OPTIMAL ASSIGNMENT OF RAPID TRAIN STOPS
— EXAMPLE OF THE JR NAMBU LINE —

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Abstract
Travel time for train passengers and their convenience are strongly dependent on the assignment of rapid train stops and the timetable of train operation. This paper proposes an algorithm to assign rapid train stops and to determine the associated timetable such that the total travel time for passengers is minimized. Taking the JR Nambu line in Japan as an example, we demonstrate the optimal assignment of rapid train stops and the associated timetable.

Keywords: railway, rapid train, timetable, diagram, transportation, optimization

1. INTRODUCTION
On many railway lines, not only trains that stop at all stations (local trains) but also trains that skip some stations (rapid trains) are operated. Operating rapid trains would improve the convenience of passengers, but that outcome depends on the assignment of rapid train stops, the associated timetable, and the number of incoming and outgoing passengers at stops on the way. This study aims at minimizing the total travel time for passengers, and proposes an algorithm to assign optimal rapid train stops and to determine the associated timetable. The consideration of the minimum interval between train operations and exploitable waiting lanes enhances the speed of finding solutions. Taking the JR Nambu line, a Japanese medium-scaled line with 25 stations, as an example and using actual origin-destination (OD) data, we find the optimal assignment of rapid train stops and determine the associated timetable. Thereby, we analyze the effectiveness of rapid train service.

Conditions for the railway line
C1. No branching line and no confluent lines exist in the railway line.
C2. All intervals between stations are double-tracked.
C3. For all trains, the two stations at the both end of the line are the only terminal stations.

Rapid trains provide rapid service by skipping several stations, whereas local trains stop at all stations.

Conditions for rapid trains
C4. In the railway line we consider, only rapid and local trains are operated, or only local ones are operated; no express, limited express, etc. are operated.
C5. All rapid trains stop at the same designated stations.

The duration between two stations by a rapid train is shorter than that by a local train. Accordingly, a rapid train passes a local train during its operation. We assume following conditions for passing.

Conditions for passing
C6. Each rapid train passes a local train at least once during its operation.
C7. Passing is allowed only at fixed stations.
C8. A rapid train stops at stations where the train does pass a local train.

As stated in C6, in this study a rapid train is assumed to pass a local train at least once during its operation. Although a rapid train without passing any local train is imaginable, such a situation does not make sense in improving transportation service, and hence we do not deal with such rapid trains.

2. PROBLEM
In this paper, we consider a railway line that satisfies the following conditions.

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We designate a station where a rapid train can pass a local train as a possible passing station. On a double-tracked line, a station normally has two platforms, of which one is for inbound trains, and the other is for outbound trains. However to allow passing, a station must have multiple platforms for one direction. A few stations provide such a facility: a waiting lane. Some stations have multiple platforms only for inbound or outbound trains. In such stations, passing for a certain direction is possible but passing for the other direction is impossible.

We designate a station where a rapid train does pass a local train as a passing station. In some railway lines, rapid trains do not stop a passing station. However, in this study, we assume that rapid trains stop at every passing station, which would be convenient for passengers making a transfer there.

Conditions for the timetable are set as shown below.

Conditions for the timetable of train operation
C9. We examine only daytime hours, i.e., 9:00–17:00, which exclude rush hours.
C10. Each station has a timetable repeating the same pattern in each one hour time zone, 9:00–10:00, 10:00–11:00, ..., and 16:00–17:00.
C11. The number of rapid trains operated per hour is at least zero (only local trains), and at most that of local trains.
C12. For local trains, excluding the waiting time at passing stations, the duration of travel between a pair of stations is a given constant.
C13. For each pair of stations, the duration between them by any rapid train is \( m - k \times 1 \) minutes, where \( m \) is the duration between them by a local train without being passed, and where \( k \) is the number of stations being skipped between them.
C14. At each station, the interval between two consecutive trains is at least two minutes.
C15. The stations where rapid trains stop are the same for both inbound and outbound rapid trains.

Excluding rush hours, we discuss just daytime hours, 9:00–17:00, when the number of passengers is stable. The proposed timetable will be the same for every 60 minutes, which is easily understandable for passengers and advance the ease of a traffic control. Consequently, each station has a patterned timetable repeating in each one hour time zone of 9:00–10:00, 10:00–11:00, ..., and 16:00–17:00. The number of rapid trains operated per hour is at least zero (operating only local trains), and at most that of local trains.

