The relationship between energy consumption and train delay in railway traffic*

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Based on deterministic NaSch model, we propose a new cellular automation model for simulating train movement. In the proposed model, the reaction time of driver/train equipment is considered. Our study is focused on the additional energy consumption arising by train delay around a traffic bottle (station). The simulation results demonstrate that the proposed model is suitable for simulating the train movement under high speed condition. Further, we discuss the relationship between the additional energy consumption and some factors which affect the formation of train delay, such as the maximum speed of trains and the station dwell time etc.

Keywords: NaSch model, energy consumption, train delay

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1. Introduction

Commonly, train delay is described by a simple train count. Some delays come from the confliction for track resources, such as the meet and pass of trains. Some delays are the results of interferences of different trains around a traffic bottle. Two main methods have been developed for studying the train delay, i.e. the mathematic and simulation methods.[1−6] Mathematic method can estimate train delay well, but it is subject to the size and complexity of considered system. Simulation method can include some stochastic elements. It estimates train delay by relative simple decision rules. Statistical method provides another way to study how the level of capacity utilization contributes to train delay.[7]

In railway traffic, the propagation of train delay results in the additional energy consumption. In the literatures related to such a problem, various approaches and policies are proposed and discussed.[8−12] Optimal train running profile provides a primary approach that is designed to reduce train delay and energy consumption. Ariano and Albrecht presented a formulation that makes it suitable for optimizing actual train running times.[9] Mazzarello and Ottaviani introduced an advanced Traffic Management System (TMS) to optimize traffic fluency in large railway network.[10] Corman and Ariano used a detailed optimal model to analyse the policy, which consists in letting trains to avoid speed profile modifications in open corridors.[12]

Cellular automation (CA) is one of the simulation methods. It has been successfully used to simulate high volume of traffic over large networks with shorter execution time.[13] NaSch model is a kind of important CA models.[14] It is useful to understand fundamental relations between microscopic rules and macroscopic measurements. CA has also been used to study the energy consumption in traffic problem.[15] The motivation for our work is twofold. First, we propose a new CA model for train movement under high speed condition, where the reaction time of trains is considered. Second, we discuss and analyse the relationship between the energy consumption and train delay. The paper is organized as follows: in Section 2, we introduce the principle of moving block system. In Section 3, a new CA model for railway traffic is proposed. The numerical and analytical results are presented in Section 4. Finally, conclusion of this approach is presented.

2. Moving block system

The moving block system is one of the train control systems, with some advantages including the in-

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creased line capacity, and the improved energy efficiency. In addition, the moving block system is expected to lead to a smoother traffic flow where train stop (or deceleration) can be reduced considerably. However, it is difficult to quantify these effects, such as the effect of moving block on traffic fluidity and the average energy consumption per stop.

With a moving block system, a radio which is linked to the control centre continuously control trains to make sure that trains are kept at safety stopping distance between each other. Data transmitted between wayside and train including the permitted train direction, the maximum speed and the current train position, etc. Using the information, controller can optimize system performance and respond to events quickly and effectively. Several types of moving block scheme have been discussed:[16] the moving space block (MSB), the moving time block (MTB) and the pure moving block (PMB), etc. MSB is the simplest scheme, in which the safety stopping distance between successive trains is

$$d_{\rm s} = \frac{v_{\max}^2}{2b} + SM, \tag{1}$$

where $v_{\max}$ and b are the maximum speed and deceleration of trains respectively. SM is the safety margin distance. In this scheme, the only information that the following train requires is the position of its leading train and its own position.

