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Longitudinal train dynamics model for a rail transit simulation system

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ABSTRACT

The paper develops a longitudinal train dynamics model in support of microscopic railway transportation simulation. The model can be calibrated without any mechanical data making it ideal for implementation in transportation simulators. The calibration and validation work is based on data collected from the Portland light rail train fleet. The calibration procedure is mathematically formulated as a constrained non-linear optimization problem. The validity of the model is assessed by comparing instantaneous model predictions against field observations, and also evaluated in the domains of acceleration/deceleration versus speed and acceleration/deceleration versus distance. A test is conducted to investigate the adequacy of the model in simulation implementation. The results demonstrate that the proposed model can adequately capture instantaneous train dynamics, and provides good performance in the simulation test. The model provides a simple theoretical foundation for microscopic simulators and will significantly support the planning, management and control of railway transportation systems.

1. Introduction

Longitudinal train dynamics characterizes the motion of rolling stock vehicles in the direction of the track. A mass point dynamics model mathematically represents the forces acting on a train along the direction of motion, in order to capture acceleration/deceleration behavior and thus transient vehicle motions in support of evaluating and optimizing rail transportation operational strategies. Accordingly, implementation of a simple and efficient dynamics model may significantly enhance the ability of railway simulators in transportation decision-making.

Numerous simulation programs have been developed and widely used to support the sustainability (e.g. safety, comfort, efficiency, environment) of the off-the-shelf railway systems. Based on the level of simulation detail, railway simulators can be classified into two categories: discrete and continuous. The discrete-event simulation, such as Radtke and Hauptmann (2004), Bahn (2010); Grube et al. (2011); Rizzoli et al. (2002); Paolucci and Pesenti (1999), models the operation of the rail system as a discrete sequence of events in time, which assumes no change in the system between consecutive events (e.g. assume constant speed over the track segment between two stations). Such simulators fail to capture the instant acting forces and thus acceleration/deceleration behavior, and thus cannot adequately emulate the details of train motion and effectively design and test various strategies (e.g. environmentally optimal operation, speed control, passenger comfort improvement) which require the acquisition of the continuous state of train activities. Continuous simulation, however, tracks the system dynamics over time, and thus can instantly model the train movement. Nonetheless, many of the existing continuous simulators, such as Nash and Huerlimann (2004), Baohua et al. (2007)), cannot emulate realistic train dynamics given a lack of accurate dynamics models to mathematically and dynamically characterize the throttle and

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brake levels. For instance, Nash and Huerlimann (2004) assumed that a train always accelerated at full throttle, which overestimates acceleration levels overall.

More advanced simulation tools have been initiated lately such as the train energy and dynamics simulator (TEDS) Andersen et al. (2012), train dynamics and energy analyser/train simulator (TDEAS) Wu et al. (2014), and the Centre for Railway Engineering Longitudinal Train Simulator (CRE-LTS) Cole (2006), TrainDy Cantone (2011). These tools cannot only simulate train motions but also serve more sophisticated functionalities such as analyzing derailments and slack action. Nonetheless, given that their built-in dynamics models comprehensively characterize the details of mechanical features, the applications of these tools require extensive mechanical data which are not easily obtained in the transportation field. Also, the need for mechanical parameters makes the integration of these tools in complex frameworks very difficult (e.g. transportation simulation software and smartphone applications). Consequently, developing a novel and simple train dynamics model is needed for efficient applications in transportation engineering.

The application of dynamics models to address acceleration behavior in railway systems is reported in some literature. The typical equation used to estimate tractive effort for acceleration analysis is illustrated in Eq. (1) (Iwnicki, 2006), with N and N_{max} the typical and maximum throttle notch, respectively, and P_{max} the maximum engine power and u the vehicle speed. The traction of locomotives or rolling stock vehicles, known as throttle notch, is controlled discretely. Namely, the typical throttle notch N varies discretely with train power conditions. It is difficult to determine a relationship between the throttle notch and engine output power without the assistance of train manufacturers. Although some studies (Seifer et al., 1997; Garg, 2012; Wu et al., 2017) have accounted for the impact of throttle notch on force profiles, yet no analytical expressions so far are available. This void highlights the need to mathematically characterize throttle input as a function of train motion data (e.g. speed) which can be easily measured using non-engine instrumentation, like for example Global Positioning Systems (GPSs).

