Simulation Model for Estimating Train Operation to Recover Knock-on Delay Earlier

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Abstract: Small irregularities in service are leading to significant delays in the urban railway system of Tokyo, Japan, because the rail system is now operating very close to its capacity. The delay factor, however, varies by hour. The increase in train running time becomes the major cause of delay during peak periods because this has become longer than that of dwelling time. However, there is limited data availability concerning the behavior of train under the delay. So, the delay time increase due to interaction between trains is not properly accounted for. No research has yet been carried out to specifically examine a feasible operating method which can recover the knock-on delay early under high frequency operation. Therefore, this research formulated a train operation simulation model which reproduces the behavior of train operation. The simulation model is taking into account the interaction between the trains. Using the simulation model, this study attempts to understand the actual situation of train operation under the knock-on delay. Finally, this paper suggests a practical method to recover the knock-on delay earlier, which involves keeping a moderate separation between trains during running time.

Key Words: Train delay, Knock-on delay, Simulation model, Train operation

1. INTRODUCTION

In Tokyo Metropolitan Area (hereinafter TMA), the railway network carries a large number of passengers everyday over a wide area with high speed, reliability, and safety. Service quality of this network has been improving constantly by developing a high density railway network, using trains consisting of many cars, operating at high-frequency intervals, sharing tracks between railway companies, and introducing platform screen doors, among other innovations. Today, the TMA’s railway network is known as one of the world’s leading transport systems in handling - huge traffic volume and delivering reliable service. Tight railway schedule and inter-connected through service are key policies of Japan’s railway. These policies aim at reducing congestion on the trains and providing convenience to the passengers. As a result, Japan has made considerable progress in improving the service through introducing these policies. However, these policies have also brought about some undesirable effects, including: (1) frequent occurrence of train delay during rush hours, (2) extension of the train delays to the wide area and (3) longer time to recover the delay. On an almost daily basis, congestion and train delay in the morning rush hours have caused intolerable inconvenience to the
passengers. The total social costs due to the train delays are estimated to be over 200 billion yen per year (Kariyazaki et al., 2009).

Because there is no statistical data on the chronic delays caused by congestion during rush hours, the actual state of the mechanism of worsening punctuality is not captured. Thus, this study has attempted to grasp the magnitude of train delays using the sum of train delay certificates, which are issued by railway operators. As Tokyo Metro operates in the center of TMA and most of their lines share tracks with other railway companies, this study calculated train delays by using the certificate issued by the Tokyo Metro. Tokyo Metro issues a certificate for a train, which is delayed longer than 5 minutes, three times a day (morning rush/ daytime/ evening rush). Certificates collected over 8 months, April 1st to November 30th of 2009, are used in this research. In Tokyo Metro, train operates at a minimum headway of 110 seconds during rush hours. The relationship between the trains scheduled during the study period and the certificates issued of delay is shown in the Figure 1. It seems that the number of the issued certificates increases when train schedule becomes tighter (i.e., less headway). It is observed that those sharing tracks have been issued the certificates more than those which do not share tracks. This is because the operation system is more complex and the operation duration is longer. Propagation of delay caused by another line is also frequently observed. So the delay has occurred in TMA almost every weekday. Because it is difficult to invest massively in infrastructure in the recent years, operating at high-frequency intervals is executed to carry a large number of passengers. However, small irregularities in service are leading to chronic delays, because the rail system is now operating very close to its capacity.

The delay is attributed to the increase in dwell time and increase in running time. Because the boarding and alighting processes get difficult due to the increase in passengers, it is difficult to avoid increase in dwell time during rush hours. Introduction of measures to prevent increase in dwell time are also difficult as they require change of passenger behavior. The increase in the dwell time affects the train running time, an operation factor characterized by the interaction between the trains. Even though the problem could be addressed by changing the passenger behavior such as shortening dwell time, improving the operation method is highly feasible and has direct effect. There are researches on avoiding the expansion of the delay such as keeping the equal train intervals at stations. However, no research has yet been carried out to examine a practical feasible operating method on how to recover the knock-on delay earlier.
Therefore, this research formulated a train operation simulation model which depicts the behavior of train operations and takes into account the interaction between the trains. Using this simulation model, this study attempted to grasp the actual 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 headway between trains during running time.

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

2. LITERATURE REVIEW AND SCOPE

Recent studies of train delay - propose a method based on a delay propagation algorithm that uses max-plus algebra for analyzing time table stability and determining infrastructure capacity (de Kort et al., 2003; Goverde, 2007, 2010). For bus services, Daganzo (2009) has showed a phenomenon of bunching bus by using recurrence formula. Some paper has discussed treatment of 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 this affects railway transportation and demand.

On other hand, some simulation models of traffic flow have been developed. One modeling framework uses cellular automaton and numerous researches have been done on this, especially for vehicles (Nagel et al., 1992, 2003; Chowdhury et al., 2000; Helbing, 2001; Daganzo, 2006; Ioanna, 2007). Likewise, models based on cellular automaton have been 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). However, because there is little data available concerning the behavior of train under the delay, these previous studies do not account for the delay time increased by the interaction between trains. Therefore, to the best of the authors’ knowledge, no research has yet been carried out to specifically examine a feasible operating method on how to early deal with the knock-on delay under high frequency operation.

