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Holding Control of Bus Bunching without Explicit Service Headways

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Abstract: Holding-based control methods for bus operation are examined to point out that allowing greater variance in headways between consecutive buses leads to possible gains in total delay, as compared to strict adherence to a service headway. This result, obtained empirically, indicates that optimal operation is not necessarily attained with even headways. Such finding is related to the well-known fact that there should not be too many control points for headway corrections when operating under the traditional method of scheduled departures from bus stations. Current feedback and predictive methods, however, can be productively applied at all stations, hence the importance of studying the effects of frequent control actions. Several feedback schemes are tested, as well as a rolling horizon predictive control method that seeks to minimize onboard and at station delays. The latter has no headway reference and hence yields larger headway variations. The scenario is a BRT corridor modeled in a microsimulation environment. Simulation results indicate gains of 29% in total delay for predictive control in relation to open loop operation, and superior performance when compared to the tested proportional feedback control methods.

Keywords: Bus bunching, headway control, predictive control, feedback control, microsimulation analysis.

1. INTRODUCTION

It has long been known that bus operation is an inherently unstable process. Newell and Potts (1964) were the first to analyze the so-called bunching of buses when the operation is subject to common disturbances such as variable boarding/alighting times. Bunching causes deterioration of service in terms of irregular headways, variations of expected time of arrival, passenger load distributions, and passenger travel time (waiting plus riding time).

In order to regulate headways, one of the most used forms of control is holding a bus that is ahead of schedule (if operation is based on timetables) or closing in on the preceding bus (if service headways are specified). We concentrate on the latter case, which is common in the operation of high-frequency lines. As presented in reviews like Strathman et al. (2001), in this case passengers arrive at the stations independently; also, the least delay at stations is obtained with even headways. However, holding-only headway control will necessarily delay some buses, thus increasing aggregated onboard delay. As a result, holding should be used sparingly; in fact, the holding computation problem may involve both deciding on few control points where to act as well as by how much a bus should be held, as discussed by authors like Eberlein et al. (2001), Strathman et al. (2001), among others.

Recently developed feedback control methods, however, do not deteriorate with holding actions at every station for all buses. For instance, Xuan et al. (2011) show that three different proportional feedback control laws are quite insensitive to the number of control points, while a more traditional fixed-schedule control suffers significantly from a large number of points where holding is applied.

In this paper, we revisit two classes of control methods to evaluate their performance regarding control objectives and improvements in quality of service indicators that are not directly controlled. The aim is to point out that allowing greater variance in headways between consecutive buses leads to possible gains in total delay as compared to adherence to a prescribed headway. The classes considered are variations of proportional feedback control with reference service headway and predictive control based on a rolling horizon, mathematical programming approach.

Feedback methods are as follows. A unity-gain forward headway control is used for establishing a benchmark for the effects of strict adherence to the service headway; a smaller gain is also tested because, in practice, gains in the range of [0.6, 0.8] would be used, see Cats et al. (2011). Another proportional feedback structure is the two-way headway method, similar to the “prefol” method described by Turnquist (1982), also used in Xuan et al. (2011) and Cats et al. (2011). The third structure is similar

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to the first, but with a threshold rule that turns off the control everytime the headway between a bus and its pre-predecessor is more than twice the reference headway, indicating large delays of the preceding bus.

Predictive control is examined to test methods that do not prescribe a reference headway, hence allowing the accommodation of disturbances without resorting to strict headway adherence. The control law is the same as presented in Koehler et al. (2011).

System performance is assessed by means of control objectives given by headway regularity (for feedback control) and passenger delay times (for predictive control). Although not being directly considered in the control objectives, comfort is analyzed by the number of standees on the bus and its related indicator, the perceived passenger delay.

