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Cost functions and multi-objective timetabling of mixed train services

Andy H.F. Chow[a,*], Aris Pavlides[b]

[a] Systems Engineering and Engineering Management, City University of Hong Kong, Kowloon Tong, Hong Kong
[b] Centre for Transport Studies, University College London, London WC1E 6BT, United Kingdom

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ABSTRACT

This paper investigates a set of cost functions for assessing and timetabling mainline train services. The present study incorporates considerations from both operators' and passengers' perspectives including service running times, punctuality, waiting times, and comfort of the journeys. The cost functions are applied to a multi-objective optimisation formulation subject to constraints representing operational requirements and signalling systems. The optimisation model is applied to the Brighton Main Line network in Southeast England as a case study, and the results demonstrate how the proposed optimisation framework can help government and train operators to derive more effective and equitable timetable with consideration of customer satisfaction. A Pareto analysis is further derived to illustrate the trade-off between conflicting objectives in the optimisation process under different circumstances.

1. Introduction

The prosperity of a society is closely linked to the performance of the transport infrastructure (Chow et al., 2014). Railway is recognised as sustainable and green compared with other modes of transport, which attracts a vast amount of investment in the recent decade. Continuous construction of new infrastructure is not a financially viable option, which leads to a number of studies looking at effective train operations for maximising the utilisation of existing railway infrastructures (Schwanhausser, 1994; Zhou and Zhong, 2005; Lee and Chen, 2009). Some existing work looking at effective timetabling or scheduling techniques for mainline train services can be found in Fang et al. (2015). Guihaire and Hao (2008) also present a review of the strategic and tactical steps of planning including the design and scheduling of the network. In general, mainline train services refer to connections between cities as opposed to the local metro services, while timetabling is regarded as the process of deriving a feasible schedule for a given set of train services over a specific route by specifying the associated arrival and departure times at each designated point. Mainline services are generally heterogeneous, which means they consist of passenger and freight trains, slow and express services, domestic and international connections, etc. The feasibility of a timetable is also subject to a number of factors including availability of trains and crew, infrastructure capacity, and travel demand (Chen and Roberts, 2012). As a consequence, deriving a timetable satisfying different stakeholders including passengers, train operators, and infrastructure manager is always a challenge (Ibarra-Rojas et al., 2014). In the literature, Vansteenwegen and Van Oudheusden (2007) study the case of the intercity network of the Belgian railways and explore ways of reducing waiting times through improving train connections. Tirachini et al. (2010) develop a microeconomic model to compare the performance of Bus Rapid Transit, light rail and heavy rail. Dollevoet et al. (2014) present an iterative train scheduling technique for minimising stochastic delays.Corman et al. (2017) investigate an integrated train scheduling approach which

* Corresponding author.
E-mail address: andychow@cityu.edu.hk (A.H.F. Chow).

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maximises the operational capacity for the system managers and minimises delays for passengers by using a mixed integer programming approach. Sama et al. (2017) explore effective neighbourhood searching strategies for real-time train re-routing under disruptions.

Many of the previous studies discussed above focus on the operators' perspective which aims to maximise the service throughput and/or minimise the operating cost such that the revenue gained from running the train services can be maximised. On the passengers' side, Chang et al. (2000) consider that planning of passenger train services requires considering the needs of both the operator and the passenger through a multi-objective optimisation model. Parbo et al. (2016) present a comprehensive review of various passenger related performance indicators for use in railway timetabling process. Parbo et al. (2016) also discuss how these performance indicators can be used to assess and analyse the travel behaviour with respect to the railway service and timetable. Conventional passenger related performances can be generally summarised as journey times and the associated reliability, passengers' service waiting times, and crowdedness. Compared with the operators' performances such as service revenue and throughout, these passenger and society related service indicators do not appear to have received the same level of attention in timetabling process. As recognised in Parbo et al. (2016) and many national railway sectors such as the Rail Safety Standard Board (RSSB) in the UK (Chen and Roberts, 2012), it is vital to take customers' perspective into account when deriving a train timetable for long term benefits such as ensuring a sustainable and viable patronage.

