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Effect of Different Inter-Stop Transport Distances of a Chinese Freight Train on Its Transport Efficiency

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Abstract

Utilizing a computer-aided simulation approach, this work studies the impacts of different inter-stop transport distances on the transport efficiency evaluated by the transport time cost intensity of a typically composed Chinese freight train hauled by representative types of locomotives in view of different target speeds. It is found that the decelerated decrease of the transport time cost intensity with improving the target speed is much traded off by decreasing the stop-spacing especially below approximately 20.00 km. Moreover, the decrease of the inter-stop transport distance especially shorter than about 20.00 km obviously increases the transport time cost intensity in an accelerated way for the same target speed. Such a trend is more apparent when the target speed becomes relatively high. Therefore, it is suggested that the inter-stop transport distance of a freight train ought to be over 20.00 km for relatively high transport efficiency.

Keywords*: freight train, inter-stop transport distance, target speed, transport efficiency, simulation study*

1. Introduction

As one of the main freight transport modes in China today, railway completes about 14.81% of the nationally total 18583.70 billion ton-kilometers (t-km) in 2014 [1]. Improving the freight transport efficiency has always been one of the most important tasks of Chinese railway transport researchers and practitioners. Though continuous effort has been made, the improvement effect is still not satisfying enough. The average Time Cost (TC) per 10,000 t-km of the daily railway freight transport work completed by one locomotive in China is decreased from approximately 0.18 hour (h) in 2010 to merely about 0.17 h in 2014 [1]. It is well known that transport TC intensity of a train is much concerned with the target speed of the train. However, the effect of increasing the target speed on decreasing the TC intensity is considerably weakened by multi-factors including rail network capacity [2], train characteristics [3, 4], transport operation techniques [5, 6], and so on. Moreover, such a decrease of the TC intensity is obtained at the expense of distinctly increasing energy cost intensity [7-9]. As a result, it is sustainably the most important to seek ways out for the win-win relationship between the transport efficiency improvement and the energy cost intensity decrease.

First of all, it is easy to find out that rationally taking advantage of downward slopes of a rail line is able to save the Traction Energy Consumption (TEC) of a train as well as optimize its TC [10]. Therefore, a plenty of studies focus on rationalizing controls of a train. For example, Liu and Golovitcher [9] apply the optimal control theory to decide the rail sites where the operating condition of a train is changed in its transport process on a certain rail line to minimize the TEC of the train for the whole trip with some TC. A two-level hierarchical model solved with the genetic algorithm is established by Ding et al. [11] to determine the coasting points of a train within a scheduled TC to decrease its TEC for a trip. In contrast to the studies concentrating on the train operation control optimization, some

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research efforts attach much importance to improving specific conditions of a train. Such efforts include decreasing train stop frequency [7, 12], rationalizing train mass distribution [13], managing out-put powers from different traction engines [14], *etc*. Moreover, some works systematically optimize the transports of multi-trains to decrease their TEC and TC in integrated manners. For instance, the dynamic programming method is ever utilized to study the dwell and run time of trains operating on the same rail route to save their TEC and regulate their transport service time [15, 16]. Acikbas and Soylemez [17] and Yang et al. [18] use artificial neural networks, genetic algorithms and simulation approaches to explore the coasting strategies of multi-trains on a rail network to minimize their general TEC for the target overall TC. Based on an original method of speed profiling performed by a multi-objective evolutionary algorithm, a bi-objective evolutionary approach is put forward to produce a set of solutions optimizing both the running time and energy consumption [19]. Li et al. [20] propose a multi-objective fuzzy scheduling model to minimize the TEC, carbon emission and TC of multi-trains.

