Improvement of Train Operation and Passenger Flow Simulator for Detailed Estimation of Train Movement on High Frequency Railway Lines

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The aim of this research was to improve the existing train operation and passenger flow simulator for detailed estimation of train movement on high frequency railway lines. For this purpose, a new method was introduced which calculates running time between stations depending on signal aspect, by simulating different signalling situations. A tool was added to calculate energy consumption for each estimated scenario. This paper explains the functions and features of the simulation system and offers an overview of the proposed method for calculating running time between stations. In addition, data was generated for a model high frequency line high, based on a hypothetical suburban commuter line to test the calculation method.

Keywords: simulation system, train operations, train scheduling, train performance curve, energy consumption

1. Introduction

During peak operations such as morning rush hours in urban areas in Japan, the minimum train headway is about 2 minutes and the maximum congestion rate is near 200%. In this situation, delays are likely to propagate. Delay propagation begins when train dwelling time lengthens as passenger concentration increases on a specific train. This results in the train being delayed and generates a longer headway with the train ahead. The late train then becomes more crowded causing greater delay. In turn, this delay raises the likelihood of making the following train vulnerable to signal-induced speed limits, further propagating delay. Accordingly, when evaluating a train operation schedule, these situations need to be simulated in detail. [1]-[6] are examples of previous studies about train operation simulator systems. However, these systems do not take signalling status or passenger behaviour into account. Consequently, existing simulators are unable to provide accurate evaluations which take these factors into account.

This study offers an improvement to the existing train operation and passenger flow simulator which can provide detailed estimation of train movements on high traffic density railway line. In practical terms, a new method was introduced with calculates running time between stations depending on signal aspect, by simulating different signalling situations. A tool was added to calculate energy consumption for each estimated scenario.

2. Train operation and passenger flow simulator

2.1 Functions and characteristics

A train operation and passenger flow simulator was developed to estimate train delays and passenger behaviour selecting which train to board and which train door they use [7]. Using the planned train diagram and passenger OD data obtained from automatic ticket gates, etc., train congestion can be simulated, reproducing what is known as an “expansion phenomenon” where passengers insist on trying to board a delayed train, causing a knock-on effect and delaying later trains. The running time between stations calculated under the existing simulation system are simplified calculations which take into account only, a) departure time from last station, b) the predetermined shortest travel time between stations, c) the predetermined minimum required train headway and d) the planned arrival time. Consequently, when a train is slowed down because of restriction by signalling, it is not taken into account, lowering the accuracy of the estimation.

To solve this problem, first, a function was found to solve this problem and include signal aspect into the calculation. Then, interaction between the signalling system, driving patterns between stations and passenger behaviour was analysed, summarised in Fig.1 and a simulator was developed taking into account this interaction. Estimated values for various elements, such as dwell time, running time and passenger behaviour were programmed differently, while the function can be changed with new functions added in order to tailor the method to specific situations. The functions and characteristics of the simulator can be summarised as follows:

(1) Estimation of passenger behaviour
(a) The system can estimate and output a history for the behaviour of each passenger, such as the train they chose to board, through which door they boarded, transfers, arrival time at the destination station, and so on.
(b) Preference factors influencing choice of train taken, such as fastest route, number of transfers, avoiding congestion, etc.
(2) Estimation of train operations
   (a) The system can calculate the dwell time according to the number of boarding and alighting passengers at each train door. It can reproduce train departure delays due to passenger concentration.
   (b) The system can reproduce the knock-on delay on following trains.
(3) Estimation of running time
   (a) The system can calculate running time between stations based on simulated signal aspects and driving patterns.
   (b) There are two possible calculation methods for driving pattern estimations: a) patterns when driving at fastest speed; b) patterns when driving according to a set time between stations.

Therefore, this study first calculates the driving pattern for Train 2, based on it driving as fast as possible, is estimated up to the next station or to the next stop signal. The calculation result of the driving pattern is represented by the curve (train performance in signal aspect which in turn is used to recalculate following train driving patterns and signal aspects, which are maintained up to date with actual train movements. This process is illustrated in Figs. 2 and 3.