In our previous studies, we have taken initial effort building an event-based modelling framework for train timetabling process (see Chow et al. (2016) and Pavlides and Chow (2018)). This study furthers our previous effort by deriving and analysing different cost functions representing interests of both operators and passengers, investigating the sensitivity of the timetabling process with respect to demand levels and service resources (e.g. availability of rolling stock), and analysing the trade-off between different interests through use of the Pareto optimality frontiers. Instead of attempting to develop any advanced solution algorithms, this paper focuses on formulations of operational constraints and cost functions, and demonstrate how they can be applied to a multi-objective timetabling process. An objective herein is to identify and derive various performance metrics applicable to the railway timetabling process. Instead of focusing on one single stakeholder in the railway industry, the interests of multiple stakeholders are considered via the multi-objective optimisation formulation. This contributes to the state-of-the-art of existing practice which mostly focuses on optimisation of two or three objective functions that are typically tailored from the operators' perspective. Important aspects or research questions to be investigated in this study include: in what ways does the off-peak (in terms of passenger demand) timetable differ from a peak-time timetable; whether there are ways to (re-)sequence and (re-)schedule trains that could lead to better overall performance and utilisation of existing infrastructure; how do different kind of passengers (commuters, business, and leisure travellers) benefit differently from the proposed optimisation framework.

The paper starts with formulating a set of timetable based decision variables and their associated operational constraints in mixed train service settings. The operational constraints represent signal blocking system, minimum train headways, minimum dwell times, and speed limits in railway systems. The operational constraints are then followed by formulations of novel cost functions reflecting various customer concerned performances. These performances include journey times, customer waiting times, punctuality, and crowdedness. The cost functions are then used to formulate a multi-objective optimisation problem (see e.g. Ghoseiri et al. (2004), Albrecht (2009), Bussieck et al. (2009), Sama et al. (2015), and Chow et al. (2017)) which is solved by an integrated Genetic Algorithm-Dijkstra heuristics. The cost functions and optimisation framework is applied to the Brighton Main Line (BML) in Southeast England as a case study. The results reveal how the current timetable is assessed and able to improve with the proposed cost functions and optimisation framework. Pareto frontiers are also derived to reflect the trade off between different objectives in the optimisation process under different circumstances.

The paper is organised as follows: Section 2 starts with presenting the model specification of timetable and its associated constraints. In Section 3, we formulate a set of cost functions for assessing different performances from both operators' and customers' perspective. The cost functions are used to formulated a multi-objective optimisation problem in Section 4 for train timetabling with the proposed solution heuristics. In Section 5, the cost functions and optimisation framework are applied to a case study of Brighton Main Line in order to demonstrate the proposed method and the results are discussed. Finally, Section 6 provides some final remarks and suggestion for future work.

2. Representation of timetable and associated constraints

Following Chow et al. (2016) and Pavlides and Chow (2018), a train timetable is represented herein as a defined series of times of train arrivals $\tau_{n,s}$ and departures $\sigma_{n,s}$ of each train n over a set of control points s (which can be a station, junction, etc.) along its service route (Assad, 1980; Caprara et al., 2002; Dorfman and Medanic, 2004). Given $\sigma_{n,s}$ and $\tau_{n,s}$, we can derive the running time $T_{n,s}$ of train n between station s and $s+1$ as

$$T_{n,s} = \tau_{n,s+1} - \sigma_{n,s}, \tag{1}$$

and also the dwell time $D_{n,s}$ of train n at station s

$$D_{n,s} = \sigma_{n,s} - \tau_{n,s}, \tag{2}$$

The setting of the variables $\sigma_{n,s}$ and $\tau_{n,s}$ will be subject to a set of operational constraints. These constraints would restrict the railway timetable in achieving the objectives during the optimisation process. These constraints will apply in terms of the business requirements, system characteristics and operational rules (Chen and Roberts, 2012). Following a comprehensive survey, Chen and Roberts (2012) summarise a set of common constraints for designing and managing railway systems and operations, which include: