The Influence of First-Delay Location and Timetable Recovery Strategies on Knock-on Delay of Taiwan Regional Railway

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Abstract: Train delays in railway system are affected by many factors, and one of the most important factors is the insufficient line capacity. Knock-on delays (delay propagation) caused by the first delays, always interrupt railway operation. This research uses a previously developed simulation model to deal with the related problems, and selects a rail section from Cidu to Shulin of Taiwan regional railway for case study, in order to explore the effects on knock-on delay of different first delay locations and recovery strategies. The main findings are as follows: (1) the closer that the first delay occurred at upstream section, the greater the knock-on delay of all stations and two end-stations are; (2) the effects of timetable recovery strategies are better in recovering to scheduled timetable when the first delay occurred at the upstream section. It is expected that the results can provide more insights about the complex interactions of railway operations.

Key Words: Simulation Model, First Delay, Knock-on Delay, Timetable Recovery Strategies

1. INTRODUCTION

It is well known that insufficient capacity will result in train delays, especially when train traffic approaches to the capacity. These factors that affect line capacity will eventually make influence on train delays and in particular, delay propagation (knock-on delay). In order to clarify the impacts of these complicated factors on knock-on delay and their interactions, Hwang & Liu (2010) developed a comprehensive simulation model to deal with the related problems. The result shows that the proposed model can be reasonably used in practice for estimating the knock-on delay. The model can be further extended to analyze the impacts on knock-on delay for many kinds of changes in infrastructures, operational situations and controlling strategies. Therefore, this research uses the proposed simulation model to extend further analysis of the previous study on train delays.

The remainder of this paper is organized as follows: In section 2, related researches about train delay are presented. The third section presents outlines of the developed simulation model. The fourth section presents processes and results of the case study, which is the core of this paper. The last section summarizes the major findings of this research.

2. LITERATURE REVIEWS

The issue of train delay estimation in different railway systems must be well-defined coherently at the beginning. Mattsson, L. G (2004) categorized train delays into two types, one is the scheduled delay, which is the difference between scheduled running time and
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Minimum running time, and the other is unscheduled delay. Unscheduled delays consist of two parts of different sources, primary (first) or exogenous delays and secondary or knock-on (reactionary) delays. The first type is caused by exogenous events that are independent of capacity utilization. The latter is generated by a first delay. Since the amount of the knock-on (secondary) delay depends not only on the frequency and duration of first delays, but also on the capacity utilization. Thus, in terms of operating efficiency, service quality and infrastructure improvement; it is believed that accurate estimation of knock-on delays play a key role of line capacity utilization.

In literature, most studies related to delays were focussed on the reliability of train services to capacity utilization. Carey (1999) presented an insightful analysis of the mechanism behind delays. He derived complex formulas for calculating probability density functions of knock-on delays, his analytical approach only dealt with the schedule reliability problem of train arrivals and departures at a station of double-track operations. Besides, Huisman and Boucherie (2001) developed a stochastic model for capturing both scheduled and unscheduled train delays. They summarized the key factors of running time, including number of trains, heterogeneity, primary delay, trains order and buffer time.

There are also some studies dealing with the assignment of trains to platforms and stations. For example, Chakroborty and Vikram (2008) developed a linear mixed integer programming model for allocating platforms optimally at a busy multi-platform station. Their model takes into account the inconvenience caused by delay, allocation of non-preferred platforms, and last minute reassignment of platforms. Carey and Crawford (2007) focused on a busy rail networks with highly complex patterns of train services that include different speeds, multi-platform stations and conflicting lines. They developed heuristic algorithms to find and resolve the conflicts in draft train schedules. Finally, Yuan and Hansen (2007) presented an analytical stochastic model for estimating the propagation of train delays at platform tracks and junctions. Their result shows that the mean knock-on delay increases exponentially as scheduled buffer time at level crossing decreases.

3. THE SIMULATION MODEL

Train interactions with each other are very complicated processes on a regional railway line. It is very difficult to model the interference in train operations and the effect on knock-on delays caused by a primary (first) delay mathematically. Since simulation approach can offer the most detailed representation of a railway system, it is considered as the most appropriate way to study the complex processes and the interactions between trains and infrastructures. Therefore, a simulation model which was developed and validated previously to deal with the train delay problems (Hwang & Liu, 2010) is used as the tool in this research. Major features of this model are briefly described in this section.

