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Energy-efficient operation of diesel–electric locomotives using ahead path data

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ABSTRACT

Diesel–electric locomotives have significant fuel consumption. In this study, fuzzy look-ahead control is considered as an online approach for fuel consumption optimization. A fuzzy controller will modify the desired speed profile by accounting for the gradient and speed limits of the path ahead. Journey time increment is used as an optimization constraint. The existing models for train motion simulation are calculating the fuel consumption by an indirect index. A new model for train-movement simulation is proposed to calculate fuel consumption more accurately. This model considers the locomotive subsystems and satisfies the experimental fuel consumption data specified in the locomotive's catalog. Simulation of a train with a GM Sd40-2 on three local tracks showed considerable reduction in fuel consumption along with an acceptable journey time increment. Simulation results also showed that fuzzy look-ahead controller has very faster calculations in comparison with the controller based on the dynamic programming method.

1. Introduction

The railway transportation systems are usually considered to be an energy-optimum method for freight and passenger transportation (Lawyer, 2007). However, the railway transportation industry is one of the primary consumers of fuel and energy. For example, the seven Class 1 railroads in the United States consumed more than 3.6 billion gallons of diesel fuel in 2012 (U.S. Department of Transportation). Therefore, reducing fuel consumption and increasing efficiency in this field would have significant economic and environmental profit.

Research in the field of fuel-consumption optimization in railway transportation has evolved primarily over the past two decades (Cheng and Howlett, 1992; Howlet, Milroy & Pudney, 1994; Howlett, 1996). The existence of an optimum speed profile for a train on a path lacking a gradient was proved using the maximum principle and functional analysis (Howlett, 1990). The effect of speed limitation was applied to the problem by Pudney and Howlett (1994). The optimized speed profile was described for train motion between two stations on the path without gradient (Hansen & Pachl, 2008). This optimized profile has four stages: acceleration to maximum speed, maintaining constant speed, coasting without traction forces and deceleration. It has been reported that using optimization algorithms can reduce fuel consumption by 13% (Howlett & Pudney, 1995). The optimization problem was solved for a path with a piecewise constant gradient (Howlett & Cheng, 1997). A set of characteristic equations was derived based on the Kuhn–Tucker equations.

The fuel consumption optimization problem was solved for each section of a given path by a local minimization of fuel consumption (Howlett & Pudney, 2009). The best point for increasing speed before an upward hill was obtained by the optimization algorithms. In another study, the maximum principle method was used to optimize the energy consumption in subway lines (Khmelnitsky, 2000). Yet other novel approaches have been described in this field. For instance, a genetic algorithm for a train speed profile has been proposed (Kang, 2011). In this study, the coasting point was the main parameter and the fitness function was defined so that the train can traverse the distance between two stations within the defined journey time. In another study, the metro train transportation of a certain metro line was examined (Zhang et al., 2014). In this study, the Comprehensive Evaluation Index (CEI) was proposed to analyze integrated optimization strategies of urban rail transport by calculating the traction energy cost and the technical operation time. A stochastic train energy-efficient operation model was proposed and the coasting phase was replaced by a quasi-coasting phase (Li et al., 2013).

In the reviewed papers, a simple model for traction force is used and fuel consumption is measured by an indirect index. Fuel consumption is a function of a diesel engine's working speed and

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torque. Considering the working points and operational constraints of locomotive subsystems may give more accurate simulation results.

Although the available numerical methods provide respectable results (Cheng, Davydova,Howlett & Pudney, 1999; Howlett, 2000; Howlett & Leizarowitz, 2001; Liu & Golovitcher, 2003), these methods use offline calculations. They are considering the static situation problem, so if any changes occur in the situation of the path ahead, these calculations must run again. Therefore, developing online algorithms that consider dynamic situations such as traffic in the path ahead may be more applicable for practical purposes in cabin computer programs.

A relatively inclusive review on traction-energy conservation of rail transport is presented (Feng et al., 2013). This review concluded that different track alignments and dynamically optimizing control programs of trains with their reasonably improved features must be considered in view of the systematic transport operation of a rail line or network.

