Punctuality analysis using a microscopic simulation in which drivers’ behaviour is considered

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Abstract
One of the recent problems in urban railways in Japan is that small delays often happen during rush hours. Because trains are running very densely, even a small delay propagates to succeeding trains and the delay tends to expand. In order to precisely evaluate the robustness of a railway system, a detailed simulation so called microscopic simulation in which components of a railway system are modelled in detail is used. There exist a lot of research papers with regard to the microscopic simulation, but they have not explicitly dealt with the manipulation by the driver, which is yet crucial to obtain a realistic result of simulation. We have developed a microscopic simulator, in which drivers’ manipulation is explicitly expressed. In this paper, we introduce how the simulator is constructed and how the simulator was effective in the analysis we did when a part of the tracks were relocated.

Keywords
Robustness, punctuality analysis, microscopic simulation, track circuit, visualization.

1 Introduction
In urban areas of Japan, there exist big demands for railway transportation. As a matter of fact, in Tokyo area, about 38 million people in total use railways a day in average. In order to satisfy such a big demand, trains are operated very densely. In many railway lines in Tokyo, trains which consist of typically ten or sometimes even 15 cars which are 200m to 300m long are running every two to three minutes per direction per track.

One of the recent problems in urban railways in Japan is that small delays often happen during rush hours. Even a small delay propagates to succeeding trains and the delay tends to expand to the whole railway network. Passengers complain even for delays of several minutes partly because they now use a transfer guidance system and if trains are delayed, they cannot catch the train indicated by the system. Another reason of their complaint is that if a train is delayed, this means transportation capacity is lost and the congestion of the trains increases. Thus, railway companies are now very keen to make the railway system more robust to reduce primary and secondary delays (Yamamura (2013), Yamamura (2014)).

A railway system should be regarded as a combination of various components, such as a timetable, rolling stock, tracks, signalling systems and operation. Passengers are also an important component of a railway system. We have to notice that there exists interaction among these components. For example, a train is compelled to stop outside a
station if the track that the train is planned to use is still occupied by another train. Where the train stops and how to drive the train to the next station after it stops are closely related with an increase/decrease of delays. These are of course, influenced by lengths of the track circuits, aspects of the signals and so on. In order to improve robustness of a railway system, detailed analysis about the function of each component and the interrelationship among them is indispensable.

In order to precisely evaluate robustness of a railway system, a detailed simulation so called microscopic simulation is helpful. In microscopic simulation, components of a railway system above mentioned are modelled in detail. Not only the events of arrival and departure of trains but also the trains’ movement between stations considering signalling systems is also simulated.

One of the key points when we apply the microscopic simulation to dense train traffic is that we need to simulate interaction among the components, especially the interaction between trains which run consecutively because trains’ movement is influenced by the preceding train via the signalling system.

When we calculate the (technically) minimum running times of trains between stations, we use similar microscopic simulation but we consider only one train. In case of punctuality analysis, however, we need to simulate the situations when trains are slightly delayed. This means that we have to simulate a group of trains and consider the interrelationship among trains which run in sequence.

Another important point is that we need to explicitly consider the behaviour of drivers. In some railway lines, so called ATO - Automatic Train Operation - is already used. In those lines, drivers just need to push the button when they want to start the train and they usually do not need to manipulate the notch and the brake. But in many railway lines, trains are still driven by drivers. Drivers try to drive the train exactly with a time prescribed in the timetable. If the train is delayed, they try to drive as fast as possible to restore the delay. Of course, they have to follow the constraints of the speed limits imposed by curves, signal aspects and so on. If we want to simulate train operation as realistically as possible, we should not assume that they drive the trains ideally as we do when we calculate the technically minimum running time. For example, they cannot run exactly at the same speed of the speed limit but the running speed might be a little less than the speed limit. In addition, the margin should be larger for a location with a down gradient because drivers are afraid that the running speed might increase and exceed the speed limit. Thus, in order to get more realistic results of simulation, it is very important to explicitly consider the psychology and behaviour of drivers.

