LIMITATIONS IN THE IMPLEMENTATION OF REAL-TIME INFORMATION CONTROL STRATEGIES PREVENTING BUS BUNCHING

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ABSTRACT

Control strategies that prevent bus bunching allow improving the level of service offered by a transit corridor, reducing travel time and its variability, thus providing to the user a higher reliability. Several optimization models based on the use of real-time information have shown to achieve this, through the planning of holding of the buses at bus stops. However, the benefits of these models have always been estimated assuming ideal operational conditions. This paper examines two phenomena that may occur during the operation of a bus service, which would limit the effectiveness of a holding based control strategy, in the sense that some of the planned holdings might not be executed. These phenomena are drivers' disobedience and the failure of communication systems with buses. The objective is to estimate the impact these phenomena can have on the benefits of the strategy, and to identify possible measures to reduce it. Both objectives are achieved using the HRT model developed by Delgado et al. (2012), which is tested in a simulation environment.

Keywords: holding control strategies, driver obedience, communication failure.

1. INTRODUCTION

One of the most important factors in the level of service offered by a bus service is its reliability. Regularity in bus headways minimizes the variability and magnitude of waiting time, thus improving reliability on the service. Regularity also improves passengers comfort inside the bus by allowing more balanced loads between buses (Delgado et al., 2012).

Regularity in bus headways is an unstable condition, in the sense that a small perturbation causes loosing this order, being the system unable to recover itself (Newell and Potts, 1964). Variability in both travel times and passenger arrival rates to bus stops causes disturbances in headways between buses, which as a positive feedback system, causes itself greater irregularity. If no action is taken, it is likely that headways irregularity increases causing bus bunching.

One of the control actions most commonly used is holding. Bus holding control strategies during the last years has been focused on the use of real time information, which has resulted in various models such as those developed by Daganzo (2009), Cortes et al. (2010), Daganzo and Pilachowski (2011), Bartholdi and Eisenstein (2012) and Delgado et al. (2012). This approach is due to the emergence of new technologies that enable real-time information at a centralized level. These models are divided into two types: control models and optimization models.

Control models seek to maintain headways between buses as regular as possible, with the least possible impact on the operating speed of the buses. In this group we found the works developed by Daganzo (2009), Daganzo and Pilachowski (2011) and Bartholdi and Eisentein (2012).

Optimization models, like the one presented in Delgado et al. (2012) and Cortés et al (2010), attempts to minimize waiting times for passengers through the use of heuristics or optimization tools, taking as decision variables the holdings that each bus should perform.

This paper focuses on the work developed by Delgado et al. (2012). In their work, the authors propose two control strategies based on real-time information: HRT (Holding with real Time Information) and HBLRT (Holding and Boarding Limits with real Time Information). These strategies allow taking decisions that keep regularity in headways, reducing user-waiting times. The HRT strategy determines how long to hold a bus every time it comes to a stop. By a selective holding of some buses, regularity is achieved. In the HBLRT a second control strategy is added to holding, consisting in limiting the number of passengers boarding a bus, whenever it comes to a stop. This measure allows increasing the speed of the buses.

These strategies were tested in four scenarios considering medium and high frequency (with 5 and 2 minute headways respectively), and a bus capacity constraint that could be active or not active. These strategies showed to be very successful, especially in the high frequency and active capacity constraint scenario. For the high frequency and active capacity constraint scenario, HRT and HBLRT had a reduction in extra waiting time of 56.95% and 61.17% respectively, compared to the No Control scenario.

The results obtained by Delgado et al. (2012) show that implementing control strategies for buses headways can significantly improve the quality of service of a bus corridor, as it drastically reduces the waiting time of the users, which is also the most valued by them. Besides, these strategies achieve more balanced load between buses, allowing users to travel more comfortable, and more importantly, reduces the number of users who cannot board the first bus that passes.

In Delgado et al. (2012), ideal conditions were assumed. That is, no phenomenon that may occur during the implementation and operation of such a strategy was considered. The purpose of this investigation is to study phenomena that could reduce the benefits of applying control strategies to a transit corridor. The studied phenomena are: *i)* driver's disobedience in following the desired strategy, and *ii)* communication failures with the buses.

2. OBJECTIVES

For each studied phenomenon, 3 objectives are set:

- Quantify the effect the phenomenon has on the benefits of applying the strategy, depending on the degree it presents.
- Determine whether there is a point in which the phenomenon presents in such degree that the strategy itself loses its purpose, or turns harmful to the system.
- Find measures that can mitigate the effect of this phenomenon.

