

Non-periodic Subway Scheduling that Minimizes Operational Cost and Passenger Waiting Time

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Abstract

Subway metro scheduling is one of the most important problems impacting passenger convenience today. To operate efficiently, the Seoul metro uses regular, periodic schedules for all lanes, both north and southbound. However, many past studies suggest that non-periodic scheduling would better optimize costs. Since the Seoul metro is continuously facing a deficit, adopting a non-periodic schedule may be necessary. Two objectives are presented; the first, to minimize the average passengers' waiting time, and the second, to minimize total costs, the sum of the passenger waiting time, and the operational costs. In this paper, we use passenger smart card data and a precise estimation of transfer times. To find the optimal time-table, a genetic algorithm is used to find the best solution for both objectives. Using Python 3.5 for the analysis, for the first objective, we are able to reduce the average waiting time, even when there are fewer trains. For the second objective, we are able to save about 4.5 thousand USD with six fewer trains.

▶ Keyword: Transfer Passenger, Subway Scheduling, Timetabling, Optimization, Genetic Algorithm. Metro Operating Cost

1. Introduction

In Seoul, Korea, more than 170 thousand people, on average, are using the Seoul metro line number 8 each weekday[1][2]. With such a large demand, the metro is facing various operating problems. One of the biggest is its endless deficit. According to Money News[3], the Seoul metro line lost more than about 370 million USD in 2014 and this has continued to increase to date. Seoul metro has pointed to several reasons for this deficit: the first is the low price of the tickets, the second is the large number of people who ride for free (legally and illegally), and the third is the decrease in its advertising earnings. In order to overcome this situation, the line has

raised ticket prices continuously. The ticket fare has increased 150% over its 2000 price. Moreover, the line has cracked down on illegal train riders. Currently, Seoul metro is considering shortening the subway schedule. Ironically, all these actions taken to save costs have incurred other costs; not only monetary costs but also non-monetary costs such as passenger inconvenience. Thus, true cost saving should be considered from better schedule efficiency.

The Seoul metro schedule is fairly regular and periodic. On line 8, most of the headways are fixed at every five minutes in rush hour, and every eight minutes

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otherwise. This periodic schedule is easy and convenient to operate. However, it may increase passenger waiting time and decrease resource efficiency. According to Barrena *et al.* [4], a regular schedule does not always minimize passenger waiting time. The Seoul Statistics reveal that line 8 has the lowest demand level and among the lowest congestion, as shown in figure 1. Before noon, demand for line 8 reaches only 71% of its capacity, while Seoul metro has stated that it can handle up to 150% of its capacity. This offers evidence that its operational efficiency is low. Thus, Seoul metro needs to adjust its operating system, the timetable, and number of subways. To increase efficiency, the subway schedule should better meet passenger demand. Thus, a non-periodic schedule based on passenger demand appears to be necessary.

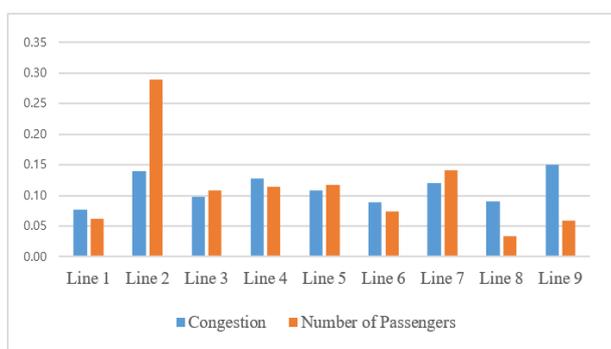


Fig. 1. Seoul Metro Congestion Level and Demand

II. Problem Statements

This study starts with the question: “How can we improve operating efficiency without passenger discomfort?” Thus, our first objective is to minimize passenger average waiting time by controlling departure times at the first station and platform wait times of trains at other stations. Needless to say, such a schedule is non-periodic. Moreover, the number of trains will decrease based on train demand level or randomly without an increase in the average waiting time.

The above objective has a cost savings limitation as it mainly focuses on passenger waiting time. Thus, the second idea arose: Would it be better to reduce the number of trains if this could be done with no significant change in passenger waiting time, even though it may increase for some? This second objective focuses on minimizing total cost, the sum of passenger waiting time converted to a cost, and operating cost. Decision variables are the same as in the first objective,

the schedule at the first station and platform wait time of the subways at the other stations. Passenger waiting time is calculated in currency by taking the average income rate per second, according to the Korea Ministry of Employment and Labor. Operating cost per train is calculated according to [5].

III. Literature Review

Public transportation scheduling as a problem was initiated in 1971 by Gordon Newell[6]. He tried to find the optimal schedule to minimize passenger waiting time. After his mathematical modeling, scholars tried to solve related problems. Many tried to minimize costs or passenger waiting time. Guan *et al.* [7] and Assis and Milani[8] used exact algorithms. On the other hand, Li [9] used simulation methods to solve a similar problem. Meta heuristic methods have also been used ([10][11][12]). Among them, Hu *et al.* [10] and Niu and Zhou [11] used genetic algorithms to find the optimal schedule to minimize passenger waiting time. Other than general scheduling problems, many scholars have tried to solve timetable synchronization problems (TTSPs) to minimize transfer passenger waiting time. Many methodologies are also used in TTSPs. Wong and Leung[13] used mixed integer programming; Feng *et al.*[14] used a simulation; and Poorjafari *et al.*[15] used genetic algorithms and simulated annealing. In passenger flow problems, Hong *et al.* [16] and Park and Lee[17] used smart card data for their predictions. Since smart card data mainly contain departure station (O), entry time at gate (OT), arrival station (D), and exit time at gate (DT), they could estimate passenger flow precisely.

As all of the studies are related, these factors should be considered at the same time. From this point of view, these past studies contain some limitations. In the regular scheduling problems, transfer passengers were not considered and neither were non-transfer passengers in the TTSP. On the Seoul metro, more than half of the passengers are transferring passengers. Especially on line 8, where more than 70% are transferring passengers. Thus, both non-transfer and transfer passengers should be considered. In this study, we precisely estimate the flow of the transfer passengers to find precise metro schedules that minimize passenger average waiting time and total cost while considering both types of passengers. We use the Seoul metro line 8 as the subject of the experiment. However, we

Seoul metro website. There are five transfer stations, Moran, Bokjeong, Garak Market, Jamsil, and Chenho. Moran and Bokjeong offer transfers to the Bundang Line, Garak Market to Line 3, Jamsil to Line 2, and Chenho to Line 5. According to these data, except for the Bundang line, the other transfer lines have exactly one transfer station. Thus, we can determine the transfer passenger's transfer station (who does not use the Bundang Line) without any problem. For Bundang line users, there are two transfer stations, Moran and Bokjeong. According to Seoul metro, transferring at Bokjeong

Due to the existence of the passenger transfer and the nearest door for the transfer, we need to estimate passenger behavior. To determine the transfer method, we manually observed six different transfer spots to find the ratio of those choosing the stairs. For the more than 40 observations we collected, we tried to find the relation between the number of passengers and the choice of the stairs as a ratio by using a linear regression model. We used IBM SPSS Statistics version 23, and the results are given in Figure 4.

Model summary			Anova			Coefficients		
R	R square	Durbin-watson		F	Sig.		B	Sig.
0.655	0.429	2.118	Regression	22.503	0.000	Constant	10.967	0.012
						Num of People	0.231	0.000

Fig. 4. Linear Regression Results

takes less time for passengers heading further than Bokjeong on line 8 (for the northbound lane) than transferring ahead at Moran. With the earlier assumption, we now can determine their transfer station.

After the transfer station is determined, the transfer passengers' O and D now switches to stations on line 8. Then, for transfer passengers 1-1 and 1-2, we can add walking and going down stairs time to their OT. Next, non-transfer passenger data reformulation is completed. For the rest of the transfer passenger types, we need to determine new platform arrival times. As we explained, this is significant factor. Thus, estimating arrival time is an important issue in this study.

2.2. Passenger arrival time estimation

To estimate transfer time, we visited all of the transfer stations to measure various factors. The findings are shown in Figure 3.

Since the Durbin-Watson value is close to 2, the model independence is approved. The R square value is 0.42, which indicates that the model explains 42% of the values, which is high enough to be used. Moreover, all of the values are less than 0.05, which indicates that the model is valid. Therefore, we can conclude that the relation between choosing the stairs and the number of passengers is as in equation (1) below.

$$\text{Ratio of Stair Choice} = 10.967 + 0.231 * (\text{Number of Passengers}) \quad (1)$$

To determine which door passengers use to exit to transfer, we constructed a survey. This factor is important because the walking distance will differ depending on which door the passenger uses. The survey included questions related to on-train or beforehand migration to faster exits after arrival using a five-point Likert scale. A total of 491 people participated. We sampled only those who use the subway more than four times a week, which represented a total of

