Research on Energy Consumption of Multi-Trains Tracking Traffic Flow Dynamics Model Under Moving Block

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Abstract. Based on the NaSch model, aiming at the characteristics of high-speed train tracking operation under moving block, a cellular automaton dynamics model is proposed to simulate the energy consumption of multi-train tracking operation on Railway lines. Through numerical simulation, this paper studies the influence of different line density and station stopping time on the energy consumption of high-speed railway traffic flow. The simulation results show that the energy consumption model can accurately reflect the energy consumption of multi-train tracking operation. At the same time, the phenomenon of traffic waves that sometimes go and sometimes stop is reproduced. According to the simulation results, it can be concluded that the energy consumption of multi-train tracking flow decreases gradually with the increase of line initialization density, and the average energy consumption of tracking traffic flow decreases with the increase of station stopping time. The results provide a scientific theoretical basis for efficient operation and energy-saving operation of high-speed railway. It has some guiding significance.

1. Introduction
With the continuous speed increase of railways in China, the construction of passenger dedicated lines and high-speed railways, the running speed of trains and the operating density of trains continue to increase. According to the medium and long-term development plan of China's railways, the operational mileage of China's railways will increase from 91,000 km to 120,000 km by 2020. The passenger dedicated lines and inter-city railways with speeds of 200-350 km/h will reach 18,000 km and the high-speed trains put into operation will reach 1,000 groups. Train operation energy consumption is an important economic index in railway operation, which is an important part of the railway transportation cost. Therefore, quantitative analysis of energy consumption characteristics in the operation of high-speed railway can be used to build a high-speed railway network, meet the high-density, fast and convenient, energy-saving and consumption-reducing passenger transport needs. Cellular automaton (CA) model is an effective tool to simulate nonlinear complex systems[1]. CA model can effectively simulate the microscopic movement of vehicles in traffic flow, which has become a hot spot in traffic flow research in recent years. Multi-Trains on the railway line can be regarded as a single lane traffic flow model simulation. The NaSch model is suitable for railway traffic flow simulation. In recent years, great progress has been made. Based on the NaSch model, many researchers applied the theory of cellular automata to the study of railway traffic problems, and
proposed the model of railway cellular automata\(^2\). At present, many scholars have carried out a lot of research work on Train Energy Consumption. Kalogirou SA puts forward a train energy consumption calculation method based on neural network\(^3\). Lucique uses theoretical model calculation and simulation method to analyze the influence of high-speed train running energy consumption\(^4\). At present, most of the energy consumption analysis methods are mainly for single train, and there are few studies on energy consumption analysis of multi-train tracking train flow. At present, most of the simulation studies on train energy consumption are based on the static energy consumption of single train. But in the moving block system, with the further improvement of train speed and train density, the influence between trains becomes more and more serious. The traditional single train energy consumption model has been difficult to reflect the characteristics of actual railway traffic flow energy consumption.

Aiming at the deficiency of the traditional calculation method of train energy consumption for high-speed trains, this paper presents a dynamic model of energy consumption calculation for multi-train tracking operation based on the theory of cellular automata and NaSch traffic flow model. Through computer simulation analysis, the influence of different departure time interval, line density and station stopping time on energy consumption of tracking train traffic flow is analyzed.

2. Railway energy consumption

Railway energy consumption mainly includes train operation energy consumption, station and signal infrastructure and other auxiliary energy consumption, in which railway operation energy consumption accounts for 80% of the total energy consumption. The train energy consumption operation is the energy consumption used to overcome the running resistance to acting, increase the kinetic energy of train and overcome the difference of gravity potential energy. Train traction energy consumption is mainly affected by locomotive attributes, line attributes, transport types, marshalling information and other related factors.

2. Statistical physical model of energy consumption

Under the condition of moving block, there is no fixed block partition. It improves train tracking density and running safety by advanced communication means. The control mode corresponding to traction starting, acceleration, inert speed regulation, braking deceleration and parking direction is generated. In the multi-train tracking model established in this paper, the tracking energy consumption analysis of multiple trains is composed of the sum of all single train starting energy consumption, traction acceleration energy consumption and deceleration energy consumption according to the running conditions of the train.

