Study on energy consumption of multi-trains tracking on long heavy down grade of high-speed railway

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Abstract. For the characteristics of high-speed train tracking operation on long heavy down grade of High-speed Railway, a cellular automaton dynamics model is proposed to simulate the energy consumption of multi-train tracking operation on long heavy down grade based on the NaSch model. Through numerical simulation, this paper studies the influence of different long slope value 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 on long heavy down grade. 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 total energy consumption of multi-train tracking flow decreases gradually with the increase of slope value. The simulation results show that the energy consumption of starting, accelerating and decelerating of high-speed trains will decrease with the decrease of slope value. 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 rapid development of high-speed railway, China's high-speed railway extends from the east to the west. However, China's topography is high in the West and low in the east. Compared with the gentle Eastern region, the topography and topography in the West are more undulating and the geological environment is complex, which makes it more difficult to build the high-speed railway in the west. Slope selection of high-speed railway is one of the important contents of the main technical standards of high-speed railway. Choosing a reasonable line gradient plays an important role in reducing the cost of high-speed railway construction and avoiding engineering risks.

During the construction of high-speed railway in central and Western China, the maximum gradient of some lines exceeds 20‰. For example, the Qinling Tunnel Group of Xicheng High-speed Railway Line adopts a large gradient of 20‰ with a continuous length of 46 km. In other countries, the maximum slope of high-speed railway is about 20, and the maximum design standard can reach 35. The maximum slope is also used in some special topographic lines. Scholars at home and abroad have done a lot of research on the Long Heavy Down Grade[1][2]. For example, Zhang Shoushuai and others calculated and analyzed the relationship between the gradient of the train running on the long heavy down grade, the speed of the train, the monitoring braking distance, the length of the block zone and the tracking interval of the train[3]. Zuo Zihui and others studied the influence of long heavy down grade of high-speed railway on the running speed and tracking interval of EMU[4]. Cui Yanqi and others started with the influencing
factors of the traffic capacity of the section, emphatically analyzed the train tracking interval in the long heavy down grade section[5]. The bottleneck area of long heavy down grade lines is the most important part of high-speed railway line. Thus, to study the bottleneck effect of long heavy down grade lines on traffic flow is of great significance to improve the speed, flow and safety of high-speed railway.

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 high-speed trains based on the theory of cellular automata. 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.

3. Definition of long heavy down grade lines of high speed railway in China
According to the technical management regulations of China's high-speed railway, long heavy down is defined as: the slope of the line exceeds 6‰, the length is 8 km or more; the slope of the line exceeds 12‰, the length is 5 km or more and the slope of the line exceeds 20‰, the length is 2 km or more. Taking CRH380BK (300T) as an example, under the condition of meeting the tracking safety interval, the maximum slope operation safety speed limit is shown in the table below[4].

| Slope /‰ | Speed limit (km/h) | Braking distance /m | Tracking interval /s |
|----------|--------------------|---------------------|----------------------|
| -5       | 300                | 11469               | 177                  |
| -10      | 260                | 9961                | 178                  |
| -15      | 220                | 8263                | 176                  |
| -20      | 180                | 6837                | 179                  |
| -25      | 130                | 4625                | 174                  |
| -30      | 95                 | 3342                | 177                  |

4. Statistical physical model of energy consumption
High-speed trains run on the line and the trains run on traction. Based on mechanics, the trains are mainly subjected to Electric Multiple Units traction F, train running resistance W and train electronically controlled air braking force B, as shown in Figure 1. According to the train running state on the line, the train has three operating conditions: traction, idle running and braking. Under traction condition, the forces acting on the train are traction force F and operation resistance w, resultant force C = F - w; under idle running condition, the forces acting on the train are only operation resistance W, resultant force C = -w; and under braking condition, the forces acting on the train are train braking force B and train operation resistance W, resultant force C = - (B + W).

Fig.1 Schematic diagram of the train's force
When the multi-train is running on the line, the calculation model of the train flow energy consumption is as follows:

\[ E_T = E_q + E_r + E_o \]  

(1)

In the formula, \( E_T \) 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:

1. Calculation of starting energy consumption

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

(2)

In the formula, \( e_q \) for single train starting and stopping energy consumption; \( M_i \) 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.

When the multi-train tracking operation is on the line, the train flow starting energy consumption \( E_q \) is calculated as follows:

\[ E_q = \frac{\sum_{i=0}^{N} \sum_{n=1}^{N} k \times \frac{1}{2} (\sum M_i) \times V^2 / (3.6^3 \times 1000)}{M} \]

(2)

2. Accelerating energy consumption of train traction

\[ e_r = (\sum M_i w_c(v)) \times S \times 9.81 \times 3600 \]

(3)

In the formula, \( e_r \) is the energy consumption of single train traction operation; \( M_i \) is the train quality; \( w_c \) is the basic resistance of the high-speed train operation; \( S \) is the train running distance. 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 \( w_c(v) = 0.66 + 0.00245 \times V + 0.000132 \times V^2 \)

3. Decelerating energy consumption of train on long heavy down grade

In the high-speed train tracking operation system, the reason for the reduction of the vehicle speed is mainly caused by the traffic density and the congestion interaction between the train tracking operations under high-speed driving conditions. Or the train slows down because of the factors such as long heavy down grade line conditions, environment, climate and so on. 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.