2.1 Studied Phenomena

2.1.1 Driver disobedience

The objective in this case is to analyse what happens when a subset of the holding instructions sent to the drivers are not obeyed. The drivers are the final executors of the strategy, so the success of it depends on their level of collaboration. The fact that Chilean bus drivers are strongly unionized, and have a conflictive background of strikes suggests that scenarios where there is not a full collaboration with the control strategy deserve to be studied.

2.1.2 Communication System Failure

A second variable, in which the success of this strategy highly depends on, is the reliability of the communication system. Even though technology for a reliable communication system is available, the operational reality of public transport buses suggests that in some point the communication devices might not work as planned.

2.1.3 Working Environment

To accomplish these goals, the HRT model developed by Delgado et al. (2012) is used. This model uses real-time information of a bus corridor to determine whether a bus should hold in each stop, and for how long, in order to minimize the total time users devote to their trip. The HRT model was tested in a simulation environment using an event based and stochastic simulator, where an event is triggered every time a bus reaches a stop.

In this investigation, the simulation environment is modified to simulate the studied phenomena, in order to analyse changes in the behaviour and performance of the HRT model.

3. OPTIMIZATION MODEL (HRT) AND SIMULATION ENVIRONMENT

In this chapter, the HRT optimization model and the simulation environment are described in order to better understand the results of this work.

3.1 General Description

The system consists of a central controller that operates on a bus corridor, using real time information of the positions of the buses and the number of passengers in them and at stops. At each stop it is either known or estimated the current number of waiting passengers, the average arrival rate and proportions vector of destinies. Each bus has an operational speed and a passenger capacity. Also the position and number of passengers in the bus are considered as known.

Every time a bus arrives at a stop, an instruction is send to the bus indicating whether it should hold and for how long. To make this decision, a deterministic optimization problem is solved. The model, calculates the holding of all buses at all future bus stops in the prediction horizon, in order to minimize travel time for all passengers considered in this horizon. However, the control implements only the holding associated with the bus that triggered the optimization. Other decision variables are discarded, as they will be recalculated every time a bus arrives to a stop.

3.1.1 Relevant Assumptions

- No overtaking of buses or station skipping.
- Average arrival rate at stops and alighting proportions vector are considered known and constant.
- Each bus stops has a specific functional form for calculating dwell times depending on boarding, alighting's and if there is friction between both processes.

3.1.2 Objective Function

The objective of the optimization model is to minimize total travel time of all passengers considered in the prediction horizon. Given that travel time between stops is considered deterministic and constant in the model, the model attempt to minimize the sum of: *i)* Waiting time of passengers until the first bus arrives; *ii)* Extra time passengers must wait at a stop after not being able to board a bus because of capacity constraint and *iii*) Holding time experience by passengers while a bus is being held. Each of these elements is multiplied by a factor allowing the modeller to give different relative valuation of time.

3.1.3 Constraints

The restrictions of the optimization model are related with the prediction of the future evolution of the system. Through these relations the following system variables are calculated:

- Departure time from each bus to each stop
- Amount of passengers in each bus through each pair of stops
- Potential demands of passengers in each stop for each bus.
- Number of passengers going in and out each bus.
- Dwell time of passengers in each bus and each stop.

A complete description of the model and their constraint is presented in Delgado et al. (2012)

3.1.4 Simulation Environment

HRT control strategy was tested in an adaptation of the simulator developed by Sáez et al. (2012). This simulator is event based and stochastic, where each event is triggered by the arrival of a bus to a bus stop. Each time this happens, the state variables are updated and sent to the control system. The control system based in the HRT strategy optimizes the system, sending back the holding action of the bus that triggered the optimization.
Table 1 summarizes the main differences between what the optimization model predicts, and what is being simulated.

Table 1: Main Differences between HRT model and Simulation

	Optimization	**Simulation**
Bus travel times	Deterministic	Stochastic (log-normal)
Passenger demand	Deterministic	Stochastic (Poisson)
Overtaking	Not allowed	Allowed
Plan Horizon	One operational cycle	2 hours of operation.

4. BUS-HOLDING APPLICATION LIMITATIONS

This chapter explores the limitations that may affect the effectiveness of the application of holding control strategies. The phenomena studied are the disobedience of drivers and technological failures in communication systems between the central controller and buses. These phenomena result in a limitation in the implementation of the strategy in the sense that some of the planned holdings are finally not executed.

4.1 General Considerations

4.1.1 Phenomena Classification

The studied phenomena are classified depending on how the programmed but not executed holdings are distributed, as shown in table 2.

Table 2: Association between phenomena and studied cases.

