Research on Virtual Coupling Train Operations Based on Moving-Block and Vehicle-to-Vehicle Communication

Haixiao Duan, Yunan Yang, Yi Duan and Jinchuan Zhang*

School of Traffic and Transportation, Beijing Jiaotong University, 3 Shangyuancun, Haidian District, Beijing 100044, P. R. China
Email: jchzh@126.com

Abstract. This paper introduces the current research status of train operation mode especially the one based on the train moving-block system. Then it improves on the basis of the Vehicle-to-Ground (V2G) communication technology and the traditional fixed-block system constructs a virtual combination model based on the train moving-block system and Vehicle-to-Vehicle (V2V) communication technology. Through the construction of state flow-diagram of the entering and leaving the Virtual Coupling train-following model and calculation of the train capacity, discussion and analysis are carried out in different scenarios, including train tracking at the station, arriving at the station, sending out from the station, etc. Finally, the scene of two trains tracking through the station is simulated and compared with the traditional fixed-block operation mode in ideal circumstances. The results show that the new operation mode proposed in this paper can improve the railway capacity and train operation efficiency. In the future railway development, this kind of operation mode has certain efficiency.

1. Background
Improving railway capacity is a hot issue in rail transit industry. Moving-block system is favored, which has been put into use in light rail and metro at home and abroad. Moving-block system has developed slowly since it was proposed by Xishi Wang, a Chinese scholar in 1960s. At present, it is still not used in the trunk railway, because of the limitation of mobile communication technology. In order to use the system, it is necessary to have a reliable data exchange in vehicle-to-vehicle (V-to-V).

For the moving-block system, Liu, Yuan and others constructed the computer simulation system of moving-block [1]. After that, the train tracking model based on multiple modes of moving-block is analyzed by Guan [2]. Xu and others have analyzed the problems faced by moving-block, and calculated the driving permission time of moving-block of high-speed railway based on vehicle-to-ground (V-to-G) communication [3]. Considering the rapid development of mobile communication technology, the possibility of rail train to achieve V-to-V communication and full-scale moving-block can be foreseen.

In the current literature, the research of moving-block system is based on V-to-G communication and simulation, there is little discussion on V-to-G communication. Therefore, based on the moving-block system and V-to-V communication technology, this paper constructs the virtual coupling train operations model of the following workshops in different scenarios.
2. Principle Analysis

2.1. Moving-Block System

2.1.1. Main Characteristics. Moving-block system is a new type of train operation system, which aims to improve the density of train operation and is realized based on 3C technology (communication technology, computer technology and control technology) [4].

It can be concluded from table 1 that the braking target points of fixed and quasi moving-block are the beginning of the physical block partition occupied by the front train, while moving-block gets rid of the shackles of the fixed-block partition on the track, sets the braking target point as the end of the front train, reduces the track-side equipment and improves the flexibility. The realization of this system reduces the section redundancy and improves the railway passing energy power.

| Table 1. Comparison of control characteristics of different ways. |
|---------------------------------------------------------------|
| **Automatic block system** | **Speed control mode** | **Starting point of braking** | **Braking target point** |
| Automatic fixed-block system | graded speed control | Start of deceleration block section | The beginning of block section occupied by front vehicle |
| Quasi moving-block system | Target distance speed control | by calculation | The beginning of block section occupied by front vehicle |
| Moving-block system | Target distance speed control | by calculation | The end of the front vehicle |

2.1.2. The Basic Principle. Assuming that the front train stops in place and continues to move forward, the train braking is divided into two types [5-6]: absolute braking mode and relative braking mode, shown in figures 1 and 2.

![Figure 1. Absolute braking mode.](image1)

![Figure 2. Relative braking mode.](image2)

It can be seen from figure 1 that under the absolute braking mode, the train only considers the position when the rear vehicle starts to brake, which is not flexible enough; while under the other mode, considering the speed of the front train, when the front train moves forward, the braking target point of the rear vehicle moves forward accordingly to achieve the real-time update. This mode has high applicability and flexibility, but it needs good data transmission technology as support.

