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Energy-Saving Schedule Design by Installing Optimized Rapid Service in DC-Electric Railways

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Abstract
DC-Electric railways offer advantages in convenience, mass transportation performance, and being a green form of transport. In this paper, a rapid train service is considered for improving the quality of railway services and providing an eco-friendly performance. The main consideration of this study is the installation of a rapid service in a line without passing tracks, which effectively improves the total traveling time of passengers, and saves energy through greater efficiency. In order to install a rapid service in a conventional schedule that consists only of local train stops, one of two timetables is chosen to be replaced by a rapid service. The passing stations for a rapid service are determined with the use of mixed integer programming, which is a method of mathematical optimization. For this calculation, a sectional flow of passengers is analyzed, and a discrete origin and destination (OD) table is proposed. The resulting optimized timetable is presented, where unpopular stations are not necessary chosen as a passing station, because this calculation is based on the sectional flow of passengers. This means that the passing stations should be determined through an analysis of the OD table, rather than the number of passengers that board or alight. Finally, the consumption of energy is compared between local trains and rapid trains that use optimized scheduling. Running curves are calculated in each case, and the energy saved through the efficiency of rapid trains is shown to be 24.7 %. This is because the amount of accelerating and decelerating time is reduced. This energy saving will be increased if the number of passengers who use the rapid trains increases.

Keywords : Energy-saving, DC-Electric railway, Rapid service, Railway scheduling, Mathematical optimization, Mixed integer programming, Discrete origin and destination table, Passenger's flow, Load-compensating device

1. Introduction

Several ideas for improving the quality of railway services have been proposed in previous studies, approaching the problem from various viewpoints. Connection times (Liebchen, 2008; Kunimatsu, et al., 2009) and the demands of passengers (Kunimatsu et al., 2009) have been studied regarding the design of timetables that improve the scheduling of services. Research by Katori, et al. (2002) focused on decreasing the total traveling time of passengers by installing a rapid service. The method used in this study was dynamic programming. In general, dynamic programming is good with numbers, but the result of a calculation is not necessarily optimized.

On the other hand, interest in energy saving railway scheduling and operations is growing, due to environmental concerns such as global warming and worldwide energy problems. DC-Electric railways perform better ecologically than other forms of transportation system. Because of their outstanding ecological properties, various railway projects have been proposed, such as the Shift 2 Rail project (Shift2Rail). In Japan, the Railway Technical Research Institute develops onboard storage devices to stock regenerative energy without regeneration cancellation (Ogasa, 2009). Storage devices consisting of batteries and supercapacitors have been installed in a substation in Korea (Lee, et al., 2011). However, these approaches are rendered very expensive by the necessity of adding or replacing the electric devices. For this reason, some operation (Watanabe and Koseki, 2014) and running patterns (Bocharnikov, et al., 2010; Doan, et al., 2014; Ko, et al., 2005; Miyatake, 2011) have been designed in previous studies.

2. Objective

The main consideration of this study the installation of a rapid service in a line without passing tracks, which effectively improves the traveling times of passengers, and saves energy through greater efficiency. Our method does not require the additional electric devices, because we only redesign the scheduling. Fig. 1 presents our basic timetable, without rapid service. The black lines and red lines show local stops. However, in optimization the black lines represent the fixed timetable as local stops, and the red lines represent the variable timetable as rapid services. Rapid trains cannot pass by local trains, as this line has no passing tracks. In this situation, we determine some equations to represent, for example, physical and logical constraints, and we calculate the optimization problem as a mixed integer programming problem. With this method, we can obtain optimized results. In this calculation, the discrete origin and destination (OD) table is proposed, and is constructed by the estimation of the sectional flow of passengers. Finally, we calculate running curves in each section and the energy consumption for each timetable.

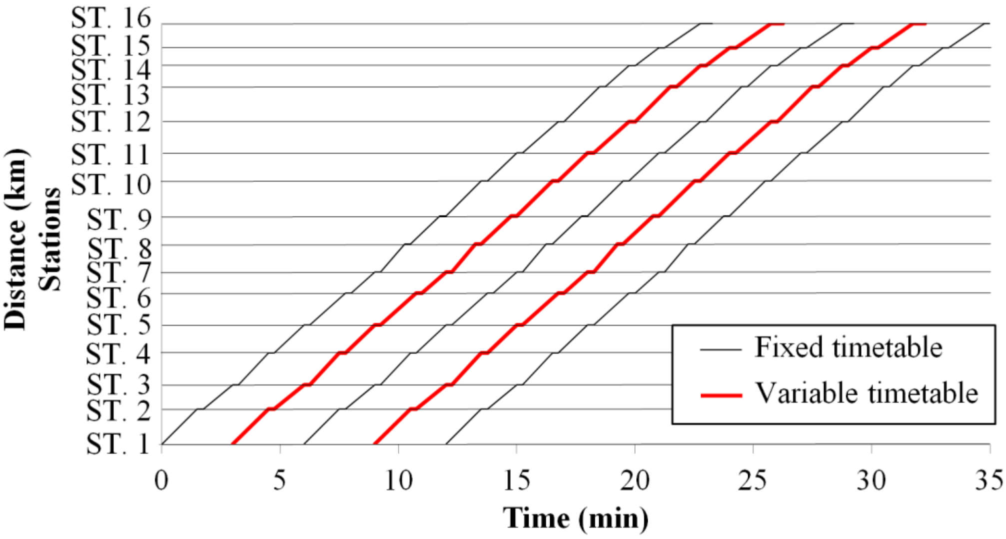

Fig. 1. The basic timetable without optimization.