There exist a lot of research results concerning the microscopic simulation model. OpenTrack (OpenTrack), RailSys (RailSys), Luks (Janecek (2010)) are widely used simulation tools and it is shown that microscopic simulation is shown to be an effective tool in timetabling (for example, see Čapek (2012), Ercolani (2014)). But as far as the authors know, none of them explicitly deals with the behaviour of drivers.

In this paper, we introduce a microscopic simulator in which drivers’ behaviour is explicitly considered. Then we show how we used the simulator to analyse the punctuality of trains in Odakyu Railway Company, which is one of the major private railway companies in Japan when some part of their track was relocated and decrease of punctuality was concerned about.
2 Punctuality analysis using micro simulation

2.1 Basic rules of train operation – the route signalling system

Drivers operate trains following the aspects of signals. In Europe, a signalling system so called the speed signalling system is often used. But in Odakyu Electric Railway Company (and in many railway companies in Japan), a signalling system so called the route signalling system is used (more exactly, some functions of the speed signalling system are also incorporated). Unlike the speed signalling system, drivers have to memorize their routes and the signals which correspond to the routes. They also have to memorize all the speed limits imposed by switches, curves, down gradients and so on because these speed limits are not reflected to the aspects of the signals. Signal aspects automatically change reflecting the positions of the preceding train. In Figure 1, the basic idea about the aspects of the signals is shown. If a train exists in a block section, the signal for the section is Red. The aspect of the next signal is Yellow and the aspect of the second next signal is Green (this Figure shows the basic idea and in reality, there are variations depending on the length of the block sections etc.) Aspects of the signals mean the speed limits as shown in Table 1. This makes it possible for a train to stop before the Red signal in any case.

![Figure 1: Basic rule of the aspects of signals](image)

<table>
<thead>
<tr>
<th>Aspect</th>
<th>Speed limit</th>
</tr>
</thead>
<tbody>
<tr>
<td>Red</td>
<td>0 km/h</td>
</tr>
<tr>
<td>Yellow+Yellow</td>
<td>25 km/h</td>
</tr>
<tr>
<td>Yellow</td>
<td>45 km/h</td>
</tr>
<tr>
<td>Yellow+Green</td>
<td>75 km/h</td>
</tr>
<tr>
<td>Green</td>
<td>110 km/h</td>
</tr>
</tbody>
</table>

When a train enters a block section, the train’s running speed must be lower than the speed limit which is specified by the aspect of the corresponding signal. The train driver has to keep the running speed lower than the speed limit until the train goes into the next section; otherwise, a brake by ATP operates. More exactly speaking, if the speed limit of the next block section is higher than that of the current section, the driver is allowed to speed up when the train passes the ground coil (beacon) for the next signal (this restriction will be improved within a couple of years when a new signalling system based on a digital communication is introduced but this is the case at present).

In designing the microscopic simulator, we have to consider these specifications of the signalling system.
2.2 Micro simulation
Simulation is a useful tool to analyse the performance of railway systems (Hansen (2008)). Models of train simulation can be categorized into two groups. One is a macroscopic simulation model. The macroscopic simulation model is a discrete simulation model, in which only arrival and departure events of trains are simulated based on the technically minimum running times and the minimum headways and trains’ movements between stations are not cared about. In the literature, two types of macroscopic simulation models are known: one is an event-driven simulator (Sato (1980)) and the other is a simulation based on the longest path algorithm (Abe(1986)). Macroscopic simulation works very fast but this does not suffice for simulating dense train traffic, because it does not explicitly deal with the signalling systems and does not simulate interactions between trains.

The other category of train traffic simulation model is the microscopic simulation model. In the microscopic simulation model, trains’ velocity and location is continuously calculated based on the formula of dynamics with a very small time unit such as one second or maybe less. In the process of the calculation, not only the performance of trains but conditions such as a gradient of the track, speed limits imposed by curves and signals are also considered. Thus, it is possible to analyse the interaction among trains which run consecutively. Microscopic simulation does not work so fast as the macroscopic simulation but as the processing speed of computers is becoming faster and faster, it is nowadays very widely used to analyse the detailed movement of trains.

