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The interplay between energy-efficient train control and scheduled running time supplements

Gerben M. Scheepmaker [a, b, *], Rob M.P. Goverde [a]

[a] Department of Transport and Planning, Delft University of Technology, P.O. Box 5048, 2600 GA Delft, The Netherlands
[b] Department of Logistics, Netherlands Railways (NS), P.O. Box 2025, 3500 HA Utrecht, The Netherlands

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ABSTRACT

Energy-efficient train operation is not yet included in the timetable design process in the Netherlands. Hence, running time supplements are not optimally distributed in the timetable. Therefore research has been conducted on the possibilities to better incorporate energy-efficient train operation into the railway timetable. This paper describes the developed *EZR model* (energy-efficient operation or in Dutch 'EnergieZuinig Rijden') based on optimal control theory and an algorithm that determines the joint optimal cruising speed and coasting point for individual train trips; taking into account a desired robustness, the possibilities for energy-efficient operation, and the desired punctuality during operations. The model is applied in a case study of a regional train line in the Netherlands between Utrecht Centraal and Rhenen. The results show that it is better to distribute the running time supplements evenly than concentrating it near the main stations.

1. Introduction

Energy consumption is an important topic nowadays, also in the railway sector. A lot of money can be saved by decreasing the energy consumption of the trains. Besides, there are external benefits like decrease in CO_2 emission and noise hindrance. At the Netherlands Railways (NS), the largest passenger Railway Undertaking (RU) in the Netherlands, a lot of attention is paid to energy-efficient train driving. At this moment, NS is using the so-called *UZI method* (Universal energy-efficient driving idea or in Dutch 'Universeel Zuinig rijden Idee') during training of all train drivers (Franke, 2012). The *UZI method* is developed by train driver Freddy Velthuizen of NS. This method advises the train driver to accelerate as fast as possible until the recommended speed is reached. Then the train starts to cruise and/or to coast at the right point so the train will reach the next station in time. Near the next stop the train driver will apply the brake control to bring the train to standstill. Hence, the *UZI method* only describes where the train driver should start coasting.

The basic *UZI method* that is currently taught to train drivers distinguishes between a short distance (running time between two stopping stations of maximum 8 min) without cruising, where the scheduled running time determines the speed at which to start coasting, and a long distance (running time between two stopping stations of more than 8 min) with cruising at maximum allowed speed, where the speed limit determines the time when to start coasting. The method is visualized in Table 1 and the basic different speed profiles of the *UZI method* are shown in Fig. 1. The method can be applied at every type of rolling stock of NS (universal). However, for rolling stock type SGM (used for regional/sprinter services) the advice is limited,

* Corresponding author. Department of Transport and Planning, Delft University of Technology, P.O. Box 5048, 2600 GA Delft, The Netherlands.
E-mail address: g.m.scheepmaker@tudelft.nl (G.M. Scheepmaker).

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Table 1
UZI method for a short or long distance (Velthuizen and Ruijsendaal, 2011).

Short distance (without cruising)		Long distance (with cruising)	
Running time [min]	Coasting speed [km/h]	Speed limit [km/h]	Coasting time before arrival [min]
2	80	140	8 (not for rolling stock SGM)
3	90	130	7 (not for rolling stock SGM)
4	100	120	6
5	110	110	5
6	120	100	4
7	130 (not for rolling stock SGM)		
8	140 (not for rolling stock SGM)		

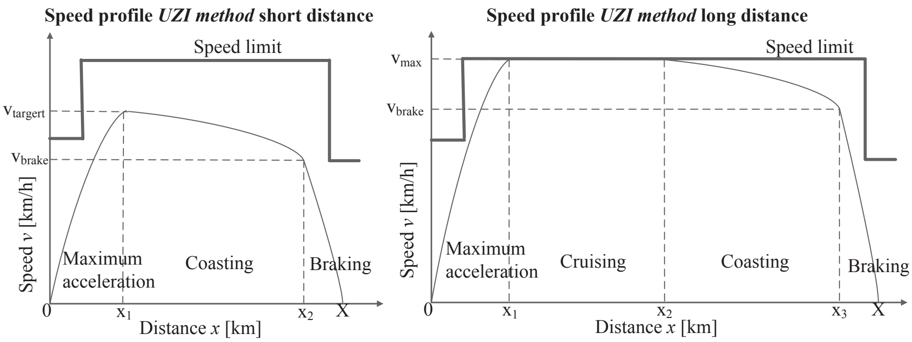

Fig. 1. *UZI method* basic speed profile (left: short distance and right: long distance).

since the maximum allowed speed of SGM is 120 km/h. The *UZI method* leads to considerable energy-savings of about 2%–5% per year.

However, the current method applied at NS is not the most energy-efficient train operation. Nowadays a lot of research is done on the topic of Driver Advisory Systems (DAS), that gives the train driver speed advice in order to minimize energy consumption and increase punctuality. A good overview of different DAS systems can be found in Kent (2009) and Panou et al. (2013). The energy-efficient driving strategy is determined by optimal control theory which leads to the theoretical optimum. In literature a lot of research has been done since the first study of Ichikawa (1968). Especially a lot of research on both continuous and discrete optimal control has been done by the Signalling and Control Group of the University of South Australia during the last thirty years, which can be found in for example Howlett and Pudney (1995), Howlett (2000) and Howlett et al. (2009). Their developed algorithms have been implemented in different DAS like *Metromiser, Freightmiser* and *Energymiser* (Albrecht et al., 2013; Howlett, 1990; Howlett et al., 2009).

All those strategies are in principle based on Pontryagin's Maximum Principle which derives the optimal train control. There are three different types of algorithms to solve the problem of energy-efficient train control between two stops:

1. Differential equations: modelling the train driving between two stops as a dynamic state model and explicitly find the solution of the optimal control by solving the differential equations. This will lead to the exact solution of the control problem. However, solving the set of different differential equations analytically is a very difficult process, so different algorithms are used to solve the control problem. Some examples can be found in Franke et al. (2000), Howlett et al. (2009), Khmelnitsky (2000) and Liu and Golovitcher (2003).
2. Artificial intelligence or searching algorithms: the driving behaviour of trains is modelled as a dynamic model and the (sub)optimal solution is estimated with artificial intelligence or searching algorithms using knowledge of the optimal control regimes. Examples can be found in Chevrier et al. (2013) and Sicre et al. (2014).
3. Simulation: the behaviour of trains is modelled as a non-linear model and the optimal control is estimated using simulated of the knowledge of the optimal control regimes. Domínguez et al. (2012) give an example of simulation.

It is also possible to solve the problem over multiple stations instead of two stations. This means that the overall journey time is fixed, but the times at the intermediate station are variable. The problem can be solved by for example Dynamic Programming (DP). In this method the train driving is simulated between successive stations, by assuming a multistage decision process and it finds the optimal solution with DP. The method uses the differential equations to solve the energy-efficient train control. An example can be found in T. Albrecht and Oettich (2002).

Energy-efficient train operation is related to the timetable, because the running time supplements in the timetable determine how much time there is for energy-efficient train operation. Running time supplements are the running times