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A tool for the rapid selection of a railway signalling strategy to implement train control optimisation for energy saving

Robert Dunbar*, Clive Roberts, Ning Zhao

Department of Electronic, Electrical and Systems Engineering, University of Birmingham, Edgbaston, Birmingham, B15 2TT, UK

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A B S T R A C T

The rail industry is being driven to reduce energy consumption and ensure value for money in order to remain competitive with emerging road transport technologies. Furthermore, rail networks are faced with the challenge of increasing capacity to meet a growing demand. The primary means of increasing capacity is to upgrade the signalling system. This paper therefore presents the development of a rapid railway simulation tool, designed to aid decision making at the conceptual stage of planning signalling upgrades. The railway simulation tool features a multi train simulator capable of evaluating the capacity and energy consumption of a section of track under two configurations of a new European signalling standard. The simulation tool also features an integrated Brute Force algorithm designed to optimise the train control strategy to reduce energy usage whilst not affecting the line capacity. Using the Cambrian line between Welshpool and Aberystwyth as a case study, the simulator found that up to 31 trains per hour is achievable. However, if the line should operate with a capacity of 10 trains per hour, the extra headway can be used to make an energy saving of 8% for a 1.2% increase in journey time.

1. Introduction

The anthropologic impact of climate change and the uncertain future of non-renewable energy resources is driving technological advancement and decision making to focus on reducing carbon emissions. As transport accounts for 38% of all energy consumption in the UK (Waters et al., 2015), reducing emissions in this sector could be significantly beneficial. Rail travel has long been considered inherently energy efficient owing to: the streamline effect of carriages, low friction between the wheels and the running rails and the fact that many passengers can be carried in one journey (Smith, 2003). It is therefore predicted that demand for rail travel will increase by an average of 2% every year until 2043 (Transport Committee, 2012). To ensure this development, the rail industry must remain environmentally competitive with hybrid and fuel cell powered vehicles, which have the potential to drastically increase the efficiency of road travel (Smith, 2003; Pollet et al., 2012). Furthermore, the rail industry must ensure value for money for customers, whilst generating the capital to develop infrastructure (D. f. T. a. O. o. R. Regulation, 2011a). In response to these factors, the UK rail industry has set targets to reduce its carbon emissions by 25% (Rail Safety and Standards Board, 2011) and reduce the unit cost per passenger kilometre by 30% (D. f. T. a. O. o. R. Regulation, 2011a) by 2019 (D. f. T. a. O. o. R. Regulation, 2011a; Rail Safety and Standards Board, 2011).

Abbreviations: STS, Single train simulator; MTS, Multi train simulator; BFA, Brute force algorithm; ERTMS, European rail traffic management system.

* Corresponding author. 65 Moss Street, Derby, DE22 3WG, UK.
E-mail addresses: robertdunbar86@gmail.com (R. Dunbar), c.roberts.20@bham.ac.uk (C. Roberts), n.zhao@bham.ac.uk (N. Zhao).

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The primary means of increasing network capacity is to upgrade the existing signalling system to reduce the service headway (Quaglietta, 2014). This is a key consideration in the design of the European Rail Traffic Management System (ERTMS) to be implemented across Europe. The new ERTMS signalling system has three configurations that vary in functionality and complexity. As such, the benefits of each configuration need to be evaluated to determine the necessary upgrade. The design of signalling systems involves railway simulation to reduce the cost of evaluating options on test tracks and to relate the design to a specific route. Such simulators provide information on: the journey time, energy consumption and capacity limits of different signalling systems (Radtke and Bendfeldt, 2001). Commercial simulators are typically expensive to purchase and require significant time and effort to generate track and train models. A cost review of the UK's rail industry has therefore highlighted a lack of the correct models and tools to allow for 'optioneering' at the conceptual stage of development, leading to the implementation of low value rail development (D. f. T. a. O. o. R. Regulation, 2011b). This is a key factor driving novel approaches to cost effective signalling design, such as the simulation tool for optimal fixed block layout proposed by Quaglietta (2014), which describes an algorithm to search for the optimum signalling block length with respect to the cost of investment. The work of this paper herein, addresses the need to consider moving block signalling as well as fixed block signalling at the design stage. As such the paper describes a tool which can rapidly evaluate whether to implement fixed block or moving block, based on the required capacity and the amount of energy that could be saved through an optimal driving strategy.

