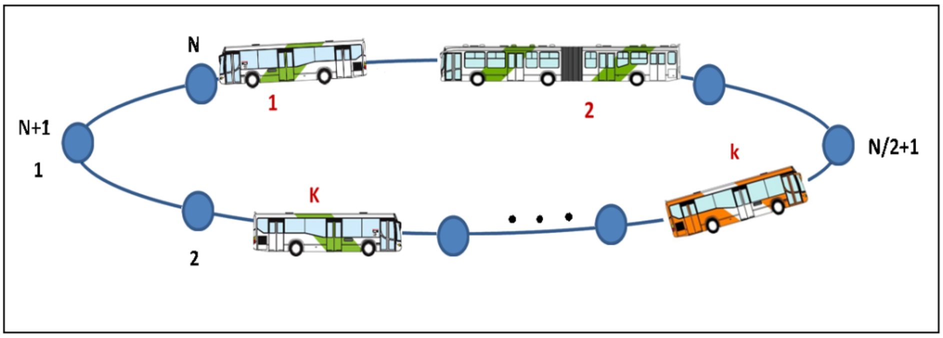


Figure 1 - Transit system model (Delgado et al., 2012)

The model was evaluated in Delgado et al (2012) using simulations in MATLAB. To stochastic components where the passenger demand (Poisson) and the travel time between bus stops (Lognormal). Simulation was based on events, an event is triggered when a bus arrives to a bus stop, then the optimization model is activated and the problem solved. The solution is traduced to simulations in terms of instructions for the bus that triggered the event: either be held or limit the number of passengers to board. The scenario considered a 30 evenly spaced bus stops corridor, with 10km length where 15 buses operated. On their evaluation, the authors assumed that travel time between bus stops and arrival rate of passengers are known and fixed during the 2 hours of simulation time.

The authors include reduction levels for the instructions, to counteract the uncertainty on the simulation process that is not considered by the deterministic model. They found out for their scenario that applying 50% of the instructions gave greater benefits.

3 METHODOLOGY

In this section is shown the new definition for the interaction between simulation and optimization in the search for a more practical and efficient application. Also are described the main modifications incorporated to the optimization model of Delgado et al. (2012) and its new mathematical formulation.

3.1 Simulation – Optimization interaction

The way that simulation communicates with the optimization solver was redefined. As mentioned, in Delgado et al. (2012) the event that triggered the optimization was the arrival of a bus to a bus stop. The proposed scheme activates the optimization every fix interval of time, defined by the user and is considered to be in the order of minutes. To illustrate this, the Figure 2 is resented. Another difference is that instructions for all the buses in the next stops are now sent to simulation.

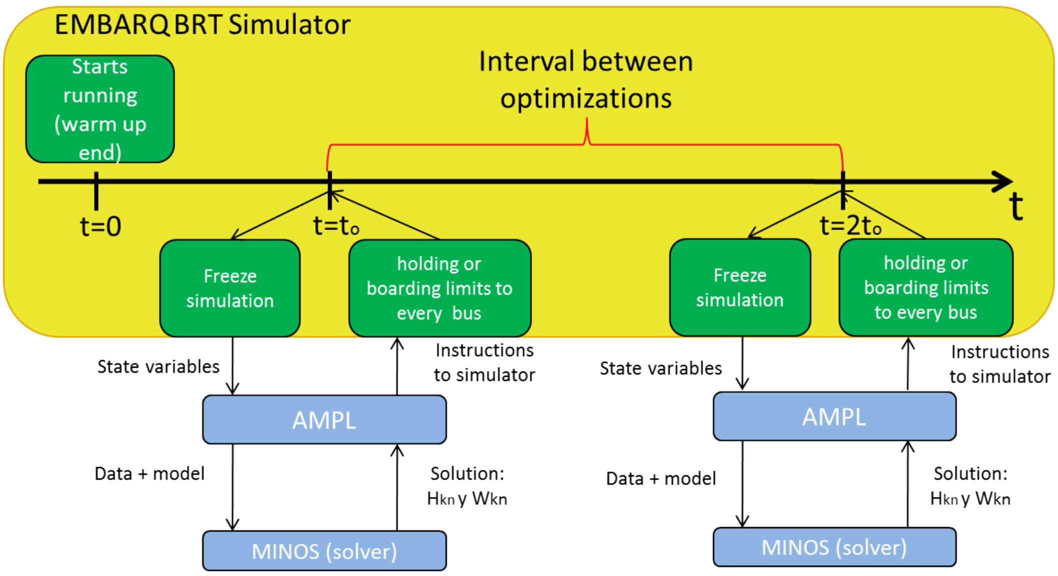


Figure 2 – proposed simulation-optimization interaction

This interaction is considered to be more effective and realistic in comparison to the used at Delgado et al. (2012); among the advantages are the following:

- It is closer to a real application, allowing a mayor feasibility to implementation
- Allows to have more time to the execution of the optimization and the delivery and application of the control instructions
- There is a much lower optimization instances involving a less amount of data transfer on real time
- The system keeps a record of instructions, which is very useful in case of communication failures during the next optimization

3.2 Modifications to Delgado et al. (2012) optimization model

Three types of modifications were made to the model: (i) input and output data, (ii) post optimization heuristics and (iii) planning horizon. (i) and (ii) has the purpose of adapting it to the new interaction with simulation, (iii) was included to allow the resolution of bigger problems. At the end of this section the adapted mathematical model is presented.

3.2.1 Input and output data

The new features in simulation due to EMBARQ BRT Simulator involved the redefinition of some parameters of the model. These are the part of the input data regarding to distance between bus stops, speed of buses in the links between bus stops and passenger alighting and boarding time. The outputs generated by the solver had to be modified too. Now three matrices are written containing the instruction for each bus in all the bus stops included in their rolling horizon. In terms of boarding limits, the instruction of amount of passenger to be left behind was changed to the maximum amount of passengers to be allowed to board. This is considered a more practical way to receive that control instruction.

3.2.2 Post optimization heuristics

It was considered necessary to modify the output from the optimization, before send it as instructions to simulation. This in order to face the new interaction or a limitation in the bus stops where control could be applied.

a) Reduction of holding times

This heuristic attempts to guarantee that all the buses will be released to receive instructions when the next optimization occurs. In other words, if the instructions for a bus include a holding that would mean that for the next optimization the bus will still be held, that holding is reduced enough to guarantee it will be released before the new optimization is done. This is all based on the estimations made by the model.

b) Holding gathering in specific bus stops

This heuristic is developed to face the real limitation where holding could be applied only in some bus stops. It consists in the grouping of all the holdings indicated for each bus in the closest bus stop that is allowed to do holding within the planning horizon. This heuristic is only applied in the scenarios were the restriction wants to be evaluated and works along the heuristic for reducing holdings.

3.2.3 Planning horizon (Ph)

Along the increase in size of the problem (i.e. more buses and more bus stops), the model started to show difficulties in solving it due to the increase in the number of active

restrictions. Besides taking longer, the results were not good. To counteract this, it was defined to reduce the rolling horizon defined by Delgado et al (2012) as the whole number of bus stops, to a partial amount. This was called the planning horizon and is defined as the number of bus stops considered in optimization for each bus, starting in the one ahead. It is a fixed number for all the buses and can be modified as a user choice.
This change reduced considerably the execution times of the solver and to enable it achieving good solutions. To adapt the model, the limits of the objective function and the restriction of the mathematical model of Delgado et al (2012) had to be reformulated.