In railway traffic, the most critical period occurs as the train approaches to station, where the leading train must leave in time for the following train to run into the station following its worst-case braking curve. In this case, the minimum headway time between two trains is[17]

$$\tau_{\min} = \begin{cases} T_{\rm r} + T_{\rm d} + \dfrac{v_{\max}}{b} + \dfrac{2a(L_t + L_{\rm d}) + v_{\max}^2}{2av_{\max}}, & v_{\max} < \sqrt{2(L_t + L_{\rm d})}/a, \\ T_{\rm r} + T_{\rm d} + \dfrac{v_{\max}}{b} + \sqrt{\dfrac{2(L_t + L_{\rm d})}{a}}, & v_{\max} \geq \sqrt{2(L_t + L_{\rm d})}/a, \end{cases} \tag{2}$$

where $T_{\rm r}$ is the reaction time of driver/train equipment, $L_{\rm t}$ is the length of trains and $L_{\rm d}$ is the distance that the leading train has left the station, called safety protection distance. $T_{\rm d}$ is defined as the station dwell time, and a represents the acceleration of trains. In the following simulations, the length of trains $L_{\rm t}$ is omitted, i.e., $L_{\rm t} = 0$.

3. The proposed model

In this work, we use the CA model to simulate the railway traffic. Our study is based on the deterministic NaSch traffic model. In the proposed model, the considered track section consists of a single-line which is divided into L cells of equal size numbered by $i = 1, 2, \ldots, L$, and the time is discrete. Each site can be either empty or occupied by a train with integer speed $v_{\rm n} = 0, 1, \ldots, v_{\max}$.

With a moving block system, in order to avoid the collision between two trains, the distance between two successive trains must be larger than the safety stopping distance. However, in a real train control system, the control centre needs a little time to receive information from trains, and then sends information to relevant trains. Such a time is called the reaction time of driver/train equipment. This means that when the distance between two successive trains is smaller than the safe stopping distance, the following train does not immediately decelerate. Based on our previous work,[17] we introduce the reaction time $T_{\rm r}$ into the current proposed model. In the proposed model, the acceleration of the n-th train is given by the following step

if $\Delta x_{\rm n} > d_{\rm s}$,
  $T_{\rm c} = 0$,
  $v_{\rm n} = \min(v_{\rm n} + a, v_{\max})$,
else if $\Delta x_{\rm n} < d_{\rm s}$,
  $T_{\rm c} = T_{\rm c} + 1$,
  if $T_{\rm c} > T_{\rm r}$,
    $v_{\rm n} = \max(v_{\rm n} - b, 0)$,
  else
    $v_{\rm n} = v_{\rm n}$,
  end
else
  $T_{\rm c} = T_{\rm c}$,
  $v_{\rm n} = v_{\rm n}$,
end

where $\Delta x_{\rm n}$ is the headway distance of the n-th train. $T_{\rm c}$ is a variable used to accumulate the simulation time in which the distance $\Delta x_{\rm n}$ is less than the safety stopping distance $d_{\rm s}$. When the distance $\Delta x_{\rm n}$ is larger than the safety stopping distance $d_{\rm s}$, the n-th train accelerates by a. When the distance $\Delta x_{\rm n}$ is smaller than

the safety stopping distance $d_{\rm s}$, we record the time $T_{\rm c}$. If the time $T_{\rm c}$ is larger than $T_{\rm r}$, the n-th train begins to decelerate by b. As mentioned above, the proposed model is based on our previous work.[17] The updated rules for implementing train acceleration in Ref. [17] are replaced by the above updated rules. Other updated rules for implementing the train control are the same as those used in Ref. [17]. Considering the reaction time $T_{\rm r}$, the safety stopping distance between successive trains is calculated by

$$d_{\rm s} = \frac{v_{\rm max}^2}{2b} + SM + v_{\rm max}T_{\rm r}. \tag{3}$$

In our method, the boundary condition for the CA model is open. It is defined as: (i) at the site $i = 1$, if the first $L_{\rm s}$ sites are empty, a train with the speed $v = v_{\rm max}$ is created. $L_{\rm s}$ is called the train departure interval. This newborn train immediately runs according to the proposed update rules; (ii) at the site $i = L$, the trains simply run out of the system. In order to compare simulation results to field measurements, one iteration step roughly corresponds to 1 second, and the length of a cell is about 1.6 m. This means, for example, that $v_{\rm max} = 10$ cells/update corresponds to $v_{\rm max} = 57.6$ km/h.

