Transportation Research Part B 46 (2012) 1202–1217

Contents lists available at SciVerse ScienceDirect

Transportation Research Part B

journal homepage: www.elsevier.com/locate/trb

How much can holding and/or limiting boarding improve transit performance?

Felipe Delgado, Juan Carlos Munoz *, Ricardo Giesen

Pontificia Universidad Católica de Chile, Department of Transport Engineering and Logistics, Vicuña Mackenna 4860, Macul, Casilla 306, Correo 22, Santiago, Chile

ARTICLE INFO

Article history:
Received 12 April 2011
Received in revised form 17 April 2012
Accepted 17 April 2012

Keywords:
Bus bunching
Transit operations
Real-time control
Holding
Boarding limits

ABSTRACT

Bus bunching affects transit operations by increasing passenger waiting times and its variability. This work proposes a new mathematical programming model to control vehicles operating on a transit corridor minimizing total delays. The model can handle a heterogeneous fleet of vehicles with different capacities without using binary variables, which make solution times compatible with real-time requirements. Two control policies are studied within a rolling horizon framework: (i) vehicle holding (HRT), which can be applied at any stop and (ii) holding combined with boarding limits (HBLRT), in which the number of boarding passengers at any stop can be limited in order to increase operational speed. Both strategies are evaluated in a simulation environment under different operational conditions. The results show that HBLRT and HRT outperform other benchmark control strategies in all scenarios, with savings of excess waiting time of up to 77% and very low variability in performance. HBLRT shows significant benefits in relation to HRT only under short headway operation and high passenger demand. Moreover, our results suggest implementing boarding limits only when the next arriving vehicle is nearby. Interestingly, in these cases HBLRT not only reduces an extra 6.3% the expected waiting time in comparison with HRT, but also outperforms other control schemes in terms of comfort and reliability to both passengers and operators. To passengers HBLRT provide a more balanced load factor across vehicles yielding a more comfortable experience. To operators the use of boarding limits speed up vehicles reducing the average cycle time and its variability, which is key for a smooth operation at terminals.

1. Introduction

Bus transit services operated without a control system tend to result in vehicle bunching. This phenomenon is produced by two main factors (i) the variability in travel time between stops and (ii) variations in passenger demand. These factors lead to an increase in bus headway variance and a consequent worsening of both the magnitude and variability of average waiting times. Since the user subjective valuation of waiting time is higher than that of any other trip time component (access time, in-vehicle time) (Boardman et al., 2001), the increase in headway variability heavily impacts the level of service perceived by users. This impact gets augmented for highly demanded transit services where vehicle capacities are often exceeded. In these cases passengers waiting at a bus stop might not be able to board the first arriving bus (especially after long

* Corresponding author. Tel.: +56 2 354 7116; fax: +56 2 553 0281.
E-mail addresses: fdb@ing.puc.cl (F. Delgado), jcm@ing.puc.cl (J.C. Munoz), Giesen@ing.puc.cl (R. Giesen).

0191-2615/$ - see front matter © 2012 Elsevier Ltd. All rights reserved.
http://dx.doi.org/10.1016/j.trb.2012.04.005

intervals), and have to wait for the next one. Thus a significant number of passengers suffer long waiting times for a full bus that they cannot board.

Previous research on control strategies (Sun and Hickman, 2008; Eberlein, 1995) have focused mainly on keeping regularity through holding buses at stops if a certain condition is satisfied, which can be very effective, but has the secondary effect of reducing the operational speed. However, an alternative approach to reach more regular headways consists on limiting the number of passengers that can board a delayed bus. This is especially attractive if that bus has a very short headway behind. We have observed this scheme informally operating worldwide when a driver tells the passengers not to board a bus, but board the next one which the passengers can already see approaching, or when passengers preferring not to take a quite loaded bus decide to wait for the next one which they expect to come emptier. This scheme is similar to the ramp metering strategy applied in highways. The main focus of this paper is to understand under which conditions this strategy combined with holding becomes beneficial in comparison with just holding control; how it affects different users in terms not only of the different components of time reductions, but also on regularity, comfort and cycle time reductions. We build on Delgado et al. (2009) in which a combined holding and boarding limits control strategy is proposed, improving the methodology and adapting it in order to handle anew only holding strategy which makes this comparison possible.

The remainder of this paper is divided into six sections. Section 2 discusses the Literature Review. Section 3 introduces the public transit system reflected in the model, describing the characteristics of the bus corridor. Section 4 presents the description of the model, including the state variables of the problem as well as the main assumptions and the notation that will be used for the different variables and parameters. Section 5 sets out the complete formulation of our proposed mathematical programming model, including the objective function and its constraints. Section 6 introduces the simulation experiment, describing the scenarios where the two proposed control strategies (boarding limits combined with holding and only holding) are applied and compares the results obtained with two benchmark strategies of no control and threshold strategy. Finally, Section 7 presents our conclusions, including a summary of the study's main contributions and some final comments on topics for future research.

2. Literature review

Holding control strategies can be grouped into two categories: holding to match a predefined schedules or aiming at regular headways without such a referential framework. A predefined schedule is normally used to serve low demand transit services, which are typical of services with long headways (Ceder, 2001; Furth and Muller, 2007, 2009; Zhao et al., 2006). On the other hand, bus transit systems with high demand and short headways (*e.g.* less than 10 min), such as the one of interest here, are normally operated without predefined schedules. In this case, previous research has proposed simple to implement headway-based threshold rules in which a bus is held at a stop if its preceding headway falls below a given threshold and dispatched immediately otherwise (Barnett, 1974; Turnquist and Blume, 1980; Fu and Yang, 2002).

The appearance of new information and communication technologies, such as GPS and AVL systems, have made possible the development of more complex holding control schemes. The control action of these models are the holding times for each vehicle so as to minimize total passenger waiting time at all stops, or a combination of this factor and in-vehicle delay of passengers due to holding. Table 1 presents a classification of a selection of previous works according to the following characteristics:

(a) Prediction Horizon considered (PH) which can involve a single or multiple events.
(b) Passenger Demand (PD) and vehicle Running Times between stops (RT), which can be deterministic or stochastic in the optimization model.
(c) Overtaking, that can be allowed or forbidden.
(d) The Objective Function to be minimized (OF), that could include waiting time experienced by passengers at stops as they wait for the first bus to arrive (W_{first}), in-vehicle waiting time for passengers aboard a bus being held at a stop

Table 1
Classification of previous work in holding strategies.

Reference	PH	PD and RT	Overtaking	OF	Veh. cap.	Control points	Buses	Sol. method
Ding and Chien (2001)	Multiple	Deterministic	Forbidden	V_h	Ignored	MSC	One	OPT
Eberlein et al. (2001)	Multiple	Deterministic	Forbidden	W_{first}	Ignored	PSS	Multiple	Heuristic
Hickman (2001)	One	Stochastic	Allowed	$W_{first} + W_{in\text{-}veh}$	Ignored	PSS	One	OPT
Zhao et al. (2003)	One	Stochastic	Forbidden	$W_{first} + W_{in\text{-}veh}$	Ignored	MSC	One	Heuristic
Sun and Hickman (2008)	Multiple	Deterministic	Forbidden	$W_{first} + W_{in\text{-}veh}$	Ignored	PMS	Multiple	Heuristic
Zolfaghari et al. (2004)	Multiple	Deterministic	Forbidden	$W_{first} + W_{extra}$	Considered	SSC	Multiple	Meta-heuristic
Puong and Wilson (2008)	Multiple	Deterministic	Forbidden	$W_{first} + W_{in\text{-}veh} + W_{extra}$	Considered	MSC	Multiple	OPT