Journal of the Eastern Asia Society for Transportation Studies, Vol.8, 2010

A Simulation Model for Estimating Knock-on Delay of Taiwan Regional Railway

Cherng-Chwan HWANG
Professor
Institute of Traffic and Transportation,
National Chiao Tung University
4F, 118 Sec.1, Chung Hsiao W.Rd. Taipei 10012 Taiwan, ROC
Fax: 886-2-23494953
E-mail: cch@mail.nctu.edu.tw

Jau-Rong LIU
Ph.D. Student
Institute of Traffic and Transportation,
National Chiao Tung University
4F, 118 Sec.1, Chung Hsiao W.Rd. Taipei 10012 Taiwan, ROC
Fax: 886-2-23494953
E-mail: jrliu.tt95g@nctu.edu.tw

Abstract: Line capacity of a railway system is affected by many factors and one of the most important factors is the knock-on delay (delay propagation). The knock-on delay of trains usually caused by route conflicts, prolonged alighting and boarding times of passengers and other exogenous delays in railway operations. To clarify the impacts of these complicated factors on knock-on delay and their interactions, this research develops a comprehensive simulation model to deal with the related problems. A rail section from Cidu to Shulin of Taiwan regional railway is selected for validation of the model. Furthermore, Keelung-Hsinchu section is selected for case study. The result shows that the proposed model can be used in practice for estimating the knock-on delay. The model can be further extended to analyze the impacts on knock-on delay for all kinds of changes in infrastructures, operational situations and controlling strategies.

Key Words: *Simulation Model, Regional Railway, Knock-on Delays, Delay Propagation*

1. INTRODUCTION

In order to cope with the increasing demand, most railway operators are extending their infrastructures to create additional line capacity, but also striving to utilize the existing capacity more efficiently. It is well known that insufficient capacity will result in train delays, especially for train traffic approaching to the capacity. Thus, those factors affect line capacity will eventually influence train delays. For railway systems with heterogeneous traffic and complex station track layouts such as Taiwan regional railway system, a big challenge is to estimate train delay to deal with all factors simultaneously. The issue of train delay estimation in different railway systems is really controversial. Mattsson, L. G (2004) categorized train delays into two types, one is the scheduled delay, which is the difference between scheduled running time and 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 former is caused by some 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 does not only depend 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 plays a key role of line capacity utilization.

In literature, most of researches related to delays were focus on the reliability of train services to capacity utilization. Carey (1999) presented an insightful analysis of the mechanism behind delays. He separated exogenous or primary delays from knock-on, or secondary delays, and noticed that one delayed train can cause delays to other trains over a large area and long periods of time under the high capacity utilization. Even though Carey 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, Vromans et al. (2004) explored the relation between the train flows and average train delays. They proposed a way to increase the reliability by reducing the propagation of delays due to the interdependencies between trains. Moreover, 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, train order and buffer time.

There are 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. The algorithms can be further used to explore random delays. Finally, Yuan and Hansen (2007) found a trade off between efficiently utilizing the capacity of railway network and improving the reliability and punctuality of train operations. They 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.

2. 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. Since simulation models offer the most detailed representation of a railway system, they should be the most appropriate and reasonable way to model the complex processes and the interactions between trains and infrastructures. Therefore, a simulation model is developed to deal with the train delay problems in this research.

2.1 Model Framework

The line capacity of a railway system is influenced by many factors, such as railway condition, operation condition, and control condition, as shown in Figure 1. Since train delays plays a key role in train headways and traffic flow in operation stage, this research focuses on the estimation of knock-on delay, and the result can be the basis for analyzing train reliability. The framework of the proposed simulation model includes four parts, including input information, scheduled timetable, delay disturbance, and the resulting timetable, as shown in Figure 2.

(1) Input Information

Figure 1 shows that the input information consists of railway condition, traffic condition, and control condition. The details of the above mentioned conditions are listed in Table 1.

