Transportation Research Part C 88 (2018) 187–207

Contents lists available at ScienceDirect

Transportation Research Part C

journal homepage: www.elsevier.com/locate/trc

Reliable frequency determination: Incorporating information on service uncertainty when setting dispatching headways

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ARTICLE INFO

Keywords:
Reliability-based frequency setting
Tactical planning
Headway variability
Dispatching headway determination
Resource constrained optimization
Non-linear programming

ABSTRACT

Frequency setting requires the determination of the dispatching headways of all bus lines in a city network and constitutes the main activity in the tactical planning of public transport operations. Determining the dispatching headways of bus services in a city network is a multi-criteria problem that typically involves balancing between passenger demand coverage and operational costs. In this study, the problem of setting the optimal dispatching headways is formulated with the explicit consideration of operational variability issues for mitigating the adverse effects of passenger demand and travel time variations inherent to bus operations. The proposed model for setting the dispatching headways of bus lines considers the demand, headway and travel time variations along every section of each bus route for different times of the day, as well as operational costs, vehicle capacity and fleet size constraints.

We first formulate the problem while accounting for the consequences of variability in service operations. The resulting optimization problem is then solved by employing a Branch and Bound approach together with Sequential Quadratic Programming in order to find the optimal dispatching headway for each bus line. Experimental results demonstrate (a) the improvement potential of the base case dispatching headways when considering the service reliability; (b) the sensitivity of the determined dispatching headways to changes in different criteria, such as passenger demand and/or bus running costs, and (c) the convergence accuracy of the proposed solution method when compared to heuristic approaches.

1. Introduction

Public transport operators need to continuously update service frequencies to cater for changes in traffic conditions and passenger demand in both space and time. The service frequencies can be updated by modifying the dispatching headways of the respective bus services since the frequency of one bus line is inversely proportional to its dispatching headway. Bus line frequencies can be adjusted to the passenger travel needs subject to resource capacities and operational cost limitations by using information from passengers (i.e., smartcard logs (Pelletier et al., 2011; Ma et al., 2013; Munizaga and Palma, 2012; Luo et al., 2017), smartphones (Alexander et al., 2015; Gkiotsalitis and Stathopoulos, 2015; Calabrese et al., 2013; de Regt et al., 2017) and operating vehicles (Cortés et al., 2011).

In transit planning, frequency setting follows the network design and precedes the timetable design and vehicle and crew scheduling (refer to Kepaptsoglou and Karlaftis, 2009; Farahani et al., 2013; Ceder, 2007 for more details on public transport planning processes). Setting the frequencies by determining the dispatching headways of bus lines and network design are commonly

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https://doi.org/10.1016/j.trc.2018.01.026
Received 1 September 2017; Received in revised form 28 January 2018; Accepted 28 January 2018
Available online 04 February 2018

considered as two consequent problems (with the exceptions of Silman et al., 1974; Ramos, 2014; Szeto and Wu, 2011). Frequency setting and network design are considered as two consequent problems due to the complexity of these problems, the inefficiency of solving approaches and the fact that frequency setting can be adjusted as part of tactical planning.

Methods to determine dispatching headways for setting the frequencies of the services are based on either passenger load profile rule-based techniques (Ceder, 2007, 1984; Hadas and Shnaiderman, 2012) or on minimizing passenger and operator costs Furth and Wilson (1981), Cipriani et al. (2012) and Gkiotsalitis and Cats (2017). For more details one can refer to the literature reviews by Ibarra-Rojas et al. (2015) and Guihaire and Hao (2008). The unsatisfied demand is a main factor of the above-mentioned problem and is generally modeled by introducing a penalization weight in the objective function (Barra et al., 2007; Cipriani et al., 2012; Fan and Machemehl, 2008). Common practice in public transit planning is to determine the dispatching headways based on accumulated hourly passenger counts, average travel time, vehicle capacity and the minimum allowed frequency limit by time of day. One exception is the work of Hadas and Shnaiderman (2012) which presented a new approach for setting the dispatching headways by introducing the stochastic properties of Automatic Vehicle Location (AVL) and Automatic Passenger Counting (APC) data within a supply chain optimization model. The optimization elements of that approach were the: (a) empty-seat driven (unproductive cost) and (b) the overload and un-served demand (increased user cost).

