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Dynamic bus substitution strategy for bunching intervention

Antoine Petit, Yanfeng Ouyang*, Chao Lei

Department of Civil and Environmental Engineering, University of Illinois at Urbana-Champaign, Urbana, IL 61801, USA

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ABSTRACT

Bus headways are typically susceptible to external disturbances (e.g., due to traffic congestion, clustered passenger arrivals, and special passenger needs), which create gaps in the system that grow eventually into bunching. Although many control strategies, such as static and dynamic holding strategies, have been implemented to mitigate the effects of unreliable bus schedules, most of them would impose longer dwell times on the passengers. In this paper, we investigate the potential of an alternative bus substitution strategy that is currently implemented by some transit agencies in an ad-hoc manner. In this strategy, the agency deploys a fleet of standby buses to take over service from any early or late buses so as to contain deviations from schedule, and the intention is to impose minimum penalties on the onboard passengers. We develop a discrete-time infinite-horizon approximate dynamic programming approach to find the optimal policy to minimize the overall agency and passenger costs. It is shown through numerical examples that schedule deviations can be controlled by regularly inserting standby buses as substitutions. In some implementation scenarios, the proposed strategy holds the potential to achieve comparable performance with some of the most advanced strategies, and to outperform the conventional slack-based schedule control scheme. In light of the emerging opportunities associated with autonomous driving, the performance of the proposed strategy can become even stronger due to the reduction in costs for keeping the fleet of standby buses.

1. Introduction

Reliability of service is a key performance indicator for transit agencies. To ensure a satisfying level of service for public transportation passengers, agencies should maintain regularity and punctuality of service. However, since bus travel time is usually subject to randomness, e.g., buses have to travel within mixed traffic which is subject to congestion and the dwell time at a stop depends on the random number of boarding/alighting passengers, bus headways are likely to be irregular and unreliable. For example, when a bus falls behind schedule, it would serve an increased number of passengers, which in turn delays it even further. In symmetry, the following bus may pick up fewer passengers and speed up. Inevitably, buses end up bunching into pairs instead of being evenly spaced. This phenomenon is well-known in the industry as an illustration of the instability of uncontrolled transit systems (Newell and Potts, 1964). Schedule unreliability from bus bunching first affects passengers. As more passengers are served by late buses than by early buses, the expected waiting time for public transit passengers increases as the variance of the headways increases (Osuna and Newell, 1972; Daganzo, 2008). In addition, passengers on the late buses have to travel in more crowded vehicles, which leads to additional discomfort and inconvenience.

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[*] Corresponding author.
E-mail address: yfouyang@illinois.edu (Y. Ouyang).

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To mitigate bunching, various control strategies have been proposed. The conventional strategy used by most agencies consists of adding slacks into the published schedule, in order to hold early transit vehicles at designated stops (Osuna and Newell, 1972; Newell, 1974). However, those holding strategies trade system stability for extra passenger dwell/travel time. While this may ensure consistent headways, passengers still experience extra delays at those stops, which potentially causes confusion and dissatisfaction. More recently, holding strategies have been proposed to take advantage of real-time information so as to reduce the waiting time at control points (Abkowitz and Lepofsky, 1990; Dessouky et al., 1999; Hickman, 2001; Eberlein et al., 2001). Some literature on headway-based dynamic holding strategies also used real-time information to develop adaptive control schemes (Daganzo, 2009; Bartholdi and Eisenstein, 2012). Yet, some of those holding strategies, especially those earlier ones, may not be able to prevent very large schedule disruptions. Typically, if the headway or the spacing between two consecutive buses becomes too large, the holding strategy could not help the following bus to catch up. Daganzo and Pilachowski (2011) filled this gap using a two-way-looking speed control strategy, where buses cooperate with each other to eliminate bus bunching, even in case of large disruptions. This approach was generalized in Xuan et al. (2011), and later expanded into robust versions that can deal with more complex systems; e.g., multiple interacting lines (Argote-Cabanero et al., 2015).