To fill in the research gap, this study focuses on the behavior of train under operation delay. To achieve this, a train operation simulation model which reproduces the behavior of train operation is formulated. The simulation model takes into account the interaction between the trains. Finally, using this simulation model, this study attempts to grasp the actual situation of train operation under the knock-on delay. It concludes by putting forth a feasible measure for early recovery of the knock-on delay under high frequency operation.

3. PRESENT DATA ANALYSIS

3.1 Date Profile
Data on dynamic operation is absolutely necessary to grasp the actual mechanism of worsening punctuality. So actual data for 19 January 2009 on the departure and arrival time of every train at each station was obtained from the Centralized Traffic Control (CTC). 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 line and is one of the most crowded lines in TMA. It connects with the Hanzomon Line at Shibuya Station, a major transfer station in TMA. These trains operate at a minimum headway of 125 second during rush hours. The maximum arrival delay in Shibuya station on the day under study was about 9 minutes. Although the Den-en-toshi Line has express trains, local trains stop at every station from Futako-tamagawa to Shibuya (involving 7 stations) during rush hours (7:50–9:00) to handle the train congestion.

Figure 2. Rail routes of Den-en-toshi line and Hanzomon line

### 3.2 Composition of Delay Time

Train schedule is usually planned by assuming travel time during rush hour to be 1.2 times that of the daytime, based on extrapolating increasing dwell time from past experience. However, delays have been longer than the assumption, and the increase in delay is irregular. Figure 3 shows the 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 route. 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. Increased amount of travel time

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 latter peak periods. So it would appear that train delay is caused 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. It can also be observed that the increase in running time is larger than that of the increase in dwell time. Therefore, examination of train operation behavior is important to explore measures for quicker recovery from the knock-on delay.

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 the sheer volume of people, thus dwell time becomes longer. Then, the following train may have to run with gradually decreasing speed owing to the departure delay of the preceding train. The decrease of speed is then propagated to other following trains as a consequence. Finally, the platform becomes awfully crowded 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 is based on cellular automaton (CA) and gives the behavior of the delay propagation based on interaction of each train operation. 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 Schreckenbg (1992) 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 $[v \rightarrow v+1]$.

2) Slowing down (due to other cars): if a vehicle at site $i$ sees the next vehicle at site $i+j$ (with $j \leq v$), it reduces its speed to $j-1$ $[v \rightarrow j-1]$.

3) Randomization: with probability $p$, the velocity of each vehicle (if greater than zero) is decreased by one $[v \rightarrow v-1]$. 
4) Car motion: each vehicle is advanced \( v \) sites.

The third step is ignored in the present model for systematic operating of trains. In the 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 the headways between trains. 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).

![Train speed curve](image)

- Signals turn red behind a train as it enters each block.
- Trains may pass green and yellow signals, but stop and wait at red signals.
- Yellow signals warn next one is red, so trains decrease running speed.

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 the behavior of the knock-on delay based on each train operation running between stations, the actual data for dwelling time of each train at stations was used.

Figure 5 shows the running time scatter diagram of each train between every station. Because the knock-on delay is propagated from several-seconds delay at the beginning of the operation, verification of the appearance of the analysis system was not enough. However, timing that determines whether 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 along this section has mostly increased against the schedule, which takes about 2 minutes. So, this paper examines a practical method to recover delays.
earlier under high frequency operation as shown in the following section.

\[
\text{RMS error}=13.5 \\
\text{coefficient of correlation}=0.938 \\
N=330
\]

![Graph](image)

**Figure 5.** The scatter diagram of the running time

![Graph](image)

**Figure 6.** The scatter diagram of the running time

### 5.2 Train Behavior

At first, the actual situation of train behavior is attempted to be understood using this simulation. Figure 7 shows the time-space diagram that reproduces train behavior estimated by the simulation from Sangen-jaya to Ikejiri-oohashi. Some of characteristic train behaviors are chosen out of trains operating during rush hours and shown. Train headway during rush hours is 125 seconds. The starting point in each graph has been set to zero. The trains after the 8:15 train have increased in running time at blocks just before Ikejiri-oohashi, blocks that are at around 1100m from Sangen-jaya. The 8:15 train is scheduled to arrive at Shibuya station at 8:15. This increase could be because the trains had to decelerate and stop owing to increase in dwell time of the preceding train. Figure 7 illustrates the actual situation that increase in
running time of a train propagates to the following trains under high frequency operation.

As mentioned above, irregularities in service lead 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 canceled due to wider operation margin. The operation margin is buffer time built into headway to accommodate irregularities in service. However, TMA’s railway network is currently handling huge traffic volume and plagued by the problem of congestion in trains. So, decreasing frequency to recover from the delay is not feasible. This measures for which an operation interval spreads 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.