3.2.4 Mathematical formulation

The model adapted to all the modifications described above is presented as follows. First the state variables, parameters, indexes and decision variable are shown. Then the objective function and the restrictions are presented, where the main modifications were made. For more detail regarding the meaning of the terms explained in this subsection refer to Delgado et al. (2012).

a) State variables

d_k:Distance between the bus k and the last visited stop, in meters.
e_k: stop immediately upstream from bus k
$\bar{m}_{ki}$: number of passenger on board of bus k whom boarded at stop i.
c_n: number of passengers waiting at the stop n

b) Indexes and parameters

k: index for buses, *k=1,…K*
n: index for bus stops, *n=1, …, N+1*
t_0: current time
θ_i:weight factor included in the objective function, *i=1,2,3,4*
cap_k: capacity, in passengers, of bus *k*.
λ_n: arrival rate of passengers to stop *n*, in passengers per minute
t_b: passenger boarding time, in minutes per passenger
t_a: passenger alighting time, in minutes per passenger
r_n: distance between the stop n and the one before (*n* and *n-1)*, in meters
v_n: average speed of buses between stops *n and n-1*, in meters per minute
p_{kij}: proportion of passengers that board the bus *k* in stop *I* and travel to stop *j*.

As a result of the dynamic of the system, the following are estimated:
mt_{kn}: total number of passenger that travel on bus *k* before arriving to stop *n*.
m_{kin}: number of passengers that board at stop *i* and are on board bus *k before arriving to stop n*. (*i* < *n*). Notice that: $m_{ki(e_k+1)} = \bar{m}_{ki}$
s_{kn}: capacidad disponible en el bus *k* antes de llegar a la parada *n*, en pasajeros.
td_{kn}: departure time of bus *k* from stop *n*, in minutes.
a_{kn}: number of passengers that alight from bus *k* at stop *n*.

dp_{kn}: potential demand of passengers that want to board bus *k* at stop *n*.
b_{kn}^{0}: number of passengers that board bus *k* at stop *n*. $(n = e_k + 1, \dots, N)$
b_{kn}: number of passengers that board bus *k* at stop *n*. $(n = 1, \dots, e_k)$
f_{kn}: dwell time of bus *k* at stop *n*, in minutes.

c) Decision variables

There are two groups of decision variables:
h_{kn}: holding time of bus k at stop n, in minutes, $\forall$ k, n
$\mathrm{w_{kn}}$: number of passengers to be prevented from boarding bus *k* at stop n

d) Objective function

In the equation (1) are showed the terms of the objective function, these are exactly the same as proposed in Delgado et al. (2012).

$$OF = Min_{\{h_{kn}, w_{kn}\}} \frac{\theta_1 \cdot W_{first} + \theta_2 \cdot W_{in-veh} + \theta_3 \cdot W_{extra} + \theta_4 \cdot PE}{PAX} \qquad (1)$$

The change required is inside of each one of the terms, where the limits for the summations are modified in order to sum only within the planning horizon as shown below.

i) Waiting time experienced by passenger until the arrival of the first bus (W_{first})

The two expressions that compound this term are:

$$W_{first\_1} = \sum_{k=1}^{K} \sum_{n=e_k+1}^{Min\{e_{(k-1)}; e_k+P_h\}} \left\{ \frac{\lambda_n}{2} \cdot (td_{kn} - t_0)^2 + c_n \cdot (td_{kn} - t_0) \right\} \qquad (2)$$

$$W_{first\_2} = \sum_{k \in E} \sum_{n=e_{(k-1)}+1}^{e_k+P_h} \left\{ \frac{\lambda_n}{2} \cdot \left(td_{kn} - td_{(k-1)n}\right)^2 \right\} + \sum_{k \in E_a} \sum_{e_K+1}^{e_1+P_h} \left\{ \frac{\lambda_n}{2} \cdot (td_{1n} - td_{Kn})^2 \right\} \qquad (3)$$

Where:
Ph: Number of bus stops considered in optimization
$E: \forall\, k \neq 1 \,/\, e_{(k-1)} - e_k < P_h$
$E_a: k = 1 \,/\, e_K - e_1 < P_h$
E is the set of buses for which the bus in front of them is closer than Ph bus stops. Ea would be the bus 1 is between it and the last one there are less than Ph bus stops. The expression *Min* in the equation (2) indicates that the sum goes until the closest bus stop between the visited by the bus in front and the end of the planning horizon.

The expressions (2) and (3) are added to form W_{first}:

$$W_{first} = W_{first\_1} + W_{first\_2} \qquad (2)$$

ii) Waiting time experienced by passengers inside the bus k while it is held (W_{in-veh})

$$W_{in-veh} = \sum_{k=1}^{K} \sum_{n=e_k+2\,/n\neq 1}^{e_k+P_h+1} mt_{kn} \cdot h_{k(n-1)} + \sum_{k\,\in\,F} mt_{k1} \cdot h_{kN} \qquad (5)$$

Where:

$F: \forall\, k\,/\,n = 1 \in \{(e_k+1), ..(e_k + P_h + 1)\}$

F represents the group of buses that have stop 1 in their planning horizon.

iii) Extra waiting time experienced by passenger that could not board the first bus due to capacity or boarding limits

$$W_{extra} = \sum_{k\in E} \sum_{n=e_{(k-1)}+1}^{e_k+P_h} w_{(k-1)n} \cdot \left(td_{kn} - td_{(k-1)n}\right) + \sum_{k\,\in\,E_a} \sum_{e_K+1}^{e_1+P_h} w_{Kn} \cdot (td_{1n} - td_{Kn}) \qquad (6)$$

iv) Penalty to regulate the application of boarding limits

$$PE = \sum_{k=1}^{K} \sum_{n=e_k+2\,/n\neq 1}^{e_k+P_h+1} w_{k(n-1)} \cdot s_{kn} + \sum_{k\in F}^{K} w_{kN} \cdot s_{k1} \qquad (7)$$

v) Number of passengers involved in the sum of waiting times

$$PAX = \sum_{k=1}^{K} \sum_{n=e_k+1}^{Min\{e_{(k-1)};e_k+P_h\}} \{\lambda_n \cdot (td_{kn} - t_0) + c_n\} + \sum_{k\in E} \sum_{n=e_{(k-1)}+1}^{e_k+P_h} \{\lambda_n \cdot \left(td_{kn} - td_{(k-1)n}\right)\} + \sum_{k\,\in\,E_a} \sum_{e_K+1}^{e_1+P_h} \{\lambda_n \cdot (td_{1n} - td_{Kn})\} \qquad (8)$$

e) Restrictions

For the restrictions, the limits are modified to make them apply only within the planning horizon plus one stop.

$$td_{kn} = t_0 + \frac{r_n - d_k}{v_n} + f_{kn} + h_{kn} \qquad \forall\, k; n = e_k + 1 \qquad (9)$$

$$td_{kn} = td_{k(n-1)} + \frac{r_n}{v_n} + f_{kn} + h_{kn} \qquad \forall\, k; n = e_k + 2, \dots, e_k + P_h + 1\,/\,n \neq 1 \qquad (10)$$

$$td_{k1} = td_{kN} + \frac{r_1}{v_1} + f_{k1} + h_{k1} \qquad \forall\, k \in F/\, e_k + 1 \neq 1 \qquad (11)$$

Restriction (9) to (11) include in addition the change regarding the speed (v_n) and distance between stops (r_n).