Despite valuable research findings from previous studies for the optimizations of not only TEC but also TC, the impacts of different inter-stop transport distances on the TC intensity of a transport service made by a freight train still cannot be explained accurately. According to the computer-aided simulations of the transports completed by a typical Chinese freight train on a hypothetical railway line, the effect of the inter-stop distance on the transport TC intensity *(i.e.,* TC per unit t-km) of the train is analyzed for different target speeds in view of the traction performance of the utilized locomotive to evaluate the railway freight transport efficiency. The remaining parts of paper are organized as follows. The simulation approach applied in this work and the composition of the studied freight train are explained in Section 2. Next, Section 3 analyzes the change of the TC per unit t-km of each transport work completed by the train with the increase of its target speed for different inter-stop transport distances. Finally, Section 4 makes conclusions, gives some suggestions for the railway freight transport in China and proposes some future research issues.

2. Simulation Approach

The transport process of a typically formed Chinese freight train consisting of 60 coupled wagons hauled by 1 locomotive on a hypothetically straight and smooth railway line is simulated. There are totally 21 stations along this hypothetical railway line. They are represented by S01, S02,……, and S21, respectively. The studied freight train stops at these 21 stations. The transport distances of the train between neighboring stations are explained by Equation (1). The 60 wagons composing the studied train in this work all take the same one of the major wagon models in China (*i.e.,* C70 whose self-weight, loading capacity and designed top-speed are 23.60 tons (t), 70.00 t and 120.00 kilometers per hour (km/h), respectively [21]. Because the loading capacity of a Chinese railway freight wagon is usually required to be fully utilized, the train studied in this work is fully loaded. The train is hauled in this research by SS1 or SS4 which are two main types of the (electric) locomotives for Chinese railway freight transports. The weights of SS1 and SS4 are 138.00 t and 184.00 t, respectively [22]. Their designed top-speeds are correspondingly 90.00 km/h and 100.00 km/h [22].

$$D_{S(m),S(m+1)} = 5.00\times10^{-4}\times m \tag{1}$$

where $D_{S(m),S(m+1)}$ denotes the transport distance from station $S(m)$ to station $S(m+1)$, $m=1,2,......,20$, Unit: 10,000 kilometers (km).

Figure 1 presents the framework of the simulation approach used to compute the transport time (*i.e.,* T) of the train between neighboring stops. The simulation is made for every successive simulation interval (*i.e.,* ΔT) which is equally set to be 0.10 second in this work. The operating condition (*i.e.* motoring, coasting or braking) and traction force of the train are assumed to be unchanged in one simulation interval. The train at a station starts up with gradually increasing its traction power to the full traction power. If the speed of the train at the end of a simulation interval is close to the upper speed limit owing to the rail condition in the next simulation interval or the target speed, the train coasts in the next interval. If the difference between the speed of the train and the upper speed limit or between the speed of the train and its target speed achieves a certain small value, the train brakes in the next simulation interval. When the distance from the train to its next stop becomes close to a value which is necessary for the safety stop of the train in the next station, the train starts to brake in latter intervals to reduce its speed to a safety value which enables the train to stop at any time. Thereafter, the train coasts if its speed keeps no bigger than the safety speed. The transport distances of the train in the successive simulation intervals are accumulated in time to judge whether the train arrives at the next station.

The traction force of the train in a simulation interval is explained by Equation (2). When the train is started up, its traction force is a relatively big constant value in such an interval. Meanwhile, the resistance force to the startup of the train is determined by both the mass of the train and the additional resistance force from the ramps, bends, *etc.* of the rail line, as interpreted by Equation (3). If the rail line is straight and smooth, the additional resistance force does not exist. After the startup of the train, the resistance force to its movement is increased with the speed of the train. Moreover, it is shown in Equation (4) that the speed of the train at the end of a simulation interval is simultaneously determined by the traction force and resistance force in this interval, the speed of the train at the end of the previous simulation interval, and the mass of the train. Furthermore, the transport distance of the train is computed by Equation (5).