2.3 Drivers’ behaviour
Drivers are responsible for safety and riding comfort of passengers on board. They have to be very careful so that they do not make mistakes; otherwise serious accidents may occur. So, drivers should keep their heads cool and take some time to decide their next action. We believe in order to obtain a more realistic and practical results of simulation, it is indispensable to explicitly reflect drivers’ behaviour, which is influenced by their experience and psychological factors. Some of such examples which we think important are:

- Drivers cannot run exactly at the same speed of the speed limit but they drive at the speed which is a little less than the speed limit because they are afraid to exceed the speed limit.
- In case drivers drive a train along a steep down slope, they have to be very careful not to exceed the speed limit. Thus, in case of a steep down slope the margin between the actual running speed and the speed limit should be larger.
- Drivers cannot keep exactly the same speed for a long time but they iterate acceleration and braking. In addition, they insert coasting between acceleration and braking because they are afraid to give a shock to the passengers on board. The time of coasting should be five seconds from acceleration to braking and 10 seconds from braking to acceleration.
- If train a track in a station a train is going to arrive at is still occupied by the preceding train, the train has to stop between stations (because the signal is Red). Then, when the aspect of the signal turns to Yellow (exactly speaking, an aspect other than Red), the train can restart. In order to exactly simulate this situation, we have to consider the behaviour of the driver because it takes some time for him to confirm the change of the aspect by pointing the signal using his fingers (this is mandatory for drivers so that they do not make errors), relax the brake and manipulate the notch. Meanwhile, the conductor gives an announcement to passengers on board to notify the train is going to move. We should consider the times necessary for these operation.
3 Micro simulator in which drivers’ behaviour is considered

3.1 Overall structure of the simulator
We show the class structure together with the cardinality for major classes of our simulator in Figure 2. In Table 2, we show the roles of these classes.

![Class structure and cardinality](image)

<table>
<thead>
<tr>
<th>Class</th>
<th>Role</th>
</tr>
</thead>
<tbody>
<tr>
<td>MainController</td>
<td>Supervise simulation process</td>
</tr>
<tr>
<td>TrainScheduleData</td>
<td>Train schedule data</td>
</tr>
<tr>
<td>TrainCarController</td>
<td>Controls a train</td>
</tr>
<tr>
<td>TrainCar</td>
<td>Controls a movement of a train</td>
</tr>
<tr>
<td>TrainCarManager</td>
<td>Manages trains</td>
</tr>
<tr>
<td>Track Sensor</td>
<td>Sensor for a track</td>
</tr>
<tr>
<td>StationMaster</td>
<td>Controls routes in a station</td>
</tr>
<tr>
<td>TracksController</td>
<td>Manages situations of tracks</td>
</tr>
<tr>
<td>Track</td>
<td>Corresponds to each track</td>
</tr>
<tr>
<td>SignalsController</td>
<td>Controls signals</td>
</tr>
<tr>
<td>Signal</td>
<td>Corresponds to a track</td>
</tr>
<tr>
<td>ViewWindow</td>
<td>Manages GUI</td>
</tr>
</tbody>
</table>

MainController class controls all the components keeping the clock inside. The unit of the clock is 100 ms for the calculation of trains’ movement and one second for the management of track circuits and signal aspects. The reason why we use the different time units is we wanted to have enough precision and simulation speed at the same time.

We prepared MotorMan class as one of the subclass of TrainCarController class (not shown in Figure 2) and this class makes it possible to consider behaviour of drivers as explained in the next section.
3.2 Algorithm to simulate drivers’ behaviour

When we calculate the (technically) minimum running times of a train, we also use the microscopic simulation. The purpose of this simulation is to obtain a performance curve with the minimum running time and in order to get such a result, a technique so called a backtracking algorithm is used. The backtracking algorithm estimates the cause from the result: for example, the algorithm decides where a train has to begin to brake so that the train can stop at the right position in a station observing the speed limits imposed by switches and so on. But in the real world, drivers cannot travel back to the past. They have to make a decision before they know the result. So, we need to devise an algorithm which works in a straightforward manner but still can make it possible for a train to decrease its running speed observing the speed limits and stop at the right position in a station.