3. Optimization Method for Design Scheduling

In this section we explain the method for the optimization and design of the timetables.

3.1 Mathematical Programming

The design of a scheduling diagram is an example of an optimization problem. This problem is formulated based on mathematical programming. The objective function and some other constraints used here follow from a previous study (Chigusa, et al., 2012), and will be explained in detail in the next section.

3.2 Objective Function

The traveling time of all passengers on a line is determined as an objective function *f*, as shown in Eq. (1). This function contains a waiting time for each passenger in the station. The aim in this study is to minimize this objective function *f* by installing a rapid service on a line, as mentioned in Section 2.

$$f = \sum P_{o,d}^{k} \times t_{o,d}^{k} \tag{1}$$

$P_{o,d}^{k}$: The number of passengers who begin at the station *o* at time k and then go to the station *d*.

$t_{o,d}^{k}$: The time required for a passenger who begins at time k to travel from the station *o* to the station *d*.

3.3 Constraints

Some inequality constraints are determined in order to ensure that the rules of railways are followed. These fall into three main categories.

The first category is physical constraints. These are determined by facilities, such as the number of platforms, the interval between trains arrival and departure, and the time required to get in or out of cars. Equations (2)-(6) are formulated based on these physical constraints. Table 1 explains the notations used in the equations presented below.

Equation (2) ensures that all train sets run over regular running times in each section.

$$a_j^{s+1} - d_j^s \geq LR^s - K \times pass_j^s \qquad \forall s \in S, \forall j \in R \tag{2}$$

Equation (3) ensures that all train sets stop for over a minimum stopping time at the station, not including way stations.

$$d_j^s - a_j^s \geq LS^s \left(1 - pass_j^s\right) \qquad \forall s \in S, \forall j \in R \tag{3}$$

Equation (4) ensures that the time intervals of all departing train sets are above a minimum departing time interval.

$$d_{j+1}^s - d_j^s \geq LD \qquad \forall s \in S, \forall j \in R \tag{4}$$

Equation (5) ensures that the time intervals of all arriving train sets are above a minimum arriving time interval.

$$a_{j+1}^s - a_j^s \geq LA \qquad \forall s \in S, \forall j \in R \tag{5}$$

Equation (6) ensures that time interval between arriving and departing is above a minimum time interval when over two train sets stop at the same platform.

$$a_{j+1}^s - d_j^s \geq LT - M\left(2 - r_{j+1}^{s,q} - r_j^{s,q}\right) \qquad \forall s \in S, \forall j \in R, \forall q \in Q^s \tag{6}$$

The next category is logical constraints. These are determined by concepts of design scheduling, such as the number of rapid cars and way stations. Equations (7)-(9) are formulated on the basis of these constraints.

Equation (7) ensures that schedules of local trains are fixed in a timetable.

$$a_j^s = A_j^s \quad d_j^s = D_j^s \qquad \forall s \in S, \forall j \in R_{loc} \tag{7}$$

Equation (8) ensures that no trains can pass the terminal stations, numbered as 1 and 16.

$$pass_j^{end} = 0 \qquad \forall j \in R \tag{8}$$

Equation (9) ensures that the total number of stations passed by a rapid service changes in each optimizing calculation.

$$\sum_{s \in S} pass_j^s = N \qquad \forall j \in R_{rap} \tag{9}$$

The final category is constraints on the flow of passengers, which are determined from the following three rules. First, no group of passengers can change from their own train to another train, because no train sets pass each other in this study. Second, no group can board a train that departs prior to the arrival of those passengers. Third, passengers cannot board or alight at passing stations when they board a rapid service train. Equations (10)-(13) are formulated based on these three rules. In addition, we assume that to each passenger is attached information on the departure and arrival stations, and the time that they appear at the station of their departure. The purpose of this is to decrease the amount of calculation needed for optimization. In this study, this appearance time is determined at intervals of 15 seconds. This hypothesis is based on the real scheduling of railway companies.

$$\sum_{j \in R} z_{t,j}^{o,d} = 1 \qquad \forall o,d \in S : o < d, \forall t \in T \tag{10}$$

$$d_j^o \geq t \times z_{t,j}^{o,d} \qquad \forall o,d \in S : o < d, \forall j \in R, \forall t \in T \tag{11}$$

$$\sum_{\substack{d \in S : o < d \\ t \in T}} z_{t,j}^{o,d} \leq M \times \left(1 - pass_j^o\right) \qquad \forall o \in S, \forall j \in R \tag{12}$$

$$\sum_{\substack{o \in S : o < d \\ t \in T}} z_{t,j}^{o,d} \leq M \times \left(1 - pass_j^d\right) \qquad \forall d \in S, \forall j \in R \tag{13}$$

Table 1. Symbols in this study.

Real Variables	
a_j^s	The time that train *j* arrives at station *s*
d_j^s	The time that train *j* departs from station *s*
Boolean Variables (when 1)	
$pass_j^s$	Train *j* passes station *s*
$r_j^{s,q}$	Train *j* uses track q at station *s*
$z_{t,j}^{o,d}$	The passengers appear at time *t*, who travel from station *o* to *d*, take train *j*
Constants	
A_j^s	The scheduled time that train *j* arrives at station *s*
D_j^s	The scheduled time that train *j* departs from station *s*
LR^s	The standard running time from station *s* to *s*+1
LS^s	The minimum standing time at station *s*
LA	The minimum interval arrival–arrival time
LD	The minimum interval departure–departure time
LT	The minimum interval departure-arrival time
K	The shorten time when a train passes a station
N	The total number of station that a train passes
M	Large number
Set	
S	Station set
R	Train set
R_{loc}	Local train set
Q^s	The track set of station *s*
T	The passengers' appearance time set

4. Discrete OD Table

This section explains the method used to construct the discrete OD table. This method is designed for application to mixed integer programming.

4.1. The Purpose of Making the Discrete OD Table

The OD table contains information on the flow of passengers, such as the number of journeys from station 1 to station 3, or from station 2 to station 7. However, it is difficult to obtain the sectional flow of passengers, such as in the OD table, because most railway companies only count the numbers of incoming and outgoing passengers at the station gate. This study follows previous a study (Ikeda and Sone, 1992), and estimates the sectional flow of passengers from the number of incoming and outgoing passengers, in order to make an OD table.

This OD table shows the number of passengers per day, so that the number of passengers appearing at a station every 15 seconds will not be an integer value, as seen in table 2. The pattern of appearing passengers is shown in Fig. 2, where Table 2 is followed. For this reason, we propose the discrete OD table in this paper. The pattern of the number of appearing passengers is determined as an integer value, as seen in Fig. 3 and the design of the discrete OD table.

4.2 Design Method and Proposed OD Table

The four rules are determined as follows:

(i) Passengers appear at the station every time a designed time interval passes. The time interval is determined as 15 seconds in this study, as mentioned in section 3.3.

(ii) At least one passenger appears at the station for every local train departure time.

(iii) Passengers appear evenly for every time period.

(iv) The patterns of the appearance of passengers occur in cycles corresponding to local train departing times. This time is shown as the “fixed timetable” in Fig.1.

Table 3 shows the discrete OD table from station 1 to stations 2-16, based on Table 2. The area labelled by A in table 3 shows the departure and arrival station of passengers. All OD tables for departures from all stations are prepared, but the OD table for departures from station 1 is used for explanation. The area labelled by B shows the number of passengers who appear at the station every 15 seconds, without discrete consideration. In considering an integer value, passengers for each 6 minute interval are calculated as a discrete value, as presented in area C. The discrete time interval is 15 seconds, and a local stop train departs every 6 minutes, so that the number of intervals for the appearance of passengers at each station is 24 for every local departure. For this reason, the value of area C is calculated by multiplying the value of area B by 24 and rounding off the non-integer part. The total number of passengers every 6 minutes is determined as shown in area C, so that the numbers of passengers are distributed in accordance with rule (iii), as shown in area E. In addition, area E and area F are the same, as a result of rule (iv).

Table 2. The original OD table for each 15 second interval.

Arr.

		St. 1	St. 2	St. 3	St. 4	St. 5	St. 6	St. 7	St. 8	St. 9	St. 10	St. 11	St. 12	St. 13	St. 14	St. 15	St. 16
Dep.	St. 1	-	0.138	0.135	0.181	0.066	0.341	0.217	0.138	0.105	0.237	0.194	0.083	0.129	0.421	0.130	1.124
	St. 2	-	-	0.094	0.126	0.046	0.236	0.150	0.095	0.073	0.164	0.135	0.057	0.089	0.291	0.090	0.778
	St. 3	-	-	-	0.123	0.045	0.231	0.147	0.093	0.071	0.160	0.131	0.056	0.087	0.284	0.088	0.760
	St. 4	-	-	-	-	0.061	0.313	0.199	0.126	0.097	0.218	0.178	0.076	0.118	0.386	0.120	1.032
	St. 5	-	-	-	-	-	0.111	0.070	0.045	0.034	0.077	0.063	0.027	0.042	0.136	0.042	0.364
	St. 6	-	-	-	-	-	-	0.393	0.249	0.190	0.428	0.351	0.150	0.233	0.760	0.236	2.030
	St. 7	-	-	-	-	-	-	-	0.153	0.117	0.263	0.216	0.092	0.143	0.467	0.145	1.249
	St. 8	-	-	-	-	-	-	-	-	0.073	0.163	0.134	0.057	0.089	0.290	0.090	0.774
	St. 9	-	-	-	-	-	-	-	-	-	0.124	0.102	0.043	0.067	0.220	0.068	0.588
	St. 10	-	-	-	-	-	-	-	-	-	-	0.237	0.101	0.157	0.512	0.159	1.369
	St. 11	-	-	-	-	-	-	-	-	-	-	-	0.082	0.127	0.415	0.129	1.110
	St. 12	-	-	-	-	-	-	-	-	-	-	-	-	0.053	0.172	0.053	0.459
	St. 13	-	-	-	-	-	-	-	-	-	-	-	-	-	0.271	0.084	0.723
	St. 14	-	-	-	-	-	-	-	-	-	-	-	-	-	-	0.297	2.560
	St. 15	-	-	-	-	-	-	-	-	-	-	-	-	-	-	-	0.732
	St. 16	-	-	-	-	-	-	-	-	-	-	-	-	-	-	-	-