4. Simulations

We use the CA model proposed in this paper to simulate the train movement under moving block condition. The block scheme adopts moving space block (MSB). A system of $L = 15000$ is considered, and the length of evolution time is $T = 10000$. The distance $L_{\rm d}$ is selected as the fixed value $L_{\rm d} = 250$. The acceleration and deceleration of trains are set to be one cell unit. The safety stopping distance between successive trains is calculated by formula (3). One station is designated at the middle of the considered system, which is regarded as a traffic bottle.

In order to test the proposed CA model, we measure the minimum headway time between two successive trains at station, and then compare the measurement results with the theoretical results calculated by formula (2). Figure 1 shows how the minimum headway time varies with the maximum speed. In Fig. 1, the dotted line denotes the simulation values using the proposed model, and the solid line denotes the theoretical values obtained by formula (2). We can see that the simulation values are close to the theoretical values. This means that the proposed model can be successfully used for the simulation of railway traffic. As $v_{\rm max} = 56$ cells/update (corresponds to $v_{\rm max} = 322.56$ km/h), the simulation values are still close to the theoretical values. The results suggest that the proposed model can well capture some characteristic behaviour of trains under high speed condition.

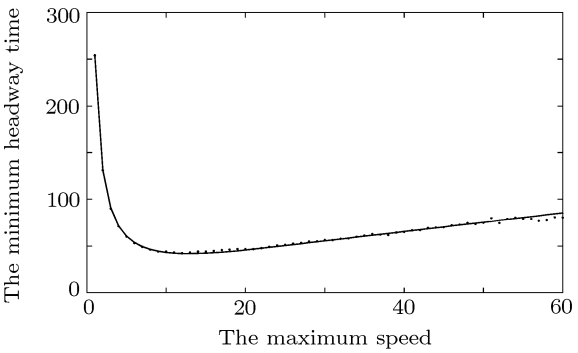


Fig. 1. A plot of $\tau_{\rm min}$ vs. $v_{\rm max}$ for $T_{\rm r} = 3$, $T_{\rm d} = 30$.

Train delay easily occurs around a station which has a fixed and commonly known capacity. If the arrival rate at a station exceeds its capacity, a queue will form outside the station. Further, train delay leads to some complex phenomena, such as the go-and-stop waves. In general, a station with null length and limited capacity can be conveniently formulated in terms of cumulative flows. In our simulations, the station can only be occupied by one train.

The go-and-stop waves result in the additional energy consumption compared to the case of the free waves. The reaction time, the station dwell time and the maximum speed are the main factors which affect the formation of go-and-stop waves. Nakayama *et al.*[18] presented the additional energy consumption with respect to the stable statue for all vehicles as follows:

$$E_{\rm a} = \sum_{\rm cars}\sum_{\rm waves}\frac{1}{2}[v_{\rm max}^2 - v_{\rm min}^2], \tag{4}$$

where $\sum_{\rm waves}$ denotes the summation of all periods of oscillation until the disturbance disappears. Equation (4) is related to the whole traffic flow. But the energy change of each vehicle is more important in understanding the effects of train delay. In this paper, we use the average of additional energy consumption $\bar{E}_{\rm a}$ to describe the additional energy consumption of each train. $\bar{E}_{\rm a}$ is calculated by $\bar{E}_{\rm a}/N$. Here N represents the number of trains.

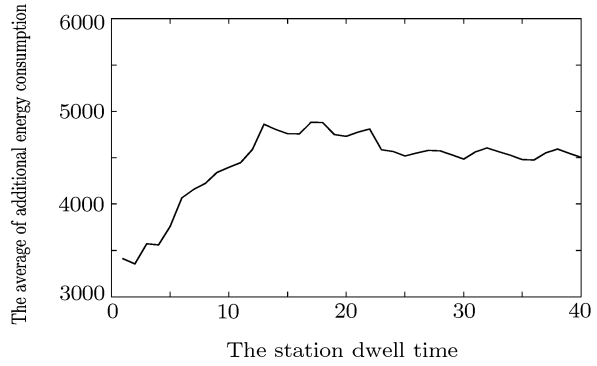


Fig. 2. The average of additional energy consumption for different station dwell time $T_{\rm d}$.