Section 2 of this paper presents a review of existing studies into single train trajectory optimisation and how it may be applied to multiple trains on a network to save energy within the constraints of a signalling system. Section 2 also describes ERTMS signalling and research which is concerned with the impact of different signalling methods on network capacity. Section 3 describes the development of a Multi Train Simulator capable of evaluating the energy consumption and line capacity for a specific section of railway line under two levels of ERTMS signalling. Section 4 describes the development of a brute force optimisation algorithm designed to evaluate the benefit of implementing energy efficient driving control. The Brute Force Algorithm is integrated with the Multi Train Simulator to create the completed Railway Simulation Tool. The Railway Simulation Tool is validated in Section 5 and applied to a case study of the Cambrian line in Wales in Section 6. The results of the simulation are discussed in Section 7. As such the main contributions of this paper are:

- Providing a summary of the existing research on train trajectory optimisation with consideration as to how signalling methods and driving strategy can impact capacity.
- Addressing the need for optioneering at the conceptual stage of railway development by providing a tool which rapidly evaluates the impact on line capacity due to different signalling strategies.
- Facilitating energy conscious railway design at the preliminary stage of development by providing a tool which rapidly assesses the energy consumption of a specific train type operating on a section of railway line for an hour under signalling constraints.
- Facilitating the early planning of energy efficient timetabling by providing a tool which evaluates the impact of increasing a train's starting headway and pre-determining the location of coasting points which most efficiently utilise the additional run time.
- Demonstrating the benefit that can be gained from implementing pre-planned energy efficient driving strategies with different signalling methods using a case study simulation of an upgrade to a section of the Cambrian railway line in Wales.

2. Review of train trajectory and signalling optimisation

Scheepmaker et al. (2016) evaluated the existing literature on energy efficient train control and timetabling. They highlight that the most recognized approach to the problem of reducing energy consumption with minimal effect on journey time stems from work done in the early 1960s by Pontryagin et al. (1962). Pontryagin's maximum principle involves finding the optimum control solution when taking a dynamic system from one state to another. When applied to finding the optimal control of a train, this involves determining the best locations to enter a specific phase of train movement. The train's trajectory for a basic interstation run, shown in Fig. 1, has 4 phases of train movement: acceleration, cruising, coasting and deceleration (Bocharnikov et al., 2007; Zhao et al., 2014). The acceleration phase increases the velocity to a constant value, which is maintained throughout the cruising phase; this precedes a braking phase to stop the train. The coasting phase, where movement is dependent on the train's momentum, is not essential, however it requires no tractive or braking effort and so can be introduced to save energy (Bocharnikov et al., 2007). Energy savings are made by modifying the active duration of these phases with train control. This incurs an additional journey time, as shown in Fig. 2, due to the average velocity being decreased (Bocharnikov et al., 2007; Zhao et al., 2014; Su et al., 2015).

Research has generally focused on the development of algorithms designed to find the optimum trajectory in real time as a train traverses a route (Bocharnikov et al., 2007; Wong and Ho, 2004; Lu et al., 2012). The duration of the current phase of operation and selection of the next phase, is evaluated by weighting the importance of energy saving against time. This is a problem that lends itself well to heuristic algorithms, which reduce computational run time by searching for an approximation of the optimum solution. Bocharnikov et al. (2007) considered that to find the optimum solution, fuzzy sets had to be defined to give coefficients of importance to energy consumption and journey time. The values obtained from the fuzzy sets

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