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Mixed logical dynamical modeling and hybrid model predictive control of public transport operations

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ABSTRACT

Bus transport systems cannot retain scheduled headways without feedback control due to their unstable nature, leading to irregularities such as bus bunching, and ultimately to increased service times and decreased bus service quality. Traditional anti-bunching methods considering only regularization of spacings might unnecessarily slow down buses en route. In this work a detailed but computationally lightweight dynamical model of a single line bus transport system involving both continuous and binary states is developed. Furthermore a hybrid model predictive control (MPC) scheme is proposed, with a dual objective of regularizing spacings and improving speed of bus service operations. Performance of the predictive controller is compared with I- and PI-controllers via extensive simulations using the proposed model. Results indicate the potential of the hybrid MPC in avoiding bus bunching and decreasing passenger delays inside and outside the buses.

1. Introduction

It is well known in the public transport systems literature that bus systems cannot maintain schedule without control (Newell and Potts, 1964). Buses that lag behind encounter more passengers waiting for them, leading to them lagging more, and buses that are slightly fast encounter less passengers. This positive feedback loop leads to the well-known phenomenon of bus bunching. Instabilities in the bus transport system (BTS) operation, resulting from spatiotemporal variability of both traffic congestion and stop-to-stop passenger demands, and manifesting themselves as headway irregularity and ultimately as bus bunching, lead to inefficient operations, increased service times, and degradation of service quality. Due to these reasons, research on modeling and control of BTSs is of high importance.

Modeling efforts to represent bus dynamics in congested routes have been investigated by various papers. The reader could refer to (Hans et al., 2015a) for a review. The authors describe models of two main categories (deterministic and stochastic) and investigate how well they can reproduce service irregularities. Influences of overtaking and common lines on the performance of bus operations are examined in Schmöcker et al. (2016), whereas (Wu et al., 2017) study the effects of dynamic passenger queue swapping considering bus bunching and capacity constraints. Recently, an interesting work (see (Hans et al., 2015b)) develops a stochastic and event based bus operation model that provides predictions of bus trajectories based on the observation of current bus positions using particle filters. While the estimates are quite accurate, such a

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framework might be difficult to be integrated in a real-time control framework, due to the potentially prohibitive computational burden associated with such models.

An interesting feature of BTSs is the presence of hybrid dynamical phenomena, suggesting the necessity of modeling them as hybrid systems, where evolution of the dynamics depend on the interaction of continuous and discrete variables (Van Der Schaft and Schumacher, 2000). Buses can be cruising (i.e., can have nonzero speed) only if they are not stopping at a stop, whereas passengers can transfer between a stop and a bus only if the bus is stopping at that stop. As a consequence, two kinds of information are needed to describe BTS dynamics: Continuous variables (e.g., bus positions or passenger accumulations) and binary variables (e.g., the condition whether a bus is currently cruising to a stop). Evolution of continuous variables are subject to linear dynamics since bus motion and passenger accumulation dynamics can be formulated using linear models, whereas binary variables evolve according to a finite state machine (e.g., the condition whether a bus is currently cruising to a stop becomes false as the condition whether the bus is currently stopping at that stop becomes true when the bus reaches the stop). Such hybrid systems can be modeled as mixed logical dynamical (MLD) systems, which are hybrid systems with dynamics evolving according to linear difference equations subject to inequality constraints involving continuous and discrete variables. Proposed by Bemporad and Morari (1999), the MLD modeling framework is a systematic approach to the mathematical modeling of dynamical systems which involve the interaction of physical laws, logic rules, and constraints. Dynamics of a BTS feature interactions of continuous (e.g., bus positions and passenger accumulations) and binary states (e.g., is bus 1 stopping at stop 2?), involving both physical laws (e.g., buses moving or passengers flowing) and logic statements (e.g., passengers may transfer between bus 1 and stop 2 only if bus 1 is stopping at stop 2). Approaching the BTS modeling problem from a hybrid systems point of view is thus necessary for building detailed dynamical models of bus operations for analysis and control purposes, whereas the MLD modeling is preferable as it enables development of hybrid dynamical models with beneficial properties for reasons of computational efficiency.

