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SIMULATION ANALYSIS OF TRAIN OPERATION TO RECOVER KNOCK-ON DELAY UNDER HIGH-FREQUENCY INTERVALS

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ABSTRACT

The railway network in Tokyo Metropolitan Area has been developed to reduce train congestion and impedance of transfers through providing high frequency train operations. However, small irregularities in services are resulting in significant delays in the railway service, as the rail system is currently operating very close to its capacity.
Therefore, this research formulated a train operation simulation model which reproduces the behaviour of train operation, taking into account the interaction between the trains. The simulation model includes the passenger boarding model at each station. The dwell time correlates with the increase in the irregularities in train headway. Using this simulation model, this study attempted to reproduce the situation of train operation under the knock-on delay. Finally, this paper suggested a practical method to recover the knock-on delays. The result shows that keeping a moderate separation between trains with adjustment at the departure time, under the delay situation, was found to be an effective measure. The measures can shorten the travel time and recover the train delay earlier.

Keywords: Train Delay, Simulation Model, Train Operation, Passenger's Flow

1. INTRODUCTION

In Tokyo Metropolitan Area (hereinafter TMA), the railway network carries a large number of passengers everyday over a wide area with high reliability, speed and safety. Today, the TMA's railway network is known as one of the world's leading transport systems in handling a huge traffic volume with reliable operation. Service quality of the network has been improving constantly through the development of a high density railway network, using train consisting of many cars, operating at high-frequency intervals, sharing tracks between railway companies, introducing platform screen doors and so on. Operating at high-frequency intervals and sharing tracks between railway companies have been, particularly, key policies of Japan's railway to reduce congestion on the trains. The introduction of these policies has considerably contributed in making the TMA`s railway network effective and in increasing the convenience for the passengers. However, these policies have also brought about undesirable effects, including (1) frequent occurrence of train delays in rush hours, (2) extension of the train delays to a wider network area and (3) making long time necessary to untangle the delayed train system. The congestion and train delay, which occur in an almost daily basis, in the morning rush hours, have caused intolerable pain to the passengers. Moreover, the total social cost by the train delays is estimated to exceed 200 billion yen per year (Kariyazaki, K and Iwakura, S (2009)).

The railway system of TMA is operating at a capacity close to its limit, so that small irregularities are causing significant delays in the service. Delay time increases by the interaction of train operation and dwell time under high-frequency. Therefore, in order to carry a large number of passengers efficiently in the limited capacity, not only an individual service improvement but comprehensive and unified measures which deal with the whole railway system are important. Simulation model which analyzes a station passenger flow and train operation comprehensively is indispensable for examination of the improvement measure of railway service.

Therefore, this research formulated a train operation simulation model which reproduces the behaviour of train operation, taking into account the interaction between the trains. The simulation model includes the passenger boarding model at each station. The dwell time correlates with the increase in the irregularities in train headway. Using this simulation model, this study attempted to reproduce the situation of train operation under the knock-on delay. Finally, this paper suggested a practical method to recover the knock-on delay earlier, which involves keeping a moderate separation between trains with adjustment at the departure time.

Relevant literature is reviewed in the following chapter, and analysis of present state using actual data is addressed in Chapter 3. Chapter 4 explains the simulation model, and Chapter 5 and Chapter 6 explain the simulation results respectively, before the conclusion in Chapter 7.

2. LITERATURE REVIEW AND SCOPE

Recent studies of train delay have proposed that a method based on a delay propagation algorithm that use max-plus algebra for analyzing time table stability and determining infrastructure capacity (de Kort et al., 2003; Goverde, 2007, 2010 and so on). In the field of the bus, Daganzo has showed a phenomenon of bunching bus by using recurrence formula (Daganzo, 2009). Some paper has discussed treatment of the train delay by changing of the network structure for modeling user equilibrium assignment (Toriumi et al., 2005; Kunimatu et al., 2007). Most studies of train delay have focused on how the delay affects railway transportation and demand.

On other hand, some simulation models of traffic flow have been developed. One of these models is Cellular automaton model, and numerous researches have been done, especially in the vehicles field (Nagel et al., 1992, 2003; Chowdhury et al., 2000; Helbing, 2001; Daganzo, 2006; Ioanna, 2007). The model based on Cellular automaton has been also adopted in train operation modeling (Fu et al., 2008; Xun et al.,2009). Iwakura et al. have proposed a multi-agent simulation model for estimating knock-on delay (Iwakura et al., 2007, 2009). Chiusolo et al. have analysed the present state and simulated the results of automation through case study (Chiusolo et al., 2012). However, because there is little data available concerning the behaviour of train under the delay, these previous studies do not enough account for the delay time increased by an interaction between the trains and by an interaction between train operation and dwell time. Therefore, to the best of the authors' knowledge, no research has yet been carried out to specifically examine a practically feasible operating method on how to recover the knock-on delay earlier.

From these backgrounds, the study focuses on the behaviour of train which is under the operation delay. To achieve this, this research formulated a train operation simulation model which reproduces the behaviour of train operation. The simulation model is taking into account the interaction between the trains, and includes the passenger boarding model at each station. Finally, using this simulation model, this study attempted to reproduce the situation of train operation under the knock-on delay. And this paper suggested a practical method to recover the knock-on delay earlier.

3. PRESENT DATA ANALYSIS

3.1 Data Profile

Data on dynamic operation is absolutely necessary to grasp actual state of the mechanism of worsening punctuality. So this study got the actual data from Centralized Traffic Control (CTC) where data on the departure and arrival time of every train at each station is recorded. This research covers Den-en-toshi line by TOKYU CORPORATION and Hanzomon Line by Tokyo Metro Co., Ltd.. Den-en-toshi line is a radial commuter train, that is one of the most crowded lines in TMA. Den-en-toshi line has interconnection with Hanzomon Line each other. These trains operate at a minimum headway of 125 second during rush hours. This study used the actual data of 19 January, 2009 in this analysis. The maximum arrival delay in Shibuya station of the research day was about 9 minutes. Shibuya station is the major one, where these trains interconnect each other. Although Den-en-toshi line has express trains, each train stops at every station from Hutako-tamagawa to Shibuya (involving 7 stations) during rush hours (7:50~9:00) to level the train congestion.

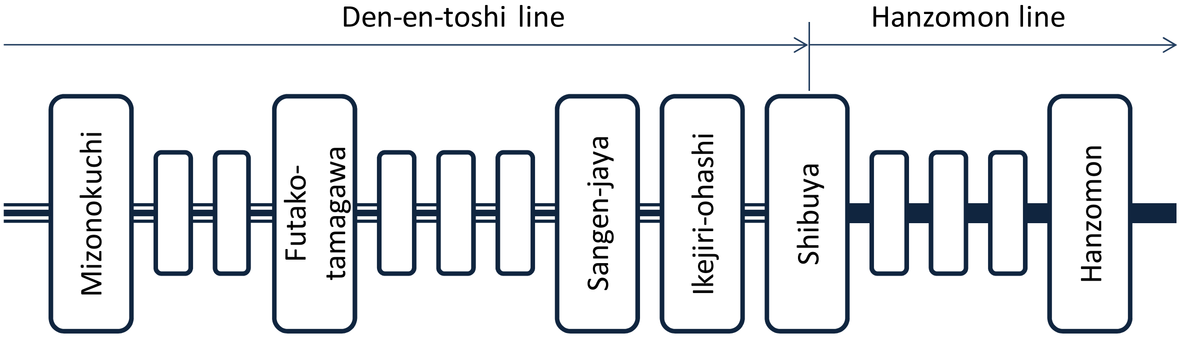

Figure 1 – Rail Routes of Den-en-toshi line and Hanzomon line

3.2 Composition of Delay Time

Figure-2 shows relations of dwell time at a station to the irregularities in headway. The horizontal axis shows the time between the departure of the train and the arrival of the following train. The time is ranked every 10 seconds, and the mean of dwell time for every rank is drawn as vertical axis. The data was acquired from 7 stations which have high congestion, Futako-tamagawa station to Shibuya station (Figure 1).
As figure-2 shows, the dwell time is directly correlated with the irregularities in train headway. Thus, when the arrival of the train is late, the passengers of the station increase and can say that the dwell time of the following train increases. This delay propagates to the following train, and the delay of the running time occurs between stations.

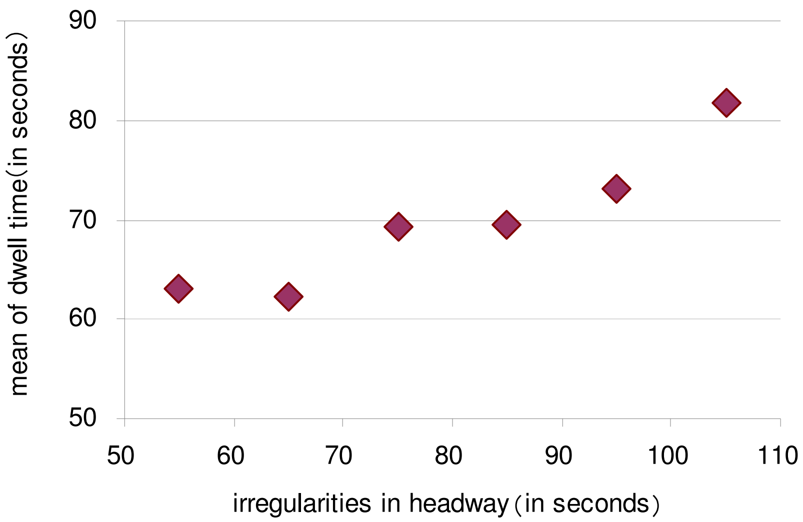

Figure 2 – Relationship between irregularities in headway and dwell time

Train schedule is usually planned by assuming travel time at rush hour to be 1.2 times as that of daytime, based on extrapolating an increasing dwell time from past experience. However, delays have been longer than the assumption, and the increase in delay is irregular. Figure-3 shows an increased travel time of each train against the schedule between specific sections that consist of 14 stations from Mizonokuchi to Hanzomon. It usually takes about 30 minutes to travel along the entire line. However, increased travel time which exceeded the normal travel time by 720 seconds was observed at about 9:20. The longest travel time was about 1.4 times as long as that of being assumed.

Figure-3 shows that during the early rush hours the station dwell time is a major cause of the train delays. However, the train running time becomes the major cause during the later rush hours. So it would appear that the train delay is occurred by increases in the dwell time and then its influence extends to the train running time. In other words, the train delay is caused by the passenger factor and later on extends to the train operation factor. It can be seen that a composition of the cause of the delay varies by hour. And the amount of an increasing running time is larger than that of an increasing dwell time. Therefore examination of train operation behaviour is important to explore measures to recover the knock-on delay early.

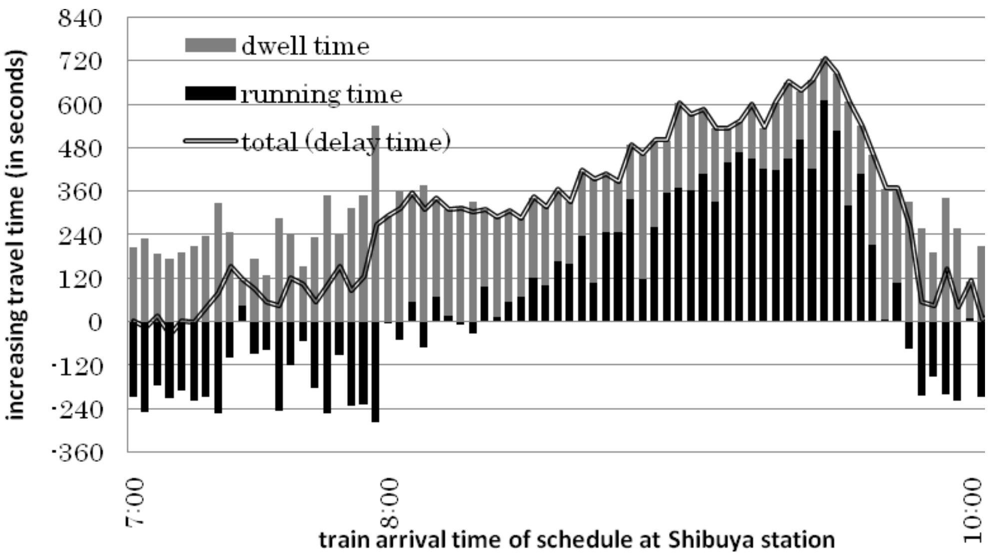

Figure 3 – Increased amount of travel time

4. SIMULATION SYSTEM OF TRAIN DELAY

4.1 Framework of Simulation System

The mechanism of knock-on delay occurrence in the TMA railway network is described as follows. At the beginning passengers on a platform congregate in front of train doors where escalators and/or stairways are located. Those passengers surge to the doors when the train arrives at the station. During rush hours, the boarding and alighting processes get difficult because of people gets crowded in the train. Therefore, the dwell time becomes longer. Then, the following train may have to run with gradually decreasing speeds owing to the departure delay of the preceding train. The decreasing of the speeds is propagated to other following trains as a consequence. Finally, awfully crowded platform occurs due to the accumulated delays of train arrivals at the station. This makes dwell time of a train at the station extremely longer. The causes of the knock-on delays in the TMA railway network are explicitly represented by such a vicious circle.

A simulation system which can reproduce the above-mentioned phenomenon is necessary to examine measures for reducing train delays. The simulation system is composed of three sub-systems. The first sub-system is for analyzing passengers flow in a railway station. This sub-system outputs the passenger volume per transfer route. The second sub-system is to analyze passengers' train boarding/alighting behavior. This sub-system outputs the train stopping time. The third sub-system is for analysis of speed control behavior of train operators which is the focus of this study.

4.2 Description of Train Operation Model

The simulation model formulated in this study gives the behavior of the delay propagation based on interaction of each train operation. We adapted the model based on Cellular Automaton (CA) model in this study. The cellular automaton is a simple model. It has been used as a base for the development of several transportation models to simulate various types of traffic flow such as vehicles and pedestrians. Nagel and Schreckenberg developed a one-dimensional probabilistic CA model, which is a model of traffic flow on a single-lane. In this model, the single-lane is divided into cells. Each site can be either empty or occupied by a vehicle with integer speed. The dynamics of the model are described by four simple rules, which are performed in parallel for all vehicles.

1. Acceleration: if the velocity v of a vehicle is lower than v-max and if the distance to the next car ahead is large than v+1, the speed is advanced by one [v →v+1].
2. Slowing down (due to other cars): if a vehicle at site i sees the next vehicle at site i+j (with j≦v), it reduces its speed to j-1 [v →j-1].
3. Randomization: with probability p, the velocity of each vehicle (if greater than zero) is decreased by one [v →v-1].
4. Car motion: each vehicle is advanced v sites.

The third step is ignored in our model for systematic operating of train. In our model, the track is divided into blocks based on actual signaling systems. The shortest block length is 60m. Most of the train operation systems rely on signaling systems to maintain safe separation between trains. The minimum distance between the trains must be long enough for a train to come to a complete stop, with a suitable safety margin between it and the preceding train. The systems are based on dividing the track into sections known as blocks. Ideally, the longest station dwell time and the minimum train separation produced by the signaling system control train headway. The longer the minimum headway between trains the lower the line capacity. Figure-4 showed the basic train signaling system with three aspects (red/ yellow/ green).

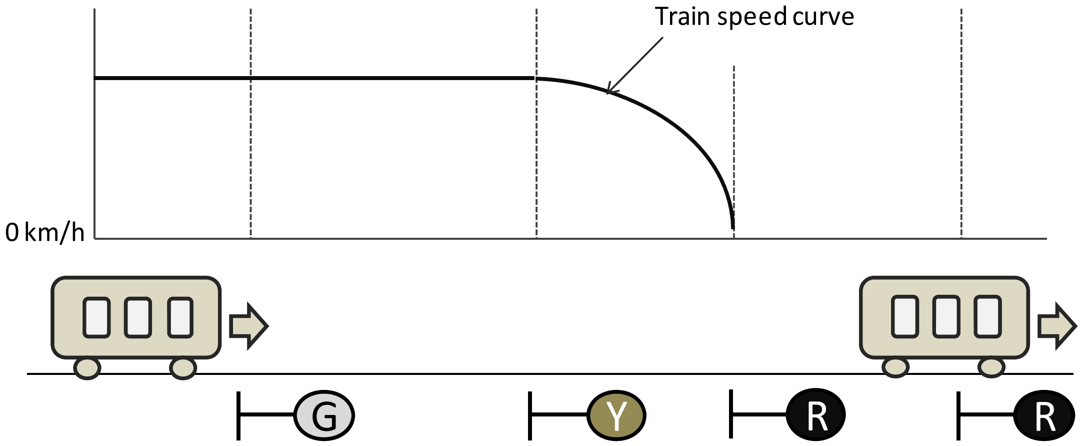

Figure 4 – The basic train signaling system

5. RESULT OF SIMULATION

5.1 Model Verification

This paper simulated 33 trains operating from Futako-tamagawa to Hanzoumon (involving 11 stations) during rush hours (7:50~9:00). Train headway is 125 seconds. These trains stop at every station. It usually takes about 25 minutes to travel along the entire line. Because this paper focus on a behaviour of the knock-on delay based on each train operation running between stations, the actual data for dwelling time of each train at stations is used.