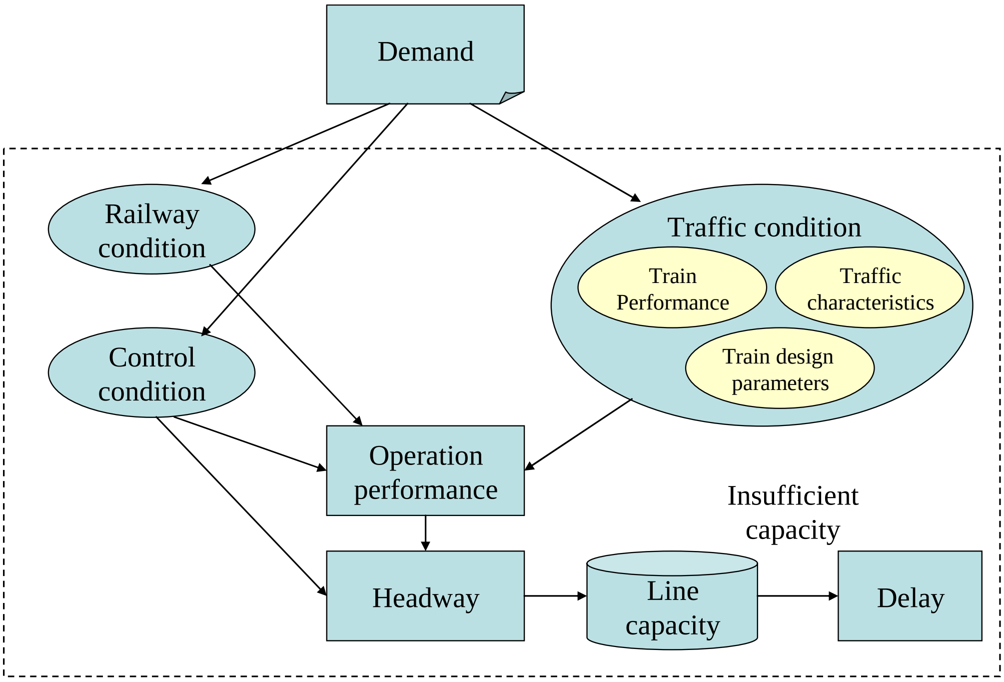


Figure 1 The generic framework of line capacity and delays analysis

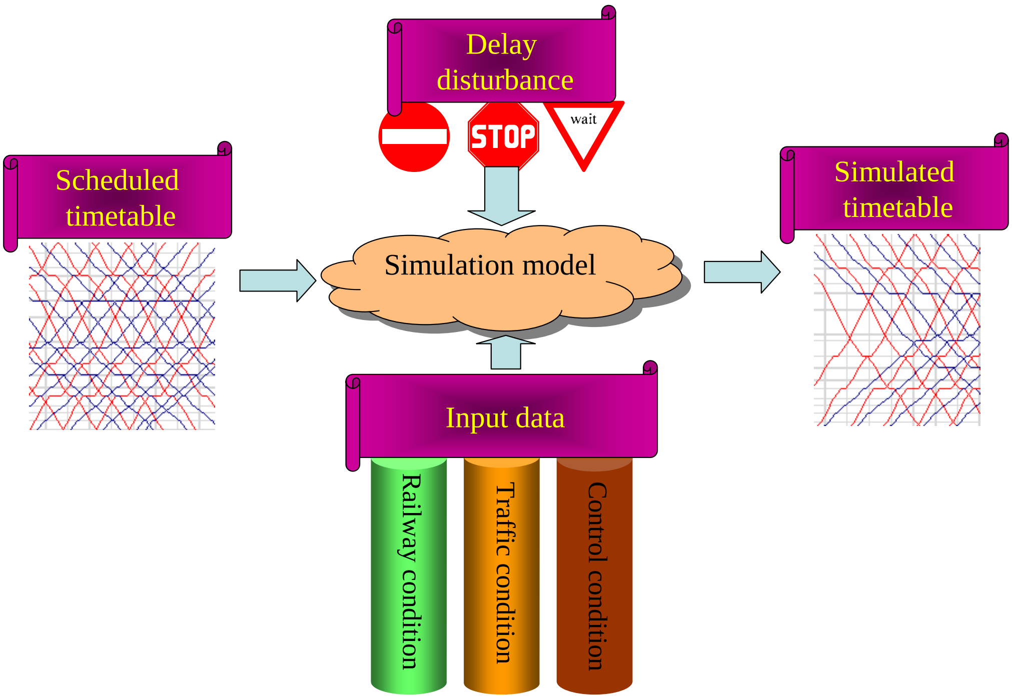


Figure 2 Conceptual framework of the delay simulation model

Table 1 The detail items of input information

Items	Railway Condition	Traffic Condition	Control Condition
Input Parameters	-Railway Line -Station List -Track Layouts of Stations	-The Minimum Dwelling Time -Scheduled Timetable	-Minimum Headway of Same direction -Minimum Headway of Reverse Direction -Section Capacity -Recovery Time

(2) Scheduled Timetable

In order to estimate the delay propagation exactly, the simulation model requires the detail 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 for originate-destination pair into account. The input timetable is an operational schedule without any train conflicts. According to 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) originate-destination stations; (v) dwelling time, etc.

(3) Delay Disturbance

Theoretically, if trains operate as the scheduled timetable, they will not have any delays. In order to deal with the issue of knock-on delay, the simulation model needs the information of the first delay to compute the propagation of the delay. The first delay can be assigned to any locations of the railway line. Table 2 displays the parameters of first delays.

Table 2 The setting rules of delay disturbance

Parameters	Explanation
The location of the first delay	On railway section – clarify the running direction On the track within station – clarify which track
Delay starting time	Track occupied, track unavailable.
Delay release time	The available time of occupied track
Magnitude of the Delay	Delay time = (Delay release Time) – (Delay starting time)

(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 the knock-on delay.

2.2 Assumptions and Limitations

Railways are very complicated systems and none of the railways in the world are exact the same. In this research, the assumptions to be made in the proposed simulation model are given below:

- There are two tracks between adjacent stations and double-track operations are provided (one for each direction).
- Only one railway line is considered
- After investigating the Taiwan regional railway system, there are five typical types of station layouts, which are graphed in Figure 3 ~ Figure 7.
- The display limitation on time-space diagram is 256 trains.
- There are at most two trains present in the same rail section in considering the signal installation of Taiwan regional railway.
- The minimal running time for schedule recovery is set as a ratio of scheduled running time (for example 0.9).

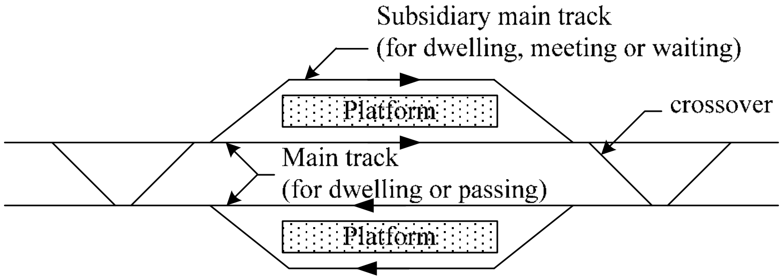


Figure 3 Type I station track layout

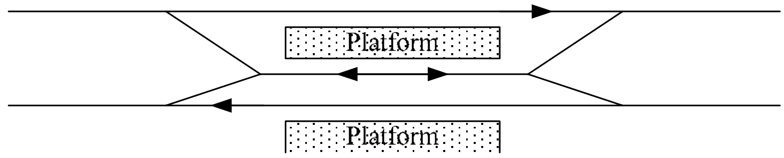


Figure 4 Type II station track layout

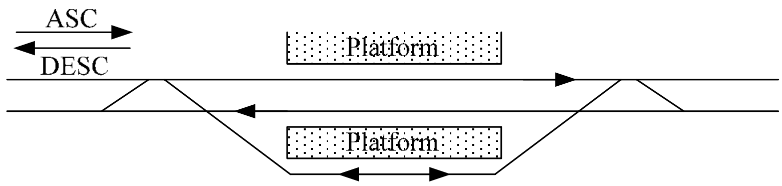


Figure 5 Type III_R station track layout

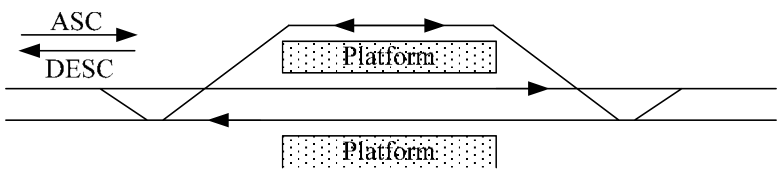


Figure 6 Type III_L station track layout

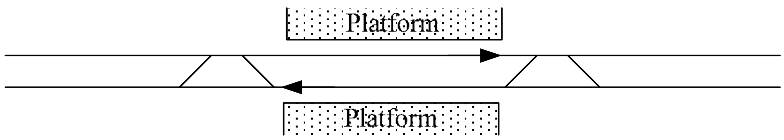


Figure 7 Type IV station track layout

2.3 Simulation Mechanisms

In order to estimate the knock-on delay precisely, the simulation model must consider 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 in the proposed simulation model are summarized below:

- The operating rule on the track between stations is based on First-In-First-Out principle, and it is not allowable for a train to overtake the other.