2.2. Vehicle-to-Vehicle Communication

2.2.1. Main Characteristics. The train operation control system based on V-to-V communication is a new generation of traffic signal system under development at home and abroad, which represents the latest development direction of the current train signal system, and also reflects the further improvement
of the automation and intelligence level of the signal system. The system is mainly composed of control center its, on-board equipment, track-side target controller and infinite transmission backbone network.

2.2.2. The Basic Principle. In the traditional CBTC system, the location of the ground ITP equipment is relatively fixed. The train only needs to register with the ground equipment and accept the management of the ground equipment. The ground equipment is responsible for analyzing the obstacles in front of the train operation, giving the current mobile authorized terminal point, and the operation cost is high [7-8].

The Vehicle-to-Vehicle(V2V) communication system takes the train analysis as the main body, and the train directly receives the track-side information and the front vehicle information. The on-board VOBC can calculate the curve between the limiting speed and the target distance from the front obstacle information, the basic line parameters, the front vehicle parameters and other information, directly calculate a more accurate MA, further shorten the tracking interval, and achieve real-time round-trip performance compared with the original information higher, less affected by communication delay. Unlike ground equipment, the front train is not a fixed concept of location and ID, but a tracking target that needs to be confirmed in actual time. The comparison between V-to-G communication and V2V communication is shown in figure 3.

![Figure 3. Comparison between V-to-G communication and V2V communication.](image)

3. Scene Analysis Based on Moving Automatic Block and Vehicle Communication

3.1. The Process of Combining with Moving Automatic Block

Based on the short-wave between trains, the new train control system in this paper establishes a communication network mainly composed of train equipment then constitutes a complete train data communication system from the front to the rear. On the basis of the traditional train control system, the ground equipment reduces the train monitoring system (ATS) and computer interlocking system (CI). In addition to the on-board controller (VOBC), the ground area control center (ZC) will be transferred to the trains, which realize the communication control of the front and rear two trains. Train uses the operation control mode of moving-block to replace the fixed-block area on the line. The VOBC of the front train sends the train positioning and the distance between the two trains to the ZC on the tracking train through the communication network. According to the received information, ZC generates the train movement authorization permission (MA), which realizes that the acceleration and deceleration of the rear train depends on the front train. The MA of the train will be rebuilt periodically. After the ZC on the tracking train generates MA, different controlling strategies are adopted to control the speed to ensure the safety of the train. This kind of operation mode is called Virtual Coupling, in which the two trains running on the same line accelerate or decelerate synchronously through V2V communication link to maintain the safe distance. With the Virtual Coupling, the interval between the two trains keeps dynamic balance, and the trains can be regarded as a one train when they are coupling [9].

When the train moves from “non-coupling” to “coupling” state, it needs to go through multiple stages. The train tracking model envisaged in this paper defines that when the train operates in virtual combination state. The operation process of the model in different Virtual Coupling scenes is described in figure 4.
3.2. Formula Derivation

Combined with the theory of train tracking interval, the conditions in the project are simplified to the operation between two trains under single line and ideal operation conditions. The change of speed and acceleration is taken as the research direction, and the preliminary scheme of virtual combination under simplified conditions is obtained.

Set \( t \) as the time, \( T \) as the reaction time of the train, \( x(t) \) indicating the position of the train [10].

\[
x'(t + T) = \begin{cases} \frac{a}{m} & \text{if } a > 0 \\ \frac{b}{m} & \text{if } a < 0 \\ 0 & \text{if } a = 0 \end{cases}
\]

In the formula, \( a = \sum F_{\text{pull}} / m \), \( \sum F_{\text{pull}} \) is the resultant force of the train under the maximum traction force, and \( m \) is the mass of the train, \( a \) is the acceleration of the train under the maximum traction force.
force; \( b = - \sum \text{break force} / m \), \( \sum \text{break} \) is the resultant force of the train under the common braking, \( b \) is the deceleration under the common braking of the train; \( x_\text{n}^\prime \) is the acceleration of the nth vehicle. From the above we can get the formula:

\[
v_n = \int x_n^\prime (t + T) dt
\]

(2)