3.1 Model Framework

The framework of the simulation model include four parts, these are input information, scheduled timetable, delay disturbance, and the resulting timetable, as shown in Figure 1.
Figure 1 shows that the input information consists of railway condition, traffic condition, and control condition. The details are listed in Table 1.

![Figure 1: Conceptual framework of the simulation model](image)

**Table 1: The detail items of input information**

<table>
<thead>
<tr>
<th>Items</th>
<th>Railway Condition</th>
<th>Traffic Condition</th>
<th>Control Condition</th>
</tr>
</thead>
<tbody>
<tr>
<td><strong>Input Parameters</strong></td>
<td>-Railway Line</td>
<td>-The Minimum Dwelling Time</td>
<td>-Minimum Headway of Same direction</td>
</tr>
<tr>
<td></td>
<td>-Station List</td>
<td>-Scheduled Timetable</td>
<td>-Minimum Headway of Reverse Direction</td>
</tr>
<tr>
<td></td>
<td>-Track Layouts of Stations</td>
<td></td>
<td>-Section Capacity</td>
</tr>
<tr>
<td></td>
<td></td>
<td></td>
<td>-Recovery Time</td>
</tr>
</tbody>
</table>

(2) **Scheduled Timetable**

In order to estimate the delay propagation, the simulation model requires input information of the whole scheduled timetable, especially the scheduled arrival and departure times at each station for each train. The model also takes train ranks and stopping patterns of origin-destination pairs into account. Based on a scheduled timetable, the simulation model can compute the impacts of different traffic scenarios, including: (i) train types with different running speed; (ii) train priorities; (iii) running time between two stations; (iv) origin-destination stations; (v) dwelling time, etc.

(3) **Delay Disturbance**

Theoretically, if trains operate as the scheduled timetable, there would be no delays. Since knock-on delay resulted from first delay, the simulation model needs the information of the first delay to compute the propagation of the delay. The first delay can occur at any locations of a railway line.

(4) **Simulated Timetable**
Basically, the simulated timetable is the final output of this model. It shows the actual arrival and departure times of the trains affected by the first delays. The difference between the simulated timetable and scheduled timetable is then calculated as the knock-on delay.

### 3.2 Assumptions and Limitations

Railways are very complicated system and none of the railways in the world are exactly the same. In this model, following assumptions are made with consideration of the characteristics of Taiwan Regional Railway System (TRRS):

- Only one railway line is considered, which is the case of TRRS.
- There are two tracks between adjacent stations and double-track operations are provided (one for each direction).
- There are five typical types of station layouts.
- There are at most two trains present in the same rail section due to the signal installation of TRRS.
- The minimal running time for schedule recovery is set as a ratio of scheduled running time (for example 0.9).
- The display on time-space diagram is limited to 256 trains, but can be enlarged if required.

### 3.3 Simulation Mechanisms

The simulation model considers all factors that affect train operations and take operational constraints into account. The proposed mechanisms are explained below:

(1) Resolution of train conflict

For safety reason, trains are separated from each other by signaling system. In addition, if a track is occupied by a train, other trains are not allowed to enter the same track before it is clear by signaling system. The constraints for train operations are summarized below:

- The operating rule on the track between stations is based on First-In-First-Out principle, and overtaking is not allowed.
- The capacity of each railway section is limited by signaling system and input by user.
- If one train stops at a track within a station, the following train can not enter.
- When the preceding train leaves a station, the following train must keep enough headway to enter the same track as shown in Figure 2.

![Figure 2](image)

**Figure 2** The departure-arrival headway of the same direction (same track)

- If two successive trains arrived at different tracks within a station, they must obey the minimal arrival-arrival headway constraint, as shown in Figure 3.
- If two consecutive trains depart from different tracks within a station, they must obey the
minimal departure-departure headway constraint, as shown in Figure 4.

- If two trains pass a level crossing or junction in different directions, the time interval for the two trains must obey the minimal headway constraint, as shown in Figure 5.