When the multi-train is running on the line, the calculation model of the train flow energy consumption is as follows:

\[
E_r = E_q + E_r + E_o
\]

In the formula, \(E_r\) is the total energy consumption of train flow during multi-train tracking operation, \(E_q\) is the starting energy consumption of train flow, \(E_r\) is the traction energy consumption of train flow, and \(E_o\) is the deceleration energy consumption of train flow. The calculation method of each parameter in formula (1) is as follows:

\(\text{① Calculation of starting energy consumption}\)

Starting energy consumption of single train: 

\[
e_q = k \times \frac{1}{2} (\sum M_e) \times V^2 / (3.6^3 \times 1000)
\]

In the formula, \(e_q\) for single train starting and stopping energy consumption; \(M_e\) is the train quality, the unit of which is t; \(k\) is the number of times the train tracks the starting and stopping in the energy consumption calculation section; \(V\) is the highest speed after starting operation, the unit of which is km/h; the unit conversion coefficient is \(3.6^3 \times 1000\). When the multi-train tracking operation is on the line, the train flow starting energy consumption \(E_q\) is calculated as follows:
(2) Accelerated energy consumption of train traction

Accelerated energy consumption of single train traction \( e_r = \left( \sum M_c w_c \right) \times S \times 9.81 \times 3600 \)

In the formula, \( e_r \) is the energy consumption of single train traction operation; \( M_c \) is the train quality, the unit of which is t; \( w_c \) is the basic resistance of the high-speed train operation, the unit of which is N/kN, and its value is different according to different types of Electric Multiple Units; \( S \) is the train running speed; \( S \) is the traction running distance, the unit of which is km. The formula for calculating the basic resistance of commonly used high-speed trains according to different types of vehicles is as follows:

- CRH1 type \( w_c(v) = 1.12 + 0.00542 \times V + 0.000146 \times V^2 \)
- CRH2 type \( w_c(v) = 0.88 + 0.00744 \times V + 0.000114 \times V^2 \)
- CRH3 type \( w_c(v) = 0.66 + 0.00245 \times V + 0.000132 \times V^2 \)
- CRH5 type \( w_c(v) = 0.69 + 0.0063 \times V + 0.00015 \times V^2 \)

Through the statistics of the traction train acceleration energy consumption of different train types, the energy consumption of the train flow traction operation \( E_r \) on the line is calculated as follows:

\[
E_r = \sum_{t=0}^{\text{max}t} \sum_{n=1}^{N} \left( \sum M_c w_c \right) \times S \times 9.81 \times 3600
\]

(3) Deceleration energy consumption of train

In the inertial and braking conditions of the train, the train decelerates. In order to calculate the energy consumption of trains running in this condition, the kinetic energy theorem is used to simulate the model. The kinetic energy loss caused by the above two reasons is called deceleration energy consumption. When the model is established, the kinetic energy theorem is used to calculate the energy consumption of single train and train flow in real time.

\[
e_o(n,t) = \begin{cases} 
\frac{1}{2} \left( m v_a^2(t) - m v_a^2(t+1) \right); v_a(t+1) < v_a(t) \\
0; v_a(t+1) = v_a(t) 
\end{cases}
\]

\[
E_o = \sum_{t=0}^{\text{max}t} \sum_{n=1}^{M} e_o(n,t)
\]

In the above formula, \( \text{max}t \) represents the system energy consumption statistics time, \( M \) represents the total number of line trains, and \( E_o \) represents deceleration energy consumption of the train flow. The whole energy consumption of train traffic flow in the maximum observation period can be calculated based on Formula (5), where deceleration can be calculated from the formula (1) to (5).

4. Model establishment

For high-speed tracking train traffic flow, according to train operation condition, the following rules based on the NaSch model are used to indicate the driving of the high-speed train on the line and the station stop rules, then carry out computational simulation.

Situation 1: the front of train N is train N-1.

1) Acceleration process:
If \( \Delta x_o > d_o \)
Before the train accelerates, the train is run and calculates the traction energy consumption.

\[ E_{nr} = (\sum M \cdot w_c) \times S \times 9.81 \times 3600 \]

Else \( e_{m} = k \times \frac{1}{2} (\sum M) \times V^2 / (3.6^3 \times 1000) \); Before the train accelerates, the train is stationary and calculates the starting energy consumption.