- 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, then the following train must keep enough headway to enter the same track as shown as Figure 8.

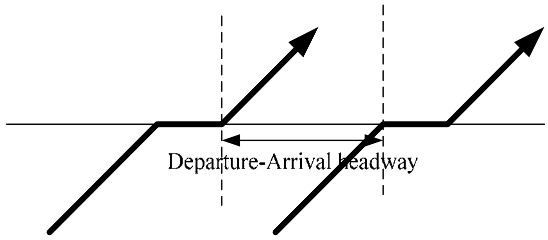


Figure 8 The deaprture-arrival headway of the same direction (same track)

- If two successive trains arrived at different tracks within a station, they must obey the minimal arrival-arrival headway constraint, as shown in Figure 9.

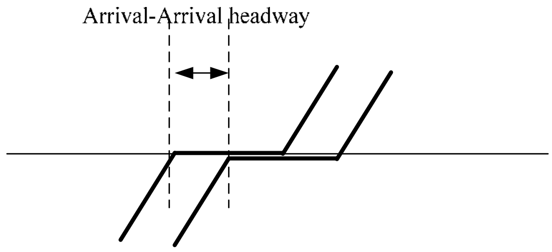


Figure 9 The arrival -arrival headway of the same direction (different tracks)

- If two consecutive trains depart from different tracks within a station, they must obey the minimal deaprture-deaprture headway constraint, as shown in Figure 10.

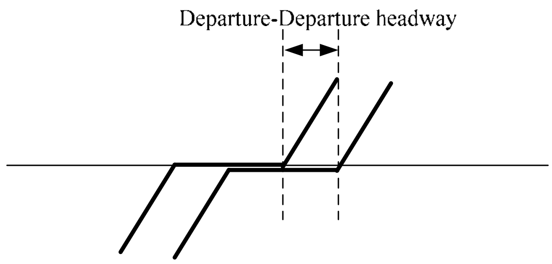
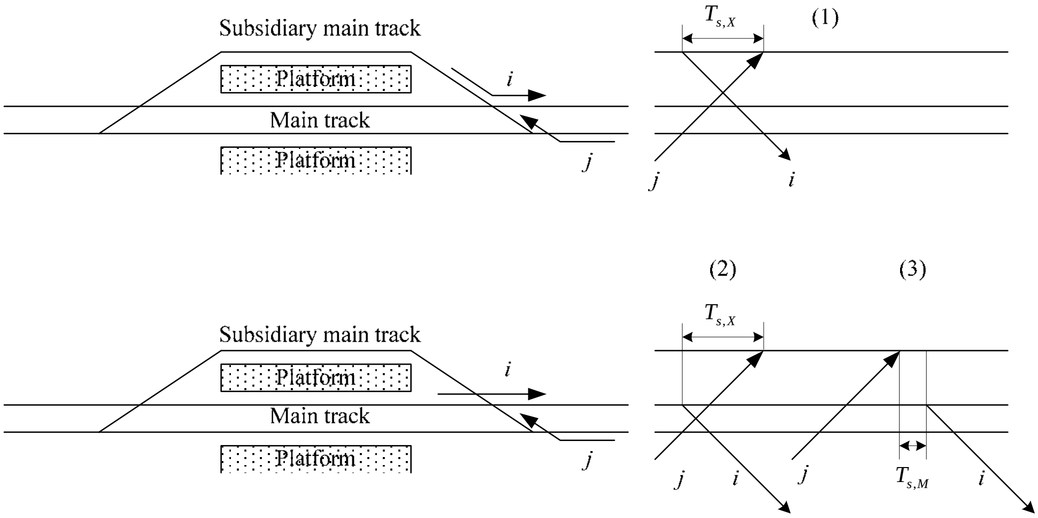


Figure10 The deaprture-deaprture headway of the same direction (different tracks)

- 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 11.

(2) Elimination of train delay

During the simulation, if the following train violates the above operation constraints, then the train cannot run forward and the knock-on delay will occur. The simulation model will advance the system time per second and keep the train waiting on the current location. The simulation will not stop until all delays are eliminated.



Source: Institution of Transportation (2005)

Figure 11 The deaprture-arrival headway of reverse directions on level crossing

(3) The re-scheduling strategy for delayed trains

In order to cope with train delays, traffic controller will employ some strategies to reorganize the schedules in some ways. Some of the re-dispatching or operational strategies, which can be used simultaneously or separately, are introduced in the simulation model, as explained below.

- No action.
- Reducing the dwell times of the delayed trains while satisfying the minimal dwell time constraints. The rescheduled departure time can not be earlier than the planned departure time.
- Reducing the running times of the delayed trains while satisfying the minimal running time constraints.

3. SYSTEM ANALYSIS AND DESIGN

Since the research is focused on the knock-on delay elimination, the simulation model will execute under a reasonable and operational timetable. The main purpose of the simulation model is to evaluate the impacts of the first and knock-on delay on the whole timetable. Besides, the model must set the location where the first delay occurs and adopt appropriate operation strategies. Therefore, the operator could compare the reliability and effects under different strategies.

3.1 Delay Setting

In the interface of the simulation program, the starting time, duration, and the location of the first delay should be set. The location of the first delay can be assigned to either in between stations or within stations. After finishing the settings of the first delay, the users can select different re-dispatching strategies to meet their management requirements. One is to reduce the running time and the other is to decrease the dwell times of trains.

3.2 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 12 to Figure 14.