$$m_{ki(e_k+1)} = \overline{m}_{ki} \qquad \forall\ k; i = 1,2,\dots,e_k \tag{12}$$

$$m_{kin} = b_{ki}^0 \cdot \left(1 - \sum_{j=i+1}^{n-1} p_{kij}\right) \qquad \forall k; n = e_k + 2,\dots, Min\,\{e_k + P_h + 1; N\};$$
$$i = 1,2,\dots,n-2 \tag{13}$$

The expression *Min* of restriction indicates that it will only apply from the subsequent stop of each bus until the closest between the end of the planning horizon plus one and the end of the corridor (stop N).

$$m_{ki1} = b_{ki}^0 \cdot \left(1 - \sum_{j=i+1}^{N} p_{kij}\right) \qquad \forall k \in F;\ i = 1,2,\dots,N \tag{14}$$

$$m_{kin} = b_{ki} \cdot \left(1 - \sum_{j=i+1}^{n-1} p_{kij}\right) \qquad \forall k\ /\ N - e_k < P_h;\ n = 2,\dots,e_k + P_h + 1;$$
$$i = 1,2,\dots,n-2 \tag{15}$$

Restriction (15) is valid only for those buses that are closer that Ph stops from the end of the corridor (stop N).

$$m_{k(n-1)n} = b_{k(n-1)} \qquad \forall k\ /\ N - e_k < P_h; n = 2,\dots,e_k + P_h + 1 \tag{16}$$

$$m_{k(n-1)n} = b_{k(n-1)}^0 \qquad \forall\ k; n = e_k + 2,\dots, Min\,\{e_k + P_h + 1; N\} \tag{17}$$

$$mt_{kn} = \sum_{i=1}^{n-1} m_{kin} \qquad \forall\ k; n = e_k + 1,\dots,e_k + P_h + 1/\ n \neq 1 \tag{18}$$

$$mt_{k1} = \sum_{i=1}^{N} m_{ki1} \qquad \forall\ k \in F \tag{19}$$

$$s_{kn} = cap_k - mt_{kn} \qquad \forall\ k; n = e_k + 1,\dots,e_k + P_h + 1 \tag{20}$$

$$dp_{kn} = c_n + \lambda_n \cdot (td_{kn} - t_0) \quad k;\ n = e_k + 1,\dots, Min\,\{e_{(k-1)}; e_k + P_h + 1\} \tag{21}$$

$$dp_{kn} = w_{(k-1)n} + \lambda_n \cdot \left(td_{kn} - td_{(k-1)n}\right) \quad \forall\ k \in E;$$
$$n = e_{(k-1)} + 1,\dots,e_k + P_h + 1 \tag{22}$$

$$dp_{kn} = w_{Kn} + \lambda_n \cdot (td_{kn} - td_{Kn}) \qquad \forall\ k \in E_a;\ n = e_K + 1,\dots,e_1 + P_h + 1 \tag{23}$$

$$a_{kn} = \sum_{i=1}^{n-1} b_{ki}^0 \cdot p_{kin} \qquad \forall\ k;\ n = e_k + 1,\dots, Min\,\{e_k + P_h + 1; N\} \tag{24}$$

$$a_{kn} = \sum_{i=1}^{n-1} b_{ki} \cdot p_{kin} \qquad \forall\ k/\ \ N - e_k < Pc;\ n = 2,\dots,e_k + P_h + 1 \tag{25}$$

$$a_{k1} = \sum_{i=1}^{n-1} b_{ki}^0 \cdot p_{ki(N+1)} \qquad \forall\ k \in F \tag{26}$$

$$w_{kn} \geq dp_{kn} - s_{kn} - a_{kn} \qquad \forall\ k, n = e_k + 1,\dots,e_k + P_h + 1 \tag{27}$$

$$w_{kn} \geq 0 \qquad \forall\ k, n \tag{28}$$

$$b_{kn}^0 = dp_{kn} - w_{kn} \qquad \forall\ k;\ n = e_k + 1,\dots, Min\,\{e_k + P_h + 1; N\} \tag{29}$$

$$b_{kn} = dp_{kn} - w_{kn} \qquad \forall\ k/\ \ N - e_k < Pc;\ n = 2,\dots,e_k + P_h + 1 \tag{30}$$

$$b_{k1} = dp_{k1} - w_{k1} \qquad \forall\ k \in F \tag{31}$$

$$f_{kn} = b_{kn}^0 \cdot t_b + a_{kn} \cdot t_a + fix \quad \forall\ k;\ n = e_k + 1,\dots, Min\,\{e_k + P_h + 1; N\} \tag{32}$$

$$f_{kn} = b_{kn} \cdot t_b + a_{kn} \cdot t_a + fix \quad \forall\ k/\ \ N - e_k < Pc;\ n = 2,\dots,e_k + P_h + 1 \tag{33}$$

$$f_{k1} = b_{k1} \cdot t_b + a_{k1} \cdot t_a + fix \qquad \forall\ k \in F \tag{34}$$

Due to modification in passenger transfer, some terms of restrictions (32) to (34) were changed. The specific parameters included in Delgado et al. (2012) were removed and a fix time relative to the stop was added.

$$td_{kn} - td_{(k-1)n} \geq 0 \qquad \forall\, k \in E;\; n = e_{(k-1)} + 1, \dots, e_k + P_h \tag{35}$$

$$td_{kn} - td_{Kn} \geq 0 \qquad \forall k \in E_a \;\; n = e_K + 1, \dots, e_1 + P_h \tag{36}$$

$$td_{(k-1)n} - td_{kn} \geq 0 \qquad \forall\, k \neq 1 \,/\, \{e_{(k-1)} + 1, \dots, e_{(k-1)} + P_h\} \cap \{e_k + 1, \dots, e_k + P_h\} \neq \emptyset; \quad n = e_k + 1, \dots, Min\,\{e_{(k-1)}; e_k + P_h\} \tag{37}$$

$$td_{Kn} - td_{kn} \geq 0 \qquad \forall\, k = 1/\{e_K + 1, \dots, e_K + P_h\} \cap \{e_1 + 1, \dots, e_1 + P_h\} \neq \emptyset; \quad n = e_1 + 1, \dots, Min\,\{e_K; e_1 + P_h\} \tag{38}$$

Restriction (37) and (38) apply just in the case where the planning horizon of a bus reaches the planning horizon of the preceding bus.

4 SIMULATION OF INSURGENTES BRT CORRIDOR (MEXICO)

In order to successfully apply the control strategies in simulation, adaptations were made to EMBARQ BRT simulator to enable its interaction with optimization. The main addition was to set a communication channel were an input file was generated from simulator containing the state variables of the actual situation. It is then sent to AMPL where the optimization model is programmed and by using MINOS the problem is solved. Finally, instructions from AMPL are received by simulator and implemented on simulation. Besides, changes on the interface were made, creating the *Headway Control System* dialog where user is able to define the parameters for control strategies. In addition, new generation of outputs was included to allow the data collection for simulation results analysis. The description of the simulation´s components, input data, and scenarios evaluated and the results are described in the following subsections.

4.1 Simulation environment

The Insurgentes BRT Corridor from Mexico City was selected for simulation, using real data of 2007. The corridor length is 19.7km per direction; it goes along the Insurgentes Avenue through a segregated single lane and intersects with 57 traffic lights. The service represented is the line 1 of Metrobus system and has 34 stations and 1 terminal at each end. The representation on EMBARQ BRT Simulator is shown in Figure 3, where the two terminals are highlighted. In addition, green arrows are added to the image to show how this corridor will work as the scheme showed in Figure 1. Therefore the problem will be modeled as a 72 bus stops (each station and terminal has two platforms, one per direction) service, where terminal I. Verdes would include bus stops 1 and 72.