Several studies have considered stochasticity in the tactical planning phase (Amberg et al., 2017). Li et al. (2013) considered stochastic parameters such as demand, arrival times, boarding/alighting times, and travel times via a stochastic optimization approach and a meta-heuristic solver that minimizes the sum of the expected value of the company costs and the waiting time costs for passengers. Bellei and Gkoumas (2010) modeled also the demand and dwell times scholastically while Barabino et al. (2017) proposed an offline framework that identifies the bus stops and the time periods in which the reliability of the bus operations is not sufficient using historical vehicle location data. An interesting extension of the models that determine the dispatching headways of bus lines which tries to minimize the passenger waiting times and operational costs while increasing ridership came from Gkiotsalitis et al. (2017), Verbas and Mahmassani (2013) and Verbas et al. (2015). Verbas et al. (2015) extended the model presented by Furth and Wilson (1981) considering demand variations along the route; thus, enabling the split of the route into sub-routes that enjoy homogeneous demand patterns in order to define dispatching headways for each sub-route independently. The variation of demand was modeled by assuming temporal and spatial heterogeneity of the ridership elasticity with respect to dispatching headways and the problem was formulated with a non-linear program which minimizes the weighted sum of ridership and wait time savings over all stops, lines, and time intervals subject to constraints such as budget, fleet size, headway bounds for each line pattern, and bounds for load factors.

Notwithstanding the above, to the best of the authors knowledge, none of the previous studies solved the problem of setting dispatching headways while considering the reliability of service operations and the consequences of travel time and demand variability during the day; even if the implications of the bus service reliability problem have been analyzed by several works such as the work of Chen et al. (2009). Neglecting service variability at the planning phase leads to the selection of sub-optimal solutions and the underestimation of both operational and passenger costs. Service reliability is mostly addressed at the operations control phase by re-adjusting planned schedules or applying other control measures such as bus holding or speed control in real-time for reacting to trip travel time and passenger demand changes (Gkiotsalitis and Maslekar, 2015; Moreira-Matias et al., 2016; Asgharzadeh and Shafahi, 2017). However, the consideration of service reliability already at the tactical planning phase can potentially generate solutions that tackle the inherent uncertainty of public transport operations which is particularly high at dense metropolitan areas with high-demand bus operations.

In the remainder of this paper, we develop and apply a reliability-based optimization framework for setting the dispatching headways of bus lines that considers historical operational data and is aware of the passenger waiting time variability at each stop and how it is affected when changing the planned dispatching headways. In the following section, the problem description is presented considering the demand variations and the travel time variability from bus stop to bus stop over time. In addition, the multi-objective problem of setting the optimal dispatching headways of several bus lines within a study area is formulated. An exact solution method for solving the resulting discrete non-linear programming problem is described. The method is applied by using General Transit Feed Specification (GTFS) data from 17 central bus lines in Stockholm and detailed AVL and APC data from central bus lines 1 and 3. After discussing the experimentation results, concluding remarks about practical implications and future work directions are presented in the closing section.

2. Reliability-based frequency setting problem

2.1. Problem formulation

In this work, we introduce the following notation for describing the main components of the frequency setting problem that requires the determination of the dispatching headways of all bus lines in a study area.

$\{\mathbf{L},\mathbf{S}\}$	is a network with **L** bus lines and **S** bus stops.
t_l^{90th} (hour)	the total travel time value of a line l for which there is only a 10% chance for a bus trip to require more travel time than that. This travel time includes the boarding/alighting times at each bus stop and the layover times before starting a new trip
$\mathbf{L} = \{L_1,L_2,...,L_{\lvert L\rvert}\}$	the bus lines of the network