We have developed an algorithm as follows:

1. Preparation
   We first calculate $sb_{next}$, which is a location where the train has to begin braking. $sb_{next}$ is calculated from the current location, the current speed of the train and the speed limits which have to be considered by the train until it arrives at the next station. If the train is running along a down slope, we calculate $vt$, which means the speed accelerated by the gravity in a specified time ($margin$) after the train stops acceleration.

2. If a train is accelerating:
   If either Condition 1 or Condition 2 below is satisfied, stop acceleration and begin coasting. If one the Conditions is not satisfied, the train keeps acceleration but chooses an appropriate notch based on the target speed.

   Condition 1: if the current running speed $v$ is close to the speed limit $vl$:
   \[ v > vl - 0.5 - vit \]

   Condition 2: current location $s$ is close to the point where braking is needed.
   \[ s \geq sb_{next} + \frac{v}{3.6} \times tmargin \]

3. If a train is coasting:
   If the current location of the train is the point where braking has to be started, the train applies the brakes. If the running speed is close to the speed limit ($vl + 0.2km/h$), the suppression brakes are applied. If all of Conditions 1, 2 and 3 below are satisfied, then the train begins acceleration.

   Condition 1: the running speed is low:
   \[ v < vl - vmargin - 0.50 - vit \]

   Condition 2: there is an enough distance to $sb_{next}$, which is the point where braking is needed.
   \[ s \geq sb_{next} + \frac{v}{3.6} \times tmargin \]

   Condition 3: A specified time has passed since the train began coasting.

4. If a train is braking:
   If the running speed is lower than the speed limit $v_{target}$, then the train begins coasting. But in case of a down slope, one more condition has to be satisfied: that
is, “the running speed does not exceed the speed limit after the train runs for a specified time.”

\[ v \leq v_{\text{target}} - v_{\text{it}} \]

If the running speed is zero (meaning the train stopped), we judge if the train stops between stations or not. If the location is between stations, the train begins coasting after the signal aspect changes and a specified time has passed.

5. If a train is applying suppression brakes:
   If the current location of the train passes \( sb_{\text{next}} \), then the train applies brakes. If both of the following conditions are satisfied, then the train begins coasting.

   Condition 1: The running speed is low enough.
   \[ v < vl - 0.5 - v_{\text{it}} \times 3 \]

   Condition 2: There is an enough distance to \( sb_{\text{next}} \).
   \[ s \geq sb_{\text{next}} - \frac{v}{3.6} \times t_{\text{margin}} \]

Steps 1-5 are reiterated with an interval of the time unit.

### 3.3 Evaluation of the simulator

We have evaluated how exactly our simulator can simulate the actual train movement. We show one of the results in Figure 3. The red dotted line shows the result obtained when we do not consider the behaviour of drivers and the blue line shows the result obtained when we considered drivers’ behaviour we discussed in 2.3.

We can conclude that the blue line is more reasonable and realistic. For example, coasting of an appropriate time is inserted between acceleration and braking (a). This is also true when aspects of the signals changed while the train is braking and it began to accelerate (b). The train ran smoothly without repeating rapid changes of acceleration and braking even when the aspects of signals changed (c).

![Figure 3: Comparison of the simulation results](image)

In Figure 4, we show results of simulation for multiple trains during morning rush hours. The train graphs in Figure 4 are so called the Chromatic diagram in which the segments are coloured reflecting the delay of the train (Ochiai (2014)). Figure 4(a) shows a result of a simulation in which we do not consider behaviour of drivers, whereas Figure 4(b) shows a result of a simulation in which drivers’ behaviour is considered. Figure 4(c)
is a result in the real world, which shows an average delay of five days. In Figure 4(a), the maximum delay at intermediate stations was 116 seconds and the maximum arrival delay at the terminal station (Shinjuku) was 31 seconds. In Figure 4(b), the maximum delay at intermediate stations was 185 seconds and the maximum delay at the terminal station (Shinjuku) was 98 seconds. Also, by comparison of Figures 4(a) (b) and Figure 4(c), we can observe that our simulator considering drivers’ behaviour succeeds to more exactly simulate the actual situation from the viewpoints of delay propagation and convergence. Differences of delays and headways for each train or each pair of trains are small but these differences are accumulated and there appears a big difference eventually.

