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Optimization of target speeds of high-speed railway trains for traction energy saving and transport efficiency improvement

Xuesong Feng [a,b,*]

[a] School of Traffic and Transportation, Beijing Jiaotong University, No. 3 Shangyuancun, Haidian District, Beijing 100044, PR China
[b] Integrated Transport Research Center of China, Beijing Jiaotong University, No. 3 Shangyuancun, Haidian District, Beijing 100044, PR China

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ABSTRACT

In the pursuit of higher operation speed at the passenger train services in China, the impacts of high-speed operation on energy consumption and transport efficiency are however not clearly identified. This research attempts to analyze the traction energy cost and transport operation time per 10,000 passenger-kilometers of high-speed railway (HSR) trains with a range of target speeds on certain HSR lines in China through a simulation approach. Having considered the effect of inter-stop transport distances, traction characteristics of HSR trains and gradients, curvatures, etc. of the rail lines, this study has deduced that the target speed of a HSR train for an inter-stop transport distance shorter than 100 km should be below 190 km/h from the perspectives of traction energy saving and transport efficiency improvement. Moreover, the study results also indicate that, unlike the actual HSR operation, the target speed should be dynamically adjusted according to the transport distances between stops if the transport capacity of the rail line is not extensively used. The exact target speed for each inter-stop transport distance shorter than 100 km should be further determined according to the traction characteristics of the train and the track geometry of the rail line.

1. Introduction

High-speed railway (HSR) development in China has been travelling on a fast lane in recent years. It started with the China Railway High-speed (CRH) Electrical Multiple Unit (EMU) type-3 (CRH3) providing passenger transport services with the maximum speed of 350 km/h between Beijing and Tianjin from August 2008 (Yang et al., 2010). As of July 2011, there are various types of CRH EMUs running with the maximum speeds over 200 km/h on more than 8000 km HSR lines in China. According to the plan of the Ministry of Railways of the People's Republic of China, over 23,000 km HSR Lines will be constructed and put into services by 2015. Despite numerous on-going studies on the CRH EMUs' shapes, structures, cardan shafts, etc. (Zhang et al., 2006; Yao et al., 2009; Huang et al., 2010; Sun et al., 2010), the maximum speeds of the CRH EMUs have been raised continually, together with the accelerated construction of the HSR lines in China. In late 2010, the maximum speed of 486 km/h was attained by the CRH EMU type-380A on the newly constructed HSR line between Beijing and Shanghai. The extraordinary progress of the high-speed train services and the rapid construction of HSR network in China do not go without inevitable questions from railway researchers and engineers.

When the maximum speed is raised, higher traction effort is required (Hay, 1982; Andrews, 1986; Martin, 1999; Mao et al., 2008), which implies different patterns of energy consumption (Kokotovic and Singh, 1972; Uher et al., 1984; Hoyt and Levary, 1990; Liu and Golovitcher, 2003; Chandra and Aqarwal, 2008; Huang and Qian, 2010). It is then necessary to investigate how the traction energy cost of a HSR train changes under a range of target speeds, taking into account the effect of inter-stop transport distances, traction characteristics of HSR trains and gradients, curvatures, etc. of the rail lines. Because of the demand on shorter travelling time, HSR system swiftly expands its market within China and beyond (Adler et al., 2010; Hsu et al., 2010) and it is competing with other transportations on long-distance commuting (Hatoko and Nakagawa, 2007; Blanco et al., 2011). However, investment cost recovery and marketing strategies are hardly addressed (Hensher, 1997; Cheng, 2010; Chou et al., 2011). In particular, time-saving (i.e. in other words, improvement of transport efficiency) may be achieved by various target speeds and the cost to attain such an improvement through high-speed operation should be evaluated. Furthermore, when the target speed of a HSR train is connected to both energy saving and transport efficiency, the setting of its target speed to improve both of them is essential to the service quality and operation cost.

Many previous studies attempt to interpret the relationships between speeds and traction energy consumptions (e.g. Chui et al., 1993; Lukaszewicz, 2001; Miller et al., 2006; Bocharnikov et al., 2007;

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[*] Correspondence address: School of Traffic and Transportation, Beijing Jiaotong University, No. 3 Shangyuancun, Haidian District, Beijing 100044, PR China. Tel./fax: +86 (0) 10 51684208.
E-mail address: xsfeng@bjtu.edu.cn

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López et al., 2009) as well as transport efficiencies (i.e. transport efficiencies) of various kinds of trains (e.g. Wong et al., 2002; Liu et al., 2007; Hsu et al., 2010). However, these studies usually focus on the changes of total energy cost and gross time loss of a train with the increase of the number of its stops along a rail line. They are not able to provide quantitative evaluations of both energy and time saving with respect to target speeds of trains under different inter-stop transport distances, traction equipment characteristics and rail lines' gradients, curvatures, etc. By analyzing the effect of these factors on the Traction Energy Cost (TEC) (i.e. energy consumed due to motoring, coasting and braking) and Technical Operation Time (TOT) (i.e. travel time excluding the time expended by stops in stations) per 10,000 passenger-kilometers (p-km), this work propose to optimize the target speeds of HSR trains in a quantificational manner from the perspectives of both traction energy saving and transport efficiency improvement. This research is based on the simulations of the passenger transport services by the HSR-Train-Type1 from Stop-A to Stop-B of one certain HSR line and the HSR-Train-Type2 from Stop-C to Stop-D of another HSR line in China.

