Transportation Research Part C 56 (2015) 281–292

Contents lists available at ScienceDirect

Transportation Research Part C

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

Coordinated cruise control for high-speed train movements based on a multi-agent model

Shukai Li *, Lixing Yang *, Ziyou Gao

State Key Laboratory of Rail Traffic Control and Safety, Beijing Jiaotong University, Beijing 100044, China

ARTICLE INFO

Article history:
Received 28 October 2014
Received in revised form 14 April 2015
Accepted 15 April 2015

Keywords:
High-speed train
Cruise control
LaSalles invariance principle
Multi-agent system

ABSTRACT

This paper investigates the coordinated cruise control strategy for multiple high-speed trains' movement. The motion of an ordered set of high-speed trains running on a railway line is modeled by a multi-agent system, in which each train communicates with its neighboring trains to adjust its speed. By using the potential fields and LaSalles invariance principle, we design a new coordinated cruise control strategy for each train based on the neighboring trains' information, under which each train can track the desired speed, and the headway distances between any two neighboring trains are stabilized in a safety range. Numerical examples are given to illustrate the effectiveness of the proposed methods.

1. Introduction

Nowadays, as the railway transportation plays a more and more important role in the social economy, the core of this traffic mode is typically to ensure that trains can be operated safely and economically. To meet this significant requirement, the existing literatures have paid tremendous attentions to the effective methods of railway traffic planning and the railway traffic control. Railway traffic planning aims to provide efficient operation plans as pre-trip traversing guidance from the viewpoint of operational levels or macroscopic aspects, such as train scheduling problems (Higgins et al., 1996; Zhou and Zhong, 2007; Fischetti et al., 2009; Niu and Zhou, 2013; Wang et al., 2013), and train pathing problems (Lee and Chen, 2009). In particular, with the given transportation plans, train control problem focuses on providing the specific microscopic operations for trains to guarantee the safety of railway traffic systems, and moreover to follow the pre-specified operational plans (Yang and Sun, 2001; Zhuan and Xia, 2008).

In recent years, high-speed railways are under construction in many countries to further enhance the efficiency of the railway traffic. Compared to the traditional rail traffic, high-speed train is a type of rail transport that operates significantly faster and more eco-friendly, in which the automatic train control (ATC) system is used to supervise, control and adjust the train operations to guarantee safety, punctuality (according to the schedule) and comfort with such a high speed (Astolfi and Menini, 2002; Song et al., 2011; Ciccarelli et al., 2012; Sun et al., 2014; Li et al., 2014). Under the ATC system, the movement of high-speed trains relies on continuous bi-directional communication link between trains and controllers, and the distances between two trains are continuously adjusted according to their actual speeds and positions, which ensure that the trains are operating safely at all times (Dong et al., 2010). Based on the ATC system, many researchers have investigated the dynamic performances (e.g. safety and reliability) and control strategies of multiple trains on the railway line by considering the trains' interactions. An improved equation model for many trains' movement on the line was proposed by Li and

* Corresponding authors. Tel.: +86 18201061093.
E-mail addresses: shkli@bjtu.edu.cn (S. Li), lxyang@bjtu.edu.cn (L. Yang).

http://dx.doi.org/10.1016/j.trc.2015.04.016
0968-090X/

Gao (2007), which considered the influences of other trains in the equation of the train movements. Li et al. (2007) proposed a cellular automaton model to simulate the train movements, which can well describe the dynamic behaviors of the train movements. An effective movement control model was designed for a group of high-speed trains on a rail network by Yang et al. (2011), and the specific traffic characteristics of high-speed trains were studied under the interruption by a stochastic irregular event.