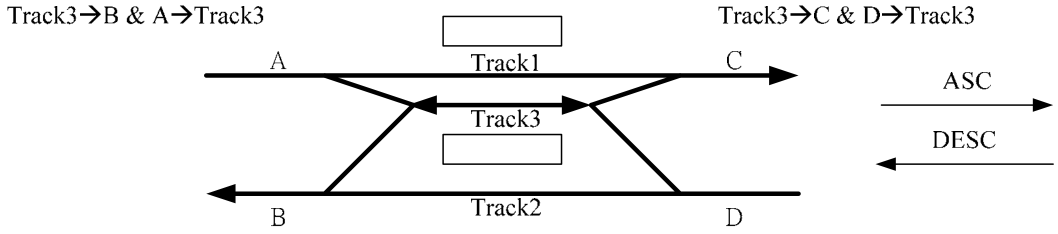


Figure 12 The route conflicts for StationII track layout

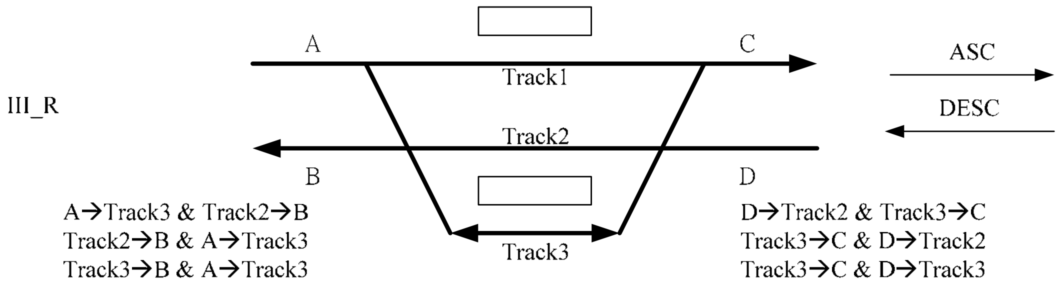


Figure 13 The route conflicts for StationIII_R track layout

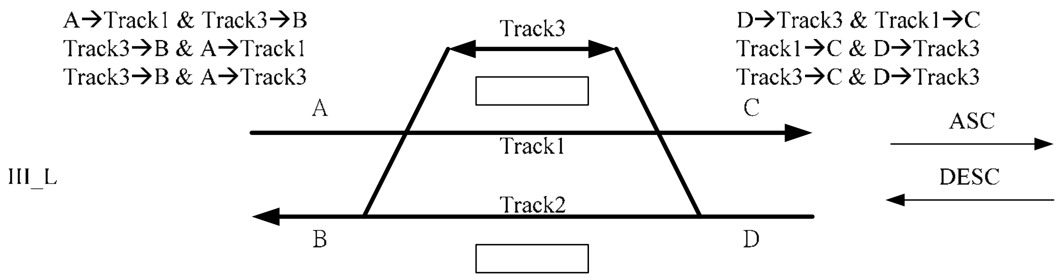


Figure 14 The route conflicts for StationIII_L track layout

3.3 Simulation Procedure

The overall procedure for estimating knock-on delays is outlined in Figure 15. It is an event-based procedure. At the beginning of the simulation, the first event of each train is generated and added to an event list, where events are sorted by time. Next, the program will check whether the event list is empty or not. If it is empty, then the program stops. Otherwise, the program will process the first event. There will have different analysis procedures for each event type, including arrival, passing, and departure. In the next step, the model will detect whether 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 where the train has the next event. The procedure will be repeated until all events are processed.

Although there is commercial software designed for simulations, few are particular for the purpose of railway operations. Thus, the proposed model is computerized by programming language for flexibility and extendibility. The program is developed under .NET Framework for its rich class library and supports. The popular C# programming language for .NET Framework is selected for coding the program.

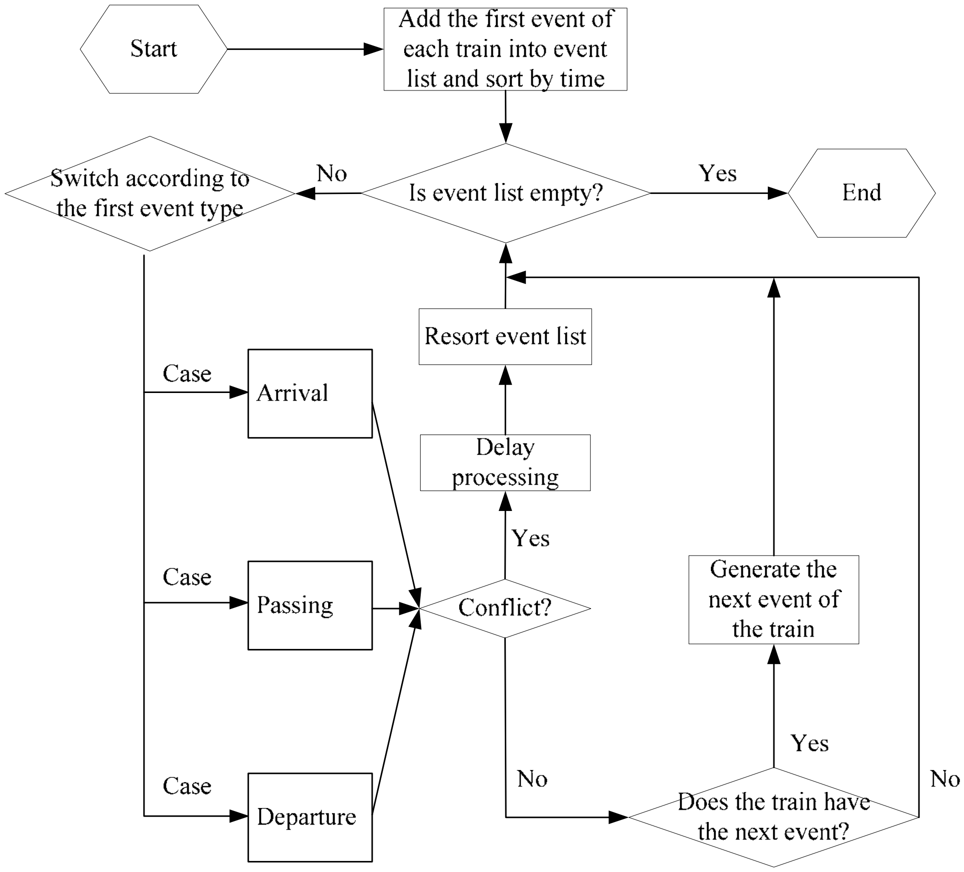


Figure 15 The main procedure for knock-on delay simulation

4. MODEL VALIDATION

In order to test the accuracy of the proposed simulation model, this research retrieves actual trains operating delay and arrival-departure time data on July 29, 2009 from the CTC (Centralized Train Control) database of Taiwan Railways Administration (TRA). Since the traffic flow through Cidu-Shulin section is the heaviest one in TRA system, this section is chosen for validation analysis.