$$F_k = \begin{cases} F, & if\ (v_{k-1} = 0) \\ P_k / v_{k-1}, & if\ (v^t - v_{k-1} > C^1)\ \&\ (v_k^l - v_{k-1} > C^1) \\ & \quad \&\ (D - d - ds > C^s)\ \&\ (v_{k-1} > 0) \\ 0, & if\ (((C^2 < v^t - v_{k-1} \le C^1)\ |\ (C^2 < v_k^l - v_{k-1} \le C^1)) \\ & \quad \&\ (D - d - ds > C^s))\ |\ ((D - d - ds \le C^s)\ \&\ (v_{k-1} \le v^0)) \\ -F^B, & if\ (v^t - v_{k-1} \le C^2)\ |\ (v_k^l - v_{k-1} \le C^2) \\ & \quad |\ ((D - d - ds \le C^s)\ \&\ (v_{k-1} > v^0)) \end{cases} \tag{2}$$

where,

F_k : Traction force of a train in the k^{th} simulation interval, Unit: N,

F : Traction force of the train for its startup, Unit: N,

P_k : Traction power of the train in the k^{th} simulation interval, Unit: W,

v_{k-1} : Speed of the train at the end of the $(k-1)^{th}$ simulation interval, Unit: m/s,

v^t : Target speed of the train, Unit: m/s,

v_k^l : Upper speed limit in the k^{th} simulation interval, Unit: m/s,

C^1, C^2 : Permitted maximum and minimum differences between the speed of the train and either its target speed or an upper limited speed, Unit: m/s,

F^B : Braking force of the train, Unit: N,

D : Rail distance in an inter-stop section, Unit: m,

d : Completed transport distance in the inter-stop section, Unit: m,

ds : Necessary distance for the train to reduce its speed from v^t to 0, Unit: m,

v^0 : Safety speed, Unit: m/s, and

C^s : Permitted maximum difference between $(D-d)$ and ds, Unit: m/s.

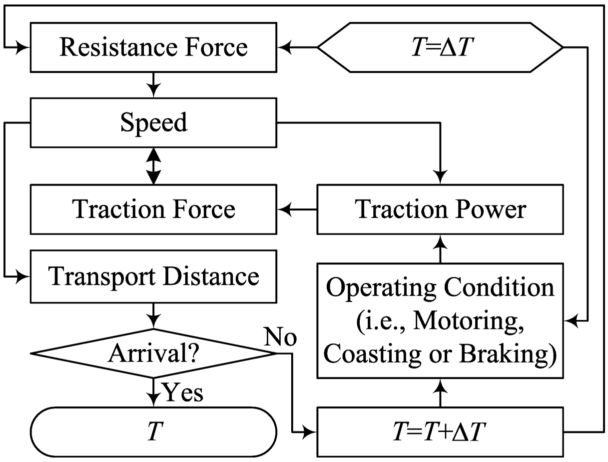

Figure 1 Framework of the simulation approach for an inter-stop transport section

$$f_k = \begin{cases} q \times M + f_k^a, if\ (v_{k-1} = 0) \\ \alpha_0 + \alpha_1 \times v_{k-1} + \alpha_2 \times (v_{k-1})^2 + f_k^a, if\ (v_{k-1} > 0) \end{cases} \quad (3)$$

where,

f_k : Resistance force of a train in the k^{th} simulation interval, Unit: N,

q : Resistance intensity for the startup of the train, Unit: N/kg,

M : Mass of the train, Unit: kg,

f_k^a : Additional resistance force, Unit: N, and

α_0, α_1, α_2 : Coefficients determined by the body streamline design of the locomotive, the friction between the wheels and the rail, *etc*.