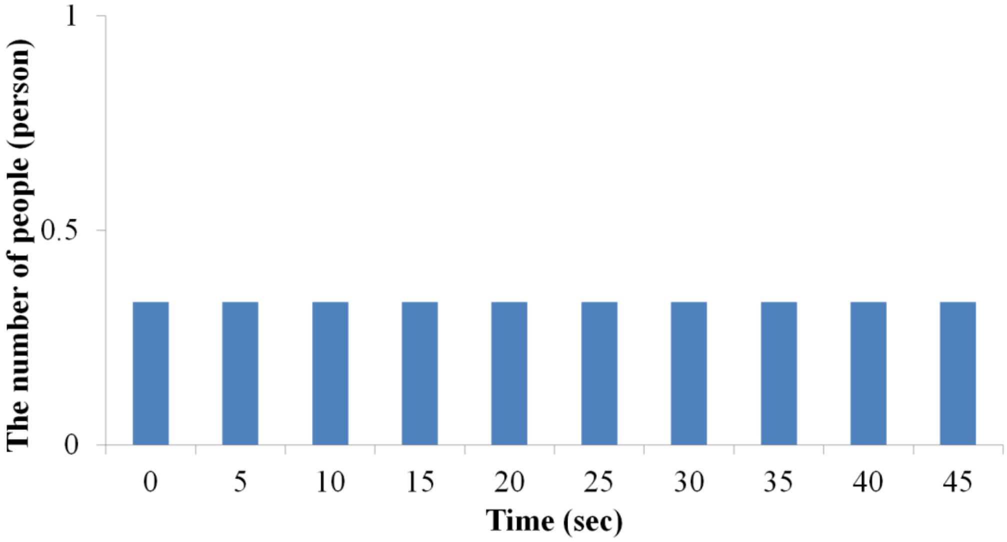

Fig. 2. Pattern of appearing passengers, without consideration of integer values.

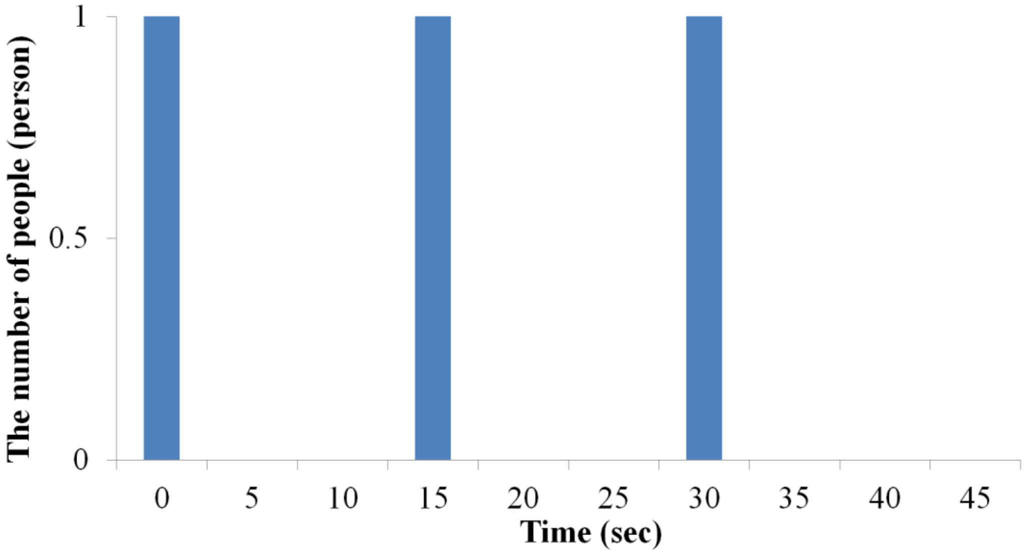

Fig. 3. Discrete pattern of appearing passengers, with integer values considered.

5. Case Studies

Parameters based on existing railways are prepared in order to calculate optimization problems and design an optimized schedule.

5.1. Calculation Conditions

Information from existing railways is prepared. Figure 4 shows the distances between each station, and the regular running times. The total number of stations is 16, and the distance between the terminal stations is 12 km. Train sets departing from station 1 to 16 are considered in this study. The parameters regarding times have been determined as presented in table 4. This optimization problem is calculated using mixed integer programming, and a solver of CPLEX12.2 (IBM) is prepared.

Table 3. The discrete OD table departing from station No.1.