2. CONTROL STRUCTURES

The following indices, parameters and variables are used to model the bus system:

λ_k	passenger arrival rate at station k (pax/s);
$a_{i,k}$	arrival time of bus i at station k (s);
C_0	time required to start boarding and alighting operations after bus arrival (s);
C_1	time for passenger boarding (s/pax);
C_2	time for passenger alighting (s/pax);
$d_{i,k}$	departure time of bus i from station k (s);
H	service headway (s);
I	set of buses in the system, $I = \{1, \ldots, n_I\}$;
i	bus index;
k	station index;
K_c	proportional control gain for feedback structures;
$l_{i,k}$	number of onboard passengers in bus i upon departure from station k (pax);
n	number of doors for alighting and boarding;
N_i	set of stations belonging to the prediction horizon of bus i;
n_I	number of buses of the system;
q_k	fraction of onboard passengers alighting at station k;
r_max	maximum holding time at stations (s);
$r_{i,k}$	holding time of bus i at station k (s);
$s_{i,k}$	duration of boarding and alighting process for bus i at station k (s);
t_k	nominal travel time between stations $k-1$ and k (s).

All control methods presented below act to regulate headways, if necessary, by holding buses at any station after alighting and boarding processes.

2.1 Forward control (FH)

The forward headway controller applies holding whenever after a bus finishes the alighting and boarding processes with a headway lower than the service headway. The holding will last for the time needed to restore the service headway, being calculated by:

$$r_{i,k} = K_\mathrm{c}[H - (a_{i,k} + s_{i,k} - d_{i-1,k})]^+ \tag{1}$$

in which $[u]^+ = \max\{0, u\}$. The headway is calculated as the difference between bus i's expected departure time $(a_{i,k} + s_{i,k})$ from station k and the departure time of its preceding bus $(d_{i-1,k})$.

Despite being simpler than other more elaborate control methods, such as predictive control, forward headway control is suited for benchmark as a headway control policy that seeks to correct any headway shorter than the service headway. Letting $K_c = 1$ implies strict adherence to the prescribed headway; in practice, $K_c < 1$ is used to avoid large holding actions.

2.2 Two-way headway control (TWH)

This method holds a bus i to balance the headway with its preceding and following buses. More precisely the holding time is given by:

$$r_{i,k} = K_\mathrm{c}[(d_{i+1,k'} - d_{i,k'}) - (a_{i,k} + s_{i,k} - d_{i-1,k})]^+ \tag{2}$$

in which k' is the station last visited by bus $i+1$, $(a_{i,k} + s_{i,k} - d_{i-1,k})$ is the expected headway between buses i and $i-1$ without holding, and $(d_{i+1,k'} - d_{i,k'})$ is the last observed headway between $i+1$ and i.

2.3 Forward headway with threshold control (FTH)

This method is derived from FH in which the holding time $r_{i,k}$ given by (1) is applied, unless the headway between i and the pre-preceding bus $i-2$ is more than twice the service headway. In mathematical notation, this method is given by:

$$r_{i,k} = \begin{cases} 0, & \text{if } (a_{i,k} + s_{i,k} - d_{i-2,k}) \geq 2H \\ \text{Eq. (1)}, & \text{otherwise} \end{cases}$$

If the headway between bus i and bus $i-2$ exceeds twice the service headway, it is considered that bus $i-1$ is over delayed. In such a situation, holding is not applied for bus i in order to prevent a ripple holding effect on all the succeeding buses, which would invariably degrade overall system performance.

2.4 Predictive control (opt.H)

The predictive control method is based on the mathematical programming model presented by Koehler et al. (2011). The control method assumes the availability of the following historical data:

- passenger arrival rates at stations;
- passenger alighting rates at stations;
- dwell time function parameters;
- bus travel times between stations;
- departure time at last visited station;
- number of onboard passengers.

The model is based on the following assumptions:

- passenger load capacity is not considered (no residue of queues at stations);
- bus travel time between stations is approximated by the expected value;
- boarding and alighting times are approximated by a deterministic linear function;
- no overtaking of buses is allowed.