Evaluation of Train Operation with Prediction Control by Simulation

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Abstract

In recent years, to increase transportation capacity, new intelligent signalling systems such as moving block have been proposed and put in operation. In addition, research and development on prediction control are now ongoing. Prediction control is a kind of optimization of train operation curves to minimize train headway, which leads to decrease the propagation of train delay. Hence, it is important to estimate the effects of new signalling systems or train control systems because replacement of current system may incur high costs. In this study, we first proposed and formulated new methods for applying prediction control for under both fixed and moving block. Then, we developed new functions on Train Operation/Passenger Behaviour Simulator to analyse the activity of trains with prediction control, taking into account the drivers' operational requirements. Finally, we applied the simulation system to an actual commuter line, aiming to evaluate the quantification of effects of moving block and prediction control. As a result, we confirmed that both moving block and prediction control are effective to decrease train headway, which lead to the faster recovery from delay.

Keywords

moving block, prediction control, train traffic control, simulation, passenger flow

1 Introduction

In railways, signalling systems are conventionally developed based on the concept "fixed block," under which only one train is allowed to enter a block section. Recently, new signalling systems, named "moving block," are now going to put into operation. Under moving block, as train headway become shorter, more trains can be set during the peak hours, and train delay is easily recovered (Baba et al. (2003)).

In addition, a new train control method named "Prediction Control," is proposed in the previous research (Hiraguri et al. (2004)). That is, based on the prediction for the departure time of the preceding train from the station, the succeeding train is controlled to arrive at the station with minimum headway. Prediction control can be applied whether the signalling system is fixed block or moving block.

When these new systems are considered to be installed, the existing system have to be replaced with train control system using radio communication It incurs high costs, and requires detailed design about location of radio base stations, and allocation of radio frequency slots. So, it is desired to analyse cost effectiveness of the new systems in advance of installations.

In this research, we focus on developing simulation system which can estimate train traffic or passenger flow under new systems. The goal of our research is to realize the method to quantitatively evaluate effects of installing new signalling systems or train control systems, such as moving block or prediction control.

We first devised the fast estimation method for train operation curves under moving block. We then devised train control algorithm based on prediction control theory under both fixed and moving block to minimize headway between successive trains. After that, we implemented those methods to "Train Operation/Passenger Behaviour Simulator," which is developed by the authors to reproduce train traffic under a certain timetable (Takeuchi et al. (2015)). Finally, we evaluated effects of installing moving block and prediction control in an actual commuter line in Japan.

In addition to our previous work (Kunimatsu et al. (2018)), we devised a new method for estimating train operation curves, by which we can prevent unnecessary delay propagation for trains running after the succeeding train. The differences among train operation curves are discussed in the case study for an actual commuter line. We also discussed changes of effects when the departure delay of the preceding train is altered.

The rest of the paper is organized as follows. Section 2 describes our target problem and aim of the research. In section 3, we introduce the conventional simulator, Train Operation /Passenger Behaviour Simulator. Details of the devised train traffic simulation method with prediction control under fixed block is described in section 4, and that under moving block is in section 5. The application results of our method for an actual commuter line are described in section 6. We summarize and conclude our research in section 7.

2 Motivation and Aim

2.1 Moving Block

In railways, to avoid collision of trains and guarantee safety of train operation, signalling systems are developed based on the concept "block." Conventionally, fixed block signalling systems are used, under which only one train is allowed to enter a block section which is mainly set between two successive signals. The succeeding train is controlled to stop in front of the block section in which the preceding train is on, and the marginal stop point is moved forward discretely, according to the change of block section which the preceding train is on.

On the other hand, new signalling systems, named "moving block," are now going to be developed and put into operation (Fig.1). That is, the marginal stop point for the succeeding train is caught and updated repeatedly by the radio communication system, according to the

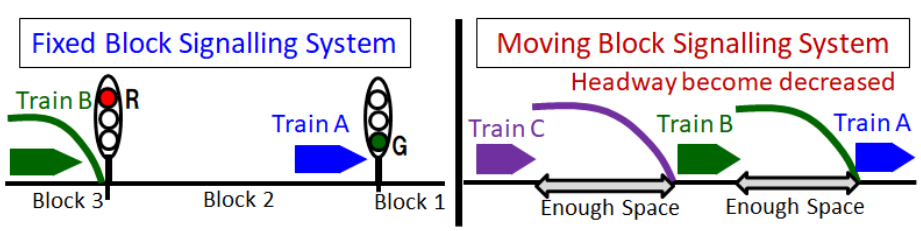

Fig. 1. Outline of fixed block and moving block

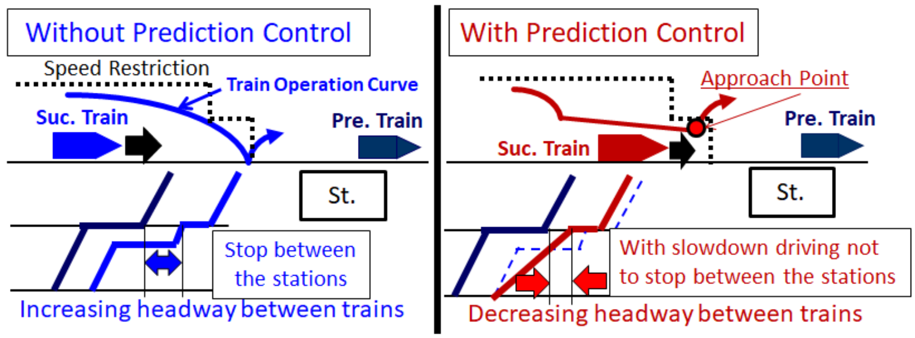

Fig. 2. Outline of prediction control

continuous change of the position of the preceding train. Under moving block, train headway become smaller. So, more trains can be set during the peak hours, and train delay is easily recovered.

