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Two-way-looking self-equalizing headway control for bus operations

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ABSTRACT

Headway variations between successive buses, which lead to bus bunching, is undesirable for both passengers and bus operators, instigating longer average passenger waiting times and capacity underutilization of buses bunched together. Limiting bus bunching, hence, is important for urban bus operations. In this study, we analyze a two-way-looking self-equalizing control method for both deterministic and stochastic running times, derive its convergence properties, study the knock-on effect, and optimize its control parameter as a function of the number of buses operating in the route. By comparing the headways from both upstream and downstream of the control point, the control scheme will hold buses, if needed, at the control point to gradually restore the common headway of the system. By utilizing properties of the headway transition matrices associated with the control scheme, we prove that the bus headways will self-equalize under deterministic travel time. In addition, under the context of stochastic travel time variations, we prove that the headway variance of all buses will be reduced to a certain value by the control scheme. Further, we analyze the headway control parameter to determine its optimal value and adopt the scheme for dynamic control. Finally, numerical simulations are conducted to illustrate the performance of this control scheme, with promising results.

1. Introduction

Maintaining steady headways between successive buses is very important for urban bus operations. The regularity of bus services will be substantially improved if we have better means of maintaining the bus headways, especially in peak hours. In public transport, bus bunching or bus platooning refers to the situation wherein two or more buses, which are supposed to be evenly spaced along the route, bunch together. To describe this phenomenon, say, a particular bus A along a route is slightly delayed at a stop, so it gets behind schedule. Then there will be more passengers waiting for A at the next stop and it will take A longer for boarding. Bus A, therefore, gets further behind schedule and the delay is gradually amplified along the route. The bus following A, say bus B, will take on fewer and fewer passengers at each stop; thus getting further and further ahead of schedule, eventually catching up with A with A and B bunched together. Due to this effect, the bus behind this bunched pair will get behind schedule, with alternate buses getting ahead and behind in pairs. Therefore, travel time variations (random headway fluctuations) initiate the knock-on effect, which jointly cause bus bunching. That is why bus bunching is a natural tendency during operations. Other than leading to irregular services and longer average waiting times

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for passengers, it will also result in underutilization of the buses bunched together, and consequential overcrowded services on the bus after the bunched buses.

To improve bus service quality, some operators maximize ridership, some minimize waiting time, others improve service coverage, reduce in-vehicle travel time and transfers. In this study, we seek to regulate the bus headways for services in a highly dense transit-oriented metropolis like Hong Kong. Due to high demand, most bus services operate at high frequencies, with headways typically within 10 min along major corridors. With such short headway, operators typically provide only rough headway information, e.g. headway: 5–7 min, but not the exact service timetables. Therefore, passenger arrivals at bus stops are essentially random rather than according to the published schedules. Accordingly, passenger arrivals are spread uniformly, rather than lumping together around the schedule arrival time.

Maintaining the en route bus sequence or order is a major concern to bus operators. This issue has received much attention over the past 50 years. Newell and Potts (1964) investigated how off-schedule running can occur, and thereafter suggested several important factors for practical operations of bus services. Aiming at minimizing the average waiting time per passenger, Osuna and Newell (1972) analyzed the optimal strategy (dispatch or hold) of one or two vehicles in an idealized public transport system. Considering both the average passenger waiting time and average delay for riders already on board the vehicle, Barnett (1974) proposed an algorithm for constructing an approximate optimal dispatching strategy at a chosen control stop for a Boston subway line. Newell (1974) then studied a shuttle route having just two vehicles and one control point. Turnquist and Bowman (1979, Turnquist, 1980) discussed the control of service reliability in transit networks, and proposed the holding strategy referred to as the “Prefol” algorithm based on the lengths of the service intervals of both the preceding and the following buses.

