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Integration of real-time traffic management and train control for rail networks - Part 2: Extensions towards energy-efficient train operations ☆

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ABSTRACT

We study the integration of real-time traffic management and train control by using mixed-integer nonlinear programming (MINLP) and mixed-integer linear programming (MILP) approaches. In Part 1 of the paper (Luan et al., 2018), three integrated optimization problems, namely the P_{NLP} problem (NLP: nonlinear programming), the P_{PWA} problem (PWA: piecewise affine), and the P_{TSPO} problem (TSPO: train speed profile option), have been developed for real-time traffic management that inherently include train control. A two-level approach and a custom-designed two-step approach have been proposed to solve these optimization problems. In Part 2 of the paper, aiming at energy-efficient train operation, we extend the three proposed optimization problems by introducing energy-related formulations. We first evaluate the energy consumption of a train motion. A set of nonlinear constraints is first proposed to calculate the energy consumption, which is further reformulated as a set of linear constraints for the P_{TSPO} problem and approximated by using a piecewise constant function for the P_{NLP} and P_{PWA} problems. Moreover, we consider the option of regenerative braking and present linear formulations to calculate the utilization of the regenerative energy obtained through braking trains. We focus on two objectives, i.e., delay recovery and energy efficiency, through using a weighted-sum formulation and an ε-constraint formulation. With these energy-related extensions, the nature of the three optimization problems remains same to Part 1. In numerical experiments conducted based on the Dutch test case, we consider the P_{NLP} approach and the P_{TSPO} approach only and compare their performance with the inclusion of the energy-related aspects; the P_{PWA} approach is neglected due to its bad performance, as evaluated in Part 1. According to the experimental results, the P_{TSPO} approach still yields a better performance within the re-

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quired computation time. The trade-off between train delay and energy consumption is investigated. The results show the possibility of reducing train delay and saving energy at the same time through managing train speed, by up to 4.0% and 5.6% respectively. In our case study, applying regenerative braking leads to a 22.9% reduction of the total energy consumption.

1. Introduction

Railway transport systems are of crucial importance for the competitiveness of national or regional economy as well as for the mobility of people and goods. To maintain the environmental advantage and business benefits of railway sectors, targets have been set by the International Union of Railways (UIC, 2012) to reduce the carbon dioxide (CO_2) emissions and energy consumption from train operations by 50% and 30% respectively in 2030, compared to 1990. Such policies reflect an increasing concern for sustainability and energy efficiency. Consequently, energy-efficient train operation is attracting more and more attention, which is seen as the most important measure to reduce the environmental impacts and the costs used to power trains.

In railway transport systems, the energy efficiency is greatly influenced by the train operation strategy, which consists of the operational train timetables and the applied driving actions. The former relates to the real-time traffic management problem, i.e., (re-)scheduling train routes, orders, and passing times at stations, aiming at adjusting the impacted schedules from perturbations and reducing negative consequences. The latter concerns the train control problem, i.e., optimizing the sequence of driving regimes (maximum acceleration, cruising, coasting, and maximum braking) and the switching points between the regimes, with the aim of minimizing energy consumption. As discussed in Part 1 of this paper, the two problems are closely related to each other. In order to achieve energy-efficient train operation, one of the most promising options is to jointly consider the two problems, i.e., (re-)constructing a timetable in a way that not only allows different driving actions, but enables eco-driving actions (resulting in better energy performance). This comes from, e.g., avoiding unneeded accelerating and braking actions, which do not only lead to trains delays, but also unnecessary waste of energy. Another promising option is to incorporate regenerative braking, so that the energy generated by braking trains can be further utilized for accelerating trains, and then the overall energy consumption of train operations decreases. As a result, to compute the energy-efficient train trajectory and further achieve the energy efficiency of train operations, the focus on only train delay is not enough; approaches that not only include train delays but also evaluate energy consumption and consider regenerative energy utilization are desired.

In most studies of the real-time traffic management problem, train delay is a commonly used objective, and any dynamics-related objective, such as energy consumption, cannot be directly considered, due to the disregard of train dynamics, However, the objective of energy consumption is considered only in train control studies. In Part 1 of this paper, the integration of the two problems has been addressed, and three integrated optimization approaches have been developed to consider both traffic-related properties (i.e., a set of times, orders, routes to be followed by trains) and train-related properties (i.e., speed trajectories) at the same time, focusing on only delay recovery. These integrated optimization approaches build up a good foundation and enable us to introduce energy-related formulations and to focus on delay recovery and energy efficiency at the same time.

In this part of the paper, we focus on the train control part of the integrated optimization approaches while including energy-related formulations. We first introduce the evaluation of energy consumption into the integrated optimization problems. To calculate the energy consumption, a set of linear constraints is proposed for the P_{TSPO} problem; for the P_{NLP} and P_{PWA} problems, the resistance function with a quadratic term of train speed is approximated with a piecewise constant function, in order to maintain the nature of these two optimization approaches. In addition, we consider the option of regenerative braking and present linear formulations to calculate the utilization of the energy obtained through regenerative braking. With the inclusion of the energy-related formulations, we consider two objectives, i.e., delay recovery and energy efficiency, by using a weighted-sum formulation and an ε-constraint formulation. We use the Dutch test case to conduct experiments, just as in Part 1. We compare the performance of the optimization approaches and investigate the trade-off between train delay and energy consumption. By our approaches, train delay and energy consumption can be reduced at the same time through managing the train speed, by up to 4.0% and 5.6% respectively. This demonstrates the benefit of the integration and shows great potential for energy efficiency of train operations. Moreover, the benefit of regenerative braking is shown. In our case study, when applying regenerative braking, up to 53.3% of the kinetic energy can be stored, and up to 46.6% of the stored energy is re-utilized for train acceleration, which further leads to a 22.9% reduction of the total energy consumption.

In the experiments, the proposed optimization approaches can obtain feasible solutions (with good quality) of the train delay and energy consumption minimization problem, for a single direction along a 50 km corridor with 9 stations and 15 trains each hour within a computation time of 3 minutes.