2.2 Prediction Control

When a train is running close to its preceding train at the next station, if dwell time of the preceding train become longer, the successive train may stopped in front of the station platform. It may increase headway between the two trains, because it takes time for the successive train to restart again. To avoid this situation, an intelligent train control method of the succeeding train, called "Prediction Control", is proposed (Hiraguri et al. (2004)). That is, if a train driver exactly know when the preceding train depart from the station, he can drive slowly to minimize train headway. However, it is difficult to evaluate effects of prediction control, because effects of that depends on train traffic condition. It is desired to evaluate quantitatively merits of prediction control, like decreasing headway and faster recovery from the delay.

In prediction control theory, to minimize headway between the two trains, there is a kind of target point for the succeeding train to pass. It is called "approach point." The approach point consists of position, speed, driving operation and time of the succeeding train. The approach point is also on the train operation curve for the train to stop at the marginal stop point in front of the station platform. By controlling the succeeding train to pass the approach point, the headway is minimized if the preceding train departs from the station just on the predicted departure time. In case when the preceding train do not depart from the station, the succeeding train stops at the marginal stop point, avoiding bump into the rear of the preceding train.

When prediction control is applied for a rail line, it is necessary to install new intelligent train traffic control system, in which both train control and traffic control functions are implemented. It is necessary for trains to continuously communicate and exchange each other about detail information of their positions, velocity, and driving operations. This may be realized by train control systems using radio communications, which are going to be actually used. In addition, computers with calculation and information processing functions have to be installed on trains to create optimal train operation curves. Moreover, to control trains to run along with the optimal train operation curves, ATO (Automatic Train Operation) system or DAS (Driver Advisory System) is essential. Although there are several problems to be solved to realize these systems, in this research, we set the preconditions that prediction control can be realized. Under the preconditions above, we developed methods for evaluating effects for train traffic and passenger flow by installing prediction control.

2.3 Purpose of Research

In this research, our goal is set to develop a simulation system which estimate both train traffic condition and passenger flow under moving block and prediction control. By using the simulator, we want to evaluate quantitatively total merits of prediction control, like decreasing headway and faster recovery from delays.

We first improved functions of existing "Train Operation/Passenger Behaviour Simulator" to reproduce train traffic under moving block. Then, we developed and implemented functions for prediction control under both fixed and moving block. After that, we applied the simulator for the existing rail lines, and evaluated effects of prediction control.

2.4 Related Works

There are some previous works about evaluation of moving block, or train control algorithm to decrease train headway. Kanda et al. analysed the extent of decrease of train delay when moving block is installed in commuter lines in Japan (Kanda et al. (2014)). D'Ariano et al. and Xu et al. proposed a method to optimize train headway or energy consumption by controlling train operation curves of group of trains (D'Ariano et al. (2005), Xu et al. (2015)). They optimize train traffic by using estimated positions or signal aspects of trains. But, they do not consider both train traffic and passenger flow in the target rail line.

In commuter lines in a big city like Tokyo, it is not sufficient for optimizing train headway or energy consumption to estimate train operation curves only by simulation. Trains may be delayed due to the excess of dwell time at stations caused by congestion. The delay may in turn affect the succeeding train, and optimized train operation curves cannot be realized. So, it is necessary for the simulation to incorporate estimation of passenger flow and dwell time at stations. The comprehensive simulation and optimization method of both train operation curves and passenger flow is not developed yet.

In our previous works, we developed "Train Operation/Passenger Behaviour Simulator," which can estimate both train operation curves and passenger flow (Takeuchi et al. (2015)). Then, by developing functions for optimizing train operation curves, and

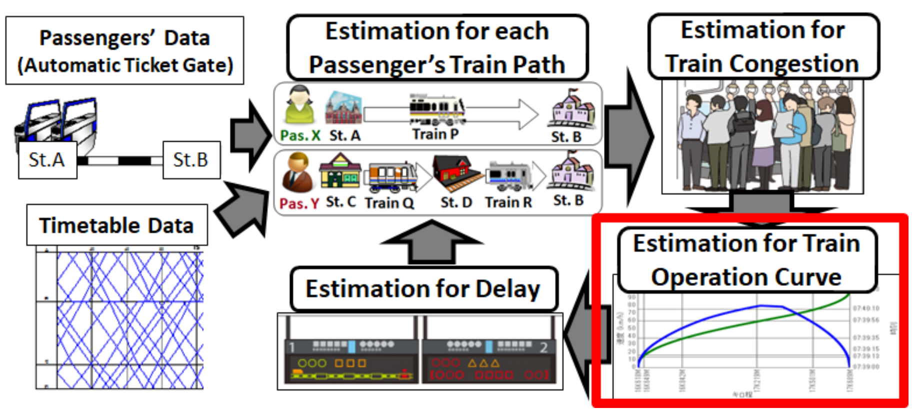

Fig. 3. Outline of train operation/passenger behaviour simulator

implementing that to the simulator, we realized train traffic and passenger flow simulation with prediction control (Kunimatsu et al. (2018)). In this research, we proposed a new method for estimating train operation curves to prevent unnecessary delay propagation. In addition, we discussed changes of effects when the departure delay of the preceding train is altered.

3 Train Operation/Passenger Behaviour Simulator

3.1 Fundamental Function of the Simulator

The overview of Train Operation/Passenger Behaviour Simulator is shown in Fig. 3. The inputs are, timetable data, passenger Origin-Destination data collected through the automatic ticket barriers, and signalling equipment data. The outputs are data for estimated train operation time, passenger train paths towards their destinations, and number of the passengers on board each train. The simulator also predicts train delays caused by congestion, and propagation of train delays. By estimating passengers' train paths, the number of passengers on board each train, and train delays successively, it is possible not only to evaluate timetables, but also various types of equipment, such as signalling systems. During morning rush hour on commuter lines in particular, the dwelling time of trains in stations is longer, because of the high number of trains being operated, and the extent of delay propagation depends on the design of the signalling system. The simulator can be used to design a signalling system to minimize train delay propagation.

Since Train Operation/Passenger Behaviour Simulator can estimate the route taken by passengers from the train operating timetables, it is possible to evaluate the timetable and signalling equipment design from the passenger point of view.

3.2 Estimation Function for Train Operation Curves under Fixed Block Systems

Train Operation/Passenger Behaviour Simulator can be applied to rail lines using fixed block systems. In the case of a fixed block system, the simulator first estimates the train

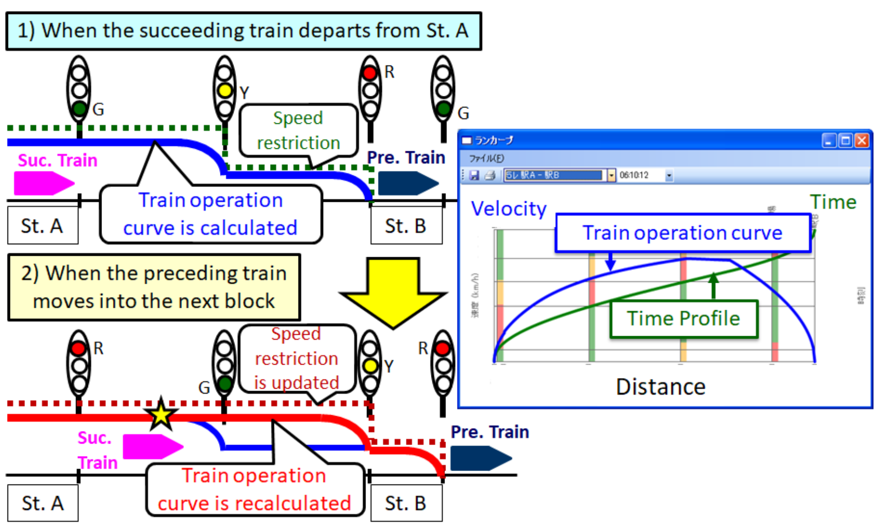

Fig. 4. Simulation of train operation curves under fixed block systems

operation curves when each train departs from a station, based on the signal aspect and all speed restrictions. Then, each train runs according to the estimated train operation curve. When the preceding train exits a block, and moves into the next block, the train operation curve is recalculated and updated (Fig. 4). The number of train operation curve recalculations is therefore equal to the number of blocks the train passes through. An approximate number of recalculations is given by the number of trains multiplied by the number of blocks. The overall simulation for an actual commuter line in Japan can be conducted within about 15 minutes with an ordinary personal computer.

The method for estimating train operation curves is the same as in SPEEDY (Yamashita (2006)), which was developed by RTRI and is used in practice for assessing train operating times. Train performance curves can therefore be rapidly estimated by predicting acceleration or deceleration of trains not only in the forward direction from the position of the train, but also in the opposite direction from where the train is stopped, which is determined by signal aspects. In addition, considering that it is difficult for trains to move from powering to braking, without coasting in between for a certain time, the estimation method of train operation curves can take into consideration these driving restrictions.

3.3 Efficient Recalculation Method for Train Operation Curves under Moving Block

In moving block systems, when the preceding train goes ahead, the marginal stop point for the succeeding train moves forward continuously. So, in a train traffic simulation under moving block, if the train operation curves are recalculated using the conventional method for fixed block systems, they would have to be recalculated for every simulation period. If the simulation period is one second, the approximate number of recalculations would be the product of the number of trains and the simulation time (sec.), which would far exceed the number of calculations for the fixed block system.

This research therefore adopts a new estimation method for train operation curves (Fig. 5). In this method, when the first train operation curve is estimated, the time when the train starts coasting to decelerate and stop at the marginal stop point is also predicted. After that, the train operation curve is not recalculated until the train starts coasting. Recalculation is not necessary during this time because the train operation curve will not be influenced by the continuous change in position of the preceding train. When the succeeding train is already located in a position closer to the preceding train than to the position where coasting starts, then the whole train operation curve may be affected by the preceding train, and so

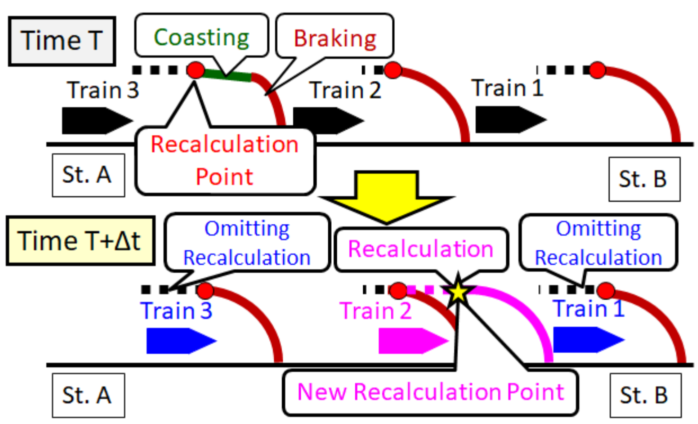

Fig. 5. Simulation of train operation curves for moving block systems

recalculation is conducted for each simulation period.

In the proposed method, the number of recalculations is lower than in the conventional method. The effect of the proposed method depends on the number of trains, or the headway of trains. If there are no succeeding trains that begin to coast to decelerate and stop at the marginal stop point, the approximate number of recalculations is equal to the number of trains multiplied by the number of times a succeeding train reaches the recalculation points. This number is much smaller than that in the conventional method.

4 Train Traffic Simulation with Prediction Control under Fixed Block

4.1 Preconditions

When we discuss prediction control under fixed block, the approach point needs to be set and calculated. It consists of position, velocity and time, on which the succeeding train is controlled to pass. In this research, considering possibility of changing signal aspects for the succeeding train during prediction control, we set the following preconditions to calculate the approach point properly.

1: The working acceleration rate for powering, coasting and braking are supposed to be constant, regardless of trains or conditions.
$Powering : \alpha\,[m\,/\,s^2],\ \ Coasting : \beta[m\,/\,s^2],\ Braking : \gamma[m\,/\,s^2]$
2: The necessary time to change driving operation from powering to coasting, or coasting to braking, are supposed to zero[sec].
3: The minimum continuous time for coasting is considered and supposed to constant time (t[sec]).
4: Prediction control is applied for a succeeding train only in cases which it and its' preceding train have stops at the next station.
5: Prediction control is applied for a succeeding train only when its' preceding train is on the block section of the platform of the next station.

