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Heavy-haul Train's Operating Ratio, Speed and Intensity Relationship for Daqin Railway Based on Cellular Automata Model

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Abstract: Proper allocation of the trains in terms of speed, intensity and carrying capacity is key to the railway line's operational competence. Based on the four-aspect fixed block system, a cellular automata model was constructed for Daqin Railway in China by combining the rail transit system and cellular automata model. In consideration of the present station equipment, rail line conditions and transport modes, different train track ups and train delay propagation were simulated based on train length, way to enter the station and other factors. Hence, the model was proved to show a true-to-word picture of Daqin Railway operations. Many schemes were achieved through relationship analysis between the operating ratio, speed and intensity. Through comparative studies, the schemes were optimized for different carrying capacity, speed and intensity conditions and then an optimized one was chosen. The results showed that the higher proportion of 20,000-ton trains then the scheme would be more optimal. However, in view of the cargo source organizing, empty train organizing and available equipment, all being 20,000-ton trains are impossible.

Key words: Cellular automata, train's speed, intensity, Daqin Railway, transportation

INTRODUCTION

In the rail system, the control of train operations is the core part to ensure operational security and improvement of operational efficiency. In the automata fixed-blocking signal system, train tracking-up is a complicated and non-linear process (Jia *et al*., 2007).

Cellular Automata (CA) theory initiated in 1940s is a key tool for the studies on transportation and other complicated non-linear systems (Wolfram, 2002). In CA model, the cellular making up the model are dispersed in time and space and of limited status. They are evolving in time and space according to certain local rules. Therefore, the CA model is especially suitable for simulation of the dynamic evolvement process of time and space conditions of complicated non-linear system. Thanks to the advantages of CA model, so far, it has made fast progress in theories and in practices home and abroad (Chen and Zhang, 2011; Mazzarello and Ottaviani, 2007; Zhou *et al*., 2009; Fu *et al*., 2008; Zhou *et al*., 2004; Ayanzadeh *et al*., 2009; Ziabari *et al*., 2008; Mahmoud, 2011; Azghadi *et al*., 2007). The most famous CA model is NaSch model proposed by Nagel and Schreckenberg (1992). The model is featured with simple algorithm and capability to simulate the macro and micro traffic phenomena. It has been widely applied in the urban road traffics and rail traffic flows. Li *et al*. (2005a, b) have analyzed train tracing model and rail traffic flows and proposed a CA model proper for rail traffic system. In traffic flow and freight transport, many national and foreign scholars have done a lot of relevant research to the railway transport (Alhassan and Ben-Edigbe, 2011; Abdelouahab *et al*., 2006; Mohan and Ravichandran, 2007; Msogoya and Maerere, 2006; D'Acierno *et al*., 2011; Mohammaditabar and Teimoury, 2008; Lin and Liang, 2011) which also provided a good foundation for this research.

The article is based on the four-aspect fixed-block signal system, constructs the CA model for Daqin Railway. By simulating the tracing process of trains from Xiazhuang to Chawu station, different marshaling models are analyzed to sum up the relationship between train ratio, average speed and marshaling intensity. Matching schemes for different conditions are provided and actual operational plans are compared. Through comparative studies, the schemes are optimized for different carrying capacity, speed and intensity conditions.

CA MODEL FOR DAQIN RAILWAY

Signal system for Daqin Railway adopts the four-aspect fixed-block mode. In the signal system, each

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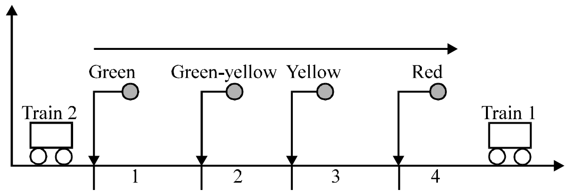