The demand of passengers used was based on data obtained from an Origen-Destination survey performed in April of 2007 for Metrobus. The morning peak was simulated, from 6:30am to 8:30am, OD matrices were defined for each 30 minutes period. The peak direction is from I. Verdes to Dr. Galvez, toward downtown, the distribution of this demand is presented in Figure 4 where station 1 corresponds to I. Verdes and 36 to Dr. Galvez. All the data from the corridor was given by EMBARQ Brazil, it was used in a previous study accomplished by them.

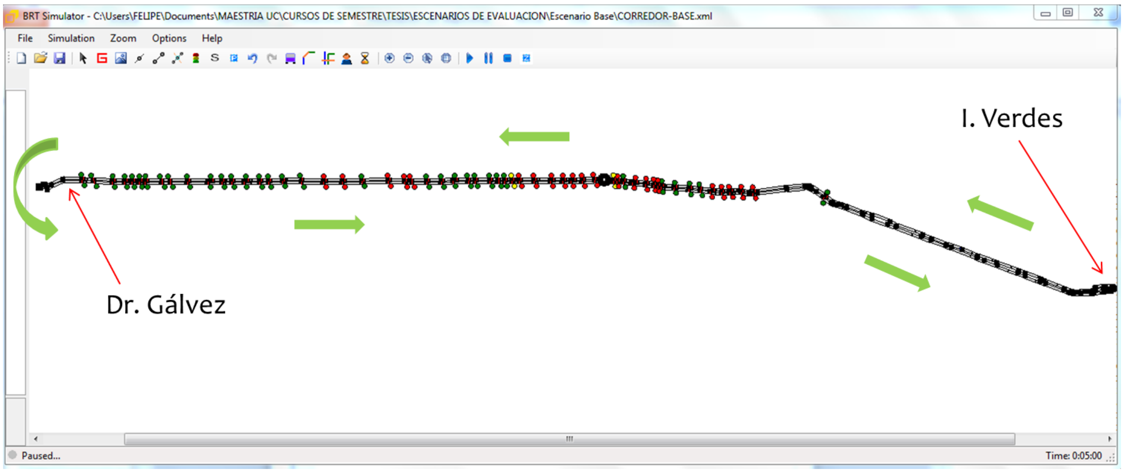


Figure 3 – Representation of Insurgentes BRT corridor on EMBARQ BRT simulator

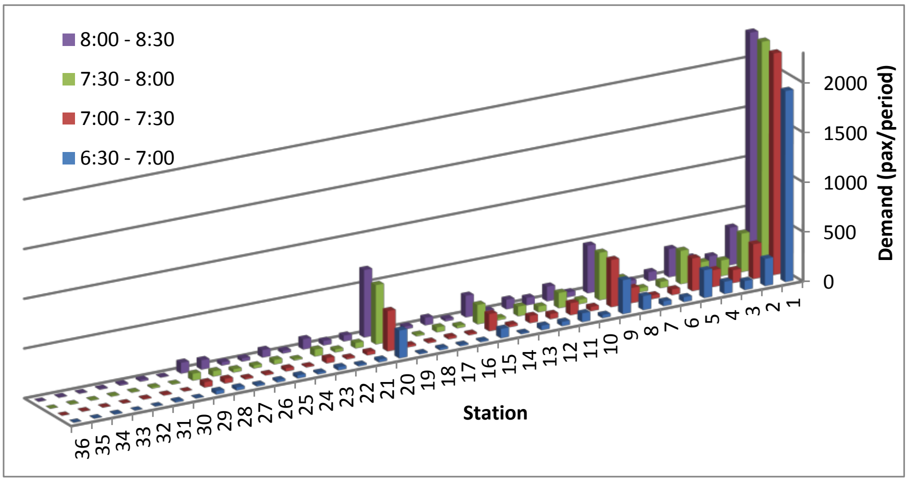


Figure 4 – Arrival rate of passengers to stations per period, direction I. Verdes to Dr. Galvez

The operating fleet of Insurgentes consists on articulated buses with capacity for 140 passengers. To guarantee a minimal frequency capable to transport all the passengers, a fleet of 80 buses was required for simulation, defining an average headway close to 1 minute. The simulation consisted in a period where the buses where located along the corridor, with no demand. Then a warm-up demand was applied for 10 minutes, corresponding to the period before the peak hour. Finally two hours with peak demand were simulated. 30 replications were made for each of the scenarios evaluated to guarantee a confidence interval of 95% and a relative error lower than 10%.

4.2 Scenarios

4.2.1 Comparison scenarios

To compare the control strategies, three scenarios for comparison were defined:

a) Base: case with no control, it is only regulated the dispatch at the two terminals using threshold-base control
b) Threshold simple: in addition to the Base scenario, it considers threshold-base control in two intermediate stations.
c) Threshold: case with threshold-base control in all stations.

4.2.2 Control strategies scenarios

The objective of these scenarios is to analyse the effect of setting different values for the optimization parameters, in the search for the best strategy for this case study. Based on results and definition in Delgado et al. (2012) values for some of the parameters have been fixed, in order to reduce the feasible space. These are shown in Table 1 and refer to weights for the objective function and reduction levels for holding (β) and boarding limits ($\propto$).

Table 1 – Values fixed for optimization parameters

Parameter	Value
θ_1	1
θ_2	0.5
θ_3	2
θ_4	0 ó 9000 (*)
$\propto$	0.5
β	0.5

(*) 0 to allow *boarding limits*, 9000 to avoid it

The strategies considered in the control scenarios consider several combination of: (i) stops were holding will be applied (all or just a few of bus stops) and the possibility to apply boarding limits in a continuum way or "all or nothing" (where no passenger is allowed to board); (ii) interval of time between optimizations; and (iii) planning horizon. These combinations are shown in Figure 5.

On the strategies axe, 4 possibilities are evaluated: i) only holding in 8 stops where is allowed to control (h8), ii) only holding in all bus stops (h), iii) holding and boarding limits in the "all or nothing" version (tn), and iv) holding and boarding limits (hb). On the vertical axe are the amount of stops included in the planning horizon which has influence on the resolution time and the quality of results. Larger than 12 could not be used since the problem turned too big for solver and the solutions were not reliable. Finally, there is the axe for the interval between optimization which affects the feasibility of implementing the model in terms of frequency and amount of information transfer. 2, 4 and 8 minutes where chosen as reasonable times for real application.

The nomenclature used for the name of scenarios from now on is Strategy-Interval-Ph.

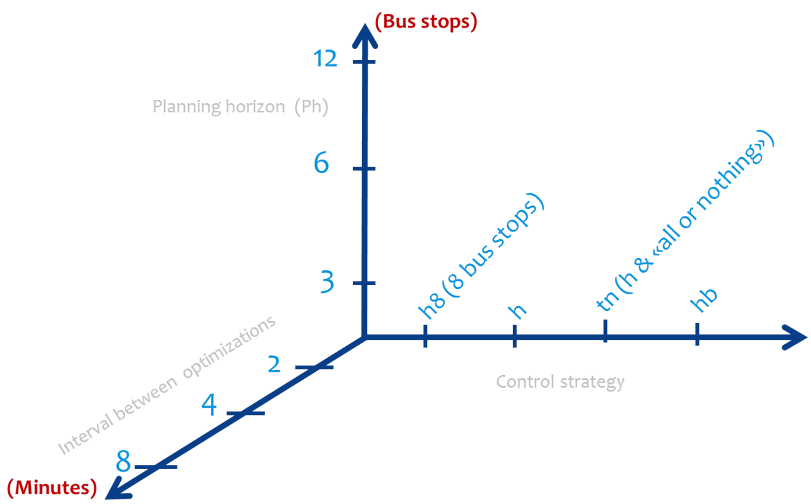


Figure 5- Control strategies movement axes.

