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A two-step linear programming model for energy-efficient timetables in metro railway networks

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ABSTRACT

In this paper we propose a novel two-step linear optimization model to calculate energy-efficient timetables in metro railway networks. The resultant timetable minimizes the total energy consumed by all trains and maximizes the utilization of regenerative energy produced by braking trains, subject to the constraints in the railway network. In contrast to other existing models, which are $\mathcal{NP}$-hard, our model is computationally the most tractable one being a linear program. We apply our optimization model to different instances of service PES2-SFM2 of line 8 of Shanghai Metro network spanning a full service period of one day (18 h) with thousands of active trains. For every instance, our model finds an optimal timetable very quickly (largest runtime being less than 13 s) with significant reduction in effective energy consumption (the worst case being 19.27%). Code based on the model has been integrated with `Thales Timetable Compiler` - the industrial timetable compiler of Thales Inc that has the largest installed base of communication-based train control systems worldwide.

1. Introduction

1.1. Background and motivation

Efficient energy management of electric vehicles using mathematical optimization has gained a lot of attention in recent years (Bashash et al., 2011; Mura et al., 2013; Nuesch et al., 2012; Patil et al., 2012; Saber and Venayagamoorthy, 2010). When a train makes a trip from an origin platform to a destination platform, its optimal speed profile consists of four phases: 1) maximum acceleration, 2) speed hold, 3) coast and 4) maximum brake (Howlett and Pudney, 1995), as shown in Fig. 1 in a qualitative manner. Most of the energy required by the train is consumed during the accelerating phase. During the speed holding phase the energy consumption is negligible compared to accelerating phase, and during the coasting phase there is no need for energy. When the train brakes, it produces energy by using a regenerative braking mechanism. This energy is called regenerative braking energy. Calculating energy-efficient timetables for trains in railway networks is a relevant problem in this regard. Electricity is the main source of energy for trains in most modern railway networks; in such networks, a train is equipped with a regenerative braking mechanism that allows it to produce electrical energy during its braking phase. In this paper, we formulate a two-step linear optimization model to obtain an energy-efficient timetable

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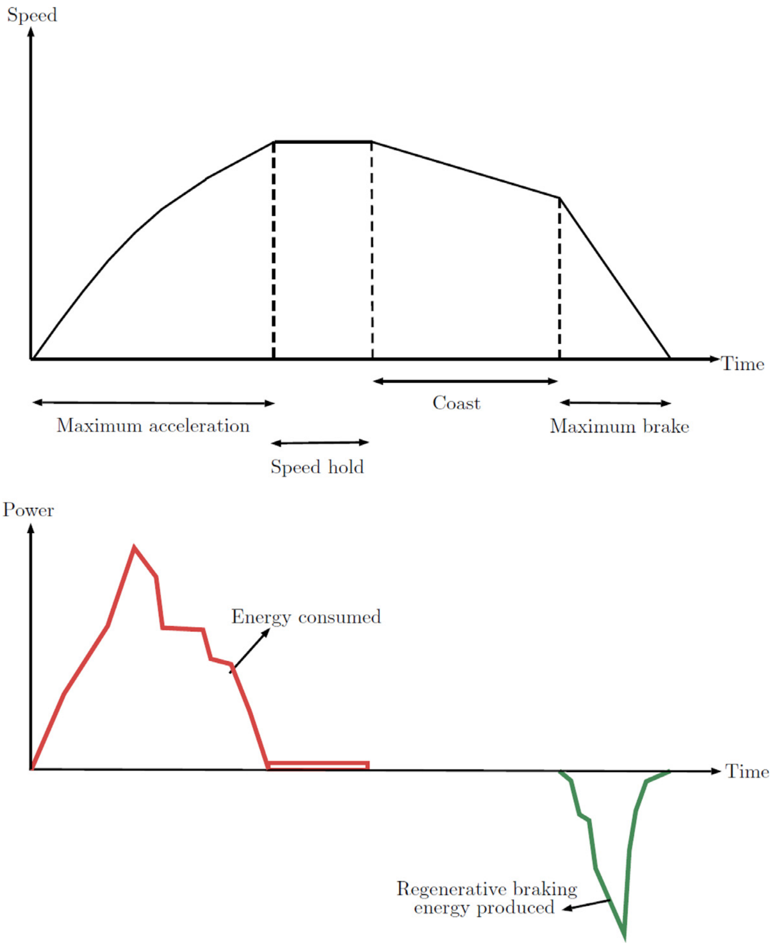

Fig. 1. Optimal speed profile of a train.

for a metro railway network. The timetable schedules the arrival time and the departure time of each train to and from the platforms it visits such that the total electrical energy consumed is minimized and the utilization of produced regenerative energy is maximized.

1.2. Related work

The general timetabling problem in a metro railway network has been studied extensively over the past three decades (Harrod, 2012). However, very few results exist that can calculate energy-efficient timetables. Now we discuss the related research. We classify the related work as follows. The first two papers are mixed integer programming model, the next three are models based on meta-heuristics and the last one is an analytical study.

A Mixed Integer Programming (MIP) model, applicable only to single train-lines, is proposed by Peña-Alcaraz et al. (2012a) to maximize the total duration of all possible synchronization processes between all possible train pairs. The model is then applied successfully to line three of the Madrid underground system. However, the model can have some drawbacks. First, considering all train pairs in the objective will result in a computationally intractable problem even for a moderate sized railway network. Second, for a train pair in which the associated trains are far apart from each other, most, if not all, of the regenerative energy will be lost due to the transmission loss of the overhead contact line. Finally, the model assumes that the durations of braking and accelerating phases stay the same with varying trip times, which is not the case in reality.

The work in Das Gupta et al. (2015) proposes a more tractable MIP model, applicable to any railway network, by considering only train pairs suitable for regenerative energy transfer. The optimization model is applied numerically to the Dockland Light Railway and shows a significant increase in the total duration of the synchronization process. Although such increase, in principle, may increase the total savings in regenerative energy, the actual energy saving is not directly addressed. Similar to Peña-Alcaraz et al. (2012a), this model too, assumes that even if the trip time changes, the duration of the associated braking and accelerating stay the same.