Figure-5 shows the running time scatter diagram of each train between every station. Because the knock-on delay is propagated by several-seconds delay origin, the verification of the appearance of the analysis system was not enough. However, a timing that the running time between each station increases or decreases can be reproduced. Figure-6 shows a running time of each train between Sangen-jaya and Ikejiri-oohashi. The running time of this section has increased most against the schedule, which takes about 2 minutes. So, this paper examines a practically method to recover delays earlier under high frequency operation as shown in the following section.

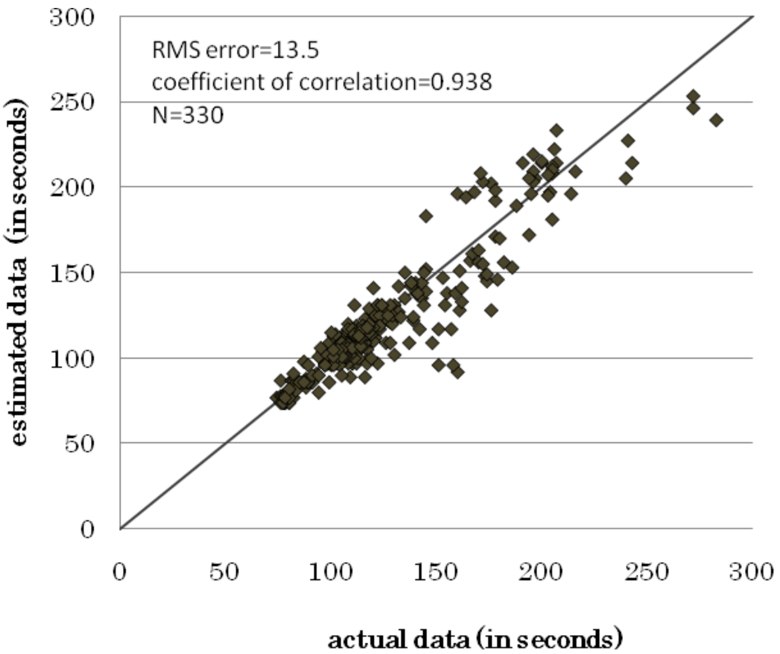

Figure 5 – The scatter diagram of the running time

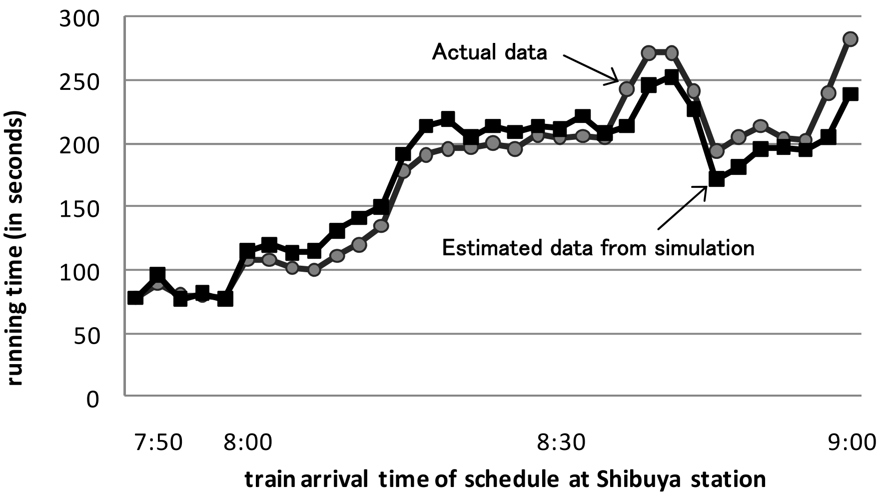

Figure 6 – The scatter diagram of the running time

5.2 Passenger Boarding Model

To reproduce train operation and dwell time integrally, the relationship between dwell time and irregularities in headway are set according to figure-7 for each station in the simulation model of Section 5.1. The horizontal axis shows the time between the departure of the train and the arrival of the following train. This enables the analysis of the knock-on delay taking into account the interaction between a passenger flow and an operation of a train. As it is supposed that the passengers increase with a fixed quantity at each station, the growth rate of the dwell time which is based on actual data is set at each station in this model.