Apart from the specific traffic characteristic analysis of multiple trains on the railway line, many train control methods have been investigated to guarantee the safety of railway traffic systems or to minimize energy consumption for the given transportation plans. In the study by Chang and Sim (1997), a dynamic train coast controller by using genetic algorithms was proposed for synthesising the train coast lookup table so as to achieve energy consumption, for which the number of coasting points was pre-determined. Moreover, by considering more realistic constraints and more comprehensive factors attributed to train movement, a dynamic flexible coast control of train movement was designed by Wong and Ho (2004) to determine the number of coasting points and search for the coasting points to minimize the energy consumption of train operation. In particular, the cruise control problem is one of the demanding control problems for high-speed train, which is used for automatically controlling the train speed to follow a desired speed to guarantee the safety with such a high speed. For high-speed railways, the maximum cruise speed of high-speed train is up to 350 km/h. For such a high speed, it is hard to keep punctual as well as comfortable by human driving. Besides, the cruise running time accounts for a large proportion of the inter-station run time of high-speed trains in practice. Therefore to ensure that the trains can run with the cruise speed more accurately, there is a necessity to design the cruise control of high-speed trains. The cruise control of high-speed trains has been intensively studied to guarantee the safety of high-speed railway traffic systems in the last few years (Astolfi and Menini, 2002; Faieghi et al., 2014). The entire train control process typically includes accelerate, cruise, coast and brake. To study the cruise control problem of high-speed trains separately, we assume that the cruise speed and the cruise running time in an inter-station run are pre-given, which are obtained from the whole train control process optimization. For the given cruise speed and the cruise running time, the cruise control algorithm can be elaborately designed to achieve high precision desired speed tracking of trains. Yang and Sun (2001) designed a cruise controller for high-speed train to achieve speed command tracking. In the study by Zhuan and Xia (2006), an optimal cruise control scheduling for the trains was introduced to minimize the in-train forces. A Lyapunov-based robust adaptive controller was designed by Faieghi et al. (2014) to achieve asymptotic tracking and disturbance rejection for high-speed trains. However, the most existing literatures are confined to the cruise control design of a single high-speed train.

By considering the continuous communication link among the high-speed trains, the coordinated cruise control design for multiple high-speed trains' movement is an essential requirement to ensure the safety and comfort of the operating of high-speed trains on the railway line in practice. Gordon and Lehrer (1998) studied the coordinated train control and energy management control strategies, which shows that the ATC system will allow not only more precise control of trains, but also coordination of the commands to multiple trains. Based on model predictive control, the coordinated control among high-speed trains was investigated to improve trains' safety and efficiency by Zhou and Wang (2011). By considering the coasting control for the optimization of trains movements, several algorithms were proposed to guarantee the safety distance of adjacent trains, and also approximate the link energy consumption and travel times (Yang et al., 2012). In particular, multi-agent systems are commonly adopted to study the coordinated control of many complex systems, such as the formation control of unmanned air vehicles, the cooperative control of mobile robots, and intelligent vehicles control for traffic flow (Reynolds, 1987; Toner and Tu, 1998; Toner et al., 2005; Olfati-Saber, 2006; de Oliveira and Camponogara, 2010; Kammoun et al., 2014). Böcker et al. (2001) used a multi-agent method to optimize the train coupling and sharing system. El-Kebbe and Gotz (2005) studied the distributed real-time control of railway systems by using multi-agent technology. For the motion of an ordered set of trains running on a railway line, each train can be regarded as an agent, and the information exchanges among the neighboring trains are the connections among the agents. Correspondingly, the coordinated cruise control strategy for the ordered set of high-speed trains' movement can be studied based on a multi-agent coordinated control framework. However, to the best of our knowledge, there is no literature to deal with the coordinated cruise control strategy for high-speed trains' movement based on the multi-agent system model.

Motivated by the previous discussions, this work firstly presents a dynamic model of an ordered set of high-speed train movements within a multi-agent system framework, and develops the coordinated cruise control problem of multiple high-speed train movements to ensure that each train tracks the desired speed and meanwhile guarantee the safety headway distances of each train with its neighboring trains at all times. According to the three heuristic rules of multi-agent systems: separation, alignment and cohesion (Reynolds, 1987; Olfati-Saber, 2006), we will design a new coordinated cruise control strategy for high-speed train movements to ensure each train on the railway line tracks the desired speed (alignment), and the headway distances of two neighboring trains are stabilized in a safety range (separation and cohesion). Based on the potential fields (Tanner et al., 2007) and LaSalles invariance principle (Khalil and Grizzle, 2002), a set of coordinated cruise control strategy for each train is designed with three parts based on the neighboring trains' information, in which the first part denotes the desired speed alignment, the second corresponds to a vector in the direction of the negated gradient of an artificial potential function that ensures the separation and cohesion of two neighboring trains, and the third is for compensating the desired speed. Under the coordinated cruise control strategy, each train tracks the desired speed, and the headway distances of each train with its neighboring trains are stabilized in a safety range. Numerical examples are given to illustrate the effectiveness of the proposed methods. From the numerical examples, we can observe that the proposed control method can be effectively used to track the desired speed for multiple high-speed trains and to guarantee the safe and