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Optimally combined headway and timetable reliable public transport system

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ABSTRACT

This paper presents a model-based multiobjective control strategy to reduce bus bunching and hence improve public transport reliability. Our goal is twofold. First, we define a proper model, consisting of multiple static and dynamic components. Bus-following model captures the longitudinal dynamics taking into account the interaction with the surrounding traffic. Furthermore, bus stop operations are modeled to estimate dwell time. Second, a shrinking horizon model predictive controller (MPC) is proposed for solving bus bunching problems. The model is able to predict short time-space behavior of public transport buses enabling constrained, finite horizon, optimal control solution to ensure homogeneity of service both in time and space. In this line, the goal with the selected rolling horizon control scheme is to choose a proper velocity profile for the public transport bus such that it keeps both timetable schedule and a desired headway from the bus in front of it (leading bus). The control strategy predicts the arrival time at a bus stop using a passenger arrival and dwell time model. In this vein, the receding horizon model predictive controller calculates an optimal velocity profile based on its current position and desired arrival time. Four different weighting strategies are proposed to test (i) timetable only, (ii) headway only, (iii) balanced timetable - headway tracking and (iv) adaptive control with varying weights. The controller is tested in a high fidelity traffic simulator with realistic scenarios. The behavior of the system is analyzed by considering extreme disturbances. Finally, the existence of a Pareto front between these two objectives is also demonstrated.

1. Introduction

In populated urban areas, often in peak hours, public transport service providers are unable to ensure a temporally and spatially homogeneous service. Increased passenger demand and interactions with dense traffic are contributing factors to bus bunching. At frequent lanes, if the schedule cannot be held and a bus arrives at the stop late, number of passengers is winding up. Increased dwell times further delay the bus. The headway between the current and the successor bus will eventually decrease so much that buses stick together. This instability in public transport is called bus bunching (Pilachowski, 2009). It leads to non-homogeneous utilization of buses and therefore degradation of service quality. Furthermore, passengers tend to board the first bus to reduce their own travel delay.

Bus bunching was first described in Newell and Potts (1964). Through improvements in sensor technology (GPS, Automatic Vehicle Location (AVL), Automatic Passenger Count (APC)) the phenomenon could be better grasped and it opened ways to deal with

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this problem. Mandelzys and Hellinga (2010) employed AVL and APC methods to identify bottlenecks at urban bus routes. Fonzone et al. (2015) studied the effect of passenger arrival patterns on bunching, concluding that unexpected passenger demands are the root cause of bunching. Due to bunching the periodicity of arrivals fail and homogeneous service cannot be provided (Ap Sorratini et al., 2008). In Daganzo (2009) and Daganzo and Pilachowski (2011) algorithms are developed to control the headway of consecutive buses. Ampountolas and Kring (2015) proposed cooperative control of buses to mitigate bunching. Bartholdi and Eisenstein (2012) formulated a self controlling algorithm without timetable. The above works focus solely on headway keeping, not considering adhering to the schedule. In Xuan et al. (2011) optimal control algorithms are considered, taking into account both headway and timetable keeping. Andres and Nair (2017) used predictive algorithms to improve public transport reliability. Recent paper from Yu et al. (2016) employ already existing information to predict bus bunching employing information from transit smart cards.

In addition to bunching, timetable reliabilityand travel time prediction are two intensively researched topics. Rahman et al. (2018) provides a predictive method based on GPS position and timetable data. A common method in improving timetable reliability provides priority to buses at signalized intersections (Estrada et al., 2016). In Estrada et al. (2016) a velocity control method considering bus-to-bus communication and green time extension is formulated. Public transport reliability is addressed in Nesheli et al. (2015) with bus holding, stop skipping to minimize passenger waiting time. Jiang et al. (2017) proposed a heuristic algorithm with stop skipping or inclusion for congested high-speed train lines.