4.2 Estimation of Train Operation Curves after the Approach Point

The approach point and train operation curves after the approach point satisfy the following conditions.

1: If the preceding train do not depart from the station even when the predicted departure time has come, the succeeding train stop at the marginal stop point in front of the block with the station platform. So, the approach point is on the braking pattern to stop at the marginal stop point.
2: If the preceding train depart from the station when the predicted departure time has come, the succeeding train passes the approach point, and stop at the designated point on station platform.
3: If the preceding train depart from the station when the predicted departure time has come, headway between two trains is minimized.

These conditions can be represented in Fig.6. By using the above three conditions, the position and velocity of the approach point can be represented as follows. The time of the approach point is when the preceding train pass signal 2, and the aspect of signal 1 become green in Fig.6.

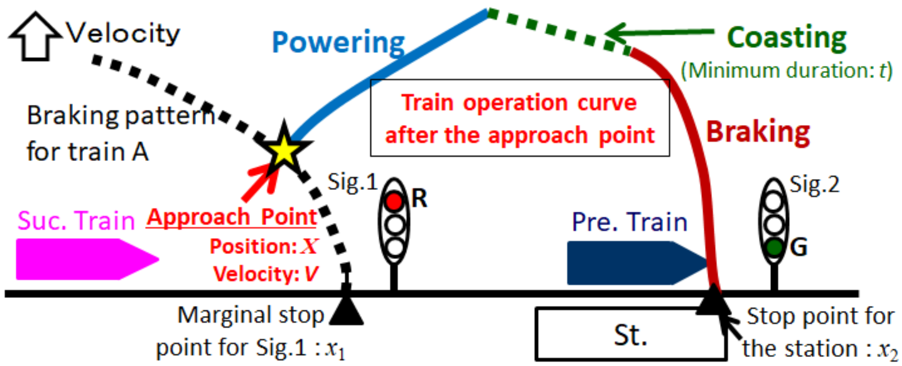

Fig. 6. Train operation curve with prediction control under fixed block

$$V = \sqrt{\frac{\beta^3\{(\gamma^2 + \alpha\beta - \beta\gamma - \gamma\alpha)t^2 - 2(\alpha - \beta)(x_2 - x_1)\}}{(\alpha - \beta)^2(\alpha - 2\beta)}} \quad (1)$$

$$X = x_1 + \frac{V^2}{2\beta} \quad (2)$$

where

x_1: Marginal stop point in front of the station platform

x_2: Designated stop point on the station platform

V: Velocity of the succeeding train at the approach point

X: Position of the succeeding train at the approach point

4.3 Estimation of Train Operation Curves before the Approach Point 1, "Energy Saving Strategy"

Based on the approach point solved in 4.2, train operation curves before the approach point is calculated based on the following preconditions and approaches.

1: The driving operation on the approach point is set as coasting. This is because the train have to change its' driving operation after the approach point, according to whether the preceding train depart from the station on the predicted time or not.

2: If the predicted departure time of the preceding train is changed due to the delay caused by congestion, (if possible) prediction control can be applied again by recalculating and updating the approach point.

In this section, we adopt the strategy for train operation curves to realize energy saving. That is, in the optimal train operation curves, we try to incorporate coasting operation as long as possible.

Estimation of train operation curves with prediction control is conducted by modifying the fastest operation curve. Slowdown driving operation, like coasting or braking, is added to that to meet the position, velocity, time of the approach point. The procedure of estimating or updating train operation curves is different depending on the following conditions.

- Whether the preceding train is on the block section of the next station or not
- Whether the succeeding train already depart from the previous station or not
- Whether the predicted departure time become earlier or later

We developed the way of estimating train operation curves for each combination of the conditions above. In this paper, we describe the way of estimating train operation curves when the preceding train is on the block section of the next station, and the succeeding train already depart from the previous station.

Figure 7 illustrates the way to modify and update the train operation curves to meet the time of the approach point. Firstly, the train operation curve which passes the approach point with coasting operation, and stops at the marginal stop point in front of the station is created. Then, it is modified by extending the duration of the coasting in front of the approach point, until the train pass the approach point on the predicted time. In case when the predicted departure time of the preceding train become later, the duration of the coasting become longer to meet the updated time of passing the approach point.

Figure 8 illustrates another way to modify and update the train operation curves to meet the time of passing the approach point. If there is no room for the operation curve to extend the duration of the coasting, braking-coasting-powering operation is added to meet the time.

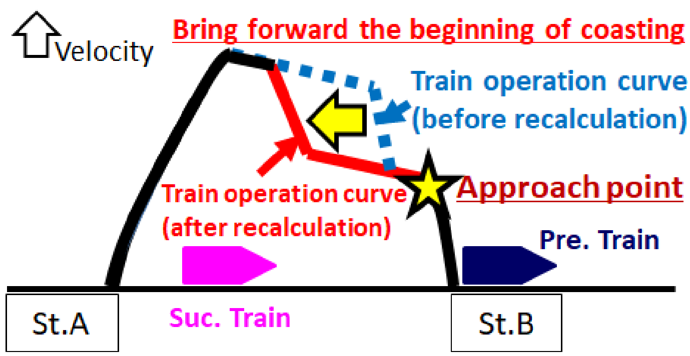

Fig. 7. Updates of train operation curve with prediction control (1)

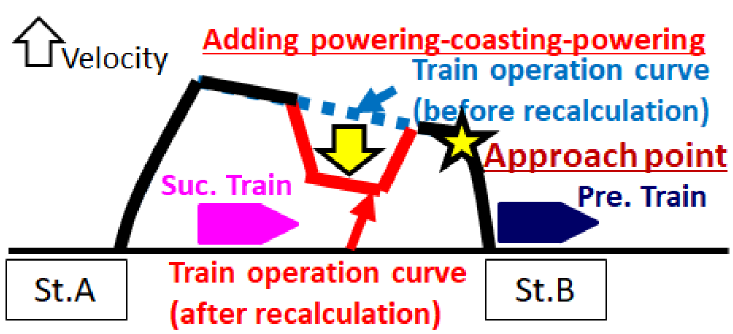

Fig. 8. Updates of train operation curve with prediction control (2)

If there is much time for the succeeding train to pass the approach point on the updated target time, it may stop between the stations, while it remains possible to pass the approach point on the updated target time by restarting.