Fig. 1: The diagram of the signal in the four-aspect fixed block system

semaphore has four display statuses: red light, yellow light, green-yellow light and green light, as indicated in Fig. 1. When the semaphore is green light, it suggests at least three block sections are available and the train shall move on at the required speed. If not limited by the line conditions, it is allowed to run at the maximum speed allowable, otherwise, it shall run at the limited speed. When the semaphore is green-yellow light, it suggests two block sections available ahead. In this case, the passenger train shall slow down to the required speed before moving to the green-yellow light, while the freight train does not need to slow down. It may pass the green-yellow light at the regular speed. When the semaphore is yellow, the passenger trains and freight trains are required to reduce to the required speed. If the semaphore is red light, both passenger and freight trains are required to stop before reaching the red light. During the operations, the colors of protection semaphores in each block section will automatically change according to the position of trains on the line.

The up direction can be divided into L cellular, each of the same size, as i = 0,1,2,..., L. Each cellular is empty or occupied by a train.

With the application of cellular automata model, the rail traffic of four-aspect block system can be simulated. When defining the speed-restriction function, the article proposes a speed-restriction function closer to the reality:

- Red-light speed-restriction function:

$$v_r(s) = \text{floor}[\sqrt{2b_2 s}, v_{l,l}] \tag{1}$$

- Yellow-light speed-restriction function:

$$v_y(s) = \text{floor}[\sqrt{2b_1 s + v_{l,l}^2}, v_{l,2}] \tag{2}$$

- Green-yellow light speed-restriction function:

$$v_{y\text{-}g}(s) = \text{floor}[\sqrt{2b_1 s}, v_{max}] \tag{3}$$

Table 1: Rules for updating of train's speed

Green light	Green-yellow light	Yellow light	Red light
$v_n = \min(v_n+a, v_{max})$	$v_n = \min(v_n+a, v_{max})$	$v_n = (v_n+a, v_y(s))$	$v_n = (v_n+a, v_y(s))$

The train's position updated as $x_n = x_n+v_n$

Where:

- s = Distance between trains and protection semaphores ahead
- $v_{l,1}$ = Speed-restriction value for yellow-light signals
- $v_{l,1}$ = Speed-restriction value for green-yellow light signals
- b_1 = Train's regular braking deceleration
- b_2 = Train's urgent braking deceleration
- a = Train's acceleration
- v_{max} = Train's maximum speed value

The above three is the maximum speed allowable for the train. The above three speed-restriction functions can ensure that the train's speed will be reduced to the required at different semaphores.

As for the four-aspect fixed block, the iteration rules are divided into two steps:

- **Updating of the train's speed and position:** In each time step, the updating of train's speed is determined by the color of the semaphore ahead and the updating rules are indicated as follows in Table 1.
- **Semaphore's color updating:** Mainly by the distribution of trains on the railway line to update the colors of semaphore on each block section. If the block section is occupied by the trains, the protection semaphore will be red, while the semaphores for the follow-up block sections are yellow, green-yellow and green. In the simulation system, the semaphore's color will be indicated with a number, 4 for green, 3 for yellow, 2 for green-yellow and 1 for red

The above is about the train in operations wayside. If it is near a station, when the station is occupied by a train closely ahead, the train (n) will have to keep a safe distance from the train closely ahead. If the station ahead is available, the train will move into the station directly at the decelerated speed b and when it stays in the station for a time of T_d, it will take leave. T_d is the time at station. Therefore, the iterative rules for trains at station are:

- Train at a certain position before reaching the station, as below:

Step 1 acceleration:
if:

$$d_s>d_b,\ v_n>45\ \text{km/h},\ v_n = \max(v_n-b_1, 45)$$

else if:

$$d_s>d_b,\ v_n>45\ \text{km/h},\ v_n = \min(v_n+a, 45)$$

else if:

$$d_s>d_b,\ v_n = 45\ \text{km/h},\ v_n = v_n$$

else if:

$$d_s<d_b,\ v_n = \max(v_n-b_1, 0)$$

end

Step 2 movement:

$$x_n = x_n+v_n$$

When the train is within the station, the rules are as follows:

When the train stays in the station longer than T_d:

- Step-1 Acceleration: $v_n = v_n+a$
- Step 2 movement: $x_n = x_n+v_n$

When the train stays in the station for no longer than T_d; $v_n = 0$. d_s suggests the distance between No. n train and the station ahead and d_b is the braking distance.