On some railway lines, local trains travel between a pair of stations in different durations to adjust the interval between the preceding and subsequent trains. However in this study, the duration of travel by local trains between a pair of stations is identical, excluding the time of waiting at passing stations, which is described later.

The assumption C13 for the duration of travel by rapid trains between two stations is a good approximation for actual railway lines. It has been used in some former studies, and we simply use it here again.

The time interval between two consecutive trains is at least two minutes to prevent train collisions. Accordingly, at any station, no train arrives there less than two minutes after the preceding one arrived there, and none departs there less than two minutes after the preceding one left there.

Conditions for passengers are set as below.

Conditions for passengers
C16. Passengers arrive at a station uniformly during daytime.
C17. Passengers manage themselves to take the earliest train(s) arriving at their destination.

When the number of operated trains is few, some smart passengers would remember the timetable and arrive at a station immediately before departure time. However, in this study, passengers are assumed to come to the station uniformly. Consequently, for example, at a station where no rapid train stops and local trains depart at 10-minute intervals, a passenger waits there five minutes on average. Although some passengers hating transfers might take a local train only, passengers in this study are assumed to make the quickest trip.

Under these conditions listed above and using OD data of passengers, we propose an algorithm to decide where a rapid train stops and to produce the associated timetable. The objective is to minimize the total travel time of passengers. Here we note that the travel time of a passenger is defined as the duration between the time when one arrives at the origin station and that when one arrives at the destination station.

3. PREVIOUS RESEARCHES

Some studies have been conducted to determine the optimal assignment of rapid train stops. Suzuki and Ishizuka (1994) applied dynamic programming to minimize the train ride duration. To improve this method, Futami, et al. (2001) used dynamic programming and genetic algorithms. Although they minimized the train ride duration, they provided no consideration of the waiting time of passengers at the origin station. Matsumura (2003) considered the waiting time at the passing station and that at the origin station. Incorporating the time at passing stations, he assigned rapid train stops and determined the services of rapid and local trains using a genetic algorithm. Katori, et al. (2005) also applied a genetic algorithm to assign rapid train stops. Hiroto (2009) used a local search to assign rapid train stops for five railway lines in Japan.

As stated above, most studies have relied on approximation methods such as genetic algorithms and local searches. However in this study, we will find an optimal solution by examining every possible pattern of rapid train stops. Although that is a feature of our study, examining every possible pattern by simple enumeration requires much CPU time.
Accordingly, we set up a few assumptions to speed up the assignment of rapid train stops and determine the timetable. The details are explained in Section 5. Experiments are carried out for the East Japan Railway Company (JR) Nambu line. Earlier reports in the literature (Matsumura, 2003) and (Hirotu, 2009) described the assignment of rapid train stops for this line. These are mentioned in the next section.

4. JR NAMBU LINE

Our research is performed for the JR Nambu line as an example. Some reasons why we draw attention to this line include the following: (i) because no rapid train service is currently given there, this line is an interesting target to evaluate the effectiveness of operating rapid trains; (ii) because a couple of preceding studies conducted similar calculations for this line, our results could be compared with them.

The JR Nambu line connecting Kawasaki Station (Kanagawa Prefecture) and Tachikawa Station (Tokyo Metropolis), is 35.5 km long. It links 25 stations including the terminal stations. The average distance between two adjacent stations is 1.42 km and that of passenger travel is 9.1 km. It takes about 53 minutes by a local train between the two terminal stations, Kawasaki and Tachikawa.

Figure 1 portrays the route map and possible passing stations of the Nambu line. Stations A and Y in Fig. 1 are the terminal stations, Kawasaki and Tachikawa, respectively. Outbound trains go from left to right on the map. The stations indicated by arrow(s) are possible passing stations; a rapid train in the direction of the arrow can pass a local train in the same direction. As the figure shows, only Stations H (Musashi-Nakahara), J (Musashi-Mizonokuchi), N (Noborito), and R (Inagi-Naganuma) allow passing. Among these, Station J allows passing only for outbound trains and Station N only for inbound trains.