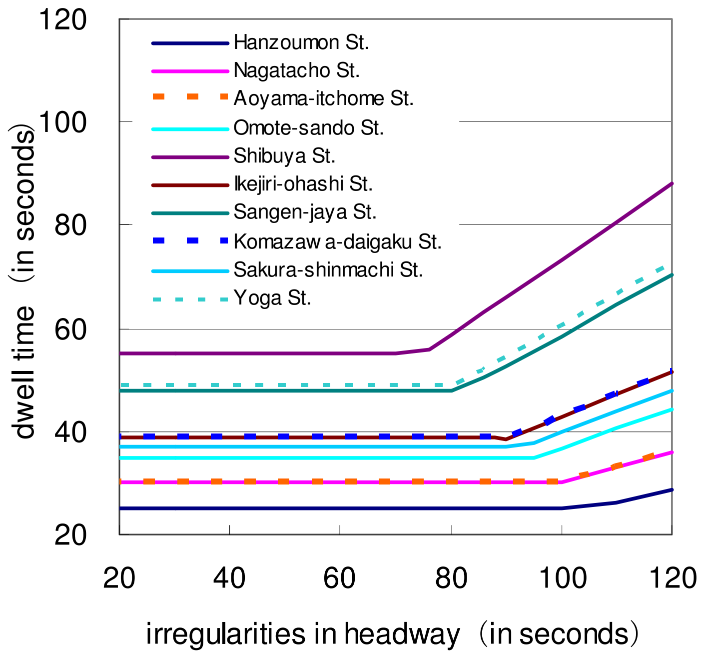

Figure 7 – The setting of relationship between irregularities in headway and dwell time

As mentioned above, irregularities in service are leading to knock-on delay, because the rail system is operating at minimum headway very close to its capacity. So, if operation interval expands, delay is cancelled, because of bringing more operation margin. The operation margin is buffer time built into headway to accommodate irregularities in service. However, TMA's railway network is handling a huge traffic volume, and there are still problems of congestion in trains. So, measures by decreasing frequency to recover the delay are not feasible approach. The measures could cause more significant delay due to increase in dwell time more than that of the present. Therefore, this study examined a practical method to recover the knock-on delay earlier while keeping present high frequency operation.

6. SIMULATION ANALYSIS

6.1 Setting of the simulation

Under the delay situation, there is a natural tendency of drivers to accelerate the train with early departure to recover the delay. However, the train has to decelerate and stop owing to maintain minimum headway from the preceding train, under high frequency operation. Moreover, when the train has to stop owing to issues like increase in dwell time of the preceding train, more time lost for restarting the movement of the train. Additionally, after restarting the acceleration is held down because headway distance is short. This has negative impact on recovering the delay, and it could be one of the causes of long recovery

time of the knock-on delays. So, this paper simulated a train operation with a departure time adjustment to widen the headway. A purpose of this method is to recover the delay that occurred early by widening the headway consciously.
Like a timetable in the morning rush hour, this paper simulates 57 trains in 125 seconds headway over the first 2 hours, and simulates 12 trains in 155 seconds headway for the next 30 minutes. A dwell time of every train at every station is increased by growth of irregularities in headway according to the figure-7. Figure-8 shows the operating diagram of the trains when the departure of the seventh train was 30 seconds late at Futako-Tamagawa station. The delays that occurred on the seventh train increase, and propagate to the following trains. The delay resulted in continuous increase of running time around Shibuya station which is a terminal station, and is not recovered until operating trains in 155 seconds headway.