4.2.3 Performance indicators

The evaluation of scenarios would be based on: (i) Average waiting time for the first bus per passenger (W_{first}); (ii) coefficient of variation of W_{first} (Cv); (iii) Average extra waiting time per passenger (W_{extra}), time from the passing of the first bus (and not boarded) until the passing of the one boarded; (iv) Average time until boarding a bus (T_a), is the sum of W_{first} and W_{extra}; (v) Average holding time experimented by passengers on board bus along their trip (Win-veh); (vi)Average total perceived waiting time per passenger (Wtotal), is the sum of Wfirst, Wextra and Win-veh, weighted by the factors θ_i used in the objective function; (vii) Cycle time (Tc); (viii) bus trajectories; (ix) bus load; and (x) solving times.

4.3 Results analysis

4.3.1 Best control strategies scenarios

In terms of waiting times for users, the best control strategies were h-2-12, tn-2-12 and hb-2-12. In the Figure 6 are showed the W_{first} and its coefficient of variation (Cv), W_{extra} and $W_{in\text{-}veh}$ for best control scenarios and comparison scenarios, showing the mean value, the confidence interval and the variation in comparison to Base.

Regarding W_{first}, it is observed how all the strategies show better results than comparison cases, reducing more than 40% compared to Base. Best result is accomplished by h-2-12, reducing 43%. In terms of Cv, the three strategies succeed in reducing it, showing that besides reducing the mean value the variability is diminished. These results demonstrate an impact on regularity of headways, effect that the threshold was not capable to do.

The W_{extra} is mainly reduced by h-2-12; tn-2-12 shows values greater than all cases, it could be a result of the extreme measure of letting passengers behind. The hb-2-12, despite boarding limits do not show to be worse than Base. $W_{in\text{-}veh}$, representing the time of holding either by optimization instructions or threshold-base control, shows how the Threshold scenario presents excessive control with no good results. On the other hand the base case has the lowest values demonstrating its no-control strategy. Under the three control strategies, a passenger in average does not suffers more than 24 seconds of holding, time that is distributed in several holdings along the trip.

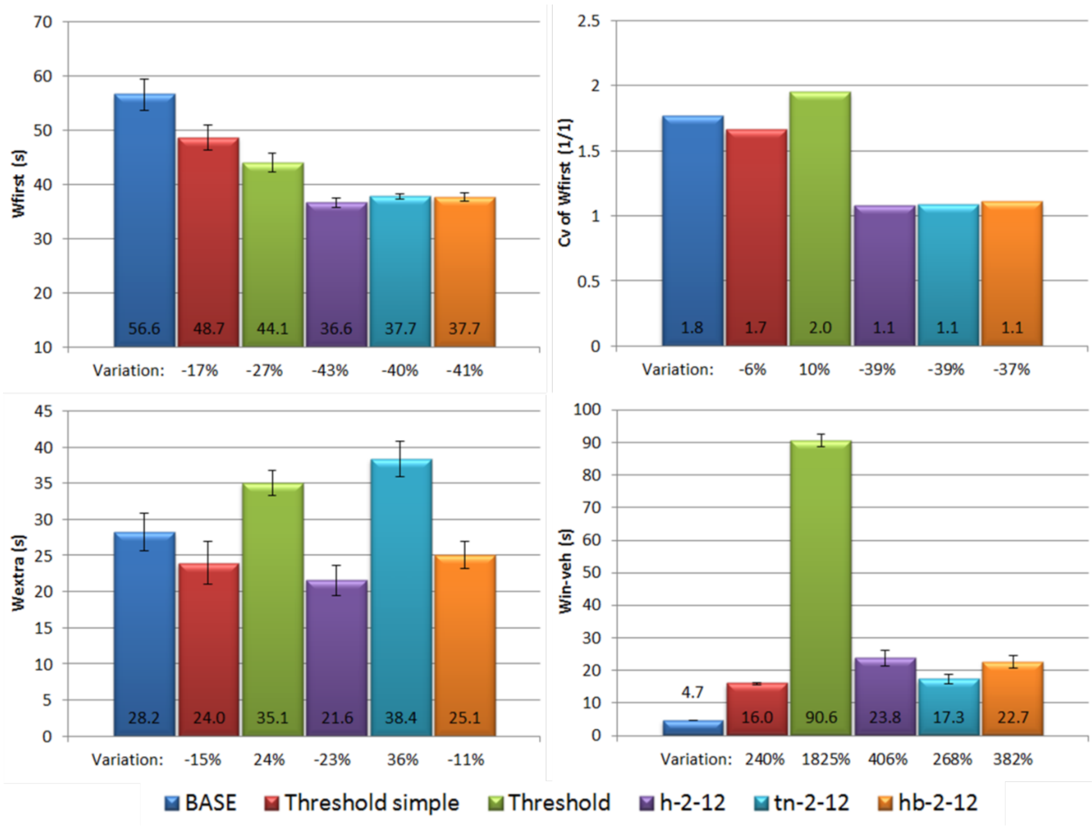


Figure 6- W_{first}, Cv, W_{extra} and $W_{in\text{-}veh}$ for best control scenarios and comparison scenarios

To observe the trade-off of waiting times, in Figure 7 is showed the total waiting time perceived by user (W_{total}), where each of three components is multiplied by the relative weight used in the objective function for optimization (see Table 1). H-2-12 and hb-2-12 despite incrementing holding time achieve to reduce the W_{total} in 21% and 14%, respectively, in comparison to Base. This is fullfiled due to the big reduction on waiting time on stops (W_{first} and W_{extra}). Times that in terms of subjective value, have demonstrated to be up to 3 times more costly for passengers than the waiting time on vehicle (Gaudry, Jara-Díaz & Ortúzar, 1989; Jara-díaz & Ortúzar, 1989). Therefore, their reduction generates greater benefits regarding costs for users than the increasing on $W_{in\text{-}veh}$.

In the figure, the trade-off among waiting times is observed. The proposed strategies reduce considerably the times on bus stops, the most costly. Also, the effect of the addition to waiting due to holding times is reduced as it is a less valued time, achieving a reduction of up to 21% on perceived total waiting time.

Based on the last results, h-2-12 is considered as the best control strategy for this study case. To show in more the detail its benefits, results regarding the other performance indexes for h-2-12 are presented in the following.