Train operation curves created by these methods satisfy preconditions and approaches described above. There are coasting driving operation in front of the approach point. Prediction control can be applied again if the estimated time of passing on the approach point is updated. Train operation curves are energy saving ones because they adopt coasting operation as long as possible.

4.4 Estimation of Train Operation Curves before the Approach Point 2, ”Preventing Delay Propagation Strategy”

Although the train operation curve of the succeeding train described in the previous section can minimize train headway, they may influence the train after the succeeding train. To realize energy saving driving, the train operation curve of the succeeding train includes coasting operation as long as possible. This may in turn affect and bring in front for the marginal stop point of the train after the succeeding train. If the succeeding train runs as fast as possible under the condition that it passes the approach point, the influence for the train after the succeeding train may be decreased, and that prevents unnecessary delay propagation for trains running after the succeeding train.

In this section, we adopt the strategy for train operation curves to prevent delay propagation. To realize this idea, we devised another method for the train operation curve of the succeeding train. The left side of Fig. 9 illustrates each train operation curve for the succeeding train under the strategy described in 4.3 or 4.4. The running time between the two stations are the same. In the operation curve in 4.3, the duration time for coasting is long. On the other hand, in the operation curve in 4.4, there is braking-coasting-powering operation in front of the approach point. By this operation, the position of the succeeding train become forward to the next station, compared to that in the operation curve in 4.3. The difference is shown in the right side of Fig. 9, which is the time-space graph of the train operation curves described on the left side. By adopting this strategy, the train after the succeeding train can go ahead to the next station, and that leads to prevent or decrease delay propagation from the preceding train to the trains running after that.

When the predicted departure time of the preceding train is changed, the way to update the train operation curve to meet the new time of passing the approach point is the same as that described in 4.3.

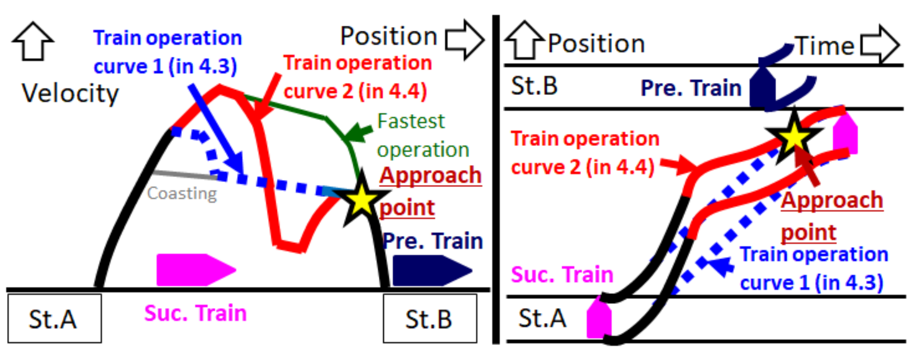

Fig. 9. Comparison of train operation curves under the two strategies

5 Train Traffic Simulation with Prediction Control under Moving Block

5.1 Precondition

Although the preconditions described in 4.1 are also adopted, as there are some differences between fixed block and moving block, it is necessary to analyse the traffic condition under moving block in which headway between trains is minimized.

Figure 10 illustrates the closest approach of successive two trains under moving block. There is the closest point at which distance between two successive trains is minimized. If we call that "contact point," we can calculate that and then the approach point, by setting and using the following preconditions in addition to those described in 4.1-4.4.

1: The driving operation of the succeeding train after the contact point is restricted to coasting and braking, until it stops at the station platform.
2: The driving operation of the succeeding train between the approach point and the contact point is restricted to coasting.
3: If the preceding train do not depart from the station even when the predicted departure time has come, the succeeding train stop at the marginal stop point in front of the station platform. So, the approach point is on the braking pattern to stop at the marginal stop point. The marginal stop point is set considering the buffer distance under moving block.

5.2 Estimation of Train Operation Curves after the Approach Point

The approach point, the contact point and train operation curve with prediction control satisfy the following conditions.

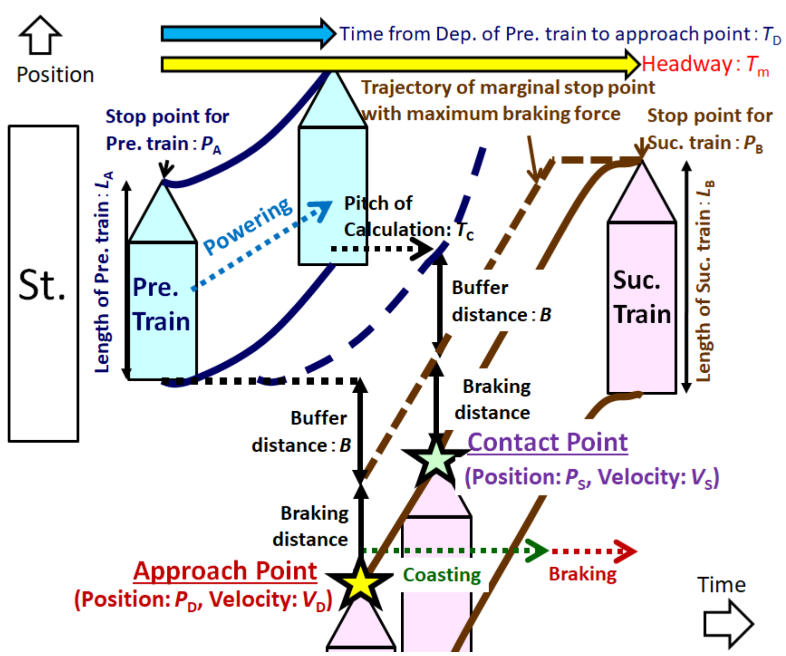

Fig. 10. Closest approach of successive two trains under moving block

1: At the contact point, the distance between the preceding train and succeeding train is minimized and the velocity of both trains become equal.
2: At the contact point, the distance between the preceding train and succeeding train is equal to sum of the buffer distance and braking distance necessary to stop by the maximum braking force.
3: If the preceding train depart from the station when the predicted departure time has come, the succeeding train passes the approach point, the contact point, and then stop at the designated point on station platform.
4: If the preceding train depart from the station when the predicted departure time has come, headway between two trains is minimized.