Holding Distribution	Associated Phenomena	
	Bus driver disobedience	**Technological Failure**
Homogeneously between buses	Common level of disobedience between bus drivers	Signal Failure
Focused on certain buses	Certain bus drivers do never collaborate	Communication equipment failure
Focused on certain bus stops	-	Area without signal

4.1.2 Limitation Quantification

To quantify the effect of limitations in the benefits of applying the strategy, the timesavings kept by the strategy after applying the limitations will be used as indicator. This indicator is defined as follow:

$$\%\ Benefits(a) = \frac{T_{Total}(No\ Control) - T_{Total}(a)}{T_{Total}(No\ Control) - T_{Total}(HRT)}$$

In this equation, $\mathrm{T_{Total}}$ corresponds to the sum of the total waiting times of all passengers during the time that the strategy is being applied, under scenario '*a*'. As previously explained, each simulation corresponds to 120-minute operational period with a 15 minutes warm-up period, during which no strategy is applied.

4.1.3 Holding in Terminal Stop

Stop number 1 is considered terminal stop. In this stop, holdings are considered independent from limitations, so no limitations will be applied to holdings in this stop.

A combined strategy is proposed between No Control and HRT, in which HRT is applied along the corridor and threshold is applied in the terminal stop. This strategy should have better results than No Control by itself for every percentage of executed holdings. Table 3 summarizes holdings done in terminal stop and along the corridor for each strategy.

Table 3: Holdings in terminal stop and along corridor according to each strategy

Strategy	**Terminal Stop**	**Other Stops**
No Control	Threshold	-
HRT (% Ob.)	Optimization	Optimization (% Ob.)
Combined Strategy (% Ob.)	Threshold	Optimization (% Ob.)

4.2 Non-executed Holding Homogeneously Distributed

In this scenario, we consider that subsets of the planned bus holdings are not executed, and these non-executed holdings are homogeneously distributed through the buses. In other words, for every programmed holding there is probability that it will not be executed. The non-executed holding could be produce by two different phenomena: *i)* a common level of disobedience between drivers; or *ii)* failure to receive the signal between the controller and the bus.

To cover all the range of possible levels of disobedience/signal failure, scenarios are defined from 100% of holdings being executed (or HRT without limitations), to a 10% of programmed holdings finally executed, through intervals of 10%.

We also analyse the effect of applying a cushioning factor Beta, so instead of applying the complete holding (*h*) suggested by the model, we only apply a fraction of it (*Beta*h*). The model introduces this factor, given that it assumes that once headways are regularized the system can perform optimal operation with minimal further holdings, and therefore it overreacts with strong and immediate measures to rush this regulation process. In Delgado et al. (2012) the optimal Beta factor was 0.5. The hypothesis in this scenario is that having a percentage of holdings not executed has a similar effect as applying this factor, in the sense that also moderates the tendency to anticipate holdings. Under this hypothesis, the optimal value for Beta should raise as the percentage of executed holdings lowers, because the need of applying Beta reduces. With this purpose, HRT is tested using Beta=1, for different percentages of executed holdings.

4.2.1 Results

In Table 4 Total Waiting Time is presented, along with the % Benefits indicator, for HRT with Beta = 0.5, HRT with Beta=1 and combined Strategy, under different percentages of executed holdings

Table 4: Comparison of strategies HRT with Beta = 0.5, HRT , with Beta=1 and Combined Strategy, under different percentages of executed holdings

% Executed Holdings	HRT, Beta=0,5		HRT, Beta=1		Combined Strategy, Beta=0,5	
	Total [Min]	**% of Ben.**	**Total [Min]**	**% of Ben.**	**Total [Min]**	**% of Ben.**
100%	**8654**	**100%**	9457	82%	9382	84%
90%	**8640**	**100%**	9410	83%	9414	83%
80%	**8692**	**99%**	9292	86%	9443	83%
70%	**8990**	**93%**	9345	85%	9525	81%
60%	**9412**	**83%**	9490	82%	9700	77%
50%	10198	66%	**9528**	**81%**	9952	71%
40%	10802	53%	**9774**	**75%**	10188	66%
30%	11984	27%	10722	54%	**10505**	**59%**
20%	14272	-24%	11869	29%	**11188**	**44%**
10%	16571	-75%	14515	-29%	**12009**	**26%**

The combined strategy showed to be worse than HRT for high percentages of executed holdings and better when this percentage was 50% and lower, proving that applying threshold over HRT in the terminal stop was beneficial in these cases. Also, for percentage below 20% of executed holdings the strategy was harmful to the system.

Regarding HRT with Beta=1, two observations can be made. The first one is that the lowest waiting times were not achieved with 100% of executed holdings, but with 80%. This proves how the model has better results when some of the holdings are not executed, similar to what happens when only half of the lengths of the holdings are executed (applying Beta=0.5). The second observation is that when the percentage of executed holdings is 50% and lower, Beta should not be applied as Total Waiting Times were higher with Beta=0,5 than with Beta=1.