The station with the most boarding passengers is A (Kawasaki) with 187,147 on average per day, followed by Y (Tachikawa) with 158,068 on average per day; the fewest passengers board at K (Tsudayama) with 3,635 on average per day (East Japan Railway Company, 2009).

As a few cases among railway lines in Tokyo area, the Nambu line currently provides no rapid train service. It runs six local trains per hour during daytime. However, the Nambu line operated rapid trains during 1969–1979, and it will resume in March 2011 for the first time in 32 years.

Previous studies (Matsumura, 2003) and (Hirotu, 2009) have examined assigning rapid train stops on the Nambu line. These two papers reported the results in which Station N is assigned as the passing station for both inbound and outbound trains; these are unrealistic because Station N allows only inbound trains to pass. In our algorithm, we remove this shortcoming, considering actual situations of possible passing stations. Thus the passing stations can be allocated independently in both directions.

5. ALGORITHM

Using the proposed algorithm, we determine an optimal pattern of rapid train stops and the associated timetable making use of enumeration, which is different from the methods used in previous studies. Since naive enumeration takes much CPU time, we set up a few assumptions to speed up the search process for finding an optimal pattern of rapid train stops and the associated timetable. In doing so, we take the actual allocation of waiting lanes on the Nambu line into consideration to keep solutions practicable.

We introduce the following assumption first. It is already assumed in C6 that a rapid train passes a local train at least once during its operation. However our preliminary experiments indicated that, in the Nambu line, passing local trains more than once would be impractical. Accordingly, in our experiment, we set up the following additional condition.

C18. Each rapid train passes a local train exactly once during its operation.

In addition, we concentrate on finding solutions satisfying the following natural condition.

C19. At the terminal stations, the order of departure of local and rapid trains is equitable.

Condition 19 must be clarified. For example, when two rapid trains and four local ones per hour depart from a terminal station, the order of “rapid, rapid, local, local, local” might be conceivable. However it is not definitely the best service for passengers. Other sequences such as “local, local, rapid, local, local, rapid” is desirable. This idea is included in C19 above. In this study, we assume that each station has a timetable repeating the same pattern in each one hour time zone (C10). Let $L$ be the number of local trains and $R$ be that of rapid trains departing in an hour. For simplicity of creating timetable, we will consider only $(L, R)$ such that not merely $L \geq R$ (C11) but also $L \mod R \equiv 0$. In this case, C19 is satisfied by the order of trains at the terminal stations such that: the first $L/R - 1$ trains in an hour are local ones and the next is a rapid one; and that this pattern is repeated in the rest of the hour.

Then we add, to prevent collision, an assumption on the operation at the passing station. We might assume that a lo-

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**Fig. 1 JR Nambu line route map and possible passing stations**
A local train must arrive at the passing station more or equal to two minutes earlier before a rapid one arrives there, and must depart there more than or equal to two minutes later the rapid train departed there \((C14)\). Here we strengthen this assumption as follows.

\(C20\). A local train must arrive at the passing station just two minutes earlier than a rapid train arrived there, and must leave there just two minutes after the rapid train departed there.

Although allowing longer waiting times of a local train at the passing station might reduce the total travel time of passengers, it would make the passengers on the local train feel inconvenience. Therefore, we have decided to stick to \(C20\). Consequently, the passengers on a local train passed by a rapid one will travel four minutes longer than that on a local train not passed by.

By \(C9\), \(C10\) and \(C16\), without loss of generality, one might set a timetable so that local trains depart the terminal stations on \(9:00, 10:00, \ldots, 16:00\).

Our algorithm determining stations where rapid train stops and the associated timetable are presented in Table 1. To explain the proposed algorithm more specific, the parameters in Table 1 are not generalized but fixed for the Nambu line.

First, we select a pair of passing stations, one for inbound and the other for outbound. There are \(3 \times 3 = 9\) possible pairs of passing stations in Nambu line (Stations H, N and R for inbound, Stations H, J and R for outbound; see Fig. 1). For each pair of passing stations, the following procedure is executed.