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

(4)

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

(5)

In the above formula, \( \max t \) 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.
5. Model establishment

5.1. Model structure
Based on the NaSch model, when multi-trains are tracking operation, train tracking targets can be divided into three situations: 1) If the train is following another running train, if the distance between the trains is greater than the minimum tracking interval, the forward train will not affect the operation of the subsequent trains, and the subsequent trains can accelerate operation. If the distance is smaller than the minimum tracking interval, the subsequent train must decelerate. If it is equal to the minimum tracking interval distance, the following train keeps track speed. 2) If the station is in front of the train and the train is going to stop at the station, the speed of the train should be guaranteed to start slowing down at this point at deceleration \( b \), so as to ensure that it will not pass the station and stop outside the station. If the guard section of the station is not empty, a safe distance is maintained between the train and the station. If the guard section of the station is empty, the train slows down and enters the station. 3) If the speed of high-speed train is higher than the speed limit of long heavy down grade, the train needs to decelerate safely in this case.

5.2. Evolution rules
For high-speed tracking train traffic flow, according to train operation condition, the following rules 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:
   \[ v_n(t+1) \rightarrow \min(v_n(t)+a,v_{\text{max}}) \]
   If \( v_n(t+1) > v_n(t) \) AND \( v_n(t) < 0 \)
   \[ E_{\text{ac}} = \left( \sum M_i \right) \times S \times 9.81 \times 3600 \]
   Else \( e_{nq} = k \times \frac{1}{2} \left( \sum M_i \right) \times V^2 / (3.6^3 \times 1000) \)
   Else If \( \Delta x_n > d_n \)
   \[ v_n(t+1) \rightarrow \max(v_n(t)-b,0) \]
   \[ e_n(t) = \frac{1}{2} \left( mv_n^2(t) - mv_n^2(t+1) \right) \] Calculate deceleration energy consumption.
   Else
   \[ v_n(t+1) \rightarrow v_n(t) \]
2) Slowing down:
   \[ v_n(t+1) \rightarrow \min(v_n(t+1),gap_n(t)) \]
   Among them, \( gap_n(t) = x_{n+1}(t) - x_n(t) - l_{\text{train}} \)
3) Safety protection process on on long heavy down grade of high-speed railway:
   \[ v_n(t+1) \rightarrow \min(v_n(t+1),v_{\text{safe}}) \]
4) Train movement:
   \[ x_n(t+1) \rightarrow x_n(t) + v_n(t+1) \]
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 \( d_s > d_n \)
\[ v_n(t+1) \rightarrow \min(v_n(t)+a,v_{\text{max}}) \]

\[ E_{\text{src}} = \left( \sum M_i v_i \right) \times S \times 9.81 \times 3600; \]

Else If \( d_s < d_m \)

\[ v_n(t+1) \rightarrow \max(v_n(t)-b,0) \]

\[ e_s(n,t) = \frac{1}{2}(mv_n^2(t) - mv_n^2(t+1)); \]

Else

\[ v_n(t+1) \rightarrow v_n(t) \]

2) Slowing down:

\[ v_n(t+1) \rightarrow \min(v_n(t+1),d_s) \]

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.

Case 1: 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.

\[ v_n(t+1) = 0, \quad t < T_d. \] Among them, \( T_d \) indicates the stopping time of train at the station.

Case 2: When the train stops at the station for longer than the prescribed stopping time \( T_d \), the train departs and quickens its departure from the station platform.

1) Max(1) min(a,v_{\text{max}}), \quad t \geq T_d.

\[ e_{\text{aq}} = k \times \frac{1}{2} \left( \sum M_i \right) \times V^2 / (3.6^2 \times 1000); \] When the train exceeds the stop time, the train departs, and then calculate starting energy consumption

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

6. Simulation analysis

When the model is established, the line is regarded as one-dimensional discrete lattice with the length of \( L \). The length of the analog line is \( L \) cells, and the length of each cell is set to 1 m. The train speed is an integer between 0 and \( v_{\text{max}} \). The state of train \( i \) at time \( t \) is represented by the speed \( v_i(t) \) of the train itself. The numerical simulation is carried out with the Harmony CRH380B Electric Multiple Units as an example. The system refresh interval is 1 s. This means that the actual train speed is 180 km/h when \( v_{\text{max}} = 50 \) cells/s and the actual train speed is 360 km/h when \( v_{\text{max}} = 100 \) cells/s.

In the numerical simulation, we take the length of the transmission line is \( L=50000 \) and the evolution time is \( T=5000 \). Suppose there is a heavy down grade with slope value \( k \) at 2/5 of the route, and a station at 4/5 of the route, the length of the station is 400 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.