Station	Line	Number of Train Selection	Distance between Exit doors (cm)	Path	Nearest Door Number for Transfer	Transfer Method	Walking distance (cm)	Number of Steps Up Stairs	Number of Steps Down Stairs	Escalator Time (sec)	Number of Steps in Escalator	
Moran	Bundang	6	332	North Bound	1-1	stair	18389		30			
				South Bound	6-4	stair	28820	29	59			
Bokjeong	Bundang	6	332	Both	1-1	stair	490		42			
					3-2	stair	931		42			
					3-2	escalator	588		34		34	40
					6-2	stair	1078		42			
Garak Market	3	10	332	Both	6-2	escalator	686		34		40	
					1-4	stair	4432		75			
					1-4	escalator	2408				61	74
Jamsil	2	10	312	3-2	escalator	4986			61	74		
				North Bound	1-1	stair	19004	30	30			
Cheonho	5	8	370	South Bound	10-4	stair	23558	30				
				Both	8-1	stair	1190	40				

Fig. 3. Measured Data from Transfer Stations

Q1. In rush hour, I would exit in the nearest door to shorten the transfer time			Q2. In non-rush hour, I would exit in the nearest door to shorten the transfer time		
Answer	%	Count	Answer	%	Count
Strongly disagree	6.46%	21	Strongly disagree	7.38%	24
Disagree	12.31%	40	Disagree	13.23%	43
Neutral	10.15%	33	Neutral	14.77%	48
Agree	29.54%	96	Agree	33.53%	109
Strongly agree	41.54%	135	Strongly agree	31.07%	101
Total	100%	325	Total	100%	325

Fig. 5. Passenger Behavior Survey Results

325 people. The results are given in Figure 5.

Finally, we have to determine when the passengers arrive at the transfer station. For transfer passengers, their arrival time is dependent on their train arrival time. Not only to reduce computation time but also to build a framework for future studies, we assume all of the transfer lines have the same number of train arrivals in an hour. In addition, the number of trains in the hour is estimated by the average number of trains arriving at the transfer lines. Moreover, we assume that the distribution of transfer passenger flow is equivalent to the non-transfer passenger flow. With these findings and assumptions, we can estimate the transfer passengers' arrival times at the platforms. Now, all of the passengers have O-D pairs only related to the Seoul metro line 8.

3. Genetic Algorithm

A genetic algorithm is widely used in scheduling problems. The following related studies have used such algorithms previously.

Thus, any solution with a maximum waiting time of more than 13 minutes would not be selected.

While many researchers generated the initial population entirely randomly, we use a partially random method. randomly generated solutions show very poor results. This interrupts the algorithm to try to improve it in limited iterations or even with infinite iterations. To improve input solution quality, we decide to generate a schedule at the first station randomly within a certain range from the original schedule. We then schedule other stations randomly. The roulette wheel method is used in selection also known as reproduction. The solution is selected by fitness and the fitness is shown as follows.

$$fitness_i = 1/Result_i \quad (2)$$

To avoid a convergence of solutions, the solutions are selected without replacement. Moreover, to increase improvement efficiency, the solutions that are better than the original solutions are automatically selected,

Author	Objective	Chromosome	Initial population	Reproduction	Crossover	Mutation	Selection
Y. Li & Y. Fang (2013)	Minimize Total Cost in Emergency Situation	Binary	Random		Single point crossover (rate=0.7)	Flip bit method (rate=0.01)	Roulette wheel
C. Rongwu <i>et al.</i> (2014)	Train Speed Optimization in Automatic System	m x n matrix (integer)	Random	Roulette wheel	Single point crossover (rate=0.8)	Random position changed to random feasible integer (rate=0.01)	
P. Tormos <i>et al.</i> (2008)	Minimize Total Travel Time	array, unit-pair: (t, s)	Regret-based random sampling		Single point crossover (rate=0.8)	re-positioning (rate=0.05)	2-tournament selection
W. Zhu & H. Hu (2014)	Minimize Total Travel Time	Binary			Two point crossover	Flip bit method	

Fig. 6. Past Studies Using Genetic Algorithms

The blank boxes represent areas that are not well defined in that particular study. Here, we use the chromosome type as in Rongwu *et al.*[21]. To generate the initial population, we use the constraints represented by Niu and Zhou[10] who used a genetic algorithm to minimize passenger waiting time. Those constraints are used to avoid any crash between subways. Other than the constraints in [10], we add a constraint to prevent passenger extreme waiting. According to Experian[22], the British research company, passengers are willing to wait 13 minutes to take public transportation.

subsequently, the others follow a roulette wheel. In the crossover, we use n point crossover to increase randomness.

