Engineering Applications of Artificial Intelligence 53 (2016) 19–31

Contents lists available at ScienceDirect

Engineering Applications of Artificial Intelligence

journal homepage: www.elsevier.com/locate/engappai

Fuzzy train tracking algorithm for the energy efficient operation of CBTC equipped metro lines

William Carvajal-Carreño, Asunción P. Cucala *, Antonio Fernández-Cardador

Institute for Research in Technology, Pontifical Comillas University, 23 Alberto Aguilera street, Madrid 28015, Spain

ARTICLE INFO

Article history:
Received 14 July 2015
Received in revised form
17 March 2016
Accepted 29 March 2016
Available online 7 April 2016

Keywords:
Energy-efficiency
Tracking algorithm
Fuzzy parameters
CBTC signaling system
Moving block
Train simulation
Ecodriving
ATO

ABSTRACT

In CBTC (Communications-Based Train Control) operated metro lines, headway can be reduced by taking advantage of the system's train–track continuous communication, thus increasing transport capacity. When a train runs close enough to the preceding one, a tracking algorithm is triggered to control the distance between the trains. The following train receives the LMA (limit of movement authority) via radio, which is updated periodically as the preceding train runs.

Besides transport capacity, one of railway operators' main goals is the reduction of energy consumption, for environmental and economic reasons. This paper firstly shows that the existing basic CBTC tracking algorithm is not energy efficient, due to the application of short braking–traction cycles. It then proposes a new efficient algorithm that makes use of coast (null traction) command, and models the uncertainty associated with the speed of the preceding train. This fuzzy algorithm is compared to the basic one in terms of energy consumption, running time and steady state interval (resulting tracking interval).

Simulation results show that the proposed fuzzy tracking algorithm provides important energy savings with minor influence on running time and steady state interval. This algorithm is suitable for implementation in on-board CBTC equipment to reduce the energy consumption of traffic operation.

1. Introduction

The evolution from discrete track circuit based metropolitan lines (fixed block) to continuous radio controlled signaling systems has led to an increase in transport capacity. A CBTC (Communications-Based Train Control) signaling system permits a closer operation of consecutive trains within the safety distance, reducing the commercial headway in metro lines.

CBTC signaling systems have a set of basic guidelines (IEEE, 2008), but each manufacturer has its own architecture. The final configuration and operation of these systems are strongly conditioned by transport operator needs and constraints (He, 2011; Morar, 2012).

Fig.1 illustrates a simplified representation of the basic configuration of a CBTC signaling system (Wang et al., 2013).

The train has the mechanisms to calculate its position, speed, and maximum speed curves, taking into account a known limit of movement authority (LMA) and the associated target point distance (S_{target}). The speed and the position of the tail of each train are reported via radio to a zone controller which calculates and sends each train its LMA. A "brick wall" assumption is used to calculate the most restrictive braking distance considering that the preceding train is stopped at the LMA point, despite the actual speed of the train. Railway signaling designers and manufactures use this concept as an extended practice (Takagi, 2012; Xu et al., 2012). The updating time period of the LMA depends on the architecture and design of the communication system, as well as on the admissible delay for latency of signals (Xun et al., 2013; Zhu et al., 2014).

The CBTC signaling system can work under moving block or virtual block systems. In a moving block system, the portion of the track occupied by a train, which is used to calculate the LMA for the following train, is a continuous variable. In a virtual block system a set of parameterized logical short sections of the track are blocked while the train is passing, which introduces an additional delay in the LMA updating period (Barrow, 2010; Morar, 2012; Platt, 2010; Schaefer and Mortlock, 2001).

There are two main trends to manage perturbations in the operation of trains. The first is timetable rescheduling (Berbey et al., 2014; Cacchiani et al., 2014; Corman et al., 2011; Cucala et al., 2012; Jia and Zhang, 1994; Mazzarello and Ottaviani, 2007; Xie and Li, 2012; Zhang et al., 2005). The second trend in ATO (Automatic Train Operation)-driven metro lines is a centralized automatic traffic regulation system. This controls the departure of each train

* Corresponding author.
E-mail address: cucala@comillas.edu (A.P. Cucala).

http://dx.doi.org/10.1016/j.engappai.2016.03.011
0952-1976/

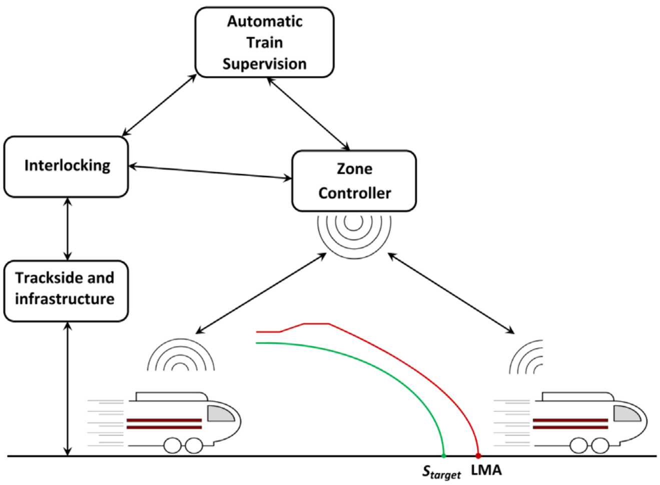

Fig. 1. Configuration of a CBTC signaling system.