Next, we fix the number of local trains \(L\) and that of rapid ones \(R\) per hour under the conditions that \(4 \leq L + R \leq 10\), \(L \geq R\) and \(L \mod R = 0\). The reason why we set the upper and lower bounds for \(L + R\) to 4 and 10, respectively, is that in the Nambu line trains are currently operated with \((L, R) = (6, 0)\) in daytime. The number of possible pairs of \((L, R)\) is 22, shown in Table 2.

At this stage, the order of leaving local and rapid trains at the terminal stations has been fixed. Next, we determine the timetable of local trains. Although we aim at minimizing the total travel time, we simultaneously wish to improve the convenience of passengers at stations where no rapid train stops. To that purpose, we adopt a new condition below.

\(C21\). The timetable is adjusted so that, at stations where no rapid train stops, local trains leave there at intervals as uniform as possible.

To simplify the explanation of \(C21\), let \((L, R)\) be \((3, 3)\) for example. By \(C19\), at the both terminal stations, local and rapid trains depart alternately. In the most uniform pattern, local trains should depart there at \(00, 20, 40\) of each time zone. Generally, in the case of \(L = R\), the depart time of local trains at the terminal stations is \(00, 60/L, 2 \times 60/L, \ldots, (L - 1) \times 60/L\)". Then local trains depart at 60/\(L\)-minute intervals at every station, which are ideal.

However for the case of \(L > R\), the uniformity of intervals for local trains is lost at stations after the passing station, even if that uniformity is held at the terminal stations. The reason is that some local trains are passed by a rapid train and the others are not. Assume that \((L, R)\) is \((6, 1)\) with local trains departing the terminal station at \(00, 10, 20, 30, 40, 50\) and a rapid train departs there at 25. At the passing station, the rapid train passes the local train that departed the terminal station at 20. Then let us examine the timetable of a station such that: (1) no rapid train stops; (2) the station located after the passing station; (3) \(m\) minutes distant from the terminal station by a local train without being passed. The timetable of local trains there becomes \("00 + m, 10 + m, 20 + m, 30 + m, 40 + m, 50 + m","\) and the uniformity of intervals between local trains is lost. Therefore we soften the loss of uniformity, when \(L > R\), by adding two minutes for the both preceding and subsequent trains of the passed local trains. Accordingly, the timetable is modified into \("00 + m, 10 + m + 2, 20 + m + 2, 30 + m + 2, 40 + m, 50 + m","\) in which uniformity is rather recovered.

At this point, we have fixed the timetables of local trains for each station. Then we enumerate patterns of rapid train stops. The number of patterns is \(2^n - 4\) for the prescribed pair of passing stations, where \(n\) is the number of stations in

**Table 1** Proposed algorithm

\[
\text{forall pair of passing stations in the set of possible pairs of passing stations}
\]

\[
\text{forall } (L, R) \text{ in } 4 \leq L + R \leq 10, L \geq R, L \mod R = 0
\]

\[
\text{fix timetable of local trains;}
\]

\[
\text{forall } \text{pattern of rapid train stops in the set of patterns that do not cause collision}
\]

\[
\text{fix timetable of rapid trains;}
\]

\[
\text{calculate total travel time for passengers;}
\]

\[
\text{endforall}
\]

\[
\text{endforall}
\]

\[
\text{output the pattern of minimum travel time and the associated timetable;}
\]

**Table 2** Possible pairs of \((L, R)\)

<table>
<thead>
<tr>
<th>(L + R)</th>
<th>((L, R))</th>
</tr>
</thead>
<tbody>
<tr>
<td>4</td>
<td>(4, 0), (3, 1), (2, 2)</td>
</tr>
<tr>
<td>5</td>
<td>(5, 0), (4, 1)</td>
</tr>
<tr>
<td>6</td>
<td>(6, 0), (5, 1), (4, 2), (3, 3)</td>
</tr>
<tr>
<td>7</td>
<td>(7, 0), (6, 1)</td>
</tr>
<tr>
<td>8</td>
<td>(8, 0), (7, 1), (6, 2), (4, 4)</td>
</tr>
<tr>
<td>9</td>
<td>(9, 0), (8, 1), (6, 3)</td>
</tr>
<tr>
<td>10</td>
<td>(10, 0), (9, 1), (8, 2), (5, 5)</td>
</tr>
</tbody>
</table>
the railway line, because by C8 and C15 rapid trains must stop at the both terminal stations and the passing stations for inbound and outbound trains; if we chose the identical passing station for inbound and outbound trains, then the number is replaced with $2^n - 3$. Hence, the naïve enumeration is difficult for large $n$. Instead, we can speed up the process of enumerating patterns of rapid train stops as follows.