Else If \( \Delta x_n < d_n \)
\[ v_n(t+1) \rightarrow \max(v_n(t) - b, 0) \]
\[ e_o(n,t) = \frac{1}{2} (mv_n^2(t) - mv_n^2(t+1)) \] Calculate deceleration energy consumption.

Else \( v_n(t+1) \rightarrow v_n(t) \);

2) Safety protection process:
\[ v_n(t+1) \rightarrow \min(v_n(t+1), gap_n(t)) \], Among them, \( gap_n(t) = x_{n+1}(t) - x_n(t) - l_{train} \) represents the distance between adjacent trains at time t, and the rule indicates the deceleration measures taken to avoid collision with the preceding vehicle when the train is running.

3) Train movement:
\[ x_n(t+1) \rightarrow x_n(t) + v_n(t+1) \]; The train moved forward at the adjusted speed.

Situation 2: the front of train N is the station.

Case1: The station is occupied by the adjacent train in front of N-1.
The update rule is the same as case 1.

Case2: The station was not occupied by other trains.

1) Acceleration process
If \( d_i > d_m \)
\[ v_n(t+1) \rightarrow \min(v_n(t) + a, v_{max}) \]
\[ E_{nr} = (\sum M \cdot w_c) \times S \times 9.81 \times 3600 \]; The train is far away from the station and calculates the traction energy consumption.

Else If \( d_i < d_m \)
\[ v_n(t+1) \rightarrow \max(v_n(t) - b, 0) \]
\[ e_o(n,t) = \frac{1}{2} (mv_n^2(t) - mv_n^2(t+1)) \] The train deceleration is ready to enter the station and calculate the deceleration energy consumption.

Else \( v_n(t+1) \rightarrow v_n(t) \)

2) Safety protection process:
\[ v_n(t+1) \rightarrow \min(v_n(t+1), d_i) \]

3) Train movement:
\[ x_n(t+1) \rightarrow x_n(t) + v_n(t+1) \]

Situation 3: The train N waiting for departure at the station.

Case1: When the train stops at the station less than the prescribed stopping time \( T_d \), the passenger at the stop station gets on the train and waits for departure.
\[ v_n(t+1) = 0, t < T_d \], Among them, \( T_d \) indicates the stopping time of train at the station.

Case2: When the train stops at the station for longer than the prescribed stopping time \( T_d \), the train...
1) $v_n(t+1) \rightarrow \min(v_n(t) + a, v_{\text{max}}), t \geq Td$

$$e_{\text{inq}} = k \times \frac{1}{2} \left( \sum M_c \right) \times V^2 / (3.6^3 \times 1000)$$

When the train exceeds the stop time, the train departs, and then calculate starting energy consumption

2) Train movement: $x_n(t+1) \rightarrow x_n(t) + v_n(t+1)$, The train moved forward at the adjusted speed.

In the above formula, $\Delta x_n$ denotes the distance between the train N and the train N-1, $d_s$ is the minimum tracking interval between trains, $a$ is the train acceleration, $b$ is the train deceleration. $x_i(t)$ denotes the position of the train $i$ in the route at time $t$, $d_e$ is the distance between the train and the station. $d_m$ is the safe distance between train braking and driving into the station. Using formula (2) to get the starting energy consumption of track tracking train flow. The traction energy consumption of line tracking train flow is obtained by formula (3). Using formula (3) and (4) to find out the energy consumption of train deceleration on line. Finally, the overall energy consumption of train tracking traffic flow is obtained by formula (1).

5. Simulation analysis
When the model is established, the line is regarded as one-dimensional discrete lattice with the length of $L$. Each lattice has the same size. Each lattice is either empty or occupied by the train. The train speed is an integer between 0 and $v_{\text{max}}$. The length of the analog line is $L$ cells, and the length of each cell is set to 1 m. The numerical simulation is carried out with the Harmony CRH5 Electric Multiple Units as an example. The train marshalling length is 212 m, and each train accounted for 212 cells. The system refresh interval is 1 s. This means that the actual train speed is 108 km/h when $v_{\text{max}} = 30$ cells/s and the actual train speed is 180 km/h when $v_{\text{max}} = 50$ cells/s.