The model applies open boundary condition. Initially, there is no train running on the line and all semaphores are green. When t = 1, a train moves into the system. Then, a train starts off when green is on or at fixed interval. If the end of a train moves out of the up direction Chawu Station, it is believed to move out of the system and will be deleted.

Before the simulation results are analyzed, it is necessary to explain the two concepts about train intensity. According to Wang (1990), two definitions are given:

First intensity concept: Statistically, the train intensity means within a certain period of time and in a certain scope (such as full trip or on a certain line), averagely for each kilometer each day, the number of passenger and freight trains allocated. It is an average number by dividing the total of kilometers all the allocated trains are running each day by the total length of the line (operational kilometer).

Train intensity:

$$\rho = (q\times t\times v)/L,\ \text{unit: No. of train/(kilometer-days)}$$

where, q is the number of passenger and freight trains passing by within a certain period of time t, v is the average speed, L is the total length of the line. There are two ways for computation of v: arithmetic mean and harmonic mean.

Arithmetic mean:

$$v = \frac{1}{N}\sum_{i=1}^{N} v_i$$

where, v_i is the speed of No. i train. The disadvantage of this method is: The intensity calculated against the background of congested traffics will be excessively low.

Harmonic mean:

$$v = 1/\frac{1}{N}\sum_{i=1}^{N}\frac{1}{v_i}$$

Intensity calculated by this method has a much higher scope than the intensity obtained by arithmetic mean method. Since in this article, only the trains running within the specified scope are considered and the train's start-stop time is not included, the speed is all about the train's operational speed, a harmonic mean method is applied to calculate the train's mean speed.

Second intensity concept: Train intensity means the number of passenger and freight trains that might pass by one day and one night within the controlled space. Generally, when the train's operational speed is high, the interval is short and the pass-through competence is large, the train intensity is large. The following formula is given:

Train intensity:

$$q = \frac{N}{T},\ \text{unit: No. of trains / day}$$

where, T is the observation time. In this article, it is one day and one night, that is, 24 h. N is the number of trains passing by the observation points within the monitored time.

In the rail traffic system, the train's intensity is always depicted with the marshaling interval. The shorter the marshaling interval is, the higher the train's intensity is.

ANALYSES OF SIMULATION RESULTS

Without any influences on the simulation results, for the simulated space, the most complicated part in the middle of Daqin Railway is chosen: the up direction from

Table 2: Coordinates of semaphores from Xiazhuang to Chawu

Serial No. of semaphores	Coordinates (km)	Serial No. of semaphores	Coordinates (km)
3100	310.005	3194	319.45
3114	311.35	3208	320.80
3132	313.15	3222	322.15
3150	314.90	3236	323.50
3164	316.30	3250	324.90
3178	317.70		

Xiazhuang to Chawu, a total length of 14.895 km which means 169,320 cellular. Xiazhuang is an intermediate station and Chawu is a district station. Eleven semaphores are provided for the up direction, the coordinates of each semaphore indicated in Table 2.

According to technical specifications for Heavy-haul on Daqin Railway, it is learnt that the maximum speed limit is 80, 55 km h^{-1} for the yellow light, 75 km h^{-1} for the green-yellow light. The 20,000-ton train is 2,672 m long and 10,000-ton train is 1,400 m.