(modifying the dwell time) and the driving command sent to the train (adapting the running time) (Fernández et al., 2006; Gong et al., 2014; Gu et al., 2013, 2010; Ning et al., 2015; Takeuchi et al., 2003; Wang et al., 2014b).

Energy efficiency in railways is currently a main concern. The strong pressure to protect the environment and the upcoming liberalization of railway markets, lead to the need to find new procedures that will increase efficiency and competitiveness (González-Gil et al., 2014). Ecodriving is one of the main strategies used to save energy and therefore reduce a railway company's operational costs (Abril et al., 2008; Ceraolo and Lutzemberger, 2014; Conti et al., 2015; Fay, 2000; Feng et al., 2013a, 2013b; Zhang et al., 2005). Ecodriving consists in optimization of the driving profile to reduce the associated energy consumption. Typically, ecodriving design is based on the application of coast command (null traction) (Yang et al., 2016). Several methodologies for reducing energy consumption by means of ecodriving have been proposed, from manual to automatic driving (Domínguez et al., 2008; Dong et al., 2010; Karvonen et al., 2011) and from metropolitan lines to high speed trains (Baranov et al., 2011; Domínguez et al., 2010; Ruelland and Al-Haddad, 2007; Sicre et al., 2012, 2014; Sun et al., 2012; Su et al., 2013).

In metropolitan lines with a centralized control, an optimal speed profile is sent to the train in real-time before departure from the station according to the target running time to the next station (Domínguez et al., 2010). In Domínguez et al. (2014, 2010), these optimal speed profiles are previously designed considering the characteristics of real ATO equipment and supposing the train is not perturbed by proximity to the preceding one. When one of these optimal speed profiles is selected in real time by the centralized traffic control system (according to the associated running time), it is executed by the train as expected in the design phase if the preceding train is far enough. However, if the train is perturbed by the preceding one during the running period, its motion will be affected by a reduction of the speed (forced by the protection system) and the tracking algorithm is triggered to maintain a safety distance from the preceding train. This algorithm has impact not only on the tracking interval (capacity) but also on passenger comfort and energy consumption (Xu et al., 2014). The continuous communication of the CBTC signaling system can be used to improve transport capacity, quality of service, and furthermore, the energy efficiency of train driving.

A method to control this separation distance for trains with a moving block signaling system is proposed in Gao et al. (2015a, 2015b) and Takagi (2012), with the application of neural adaptive, observer-based or direct control. In Baek (2009), Baek and Lee (2007) and Pan and Zheng (2014) train separation calculations are made for long distance or high speed trains. However, these works do not consider energy efficiency.

Lu and Feng (2013) propose a tracking algorithm under a fixed block signaling system. In Gu et al. (2011) the proposed tracking algorithm for a moving block signaling system is based on a quadratic programming method. However, the algorithm contains some simplifications, such as not considering track slopes, train aerodynamics or saturation of the traction effort curve. Ding et al. (2009) propose a heuristic algorithm for train control under a moving block system to reduce energy consumption and in Wang et al. (2014a) the speed profile of the train is optimized both for fixed and moving block signaling systems as a MILP problem (mixed integer linear programming). However these algorithms do not include a realistic model of existing ATO equipment.

This paper proposes a new, efficient tracking algorithm that controls the approach of two consecutive trains equipped with a CBTC signaling system to reduce energy consumption. This new algorithm takes into account the real characteristics of ATO equipment. It makes use of the coast (null traction) command to reduce energy consumption and takes account of the uncertainty associated with the speed of the preceding train, which is modeled as a fuzzy number. Thus, the proposed method is a fuzzy tracking algorithm that provides close tracking intervals within safety margins and improves energy efficiency.

The CBTC train tracking simulation model is described in Section 2. Then, Section 3 provides details of the proposed fuzzy efficient tracking algorithm. Section 4 describes the case study, in addition to showing and discussing the results. Finally, the conclusions are presented in Section 5.

2. CBTC train tracking simulation model

A simulation model of metropolitan lines equipped with ATO and a CBTC signaling system was proposed in Carvajal-Carreño et al. (2014). Simulation is very useful to produce precise results in the study of energy consumption and running times, especially when constraints associated with real train control equipment have to be taken into account (Mao et al., 2007).

The developed simulation model consists of three modules: train, line, and ATO modules, and considers all of the main variables that affect train dynamics (speed limitations, maximum traction effort, etc.).

The model of the train takes into account the length and mass of the train, running resistance, traction and braking maximum effort curves, variations of motor efficiency with respect to effort ratio, and rotary inertia. The line characteristics included in the model are speed limits, tunnels, track slopes, slope transition curves (and the effect along the train) and track bends (Domínguez et al., 2011a, 2011b).

The ATO module interprets and executes the driving commands that can be programmed in real ATO equipment and always observes the speed limitations provided by the ATP (Automatic Train Protection) system (Allotta et al., 2013).

The ATP part of CBTC equipment is the safety critical system in charge of supervising maximum speed limitations, train location (front and rear) and safe train separation, among others (Allotta et al., 2015). The ATP equipment has the information about fixed speed limits, receives the LMA and calculates the target point (S_{target}), ATP emergency brake curve, ATP overspeed detection curve and ATP profile, which is the ATO authorized path curve to be provided to the ATO equipment (see Fig. 2). In this way, the ATP system provides safety margins and the simulated ATO module will have the ATO authorized path as its maximum permitted curve (IEEE, 2004).