# Multiple-phase train trajectory optimization with signalling and operational constraints 

Pengling Wang ${ }^{\mathrm{a}, \mathrm{b}, *}$, Rob M.P. Goverde ${ }^{\mathrm{a}}$<br>${ }^{\text {a }}$ Department of Transport and Planning, Delft University of Technology, Delft, The Netherlands<br>${ }^{\mathrm{b}}$ School of Electrical Engineering, Southwest Jiaotong University, Chengdu, China

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#### Abstract

The train trajectory optimization problem aims at finding the optimal speed profiles and control regimes for a safe, punctual, comfortable, and energy-efficient train operation. This paper studies the train trajectory optimization problem with consideration of general operational constraints as well as signalling constraints. Operational constraints refer to time and speed restrictions from the actual timetable, while signalling constraints refer to the influences of signal aspects and automatic train protection on train operation. A railway timetable provides each train with a train path envelope, which consists of a set of positions on the route with a specified target time and speed point or window. The train trajectory optimization problem is formulated as a multiple-phase optimal control model and solved by a pseudospectral method. This model is able to capture varying gradients and speed limits, as well as time and speed constraints from the train path envelope. Train trajectory calculation methods under delay and no-delay situations are discussed. When the train follows the planned timetable, the train trajectory calculation aims at minimizing energy consumption, whereas in the case of delays the train trajectory is recalculated to track the possibly adjusted timetable with the aim of minimizing delays as well as energy consumption. Moreover, the train operation could be affected by yellow or red signals, which is taken into account in the train speed regulation. For this purpose, two optimization policies are developed with either limited or full information of the train ahead. A local signal response policy ensures that the train makes correct and quick responses to different signalling aspects, while a global green wave policy aims at avoiding yellow signals and thus proceed with all green signals. The method is applied in a case study of two successive trains running on a corridor with various delays showing the benefit of accurate predictive information of the leading train on energy consumption and train delay of the following train.


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## 1. Introduction

Improving transport capacity and saving energy consumption are the most urgent challenges faced by modern railway transportation all around the world. Optimizing train operation is one promising method, which doesn't need extra infrastructure, but improves rail traffic efficiency by optimizing train speed and control trajectories. One core function of train operation optimization is train trajectory calculation, which uses optimal control theory to calculate the optimal speed

[^0]profiles and control regimes, aiming at safe, on-time and energy saving train operation. These profiles are used to generate driving advise to support train drivers in train control.

Research on train trajectory calculation started in the 1960s. The solution methods of the train trajectory optimization problem can be divided into three categories: indirect methods, direct methods and artificial intelligence algorithms. The indirect approach solves the problem indirectly by converting the optimal control problem to a boundary-value problem. The direct method finds the optimal solution by transcribing a continuous optimization problem to a nonlinear programming problem (NLP). Researchers who focus on indirect methods are interested largely in solving differential equations, while researchers who focus on direct methods are interested more in optimization techniques (Betts, 1998; Rao, 2009). Pontryagin's Maximum Principle is a typical indirect method. The optimal train control strategy following from application of Pontryagin's Maximum Principle to a long journey on flat track with sufficient running time supplement consists of the sequence Maximum Power-Cruising-Coasting-Maximum Braking (Cheng and Howlett, 1992; Howlett and Pudney, 2012; Milroy, 1980). For a train operating on a track with varying speed limits and gradients the optimal control strategy is a sequence of these optimal regimes where the succession of regimes and their switching points also depends on the speed limits and gradients (Howlett, 1996; Khmelnitsky, 2000; Liu and Golovitcher, 2003; Pudney and Howlett, 1994). Finding the optimal switching points is a difficult problem except for simple cases such as a single speed limit and flat track (Albrecht et al., in press-b; Albrecht et al., in press-c). Direct approaches transform the optimal control problem into a mathematical programming problem. Wang et al. $(2013,2015)$ and Wang and Goverde (2016) reformulate the problem as a multiple-phase optimal control model, and solve it with Pseudospectral methods (Gong et al., 2008; Rao, 2003; Ross and Fahroo, 2004; Ross and Karpenko, 2012). Pseudospectral methods transcribe the continuous-time optimal control problem into a nonlinear programming problem, after which nonlinear programming solvers are adopted to directly solve the problem. In addition, a variety of heuristic and artificial intelligence algorithms have been applied to locate the energy-efficient train trajectory, such as fuzzy predictive algorithms (Yasunobu and Miyamoto, 1985) and genetic algorithms (Kang, 2011).