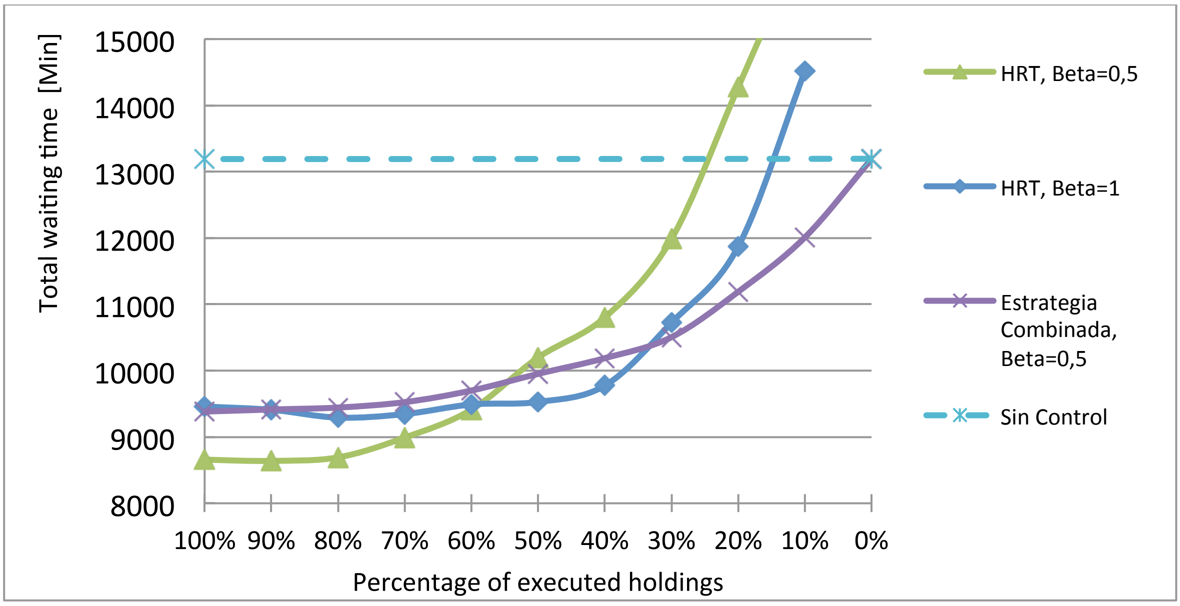

Figure 1: Total Waiting Time for 3 strategies, based on percentage of executed holdings

Figure 1 shows Total Waiting Time of the three strategies described, depending on the percentage of executed holdings. For each percentage, the curve with the lowest total waiting time represents the best strategy. For high percentage of executed holdings the best strategy is HRT with Beta=0.5. As this percentage lowers, the need for applying Beta diminishes, where for each percentage an optimal value of Beta could be calibrated. For percentages of 50% and lower, it was proved that Beta should not be applied at all.

When the percentage of executed holdings is too low, it reaches a level where HRT has worse results than No Control strategy. This no longer happens when strategies are combined, and threshold is programmed in the terminal stop, not considering what the HRT model indicates.

4.3 Non-executed Holding Focused on Certain Buses

In this section, the scenario studied simulates the case were certain drivers do not collaborate with the strategy at all, never following the holding instructions. In this case, the other drivers are assumed to always follow the instructions. This behaviour also represent a scenario were certain buses have their communication devices failing to receive the holding instructions, so they do not make holdings at all. The buses that do not make holdings will be defined as deaf buses.

Scenarios were simulated from all 15 buses doing holdings (cero deaf buses), to 7 buses doing holding (8 deaf buses). In each case the deaf buses are evenly distributed among the rest. This means that for example in the case of 3 deaf buses, they will be set in positions 1, 6, and 11 among the 15 buses in the beginning of the simulation. Note that this can change during the simulation because of overtakes.

4.3.1 Results

Table 5 shows Total Waiting Time, along with the % Benefits indicator, for HRT with Beta = 0.5, HRT with Beta=1 and combined Strategy, under different number of deaf buses. It shows with up to 3 deaf buses HRT defeats the combined strategy, although with 2 and 3 deaf buses results are very similar.

The results of HRT with Beta=1 are interesting, as for no number of deaf buses this strategy outperform HRT with Beta=0.5. This shows that, differently with what happened with a percentage of not executed holdings, deaf buses do not replace the need of applying Beta to the model. This happens because disregarding the value of Beta, deaf buses never execute holdings, and so recalibrating this parameter does not help in this case.