Again $(L, R) = (3, 3)$ is considered as an example here. Local trains depart from the terminal stations at "00, 20, 40." Then the first rapid train should depart there between 02 and 18 inclusive, to avoid collision. Let $m$ be the duration from the terminal station to the passing station by a local train. Consider a pattern of rapid train stops with $k$ skipped stations between the terminal and passing stations. In such a case, a rapid train takes $m - k$ minutes from the terminal station to the passing one (C13). From C19, a local train must arrive at the passing station just two minutes earlier before a rapid arrives there. Therefore, the time $t$ of departure of rapid train from the terminal station must satisfy $t + m - k = m + 2$ and $2 \leq t \leq 18$. If $k \leq 16$, we can create a timetable satisfying all conditions by letting $t$ be $k + 2$. However, if $k > 16$, which corresponds to patterns such that the number of rapid train stops is very small, a rapid train will collide with the preceding local train if the rapid train departs from the terminal station much behind the local train. Consequently, from the above discussion, if a collision is expected for some $k$, examining patterns with larger $k$ does not make sense.

These considerations speed up the process of enumerating patterns of rapid train stops. For $(L, R) = (8, 2)$ and nine patterns of a pair of passing stations in the Nambu line, there are $23,068,672$ patterns of rapid train stops if restriction above is not applied. The restriction reduces that number to $4,736,766$; around one-fifth.

For each enumerated pattern of rapid train stops, we calculate the total travel duration of passengers. The pattern of rapid train stops and the associated timetable that minimizes the total travel duration is output as an optimal solution.

### 6. COMPUTATIONAL EXPERIMENTS

For numerical experiments, we used data of passengers from Transportation Census of Urban Cities (2005), extracted for the JR Nambu line and for the times of 9:00–17:00. Four different datasets are available, and for each dataset we performed experiments. Here, because of limited space, we show only the results for $(L, R) = (6, 0), (5, 1), (4, 2), (8, 0), (6, 2), (4, 4)$.

Table 3 and 4 display the results of experiments for the case of $L + R = 6$ and $L + R = 8$, respectively. In the tables below, "#passengers" stands for the number of passengers per hour, "time" stands for the average duration of travel per passenger (minute), and "→" and "←" are the optimal passing stations for outbound and inbound trains, respectively. Figures 2, 3 and 4 represents the optimal rapid train stops and passing stations for each dataset with

### Table 3 Results for $L + R = 6$

<table>
<thead>
<tr>
<th>data no.</th>
<th>#passengers</th>
<th>$(L, R)$</th>
<th>time (m)</th>
<th>→</th>
</tr>
</thead>
<tbody>
<tr>
<td>1</td>
<td>7,700</td>
<td>(6, 0)</td>
<td>18.33</td>
<td>N</td>
</tr>
<tr>
<td></td>
<td></td>
<td>(5, 1)</td>
<td>18.50</td>
<td>J</td>
</tr>
<tr>
<td></td>
<td></td>
<td>(4, 2)</td>
<td>18.65</td>
<td>J</td>
</tr>
<tr>
<td>2</td>
<td>10,931</td>
<td>(6, 0)</td>
<td>19.12</td>
<td>R</td>
</tr>
<tr>
<td></td>
<td></td>
<td>(5, 1)</td>
<td>19.40</td>
<td>R</td>
</tr>
<tr>
<td></td>
<td></td>
<td>(4, 2)</td>
<td>19.55</td>
<td>R</td>
</tr>
<tr>
<td>3</td>
<td>13,098</td>
<td>(6, 0)</td>
<td>16.87</td>
<td>N</td>
</tr>
<tr>
<td></td>
<td></td>
<td>(5, 1)</td>
<td>17.17</td>
<td>R</td>
</tr>
<tr>
<td></td>
<td></td>
<td>(4, 2)</td>
<td>17.47</td>
<td>R</td>
</tr>
<tr>
<td>4</td>
<td>16,329</td>
<td>(6, 0)</td>
<td>17.92</td>
<td>R</td>
</tr>
<tr>
<td></td>
<td></td>
<td>(5, 1)</td>
<td>18.19</td>
<td>R</td>
</tr>
<tr>
<td></td>
<td></td>
<td>(4, 2)</td>
<td>18.45</td>
<td>R</td>
</tr>
</tbody>
</table>