4 Application of the simulator

In this section, we describe our experience of punctuality analysis using our simulator when a part of the track in the busiest area was relocated.
4.1 Odakyu Electric Railway Company – Facts and Figures

Odakyu Electric Railway Company (OER, in short) is one of the major private railway companies in Japan. OER operates several railway lines, which connect suburban areas of Tokyo and Shinjuku station, which is located in the centre of Tokyo and known to be the busiest station in the world. The whole length of the tracks is about 120km and there exist 70 stations (see Figure 5). The gauge is narrow (1,057mm) and about 8% (9.5km) of the tracks are quadruple and the remaining parts are double. OER is planning to expand the quadruple tracks but it will take a few more years because it is not an easy job to do such a construction work in populated areas.

OER transports about 721 million passengers a year (about 2 million a day in average). Various kinds of trains are operated: a regular train, several types of express trains and a limited express. The maximum speed of trains is 110km/h. The limited express directly connects Shinjuku and Hakone area, which is known to be one of the most famous resort areas in Japan with a good view of Mt. Fuji.

![Figure 5: Odakyu Electric Railway Company.](image)

There exists a big demand for commuting especially in OER Tokyo area. To fulfil the demands, trains are operated very densely. During the busiest hours, that is, from 7:47 to 8:49, 29 trains are operated upward. In Figure 6, we show a part of the train graph (7:30-9:00) of OER. In Figure 7, we show the basic pattern of the timetable at the most critical part (H, S, D and U are the initials of the stations). The pattern should be considered as a repetition of a combination of one regular train (Regular – depicted in thin black lines) and two express trains (Express 1 and Express 2, respectively – depicted in thick purple lines) with a cycle time of 6 minutes and 40 seconds. This part is the most critical because from Station U to the terminal station, tracks are still double and all the trains have to stop at Station S, where a lot of passengers get on and off and dwell times tend to increase.

4.2 Punctuality target of Odakyu electric railway company

OER is very keen to reduce small delays during rush hours. The target of punctuality is “less than two minutes.” This means that all the trains have to arrive at Shinjuku (the terminal) station with a delay less than two minutes every day. At present, this target is not achieved and OER is making every effort to improve punctuality.
4.3 Relocation work of tracks
As a part of the construction of quadruple tracks, a relocation of tracks was planned. The purpose of this construction work is twofold. One is a preparation for expansion of quadruple tracks. The current tracks on the ground are removed and new tracks are constructed underground. In the near future, one more pair of tracks (upward and downward) will be newly constructed also in the underground. The other purpose is to abolish level crossings, because level crossings are almost all the time shut in urban areas of Tokyo and there are a lot of complaints from drivers of automobiles and pedestrians.

Details of the construction are as follows (see Figure 8):

- New tracks are constructed underground between Yoyogi-Uehara station (Station Y, hereafter) and Umegaoka station (Station U). The length of the new tracks is about 2.2km. Please note the tracks between these two stations are still double even after the relocation is completed, because the old tracks on the ground are removed. As the result, nine level crossings are abolished.

- Three stations (Setagaya-Daita, Shimokitazawa and Higashikitazawa; hereafter, we call Station D, Station S, Station H, respectively) are moved to underground.

- Due to some constraints of construction work, locations of Station S and Station D have to be slightly changed. Station S is moved 80m westward and Station D is moved 20m eastward, which means the distance between these two stations is shortened by 100m and the distance between these two stations becomes only about 750m. Of course, signals of these stations are also moved.

Taking this opportunity, signalling operation at Station H is changed. There used to exist two tracks for upper bound direction at Station H, but one track had been already removed. Thus, switches did not exist anymore at Station H. But for some reason, there still remained an arrival signal and a departure signal there. It was decided to change these signals into block signals. There is a difference in the procedure to manipulate the signals as illustrated in Figure 9. In case of departure/arrival signals, if you want to operate a train which passes the station, you first have to turn the departure signal from Red to Yellow or
Green (exactly speaking, “an aspect other than Red”) and after that you switch the arrival signal from Red to Green (“other than Red”). On the other hand, in case of block signals, there are no such rules and when the preceding train passes through the block section of Station H, the signal for the succeeding passing train automatically turn into Green immediately.