Figure 2 shows how the average of additional energy consumption varies with the station dwell time for $v_{\max} = 40$ and $T_{\rm r} = 3$. In Fig. 2, as the station dwell time $T_{\rm d}$ is less than 13 s, the average of additional energy consumption increases rapidly, then it changes with a small fluctuation after $T_{\rm d}$ is larger than 13 s. Figure 3 is the space-time diagram of train flow for different $T_{\rm d}$. Here the parameters $v_{\max}$ and $T_{\rm r}$ are the same as those used in Fig. 2. In Fig. 3, we can clearly see that the number of train stopping shown in Fig. 3(a) is smaller than that shown in Fig. 3(b).

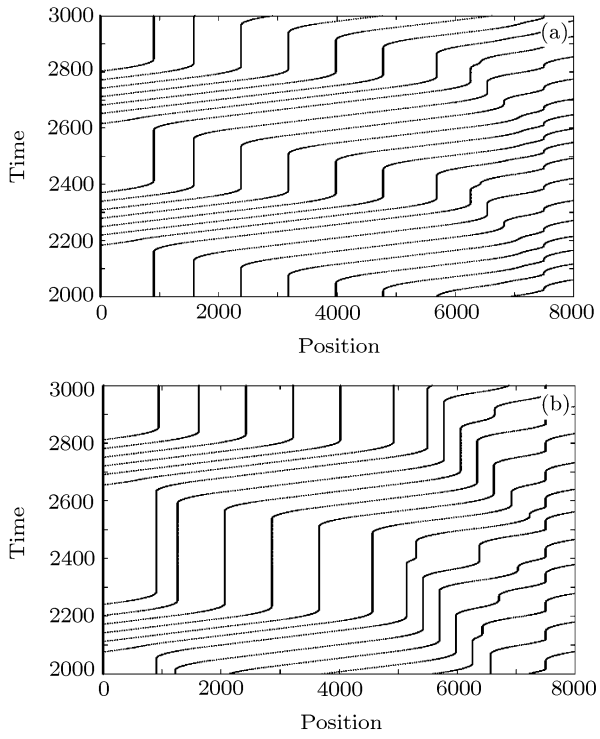


Fig. 3. Space-time diagram of railway traffic flow. (a) $T_{\rm d} = 5$, (b) $T_{\rm d} = 30$.

It should be pointed out that the number of trains stopping does not include that at the station. The reason is that as the station dwell time $T_{\rm d}$ is larger, the number of trains stopping is larger. This results in that train runs with more additional energy consumption.

Further, we discuss the relationship between the additional energy consumption and the reaction time. Figure 4 presents the results for $v_{\max} = 40$ and $T_{\rm d} = 30$. In Fig. 4, it is obvious that the average of additional energy consumption changes with the reaction time with a downward trend, which indicates that the reaction time has action on the additional consumption of energy. As the reaction time $T_{\rm r}$ is larger, the safety stopping distance between two successive trains is larger. Under this situation, in order to avoid collision, the number of train braking is small.



Fig. 4. The average of additional energy consumption varies with the reaction time $T_{\rm r}$.

In general, the formation of train delay is strongly related to the maximum speed of trains. So, the maximum speed is also one of the important factors which affect the additional energy consumption of trains. Figure 5 shows how the additional energy consumption varies with the maximum speed $v_{\max}$.