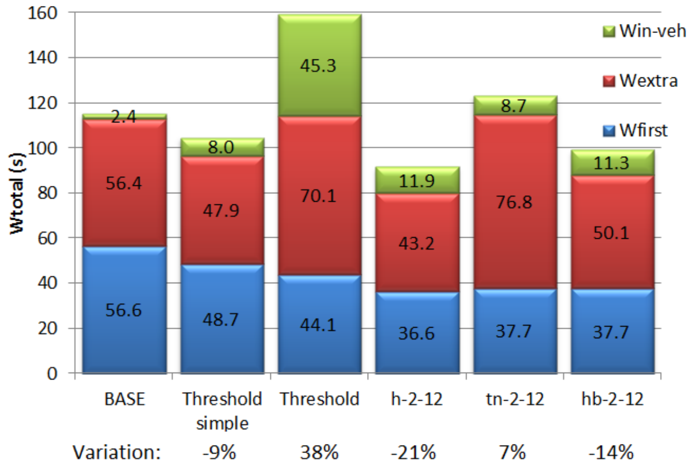
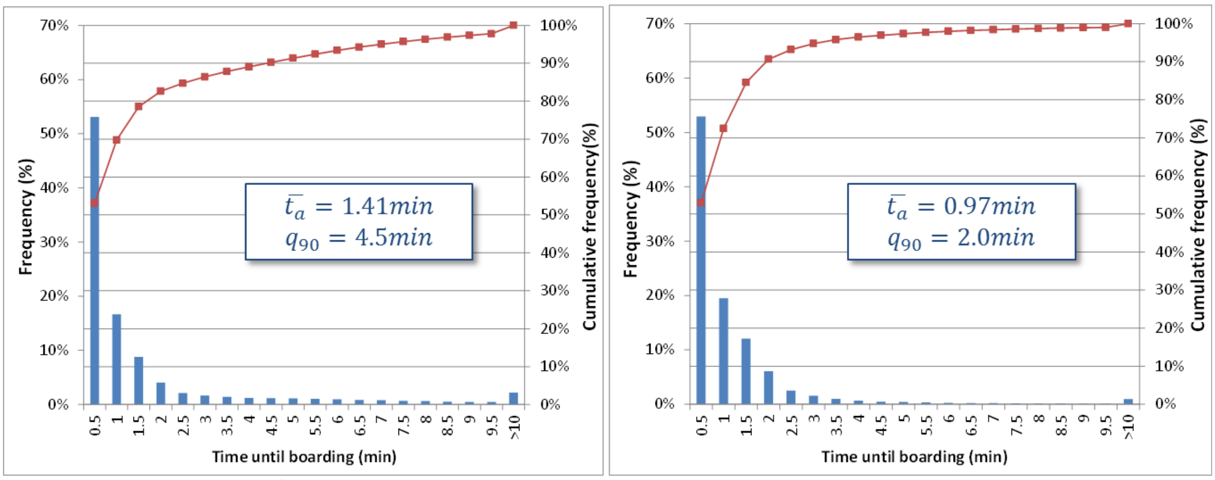


Figure 7- W_{total} for best control scenarios and comparison scenarios

Histograms for time until boarding of all passengers are presented in Figure 8. In blue bars the frequency is shown, the dot red line is the cumulative frequency, for ranges of 0.5 minutes in Ta. In addition the average ($\overline{t_a}$) and the quantile 90 (q_{90}) are shown.

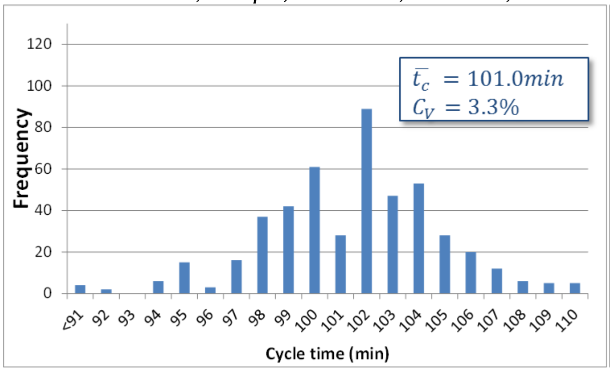


a) Base b) h-2-12

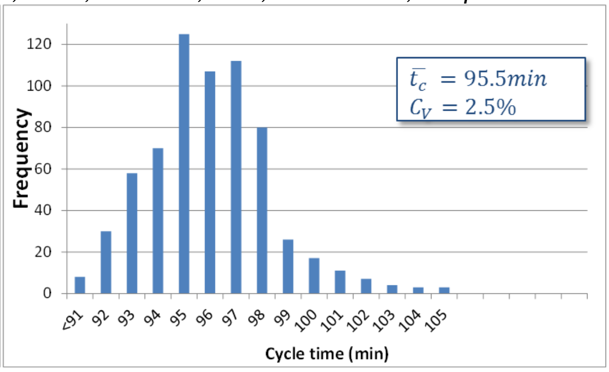
Figure 8- Histogram for time until boarding (Ta)

Comparing to Base, the control strategy considerably reduce the dispersion of data, where values greater than 6 minutes are rarely observed. Due to demand structure, concentrated at the beginning of service, in all cases passenger that wait more than 10 minutes are present. Nevertheless control strategies managed to reduce them. In Base, the 90% of passengers waits up to 4.5 minutes; in h-2-12 only up to 2.0 minutes. The above is also reflected in the red dotted line which starts with higher slope.

In terms of cycle time, histograms are shown in Figure 9. Base shows a greater dispersion, having cycle time up to 110 minutes; h-2-12 has no values over 105 minutes and the values are more concentrated and to the left. In terms of means, h-2-12 reduces it in 5.5% indicating a feasible reduction of 4 of the 80 buses while keeping the same frequency (i.e. saving of 5% in fleet for operator).



a) Base



b) h-2-12

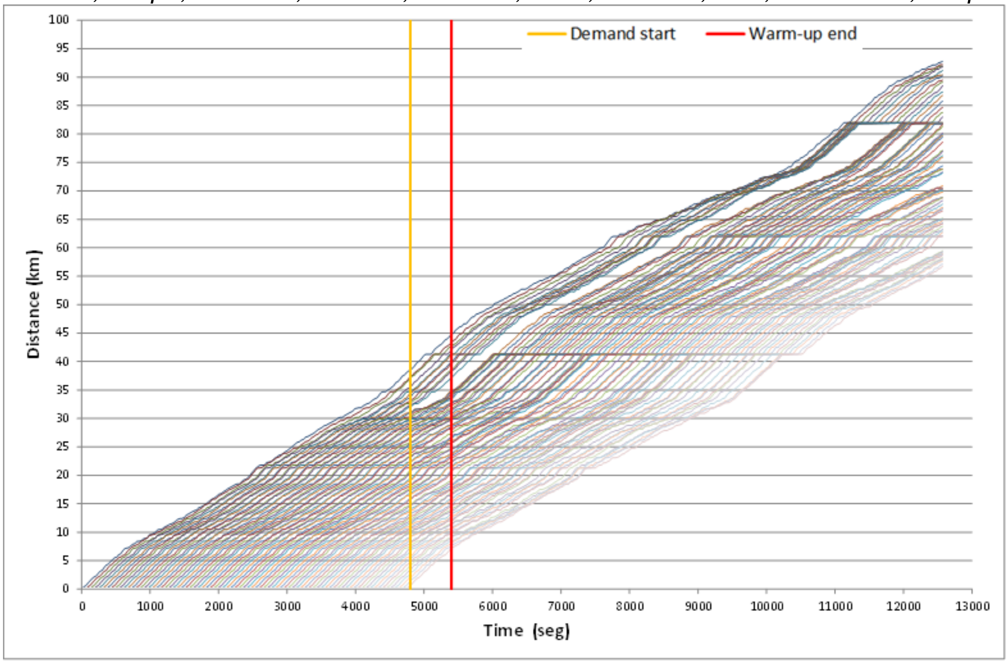
Figure 9- Histogram for cycle time (Tc)

Taking a representative replication, trajectories of buses are shown in Figure 10. The vertical axe represents the kilometers traveled by buses. In addition the instant where the location of buses ends and demand starts is highlighted with the yellow line; the red line represents the instant where appliance of control strategies begins. For Base, it is clearly observed how big headways between buses form and bus bunching is generated. To highlight, there is a critical case where a gap is formed since the beginning of demand and last until the end of simulation. A headway bigger than 10 minutes (near km 80) is the result at the end of simulation.