5.3 Simulation Analysis

Under the delay situation, the possibility of operating the trains at maximum design speed to recover the delay is considered. However, the train has to decelerate and stop due to short separation from the preceding train under high frequency operation. Moreover, when the train stops due to an increase in dwell time of the preceding train, time loss is caused in restarting movement of the train. Additionally, after restarting the acceleration is held down because headway distance is short. This has negative impact on recovering from the delay and could become one of the causes for longer period to recover from the knock-on delay.

In consideration of this situation, train operation with running speed less than maximum design speed to widen the headway was instead simulated. The method of the deceleration simulation lowers only the maximum design speed in blocks determined by railway alignments. However, the simulation is set so that the maximum design speed after the departure does not decrease to avoid its influence on the following train. Seventy percent (70%) of maximum design speed is set for blocks at the interval of about 600m to 850m from Sangen-jiaya. On the other hand, half of the maximum design speed is set for blocks at the interval of about 850m to 1300m from Sangen-jiaya. However, every train relies on usual
signaling systems to maintain safe separation between trains. This paper simulated train movements by applying the deceleration maximum design speed operating method for the 8:30 train only, a train that is scheduled to arrive at Shibuya station at 8:30. After the 8:30 train, 14 trains with usual maximum design speed were simulated from Sangen-jaya to Ikejiri-oohashi. Actual data of departure time from Sangen-jaya and dwelling time of Ikejiri-oohashi of each train were used.

Figure 8 shows the speed-space diagram and the time-space diagram of the 8:30 train. The result of this simulation shows that the 8:30 train arrived at the station about four seconds earlier than the simulation of the present situation. This is because the separation from the preceding train was extended by the deceleration of the train operation at around 700m from Sangen-jaya. So, smooth acceleration became possible because the preceding train was leaving Ikejiri-oohashi when the 8:30 train was approaching at 1100m from Sangen-jaya.

Table 1 shows the running time comparison of the following trains. Owing to the early arrival and departure of the 8:30 train, the separation from a following train extended, and as a result, the running time of the following train has been shortened. This effect has propagated to the following trains one after another, and the running time of the 9:00 train was reduced by 40 seconds. These results suggest that keeping a moderate separation between the trains could shorten the running time and recover from knock-on delay earlier, even if this is kept with only one train during running time.
Table 1. Comparison of the running time

<table>
<thead>
<tr>
<th>train No. (arrival time of schedule at Shibuya St.)</th>
<th>8:30</th>
<th>8:32</th>
<th>8:34</th>
<th>8:37</th>
<th>8:41</th>
<th>8:43</th>
<th>8:45</th>
<th>8:47</th>
<th>8:50</th>
<th>8:52</th>
<th>8:54</th>
<th>8:56</th>
<th>8:58</th>
<th>9:00</th>
</tr>
</thead>
<tbody>
<tr>
<td>estimated present situation</td>
<td>214</td>
<td>212</td>
<td>222</td>
<td>208</td>
<td>214</td>
<td>246</td>
<td>253</td>
<td>227</td>
<td>172</td>
<td>181</td>
<td>196</td>
<td>197</td>
<td>195</td>
<td>205</td>
</tr>
<tr>
<td>estimated deceleration method</td>
<td>210</td>
<td>206</td>
<td>211</td>
<td>193</td>
<td>193</td>
<td>221</td>
<td>223</td>
<td>192</td>
<td>134</td>
<td>141</td>
<td>155</td>
<td>156</td>
<td>151</td>
<td>170</td>
</tr>
<tr>
<td>difference (in seconds)</td>
<td>-4</td>
<td>-6</td>
<td>-11</td>
<td>-15</td>
<td>-21</td>
<td>-25</td>
<td>-30</td>
<td>-35</td>
<td>-38</td>
<td>-40</td>
<td>-41</td>
<td>-41</td>
<td>-44</td>
<td>-35</td>
</tr>
</tbody>
</table>

6. CONCLUSION

Actual data from CTC suggested that examination of train operation behavior becomes one of the effective measures to recover from the delay earlier. Even though the problem could be addressed by changing the passenger behavior such as shortening dwell time, improving the operation method is highly feasible and has direct effect. So, this study formulated a train operation simulation model which reproduces the behavior of train operation. The simulation model takes into account the interaction between the trains. Using the formulated simulation model, this study grasped the actual situation of running train behavior under the knock-on delay. The result shows that keeping a moderate separation between trains during running time, under the delay situation, was found to be an effective measure. The measure can shorten the running time and recover the train delay earlier. From these results, this paper suggested a practical method to recover from the knock-on delay earlier while keeping high frequency operation. This study is a first step toward formulating a feasible measure for early recovery of the knock-on delay by use of the new train operating method under high frequency operation. However, further research is needed to better understand how to keep a moderate separation between trains such as optimal interval and timing.

Because a delay of a few seconds propagates and swells under high frequency operation, every second is highly valuable to railway companies. In addition, effective use of existing equipment without massive investment is an important issue in Japan. The suggestion of this research is valuable because urban railway in Asian nations is expected to face similar problem in the future.

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