4.1 Data Collection

There are many input data required for the simulation model, including station and mileage (from Cidu to Shulin), 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. In addition to these basic data, actual delay data for a real event was also collected from CTC database, in order to compare with the outputs of the simulation model. The real event selected is a route conflict delay (first delay event) occurred in Wanhua-Taipei section at 10:10 AM in north direction of an intercity train (train No. 42) with a real delay time of 18.2 minutes.

4.2 Validation Results

To validate the accuracy of proposed model, this research compares the actual and estimated delays at the five stations on the north of Taipei station. Since there are 8 trains being affected by the first delay, a total number of 40 train samples are obtained. Figure 16 shows the dispersion of the estimated errors. It is found that the errors fluctuate around the zero axis, and are very close to zero with little exceptions. Figure 17 and Table 3 display the frequency and accumulated percentage of the estimated errors in different ranges. The results demonstrate that the estimated delays are exactly the same as the actual delay for 30% of the samples, and about 90% of the samples are within five-minute range. Since the definition of train delay for TRA is five minutes, it concludes that the proposed model can estimate knock-on delays precisely.

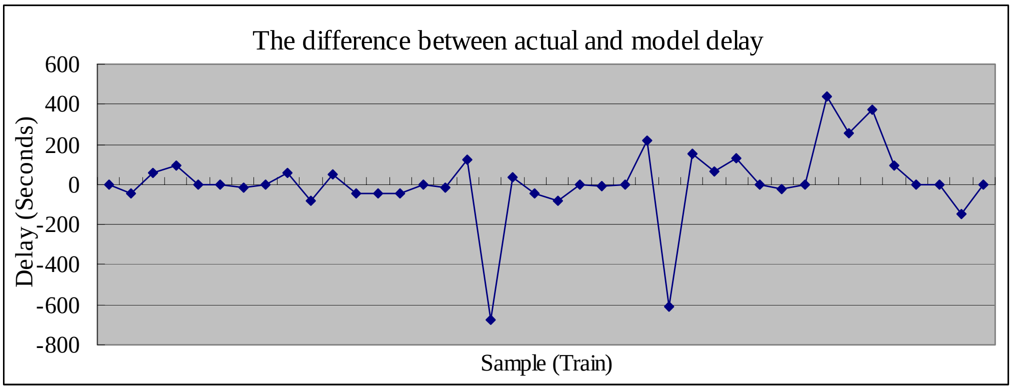


Figure 16 The dispersion of the estimated error at the five stations

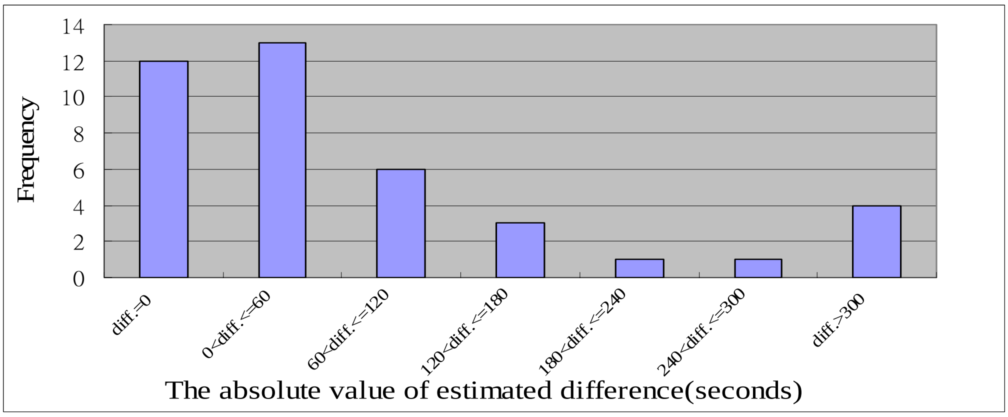


Figure 17 The frequency of the estimated error at the five stations

Table 3 The accumulated percentage and frequency of the estimated difference samples

The absolute value of estimated difference(seconds)	Frequency	%	Accumulated %
diff.=0	12	30.0%	30.0%
0<diff.<=60	13	32.5%	62.5%
60<diff.<=120	6	15.0%	77.5%
120<diff.<=180	3	7.5%	85.0%
180<diff.<=240	1	2.5%	87.5%
240<diff.<=300	1	2.5%	90.0%
diff.>300	4	10.0%	100.0%
	Total = 40	100.0%	

5. CASE STUDY

In the real world, it is impossible to investigate the effects of different timetable recovery strategies on knock-on delay under the same conditions. This is not only because that we are not able to rebuild the situations, but also because field test is very expensive. On the contrary, it would be easier to conduct such kinds of analysis through simulation model. To demonstrate the capacity of proposed simulation model for estimating knock-on train delay, another section of TRA is selected for the case study. Since Keelung to Hsinchu is the overlap section for western-eastern service line, and commuting service of north metropolitan area, it is the busiest section of TRA in terms of service frequencies, stopping patterns, and train types. This section displays complex characteristics and interactions of the TRA system, and is difficult enough to test the proposed simulation model. Therefore, this section is selected for the case study.

5.1 Input Data

As mentioned like as section 4.1, the model should be needed to input all kinds of the TRA data about Keelung-Hsinchu section. There are totally 184 trains of two types of train, i.e., Push-Pull (PP) and Electric Multiple Unit (EMU) in two directions for this case study.