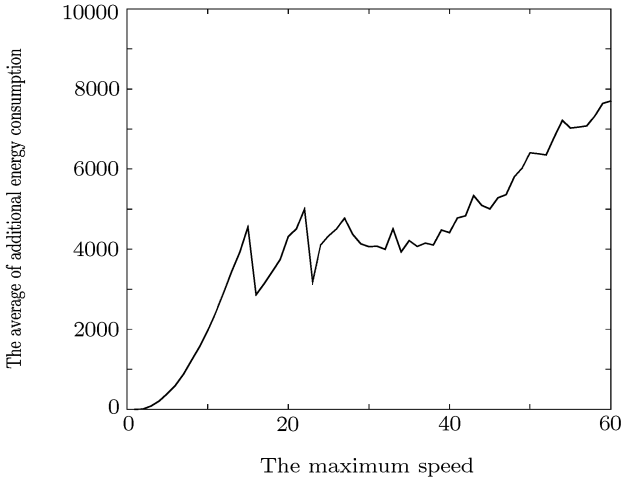


Fig. 5. The average of additional energy consumption changes with the maximum speed for $T_{\rm r} = 3$, $T_{\rm d} = 20$.

The abscissa indicates the maximum speed of trains, and the ordinate indicates the additional energy consumption. From Fig. 5, it is obvious that the additional energy consumption increases rapidly when the maximum speed increases from 1 to 15. As the maximum speed $v_{\max}$ is larger than 15, the additional energy consumption changes with a small amplitude.

5. Conclusions

In conclusions, a new cellular automation model is proposed to simulate the train movement. Numerical simulations indicate that the proposed model can be successfully used for describing train movement under high speed condition. Moreover, we discuss the influence of train delay on the process of train control. We find that the formation and propagation of train delay would lead to additional energy consumption. The additional energy consumption is strongly related to the station dwell time and the maximum speed etc.

In this paper, station is regarded as a traffic bottle which is simplified. In real railway traffic, a station usually includes several platforms which have important impacts on train delay. In addition, in our method, some factors that affect the behaviour of train have not been taken into account, such as train length and braking rate etc. So we think that it is worth while to be studied further.

References

[1] Vromans M, Dekker R and Kroon L 2006 *European Journal of Operational Research* **172** 647

[2] Harrod S 2008 *Railway Capacity Management and Planning* Ph.D. dissertation, University of Cincinnati

[3] Higgins A, Kozan E and Ferreira L 1995 *Transportation Planning and Technology* **19** 89

[4] Kozan E and Burdett R 2005 *Transportation Planning and Technology* **28** 27

[5] Li K P and Gao Z Y 2007 *Chin. Phys.* **16** 359

[6] Li K P and Guan L J 2009 *Chin. Phys.* B **18** 2200

[7] Gibson S, Cooper G and Ball B 2002 *Journal of Transport Economics and Policy* **36** 341

[8] Hansen I A and Pachl J 2008 *Railway Timetable and Traffic: Analysis, Modelling and Simulation* (Hamburg: Eurailpress)

[9] DAriano A and Albrecht T 2006 *Running Time Reoptimization During Real-time Timetable Perturbations*, in *Computers in Railways X* ed. Allan J, Berbbia C A, Rumsey A F, Sciutto G, Sone S and Goodman C J (Southampton: WIT Press) pp. 531–540

[10] Mazzarello M and Ottaviani E 2007 *Transportation Research* Part B **41** 246

[11] Albrecht T 2009 *Network and Spatial Economics* **9** 85

[12] Cormana F, Arianoa A D, Pacciarellib D and Pranzoc M 2009 *Transportation Research* Part C **17** 607

[13] Chowdhury D, Santen L and Schadschneider A 2000 *Phys. Rep.* **329** 199

[14] Nagel K and Schreckenberg M 1992 *J. Phys.* I **2** 2221

[15] Kan S J, Liang Y J, Tian H H and Xue Y 2009 *Acta Phys. Sin.* **58** 4506 (in Chinese)

[16] Pearson L V 1973 *Moving Block Signalling* Ph.D. Thesis Loughborough University of Technology, England

[17] Tang T and Li K P 2007 *Commun. Theor. Phys.* **47** 601

[18] Nakayama A, Sugiyama Y and Hasebe K 2002 *Phys. Rev.* E **65** 06112