By using the above conditions, the position and velocity of the contact point can be calculated as follows. The minimum headway between the two trains are also calculated as follows.

$$V_s = \sqrt{\frac{-2\alpha\beta^3(\alpha-\gamma)^2 H}{\alpha^3(\beta-\gamma)(2\beta-\gamma)-\beta^3(\alpha-\gamma)^2-2\alpha^2\beta^2\gamma}} \tag{3}$$

$$P_B - P_s = H - \frac{(\alpha+\beta)V_s^2}{2\alpha\beta} \tag{4}$$

$$T_m = T_C + \frac{\gamma-\alpha}{\alpha\gamma}V_S - \frac{\sqrt{(\beta-\gamma)\left\{\left(\beta-\gamma-\frac{\beta\gamma}{\alpha}\right)V_S^2+2\beta\gamma H\right\}}}{\beta\gamma} \tag{5}$$

$$H = L_A + B - P_A + P_B \tag{6}$$

where

V_S: Velocity of the succeeding train at the contact point

P_A:Designated stop point on the station platform for the preceding train

P_B:Designated stop point on the station platform for the succeeding train

P_S: Position of the succeeding train at the contact point

T_m: Minimum headway between two successive trains

T_C: Cycle of calculation for train operation curves

L_A: Length of the preceding train

B: Buffer distance under moving block

The position, velocity and time of the approach point can also be calculated as follows.

$$V_D = \sqrt{\frac{\alpha\beta-\alpha\gamma-\beta\gamma}{\alpha(\beta-\gamma)}}V_S \tag{7}$$

$$P_A - P_D = L_A + B - \frac{V_D^2}{2\beta} \tag{8}$$

$$T_D = T_C + \frac{\gamma - \alpha}{\alpha\gamma} V_S + \frac{V_D^2}{\gamma} \tag{9}$$

where

V_D: Velocity of the succeeding train at the approach point

P_D: Position of the succeeding train at the approach point

T_D: Time period from departure of the preceding train from the station to passing of the succeeding train on the approach point

5.3 Confirmation of the Approach Point

To confirm the mathematical solutions described in 5.2, we calculated the approach point based on the parameters described in Table 1. In case 1, we suppose that train performance is general one, and the length of train is 200[m], which is typical in commuter lines in Tokyo. In case 2, high performance train, such as metros, is supposed to be operated in commuter lines in Tokyo. In case 3, the rail line in which the length of trains is short is supposed.

As the calculation results of minimum headway are realistic ones, we conclude that the calculation method is appropriate one.

Table 1. Calculation examples of the approach point

Parameters	Value		
	Case 1	Case 2	Case 3
α $[km/h/s]$	1.6	3.0	1.6
β $[km/h/s]$	-1.8	-4.0	-1.8
γ $[km/h/s]$	-0.03	-0.05	-0.03
$L_A + B - P_A + P_B$ $[m]$	210	210	100
T_C $[s]$	3.0	1.0	3.0
Calculation Results			
V_S $[km/h]$	29.9	43.0	20.6
$P_B - P_S$ $[m]$	201	189	95.9
T_m $[s]$	54.4	36.6	38.4
V_D $[km/h]$	30.2	43.4	20.8
$P_A - P_D$ $[m]$	280	275	134
T_D $[s]$	12.2	8.11	9.37

5.4 Estimation of Train Operation Curves before the Approach Point

Based on the approach point solved in 5.2, train operation curves before the approach point are calculated based on the same preconditions and approaches as those described in 4.3 or 4.4.

6 Test Calculation of Train Traffic under Commuter Line

6.1 Outline of the target rail line

In this paper, the effects of installing prediction control were evaluated. The railway line used in the evaluation had 19 stations, and about 1,000 trains in operation in a single day. The period used for the study was the morning rush hour between 7AM and 10AM, during which trains were running every 3 or 4 minutes. There were 208,335 passengers departing from origin stations between 7AM and 10AM.

We mainly analysed the train operation curves of the succeeding train supposing that the signalling system and train control system were as follows.

1) Fixed block without prediction control
2) Fixed block with prediction control
3) Moving block without prediction control
4) Moving block with prediction control

6.2 Scenario 1

We supposed that a small accident was occurred on the train in St. B at 8AM, and the train remain stopping during 3 minutes and 12 seconds. We estimated train traffic conditions under the scenario by using the improved simulator. When prediction control is applied, train operation curves before the approach point are estimated based on energy saving strategy described in 4.3.

Figure 11 illustrates the train operation curves of the succeeding train in case 1) and 4). In case 1), after the succeeding train depart from St. A, it stops between the stations due to the speed restrictions by the signal. Then, the preceding train departs from St. B, and the succeeding train restarts, and arrives at St. B. It takes 82 seconds in St. B from the departure of the preceding train to the arrival of the succeeding train.

