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Design of energy-Efficient timetables in two-way railway rapid transit lines

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ABSTRACT

A methodology to design energy-efficient timetables in Rapid Railway Transit Networks is presented. Using an empirical description of the train energy consumption as a function of running times, the timetable design problem is modelled as a Mixed Integer Non-Linear optimization problem (MINLP) for a complete two-way line. In doing so, all the services in both directions along a certain planning horizon are considered while attending a known passengers' demand. The MINLP formulation, which depends on train loads, is fully linearised supposing train loads are fixed. A sequential Mixed Integer Linear solving procedure is then used to solve the timetabling optimization problem with unknown train loads. The proposed methodology emphasizes the need of considering all the services running during the planning horizon when designing energy-efficient timetables, as consequence of the relationship among train speeds, frequency and fleet size of each line. Moreover, the convenience of considering the energy consumption as part of a broad objective function that includes other relevant costs is pointed out. Otherwise, passengers and operators could face up to an increase in the whole cost and a decrease in the quality of service. A real data scenario, based on the C-2 Line of the Madrid Metropolitan Railways, is used to illustrate the proposed methodology and to discuss the differences between the energy-efficient solutions and those obtained when considering operation and acquisition costs.

1. Introduction

Railway transportation is the cheapest land transportation mode. A quick view tell us that this fact can rely in the big capacity of trains as compared with other modes and also in the broad typology and versatility of train services, including passengers and freight transportation, long, short and medium distance trips, each one with its own characteristics. In this paper we concentrate our analysis on Railway Rapid Transit systems (RRT systems for short), which are daily chosen by thousands of commuters to access the city centers for work or, conversely, to travel from the city to universities and industrial areas. To be more precise but generally speaking, our attention will be centered around the role of timetables design in the context of RRT systems costs with a special emphasis on energy consumption.

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Some interesting data can be obtained from the literature. For example, in Zhang (2010) it is concluded that energy consumption in RRT systems accounts for about one third of the corresponding to the bus mode and lees than the 12% of energy consumed by the private cars. Some studies concerning railway transportation costs (see e.g. Coto-Millán et al., 2013; de Rus, 2009) give us an idea about the real impact of energy consumption among all the railway development and exploitation costs. In particular, from the work presented in de Rus (2009), which conducted a research of 166 international railway development projects, we can conclude that fixed costs (construction plus rolling stock) suppose between 50%–60% of the total project costs (5% attributable to rolling stock), whereas exploitation accounts for the remaining 50%-40%. Just to have an idea of how much money is involved, let us mention the monograph Coto-Millán et al. (2013) where, in the context of high-speed lines (Madrid-Valencia AVE in Spain), the rolling stock cost is shown to reach 286 million euros.

From all of these studies, a more or less standard classification of operational costs comes out. They can be divided into personnel costs ($\approx$ 20%), infrastructure maintenance ($\approx$ 20%), maintenance of vehicles ($\approx$ 7%), energy ($\approx$ 7%), depreciation ($\approx$ 10%), financial costs ($\approx$ 6%) and other costs ($\approx$ 30%). From the percentage due to energy consumption, around 50% is consumed by train units. The rest is used to operate infrastructure facilities (e.g., stations and depots, tunnel ventilation fans, tunnel lighting, etc.) González-Gil et al. (2014); 2015). These results are consistent with those of Sinha and Labi (2007, Chapter 4). On the other hand, for other kinds of railway systems (e.g. non high-speed railways), operational costs can reach the 70% of investments when considering long planning horizons. In any case, energy consumption for electrical railways represents less than 10–12% of the operational costs (see e.g. Sinha and Labi, 2007; Song et al., 2014; Steer Davies Gleave, 2015). This fact gives us an idea about the role that the minimization of energy consumption could play in reducing the operational costs, and calls into question the convenience of using it as the only criterion when designing saving cost timetables. Since it could give rise to an increase in other important costs, a more in-depth analysis becomes necessary, at least to have a deeper idea of the price to be paid for reducing consumption and emissions in order to meet criteria of environmental preservation.

Due in part to the growing importance of this type of ecological criteria (see e.g. the European Union energy efficiency directives Directive 2012/27/EU of the European Parliament and of the Council of 25 October 2012, 2012; European Commission, 2016), during last years many researchers have focused their efforts on the energy-efficient analysis of railways, concerning two main aspects. The first one related with the design of optimal speed profiles and optimal driving strategies with the objective of minimizing the journey energy consumption (see e.g. Howlett, 2000; Albrecht and Oettich, 2002; Albrecht et al., 2013; Xu and Li, 2016; Yang et al., 2015b; Yun et al., 2009; Howlett, 2016 and references therein). The second one has been directed towards the problem of optimizing energy-efficient partial timetables (see e.g. Goverde et al., 2016; Su et al., 2013; Xu and Li, 2016; Yang et al., 2014; Li and Lo, 2014b, Li and Lo, 2014a and references therein). In the context of energy-efficiency rail operation, timetable optimization refers to the synchronization of train acceleration and braking in order to maximize the utilization of regenerative energy rather than designing timetables from scratch in order to meet a given demand.

The optimal driving strategy can be obtained by using the well-known Pontryagin maximum principle Pontryagin et al. (1962), which decomposes the running time in an open track in several regimes: maximum acceleration, cruising, coasting, and maximum braking Albrecht et al. (2015); 2016a); 2016b). The minimization of the energy consumption consists in determining the so-called switching points, where the trains must change from one regime to another. Following this direction, Howlett (2000) considered the problem of determining an optimal driving strategy in a train control problem with a generalised equation of motion. Considering that the total running time is fixed, this work analyses the case of continuous and discrete control. In the first case, the author used the Pontryagin principle to find necessary conditions on an optimal strategy. In the discrete control problem, Howlett showed that for each fixed control sequence the cost of fuel can be minimised by finding the optimal switching times, obtained by means of the Kuhn–Tucker conditions. Albrecht and Oettich (2002) presented a new approach to fulfil conflicting goals in dynamic schedule synchronization and energy saving for rapid railway transit systems. They proposed a dynamic programming approach to obtain the minimum energy trip times based on the solution of the optimal train control problem, reducing power peaks and energy consumption by modifying the running times of trains. A different and more complete approach is given in Su et al. (2013), where an iterative algorithm is used to obtain the driving strategy for the entire line, integrating the driving strategy optimization and the distribution of trip times. Ye and Liu (2016) considered a combined train control and scheduling problem involving multiple trains in a railway line with a predetermined departure/arrival sequence of trains at stations and meeting points along the line. The problem was formulated as a multiphase optimal control problem incorporating complex train running conditions such as variable speed, running resistances, speed-dependent maximum tractive and braking forces and practical operation constraints concerning departure, arrival, running and dwell times. Howlett (2016) presented a new derivation of a key formula for the rate of change of energy consumption with respect to journey time on an optimal train journey. The formula is derived by using the local energy minimization principle. When no speed limits are imposed, the optimal strategy consists of a finite sequence of phases with only five permissible control modes: Maximum acceleration, speedhold with partial acceleration at the optimal driving speed, coast, speedhold with partial brake at the optimal regenerative braking speed and maximum brake. Haahr et al. (2017) considered a novel solution method for generating improved train speed profiles with reduced energy consumption. Instead of using a uniform discretization of time and space, they considered an event-based decomposition that reduces the search space. The solution method makes use of a time-space graph formulation which can be solved by using dynamic programming.