Scene 1: Trains Depart

With the CTCS4-D, the trains start from the station in turn. When the front train(train-A) drives \( Sm \) away from the railroad switch of the station, the tracking train(train-B) is sent from the station to the departure line. In figure 5, \( L_1 \) is the distance between the front end of the train-B and the outer end of the switch is shown; \( Sm \) is the safety distance between the two trains; \( \overline{v}_1 \) is the fixed value for the tracking train speed \( v_0 \).

\[
I_{\text{depart}} = \frac{L_1}{v_0} + \frac{Sm}{v_B} + t_{\text{depart}}
\]

(3)

Scene 2: Coupling Running

Whenever the following train approaches the front train, the Virtual Coupling conditions of the two trains are checked. There are two situations: \( v_B > v_A \) or \( v_B < v_A \). The following train needs to travel a distance to reach the speed of the front train. This distance of adjusting speed is called coordination distance (CD). The train interval tracking is shown in figure 5.

Figure 5. Train interval tracking.

(1) When \( v_B > v_A \), deceleration coupling:

\[
I_{\text{track}} = \int_{v_B}^{v_A} \frac{1}{x_n^\prime} dv + \frac{Sm}{v_A}
\]

(4)

(2) When \( v_B < v_A \), acceleration coupling:

\[
I_{\text{track}} = \int_{v_B}^{v_A} \frac{1}{x_n^\prime} dv + \int_{v_B}^{v_A} \frac{1}{x_n^\prime} dv + \frac{Sm}{v_A}
\]

(5)

When \( v_B < v_A \), the following train B needs to accelerate to a higher speed \( v_B^\prime \), and then decelerate to \( v_A \); the \( x_n^\prime \) mentioned in the above formula are respectively the state of acceleration and deceleration.

After coupling, the rear vehicle will accelerate, decelerate and brake at the same speed as the front train. Set the minimum tracking interval of the train in the section as \( L_{AB} \); after the two trains stop, the distance between the two trains is \( S \); the time for the tracking train to receive the information of the
front train is \( \tau \); if the deceleration \( b \) which under the common braking of the train is constant, the distance from the initial speed \( v \) of the train to the stop is:

\[
d(v) = \frac{v^2}{2b}
\]

(6)

If the two trains brake at the deceleration \( b \), they meet the following inequality, the rear end can be avoided when the speed is zero:

\[
S = L_A - (L_B - L_{AB}) > 0
\]

(7)

\[
L_A > L_B - L_{AB}
\]

(8)

According to the process of train tracking operation in the section, it can be seen that:

\[
L_B = v_B \tau + d(v_B)
\]

(9)

\[
L_A = d(v_A)
\]

(10)

Substituting the above formulas (9)-(10) into formula (8)

\[
d(v_B) + v_B \tau < d(v_A) + L
\]

\[
L > d(v_B) - d(v_A) + v_B \tau
\]

\[
L > \frac{v_B^2 - v_A^2}{2b} + v_B \tau
\]

(11)

According to the above discussion, the minimum tracking interval of two trains:

\[
L_n = \frac{v_B^2 - v_A^2}{2b} + v_B \tau
\]

(12)

In the formula, \( v_1 \) and \( v_2 \) are the running speed of the tracking train and the front train. Therefore, the calculation formula of the interval time of train tracking in the section can be obtained as follows:

\[
I_{\text{track}} = \frac{v_B^2 - v_A^2}{2bv_B} + \tau
\]

(13)

Scene 3: Trains Arrive

When trains arrive at the station, the Virtual Coupling should be removed in advance due to safety factors. The front train moves into the arrival departure track first. In figure 4, \( L_{\text{response}} = v_B \cdot \tau \) is the distance for tracking the train to receive the information of the front train and make the braking response, \( \tau \) is the response time; \( L_2 \) is the distance between the outer end of the station switch and the tail of the train in the arrival departure track. According to formula (3), \( d(v_B) \) is the braking distance for tracking the deceleration of train-B under the service braking. \( S_m \) is the safety distance.

\[
I_{\text{arrive}} = \frac{v_B}{2b} + \tau + \frac{S_m + L_2}{v_0}
\]

(14)

Scene 4: Trains Pass through Station

When two trains pass through the station, only one train is allowed to pass through the main line in the station at a time. When two trains operate under the Virtual Coupling, the distance between two trains (\( L_{AB} \)) and the length of the main line (\( L_z \)) in the virtual combination state are detected according to the basic information transmitted by the station and the communication technology between the trains. At this time, the following train judges the distance of two trains.