5.2 Simulation Results

Several scenarios are designed to test the model and to estimate knock-on delay. In this case study, it is assumed that a first delay event is occurred in this section at 8:00 AM in downward direction, and the delay duration is from 0 to 3,600 seconds. With the input data, this simulation model can estimate the knock-on delay for different situations.

(1) Effects of first delay durations
Figure 18 and Figure 19 show the train diagrams of scheduled and simulated timetables (the first delay duration is 3,600 seconds), respectively. Comparing these two figures, it can be seen from Figure 19 that there are 12 trains having knock-on delays caused by the event of 3,600 second first delay.

(2) Total knock-on delay

Figure 20 shows the total knock-on delays of all trains at their destination stations. Apparently, the total knock-on delays at all stations are greater than the delays at destination stations only.

(3) The total knock-on delay of each train

Figure 21 shows the total knock-on delays of 12 affected trains at all stations under different first delays. Consequently, the knock-on delay of the commuter train EMU_0006 (the nearest train affected by the first delay event) is the highest among all trains.

(4) The total knock-on delay at all stations

Figure 22 shows the total knock-on delay of the affected trains at all stations under different first delays. It is found that the total knock-on delays at any stations in Songshan–Hsinchu section are greater than those in Keelung–Songshan section. This is because the first delay occurs in Songshan–Taipei section and the knock-on delays propagate at downstream stations.

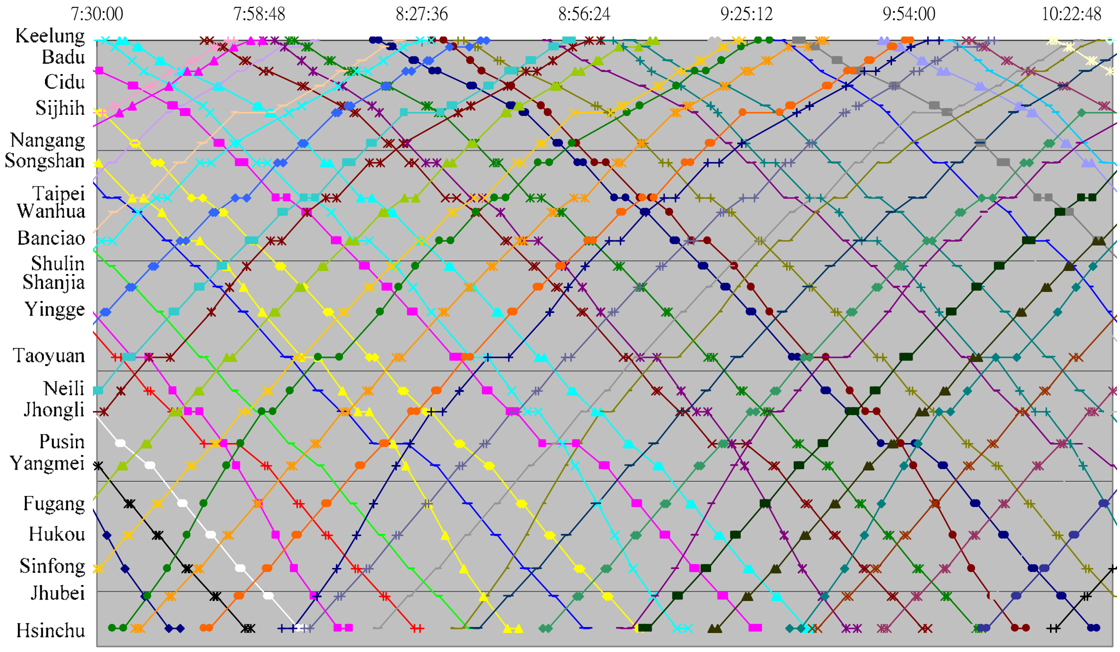


Figure 18 The train diagram of scheduled timetable

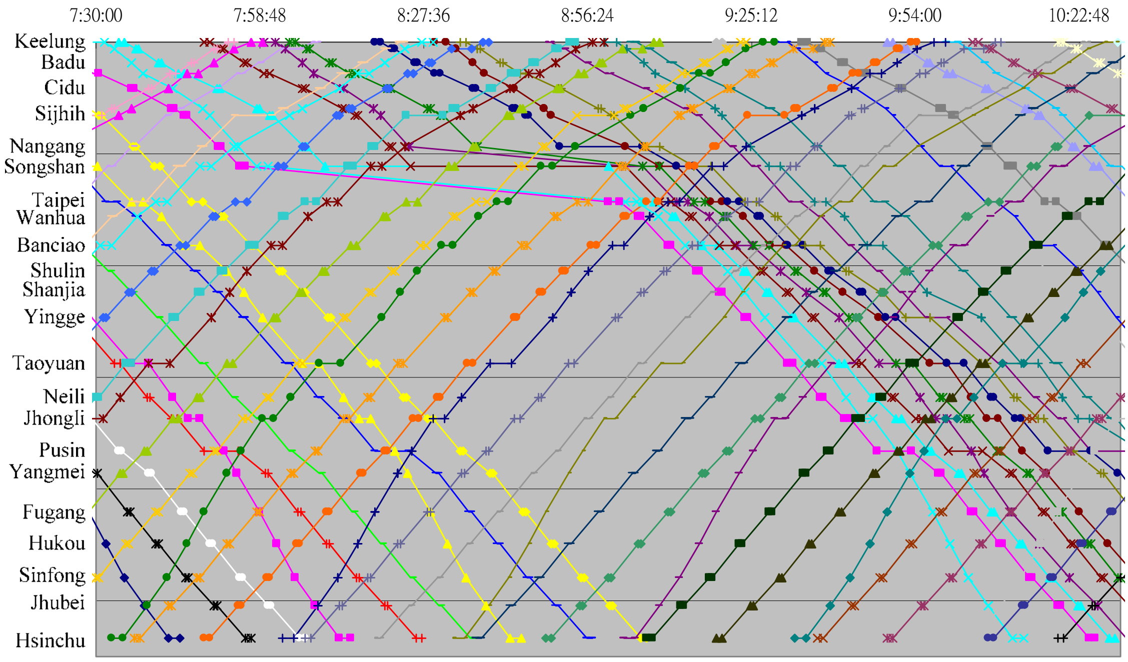


Figure 19 The train diagram of simulated timetable
(The first delay duration is 3,600 seconds)