The “Look-Ahead” control method (Ganji & Kouzani, 2010) is a new approach to optimizing the fuel consumption of road vehicles. This approach is based on using future path information for acceleration and deceleration control commands. The look-ahead approach was used as an effective tool in reducing fuel consumption by using dynamic programming to solve the optimal control problem (Hellstrom, Ivarsson, Aslaund & Nielsen, 2009). The look-ahead fuzzy control approach was used as a quick and effective method in optimizing fuel consumption for hybrid electric cars (Ganji et al., 2011). This method was also used to optimize automotive ventilation systems (Khayyam et al., 2011). The results obtained show significant proficiency of applying this method in road transportation (Hellstrom, Aslaund & Nielsen, 2010; Sahlholm & Johansson, 2010). The papers reviewed in the field of look-ahead control did not consider the speed limits of the path ahead. For example, their proposed algorithm increases the vehicle speed before an uphill section, but it is incorrect to increase the speed if there is a curved path or other speed limit in the uphill section.

The look-ahead approach has not been used in the field of railway transportation yet. The obvious contribution of this approach would be in optimizing energy consumption in railway transportation. This algorithm can be used to train locomotive drivers and may also be used as an auxiliary train-control instrument.

The fuzzy look-ahead control algorithm as a dynamic approach with online calculations is implemented in this paper by considering the speed limits of the path ahead. For a more accurate fuel consumption calculation, a dynamic model for train motion simulation is proposed in Section 2. The optimization problem is defined in Section 3. The cost function is defined as journey fuel consumption and journey time is considered as a constraint. The designed fuzzy look-ahead controller is presented in Section 4. Finally, in Section 5, the effectiveness of the proposed algorithm in comparison with the controller based on dynamic programing is discussed by a simulation of a freight train with the GM Sd40-2 locomotive on a local track.

2. Train model

Reviewing the models developed for train motion simulation in Section 1 indicates that the fuel consumption is calculated by an indirect index in these models. Therefore, a new model for train-movement simulation is proposed to calculate fuel consumption more accurately. This model considers all of the locomotive subsystems that have a role in power generation or transmission in the locomotive. The main block diagram of Simulink modeling of the locomotive is shown in Fig. 1.

The diesel engine, generator, electric motor, final drive, wheel and axle blocks shown in Fig. 1 are the same as those in the models used in ADVISOR software. ADVISOR (Advanced Vehicle Simulator) is a MATLAB toolbox used for hybrid electric vehicles simulation (NREL, 2001). In the proposed model, fuel consumption is calculated graphically based on the specific fuel consumption (SFC) graphs as a function of the diesel engine's speed and torque. Therefore, the proposed model can calculate the fuel consumption directly and more accurately compared with the existing models for train motion simulation.

The locomotive has an internal control loop in which the diesel engine's governor and a companion device, the load regulator are the main components (Electro-motive division of General Motors, 1978). External inputs of the governor include requested engine speed which is determined by the train driver's throttle position and actual engine speed. The governor controls the fuel injector setting, which determines the diesel engine fuel rate, and also the load regulator position. The load regulator is essentially a large potentiometer that controls the main generator power output by varying its field excitation and hence the degree of loading applied to the diesel engine. As the load on the diesel engine changes, its rotational speed will also change. This is detected by the governor through a change in the engine speed feedback signal. The net effect is to adjust both the fuel rate and the load regulator position so that the diesel engine's speed and torque (and thus output power) will remain constant for any given throttle position, regardless of actual train speed on the path. The nominal constant power curves corresponding to eight throttle positions are shown in Fig. 2.

A train driver or controller can control the train speed by setting the throttle position or using the brake handle. The locomotive maximum traction force F_t is defined as:

$$F_t = \min(F_1, F_2) \tag{1}$$

F_1 is the traction force generated by electrical motors (traction motors) and F_2 is the maximum adhesion between wheel and rail.

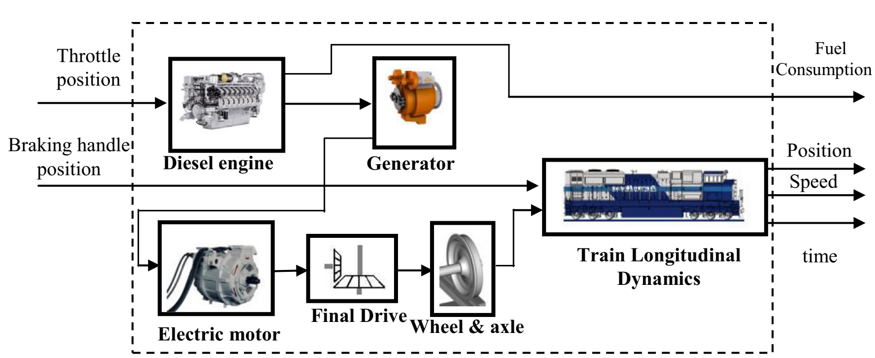

Fig. 1. Train model block diagram.