We do not change the timetable in principle, except that the running time of trains between Station U and Station Y was shortened by 50 seconds. This is because while the construction work was being done along the tracks, trains had to decrease their running speed. After the relocation is finished, reduction of running speed is not necessary anymore.

(a) Signalling Operation at Station H – before track relocation

(b) Signalling Operation at Station H – after track relocation

Figure 9: Signalling operation at Station H.
4.4 Estimation of impacts of the track relocation to punctuality

The area where track relocation was planned is the most congested area in OER and trains are running very densely. So, we were strongly concerned about if the relocations of tracks and relevant changes might give a negative influence to punctuality. On the other hand, we expected the change of the signalling operation at Station H is favourable to reduce delays. We picked up the factors which we believe are related with punctuality and decided to analyse their impacts using our microscopic simulator.

4.4.1 Negative factors

(1) Steep gradient around Station S

Because Station S was moved to deep under the ground, trains have to go down a steep gradient when they arrive at Station S. As the result, the braking distance has become longer. In addition, lengths of block sections have become very short. So, for safety reason, signal aspects are slightly changed to limit the running speed of trains and this is disadvantageous to recover delays. We wondered if drivers tend to drive with an enough margin between the running speed and the speed limit due to the steep down gradient.

(2) Distance between Station D and Station S is shortened

The distance between the signals of Station S and Station D becomes shorter. As illustrated in Figure 10(a), before the relocation of tracks, when a train (typically, Express 1) is stopping at Station S (please remember all the trains stop at Station S), the train after the next (typically Regular) can arrive at Station D. But it was proved that after the relocation of tracks, when a train exists at Station S, the train after the next cannot enter Station D because the distance between these stations is shortened. This implies that the headway between these trains may increase. We were very much anxious if this might give a significant influence to punctuality. So, we devised two plans (Plan A and Plan B) and decided to compare these plans using our simulator. Plan A is based on the normal operation of OER and if a train has to stop before it arrives at Station S, the location where the train stops is 50m short of the signal of Station S (Figure 10 (b)). In Plan A, the next train cannot arrive at Station D and has to wait before it arrives at Station D. In Plan B, which is a rather unusual operation in OER, the second train stops 30m short of the signal of Station S. If we adopt Plan B, however, it is possible for the third train to arrive at Station D (Figure 10(c)). We thought that Plan B must be better from the viewpoint of punctuality.

4.4.2 Positive factor

The change of signalling operation at Station H was considered to give a favourable influence to punctuality because express can run more closely to the preceding train as we have already illustrated in Figure 9. Before the headway of two Express trains at Station S tends to become 80 seconds or even 90 seconds although the headway on the timetable is 67 seconds to 72 seconds. We expected the headway becomes 65 seconds by a simple calculation but we wanted to confirm whether this calculation is correct and how this change affects to the whole train traffic.
Figure 10: Train operation at Station S.

4.5 Decision making based on the punctuality analysis by the simulator

We show the results of our punctuality analysis.

(1) Station S

Figure 11 shows the expected delays at the terminal (Shinjuku) station varying the dwell times at Station S, which is the most critical station because all trains stop and the dwell times tend to increase due to congestion as explained before. From this result, we can conclude that Plan A is better than Plan B especially when the dwell times at Station S become bigger than 65 seconds.

This result is a bit different from our first expectation and we analysed the reason using the results shown in Figure 12, which is also one of the outputs of our simulator. If we look at this figure carefully, we can know that the reason why Plan A is better is that although Regular train has to wait before it arrives at Station D, Express 2 can arrive smoothly at Station S after its restarting. The situation is as follows:

- If Express 1 is delayed more than 1 minute 50 seconds, Express 2 is compelled to stop outside Station S.
- In Plan B, a speed limitation of 15 km/h is imposed by the signal of Station S to Express 2, when it restarts.
- Because there is a steep down slope, drivers do not want to operate the notch to speed up in Plan B. They are afraid to exceed the speed limit, because if the running speed is higher than the speed limit, an emergency brake operates and the train stops.
- Hence, it takes 13 seconds more for Express 2 from its restarting to its arrival at Station S if we adopt Plan B.