$$v_k = v_{k-1} + \frac{F_k - f_k}{M} \times \Delta t \quad (4)$$

$$d = \sum_k v_k \cdot \Delta t \quad (5)$$

3. Transport Efficiency Evaluation

The TC per 10,000 t-km of a transport work completed by a train is defined by Equation (6) to measure the TC intensity for the evaluation of the freight transport efficiency which is improved with the decrease of the TC per 10,000 t-km. With regard to the same target speed, the time consumed for starting up and stopping a train will not be reduced with the decrease of the transport distance between neighboring stops. In other words, decreasing the completion of the t-km by shortening the transport distance will have a less proportional decrease of the time used for the whole inter-stop transport. As a result, the TC intensity will be increased with reducing the inter-stop transport distance. The TC intensities of the freight transport services made by the studied train hauled by either SS1 or SS4 for various target speeds and different inter-stop transport sections are presented in Figure 2 and Figure 3.

$$t_{ij}^v = \frac{T_{ij}^v}{(\sum_{q=1}^{n}(C_{ij}^{v,q} \times R_{ij}^{v,q})) \times D_{ij}^v} \quad (6)$$

where,

t_{ij}^v : TC per 10,000 t-km of the transport completed by the train with the target speed of v from station i to station j, Unit: h/10,000 t-km,

T_{ij}^{v} : TC of the transport completed by the train with the target speed of v from station i to station j, Unit: h,

n : Number of all the wagons composing the train,

$C_{ij}^{v,q}$: Loading capacity of the q^{th} wagon of the train providing the transport service with the target speed of v from station i to station j, Unit: t,

$R_{ij}^{v,q}$: Utilization ratio of the loading capacity of the q^{th} wagon of the train providing the transport service with the target speed of v from station i to station j, Unit: %, and

D_{ij}^{v} : Distance of the transport completed by the train with the target speed of v from station i to station j, Unit: 10,000 km.

It is first found in Figure 2 and Figure 3 that the TC per 10,000 t-km is decreased in a decelerated manner with the increase of the target speed. Furthermore, it is revealed in these two figures that, the effect of increasing transport efficiency by improving the target speed is much traded off by decreasing the inter-stop transport distance as well especially when the stop-spacing becomes shorter than about 20.00 km. This in fact causes frequent starts and stops of a train, as ever indicated by van Wee et al. [23] and Lindgreen and Sorenson [12]. Moreover, for any a certain target speed, the TC per 10,000 t-km is increased with decreasing the transport distance between neighboring stops. Such an increase is also accelerated with shortening inter-stop transport distance, which becomes particularly obvious if the stop-spacing is below approximately 20.00 km. This trend is more evident for a relatively high target speed. In contrast, changes of the inter-stop transport distances over about 20.00 km have much less effect on the TC per 10,000 t-km.

In addition, it is also indicated that, because of the restriction of the traction performance of the locomotive, the speed of the train cannot be accelerated to certain relatively high target speeds in a comparatively short inter-stop transport distance before the train starts to brakes for its stop at the next station. As a result, some different target speeds of the train for its transports between the same neighboring stations have the same TC per 10,000 t-km. For instance, as shown in Figure 2, the speed of the studied freight train hauled by SS1 is only able to reach 60.00 km/h for the inter-stop transport distance of 5.00 km from S01 to S02. Therefore, the TC per 10,000 t-km of the transport work completed by the train does not decrease with the target speed over 60.00 km/h for this inter-stop section. Furthermore, it is evidently shown in Figure 2 and Figure 3 that the transport efficiency of the train hauled by SS4 is higher than that of the same train hauled by SS1 with the same target speed for the same inter-stop transport section. It is accordingly proved that the traction performance of SS4 is superior to that of SS1.