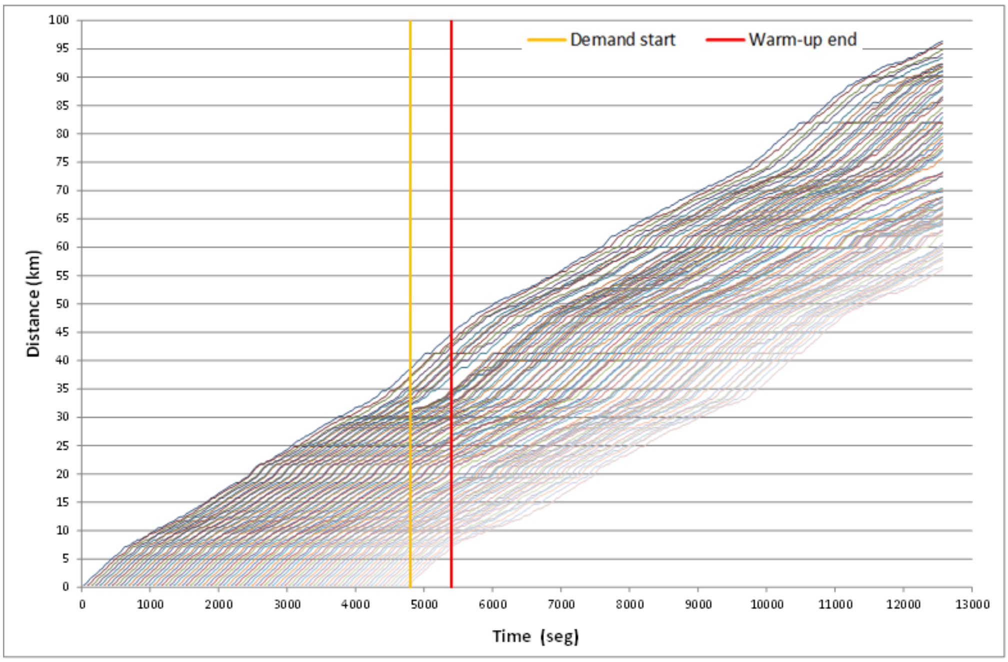
On the contrary, h-2-12 does not show big headways or bunches during simulation. As well, the critical case above mentioned is controlled in less than 20 minutes after control begins.

To evaluate comfort, bus load graphics for the same representative replication are shown in Figure 11. This represents the load of each bus when departing from each stop, since leaves terminal I. Verdes (IV_S, in the graphic) for the first time after warm-up ends. The difference in the demand at each direction is captured: buses in direction I. Verdes to Dr. Galvez (DG_N) are more loaded than in the other direction. In the Base, when leaving I. Verdes many buses reach capacity and do it for several stops, also buses reach capacity some stops later. In the opposite direction, a critical dispersion is observed.

Under h-2-12, buses begin more balanced, with fewer buses at capacity and after several stops it is never reached again. On the opposite direction, the dispersion is considerably reduced and no buses reach capacity.

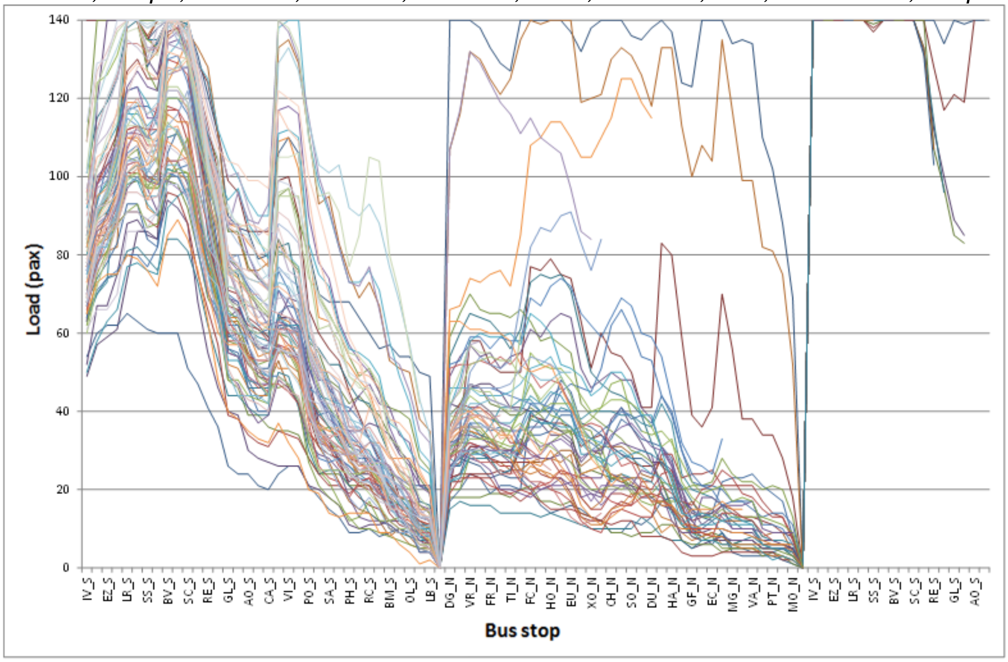


a) Base

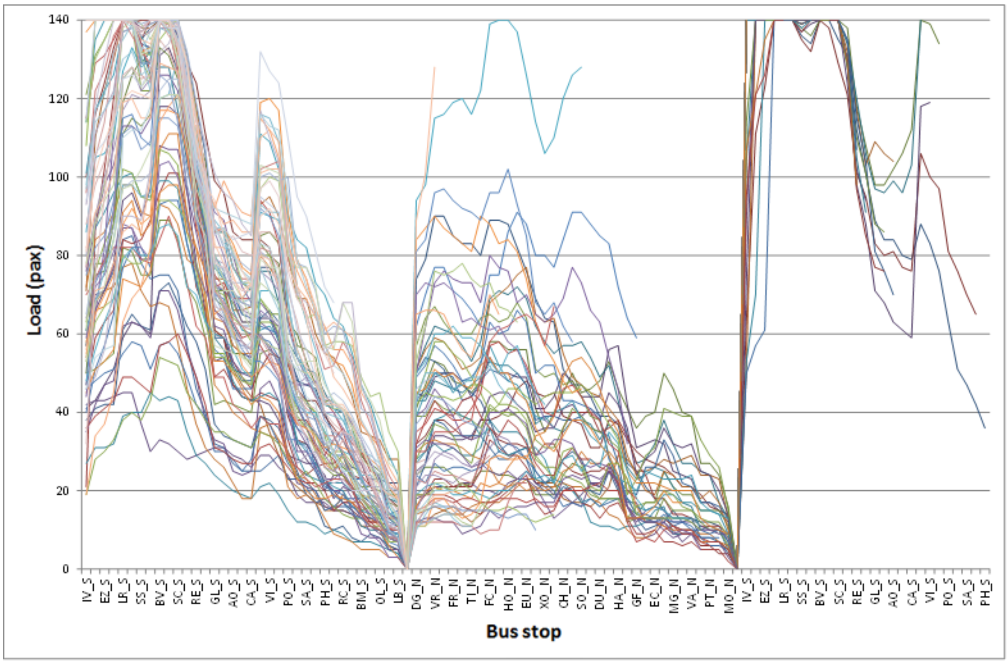


b) h-2-12

Figure 10- Trajectories for buses in a representative replication



a) Base



b) h-2-12

Figure 11- Load of buses in a representative replication

4.3.2 Effects of practical limitations

a) Holding control only allowed in some stops

Logistic or physic restriction could prevent from perform holding control on all stops. h8-2-12, within the plane showed in Figure 5, is a strategy where control is performed in 8 of the 72 bus stops (1/9 th. of stops). In addition, the holding gathering heuristic is applied.