On the other hand, in case 4), after the succeeding train depart from St. A, it drives slowly to St. B. It avoids intermediate stops between stations. When the preceding train depart from St. B, the succeeding train pass the approach point, and arrive at St. B. Headway becomes only 51 seconds. As a result, the extent of delay propagation to the succeeding train is reduced about 30 seconds. Figure 12 illustrates the train trajectory of both the preceding and succeeding train in case 1). Figure 13 illustrates that in case 4). In Fig.12, the succeeding train stops between St. A and St. B, and that leads to increase headway between trains. Moreover, as the signalling system is fixed block in 1), the succeeding train have to run within the speed restriction by the signal between St. B and St. C. It leads to increase of running time for the succeeding train. On the other hand, in Fig. 13, the succeeding train do not stop between St. A and St. B, and that leads to decrease headway between trains. Also, as the signalling system is moving block in 4), the succeeding train can run without the speed restriction by the signal between St. B and St. C.

Table 2 summarized the result of calculated headway in each case when the preceding train is delayed by 3 minutes and 12 seconds. It can be said that both moving block and prediction control is effective for the train traffic condition.

In addition, we evaluated effects of decreasing train headway under various conditions of departure delay of the preceding train. We set the preconditions that the time period of the preceding train remain stopping is varied from 60 sec. to 200 sec. Train headway between the two trains is calculated under each condition of block system and prediction control. The results are shown in Fig.14. By applying prediction control under moving block, train headway is minimized regardless of departure delay of the preceding train.

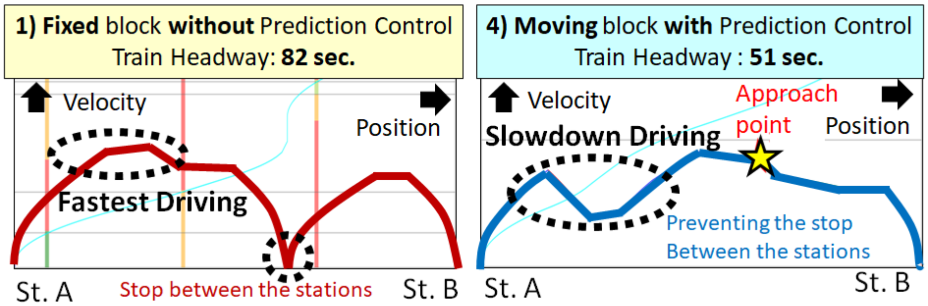

Fig. 11. Train operation curve of the succeeding train under each control system

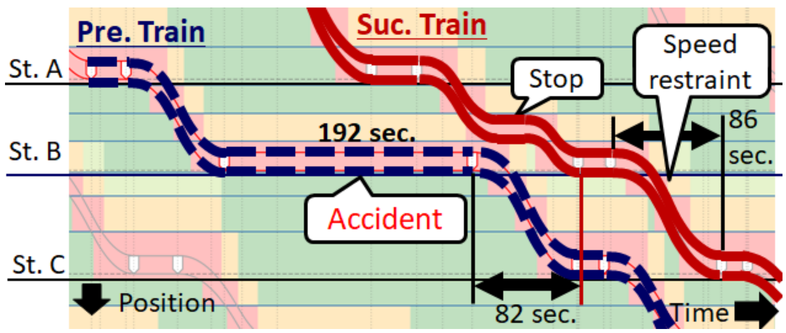

Fig. 12. Train trajectory under fixed block without prediction control

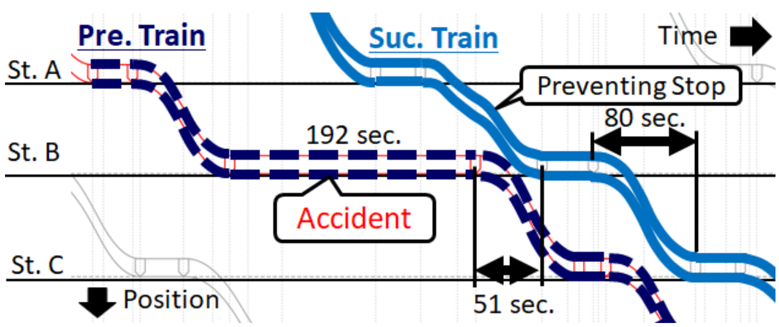

Fig. 13. Train trajectory under moving block with prediction control

Table 2. Comparison of headways

	Without prediction control	With prediction control 1: Energy Saving Strategy
Fixed block	1) 82 sec.	2) 80 sec.
Moving block	3) 56 sec.	4) 51 sec.

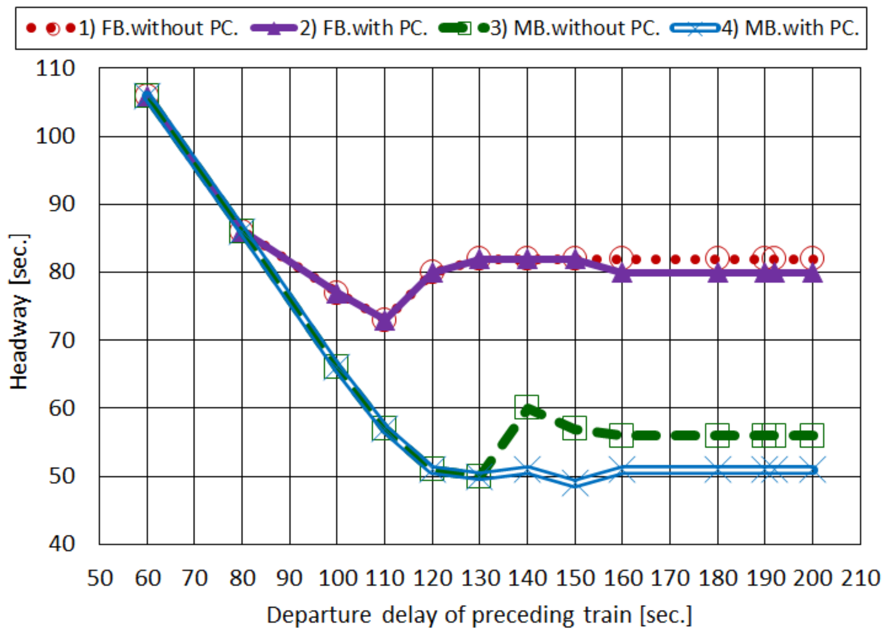

Fig. 14. Train headways under each condition

6.3 Scenario 2

We supposed that a small accident was occurred on the train in St. Q at 7:17, and the train remain stopping during 2 minutes and 5 seconds. We estimated train traffic conditions under the scenario by using the simulator. In this scenario, effects of prediction control under moving block is tested by comparing train operation curves under the conditions 3) or 4). When prediction control is applied, train operation curves before the approach point are estimated based on either strategy described in 4.3 or 4.4.