In the simulation system, one cellular is 0.088 m and the system updating time step is 1s. The acceleration is 1 cell s^{-2}, the regular deceleration speed is 2 cell s^{-2}, the braking distance is 1400 m which means 15,909 cells. As it is supposed that all the trains are having the stop operations at Chawu station, the actual 20,000-ton train is passing directly by. To reduce the influences on simulation results, four lines are set for up direction, two more than the actually adopted (two lines). Suppose the train, due to technical considerations, will stop and stay in the station for 25 min, that is, 1,500 steps. The system evolvement time is 12,000 steps. The initial conditions are: no trains running in the space, all semaphores being green, the first train starting off right at the time t = 1, the initial speed being 40 km h^{-1} which means 126 cells sec^{-1}. Therefore, to minimize the influences of initial conditions, consider the simulation started within one shift time (3 h). For statistical purpose, the data in first 1,200 time steps are abandoned and only the data for the follow-up 10,800 time steps are adopted.

Departure at green light: For departure at green light, the train delays are obvious. Therefore, it is relatively convenient to analyze the relationship between train proportion, speed and intensity against such a background.

Figure 2 is a time-space diagram about a 20,000-ton train running within the controlled space. It shows obvious train delays and continuous spreading of the delays. It indicates that the simulation system can well simulate the train's operational features.

Figure 3 is about the relationship between trains of 10,000 and 20,000 tons planned to operate and the average interval when the departure-at-green-light mode is adopted. In the Fig. 3, the smooth curve is obtained after fitting the higher-order function and the fold is based on simulations. From the Fig. 3, it is learnt that the interval is the longest when all trains are of 20,000 tons. With more 10,000-ton trains are in operations, the mean interval is reduced which is consistent with the actual operations. The length of 20,000-ton train doubles that of the 10,000-ton train, therefore in the operations, it will occupy two block sections while the 10,000-ton train has just one block space. For departure at green light, actually one more block section is needed for the 20,000-ton train than for 10,000-ton train. Of course, the interval is also longer.

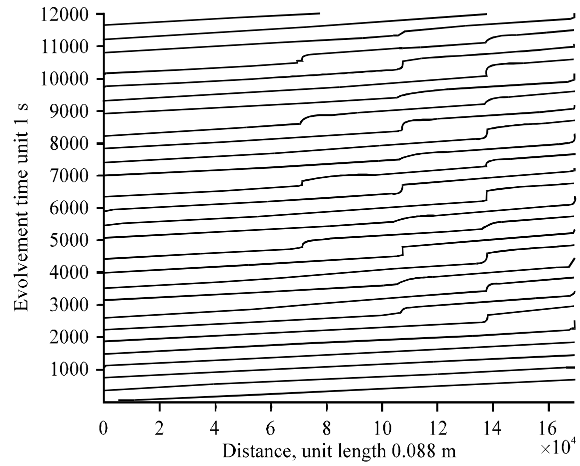

Fig. 2: Time-space diagram of 20, 000-ton train

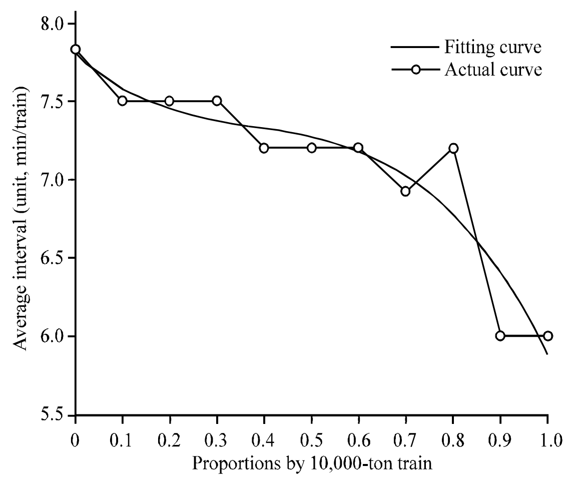

Fig. 3: Relationship between train proportion and average interval (departure at green light)

In Fig. 4, the highest tons of cargo are carried when all trains are 20,000-ton train. However, according to Fig. 3, the interval is the longest when all trains are of