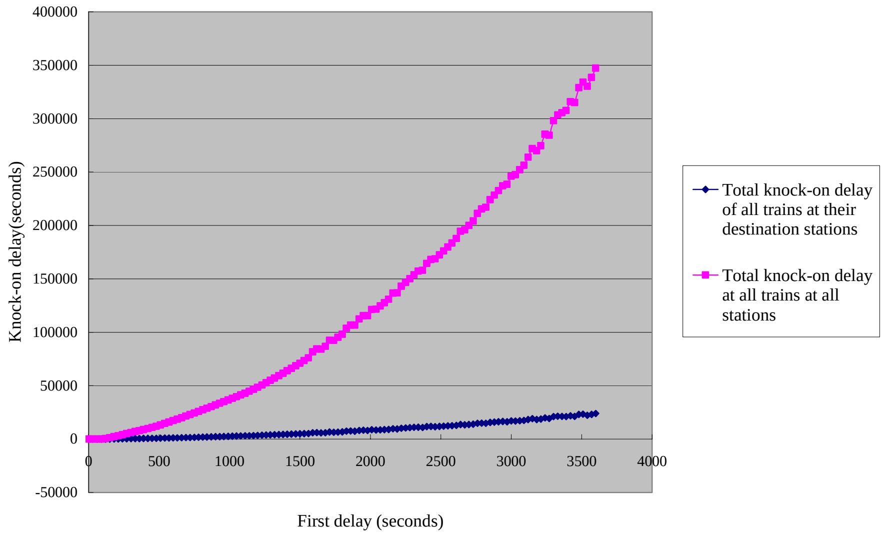


Figure 20 The total knock-on delay of all trains

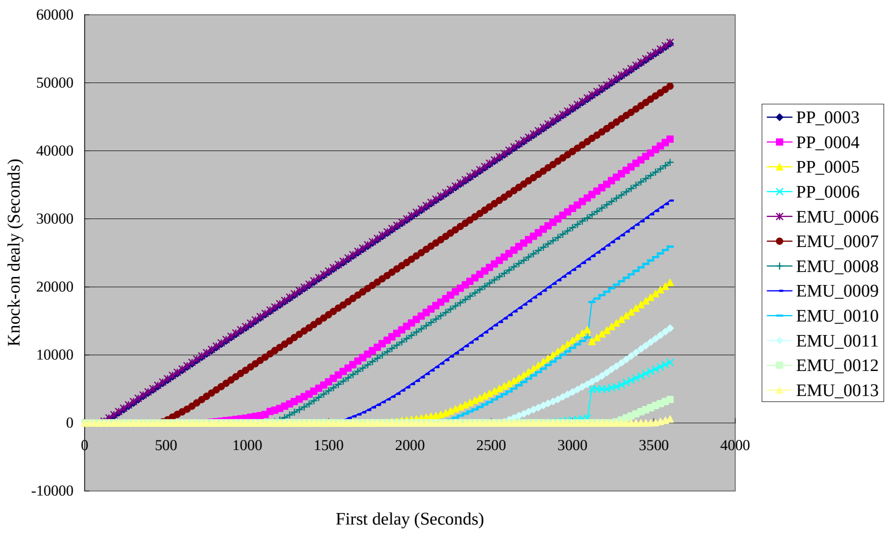


Figure 21 The total knock-on delay of each train

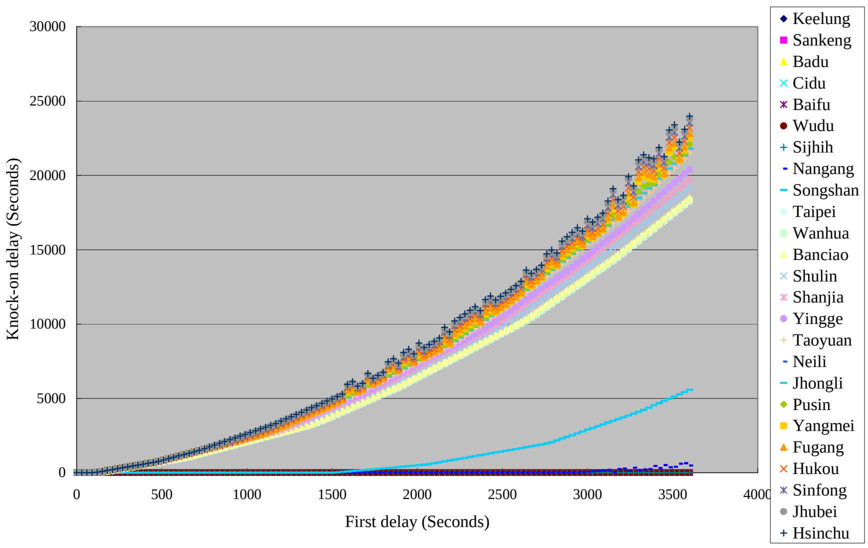


Figure 22 The total knock-on delay of each station

5.3 Analysis of Timetable Recovery Strategies

In order to alleviate the impacts of knock-on delays, the operators always take some strategies to catch up with the scheduled timetable, such as reducing dwell times and decreasing running times. The effects of these strategies are analyzed as follows:

(1) The knock-on delays for different timetable recovery strategies

If dispatchers take some strategies to control train operations, the delays can be reduced. Figure 23 and Figure 24 illustrate the effects of four different strategies. If the reductions in knock-on delays are ranked, it is clear from Figure 24 that the best strategy is reducing the dwell times and running times simultaneously. If only the knock-on delays at the destination stations are considered, Figure 23 shows that the best strategy is reducing dwell times. Therefore some of the affecting factors such as the track selection in each station and train priority could balance the effects of knock-on delay.