This paper is organized as follows. The simulation approach to calculate the TEC and the TOT of a HSR train is first explained in Section 2. Thereafter, Sections 3 and 4 analyze the TEC per 10,000 p-km and the TOT per 10,000 p-km of various types of HSR trains with different target speeds between different stops, respectively. Based on the results attained, the performance of introducing the variable Technical Operation Cost (TOC) per 10,000 p-km is evaluated in Section 5. Finally, conclusions are given and future research issues are discussed in Section 6.

2. Simulation approach to calculate TEC and TOT

According to the train traction calculation methods introduced in the works of Andrews (1986) and Mao et al. (2008), the computer-aided simulation approach presented in Fig. 1 is applied in this study to calculate the TEC and TOT of a passenger transport service by a HSR train. The whole trip of the train from one stop to the next is simulated in successive intervals. The lengths of the calculation intervals are equal to 1 s in the simulation work of this research. The traction force, speed and operating condition (i.e. motoring, coasting or braking) of the train are considered to be unchanged in one calculation interval. The train at a station is started up with its full traction power towards the target speed. With the first achievement of the target speed by the sustaining acceleration of the train from its startup, the train commences to coast till the difference between its speed and the target speed reaches a pre-set value, which is 10.00 km/h in this work, thereafter accelerate with its full traction power to the target speed alternately. In order to ensure accurate and safe stopping at stations, the train begins to decide whether brakes are necessary or not in a calculation interval when the train arrives at a rail site where there is a certain distance away from the next stop. This is decided according to the speed ($v1$) of the train and the permitted speed ($v2$), which is determined based on the braking performance of the train and the transport distance from the site of the train at the beginning of this calculation interval to the next stop. If $v1 \geq v2$, the train brakes to decrease its speed as soon as possible to a comparatively very small value, which is able to ensure absolute safety of its stop in the next station; if $v1 < v2$, the train coasts. Such decisions are made for each of the latter calculation intervals till the train accurately stops in safety in the next station according to the $v1$ of the train in each latter calculation interval and the $v2$, which is determined based on the location of the train at the beginning of each latter calculation interval and the braking performance of the train.

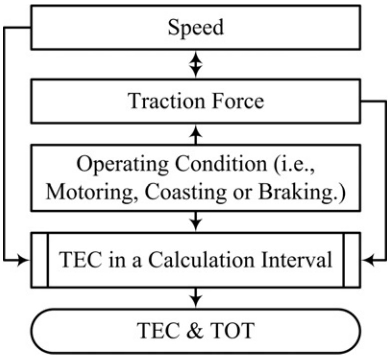

Fig. 1. Simulation approach to calculate the TEC and TOT.

The traction force of a train utilizing a certain ratio, i.e. $r\%$, of its full traction power in a calculation interval is first determined by the speed of this train, as expressed by Eq. (1):

$$f_k^r = \frac{P_k^r}{v_k^r} \tag{1}$$

where f_k^r is the traction force of the train utilizing $r\%$ of its full traction power in the kth calculation interval, unit is N, P_k^r is the traction power of the train utilizing $r\%$ of its full traction power in the kth calculation interval, unit is W and v_k^r is the speed of the train utilizing $r\%$ of its full traction power in the kth calculation interval, unit is m/s.

Besides the speed, the traction force of a train is also affected by its operating condition. When a train is coasting or braking, its traction force is 0 N. As a result, the traction force of a train utilizing $r\%$ of its full traction power in a calculation interval is able to be generally interpreted by Eq. (2):

$$f_k^r = \begin{cases} \frac{P_k^r}{v_k^r} & \text{if } (v^{tm} - v_{k-1}^{pr}) > C^{tm} \text{ or } (v_k^{ul} - v_{k-1}^{pr}) > C^{ul} \\ 0 & \text{if } (v^{tm} - v_{k-1}^{pr}) \leq C^{tm} \text{ or } (v_k^{ul} - v_{k-1}^{pr}) \leq C^{ul} \end{cases} \tag{2}$$

where v^{tm} is the target speed of the train, unit is m/s, v_k^{ul} is the upper speed limit in the kth calculation interval, which is equal to v^{tm} when there is no requirement by the track geometry of the rail line, unit is m/s, v_{k-1}^{pr} is the speed of the train utilizing $pr\%$ of its full traction power in the $(k-1)^{th}$ calculation interval, unit is m/s, C^{tm} is the permitted maximum difference between speed of the train and the target speed, unit is m/s and C^{ul} is the permitted maximum difference between speed of the train and the upper speed limit, which is equal to C^{tm} when there is no requirement by the track geometry of the rail line, unit is m/s.

As illuminated by Eqs. (2) and (3), the speed of a train in a calculation interval is decided by the traction force of the train utilizing some proportion of its full traction power, according to the target speed of the train, the upper speed limit required by the track geometry of the rail line in this calculation interval, the speed of the train in the previous calculation interval, the mass of the train and the resistance force from the rail line:

$$v_k^r = v_{k-1}^{pr} + \frac{f_k^r - f_k^L}{M} \Delta t \tag{3}$$

where, f_k^L is the resistance force from the rail line in the kth calculation interval, unit is N, which is explained by Eq. (4), M is the mass of the train, unit is kg and Δt is the equivalent length of the calculation intervals, i.e. 1.00 s in this work:

$$f_k^L = f_k^B + f_k^S \tag{4}$$

where f_k^B is the basic resistance force from the rail line in the kth calculation interval, unit is N, which is given by Eq. (5), and f_k^S is the special resistance force from the gradient, curvature, etc. of the rail line in the kth calculation interval, unit is N. The special