### Table 4 Results for $L + R = 8$

<table>
<thead>
<tr>
<th>data no.</th>
<th>#passengers</th>
<th>$(L, R)$</th>
<th>time (m)</th>
<th>→</th>
</tr>
</thead>
<tbody>
<tr>
<td>1</td>
<td>7,700</td>
<td>(8, 0)</td>
<td>17.08</td>
<td>N</td>
</tr>
<tr>
<td></td>
<td></td>
<td>(6, 2)</td>
<td>17.04</td>
<td>J</td>
</tr>
<tr>
<td></td>
<td></td>
<td>(4, 4)</td>
<td>16.90</td>
<td>J</td>
</tr>
<tr>
<td>2</td>
<td>10,931</td>
<td>(8, 0)</td>
<td>17.94</td>
<td>N</td>
</tr>
<tr>
<td></td>
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<td>(6, 2)</td>
<td>17.96</td>
<td>R</td>
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<td>17.88</td>
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</tr>
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<td>3</td>
<td>13,098</td>
<td>(8, 0)</td>
<td>15.62</td>
<td>R</td>
</tr>
<tr>
<td></td>
<td></td>
<td>(6, 2)</td>
<td>15.80</td>
<td>R</td>
</tr>
<tr>
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<td>15.97</td>
<td>R</td>
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<tr>
<td>4</td>
<td>16,329</td>
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<td>(6, 2)</td>
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<td>R</td>
</tr>
<tr>
<td></td>
<td></td>
<td>(4, 4)</td>
<td>16.90</td>
<td>R</td>
</tr>
</tbody>
</table>

**Fig. 2 Optimal rapid train stops and passing stations for $(L, R) = (5, 1), (4, 2)$**

$(L, R) = (5, 1), (4, 2), (L, R) = (6, 2)$ and $(L, R) = (4, 4)$, respectively.

We infer the following points from the experiments:

- Station R is important for a passing station, whereas Station H is of small importance as a passing station.
- Although the optimal pattern of rapid train stops depends on the OD data used, it does not change much.
- For $L + R = 6$, rapid train service does not improve the total travel duration of passengers.
- For $L + R = 8$, the experiments for $(L, R) = (6, 2)$ and $(L, R) = (4, 4)$ indicate probable improvement of the total travel duration of passengers, depending on the OD data.
Table 5 shows the comparison between the previous study by Hiroto (2009) and the obtained results. (Here we note that although Matsumura (2003) dealt with the Nambu line, his results cannot be compared with ours because the total travel duration of passengers was not reported in his results.) The OD data used in Hiroto (2009) is Data 4 of 16,329 passengers, and thus we compare our results using Data 4 here. In his study, the pair of passing stations is fixed to (N, N) a priori, which is different from our study. In this paper, a pair of passing stations is variable, and Station N can be used as a passing station only for inbound trains. For \((L, R) = (4, 2)\), our result uses Station J as a passing station for inbound trains instead of Station N, and the total travel time is reduced. For \((L, R) = (6, 2)\) and \((4, 4)\), his results and ours are comparable. It means that, under the practical constraint of possible passing stations, we can obtain a timetable at least as good as the results with setting Station N as the passing station for both inbound and outbound trains, which is an impractical setting.

As shown above, these experiments can provide quantitative analysis, in addition to a qualitative one, to determine the rapid train stops, passing stations and associated timetables. More detailed results will be shown in the presentation.

7. CONCLUSION

In this paper, we proposed an enumeration-based algorithm for determining an optimal pattern of rapid train stops and the associated timetable that minimize total travel time for passengers. Considering the minimum interval of train operation and the availability of waiting lanes, we did determine an optimal pattern of rapid train stops for the JR Nambu line, which is a medium-sized railway line with 25 stations.

The procedure introduced here does not allow railway lines with branches and operations over part of a line. The modifications of our present procedure to accommodate the items above and for large-scaled lines are future works.

References