Label A	Arr. St. Dep. St.1		St.2	St.3	St.4	St.5	St.6	St.7	St.8	St.9	St.10	St.11	St.12	St.13	St.14	St.15	St.16
B	OD table of each 15 second without discrete consideration		0.138	0.135	0.181	0.066	0.341	0.217	0.138	0.105	0.237	0.194	0.083	0.129	0.421	0.130	1.124
C	The number of passenger of each 6 minutes with discrete consideration		3	3	4	2	8	5	3	3	6	5	2	3	10	3	27
D	Min	Sec															
E	0	0	1	1	1	1	1	1	1	1	1	1	1	1	1	1	2
		15	0	0	0	0	0	0	0	0	0	0	0	0	0	0	1
		30	0	0	0	0	0	0	0	0	0	0	0	0	0	0	1
		45	0	0	0	0	1	0	0	0	0	0	0	0	1	0	1
	1	0	0	0	0	0	0	0	0	0	1	0	0	0	0	0	1
		15	0	0	0	0	0	1	0	0	0	1	0	0	1	0	1
		30	0	0	1	0	1	0	0	0	0	0	0	0	0	0	1
		45	0	0	0	0	0	0	0	0	0	0	0	0	0	0	1
	2	0	1	1	0	0	0	0	1	1	1	0	0	1	1	1	2
		15	0	0	0	0	1	0	0	0	0	0	0	0	0	0	1
		30	0	0	0	0	0	1	0	0	0	1	0	0	1	0	1
		45	0	0	0	0	0	0	0	0	0	0	0	0	0	0	1
	3	0	0	0	1	1	1	0	0	0	1	0	1	0	1	0	1
		15	0	0	0	0	0	0	0	0	0	0	0	0	0	0	1
		30	0	0	0	0	0	0	0	0	0	0	0	0	0	0	1
		45	0	0	0	0	1	1	0	0	0	1	0	0	1	0	1
	4	0	1	1	0	0	0	0	1	1	1	0	0	1	0	1	2
		15	0	0	0	0	0	0	0	0	0	0	0	0	1	0	1
		30	0	0	1	0	1	0	0	0	0	0	0	0	0	0	1
		45	0	0	0	0	0	0	0	0	0	0	0	0	0	0	1
	5	0	0	0	0	0	0	1	0	0	1	1	0	0	1	0	1
		15	0	0	0	0	1	0	0	0	0	0	0	0	0	0	1
		30	0	0	0	0	0	0	0	0	0	0	0	0	1	0	1
		45	0	0	0	0	0	0	0	0	0	0	0	0	0	0	1
F	6	0	1	1	1	1	1	1	1	1	1	1	1	1	1	1	2
		15	0	0	0	0	0	0	0	0	0	0	0	0	0	0	1
		30	0	0	0	0	0	0	0	0	0	0	0	0	0	0	1
		45	0	0	0	0	1	0	0	0	0	0	0	0	1	0	1
	7	0	0	0	0	0	0	0	0	0	1	0	0	0	0	0	1
		15	0	0	0	0	0	1	0	0	0	1	0	0	1	0	1
		30	0	0	1	0	1	0	0	0	0	0	0	0	0	0	1
		45	0	0	0	0	0	0	0	0	0	0	0	0	0	0	1
	8	0	1	1	0	0	0	0	1	1	1	0	0	1	1	1	2
		15	0	0	0	0	1	0	0	0	0	0	0	0	0	0	1
		30	0	0	0	0	0	1	0	0	0	1	0	0	1	0	1
		45	0	0	0	0	0	0	0	0	0	0	0	0	0	0	1
	9	0	0	0	1	1	1	0	0	0	1	0	1	0	1	0	1
		15	0	0	0	0	0	0	0	0	0	0	0	0	0	0	1
		30	0	0	0	0	0	0	0	0	0	0	0	0	0	0	1
		45	0	0	0	0	1	1	0	0	0	1	0	0	1	0	1
	10	0	1	1	0	0	0	0	1	1	1	0	0	1	0	1	2
		15	0	0	0	0	0	0	0	0	0	0	0	0	1	0	1
		30	0	0	1	0	1	0	0	0	0	0	0	0	0	0	1
		45	0	0	0	0	0	0	0	0	0	0	0	0	0	0	1
	11	0	0	0	0	0	0	1	0	0	1	1	0	0	1	0	1
		15	0	0	0	0	1	0	0	0	0	0	0	0	0	0	1
		30	0	0	0	0	0	0	0	0	0	0	0	0	1	0	1
		45	0	0	0	0	0	0	0	0	0	0	0	0	0	0	1
	12	0	1	1	1	1	1	1	1	1	1	1	1	1	1	1	2

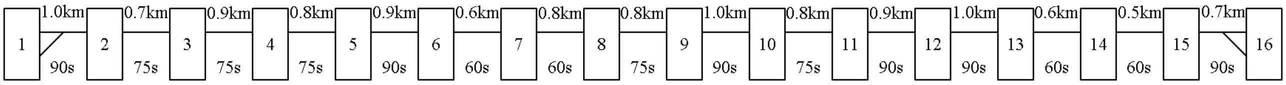

Fig.4. The outline of the simulated railway

Table 4. Settings for time parameters

LS^s	15sec (the terminal stations are 30 sec)
LA	60 sec
LD	60 sec
LT	90 sec
K	30 sec
M	1000

5.2. Calculation Results

First, the number of passing stations should be determined. For this purpose, only the parameter representing the number of passing stations is altered in the calculation of optimization problems. Figure 5 shows the relationship between the number of passing stations and the objective function, which is the product of the number of passengers and the traveling time. The original scheduling, which consists only of local stop trains, represents the case with zero passing stations in Fig. 5. The traveling time of passengers who get on a rapid train is reduced. On the other hand, the traveling time of passengers who get on a local train to a destination station passed by rapid trains is increased. Because of this trade-off relationship, the number of passing stations is determined as an optimization problem. In this study, the number of stations is determined to be four. In this case, the objective function, which denotes the total traveling time, is decreased by 3.3%. However, the optimized schedule is calculated using the conventional OD table, and following rule (iii) from section 4.2. The number of passengers who board rapid trains will be increased when running this optimized schedule.

