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Comparing bus holding methods with and without real-time predictions

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ABSTRACT

On high-frequency routes, transit agencies hold buses at control points and seek to dispatch them with even headways to avoid bus bunching. This paper compares holding methods used in practice and recommended in the literature using simulated and historical data from Tri-Met route 72 in Portland, Oregon. We evaluated the performance of each holding method in terms of headway instability and mean holding time. We tested the sensitivity of holding methods to their parameterization and to the number of control points. We found that Schedule-Based methods require little holding time but are unable to stabilize headways even when applied at a high control point density. The Headway-Based methods are able to successfully control headways but they require long holding times. Prediction-Based methods achieve the best compromise between headway regularity and holding time on a wide range of desired trade-offs. Finally, we found the prediction-based methods to be sensitive to prediction accuracy, but using an existing prediction method we were able to minimize this sensitivity. These results can be used to inform the decision of transit agencies to implement holding methods on routes similar to TriMet 72.

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1. Introduction

On high frequency routes, there is a natural tendency for buses to *bunch* together. When a bus is traveling with a long headway,[1] it has to pick up and drop off a relatively greater number of passengers, which slows down the bus even more. As the lagging bus becomes crowded, the following buses only have a few passengers to serve, which they can do relatively fast. Eventually the lead bus may get caught by one or several following buses and they start traveling as a platoon. Bus bunching is the product of unstable dynamics that cause delays to grow (Hickman, 2001). Even a small perturbation such as a traffic signal or a passenger paying in cash can destabilize the route and lead to bus bunching (Kittelson, 2003; Milkovits, 2008).

Unstable headway dynamics are a systemic problem that causes passenger wait and crowding. Fan and Machemehl (2009) showed that on routes where headways are less than 12 min, passengers tend to arrive randomly, even if a schedule is available. Because more passengers arrive during long headways than during short ones, gaps in service cause disutility to passengers in the form of undue waiting time and crowding (Newell and Potts, 1964; Milkovits, 2008; Cats et al., 2016). Bus

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[1] In this text, the term *headway* will be used as the time between the passing of two consecutive buses at a single location. Later, we will distinguish between the headway (or forward headway) and the backward headway, which is the time until the following vehicle will reach the current location.

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bunching also increases dwell time and running time, causing additional operating costs to the transit agency Verbich et al. (2016). One way for transit agencies to stop the progression of instability among headways, is to provide control points, where buses with short headways can be held to absorb the delay of following buses.

Holding buses at control points can help reduce at-stop passenger waiting time, but it increases the wait of passengers who have already boarded. There is a trade-off between stabilizing headways and maintaining high operating speed (Furth et al., 2006; Furth and Wilson, 1981; Cats et al., 2011). This is why transit agencies value the benefit of headway reliability and the disadvantage of holding time differently. Holding methods used in practice and recommended in the literature make different trade-offs between the two conflicting objectives. Therefore, the adequacy of a holding method may depend on the route it is applied to.

In addition to selecting a holding method for their routes, transit agencies also need to decide how to implement it. Several holding methods in the literature require setting a parameter, which affects the trade-off between holding time and headway stability (Daganzo, 2009; Xuan et al., 2011; Bartholdi and Eisenstein, 2011; Daganzo and Pilachowski, 2011). Holding methods can also be applied at one or several control points along the route, which may impact the performance of each method. Understanding sensitivity of holding methods on the parameterization and number of control point is necessary to select the best holding method based on route characteristics and desired trade-offs.

Several methods are based on predictions for the arrival times of following buses (Bartholdi and Eisenstein, 2011; Daganzo and Pilachowski, 2011; Berrebi et al., 2015). The quality of the predictions may affect transit operators' ability to leverage headway stability from holding time. The required level of prediction accuracy and confidence can be burdensome for certain transit operators that may not need high-quality predictions for other applications. The ubiquity of prediction-based methods is therefore dependent on their sensitivity to prediction quality.

Research in the literature has compared holding methods, but there currently lacks a unified framework to evaluate the conflicting objectives of stabilizing headways and minimizing holding time. Xuan et al. (2011) and Berrebi et al. (2015) have case study sections to compare methods in the literature to their own. Cats et al. (2011) compare naive methods used in practice and a headway-based method similar to the method in Daganzo and Pilachowski (2011). There is a need for a sensitivity analysis to support the choice of holding methods and their parameterization based on route characteristics, including the number of control points on routes similar to Tri-Met 72.

In this paper, we investigate the holding trade-off of holding methods used in practice and recommended in the literature. To this end, we evaluate holding methods on a simulated bus route using historical data from Tri-Met Route 72 in Portland, Oregon. We use the prediction tool developed in Hans et al. (2015) to reproduce the predictions in a realistic setting. In the following section, we describe the holding methods used in practice and recommended in the literature. In Section 3, we discuss the simulation experiment, and particularly the methods evaluated. In Section 4 we compare the performance of each holding method. In Section 5, we investigate the impact of parameter choice, and number of control points on the trade-off between stabilizing headways and keeping short holding times. In Section 6 we test the sensitivity of prediction-based holding methods on the accuracy and confidence of predictions. Finally, we provide concluding remarks in Section 7.

2. Holding methods in the literature

Methods to hold buses at control points have been addressed for many decades. Osuana and Newell (1972) and Newell (1974) formulated the theoretical basis for holding mechanisms to minimize passenger waiting time on simple routes in the 1970's. Since then, two main approaches to the bus holding problem have been developed in the literature, mathematical optimization and analytical.

The first approach consists in optimizing a weighted function of passenger wait in mathematical programs that consider the dynamics of bus trajectories (analytically or by simulation). At each decision stage, the optimization tools model the future states of the system, and assign holds on a rolling horizon. Hickman (2001) developed a linear search optimization algorithm which considers holding decisions in isolation of each other based on a stochastic model for bus trajectories. In Eberlein et al. (2001) a heuristic algorithm is used to minimize the waiting time of passengers at stops in a quadratic program. Bukkapatnam and Dessouky (2003) developed an iterative model where buses and stations *negotiate* holding time to minimize marginal costs. The method in Zolfaghari et al. (2004) assigns all holding decisions simultaneously, while considering capacity constraints, using AVL data and perfect predictions. Delgado et al. (2009) and Delgado et al. (2012) developed a simulation-based optimization algorithm that reproduces stationary bus trajectories deterministically and minimizes a weighted function of wait time. Sánchez-Martínez et al. (2016, 2015) and Sánchez-Martínez et al. (2017) extended their methods to consider dynamic passenger arrival rates, travel time, and other forms of control. Cortés et al. (2010) used a genetic algorithm to solve a multi-objective dynamic problem.

The second approach assigns holds as closed-form functions of bus arrival times (Daganzo, 2009; Daganzo and Pilachowski, 2011; Xuan et al., 2011; Bartholdi and Eisenstein, 2011; Berrebi et al., 2015). Buses are held with the objective of maintaining stable headways, and preventing bus bunching from the onset, which can minimize passenger waiting time globally and durably. Methods assign holds to buses as a function of the schedule, headways and, for some, predicted arrival times.[2] Unlike the

[2] In the remainder of this text, we refer to holding methods that consider schedules as "schedule-based" and methods that consider headways as their main input as "headway-based". Schedule-based methods include the Naive Schedule and the method recommended in Xuan et al. (2011). Headway based methods include the Naive Headway and the method recommended in Daganzo (2009).