![Image](image-url)

**Figure 3** The arrival-arrival headway of the same direction (different tracks)

**Figure 4** The departure-departure headway of the same direction (different tracks)

(2) Elimination of train delay

During simulation, if a following train violates the above operation constraints, it cannot run forward and the knock-on delay occurs. The simulation model advances the clock time every one second and keep the train waiting at the current location. The simulation will not stop until all delays are eliminated.

(3) The re-scheduling strategy for delayed trains

In order to cope with train delays, traffic controller can employ proper strategies to reorganize the schedules in some ways. Some re-dispatching or operational strategies, which can be used simultaneously or separately, are listed as follows:

- Reducing the dwell times of the delayed trains while satisfying the minimal dwell time constraints.
- Reducing the running times of the delayed trains while satisfying the minimal running time constraints.
(4) Delay Setting

Since the main purpose of the simulation model is to evaluate the impacts of the first and knock-on delay on the whole timetable, the model must input the location where the first delay occurs, the starting time and duration. The location of the first delay can be set to either in between stations or within stations. After setting the first delay, the users can also select different re-dispatching strategies such as reducing the running time and/or decreasing the dwell times of trains.

(5) Class Design

There are nine classes designed for the simulation model, including RailSystem, Train, DwellPlan, Station, StationI, StationII, StationIII_R, StationIII_L, and Tracks. In order to deal with the conflicts of different routes at level junctions of tracks, another class “CrossOverInfo” is designed to simplify the route settings for classes StationII, StationIII_R, StationIII_L. The route conflicts that require sufficient headways for the above classes are illustrated in Figure 6 to Figure 8.

Figure 6 The route conflicts for StationII track layout

Figure 7 The route conflicts for StationIII_R track layout

Figure 8 The route conflicts for StationIII_L track layout

3.4 Simulation Procedure

The overall procedure for estimating knock-on delays is outlined in Figure 9. It is an event-based procedure. At the beginning of the simulation, the first delay events are added to an event list, and are sorted by time. Next, the program will check whether the event list is
empty. If it is empty, then the program stops. Otherwise, the program will process the next event. There are different procedures for different types of event, including arrival, passing, and departure. In the next step, the model will detect if there are train conflicts caused by the event. If a conflict is detected, the train being processed is delayed by 1 second and the new event is added back to the event list for resorting. If no conflict is found, the program will check the next event. The procedure will be repeated until all events are processed.

The program of the model is developed under .NET Framework for its rich class library and supports. The popular C# programming language is selected for coding the program.

Figure 9 The main procedure for knock-on delay simulation

3.5 Model Validation

The model was developed and validated in a previous study by Hwang and Liu (2010) in which the actual and estimated delays at the five stations on the north of Taipei station were compared. The results demonstrated that the estimated delays are exactly the same as the actual delay for 30% of the total samples, and the differences of about 90% of the total samples are within five minutes range. Since the definition of train delay for TRA is five minutes, it was concluded that the proposed model can estimate knock-on delays with acceptable accuracy. It is thus directly applied to the following case of this paper.

4. CASE STUDY

A real rail section and an operational timetable from Taiwan Railways Administration (TRA) were selected for this case study. Cidu to Shulin is selected since it is the overlapped area of the western service line, eastern service line, and commuting service of north metropolitan area. In other words, it is the busiest section of TRA in terms of service frequencies, stopping
patterns and train types. This section includes 11 stations and displays complex characteristics and interactions of the TRA system.

To compare the influences of different first-delay location on knock-on delay, several scenarios are designed. In terms of location, it simulates first delay event occurred at any of the 10 locations between two adjacent stations every hour from 7:00 to 22:00, and the delay duration is ranged from 0 to 3,600 seconds. However, the following results show only the average knock-on delays for every hour. In addition to the different first-delay location assumptions, this research also explores the effects of recovery strategies, and compares the simulation results of all stations and two end-stations (Cidu and Shulin). Furthermore, first-delay event occurred at downstream and upstream locations are compared, and the relationship of knock-on delay reduction of all stations and two end-stations by recovery strategies, first-delay location and first-delay duration are shown by 3 dimensional figures.

