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Demand-driven timetable design for metro services

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ABSTRACT

Timetable design is crucial to the metro service reliability. A straightforward and commonly adopted strategy in daily operation is a peak/off-peak-based schedule. However, such a strategy may fail to meet dynamic temporal passenger demand, resulting in long passenger waiting time at platforms and over-crowding in trains. Thanks to the emergence of smart card-based automated fare collection systems, we can now better quantify spatial–temporal demand on a microscopic level. In this paper, we formulate three optimization models to design demand-sensitive timetables by demonstrating train operation using equivalent time (interval). The first model aims at making the timetable more dynamic; the second model is an extension allowing for capacity constraints. The third model aims at designing a capacitated demand-sensitive peak/off-peak timetable. We assessed the performance of these three models and conducted sensitivity analyzes on different parameters on a metro line in Singapore, finding that dynamical timetable built with capacity constraints is most advantageous. Finally, we conclude our study and discuss the implications of the three models: the capacitated model provides a timetable which shows best performance under fixed capacity constraints, while the uncapacitated model may offer optimal temporal train configuration. Although we imposed capacity constraints when designing the optimal peak/off-peak timetable, its performance is not as good as models with dynamical headways. However, it shows advantages such as being easier to operate and more understandable to the passengers.

1. Introduction

With the increasing amount and range of urban mobility, making public transit more efficient has become a primary task for many cities. Owing to its greater capacity, higher speed and increased reliability, rail-based metro systems, such as Singapore's "Mass Rapid Transit" (MRT), the London Underground and the Tokyo Metro are particularly important to a metropolis. To improve service quality and reduce passenger waiting time, recent studies demonstrate an increasing interest in designing efficient operation strategies—such as adjusting train speed dynamically, increasing or decreasing the dwell time at stations and designing new service timetables—to improve metro service reliability. Of all these approaches, timetable design has been accepted as the most straightforward and effective solution.

To provide user-centric public transit services, the principle of timetable design is to meet passenger demand, reduce passenger waiting time and avoid overcrowding as far as possible (Ceder and Wilson, 1986). Without an in-depth under-

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standing of temporal demand patterns, operators' straightforward and commonly adopted strategy is a peak/off-peak-based schedule, where two types of service frequencies are set for peak and off-peak time, respectively. For example, the MRT system in Singapore operates at double frequency during morning and evening peaks. This strategy is easy to apply and performs well when supply is sufficient; however, given that passenger demand is not steady even during off-peak time, waiting time under fixed headway is still unbalanced when passenger arrival rate varies with time. On the other hand, under congested conditions or strong temporal demand heterogeneity, passengers might be unable to board a full train and they have to wait for another train. In these cases, the peak/off-peak timetable may fail to meet the temporal demand with limited supply. Furthermore, ignoring such demand dynamics may result in minor disruptions and poor service reliability. Thus, understanding the temporal demand variation and adjusting service frequency dynamically become crucial, since commuters are sensitive to their daily travel itineraries even at the minute level. Instead of assuming passengers will adjust their behavior to the service given, transit operators must better understand the nature of demand dynamics and design demand-sensitive timetables to meet greater demand with capacity-limited train services (Ceder, 2007; Niu and Zhou, 2013), reducing the risk of disruptions and attracting more ridership (Jin et al., 2013; Jin et al., 2014).

Lacking detailed passenger demand data, previous research works on scheduling mainly focused on an idealized transit system (de Palma and Lindsey, 2001; Newell, 1971; Osuna and Newell, 1972), while only a few noted the importance of passenger demand dynamics (Ceder, 1984; Ceder, 1986; Ceder, 2001). Thanks to the emergence of smart card-based automated fare collection (AFC) systems (normally on-board registration for bus systems, while off-board registration at fare gantries for metro services), we can now extract the spatial–temporally stamped journey information on an individual level from days to weeks, helping us to better understand demand variations.

In this paper, we present three optimization models for demand-driven timetable design. The first does not take train capacity as a constraint, while the second and the third allow for limited capacity constraints. The contributions of this paper are twofold; first, we propose three demand-driven timetable design models, the results of which can be further used as operational guidelines and benchmarks; second, we use smart card data to conduct an in-depth analysis of daily transit demand pattern variation and obtain detailed spatial–temporal service loading profiles.

The remainder of this paper is organized as follows: in the next section, we review previous studies on timetable design problems and the use of smart card data in transport modeling; in Section 3, we introduce our single-track timetable design problem and set out three different formulations; in Section 4, we employ a metro line in Singapore as a case and analyze the corresponding demand variation. Using the performance of the proposed models, we demonstrate the balance of different parameters against timetables in Section 5; finally, we summarize our main findings and discuss future work in Section 6.

2. Background

Previous studies on timetable design can be divided into two categories:

(1) Network timetable design problem; and
(2) Single track timetable design problem.

A network timetable design problem attempts to set up a timetable for multiple services in a connected transit network. The most common objective is to minimize transfer cost through transit coordination and synchronization among different routes. These problems have been investigated extensively on both bus networks (Ceder, 2001; de Palma and Lindsey, 2001; Ibarra-Rojas and Rios-Solis, 2012; Rapp and Gehner, 1976; Ting and Schonfeld, 2005) and metro networks (Caprara et al., 2002; Liebchen, 2008; Wong et al., 2008). Essentially, the motivation for synchronization arises from services with longer headway and higher reliability; transit services in rural areas might be a good example illustrating these characteristics. In this case, passenger waiting time can be reduced by increasing the simultaneous vehicle arrivals at transfer points. In other words, when timetables are independent (without synchronization), missing a connection will result in long delay.

In this paper, we treat the demand-driven timetable design as a single track scheduling problem. This issue was first introduced to urban bus systems as setting service frequency. Furth and Wilson (1981) proposed a model to find optimal headway by maximizing social welfare, which included both ridership benefit and waiting-time savings. The corresponding constraints were total subsidy, fleet size and occupancy levels. However, due to lack of data, the importance of time-dependent demand was not addressed and frequencies were assumed to be constants during peak and off-peak time, respectively. To characterize the time-dependent nature of transit demand and take crowding cost into account, Koutsopoulos et al. (1985) extended this model using a non-linear programming model. With the development of data collection techniques, Ceder (1984) first addressed the importance of ridership information and stated that service frequency should correspond to temporal passenger demand. This study summarized and analyzed four data collection techniques and evaluated their efficiency, using a frequency-setting problem, suggesting that a comprehensive load profile (ride check) is always superior to stop check (point check). However, the cost of such a ride check is much higher setting service because of the labor-intensive manual data collection. In a follow-up study, Ceder (1986) introduced an alternative approach for timetable design, with the objective of maximizing the correspondence of vehicle departure times with dynamic passenger demand. To evaluate the contribution of automated data collection system (ADCS) techniques, an automated procedure for efficiently setting bus time