Stop-skipping strategies have also been proposed to help transit systems recover from severe schedule disruptions (Fu et al., 2003; Sun and Hickman, 2005; Liu et al., 2013). Similar “limited-boarding” strategies, in which some passengers waiting for a late bus could be requested to wait for the next bus, have been developed as well (Delgado et al., 2009; 2012). However, these types of strategies downgrade services to a large fraction of passengers whose demand is either skipped or delayed. This is usually not desirable as it often creates frustration among the affected passengers, who have to either walk a longer distance or resort to additional transfers. Another set of strategies, called transit signal priority strategies, consists in optimizing the traffic flow (e.g., using controlled traffic lights) to help late buses to catch up (Liu et al., 2003; Ling and Shalaby, 2004; Estrada et al., 2016). But those strategies could be difficult to implement in many cities as transit agencies have limited control over traffic signals or roadway infrastructures.

The transit agency in Champaign-Urbana area in Illinois, United States, Champaign-Urbana Mass Transit District (CUMTD), uses a bus substitution strategy to deal with bunching. The agency is able to monitor the locations of all running buses in real time with Global Positioning System (GPS) units. Once a running bus is detected to be significantly late at a control point, or when bunching is about to form, CUMTD dispatches a standby bus from a small reserve pool to take over the schedule of the late bus. Then, the late bus goes to *“not-in-service”* mode and it keeps running along the line but only drops off current onboard passengers. Once the not-in-service bus is empty, it is either positioned at a standby location or directly inserted at another location. As of now, there are no precise guidelines from CUMTD on the operational details of the strategy, such as the exact triggering condition to substitute a bus (e.g., a bus being “too late”), and the bus substitution decision is typically left to the discretion of the dispatcher.

This bus substitution strategy is appealing to transit agencies because it requires minimal hardware (e.g., GPS units and communications devices are already in place nowadays), it is extremely simple to implement, and it does not affect bus drivers’ driving behavior. It is particularly friendly to the onboard passengers as they do not get disrupted by any extra dwell time or transfers. The obvious shortcoming, nevertheless, is the extra resources (vehicles and drivers) needed in the standby fleet. Hence, it is important for the transit industry to not only have a clear understanding of such benefit-cost trade-offs, but also seek systematic implementation policies to maximize the overall benefits. To the authors’ best knowledge, however, this substitution strategy has not yet been studied systematically; its effectiveness has not been quantified and compared with other state-of-art bunching mitigation strategies. In addition, the optimal implementation policy for substituting transit vehicles (e.g., timing and location) and the associated resource planning and management decisions (e.g., the size of standby bus fleet) are lacking.

This paper aims at filling these gaps by developing a systematic modeling framework to reveal the optimal policy structure and implementation guidelines. Our model allows the transit agency to make dynamic substitution decisions at regular time intervals to minimize the sum of passenger and agency costs. We develop a non-myopic approximate dynamic programming (ADP) algorithm, combined with offline simulations and estimation modules, to solve the proposed model. Numerical examples with realistic parameters show that bus schedule deviations as well as bunching can be effectively controlled. If the agency cannot make extra investments in the standby bus fleet, the ransom for the substitution strategy is the reallocation of some available resources (buses and drivers) to the reserve pool, which could be otherwise used in operation. Even though this may increase the waiting time experienced by passengers due to larger headways, the system costs can be noticeably reduced if the resources are optimally allocated between the operating and the standby fleets. If the agency can afford to operate additional standby buses, the substitution strategy could yield significant passenger cost reductions at the expense of increased agency costs (as expected, due to standby buses). Our analysis also considers a number of alternative implementation scenarios such as provision of real-time schedule information to passengers, and the use of emerging self-driving vehicles. It is shown that, in the very near future when transit systems become more intelligent and people’s needs for high-quality transit services become more significant, the substitution strategy would be a more promising approach to improving the reliability and the overall performance of transit systems.

The remainder of the paper is organized as follows. Section 2 describes the system characteristics and operations as well as the formulation of the bus substitution problem. Section 3 describes the solution algorithm based on ADP. Then, Section 4 presents multiple numerical examples. Finally, Section 5 provides concluding remarks.