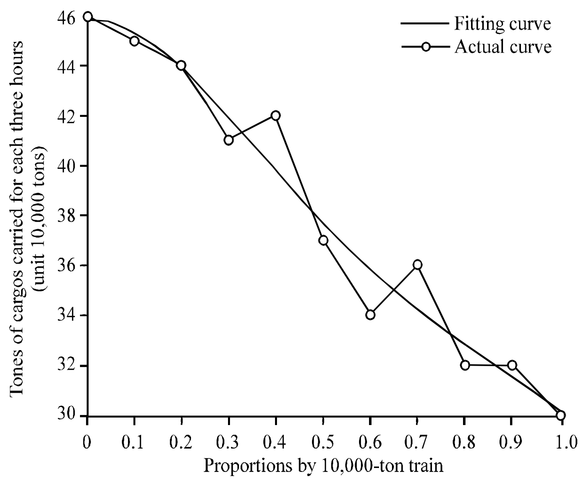

Fig. 4: Relationship between train proportions and tons of cargos carried (departure at green light)

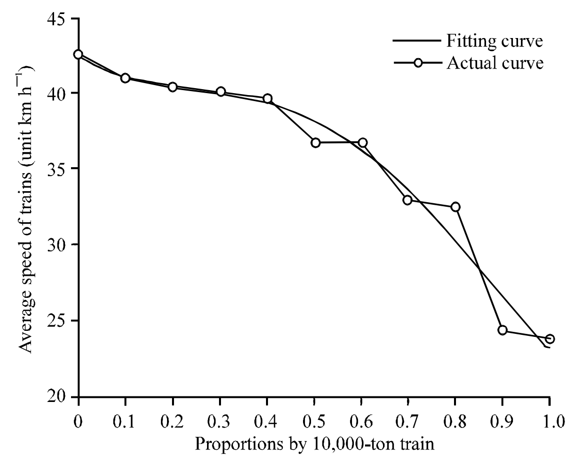

Fig. 5: Relationship between train proportions and average speed of trains (departure at green light)

20,000 tons and the interval is the shortest when all trains are of 10,000 tons. Although, the maximum number of trains is dispatched when all trains are 10,000 tons, the total tons of cargo carried are the smallest.

In Fig. 5, with the increase in the proportion of 10,000-ton trains, the average speed of trains is slowed down. It is because the proportion of 10,000-ton train is rising and the number of trains into the space within the unit time is also increasing. Therefore, the arrival and departure lines are unavailable for the trains planning to stop. It results in delays from time to time and slowing-down of the trains. Thus the conclusion is when the trains need to stop at stations, increased number of arrival and departure lines will reduce the chances of delays.

From Fig. 6a and b, it is learnt that when the second train intensity concept is applied, with the increase in 10,000-ton trains, the train intensity is rising. When the first train intensity concept is applied, with the increase in 10,000-ton trains, the train intensity is reducing. It is because the first train intensity has taken into consideration the average speed and it is the demonstration of the line's utilization rate. The higher the train intensity is, the utilization rate is higher and the organization will be optimized. According to the figure in left, when trains of 20,000-tons account for 0.4~0.5, the train intensity is reducing dramatically. Therefore when conditions allow, trains of 20,000-tons are to be dispatched as much as possible, to ensure the high train intensity and full utilization of the line. To make full use of the line, when cargo source and loading operations are under restrictions, it is proper to select this ratio for marshaling which is actually consistent with the actuality of Daqin Railway (38:46, first being the number of train couples of 20,000 tons).

Departure mode at fixed interval: Considering the departure mode adopted for Daqin Railway at fixed intervals, the matching relationship between train proportion, speed and intensity is simply discussed against the background of fixed intervals. According to the current transportation mode for Daqin Railway, the traced interval for 10,000-ton train is 10 min and the traced interval for composite combination of trains is 12 min. As the 20,000-ton train is relatively long, the traced interval is 16 min, while the average traced interval for various trains is 14 min. According to above discussion, a matching scheme for the relationship between train proportion, speed and intensity at different train interval is proposed. Four groups are specified according to the intervals, as indicated in Fig. 3. Scheme for 8 min is simply for comparison, as in reality it is impossible.