6.2 Measures to Recover

As keeping a moderate separation between trains is one of measures to recover the delay, this paper simulates a train operation with a departure time adjustment at a station to widen the headway. The adjustment is achieved by delaying the departure time by 30 seconds consciously. Thus, trains in 155 seconds headway are operated at early time under delay situation. Then, the same number of trains, 12 trains, with headways of 155 seconds is simulated.
Table-1 shows the setting conditions and the result of three cases of the simulation. The first case adjusts a departure time continuously under the delay. The second case adjusts it three by three. The third case adjusts it alternately. Because the third case is assumed as the most realistic measure to prevent a decrease in traffic volume at rush hours, Figure-9 shows the operating diagram of the trains of the third case. As carry out adjustment at the departure time, a separation between trains is maintained moderately, and a continuous increase of running time is recovered earlier. And 120 minutes after starting the simulation, the train number arriving at Shibuya Station is the same as in case 1 and case 3. Thus, this result shows that the method of adjustment at the departure time in case 3 maintains high frequency operation at Shibuya station.

Table 1 – condition setting and the result in simulation

Case	Condition Setting	Simulation Result		
	Train Number in 155 seconds headway	Departure time at Shibuya of last train(No.69)	Mean of Travel Time (No.30～No.69)	Total of Recovery Time
Base Case	No.58～No.69（total 12 trains）	2:42:39	19:57	－
①Continuously	No.30～No.41（total 12 trains）	2:42:03	15:58	2:39:27
②Three by Three	No.30～No.32,No.39～No.41, No.48～No.50,No.57～No.59（total 12 trains）	2:43:08	18:02	1:16:41
③Alternately	No.30,No.32,No.34,No.36,No.38,No.40,No.42, No.44,No46,No.48,No.50,No.52（total 12 trains）	2:42:02	16:52	2:03:16

（Futako-tamagawa St.～Shibuya St.）

Figure-10 shows the time required according to the train in each case. In each case which carried out adjustment at the departure time, the separation from a following train extended, and as a result, the travel time of the following train has been shortened. This effect has propagated to the following trains one after another, and the delays are recovered earlier than without adjustment at the departure time. These results suggest that keeping a moderate separation between the trains could shorten the travel time and recover the knock-on delay earlier without decrease in the traffic volume of this line at terminal station.

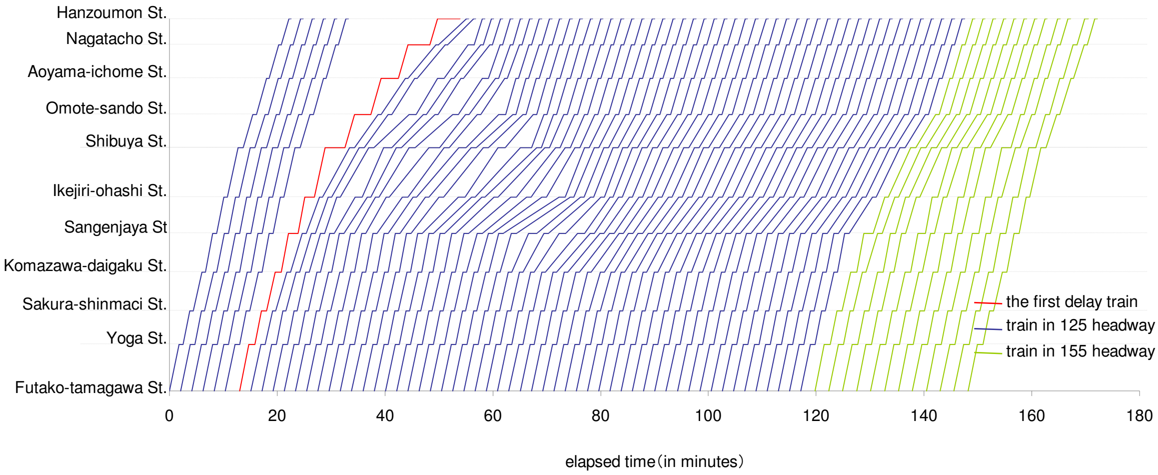

Figure 8 – operating diagram of the trains (base case)