4.1 Input Data

There are many input parameters for the simulation model, including station mileage, train properties, timetable recovery rules, operation parameters, stopping patterns, track layouts, headway, section capacity, ratio of minimal running time to scheduled running time, and scheduled timetable, etc. Real data of traffic and control condition are listed in Table 2. Besides, the strategy to catch up with the scheduled timetable by reducing station dwell times are also shown as minimal dwell time in table 2, and the strategy of decreasing running time is set as 90% of scheduled running time in comply with practices’ of TRA. There are totally 256 trains consisted by two typical types of train, i.e., express and commuter trains in two directions for this case study.

<table>
<thead>
<tr>
<th>Station Name</th>
<th>Distance (km)</th>
<th>Express Train</th>
<th>Commuter Train</th>
<th>Minimal Dwell Time (Seconds)</th>
<th>Station Track Layout</th>
</tr>
</thead>
<tbody>
<tr>
<td>Cidu</td>
<td>2.7</td>
<td>120</td>
<td>60</td>
<td>60</td>
<td>Type I</td>
</tr>
<tr>
<td>Baifu</td>
<td>3.6</td>
<td>--</td>
<td>30</td>
<td>30</td>
<td>Type IV</td>
</tr>
<tr>
<td>Wudu</td>
<td>1.2</td>
<td>150</td>
<td>30</td>
<td>180</td>
<td>Type IV</td>
</tr>
<tr>
<td>Sijuh</td>
<td>1.5</td>
<td>90</td>
<td>60</td>
<td>120</td>
<td>Type I</td>
</tr>
<tr>
<td>Sike</td>
<td>4.1</td>
<td>120</td>
<td>30</td>
<td>240</td>
<td>Type IV</td>
</tr>
<tr>
<td>Nangang</td>
<td>3.5</td>
<td>210</td>
<td>60</td>
<td>210</td>
<td>Type I</td>
</tr>
<tr>
<td>Songshan</td>
<td>6.4</td>
<td>240</td>
<td>60</td>
<td>360</td>
<td>Type I</td>
</tr>
<tr>
<td>Taipei</td>
<td>2.6</td>
<td>240</td>
<td>120</td>
<td>240</td>
<td>Type I</td>
</tr>
<tr>
<td>Wanhua</td>
<td>5.2</td>
<td>240</td>
<td>30</td>
<td>270</td>
<td>Type II</td>
</tr>
<tr>
<td>Baoxiao</td>
<td>4.6</td>
<td>270</td>
<td>60</td>
<td>300</td>
<td>Type I</td>
</tr>
</tbody>
</table>

4.2 The Simulation Results of All Stations
With different input data, this simulation model estimates the knock-on delay of different situations. First of all, for the effects of first delay duration, Figure 10 and Figure 11 show the train diagrams of scheduled and simulated timetables respectively (ex. the first delay duration is 3,600 seconds in Songshang-Taipei section in downward direction at 7:00 AM). Comparing these two figures, Figure 11 shows that there are 13 trains have knock-on delays. In order to analyze the effects of different first-delay locations, the simulation results of knock-on delay of all stations in downward direction are described as follows:

(1) The total knock-on delay at all stations of different first-delay duration and location without timetable recovery strategies
Figure 12 shows the total knock-on delays of all trains at all stations without timetable recovery strategies when first delay occurred at different locations. Apparently, the results demonstrate that total knock-on delays at all stations are greater if the duration of first delay is longer and first delay occurred at upstream section.

(2) The total knock-on delay at all stations for different first-delay duration and location with timetable recovery strategies

Figure 13 shows the total knock-on delays of all trains at all stations with the two timetable recovery strategies simultaneously. Compare with Figure 12, it shows that with above recovery strategies, the total knock-on delay at all station is obviously lower than without any strategy.

(3) The total knock-on delay reductions for simultaneously reduce dwell and running time

Figure 14 shows the total knock-on delay reductions for simultaneously use reducing dwell and running time recovery strategies. Apparently, if the first delay occurred closer at upstream section, the knock-on delay reductions is better than at downstream sections. It also indicates that the strategies can reduce significant amount knock-on delays if the first delay occurred location is far from two end-stations.