$$F_t = \left(\frac{N}{N_{max}}\right)^2 \frac{P_{max}}{u} \tag{1}$$

Towards this goal, the achievements on motor vehicle dynamics may provide valuable insights. Searle (1999), one of the pioneers using dynamics model for acceleration prediction, linked vehicle motion to the ratio of engine power to vehicle weight by introducing a constant acceleration efficiency that accounts for external resistance forces and the losses in the transmission. The model assumes the acting force to be a constant and thus cannot account for the change of dynamics with vehicle operational conditions. To enhance vehicle dynamics modeling, Rakha et al. (2001), Rakha and Lucic (2002) developed a standard dynamics model considering the impact of vehicle speed on tractive force, yet failing to capture the realistic driver throttle input given the assumption that vehicles always accelerate at full throttle. An enhancement to the standard model was proposed by Rakha et al. (2004) through introducing a constant throttle level. Nonetheless, recent studies by Fadhloun et al. (2015), Fadhloun et al. (2017) found that the driver throttle level input varied as a hyperbolic function of the ratio of vehicle speed to the facility desired speed. The model was demonstrated to generate a better match to empirical acceleration behavior compared to other dynamics models. The proposed dynamics model for the acceleration counterpart was thus developed based on Fadhloun et. al's modeling framework which is presented in Section 2.

For deceleration estimation, researchers have either empirically or mathematically addressed train dynamics. Hay (1982) presented empirical results, indicating that the brake force linearly increased up to the maximum level with the increasing speed at the low speed level (smaller than 10 km/h), and fluctuated at the vicinity of the maximum force level within a specific speed range (10–30 km/h), then decayed at relatively high speed levels (larger than 30 km/h). Namely, they assumed the brake force to be a piecewise function of speed. A later study by Iwnicki (2006) confirmed Hay's results and further demonstrated that the modern locomotive design ensured a constant brake force at the maximum force level. In addition to empirical experiments, many mathematical models have been developed in the field of mechanical engineering (Perpinya, 2012; Zobory et al., 2000; Piechowiak, 2009; Yang et al., 2013; Wu et al., 2016). These models, however, cannot be easily calibrated and used in simulators or control systems given that the model calibration requires considerable mechanical data that are not easily accessible without seeking assistance from train manufacturers. For instance, the model in Eq. (2), developed by Perpinya (2012), requires 10 mechanical parameters [1] as the model inputs to estimate the brake force, which significantly limits the model application in transportation systems. Hay (1982) developed a simple brake force model that characterizes the brake force as a function of the braking ratio, the weight of rolling stock, the efficiency of the brake lever system, and the coefficient of friction between the wheel and the brake shoe. The coefficient of friction is the only variable in the model that dynamically varies as a function of speed, and needs to be functionally determined. Given the simplicity in model specification, Hay's brake model was used for the deceleration modeling within our proposed model.

$$F_{b,i} = \left[\left(\frac{\pi\cdot d_{bc}^2\cdot p_{bc,i}}{4} - F_R\right)\cdot i_c - R_{sa}\right]\cdot i_l\cdot n_\Delta\cdot n_{bc}\cdot f\,(P_s,v_i)\cdot\eta_{br} \tag{2}$$

To quantify the coefficient of friction, earlier studies (Schrader, 1938; Blaine and Hengel, 1971) tested various train fleets and generated experimental curves to determine the magnitude of the coefficient of friction at each speed level, yet without mathematical generalization. This limits the use of the results by other researchers once the empirical brake data is not available. Some researchers (Karvatski, 1950; UIC, 2004, 2006, 2010; Perpinya, 2012) mathematically developed functions to analytically compute the

[1] d_{bc} brake cylinder diameter, $p_{bc,i}$ the instantaneous relative air pressure in the brake cylinder, F_R and R_{sa} the resistance force due to the brake cylinders back spring and to the self-adjusting mechanism incorporated in the piston rod respectively, i_c the central brake rigging, i_l the amplification ratio of the brake rigging vertical levers, n_Δ the number of triangular axles, n_{bc} the number of brake cylinders of the vehicle, f the coefficient of friction between the wheel and the brake shoe, η_{br} the mechanical efficiency of the brake rigging.