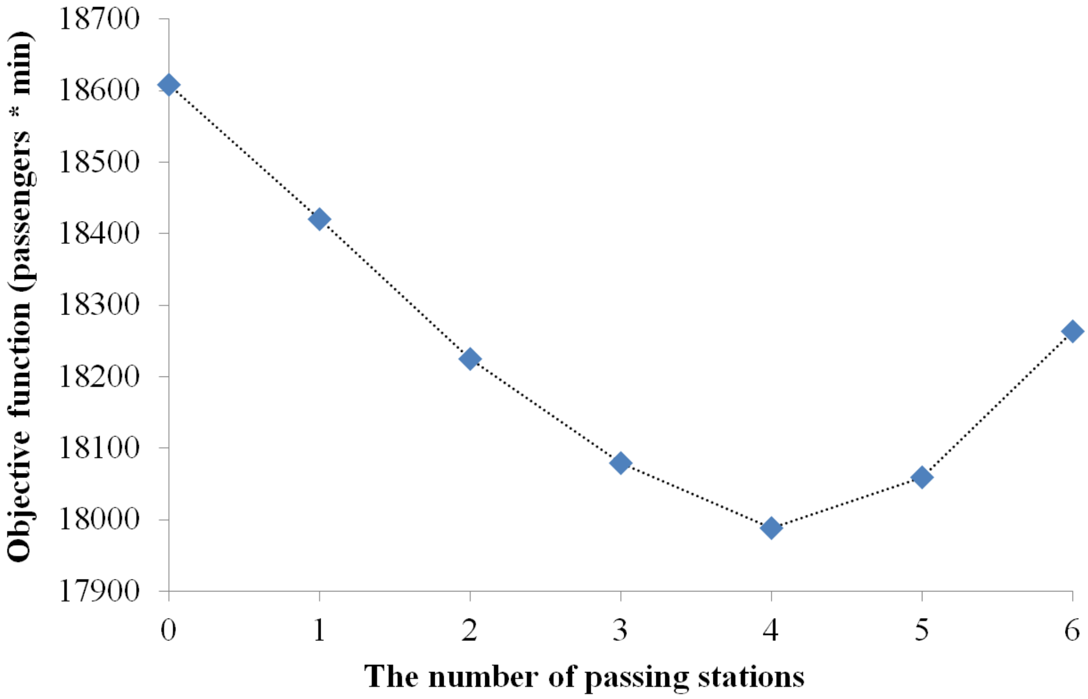

Fig. 5. The relationship between the number of passing stations and the objective function.

Figs. 6 and 7 show the optimized schedule and timetables in the case with four passing stations. In order to preserve the minimum distance between local and rapid trains, they each spare 105 sec, which is the sum of *LT* and *LS*. The time interval between local trains is 6 minutes, so that 150 sec, which is calculated by subtracting 210 seconds from 6 minutes, is the short-cut time for a rapid service. Rapid trains can reduce the total running time by 45 seconds, which is the sum of *K* and *LS* from stations 1 to 16, when passing a station. Rapid trains cannot reduce the total running time if more than five stations are passed, because all trains must preserve the minimum distance between local and rapid trains. However, stations 1 and 16 have two platforms, so that the minimum running time interval is *LA* or *LD*, rather than *LT*. In the case that stations 2 or 15 are a passing station, the spare time of local and rapid trains can be reduced. These factors are trade-off points, and determine the optimization result.

Table 5 shows the numbers of passengers boarding or alighting at the unpopular stations. In the optimized timetable, as shown in Fig. 7, stations 9, 12, 13, and 15 are chosen as passing stations. This is because there are many passengers traveling in the direction of station 16 on this line, so that rapid trains stop at stations near to the start of the route, and pass by station 15. In addition, this has the merit of decrease the spare time of local and rapid trains at station 15. These results show the important point used in determining the passing stations. The passing stations should be determined by an analysis of the OD table, and not the numbers of passengers to board or alight.

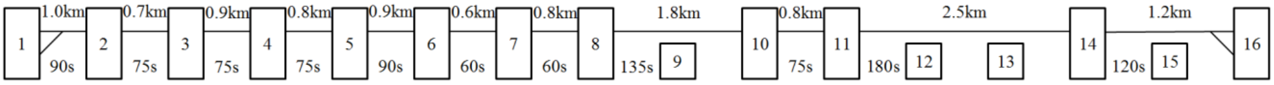

Fig. 6. The schedule of rapid trains with optimized passing stations.