(4) The relationship of total knock-on delay reduction, first delay duration and location

Figure 15 shows the 3-dimension relationship of total knock-on delay, first delay duration and location. It indicates that if the first delay is higher and the first delay occurred near the upstream section (Cidu-Nangang section), the knock-on delay reduction of all stations will be greater. It also shows that the effects of strategies are better in recovering to the scheduled timetable when the first delay occurred at the upstream section.

Figure 12 The total knock-on delay of all trains of different first delay duration and locations without timetable recovery strategies
Figure 13 The total knock-on delay of all trains of different first delay duration and locations with timetable recovery strategies

Figure 14 The total knock-on delay reductions with & without timetable recovery strategy of all trains under different first delay duration
4.3 The Simulation Results of End-Stations

In order to compare with the knock-on delay of all stations, the knock-on delays of two end-stations are analyzed as follows:

(1) The knock-on delays at two end-stations of different first-delay duration and location without timetable recovery strategies

Figure 16 shows the knock-on delays of all trains at two end-stations without any timetable recovery strategies when first delay occurred at different locations. Overall, the differences of the simulated knock-on delays at all sections are not distinct except for Banciao-Shulin section. According to the results, the knock-on delay of the 13 affected trains at Banciao-Shulin section is about 72 minutes lower than others when the first delay is 60 minutes. It is because that if the first delay occurs too closed to end-station, the knock-on delay would not propagate significantly.

(2) The knock-on delays at end-stations of different first-delay duration and location with timetable recovery strategies

Figure 17 shows the knock-on delays of all trains at two end-stations while reducing dwell and running time strategies are simultaneously used. Comparing with Figure 16, apparently, the knock-on delays of downstream sections (Songshan to Shulin) are higher than that of the other sections.

(3) The knock-on delay reductions for simultaneously reduce dwell time and running time
Figure 18 shows the knock-on delay reductions for simultaneously use reducing dwell and running time recovery strategies at two end-stations. Apparently, if the first delay occurred closer at upstream section (Cidu to Nangang), the average knock-on delay reductions is about 122 minutes higher than downstream sections when the first delay is 60 minutes. It also illustrates the effects of using recovery strategies if the first delay occurred at the location which is far from end-stations.

(4) The relationship of knock-on delay reduction, first delay duration and location

Figure 19 shows the relationship in 3-dimension of knock-on delay reduction, first delay duration and location at two end-stations. The result is similar to the all stations scenario in that if the first delay is higher and the first delay occurred near the upstream section (Cidu-Nangang section), the knock-on delay reduction of end-stations would be greater. Therefore, it also reveals that the effects of strategies are better in recovering to the scheduled timetable when the first delay occurred at the upstream section in this scenario.

Figure 16 The knock-on delay of different first delay duration and location without timetable recovery strategies at two end-stations
Figure 17 The knock-on delay of different first delay duration and location with timetable recovery strategies at two end-stations

Figure 18 The knock-on delay reductions with & without timetable recovery strategy at two end-stations
5. CONCLUDING REMARKS

The primary objective of this study is to explore the influence of first-delay location and timetable recovery strategies on knock-on delay in a busy section of Taiwan regional railway system. Using a previously developed simulation model as tool, this research estimates and compares the knock-on delays of all stations and two end-stations under various scenarios, such as different combinations of railway, traffic, and control conditions, as well as timetable recovery strategies. The busiest Cidu-Shulin section of Taiwan Railways Administration is selected for the case study. The selected section includes 11 stations, 256 trains consisted by two types of trains and 5 different kinds of track layouts at stations.

The results of the case study indicate that the proposed simulation model can be used to reasonably simulate the complex knock-on delay problems and explores the influence of many kinds of first-delay scenarios. The case study produces many meaningful results, such as the first delay occurred closer to upstream section, the knock-on delay of both end-stations and all stations are greater. In addition, the study also finds that the effects of timetable recovery strategies are better in recovering to the scheduled timetable when the first delay occurred at the upstream section. It is expected that the results obtained in this study can help to gain more insights about the complex interactions of railway operations.

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