6.1. Influence of different slope values on long heavy down grade of traffic flow

In order to study the influence of different long heavy down gradients of high-speed railway on tracking train traffic flow, we take the maximum speed of CRH380B as 180 km/h. By changing the slope value \( k \) of long heavy down line, the train speed curves of different long and long downhill slope values are obtained by simulation, as shown in Fig. 2. Among them, one of the curves shows the variation of train
speed and position under the condition of slope value \( k = -25\% \) and the slope length 5000m. From the figure, it can be seen that when the train starts at the maximum speed and drives to the upstream of the station from 20000 cells to 25000 cells, the train enters the long slope area of the line. When \( k = -25\% \), the safe running speed of the slope is 130 km/h, because the train speed is greater than the speed limit value, the train needs to decelerate in order to drive safely across the long slope. After the train leaves the long ramp, it slows down and stops at the station when it is near the station in front. After 90 seconds of the train stops, the train speeds up to the maximum speed after leaving the station. Another curve shows the change curve of train speed and position under the condition of slope value \( k = -10\% \), the same length of ramp. It can be seen from the figure that under the condition of the gradient value, the train does not decelerate to cross the long ramp. This is because when \( k = -10\% \), the safe speed of the long ramp is 260 km/h, and the maximum speed of the train is less than the speed limit. The train passes the long ramp safely after 180 km/h without deceleration. When the distance between the train and the station ahead is less than the safe braking distance, the train slows down gradually and stops at the station. When the stopover time exceeds, the train speeds up to leave the station.

Fig.2  Map of Train Speed Change with Location under different Long heavy Slope Values

Following is the simulation of multi-train tracking traffic flow phenomenon on long ramp. By changing the slope value \( k \) of long heavy down line, the time-space diagram of high-speed railway traffic flow under different slope values are obtained by simulation. Fig. 3 (a) is a time-space diagram of train traffic flow obtained under the condition of \( k = -25\% \), slope length 5000m. When the slope value of the long ramp \( k = -25\% \), and the safe running speed of the ramp is 130 km/h, the train speed is larger than the speed limit. The train needs to decelerate in order to drive safely across the long ramp. At this time, the long ramp can be regarded as the "bottleneck" section of the line, and the phenomenon of traffic waves stopping and going appears in the system. Fig. 3 (b) is the variation curve of train speed and position under the condition of slope value \( k = -10\% \) and the same length of ramp. It can be seen from the figure that under the condition of the gradient value, the train does not decelerate to cross the long ramp. This is because when \( k = -10\% \), the safe running speed of the long ramp is 260 km/h, the maximum speed of the train is less than the speed limit. The train does not need to decelerate when passing the long ramp. From the space-time evolution map, it can be concluded that with the increase of the slope value of long heavy slopes, the "bottleneck" effect on line traffic is more obvious.
6.2. Influence of long heavy down grade on energy consumption of traffic flow

In order to study the effect of different long heavy down grade on energy consumption of tracking train traffic flow, we set the maximum train speed is 290km/h. Through simulation, the relationship between different slope ratio and deceleration energy consumption in long heavy down grade section of different departure workshops is obtained. It can be seen from Fig. 4 that the deceleration energy consumption of tracking train flow on the whole line decreases gradually with the increase of train departure interval. As can be seen from Fig. 4, when $k=-5\%$, the ramp safety speed limit is 300 km/h, and the maximum speed of the simulation tracking train is 290 km/h at this time. The maximum speed is less than the safe speed limit of 300 km/h under $k=-5\%$. When the train passes through the long ramp, there is no need for deceleration. The curve in Fig. 4 shows that under the conditions of $k=-30\%$, -25\%, -20\%, when the train enters the ramp section, it needs to decelerate. The energy consumption of deceleration is much larger than that of slope value $k=-5\%$. 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.

Fig.4 Decelerating Energy Consumption under Different Long heavy Slope Values

In addition, the relationship between traction energy consumption and starting energy consumption of train flow is tracked under different long heavy ramp values. As can be seen from figs. 5 and 6, with the increase of departure time interval, traction energy consumption and starting energy consumption gradually decrease, because with the increase of departure time, the interaction between trains decreases, and the overall traffic flow is basically in a free flow state. In Fig. 5, it can also be found that the traction energy consumption is lower when the gradient is smaller, such as $k=-5$. This is because compared with
the larger gradient, the train deceleration factor decreases, and some trains are running at a uniform speed with less energy consumption. As can be seen in Fig. 6, in the smaller departure interval, the larger the gradient value, the greater the starting energy consumption.

7. Conclusion
Aiming at the characteristics of high-speed train running under on long heavy down grade based on the NaSch model, an energy consumption model of tracking train flow under on long heavy down grade condition is established. Then we use the cellular automata model to study the influence of different long heavy down grade on energy consumption of tracing train flow. The results showed that: 1) different slope value conditions has a significant impact on the energy consumption of multi-train tracking. 2) The time-space phase diagram reproduces the process of congestion and dissipation of tracking train flow on long heavy down grade. 3) with the increase of slope value of long heavy down grade, the total energy consumption of traffic gradually decreases, and the simulation results show that the energy consumption of starting, accelerated and deceleration of high-speed trains will decrease with the decrease of slope value. The energy consumption model of multi-train traffic flow on long heavy down grade proposed in this paper provides a scientific theoretical basis for efficient operation and energy-saving operation of high-speed railway, and it has certain reference significance and practical value.

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