Figure 2 shows the situation at the time of Train 2’s departure from Sta.A. At the time, Train 1 is standing at Sta.B. First, a speed restriction is introduced using signals $L_1$ according to the predicted signal aspects at that time. Secondly, while satisfying the speed restriction conditions $L_2$, the driving pattern for Train 2, based on it driving as fast as possible, is estimated up to the next station or to the next stop signal. The calculation result of the driving pattern is represented by the curve (train performance

![Diagrams of interaction between signalling system, driving patterns, and passenger behaviour](image)

**Fig. 1 Interaction between signalling system, driving patterns and passenger behaviour**

### 2.2 Calculation of running time based on signalling system and driving patterns between stations

#### 2.2.1 Fundamental procedures

Signal aspects vary constantly as trains move across track circuits. In turn, actual train movements are affected by trains departing late from stations. Thus, it is difficult to simulate dynamic changes in signal aspect, which actually reflect real train movement between stations and increase in dwell time caused by passenger behaviour.

Train drivers follow speed restrictions indicated by signal aspects. Therefore, to calculate driving patterns, such as the combination of traction, coasting and breaking, of a certain train between two stations, it is necessary to also calculate the driving pattern of the trains ahead between stations. However, there is no guarantee that such a calculation can be completed in time for the departure of the said train. Signal aspect depends on not only train movements between stations but also on passenger behaviour as described above.

Therefore, this study first calculates the driving patterns of the first train which is unaffected by other trains. Secondly, these driving patterns are used to predict change

![Example of the running time calculation procedure](image)

**Fig. 2 Example of the running time calculation procedure**

![Example of the running time calculation procedure](image)

**Fig. 3 Example of the running time calculation procedure**
curve) in Fig.2, the horizontal axis means the distance and the vertical axis means the speed. The result of the driving pattern of Train 2 at that time, is that it stops just before Signal α.

Passenger behaviour is then estimated and dwell time and departure time of Train 1 at Sta.B are calculated. The driving pattern of Train 1 after leaving Sta.B is then estimated using the predicted values of signal aspects at the newly calculated departure time and predicted signal aspects including Signals α and β. As Train 1 runs through Signal β (time t), the aspects of Signals α and β change. Figure 3 shows the positions of Train 1 and Train 2 at time t. At time t, new speed restriction L1 is estimated using predicted signal aspects and the train performance curve R is then recalculated for Train 2 after time t. Figure 3 shows three examples: the dwell time of Train 1 at Sta.B is (a) the same as planned, (b) increasing slightly and (c) increasing significantly. When the headway of Train 1 and Train 2 is short, Train 2 must slow down like (b) or stop short of Signal α like (c) (stopping between stations).

This study uses a calculation method from the applied driving performance curve generation system called Speedy. Using this calculation method offers several advantages: firstly, the driving performance curves are calculated taking signal aspect into account, furthermore, the method is applicable in practice and calculation time is short.

In addition, since it is possible to recalculate the driving performance curve for the target train (Train 2) using only the changed time of the speed restrictions, it shortens computation time even further.

2.2.2 Approach using set target running times

The driving pattern between stations estimate using the method described in 2.2.1 is based on the assumption that once the signal is opened after the previous train has cleared the section, the fastest driving mode will be adopted. Therefore, if the set running time between stations happens to be also based on fastest running time, then using the basic method described in 2.2.1 will reproduce a driving pattern close to reality.

However, there are quite a number of set running times between stations which have an amount of built-in time margin. Therefore, for these scenarios rather than getting to Sta.B as fast as possible, a different driving pattern is adopted, focused on achieving the expected arrival time. In order to take this type of situation into account another model driving pattern was designed and made as a programme, so that the built-in time margin is consumed by reducing speed.

Figure 4 shows the procedure and two calculation results for one set run time between two stations. The horizontal axis shows time and the vertical axis shows speed. The shaded area on the graph shows the objective distance between stations. Notations in Fig. 4 are as follows.

- \( S_m \): maximum speed of fastest driving pattern
- \( S' \): modified maximum speed after applying this method
- \( t_0 \): time when lower maximum speed begins (is equal to or later than the departure time)

\[ P(t) = \frac{(V(t) \times T(t))}{3600} \]  
\[ W = \frac{1}{3600} \int (P(t) + P_{aux}) dt \]  

**Fig. 4 Principle for modifying train performance curve**

- \( t_n^* \): shortest running time
- \( t_{plan} \): target running time
- \( t_s \): time margin (= \( t_{plan} - t_n^* \))

The starting time of the lower maximum speed \( t_0 \) can be set arbitrarily to choose the degree of freedom. The following assumption is applied:

- When the modified maximum speed is not exceeded either before \( t_s \) or after \( t_s \), then the same driving pattern as in the fundamental method in 2.2.1 is adopted.