Figure 12 is presented with W_{total}. The limited case, h8-2-12, still shows great benefits compared to the comparison scenarios. It achieves a reduction of 16% in respect to Base; only 5% less than its unrestricted version. In h8-2-12 it is observed how in presence of less control (i.e. lower $W_{in\text{-}veh}$), waiting time in vehicle is traded for waiting time at stops. Holding times are reduced, due to the lack of stops for applying it, but control is still present (e.g. Cv for W_{frist} stays in 1.1 as in h-2-12).

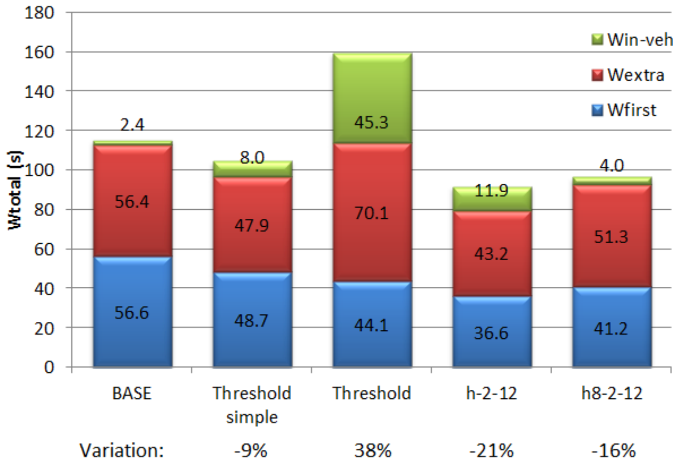


Figure 12 - W_{total} for h-2-12, h8-2-12 comparison scenarios

b) A minimum for interval between optimizations

In reality, a wide interval between optimization may be required to successfully transfer and process information. So far, results for strategies that optimize every 2 minutes have been presented. Now, for only holding, results of optimizing every 1, 2, 4 and 8 minutes are presented in Figure 13. Changing from optimizing every 2 minutes to 1 minute does not bring any benfit; on the contrary, it increases W_{extra}. Optimizing every 4 minutes does not generate a significant loss of benefits, keeping W_{frist} at low levels. Thus, 4 minutes could be a good interval. When optimizing every 8 minutes, the strategy loses its effectiveness. Although not shown, the Cv of W_{frist} for h-1-12, h-2-12 and h-4-12 maintained at 1.1, indicating that regularity is kept.

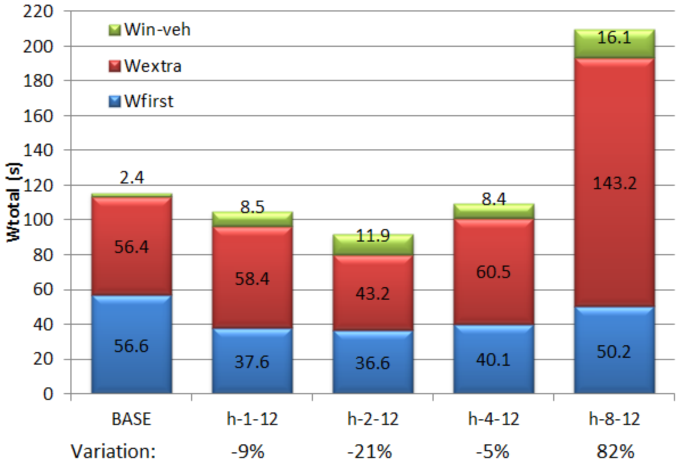


Figure 13 - W_{total} with components weighted and minimum waiting time removed for holding optimizing every 1, 2, 4 and 8 minutes and Ph=12.

c) Low solving times required

Since application of model must be on real-time, the solving times are expected to be low. Given a corridor, this time is determined by the size of the planning horizon (Ph). To study this effect, for holding every 2 minutes, scenarios with Ph=3, 6, 9 and 12 are compared. The Figure 14 presents the trade-off between benefits (W_{total}) and solving times (on personal computer with processor Intel Core i7 @2.2 Ghz), as function of Ph. The W_{total} is reduced as Ph is increased; solving time increases exponentially. Using Ph lower or equal to 6 does not bring good results as goods as Ph= 9 or 12, which have similar results. In practical terms, even with the highest Ph the solving times are still low, under 9 seconds, demonstrating feasibility of implementation.

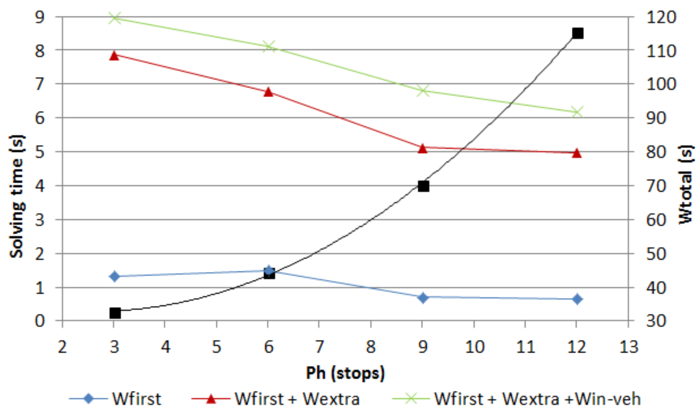


Figure 14- Effect of Ph in solving times

5 CONCLUSIONS

The corridor Insurgentes from Mexico City allowed the evaluation of the control strategies on a big size problem (80 buses, 72 stops) and real data. A new version of Delgado et al. (2012) with partial planning horizon and post optimization heuristics was developed, showing: (i) capability for solving problems with large amount of variables; (ii) reduced solving times; and (iii) practical scheme for application.

Several control strategies were evaluated, allowing to identify the effects of changing the different parameters. For the case study, the application of holding, optimizing every 2 minutes and considering a planning horizon of 12 stops showed the best results. Among the benefits: reduction of 21% on the perceived total waiting time for passenger, including a 43% reduction in the waiting for the first bus and 39% in its variability; reduction of 31% for time until boarding; and savings of 5% in fleet (i.e. 4 articulated buses) for operator as a product cycle time reduction. It is considered that due to the nature of demand, application of boarding limits did not bring extra benefits.

Under practical limitations the model performed good results. Controlling in a fraction of the stops (1/9) still brought great benefits for users, assuring regularity on headways. Interval for optimization of 2 or 4 minutes was required for good results, a reasonable time for data transfer. Also solving times were in all cases lower than 10 seconds, even though it was executed on a personal computer.

A as future work, due to the benefits showed and its feasibility, it is recommended to implement the control strategies in a real corridor. EMBARQ BRT Simulator could be used for the previous definition of the strategy that best fits the corridor of interest.

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