In reviewing the literature, Andersson and Scalia-Tomba (1981) analyzed the transit vehicle holding problem based on a stochastic approach, which was subsequently enhanced by Marguier (1985). Hickman (2001) described an analytic model to deal with this problem, including stochastic bus service attributes, such as vehicle running times and passengers boarding and alighting processes, for real-time control purposes. Delgado et al. (2009) determined the optimal vehicle control strategy that minimizes the total weighted waiting time by incorporating vehicle holding and boarding limits simultaneously. To mitigate the problem of instability of bus headways, bus companies insert slack time into the schedules: Zhao et al. (2006) studied how to determine the optimal slack time for schedule-based bus operations to minimize passengers’ expected waiting times. Recently, He (2015) illustrated an adaptive approach to determine the holding time and/or adjust the cruising speed of buses. Fonzone et al. (2015) discussed the relationship between passenger arrival patterns and dwell times that might lead to bunching. Andres and Nair (2017) addressed bus bunching by considering both data-driven headway prediction and dynamic holding strategies. Sun and Schmöcker (2017) modelled and explained passenger choices and overtaking in the bus bunching problem.

The bunching problem has also been studied with real-time headway-based approaches. Fu and Yang (2002) investigated two holding control models: one determined the holding times on the basis of headway to the preceding bus, while the other made use of both the preceding and following headways with real-time bus location information. Daganzo (2009) introduced the use of dynamic holding times based on real-time headway to mitigate bus bunching. Daganzo and Pilachowski (2011) proposed an adaptive control scheme that considered both the front and rear spacings, and an estimation of passenger demand to adjust the cruising speed in real-time (equivalent to the target headway method). Cats et al. (2011, 2012) studied the holding strategy based on even-headways (equal-headways) of the controlled bus to the preceding bus and to the following bus in BusMezzo, a dynamic transit simulation model, and applied to a high-frequency trunk bus line in Stockholm, Sweden. Xuan et al. (2011) presented a family of dynamic holding strategies using bus arrival deviations from a virtual schedule at the control points. Such dynamic holding strategies may lose effectiveness under system disruption, however. For instance, when a bus breaks down or under severe congestion, the target headway and virtual schedule may become obsolete or invalid. Berrebi et al. (2015) proposed a real-time holding mechanism to dispatch buses on a loop-shaped route using real-time information. Sánchez-Martínez et al. (2016) formulated a mathematical model for holding control optimization while considering dynamic running time and demand.

Similar to Ibarra-Rojas et al. (2015), we compare various control schemes and the control scheme addressed in this paper in Table 1. The first column gives the reference. The second column “Input” indicates whether the travel time and passenger demand are deterministic (Det) or stochastic (Stoch). The third column shows the optimization objective of the approach: waiting time for the first bus (W_{first}), in-vehicle waiting time ($W_{in\text{-}veh}$), extra waiting time for passengers who cannot get on the first bus (W_{extra}), or waiting time at transfer (W_{trans}); V_h denotes headway variance, S_v for vehicle speed and *LOS* for Level of Service. The column “Control Point” indicates location(s) of the control points: predefined single stop (PSS) and predefined multiple stops (PMS), single stop determined by the control process (SSC), or multiple stops determined by the control process (MSC). The column “Vehicle” shows the number of vehicles considered in the control scheme, single or multiple vehicles. The column “TWL” refers to “two-way-looking”, indicating whether the control scheme considers the two-way-looking approach. The column “Information” indicates the input information of the schemes, where “Arr” and “Dep” represents arrival time and departure time, respectively. As shown in Table 1, the control scheme addressed in this paper uses minimal information, has a simple objective, hence is easy to implement.

Previous studies mainly focused on the development of a schedule (Zhao et al., 2006; Xuan et al., 2011; He, 2015; Fonzone et al., 2015) or a priori target headway (Hickman, 2001; Fu and Yang, 2002; Daganzo, 2009; Daganzo and Pilachowski, 2011; Berrebi et al., 2015) to prevent bus bunching, and some strategies are based on rolling-horizon optimization (Eberlein et al., 2001; Delgado et al., 2009, 2012; Sáez et al., 2012; Sánchez-Martínez et al., 2016). Under variable congestion and