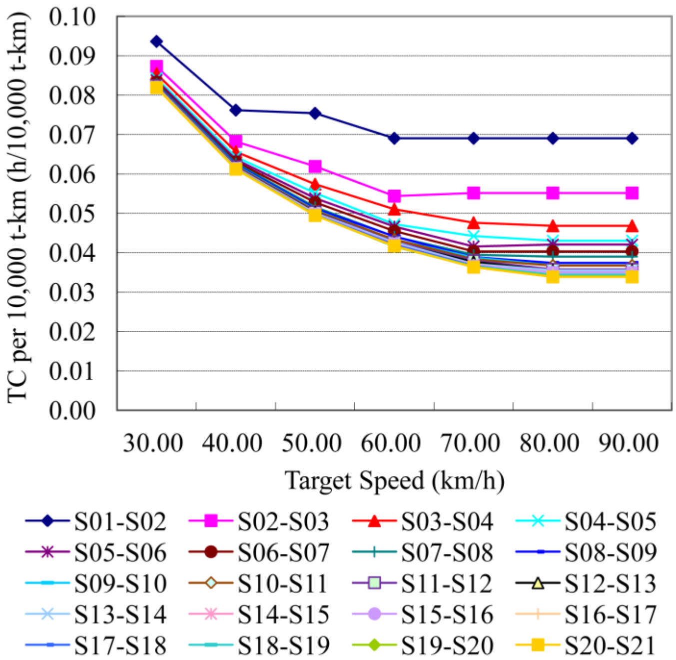

Figure 2 TC Intensities of the Transports Completed by the Studied Train Hauled By The SS1

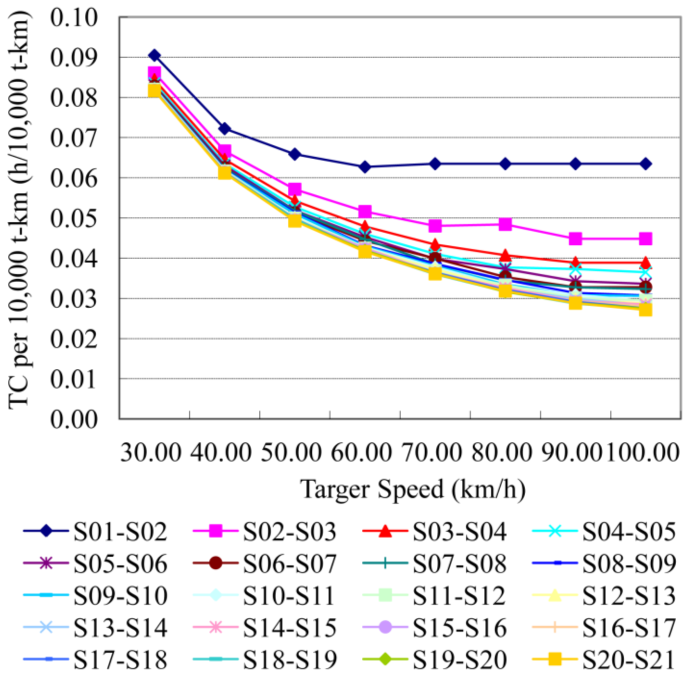

Figure 3 TC Intensities of the Transports Completed by the Studied Train Hauled By the SS4

4. Conclusions

Now it is confirmed that the TC per unit t-km of a transport service provided by a freight train get an accelerated increase with the decrease of the inter-stop transport distance especially below approximately 20.00 km for the same target speed of the train. Such a trend is strengthened by improving the target speed. In addition, the decelerated decrease of the TC per unit t-km with the increase of the target speed is further slowed down apparently by decreasing the stop-spacing particularly shorter than about 20.00 km. As a result, it is suggested that the transport distance of a freight train between neighboring stops should be over 20.00 km in order to ensure comparatively high transport efficiency of the train besides its relatively low TEC intensity [24]. Moreover, a freight train ought to make a full use of the traction performance of its locomotive(s).

Due to data limitation, this study analyzes the transport processes of only one formation type of a Chinese freight train hauled by either of two representative models of the railway locomotives on a hypothetical rail line. Efforts should be made in future research to explore more integrated effect of inter-stop transport distance, track alignment, target speed, sustained strong wind, air temperature, *etc*. on the TC per unit transport of a freight train. Furthermore, more kinds of the compositions of freight trains hauled by varied types of the locomotives with distinct traction performances in different countries should also be studied to further validate the findings and conclusions in this work.

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