The classic single-train control problem focuses on one independent train from one station to the next under a scheduled traffic plan. Dynamic influences such as delays and signalling systems, are considered only recently. Delays or other disturbances cause deviations from the traffic plan, in which case the train may meet yellow or red signals, which require speed reductions and unscheduled stops. A rescheduling process is required to produce a new timetable when the deviation is big enough. As a result, the train trajectories also need to be adjusted accordingly. Albrecht et al. (2010) considered the influence of signalling and automatic train protection on the train trajectory optimization. This research is based on the optimal control regimes obtained from Pontryagin's Maximum Principle, and focuses on finding the optimal switching points to handle the influence of the signalling system. Albrecht et al. (2011) discuss energy-efficient delay recovery strategies for trains in opposite directions. They find a set of interaction times that allows each affected train to recover from delays as well as to save energy consumption, but energy-efficient train trajectory calculation is not discussed. Albrecht et al. (2015a) study the safe separation problem for two trains travelling in the same direction. To satisfy the safe separation for two following trains. An optimal set of specified intermediate clearance times for each section is calculated, which also aims at minimizing total energy consumption. Wang et al. (2014) consider the train trajectory planning problem under fixed and moving block signalling systems. They transform the optimal control problem into a mixed-integer linear programming problem. The nonlinear train dynamic movement model is simplified into a linear model, which speeds up the computation process but degrades the solutions' accuracy.

This paper gives several contributions to the literature. First, a rescheduling process may change the train's traffic plan, which requires adjustment of the train speed to track the new timetable. Second, a safe separation between trains running on the same line should be guaranteed. Third, an accurate calculation taking into account operational and signalling constraints is necessary since the train trajectory is designed to help train drivers in practical operation. Based on these three points, this paper formulates the real-time traffic plan for each train as a train path envelope (TPE), which was proposed first by Albrecht et al. (2013), see also ON-TIME (2014). Similar to the quadratic time geography theory (Ma et al., 2016; Zhou et al., 2015), train path envelopes set bounds to feasible trajectory ranges, including time and/or speed ranges at specific points. These time and/or speed ranges are available in real operation along a train run, within which the train can move without running late with respect to the timetable and hindering other trains' operations. If the timetable is changed by a rescheduling process, a new train path envelope must be generated and sent to the train trajectory calculation module. Based on this, new speed and control profiles are calculated.

Train separation is guaranteed by a signalling system. Generally speaking, if the train operation deviates from a conflictfree timetable, it might meet yellow or red signals. The influence from the signalling system cannot be ignored when calculating train trajectories, and in particular the information available about the future signal aspects affects the train trajectory calculation. Two different scenarios are proposed about the amount of signal information available to the trajectory optimization. In the first scenario, we assume that only information is available about the next signal aspect. An optimization strategy called signal response policy is developed to ensure that the train makes correct and quick responses to different signalling aspects. In the other scenario, we assume that a full prediction is available about the signal aspect timings in rear of the train ahead. A green wave policy (Corman et al., 2009) is then used to avoid yellow signals and thus separate successive trains. The focus of this paper is on successive trains in the same direction over the same line. The signalling system discussed is the Dutch signalling system, which is a variant of a three-aspect two-block system with additional speed indications together with a continuous ATP system. The method is however generic and any signalling system can be taken into account. Moreover, the work assumes an advanced traffic management environment such as the ON-TIME real-time railway

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[^0]:    * Corresponding author at: Department of Transport and Planning, Delft University of Technology, P.O. Box 5048, 2600 GA Delft, The Netherlands.

    E-mail addresses: P.L.Wang@tudelft.nl (P. Wang), R.M.P.Goverde@tudelft.nl (R.M.P. Goverde).