Figure 15 illustrates the train operation curve for the succeeding train under each condition. By applying prediction control, train headway become shorter. Comparing 4-1) and 4-2), although train headways are almost the same, the shape of train operation curves are different. In 4-2), the succeeding train can be operated halfway the same as that in 3). It decreases influences of delay propagation to the train after the succeeding train. So, we can select either strategy 4-1) or 4-2), along with the policies for train operation.

7 Conclusions

In this paper, we improved functions of “Train Operation/Passenger behaviour simulator” to reproduce train traffic under moving block and prediction control. We conducted test evaluation for train traffic in an actual commuter line in Japan, and confirmed the effects.

In particular, we proposed and formulated a new method for applying prediction control for trains under moving block. By combining the estimation function for passenger flow and train delay, we realized the simulation system by which prediction control can be applied repeatedly to minimize train headway, considering possibility of extension of dwell

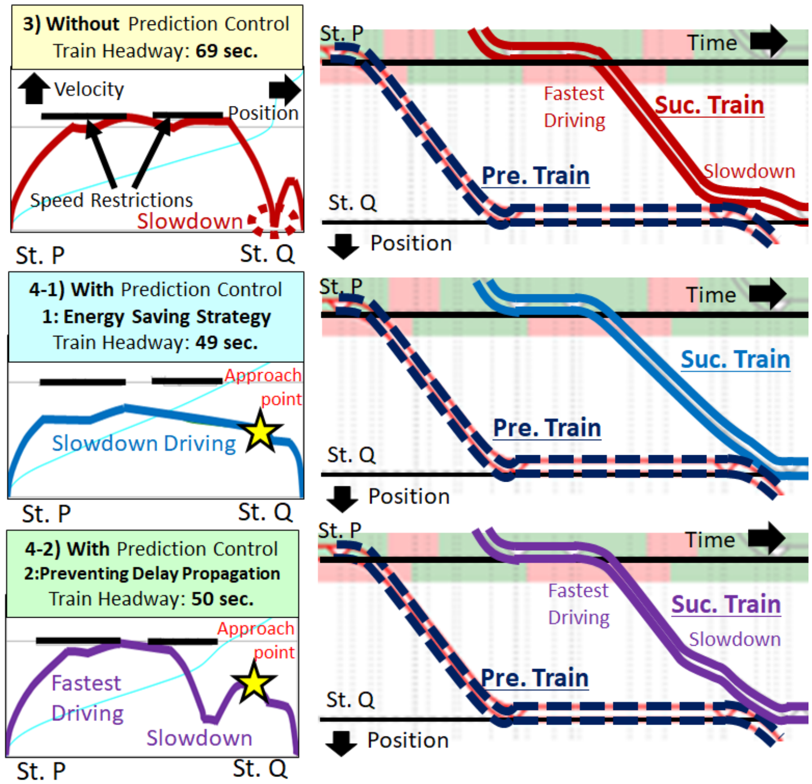

Fig. 15. Train operation curve of the succeeding train under each condition

time caused by passengers. Moreover, the simulation system can also reproduce the situation that prediction of departure of the preceding train was failed, and the succeeding train cannot be operated along with the optimized train operation curve by prediction control. At the left side of Fig. 16, when the preceding train arrive at the next station, the train operation curve for the succeeding train is optimized based on the planned dwell time of the preceding train. But, if the necessary time for boarding and alighting is estimated to be longer than the planned dwell time, the preceding train postpone the departure from the station. At the same time, as described on the right side of Fig.15, the train operation curve for the succeeding train is calculated and optimized again, based on the updated departure time of the preceding train. As there are many cases that predictions for dwell time are failed in commuter lines, we think the devised simulation method to reproduce the condition is one of the major contribution of this research.

For the future works, it is desired to evaluate under various scenario and conditions. We are also going to implement the method of predicting train delay based on past recorded data of actual delay (Nakabasami et al. (2019)). By combining the prediction method for train delay, we can utilize prediction control effectively, avoiding failure of prediction for the departure time of the preceding train. We will confirm and evaluate effects of the delay prediction by updating the simulator.

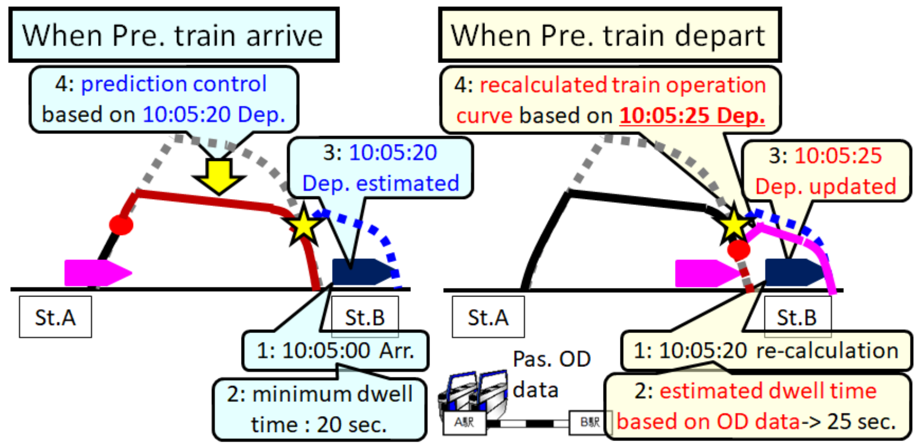

Fig. 16. Recalculation of train operation curves reflecting estimated dwell time based on passenger data

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