Based on this assumption, \( t_s \) is used as input data and the calculation results from the method in 2.2.1 (green dashed line in Fig. 4) are used as a basis for the system to produce the calculation results in this second procedure. In short, since the distance between target stations is identical in both the 2.2.1 method and the present procedure, the surface U in Fig.4 is equivalent to surface T. This relational expression can be used to compute the modified maximum speed \( S' \).

2.3 Calculation of Energy Consumption

A tool for calculating energy consumption during train operation was introduced, using the results of the train running performance between stations from either the procedure in 2.2.1 or in 2.2.2. Energy consumption for each train is calculated using the tractive force and speed of the train for each run and then finding the sum total of the train’s energy consumption over time. The energy consumption obtained in this way only gives energy consumed for acceleration and operation of on-board auxiliary equipment, and leaves out any regenerative power produced during breaking.

Formulae (1) and (2) show the calculation method for converting motional energy to energy consumption. The notations in (1) and (2) are as follows.

- \( w \): value of energy consumption [kWh]
- \( t \): time [sec]
- \( V(t) \): speed of train at time \( t \)
- \( T(t) \): tractive force of train at time \( t \)
- \( P(t) \): momentary electric power [kW]
- \( P_{aux} \): electric power of auxiliary machines [kW].

\[ P(t) = \frac{(V(t) \times T(t))}{3600} \]  
\[ W = \frac{1}{3600} \int (P(t) + P_{aux}) dt \]
3. Calculation results of the simulator

To verify the effectiveness of the developed system, data for a model line was generated and input into the simulation system. The model line and computation time are described in 3.1, the calculation results for the two driving patterns indicated in 2.2.1 and 2.2.2 are described in 3.2, the results of train operation prediction when delay occurs are covered in 3.3 and the calculation results of energy consumption are given in 3.4.

3.1 Outline of the model line and computation time

The model line was based on a high traffic density urban commuter line with 20 stations and about 22 km long. The total number of trains running on the model line was 1,072 per day, the maximum number of trains was 16 to 19 per hour, the total number of passengers was about 193,000 per day.

Figure 5 shows an example display screenshot of the simulation results. Besides the train operation diagram, the system can display the number of passengers on board in each car, the degree of passenger congestion in each car, the number of waiting passengers at each station, the position of trains, signal aspects, and so on.

Furthermore, the time required to compute the model line was 17 minutes 30 seconds using a general-purpose computer system (i3-2100 CPU @ 3.10GHz core and 2GB memory). This computation time is acceptable for practical use.

3.2 Calculation results of the train performance curves based on the two procedures, one for each driving pattern

Figure 6 shows calculation results of train performance curves for journeys between a pair of stations using the two driving patterns associated to the procedures in 2.2.1 and 2.2.2. Figure 6 (a) shows the fastest train performance curve with a running time of 76 seconds. Figure 6 (b) shows the results of the calculation based on a specification of 85 seconds running time using procedure 2.2.2. The maximum speed is lower to achieve the running time of 86 seconds.

3.3 Train operation prediction in the case of delay

In order to simulate high frequency train operation in an urban area, detailed estimation of train operations need to be made when a delay occurs. This section therefore compares three cases using the model line described in 3.1. (A) no delayed train, (B) departure time of a certain train (called Train 1) is delayed at Sta.B for about 10 minutes and (C) Train 1 is delayed at Sta.B for about 10 minutes and following trains are stopped in the preceding stations with suspended or “postponed” departure times. Postponed departure time is a useful way to reduce deceleration and stopping between stations, and in fact is often applied by operators.

Figure 7 shows the calculation results of estimated train headway curves and the timing of signal aspect changes for case (A). The train headway curve represents the trajectories of both the front and tail ends of the train, the horizontal axis is time and the vertical axis is the distance, and the space enclosed by two curves is the train position at each time. In the system several train headway curves are plotted and different times for signal aspect changes are calculated and shown as green, yellow and red in Fig.7.

Figure 8 shows the calculation results of estimated train headway curves when Train1 is delayed for 10 minutes at Sta.B for case (B). Several estimated train headway curves for following trains, i.e. Train 2, Train 3 etc., are flat as they stop between stations. More detailed analysis is shown in Fig.9 which illustrates the estimated train performance curve for Train 3 from Sta.A to Sta.B. Train 3 is the next train but one after Train 1. The speed reaches zero twice between Sta.A and Sta.B as Train 3 is stopped twice in front of a signal.

Figure 10 shows estimated train headway curves when departure is suspended for Train 3, Train 4 and Train 5 following case (C), applied to avoid stopping between stations. Table 1 shows the length of the postponement for each train at Sta.A. Figure 11 shows the train performance curve for Train 3 from Sta.A to Sta.B. Figure 10 and 11 confirm that stopping between stations was prevented.