When the interval is 14 min, the shortest time, as obtained from the simulation test, for train running from Xiazhuang to Chawu is 701 s, with an average speed of 76.4936 km h^{-1}. The actual operational time is: 26 min for a combination of trains, 24 min for other trains, with an average speed of 34.3731 and 37.2375 km h^{-1}, respectively. There is a major difference between the simulation value and actual value. When the departure interval is 14 min, in the simulation system, all trains show no delay. They are accelerating to the highest speed and then decelerate when close to the station. During the operations, all semaphores are green lights, with only the maximum limit provided. However, the actuality is much more complicated than the simulated. There are two slopes (12‰) from Xiazhuang to Chawu, in addition to

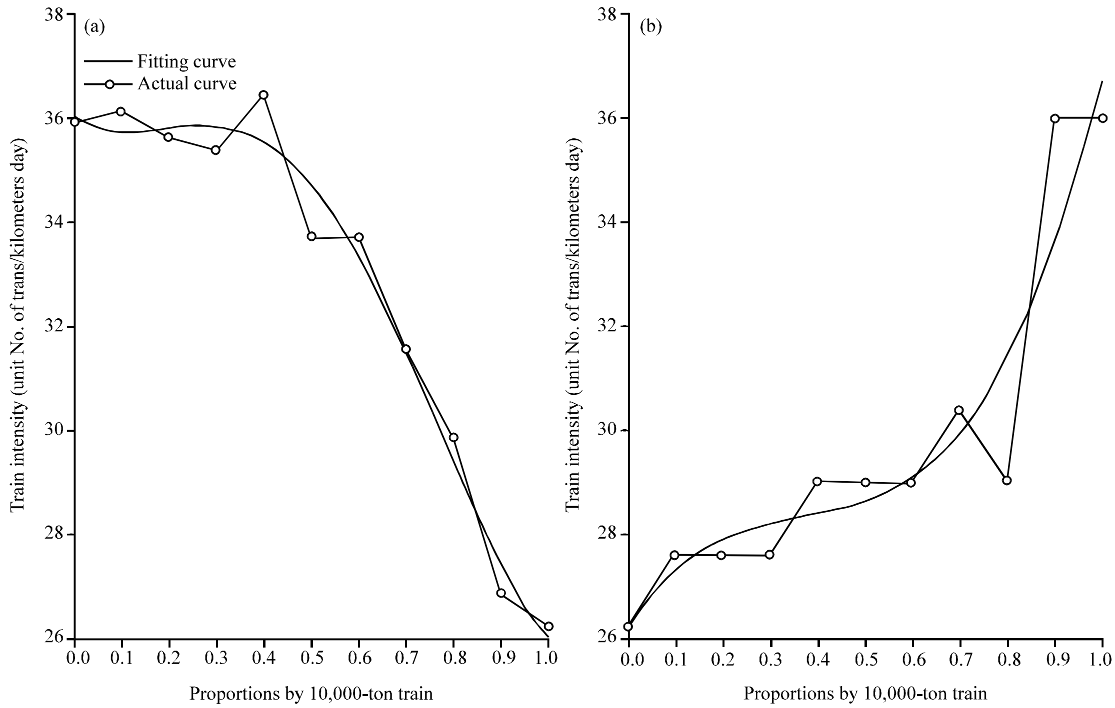

Fig. 6 (a-b): (a) Relationship between train proportion and first train intensity (departure at green light) and (b) Relationship between train proportion and second train intensity (departure at green light)