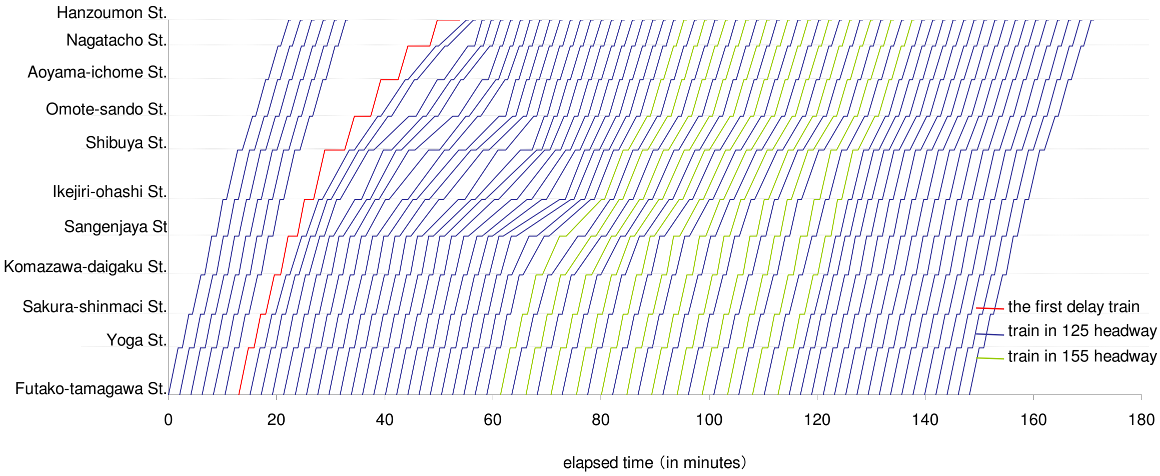

Figure 9 – operating diagram of the trains (alternately)

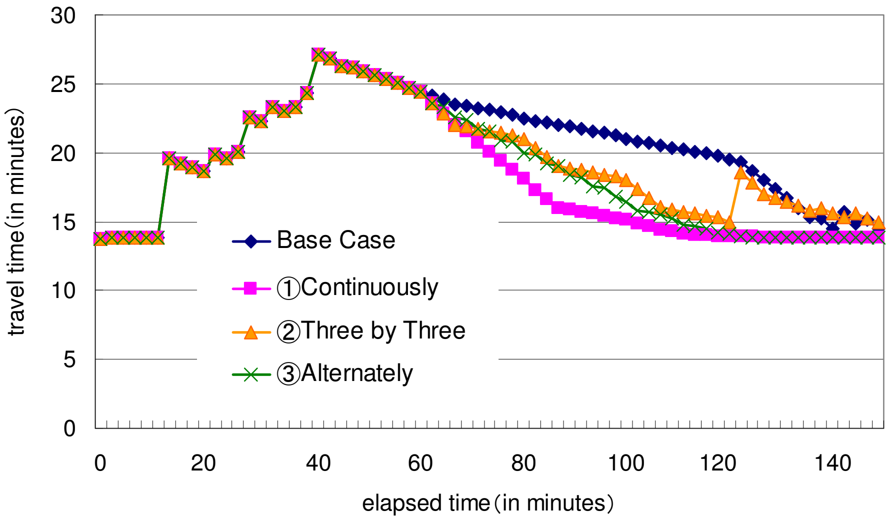

Figure 10 – Travel time of each train in each case

7. CONCLUSION

Actual data from CTC suggested that examination of train operation behaviour becomes one of the effective measures to recover the delay earlier. Delay time increases by the interaction of train operation and dwell time under high-frequency. So, this study formulated a train operation simulation model which reproduces the behaviour of train operation. The simulation model is taking into account the interaction between the trains. Moreover, the simulation model includes the passenger boarding model at each station. The dwell time correlates with the increase in the irregularities in train headway. Using the formulated simulation model, this study reproduced the situation of train operation behaviour under the knock-on delay. The result shows that keeping a moderate separation between trains with adjustment at the departure time, under the delay situation, was found to be an effective measures. The measures can shorten the travel time and recover the train delay earlier. From these results, this paper suggested a practically feasible method to recover the knock-on delay earlier keeping high frequency operation at a terminal station. Further research is necessary to understand better of how to introduce the separation between trains such as optimal interval and timing. Also because a delay of a few seconds propagates and expands by vicious circle under high frequency operation, the verification of the appearance of simulation model is not enough. Especially, the passenger boarding model needs to be improved to reproduce an actual passenger flow. Formulation including the random variable is essential to consider the characteristic of the delay. However, this study is a first step toward practically feasible measures for an early recovery of the knock-on delay using new train operating methods under high frequency operation.

Because a delay of a few seconds propagates and expands by vicious circle under high frequency operation, every second is high valuable to railway companies. In addition, effective use of existing equipment without massive investment is an important issue in

Japan. The suggestion of this study is valuable because urban railway in emergent countries is expected to face similar problem in the future.

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