(1) If \( L_{AB} \geq L_z \)

As a result of \( L_{AB} \geq L_z \), when the front train passes through the station, the rear train is always behind the arrival signal of the station, so the rear train don’t need to slow down or wait to pass through
the station; at this time, the station is a special section, and the train tracking operation mode is the same as the section tracking operation.

(2) If \( L_{AB} < L_z \)

Because the distance between the two trains is less than the length of the main line of the station, the train needs to slow down or stop when passing, which reduces the passing capacity. In order to make the following train not slow down because it does not see the green light of the arrival signal; therefore, before passing the station, the following train needs to adjust its own speed to make \( L_{AB} \geq L_z \).

CD is the distance travelled by the following train when adjusting the speed, and the tracking interval between the front and rear trains after adjustment is \( L_{AB} = S_m + \Delta L \geq L_z \); the time required for adjustment is calculated by the following formulas.

\[
t_{Cd} = \int_{x_n}^{x_g} \left( \frac{1}{X_g} \right) dv + \int_{x_n}^{x_g} \left( \frac{1}{X_n} \right) dv
\]

\[
I_{pass} = t_{Cd} + \frac{S_m + \Delta L}{V_B} + \tau
\]

4. Model Simulation and Analysis

Now imagine a line for specific calculation. Data shows that the maximum acceleration sum of passenger train is 1.65 \( m/s^2 \) and that of freight train is 0.98 \( m/s^2 \). The maximum speed limit of this section can reach 44.4m/s. In this case, the CRH380D EMU with a total marshalling length of 215.3 m may be selected as the research object. The front car is A and the rear car is B. Because the time for tracking train to receive the information of the front train is very small and can be ignored relative to the running time of the train, all \( \tau \) in this example are calculated to be approximately 0.

4.1. Traditional Fixed-Block Operation

When two trains track through the station, the distance between two trains in the following train shall be judged according to \( L_{AB} \) and \( L_z \) under the virtual combination state. As the effective length of arrival departure track of freight train is generally 850m, and the effective length of arrival departure track of passenger train is not less than 650m, \( L_z = 850m \) is selected here for calculation.

(1) When \( L_{AB} \geq 850m \), the rear train does not need to slow down to pass through the station, and the tracking operation mode of the two trains is the same as that of the interval tracking operation. At this time, no matter fixed-block or moving-block is adopted, the calculation method of passing time is the same. Assuming that the front and rear trains pass through the station at a speed of 40 m/s without deceleration, the passing time is

\[
I_{pass} = \frac{L_{AB} + L_z}{V} + \tau \approx 26.6\ (s)
\]

The speed time image of the front and rear two trains in this process is obtained by MATLAB simulation as shown in figure 6. It can be seen from the figure that the front and rear trains keep a constant distance and pass through the station at a uniform speed, and the rear train does not need to slow down.

(2) When \( L_{AB} < 850m \), if the fixed-block mode is adopted, the front train will run through the station at a constant speed, and when it is detected that the previous section is occupied by the train, the rear train shall decelerate to zero at the entrance signal, and then accelerate through the station after the front train passes through the station. Set \( v_A = v_B = 40m/s \), \( L_{AB} = 800m \). At this time, the speed time relationship between the two trains is shown in figure 7 (The dotted line part is the train operation curve drawn according to the actual situation).
Figure 6. When $L_{AB} \geq 850m$, the trains speed.  

Figure 7. When $L_{AB} < 850m$, the trains speed.