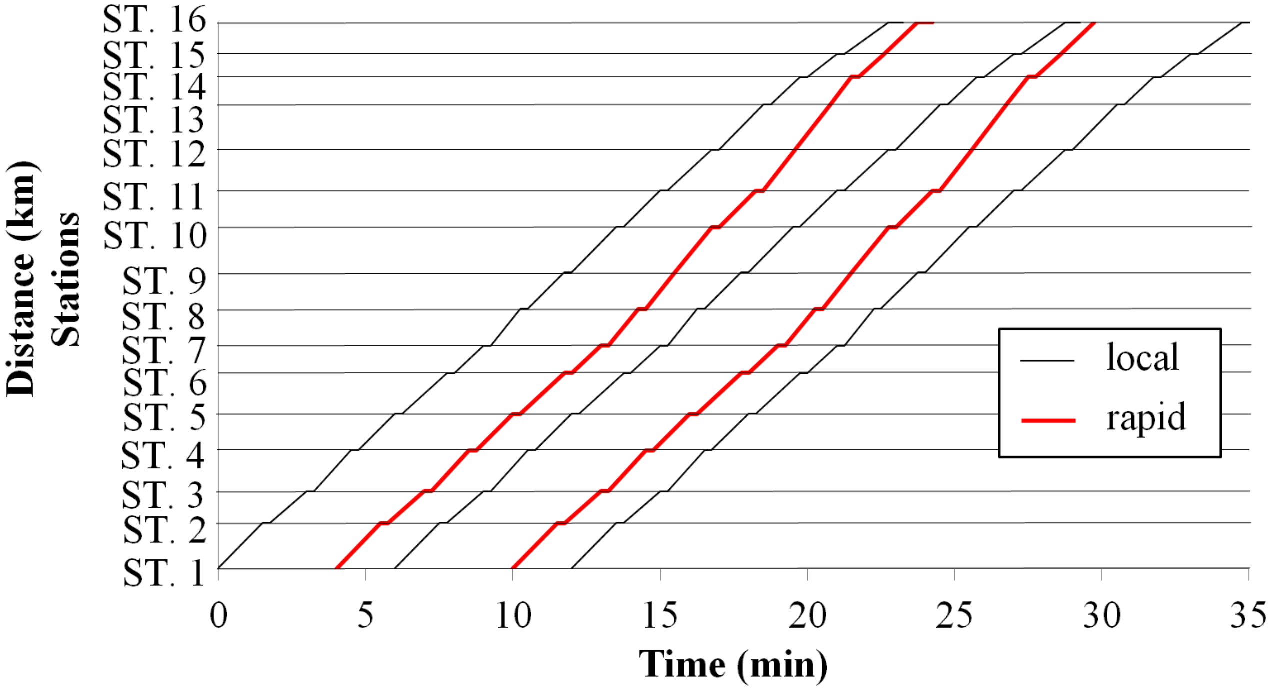

Fig.7. The timetables consisting of local and rapid trains with optimization.

Table 5. The number of passengers boarding or alighting at unpopular stations.

Rank	1	2	3	4	5
Unpopular stations	ST. 5	ST. 12	ST. 9	ST. 15	ST. 13

6. Analysis of Energy-Saving Effects

The main purpose of this study is to show the energy efficiency achieved by an optimized rapid timetable. In this section, the energy consumption between stations 8 and 10 is calculated. The energy-saving effect is compared between the cases of local stops and rapid trains.

6.1. Calculation Conditions for Energy-Saving Effects

In this study, the stations from 8 to 10 are chosen for our calculation. Table 6 shows the calculation conditions for rolling stocks. The capacity is altered using a load compensating device for every section, because a tractive force should be applied in order to achieve the same acceleration and deceleration. The running pattern consists of accelerating, cruising, and decelerating, as shown in Fig. 8.

Table 7 shows the number of passengers. Passengers who depart from station 8 to arrive at station 10 board the rapid service train. The running time has already been determined, in Figs. 4 and 6.

Table 6. Calculation conditions of rolling stocks.

	Parameters	**Remarks column**
Number of cars	4	4M0T
Capacity	Changing	Load-compensating device is considered
Operation	ATO	
	Single way	Not a round trip
Environment	Subway	Platform doors are installed
Pantograph voltage	DC 1500 V	In acceleration
	DC 1650 V	In regeneration

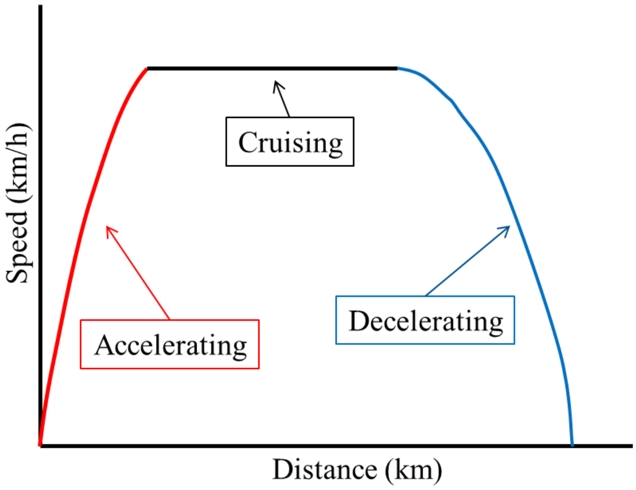

Fig. 8. Running patterns for calculating energy consumption.

Table 7. Calculation conditions for the number of passengers.

Arr. Dep.	ST. 8	ST. 9	ST. 10
ST. 8	-	210 (Local stop)	201 (Rapid service)
ST. 9	-	-	215 (Local stop)
ST. 10	-	-	-

6.2. Calculation Results for Energy Consumption

Fig. 9 shows the relationship between energy consumption and running time. This relationship is determined by calculating running curves. Table 8 shows the energy consumption of local and rapid trains, based on Fig. 9. The running time is chosen based on the previous optimization, as mentioned in section 5.2, and as shown in Fig. 6. Energy consumption is calculated by subtracting regenerative energy from acceleration energy. The total energy consumption of local trains is calculated as the sum of all sections. In this study, the energy saved though improved efficiency is calculated to be 24.7 %.