From this result, we decided to adopt Plan A.

Figure 11: Expectation of delays at the terminal station.

Figure 12: Detailed Comparison of Plan A and Plan B.

(2) Station H
In Figure 13, we show outputs of our simulator with regard to Station H. From these figures, we can estimate that the headways around Station H could be reduced and it is expected that delays are restored. The reason is:
- In Figure 13(a), if the departure of the regular train is delayed, a speed restriction is imposed to the succeeding train (Express 1). Thus, the speed of Express 1 is not high enough and as the result, the interval between Express 1 and Express 2 increases.
- On the other hand, in Figure 13(b), because the signalling operation of Station H was changed, even when the departure of the regular train is delayed, no speed restriction is imposed to Express 1 as long as the delay is less than the certain threshold. Thus, Express 2 can also run as usual.
(3) Dwell times at Station H and Station D
We further analysed how the increase of dwell times will influence the delays at the terminal station. In Figure 13, we show the results of the simulation when the dwell times at Station S is fixed to be 65 seconds and the dwell times of Station H and Station D are changed. From these results, we can estimate that before the track relocation, increases of the dwell time of Station H had a big influence to the delays at the terminal, whereas after the track relocation, increases of the dwell times at Station D will give greater impact to the delays at the terminal.

We paid a lot of attention so that dwell times at Station H do not increase before the track relocation. But from these results, we can estimate that an increase of the dwell time at Station H doesn’t matter as long as the dwell time is less than 60 seconds. Instead, we decided to pay more attention to Station D by deploying more station staff at the platform so that trains can depart more smoothly.

4.6 Punctuality after the track relocation
On March 23, the construction work of the track relocation was successfully completed. We show how the punctuality changed after the relocation. As stated earlier, in OER the target of punctuality is that the delays of the arrival at the terminal during the rush hours are less than two minutes. In Figure 13, we show the number of days when the punctuality
target was achieved month by month. As you see, there is a big difference between 2012 (before the relocation) and 2013 (after the relocation). In almost all months, the number of days when the target was achieved was greater in 2013 than in 2012. In 2012, the number of days when the target was achieved was 127 and in 2013 the number was 144.

![Figure 13: Train performance curves of Plans A and B.](image)

In Figure 14, we show chromatic diagrams when the target cannot be achieved. Figure 14(a) is an average delay of 19 days from 2012 December to 2013 March and Figure 14(b) is an average delay of 32 days from 2013 April to July. As you see, there is a big difference between 2012 and 2013. In 2012, once there is a delay of one minute at Station S, the delay propagates to other trains and expands to 4minutes 37seconds. On the other hand, in 2013, even when the delay at Station S is 2minutes 53seconds, the arrival delay at the terminal is only 2minutes and 53seconds and delays converge before 9 o’clock. As a matter of fact, it takes 1 hour 6minutes 15 seconds from the arrival of the first train of the 29 trains during rush hours till the arrival of the 29th train in 2012 whereas the time is shortened to 1hour 3minutes 39 seconds in 2013.

From these observations, it may well be concluded that the punctuality analysis using our simulator was very successful.
Figure 14: Number of days when the target was achieved.

(a) December 2012 – March 2013.

(b) April 2013 – July 2013.

Figure 15: Chromatic diagram for the days when the target was not achieved.


5 Conclusions

We have introduced a microscopic simulator in which drivers’ psychology and behaviour is considered. Such consideration is necessary in order to obtain realistic simulation results, because trains are driven by drivers and it is not possible for drivers to drive their trains following an ideal assumption. Then we showed the simulator succeeds to produce realistic results by comparing the results and the actual train traffic record data. We showed that the simulator was very useful for punctuality analysis when a part of the tracks were relocated to underground and we were anxious that punctuality will be decreased. We also showed how we used the simulator in the analysis and finally we proved that punctuality was not lost but slightly improved thanks to the preliminary analysis using the simulator.

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References

Ochiai Y., Nishimura J., Tomii N. 2014, “Punctuality analysis by microscopic simulation and visualization of web-based train information system data,” COMPRAIL2014, Rome, Italy.
OpenTrack http://www.opentrack.ch
RailSys http://www.rmcon.de