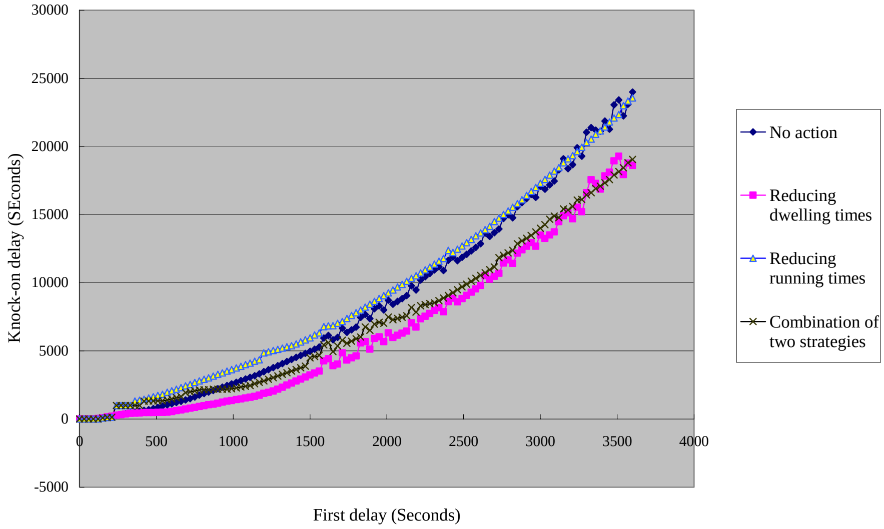


Figure 23 The total knock-on delays at the destination station

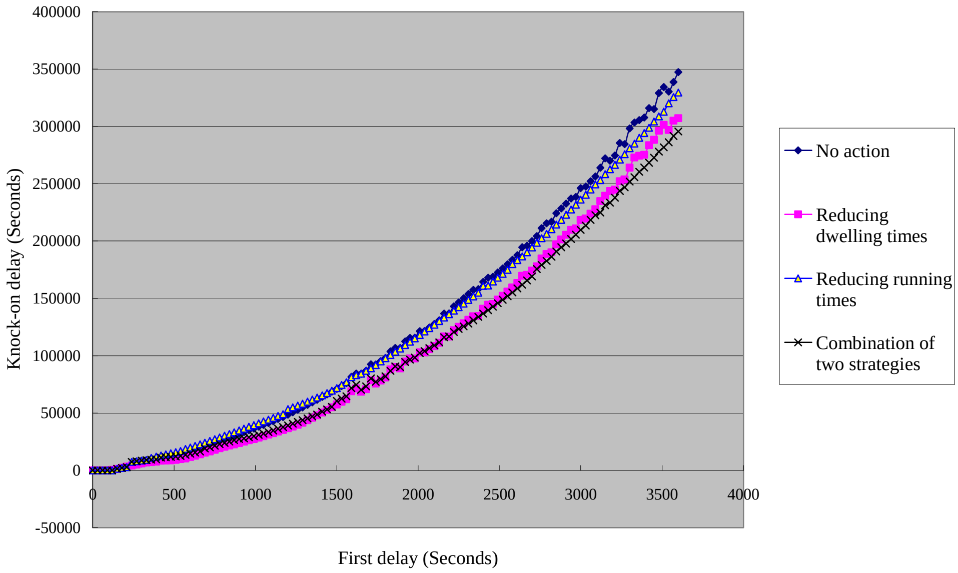


Figure 24 The total knock-on delays at all stations

(2) The knock-on delays at each station for simultaneously reducing dwell and running times

Figure 25 shows the knock-on delays at each station while simultaneously reducing dwell and running times. Apparently, if trains are operated under the above strategies, the total knock-on delay at each station is lower than that without any control. For example, when the above two strategies are applied, the knock-on delay caused by 3,600 second first delay could be reduced from 23,989 seconds to 19,050 seconds at Hsinchu station.

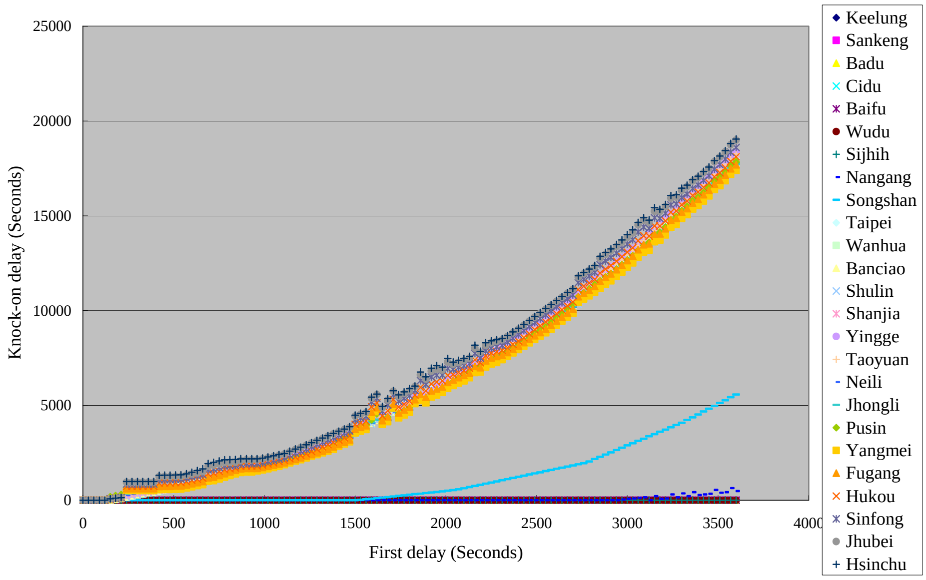


Figure 25 The total knock-on delays at each station

6. CONCLUDING REMARKS

The primary objective of the study is to develop a simulation model for estimating the knock-on delays of Taiwan regional railway system. The proposed model considers railway, operation, and control conditions, as well as timetable recovery strategies that have not been taken into account simultaneously in previous studies. In order to demonstrate the capability of the simulation model, Keelung-Hsinchu section from TRA is selected for the case study. The rail section includes 25 stations, 184 trains of two types of trains and 5 kinds of track layouts at stations, etc. Before the case study, the model was validated by comparing the difference of actual delays and model delays of a real event occurred in TRA.

The results of the case study indicate that the proposed simulation model can be used to reasonably simulate the complex knock-on delay problems. The model produces many useful results, such as the railway scope and the number of trains affected by the first delays and the knock-on delays for different scenarios. It is expected that the model can be further applied to capacity research, infrastructure improvements, and evaluation of operation strategies.

ACKNOWLEDGEMENTS

The authors would like to thank En-Fu CHANG and Sheng-Hsuan HUANG for their cooperation and making some useful suggestions and Jyh-Cherng JONG for his remarks on the application of the model.

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