Table 5: Comparison of strategies HRT with Beta = 0.5, HRT with Beta=1 and Combined Strategy, according to number of deaf buses

Deaf Buses	**HRT, Beta=0,5**		**HRT, Beta=1**		**Combined Strategy, Beta=0,5**	
	Total [Min]	**% of Ben.**	**Total [Min]**	**Total [Min]**	**% of Ben.**	**Total [Min]**
0	**8673**	**100%**	9457	83%	9382	84%
1	**9559**	**80%**	10186	67%	10048	70%
2	**10460**	**60%**	10923	50%	10481	60%
3	**10672**	**56%**	11109	46%	10724	55%
4	11721	33%	12302	20%	**11282**	**42%**
5	12197	22%	12911	6%	**11727**	**32%**
6	14286	-24%	15021	-41%	**12044**	**25%**
7	15673	-55%	16406	-71%	**12150**	**23%**

Figure 2 shows Total Waiting Time of the three studied scenarios, depending on the number of deaf buses. It shows how the combined strategy defeats HRT with beta=0.5 when deaf buses are more than 3. Also shows how Beta=1 is never better than HRT with beta=0,5.

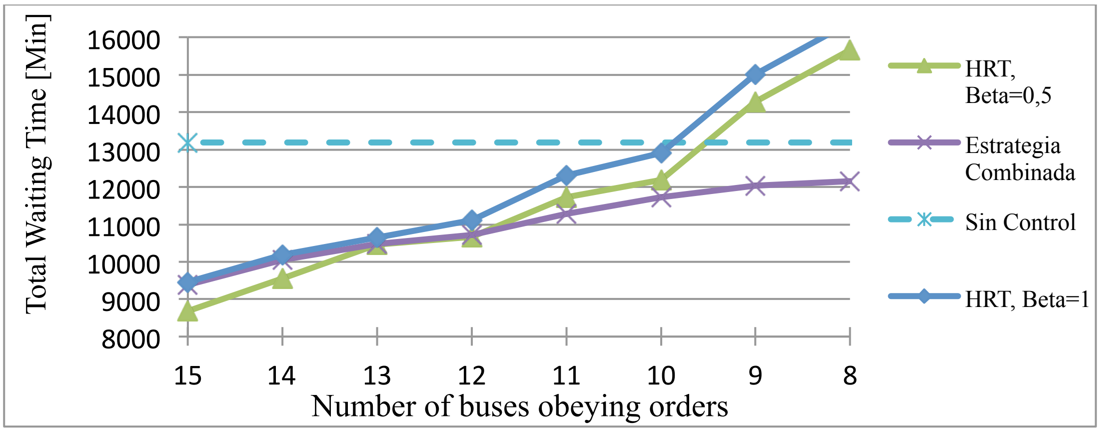

Figure 2: Total Waiting Time for 3 strategies based on number of deaf buses.

4.3.2 Known Deaf Buses

In the previous section, deaf buses have been treated as unknown. Here, we assume to know which buses are deaf, so this information can be included when programing holdings. What is expected is that the model can regulate headways programing holdings only in the buses that can actually execute them. However, it's important to recognize the hypothesis of the model, which assumes no takeovers along the corridor are allowed. In the presence of buses that have a higher average speed than the rest because of not executing holdings, the model could have a worst performance that may not match with the simulation, in which takeovers are allowed.

Results are shown on figure 3, where the trajectories for the scenario with 2 deaf buses is presented, for a) optimization ignores the fact that deaf buses exist and b) optimization knows which two buses do not execute holdings, and so it doesn't program holdings for them. In the figure it is distinguishable how the proposed measure did not have the desired effect, as irregularity between headways is visibly higher in this case.

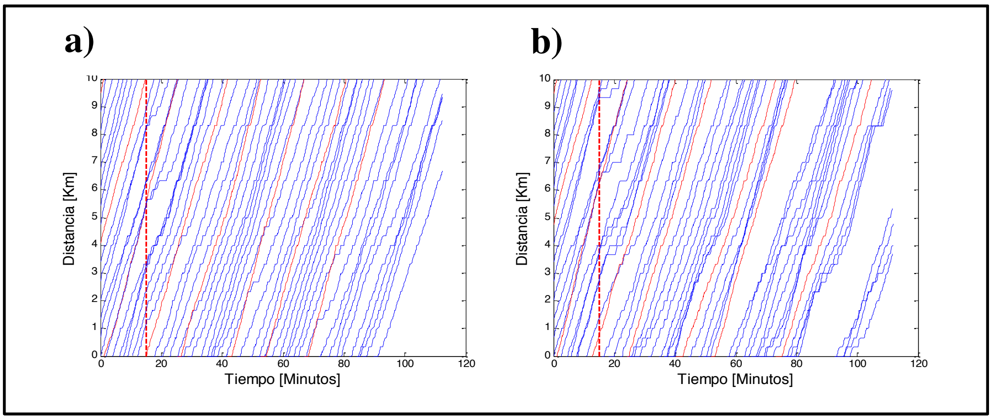

Figure 3: Bus trajectories for HRT with 2 deaf buses for two scenarios a) Assigned holdings to deaf buses b) No assigned holdings to deaf buses

It could seem counterintuitive that having a model with more accurate information of what is simulated gives a worse strategy as output. The issue here is that the optimization tool does not contemplate overtaking, not matching what happens in the simulation, and distorting the analysis by having buses going faster than the rest.

