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Integration of real-time traffic management and train control for rail networks - Part 1: Optimization problems and solution approaches

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A B S T R A C T

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. Three innovative integrated optimization approaches for real-time traffic management that inherently include train control are developed to deliver both a train dispatching solution (including train routes, orders, departure and arrival times at passing stations) and a train control solution (i.e., train speed trajectories). Train speed is considered variable, and the blocking time of a train on a block section dynamically depends on its real speed. To formulate the integrated problem, we first propose an MINLP problem (P_{NLP}), which is solved by a two-level approach. This MINLP problem is then reformulated by approximating the nonlinear terms with piecewise affine functions, resulting in an MILP problem (P_{PWA}). Moreover, we consider a preprocessing method to generate the possible speed profile options for each train on each block section, one of which is further selected by a proposed MILP problem (P_{TSPO}) with respect to safety, capacity, and speed consistency constraints. This problem is solved by means of a custom-designed two-step approach, in order to speed up the solving procedure. Numerical experiments are conducted using data from the Dutch railway network to comparatively evaluate the effectiveness and efficiency of the three proposed approaches with heterogeneous traffic. According to the experimental results, the MILP approach (P_{TSPO}) yields the best overall performance within the required computation time. The experimental results demonstrate the benefits of the integration, i.e., train delays can be reduced by managing train speed.

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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 improve reliability of train services and increase satisfaction of customers, many railway infrastructure managers (e.g., Network Rail in United Kingdom and Banedanmark in Denmark) and train operating companies (e.g., V/Line in Australia) have set their own targets for train punctuality, in terms of punctuality rates. Moreover, there have been many projects over the years that have aimed at improving the punctuality of trains, such as the On-Time project (Quaglietta et al., 2016). Policy makers and researchers have been seeking approaches for attaining the punctuality goals.

In real operations, unavoidable perturbations (caused by bad weather, infrastructure failure, extra passenger flow, etc.) often happen and result in delays to the original train timetable, which make difficulties in achieving the punctuality goals. When trains are delayed from the normal operation, train dispatchers are in charge of adjusting the impacted train timetables from perturbations (by means of taking proper dispatching measures, e.g., re-timing, re-ordering, and re-routing), so as to reduce potential negative consequences (train delays); train drivers are responsible for controlling the delayed trains (by means of taking proper driving actions, i.e., accelerating, cruising, coasting, and braking) to reach the stations at the times specified by train dispatchers, with the aim of minimizing energy consumption. The problem faced by train dispatchers is well-known as the real-time traffic management problem, and the problem encountered by train drivers is the so-called train control problem. In fact, significant interconnections exist between these two problems, as the traffic-related properties have impact on the train-related properties, and vice versa. Solving the two problems in a sequential way hides the potential improvements in performance of train operations. Better train operations can be potentially achieved by jointly considering the two problems, i.e., (re-)constructing a train timetable in a way that applies different diving actions. However, such a joint consideration leads to a very complex and difficult optimization problem, because not only the timetable should be well-defined for synchronizing the accelerating and braking actions of trains in the same block section, but also the driving actions should be controlled under the speed limits, travel time, and distance constraints (Tuyttens et al., 2013). This is even more critical and difficult for real-time operations. Moreover, the safety headway between two consecutive trains dynamically depends on their real speed and acceleration/deceleration rate. As a result, a prompt and reliable decision-making support tool for both dispatchers and drivers is desired, which requires the integration of a rescheduling optimization with microscopic details and highly accurate real-time train speed trajectory optimization at once.

A growing body of scientific literature is available for real-time traffic management (e.g., the recent survey by Fang et al., 2015) and train control (e.g., the recent review by Yang et al., 2016). These two problems are well-studied separately, but a gap still exists with regards to their integration. Most approaches focus only on one side of the problem and include parts of the other by control loops, extra constraints, hierarchical decomposition, or additional objectives. Such focus on a single side of the problem leaves an open gap in terms of operational performance of jointly considering those two perspectives at once. The purpose of achieving better train operation and the gap in the scientific literature motivate us to address their integration.

We therefore address the integration of real-time traffic management and train control by using optimization methods, identifying 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 once. To formulate the integrated problem, a mixed-integer non-linear programming (MINLP) problem (P_{NLP}) is first proposed and solved by a two-level approach. An approximation based on piecewise affine functions, is applied to the nonlinear terms in the P_{NLP} problem, which results in a mixed-integer linear programming (MILP) problem (P_{PWA}). Furthermore, a preprocessing method for generating the possible train speed profile options (TSPOs) for each train on each block section is considered to reduce the complexity of the problem and to restrict the search only to a subset that allows better energy performance. An MILP problem (P_{TSPO}) is developed to determine the optimal option with minimum train delays. The two MILP problems are both solved by using an MILP solver, but a custom-designed two-step method is particularly used for the P_{TSPO} problem to speed up the solving procedure. In our optimization problems, the blocking time of a train on a block section dynamically depends on its real speed. We consider the minimization of the total train delay times as the objective. According to the experimental results, the proposed approach can obtain feasible solutions (with good quality) of the integrated traffic management and train control problem for a single direction along a 50 km corridor with 9 stations and 15 trains each hour within 3-min computation time, meanwhile the goal of reducing train delays by managing train speed can be achieved. In Part 2 of this paper, we further discuss energy-related extensions based on the proposed optimization approaches, i.e., evaluating energy consumption and computing regenerative energy utilization. With the inclusion of the energy-related aspects, we aim at both delay recovery and energy efficiency, in order to achieve energy-efficient train operation.

The remainder of this paper is organized as follows. Section 2 provides a detailed literature review on the studies addressing the real-time railway traffic management problem without considering train dynamics, and the studies dealing with the interaction of traffic management and train control for better train operations. In Section 3, a problem statement and assumptions are given first. Then, three optimization problems formulating the integration of traffic management and train control are presented. Section 4 introduces the solution approaches for the three proposed problems, i.e., a two-level approach for solving the MINLP problem (P_{NLP}), and a custom-designed two-step method for improving the computational efficiency of the MILP problem (P_{TSPO}). Experimental results based on a real-world railway network are given