The time from decelerating to zero to accelerating to 40 m/s is 

$$t_1 = \frac{v_B}{b} \times 2 + 3.8s = 62.2s$$

The distance is 

$$x_1 = \frac{v_B^2}{2b} \times 2 = 969.7m$$

After that, the time for the rear car to pass the station completely is 

$$t_2 = \frac{L_{AB} + L_Z - x_1 + L_T}{v_B} = 22.39s$$

Therefore, the time for two vehicles to pass through the station under the fixed-block is 

$$t_{pass} = t_1 + t_2 = 84.59s$$

4.2. Moving-Block Operation

If the moving-block mode is adopted, the train must adjust its speed before passing the station until $L_{AB} \geq 850m$. The operation speed of the two trains before the speed adjustment is still set as $v_A = v_B = 40m/s$ and after the speed adjustment $v_B' = 25m/s$. The track interval before and after adjustment is $L_{AB} = 800m$. When the rear car receives the front car information and finds that the distance between the rear car and the front car is too small at this time, the rear car starts to brake at the maximum deceleration, decelerates to 25m/s after 9.09 seconds, and maintains the speed of 25m/s for $\Delta t = 8.91s$, then increases the speed to 40m/s at the maximum acceleration, and continues to run until passing the station. The speed time curve of the two trains before and after this process is drawn by software simulation as shown in figure 8 (the dotted line part is the train operation curve drawn according to the actual situation).

According to figure 9, the area of the shaded part is the increased space of the rear vehicle in the process of speed adjustment:
Figure 8. The speed of two trains when the moving-block mode is adopted for train operation.

Figure 9. Adjusted rear train speed.

\[ \Delta L = \frac{(8.91 + 27.09) \times 15}{2} = 270 \text{m} \]

The track interval of the front and rear trains after adjustment is the sum of the interval before adjustment and the interval increased during the speed adjustment of the rear train, that is \( L_{AB}' = L_{AB} + \Delta L = 1070 \text{m} \). Now, \( L_{AB} > L_Z \), which meets the conditions of two trains passing through the station, the front and rear two trains can pass through the station at a speed of 40m/s after that.

Then the time required for the rear vehicle to adjust its speed is

\[ t_{Cd} = \frac{v_B - v_B'}{b} \times 2 + \Delta t + \tau \approx 27.09 \text{s} \]

The distance traveled by the front car during the speed adjustment of the rear car is

\[ x_A = v_A t_{Cd} = 1083.6 \text{m} \]

Because of \( x_A > L_Z + L_r \), At this time, the front end of the car has passed and left 18m, and the rear end of the car has entered the station 13.6m. After that, the time required for the rear train to pass the station is

\[ I_B = \frac{L_Z - 13.6m + L_r}{v_B} = 26.29 \text{s} \]

To sum up, the passing time is

\[ I_{pass} = t_{Cd} + I_B + \tau \approx 53.38 \text{s} \]

By comparing the running time of fixed-block and moving-block, we can see that the time of two trains passing through the station is shortened by 84.59-53.38=31.21s. Know from

\[ 31.21 \div 84.59 \times 100\% = 36.90\% \]

The passing time has been shortened by 36.90%, and the railway passing capacity has been significantly improved.

4.3. Analysis of Simulation Results
Through the comparison between the traditional fixed-block operation mode and the moving-block
operation mode proposed in this paper, it can be seen that when the virtual combination and parallel
operation of trains are achieved, the time to pass through the station is shortened by 36.90%. In this way,
the number of vehicles that can pass through the station in the same time is greatly increased. When
fixed-block is adopted, if 1000 trains pass through the station in one day, at least 1584 trains can pass
through the station in one day when the new tracking operation mode proposed in this paper is adopted.
Therefore, the operation mode based on moving-block proposed in this paper can greatly improve the
railway capacity and train operation efficiency, which has high feasibility and practical significance.

5. Conclusion
With the rapid development of the railway industry, improving the running efficiency has become an
important topic for scholars to study. Therefore, the wide application of moving-block and vehicle
communication standard will effectively promote the topic and play an important role. This paper first
introduces the moving-block system and vehicle communication technology, and then establishes and
analyzes the virtual combined model in different scenes. Finally, based on MATLAB simulation, the
whole process is analyzed completely, and the tracking interval is calculated. The simulation results
show the feasibility of the model and its advantages over the traditional fixed block. However, the model
presented in this paper gives the simulation data. If it is used in practice, it still needs further calculation
and verification.

Acknowledgments
This work is supported by TCT Funding Program (9907006514). We would like to thank the editors and
the anonymous reviewers for their fruitful comments and remarks that allowed us to improve the quality
of this paper significantly.

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