In case a), HRT programs holdings for all the buses, but deaf buses do not execute them, which leads to takeovers in the simulation. In case b), the model only program holding to those buses that can execute them, but because of the takeover restriction, when a deaf bus is behind another bus, this last bus cannot have programmed holdings either. This prevents the strategy to be implemented correctly, by not only limiting holdings to deaf buses, it also limits buses downwards, generating big headways as visible in figure 3 b).

4.3.3 Results Comparison

A comparison is made between the effects of limitations when they prevent holdings from being executed in a homogenous way between buses, and when they are focused on certain buses. To quantify the percentage of executed holdings in the latter case, the percentage of deaf buses will be used.

Figure 4 shows the described comparison, where is clear that non-executed holdings have a stronger effect on the strategy when they focus on certain buses than when it is homogeneously distributed among buses. As shown in the figure, a single bus that doesn't follow the strategy (in other words, 93% of the buses making holdings) has a greater effect than 40% of holdings not executed if they are homogeneously distributed among the buses.

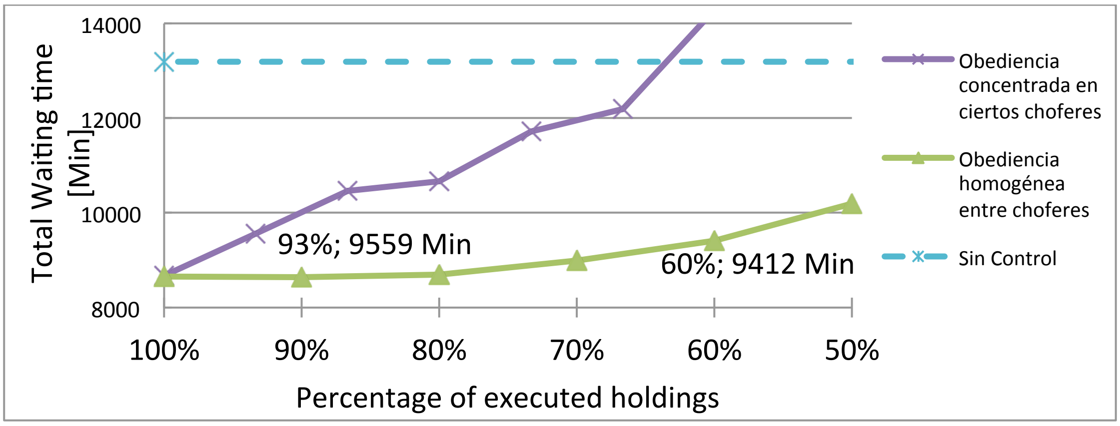

Figure 4: Total Waiting Time for HRT, based on percentage of executed holdings and its distribution

4.4 No Signal Area

If this section we explore the benefits of the model proposed by Delgado et al. (2012) if the signal could not be reached in a part of the corridor. This situation is analogous of having programmed but not-executed holdings focused in a subset of stops. For the analysis, we consider a defined area of 10 stops (from stops 14 to 23), representing one third of the corridor's stops. Three scenarios were simulated: in the first one, programmed holdings are simply not executed, and in the other two, different modifications are tested seeking to reduce the impact of the no signal area. It is important to clarify that although buses do not receive the holdings instructions inside the area, they can send their position to the centralized controller.

In the first modification, the no signal area is considered as known. This information is added to the model so that holdings are not programmed in this area. This is achieved by adding a penalization term in the objective function, multiplied by a number such that holdings are never programmed.

In the second modification, instructions sent to each bus contain holdings for all future stops, not only for the next stop, and this information is constantly being refreshed. This way when the bus enters the area without signal, it can use the last updated instruction.

In Table 6 the results for the 3 scenarios are shown, also with HRT without simulations and No Control strategies for comparison. For each case, the total waiting times and its components, and the percentage of benefits obtained.