Table 2 shows the estimated arrival times after delay in Stations B to D for each of the trains listed in Table 1. Delays vary from 4 seconds to 14 seconds and were systematically shorter when departures were postponed. As a result, were the existing system which cannot simulate signal aspect used, results for the arrival time of Train 3 at Sta.B would be the same regardless whether departure
Table 1: Length of postponement

| Train Number | Position when departure postponed | Postponement time (seconds) |
|--------------|-----------------------------------|-----------------------------|
| Train 3      | Sta.A                             | 240                         |
| Train 4      | Sta.A                             | 125                         |
| Train 5      | Sta.A                             | 15                          |

Table 2: Comparison of delays on arrival

| Train Number | Postponement | Arrival delay (seconds) |
|--------------|--------------|-------------------------|
|              |              | Sta.B  | Sta.C  | Sta.D  |
| Train 3      | Without      | 250    | 264    | 248    |
|              | With         | 243    | 257    | 244    |
| Train 4      | Without      | 135    | 150    | 135    |
|              | With         | 127    | 141    | 129    |
| Train 5      | Without      | 32     | 46     | 33     |
|              | With         | 18     | 34     | 26     |

Fig. 7: Train headway curves (no delay)

Fig. 8: Train headway curves (delay at Sta.B)

Fig. 9: Train performance curve of Train 3 from Sta.A to Sta.B for situation shown in Fig. 8

was or not postponed. This is because the arrival time of Train 3 at Sta.B equals the departure time of Train 2 at Sta.B plus the predetermined minimum required train headway in the existing system. However, in actual train operation, the value of the arrival delay of Train 3 closely depends on the positions of preceding trains at each time. In sum, these results confirm that this improved system makes it possible to estimate detailed train delays, which the previous system could not do.

3.4 Energy consumption calculation results

Figure 12 shows the results of energy consumption calculations using data from fastest running time (Fig. 6 (a)) and for when the set running time is 85 seconds (Fig. 6 (b)). During powered traction and acceleration, energy consumption increases proportionally with train speed, during coasting or braking, only auxiliary equipment consumes energy.

Figure 13 shows the results of the energy consumption calculations over one day of operation on the model line described in 3.1 based on this simulator’s calculations. Auxiliary equipment power consumption was set at 0 [kW]. The histogram unit is 30 minutes. The value of energy consumption increases during rush hour in the morning and the evening.
4. Conclusion

This paper investigates a programme which improves a simulation system for gaining insight into on-board congestion, and passenger behaviour. The purpose of this study was to be able to generate more accurate operational plans, by being able to reproduce common small-scale delays in urban areas with dense traffic, in order to determine the impact of small delays on small groups of trains.

This train operation and passenger flow simulation system, makes it possible to evaluate railway operations from various foreseeable perspectives. It is envisaged to employ this simulation system for other applications such as more detailed evaluation of energy consumption and evaluation of various train control systems.

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References

[1] OpenTrack: http://www.opentrack.ch/opentrack/opentrack_e/opentrack_e.html
[2] Ding. Y, “Simulation model and algorithm for train speed regulation in disturbed operating condition,” ZEVrail, Vol.135, No.10, pp.386-391,2011.
[3] Takahashi. I, Ogi. A, and Iwakura. S, “Prediction of knock-on delays of high frequency trains using multi agent simulation,” J-Rail2011, pp.297-300,2011(in Japanese).
[4] Nishiyama. M, and Tomii. N, “Locomotion simulation for series of trains considering difference of drivers’ manoeuvring,” This papers of Technical Meeting on “Transportation and Electric Railway,” IEE Japan, TER-13-049,2013 (in Japanese).
[5] Hiraguri. S, and Kitagawa. H, “Evaluation of Prediction Control Considering Conditions of Signalling System,” RTRI REPORT, Vol.21, No.11, pp.29-34, 2007 (in Japanese).
[6] Fujiwara. M, Kato.M , and Fushiki.T, “Development of Railway Passenger Flow Simulator,” 2013 National convention Record, IEE Japan, Vol.3, pp.123-124, 2013 (in Japanese).
[7] Kunimatsu.T, Hirai.C , and Tomii.N, “Train Timetable Evaluation from the Viewpoints of Passengers by Microsimulation of Train Operation and Passenger Flow,” IEEJ Trans. IA, Vol.130, No.4, pp.459-467, 2010 (in Japanese).

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