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Real-time energy consumption minimization in railway networks

Teresa Montrone[a,*], Paola Pellegrini[b], Paolo Nobili[c]

[a] ESTECO S.p.A, AREA Science Park, Padriciano 99, Trieste 34149, Italy
[b] University Lille Nord de France, F-59000 Lille, IFSTTAR, COSYS, LEOST, Rue Élisée Reclus, BP-70317, F-59650 Villeneuve d'Ascq, F-59666, France
[c] University of Salento, Via per Arnesano, Lecce 73100, Italy

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ABSTRACT

A new timetable must be calculated in real-time when train operations are perturbed. Although energy consumption is becoming a central issue both from the environmental and economic perspective, it is usually neglected in the timetable recalculation. In this paper, we formalize the real-time Energy Consumption Minimization Problem (rtECMP). It finds in real-time the driving regime combination for each train that minimizes energy consumption, respecting given routing and precedences between trains. In the possible driving regime combinations, train routes are split in subsections for which one of the regimes resulting from the Pontryagin's Maximum Principle is to be chosen. We model the trade-off between minimizing energy consumption and total delay by considering as objective function their weighted sum. We propose an algorithm to solve the rtECMP, based on the solution of a mixed-integer linear programming model. We test this algorithm on the Pierrefitte-Gonesse control area, which is a critical area in France with dense mixed traffic. The results show that the problem is tractable and an optimal solution of the model tackled can often be found in real-time for most instances.

1. Introduction

In the railway system, the *timetable* is designed so that traffic can be smoothly operated. The timetable specifies the passing and stopping times of each train at a set of relevant points along the infrastructure. These times are such that, in absence of perturbations, trains traveling at their planned speed never encounter signals with restrictive aspects. However, when unexpected events occur during operations, causing train delays, a new timetable must be computed in real-time. In practice, this computation is usually not fully automated, but a dispatcher manually establishes routes and schedules to perform traffic operations minimizing delays.

The real-time Railway Traffic Management Problem (rtRTMP) is the problem of automatically establishing the train routing and scheduling in real-time, minimizing a function of delay propagation. In the literature, several models and algorithms are proposed for handling and solving the rtRTMP, e.g., Corman et al. (2010), D'Ariano et al. (2008), Mannino and Lamorgese (2010) and Pellegrini et al. (2015). Typically, the rtRTMP does not consider energy consumption, which, however, is becoming a central issue both from the environmental and economic perspective.

In this paper, we define the real-time Energy Consumption Minimization Problem (rtECMP). Indeed, when a train travels through an infrastructure, it uses different driving regimes to follow a speed profile compatible both with the infrastructure characteristics and the traffic condition. Energy consumption depends on the driving regimes followed by the trains. The rtECMP finds the driving regime combinations which minimize energy consumption in real-time. These combinations consider as an input the routing and the

* Corresponding author.
E-mail address: montrone@esteco.com (T. Montrone).

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precedences between the trains of an rtRTMP solution and comply with them. The objective of the problem is the minimization of the weighted sum of energy consumption and total delay. Therefore, the importance of energy consumption and total delay in the problem depends on their weights in the objective function.

Few approaches exist in the literature to deal with this problem, as we discuss in the literature review. Typically, they are adaptations of approaches originally designed for optimizing train speed profiles in absence of traffic, and can deal with no more than a couple of trains at a time.

In this work, we propose a Mixed-Integer Linear Programming (MILP) model to formalize the rtECMP. Moreover, we define an algorithm based on the solution of this MILP model, which we call Train Driving Regime Combination-MILP, or TDRC-MILP. TDRC-MILP starts with the calculation of the trains travel times and energy consumption corresponding to different driving regime combinations. After this calculation, it creates the model, solves it through a MILP solver and returns the optimal solution or the best solution found after the elapse of a predefined maximum computation time. We propose an experimental analysis on instances representing traffic in the Pierrefitte-Gonesse control area in France. This control area corresponds to a complex junction with dense mixed traffic.

The rest of the paper is organized as follows. Section 2 introduces some railway definitions that are used in the rest of the paper. Section 3 describes the train movements, in particular the train driving regimes used in this work. Section 4 presents a detailed literature review on the methods to minimize energy consumption in real-time. Section 5 introduces the rtECMP and Section 6 describes the MILP model which formalizes it. Section 7 presents the algorithm and Section 8 reports the experimental analysis. Section 9 concludes the paper. Finally, Appendix A summarizes the main notation used here and Appendix B reports some detailed results omitted in the text for sake of brevity.

2. Railway definitions

Railway networks are split in *control areas* that are managed by dispatchers. A control area may contain *junctions* that are locations where several lines cross. Moreover, a control area may include *stations*, i.e., particular junctions where trains may stop for what is called *dwell time* for some specific activities or services, such as boarding and unloading passengers.

In a control area, the safety separation between trains is ensured by the signaling system. In railway signaling systems, the interlocking describes how tracks and signals are electrically or otherwise interconnected to prevent conflicting train movements and to ensure that movements are safe.

Signals delimit sections of tracks called *block sections*. More specifically, a block section is delimited by two signals, one at its start (entry signal) and another at its end (exit signal). The exit signal of a block section corresponds to the entry signal of the subsequent one. Each block section contains one or more *track-circuits*, which are portions of tracks where the presence of a train is automatically detected. Block sections that share some track-circuits are called *incompatible*, an example of which is presented in Fig. 1. Here, block section 1 is composed of track-circuits A, B, D and block section 2 is composed of A, B, C. Track-circuit B contains a *switch*, which is a mechanical installation that enables the train to be guided from a track to another. The block sections share track-circuits A and B: they have the same entry signals but different exit signals. They are said to be incompatible because their simultaneous use by two trains is not compatible with the safety regulations, unless the precise position of the trains is known and the common track-circuits are guaranteed to be cleared by the first one before the second one can occupy them.

Block sections can be used by at most one train at a time. To warrant the respect of this rule, when a block section is to be traversed by a train, all its track-circuits need to be reserved concurrently before the start of their physical occupation. When these track-circuits are reserved, all block sections, including one or more of them, are locked. These are the block sections incompatible with the one that is to be traversed. The unlocking of the block sections depends on the interlocking system. In this paper, we consider the *route-lock route-release interlocking system* (Pachl, 2008), in which all the incompatible block sections are released simultaneously shortly after the train exits the traversed one.

For precision, let us mention that the reservation of the track-circuits and the lock of the block sections start shortly in advance to consider the *formation time*. The formation time is given by the time for clearing the signals, the time needed by the train driver to see the signal aspect, and the route formation time. Similarly, the unlocking is not immediate after the exit of the train, indeed a short time is necessary for resetting the block sections in the default condition. This is named *release time*.

The signaling systems can have n aspects, the most frequent being three. In a three-aspect signaling system, all block sections are long enough to assure that each train that enters one of them at its maximum allowed speed is able to stop at the end of it. More specifically, the three-aspects are green, yellow and red. When a block section is opened by a green signal, both the block section itself and the following one are available. Therefore, a train crossing the green signal can travel at its planned speed, and both the block section in which it is entering and the following one are reserved for it. When a block section is opened by a yellow signal, the subsequent block section is available, but the following one is not. Hence, the train travel must be such that the train itself will be able

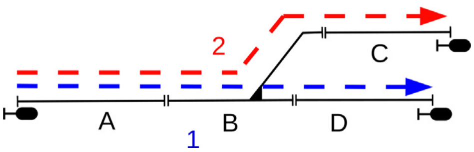

Fig. 1. Example of incompatible block sections.