Energy consumption is reduced when a rapid train passes a station. This means that the amount of acceleration and deceleration time is reduced, and also the conversion loss of both mechanical and electric energy decreases.

These results are based on the OD table that is estimated for the case where all trains are local stops. Appearance patterns for passengers will be altered if rapid services are installed on this line. The energy saving efficiency will be increased if the number of passengers who get on rapid trains increases. This is because rapid trains are more efficient, with a lower conversion loss.

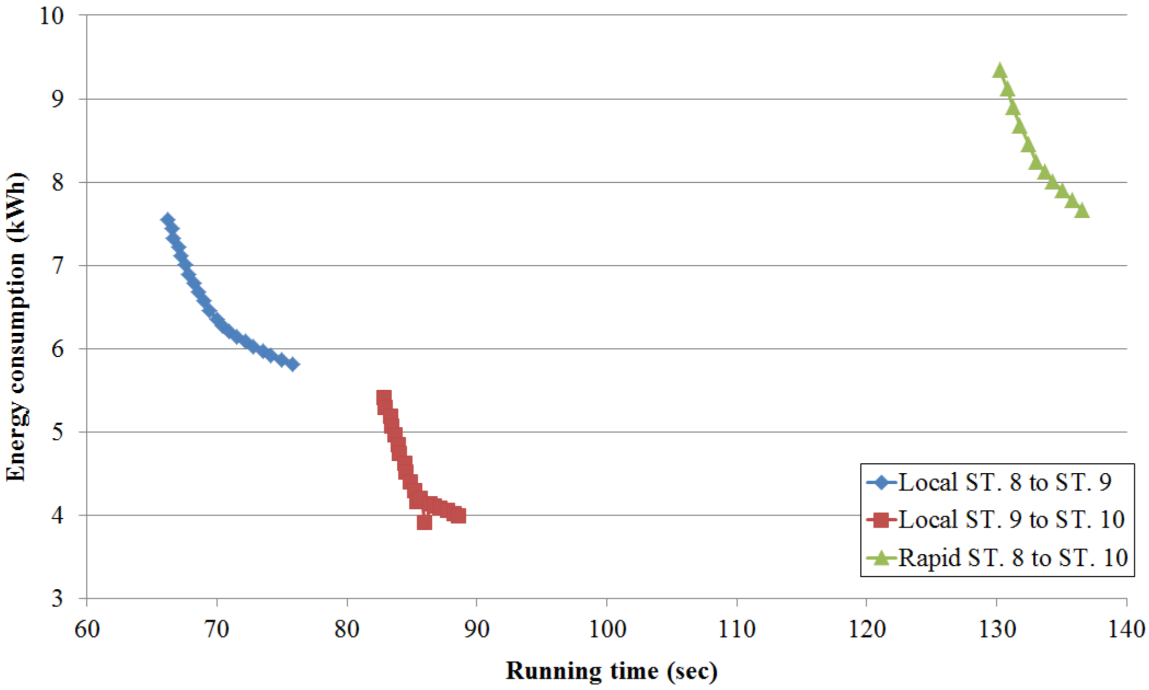

Fig. 9. Relationship between energy consumption and running time.

Table 8. Energy consumption for each section.

	Running time	Acceleration energy	Regenerative energy	Energy consumption	Energy saving efficiency
Local ST.8 to ST.9	74.97 sec	7.98 kWh	2.12 kWh	5.86 kWh	-
Local ST.9 to ST.10	88.59 sec	10.89 kWh	6.90 kWh	3.99 kWh	-
Local ST8 to 10	-	-	-	9.85 kWh	24.7 %
Rapid St.8 to ST.10	135.03 sec	16.58 kWh	8.68 kWh	7.90 kWh	

7. Conclusions

In this paper we proposed the installation of a rapid service on a line without passing tracks, effectively improving traveling times and saving energy through improved efficiency. We chose one of two timetables as a variable timetable to install rapid services. Rapid trains cannot pass local trains, so we determined some equations using physical and logical constraints, and calculated the optimization problem using mixed integer programming. In this calculation, the discrete origin and destination (OD) table was constructed by estimating the sectional flow of passengers. The resulting optimized timetable was presented, and unpopular stations were not necessary chosen to be passing stations. This signifies that it is important to analyze the sectional flow of passengers, as we did with the OD table. Passing stations should be determined by an analysis of the OD table, rather than the number of passengers boarding or alighting. Finally, we calculated running curves for each section, as well as energy consumptions. The energy saved by increased efficiency was calculated to be 24.7 %. Energy consumption is reduced, because the amount of acceleration and deceleration time is reduced. The amount of saved energy will increase if the number of passengers who board rapid trains is increased.

8. Future Work

In this study, only three stations are chosen for calculating the amount of energy saved by improved efficiency, so in the future this should be calculated for all sections. This is because these results are based on the OD table that is estimated for the case where trains are local stops. Appearance patterns for passengers will be change if rapid services are introduced. The energy efficiency of this line can be determined when this appearance case is estimated.

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