Table 6: Different measures comparison on a no signal area scenario

Scenario	**Measure**	**Total Waiting Time [Min]**	**Waiting Time [Min]**	**Extra Time [Min]**	**Holding Time [Min]**	**% of Ben.**
Normal Scenario	-	8673	6833	73	3235	100%
No Signal Area	None	9355	7288	67	3866	85%
	No signal area integrated in the model	8911	7372	101	2674	95%
	Buses store future holdings information	8795	7256	83	2748	97%
No Control	-	13190	11267	768	777	0%

First, having a no signal area shows having a relatively low impact on the benefits of HRT. The area covers 10 of the 30 stops of the entire corridor, and still 85% of the savings are obtained. It was also possible to reduce this decline in savings through various changes in the model. When anticipated the existence of the area without signal, it was possible to obtain 95% of the savings. This result is interesting because it would also be possible to apply in the case that, because of the physical constraints of the corridor, there is an area or set of stops where buses cannot hold. If this information is integrated into the model, so that no holdings are programed, headways can be regularized through holdings in the rest of the stops. In the latter case it is clear that if the stops where there is no possibility of holding are not consecutive, then the impact on benefits would be even smaller.

In the second modification, consisting in buses executing holdings in the no signal area by using their latest available information was even more successful, with 97% of benefits. This shows that HRT, despite being a strategy based on real time information, can use moderately delayed information with very slight effect, at least when this is only in an area of the corridor. Note that this strategy has an advantage over the previous one in the sense that it is not necessary to know which stops are inside the no signal area, as buses are constantly withholding the information of holdings that should be made in the next stops.

Figure 5 shows the trajectories of buses for the 3 strategies described, where the boundaries of the area without signal are marked with horizontal lines, positioned at km 4.3 and km 7.3, stops 14 and 23 respectively. In a) and b) the graphs reveal very similar regularity between buses in the two strategies, which is confirmed by comparing waiting times (7288 and 7372 Min respectively). In both cases, it can be distinguished how the irregularity generated during the initiation period cannot be corrected until buses leave the area without a signal. Graph c), corresponding to the case where the buses keep withholding information to make the following stops, shows how holdings where effectively made inside the area without signal, so the strategy managed to regulate headways. In this case, those holdings are planned before the bus enters the area without signal.

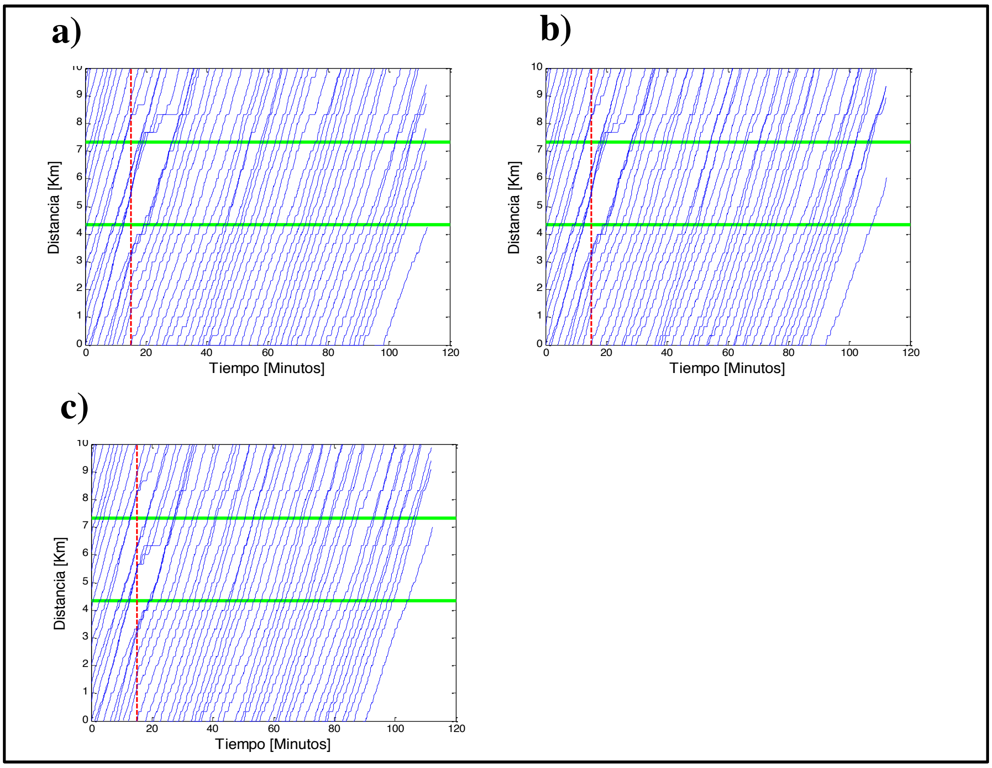

Figure 5: Bus trajectories for HRT Beta=0.5, with no signal area for different measures: a) None; b) No signal area integrated in optimization model; c) Buses store future holding information.