Table 3: Matching scheme and transport competence

Scheme	Tracing time I (min)	Proportion of 20,000-ton trains	v_{max} km h^{-1}	Train intensity (up direction, unit; train/day)	Train intensity (considered speed, unit: No. of trains/kilometer*day)	Cargo carrying capacity Unit: 10,000-ton/year
1	14	1.0	76.4195	91	36.5128	(0+13*2)*7*365 = 66,430
2	14	0.6	76.1690	91	36.3932	(4+9*2)*7*365 = 56,210
3	14	0.5	76.1690	91	36.3932	(5+8*2)*7*365 = 53,655
4	14	0.0	75.8081	91	36.2207	(13+0*2)*7*365 = 33,215
5	12	1.0	76.3995	105	42.1192	(0+15*2)*7*365 = 76,650
6	12	0.6	76.2404	105	42.0315	(2+13*2)*7*365 = 71,540
7	12	0.5	75.8247	105	41.8023	(6+9*2)*7*365 = 61,320
8	12	0.0	76.0936	105	41.9505	(15+0*2)*7*365 = 38,325
9	10	1.0	76.4175	126	50.5549	(0+18*2)*7*365 = 91,980
10	10	0.6	75.1640	126	49.7256	(8+10*2)*7*365 = 71,540
11	10	0.5	76.2131	126	50.4197	(7+11*2)*7*365 = 74,095
12	10	0.0	75.7887	126	50.1389	(18+0*2)*7*365 = 45,990
13	8	1.0	72.3058	161	61.1222	(0+23*2)*7*365=117,530
14	8	0.6	60.1223	154	48.6134	(6+16*2)*7*365 = 97,090
15	8	0.5	60.3996	154	48.8377	(12+10*2)*7*365=81,760
16	8	0.0	62.9233	161	53.1909	(23+0*2)*7*365 = 58,765

curves of small radius and slopes of smaller rates of inclination. Therefore in actual operations, trains cannot always run at the maximum speed. In the simulation system, curves and speed restrictions are not considered which is partly responsible for the speed given from the simulation much higher than reality.

In the 16 schemes provided in Table 3, scheme 2 is most close to the operational scheme specified in Daqin Railway 400-million-ton organizational scheme (Feng, 2011) and the number of trains in up direction is matched with the 90 trains as indicated in the actuality.

The train intensity after considering the train speed shows no apparent changes in the train speed as specified in scheme for intervals over 10 min. Therefore, the train intensity with consideration of the speed is not high. However, the general trend that the train intensity will reduce with the reduction in the proportion of 20,000-ton trains is consistent with the above discussion. As for the scheme specifying a traced interval of more than 12 min, considering the relatively small number of trains dispatched, the train intensity even having taken into consideration the speed is relatively low.

On the prerequisite that the annual cargo carrying capacity is 400-million-ton, scheme 4 and 8 are not compliant. With consideration of the 14-min interval, only scheme 1~3 are compliant. From the data above, when more 20,000-ton trains are used, the annual cargo carrying capacity is higher. However, in view of the cargo source organizing, empty train organizing and available equipment, all being 20,000-ton trains are impossible.

Of the four schemes for 8 min-interval, the train's speed is much smaller than those specified in other schemes. Reduction in the interval will allow more trains to be dispatched and therefore more cargo to be carried. However, reduction in the train's sped is a restraining factor.

As for which scheme is to be adopted, except for the above considerations, the economical and technological assessment is also necessary, including the scheme for train set and expenses. A decision is to be made with full consideration of the economic, operational costs, technical demands and task indexes.

CONCLUSION

As the line conditions, such as slope, radius of slopes and speed restrictions, deceleration and acceleration, are not considered and only one section of Daqin Railway is simulated, the data obtained from this simulation system shows difference from the actuality. However, the simulation system can well simulate the trains in operation and the relationship indicated between train proportion, speed and train intensity is consistent with reality. Through simulations, an optimized matching scheme for train speed, intensity and proportion is provided. Therefore, CA model is significant for simulation of Daqin Railway, so as to obtain more precise data and to improve the system.

Simulation results suggest that more 20,000-ton trains are adopted, the scheme is more effective. However in reality, it is almost impossible to all applying the 20,000-ton trains. Firstly, it is out of the consideration for cargo source and secondly the scheme for empty train on the returning. With the optimization of cargo source and organizational mode, as well as the improvement of scheme for empty train on the returning and the enhancement of railway technologies, the trend is that a higher proportion of 20,000-ton trains will be used for Daqin Railway transport.

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