In the numerical simulation, we take the length of the transmission line is $L=30000$ and the evolution time is $T=5000$. Suppose there is a station at 2/3 of the route, the length of the station is 200 m, the acceleration $a$ and deceleration $b$ are 1 m/s$^2$, the safety protection distance $S_M = 100$, and the stopping time $T_d = 90$ s. The cellular automata model adopts the open boundary condition. In order to eliminate the influence of the randomness of the initial state, the last 5000 steps of each evolution to the steady state are recorded as the simulation time step, and the sample data are averaged after 20 iterations to obtain the space average speed of each time step, so as to ensure the maximum elimination of the effect of initial random distribution on the simulation results.

5.1. Influence of line density on energy consumption of traffic flow
Figure 1. Relationship between the density of the same line and the energy consumption of train flow

In order to study the effect of different line density on energy consumption of tracking train traffic flow, setting the maximum train speed is 50 cells/s, that is, \( V_{\text{max}} = 180 \text{km/h} \). Through simulation, the energy consumption relation diagram of train traffic flow under different initial line conditions is obtained. Figure 1 shows the relationship between the initial line density and train energy consumption under different line initialization densities. In the figure, the ordinate axis represents the average energy consumption of the tracking train, and the abscissa axis represents the initial density value of the train.

It can be seen from Figure 1 that the average energy consumption of tracking train flow on the whole line decreases gradually with the increase of initial line density. This is because as the initial traffic density continues to increase, the number of trains initially distributed on the line increases, resulting in increased interaction between CRH5 tracking trains. As new trains from upstream continue to add to the congestion, so the speed is slower and slower, more and more vehicles stop running, the energy consumption of train deceleration is becoming smaller and smaller, and the traffic condition of the whole line is gradually deteriorating. When the train flow density is increasing, but its traffic energy consumption is zero, this shows that the line has been seriously blocked, forming a traffic jam.

In order to describe the evolution process of high-speed tracking train flow more vividly, the time-space diagram of traffic flow was simulated. The simulation results are shown in Figure 2, it can be clearly seen that when the time is 300s, the trains running on the line have less interaction, the traffic flow on the line is stable in this condition, the running speed is high, and the traffic flow on the tracking train is free under moving block.

Figure 2. Spatiotemporal phase diagram of traffic flow
(a) \( T_{\text{int}}=300\text{s} \); (b) \( T_{\text{int}}=300\text{s} \);

5.2. Influence of station stopping time on tracking trains flow

In addition, the relationship between the different station stopping time \( T_d \) and the average energy consumption of tracing train flow can be obtained by numerical simulation, as shown in Figure 3. Figure 3 is simulated for initializing line density \( p=0.01 \). As can be seen from the diagram, with the increase of station stop time, the average energy consumption of tracing train flow shows a gradual downward trend. This simulation conclusion is consistent with the actual traffic situation. That is to say, the station stop time is small at the beginning, at this time, new trains are constantly coming from the left side of the line, trains do not need to wait for more time to stop, the interaction between the trains is small, the acceleration energy consumption of train traction is large, most of the vehicles are in the free flow driving area, and the deceleration probability is small. With the increase of stopping time, the probability of train deceleration becomes larger and larger due to waiting for the train to
enter the station. The number of low-speed trains increases, and the phenomenon of road congestion begins to appear. From Figure 3, it can be concluded that the longer the station stop time is, the smaller the energy consumption is at the same initialization density. This is because that the longer the station stop time is, the earlier the system enters the blocking phase; The longer the station stop time is, the larger the congestion range is. Because of the congestion, the low-speed traffic flow is formed, so the kinetic energy loss is small, and the corresponding flow and average energy consumption are also minimal.

**Figure 3.** Energy consumption diagram of train traffic flow under different stopping time

6. Conclusion

Moving block technology is a step further in the safety interval control of trains. Aiming at the characteristics of high-speed train running under moving block, based on the NaSch model, an energy consumption model of tracking train flow under moving block condition is established. Then using cellular automata model to study the influence of railway line density and station stopping time on energy consumption of tracing train flow. The results showed that: 1) different railway line density has a significant impact on the energy consumption of multi-train tracking under moving block condition. 2) The time-space phase diagram reproduces the process of congestion and dissipation of tracking train flow. 3) with the increase of station stopping time, the average energy consumption of traffic gradually decreases.

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