5. CONCLUSIONS

This study analysed the impact of phenomena that would limit the benefits of implementing headway control strategies using real time information. To estimate this impact the HRT model developed by Delgado et al. (2012) was used, which consists of an optimization tool that minimizes waiting time of passengers using real-time information by programming holding of buses at stops. We analysed phenomena associated with the level of commitment of the bus drivers with the strategy who may not obey all the instructions and technological failures in the communication system between a central controller where the strategy is planned and the buses. It was possible to quantify the effect that the different limitations have on the benefits of implementing such strategy. Also, several measures to reduce the impact of these limitations were proposed and tested, showing in some cases to be effective.

Limitations impact the implementation of the strategy, as some of the programmed holdings are not executed. Different limitations differ from each other in how the not executed holdings distribute. In this research three different distributions were analysed: when they are evenly distributed between buses, which is associated to a common level of collaboration between drivers or problems with the communication signal; when they are focused in certain buses, associated with having drivers that never collaborate with the strategy or communication equipment failing; and when they are focused in certain bus stops, representing a scenario where part of the bus corridor does not receive signal, or where holdings are not permitted.

In the first case, in which non-executed holdings are evenly distributed between buses, the HRT model proved to be robust. When only half of the programmed holdings are finally executed, the benefit of implementing the strategy remains above 80% of the maximum potential (when all programmed holdings are executed). In the second case, where there are buses that do not perform any holdings, the impact on the benefits of the strategy was much higher. For example, when 4 of the 15 buses did not execute holdings, benefits are reduced to a third, while when more than 5 buses stopped executing holdings, the implementation of the strategy was harmful to the system as total waiting time was higher than the No Control scenario. This showed that for the strategy to be successful both the collaboration of all drivers and that correct functioning of the equipment receiving the signal are crucial. Finally in an area with no signal, which was defined from bus stops 14 to 23 (out of 30), the effect was moderate, as benefits kept over 85%.

The model uses a cushioning factor beta, whose function is to moderate the tendency that the model has to overreact in its decisions, and it must be calibrated once operating, conditions are known. When not executed holdings were homogeneously distributed among the buses, the recalibration of this factor could reduce the impact on the benefits, as the reduction in the amount of executed holdings was compensated by increasing their magnitude. When not executed holdings were focused on certain buses, increasing the beta factor was not helpful, as total waiting time increased. In this case harm caused by buses not being part of the strategy cannot be compensated by an increase in the amount of holdings.

The performance of HRT was successfully improved for certain scenarios of high level of driver disobedience or technological flaws, applying a threshold strategy in the terminal stop, ignoring in this case the solution suggested by the optimization. Applying this method, called Combined Strategy, benefit was always achieved with the implementation of HRT, regardless of the level of limitations. As a conclusion, when more than half of the programmed holdings are not executed, or when more than 3 of the 15 buses do not follow holding instructions, it is preferable to use a threshold strategy rather than the model solution for programming holdings in the terminal stop.

Two measures were proposed to reduce the impact of having an area with no signal, and both showed excellent results. The first was to integrate in the optimization model the fact that buses do not make holdings in the stops inside this area. This increased the strategy benefits from 85% to 95%. This result is extendable to a scenario where by physical constraints of the corridor it is not possible to make buses hold in a determined area. It is concluded that if there is an area where no holdings can be made either by signal issues or by physical constraints, the effect on the strategy is small as long as this information is integrated into the model. The second measure was that the buses stored the holdings to be made in the upcoming stops, so that if they lose communication, they can use their latest available update. Adding this feature to the model, which has the advantage of not being necessary to know which stops are not in area without signal, 97% of the benefits were obtained.

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REFERENCES

Bartholdi III, J.J., Eisenstein, D.D., 2012. A self-coördinating bus route to resist bus bunching. Transportation Research Part B 46 (4), 481–491.

Cortés, C. E., Sáez, D., Milla, F., and Riquelme, M. (2010) Hybrid predictive control for real-time optimization of public transport systems' operations based on evolutionary multi-objective optimization. Transportation Research Part C: Emerging Technologies, 18(5), 757-769.

Daganzo, C. (2009) A headway-based approach to eliminate bus bunching: Systematic analysis and comparisons. Transportation Research Part B: Methodological, 43(10), 913-921.

Daganzo, C., and Pilachowski, J. (2011) Reducing bunching with bus-to-bus cooperation. Transportation Research Part B: Methodological, 45(1), 267-277.

Delgado F., Muñoz J.C. and Giesen R. (2012) How much can holding and limiting boarding improve transit performance?. Transportation Research Part B: 46 (9), 1202-1217.

Newell, G. F., and Potts, R. B. (1964) Maintaining a bus schedule. Australian Road Research Board, 2, 388-393.

Sáez, D., Cortés, C. E., Milla, F., Núñez, A., Tirachini, A., and Riquelme, M. (2012) Hybrid predictive control strategy for a public transport system with uncertain demand. Transpormetrica, 8(1), 61-86.