References Fonzone et al. (2015), Helbing and Tilch (1998), Holroyd and Scraggs (1966), Hoogendoorn and Bovy (2001), Horn et al. (1994), Horn and Johnson (1990), and Jiang et al. (2017) seek to remedy bunching by including slack times or stop skipping. In densely populated urban areas where city space is scarce, including slack times might not be possible due to bus stop configurations (Cats et al., 2012). Furthermore, slacks are an unproductive allocation of time in the cycle time of buses and results in queuing at stops (Daganzo, 2009). Slack times can be dynamically addressed via changing the speed of the vehicle rather than holding it. In that sense, we propose a smoothed and pro-active way of slack time reduction foreseeing the trajectories (headway, timetable) to track. Our method is based on a dynamic prediction to better model the vehicle's future dynamics instead of regarding the trip times between stops as random variables as done in Xuan et al. (2011).

In this paper we present a velocity control algorithm based on communication between public transport buses and their infrastructure. The velocity control can act as an assistance to the driver or with the emergence of autonomous vehicles, a strict reference speed in a cruise control application (Daganzo and Pilachowski, 2011). We describe an optimal, decentralized, shrinking horizon model predictive control (MPC) algorithm to achieve headway homogeneity in both time and space on an urban bus route. Several of the aforementioned works consider forward-backward-headway control, e.g. Daganzo (2009), Ampountolas and Kring (2015), and Andres and Nair (2017). In our model predictive approach, considering the bus behind is not possible, future trajectory of the following would be an unreliable reference.

The proposed control oriented model on top of the longitudinal bus dynamics, takes into account uncertainties such as varying dwell times and delays due to interaction with traffic. The MPC is an adequate choice for predicting arrival times and calculating an optimal velocity profile. Decentralized control means there is a speed controller running on each bus. The control design is based on a quadratic cost function, weighting delays or early arrivals and deviation from the defined headway. The linear nature of the control oriented model and the constraints represented by linear relationships enables us to solve the optimization effectively on individual vehicles.

The paper is organized as follows. Methodological overview section gives an overview of the proposed system architecture and control strategy. In the System modeling part the subsystems proposed in the system architecture are detailed. A passenger arrival model and a dwell time model are presented to describe operations at a bus stop. Then, a control oriented bus following model is formulated. In the reference speed control design section shrinking horizon model predictive controllers are proposed with different weighting strategies. For comparative analysis of the controllers a simulation scenario is created in a high fidelity traffic simulator based on real world data. Next, simulation results are analyzed. First, the operation of the controller is shown for one bus, then it is extended for several buses. Finally, the system is evaluated under extreme disturbances.

2. Methodological overview

Buses operate on a given route based on their timetable. During operation, due to irregular dwell time, they tend to get out of sync with the schedule and start bunching.

The goal of the control algorithm is to calculate an optimal velocity profile for each bus, which ensures its timetable and headway reliability. To this end, a model is proposed to describe bus operations on a line. This model has modular layout and can be disassembled into subsystems: the passenger arrival model and dwell time model describes operations at a bus stop. Movement between stops is characterized by the vehicle dynamics subsystem, which consists of a longitudinal car following model. Surrounding traffic conditions are also taken into consideration.

The velocity controller calculates a reference velocity profile v_{des} for the bus based on two reference signals: (i) given the estimated dwell time and the scheduled departure time from a stop, a desired trajectory is calculated $x_{des}(t)$; (ii) to keep equidistant headways, trajectory of the leading bus $x_{ref}(t)$ is also taken into account. By means of balancing between these conflicting references, an optimal velocity profile is formulated. The proposed system can be classified as an overlapped, decentralized control. The controlled bus only requires the historical position of the leader bus and the schedule (stop locations and desired departure times), see Fig. 1. In case either of them is missing or disabled, the system can operate in either headway tracking or timetable tracking mode. The control algorithm is generic, it can be applied to different routes, fleet configurations, schedules, etc.

Fig. 2 depicts the modularity of the proposed control system. Subsystems and notations are further detailed in the following parts.