Considerable research has been directed, especially in the last 4 decades, to developing real-time bus control methods for avoiding bus bunching and ensuring efficient and reliable operation of BTSs (see (Ibarra-Rojas et al., 2015) and (Sánchez-Martínez et al., 2016) for detailed reviews, and (Berrebi et al., 2017) for an extensive review focusing on holding methods).

Most of the literature on bus operations via real-time control focus on station control methods, which involve taking decisions at a subset of stops of the bus line. Some methods of this class focus on regularizing headways via holding, with the assumption that this would lead to efficient operation and decreased travel times (Abkowitz and Lepofsky, 1990; Daganzo, 2009; Xuan et al., 2011; Andres and Nair, 2017). In situations where there is high variability in the demands, passenger waiting times need to be taken into account in the holding problem formulation alongside headways (Ibarra-Rojas et al., 2015). A recent study by Berrebi et al. (2015) considers stochasticity in bus arrival times and derives an optimal holding policy for minimizing headway irregularity by assuming that the distribution of bus arrivals is known and not influenced by decisions further upstream. Holding can also be used to improve timing of passenger transfers (Hall et al., 2001; Delgado et al., 2013). Another subclass of station control methods is the stop-skipping strategies, where the control decisions are realized by forcing buses to skip some stops, to increase speed and thus efficiency (Fu et al., 2003). Although station control strategies can be effective in regularizing headways in moderate demand situations, for high demands they have adverse affects on BTS performance as they actuate via holding the bus at a stop or making the bus skip a stop. Under some circumstances they can make buses significantly slower, which will influence the quality of in-vehicle service, but also increase the operating cost and required fleet size. Another disadvantage of station control methods is that decisions can be taken only at stops, resulting in a significant time lag between observations and control actions. This can play a vital role if the system experiences various uncertainties both in time and space, which is the case en route (congestion heterogeneity) and at stops (passenger demand heterogeneity).

Another class of real-time bus control methods is the inter-station control, where decisions are taken while the bus is moving between stops. Traffic signal priority methods belong to this category, where the aim is to manage traffic flow efficiently via prioritizing certain circulations of an intersection with actuation over traffic lights (Liu et al., 2003; Van Oort et al., 2012; Chow et al., 2017). Although consistent with the standard framework where control inputs belong to the n-dimensional real space $\mathbb{R}^n$ that is prevalent in the control systems literature, bus speed control methods (another member of the inter-station control class) received relatively little attention compared to holding methods in the public transport literature. Signal priority is not studied in this work.

The idea in bus speed control is to manipulate the speed of each bus in real-time during its movement via feedback control mechanisms to avoid bunching and increase BTS efficiency. On this direction, a control strategy combining bus speed control and signal priority is developed in Chandrasekar et al. (2002), where control actions are taken to ensure that the buses operate with spacings equal to a desired spacing, which is shown to be able to regularize headways. A bus speed control method is proposed by Daganzo and Pilachowski (2011), where the speed command for each bus is computed according to its forward and backward spacings, which can enforce speed bounds and prevent bus bunching. A more recent study by Ampountolas and Kring (2015) develops a combined state estimation and linear quadratic regulator scheme to achieve coordination between the buses, leading to headway regularity and improved service.

The following points are crucial for real-time control of bus operations: (a) Constraints on speeds and passenger capacities of buses, (b) hybrid dynamical phenomena (e.g., a bus can either cruise or stop while passengers can transfer only if a bus is stopping at the stop), (c) possibility of access to demand and traffic information without perfect knowledge. Considering these points, model predictive control (MPC) emerges as a control design paradigm highly applicable to control of bus operations. Based on real-time repeated optimization, MPC is an advanced control technique suited to optimal control