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Optimal cruise control of heavy-haul trains equipped with electronically controlled pneumatic brake systems☆

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Abstract

A closed-loop cruise controller is proposed to minimise the running cost of heavy-haul trains equipped with electronically controlled pneumatic brake systems. Consideration is given to improving velocity tracking, in-train force management and energy usage. To overcome the communication constraints, a fencing concept is introduced, whereby the controller reconfigures adaptively to the current track topology. Simulation results of comparisons between different controllers are provided: open-loop versus closed-loop; velocity tracking versus in-train force. Different train control configurations are also compared: unified control, adaptive fencing and full independent traction and braking.

Keywords: Closed-loop; Cruise control; Electronically controlled pneumatic (ECP) brake system; Heavy-haul train; LQR; Optimal control

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1. Introduction

Optimisation objectives are one of the key parameters in controller design. In heavy-haul trains, optimal control entails minimising operational cost while arriving at the destination within the required time frame.

The three main factors contributing to the running cost of heavy-haul trains are energy consumption, travelling time and maintenance: energy consumption is directly proportional to the amount of control action used; extended travelling time results in heavy fines charged by the client for late deliveries, especially in the case of port export; maintenance and repair of damage to the brake and coupler system, mainly caused by excess in-train forces in long heavy-haul trains, are expensive.

In this paper, control methods for both passenger and heavy-haul trains are examined. An optimal cruise controller is designed for heavy-haul trains equipped with electronically controlled pneumatic (ECP) brake systems. The controller design is based on a longitudinal dynamical model proposed and validated against real data in the companion paper (Chou, Xia, & Kayser, 2006).

The controller is tested on this model as well. The performance of different controller configurations, as well as the effects of individual control over unified control, is compared. Three controller configurations are considered: velocity tracking emphasised controller, in-train forces emphasised controller and energy usage emphasised controller. A unified braking and traction controlled train is compared with a full individual brake and traction controlled train. The performance indices are velocity deviation, maximum in-train forces and energy usage.

This paper describes the controller design process in four main steps: description of existing methods, a brief description of the model, controller design and results.

2. Control methods

Energy efficiency comes first, maybe indirectly, from optimal local control of traction, braking and more recently active steering and suspension. An example is the slip controller. Maintaining maximum slip improves tractive efforts, hence reduces energy consumption. To achieve this, an accurate measurement of the wheel velocity

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is required. This is difficult and expensive owing to the harsh environment found at the under-carriage. A novel wheel slip detector via the measurement of the traction motor current changes was shown by Watanabe and Yamashita (2001), while Ishikawa and Kawamura (1997) demonstrated a PI-based controller that is able to maintain the slip velocity very closely around the optimal point with minimum jittering.

Another example is the mechatronic control system for passenger trains equipped with actively controlled suspension (Goodall & Kortum, 2002; Mei, Nagy, Goodall, & Wickens, 2002). Bogie[1]-based control methods for steering and stability are proposed by Pearson, Goodall, Mei, and Himmelstein (2004) and Perez, Busturia, and Goodall (2002).

These studies offer some insights into train dynamics. However, these control methods require new vehicles because of the extensive use of advance actuators. Moreover, these controllers focus on the ride quality of the trip, a minor concern in heavy-haul trains.

On the train operational level, an energy efficient controller uses optimal scheduling. Howlett (1996) and Howlett, Milroy, and Pudney (1994) proposed such a controller for a diesel-powered passenger train that is able to reduce energy consumption while completing the journey within a certain time limit. A similar method was also proposed by Khmelnitsky (2000).

In practice optimal scheduling suffers from some deficiencies. These studies use a point-mass model, ignoring the in-train dynamics. Scheduling predetermines the control strategies under an assumed condition. Lengthy recalculation will have to be performed if disturbances are present. Possible scenarios include stopping for additional wagons to be attached and emergency stops. Unpredictable factors such as weather conditions will also affect the performance of the optimal strategy.

Automatic speed controllers discussed by Thelen and Tse (1990) and Tang and Gao (1996) are examples of the handling of in-train forces. The controllers calculate the optimal speed profile the train should adhere to before reaching its stop. These studies conclude that by following a smooth speed profile, extreme control force are avoided while minimising in-train forces. However, these studies are limited to the stopping of the train.

More recently, Yang and Sun (2001) discussed the use of the H_2/H_∞ control method for the cruising of a high-speed passenger train. The main improvement was the disturbance rejection property and the use of a spring-mass model. Astolfi and Menini (2002) explored the decoupling property of the model proposed by Yang and Sun (2001).

Point-mass models used by previous heavy-haul train studies ignore in-train dynamics. In comparison, a spring-mass model considers the train as individual masses that are inter-connected via spring-like couplers. This allows the in-train dynamics to be analysed.

In heavy-haul trains, the use of a spring-mass model was hindered by the use of pneumatically controlled brakes. The slow propagating pneumatic signal poses a delay problem in heavy-haul trains, which could extend over 2.5 km or longer. The result is uneven braking throughout the train. In earlier studies, such complex dynamics was neglected. An example is the suboptimal control proposed by Gruber and Bayoumi (1982). In that paper, other simplifications were made to reduce overall train length by considering only the rear coupler of each car. Without model validation, it is difficult to evaluate the practicality of the proposed controller.

The introduction of the ECP brake system (Kull, 2001; Hawthorne, 2003) solves the dilemma. Electronic control signals allow simultaneous braking throughout the train as well as individual braking of each wagon and locomotive. A longitudinal dynamical model of heavy-haul trains equipped with ECP was proposed and validated in Chou et al. (2006).

Two issues need to be addressed before an ECP system can improve operational efficiency. Firstly, fully individual brake control is limited by computation and bandwidth constraints. In the specification by AAR (2002), a maximum of 32 control channels is specified. With a typical heavy-haul train consisting of 200 wagons, individual control is currently not possible. Secondly, the existing controller does not take advantage of the additional control inputs.

In this study, adaptive grouping, termed adaptive wagon fencing, is used to tackle the bandwidth problem: cars experiencing a similar track environment are controlled as a group, reducing the required control signals and thus the bandwidth requirement.

The second issue is that existing controllers do not utilise the additional control inputs. In this study, the cruise controller is designed generically so it can adapt to different train configurations in terms of a varying number of locomotives and wagons and their placements. This allows the controller to take advantage of the ECP technology.

3. Train model

In the proposed model, equations of motion are used to describe the longitudinal motion of the train. Through coupler forces, the in-train dynamics is examined. Rolling resistance and aerodynamic resistances, as well as gravitational and curvature resistances, are considered. Of the four, gravitational resistance is the largest.

For details of the modelling, refer to Chou et al. (2006). Equations of motion are included in the following for completeness:

$$\begin{aligned} m_1\ddot{x}_1 &= u_1 - k_1(x_1 - x_2) - d_1(\dot{x}_1 - \dot{x}_2) \\ &\quad - (c_0 + c_v\dot{x}_1)m_1 - c_a\dot{x}_1^2\left(\sum_{i=1}^{n} m_i\right) \\ &\quad - 9.98\sin\theta_1 m_1 - 0.004 D_1 m_1, \end{aligned}$$

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[1] The suspension system including wheel set(s).