Unlike usual genetic algorithms, this study uses two different mutations. Mutation one is the regular mutation which changes the value of n elements in the solution, with a certain mutation rate, within a feasible boundary as in [21]. In the second mutation, one of the trains will be removed from the schedule at a certain mutation rate. This is necessary because our objective is to not only to consider passenger waiting time but also the number of trains. Two methods are used:

first, we remove the lowest demand train; second, we remove a randomly selected train. Those options are also presented in [4]. Both are considered because this study focuses on two different objectives and we are willing to assess which method is more effective to solve the problems.

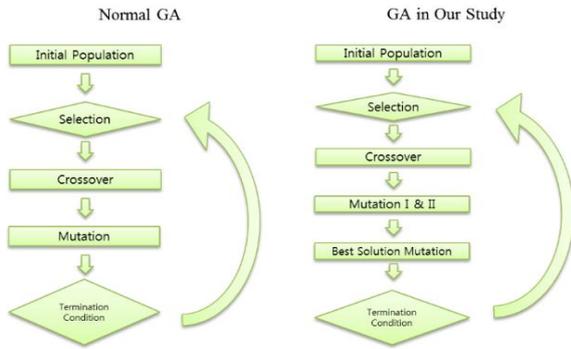


Fig. 7. Comparison in GA

One more difference in this study in the genetic algorithm is our use of the best solution mutation. In this stage, we forcibly

V. Results and Discussion

To determine the schedule efficiency, this study classifies passengers into two different types. Type I passengers are passengers who take the subway without facing any capacity issues and Type II passengers are those who do. In other words, Type II passengers will have waited for other trains due to oversaturated train conditions. We use Python 3.5 in Intel® Core™ i3-6100 CPU @ 3.70GHz with 8.00GB RAM.

1.1 Problem 1 and Removing the lowest demand level train

Compared to the original solution, the passenger average waiting time decreased by 10 seconds while one less train was used. Moreover, since an average of 11 more passengers rode each train with no Type II passengers, operational efficiency improved significantly. On the other hand, the maximum waiting time, the waiting

	Average Waiting Time	Type I Average Waiting Time	Number of Type I	Type II Average Waiting Time	Number of Type II	Number of Trains	Max Demand	Min Demand	Average Demand	Max Waiting Time	Average Waiting Time in Transfer Station	Average Waiting Time in Non-Transfer Station
Original Solution	182.53	182.53	34,547	0	0	51	1,102	36	587.61	599	184.77	181.37
Improved Solution	173.00	173.00	34,547	0	0	50	1,151	155	598.64	719	169.81	174.66

Fig. 8. Result of Problem 1 and Removing the Lowest Demand Level Train

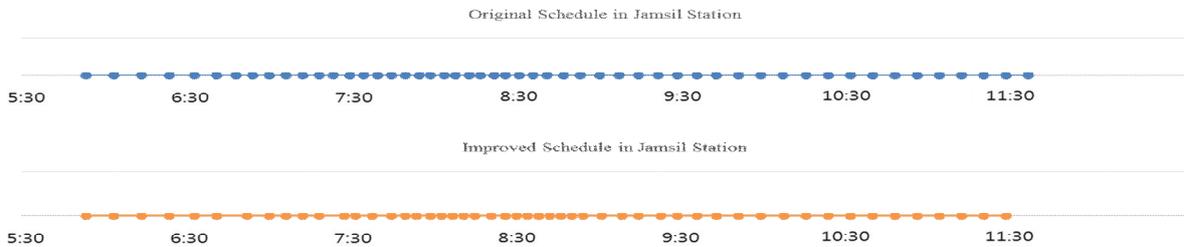


Fig. 9. Schedules at the Jamsil Station in Problem 1 and Removing the Lowest Demand Level Train

mutate a copy of the best solution among the solutions generated; we then add it to the generations. This is the other point that differs from regular genetic algorithms. This method is meant to reduce the number of iterations to reach a better solution. As a result of the experiment with small instances, the solution is improved much faster using this method.

time for passengers who had to wait the longest, increased by two minutes. This was expected since we adopted a non-periodic schedule without increasing the number of trains.

1.2 Problem 1 and Removing the randomly selected train

Although the number of trains used was the same, the average waiting time decreased by six seconds. There

	Average Waiting Time	Type I Average Waiting Time	Number of Type I	Type II Average Waiting Time	Number of Type II	Number of Trains	Max Demand	Min Demand	Average Demand	Max Waiting Time	Average Waiting Time in Transfer Station	Average Waiting Time in Non-Transfer Station
Original Solution	182.53	182.53	34,547	0	0	51	1,102	36	587.61	599	184.77	181.37
Improved Solution	176.05	176.05	34,547	0	0	51	1,210	36	587.61	685	176.28	175.93

Fig. 10. Result of Problem 1 and Removing Randomly Selected Train

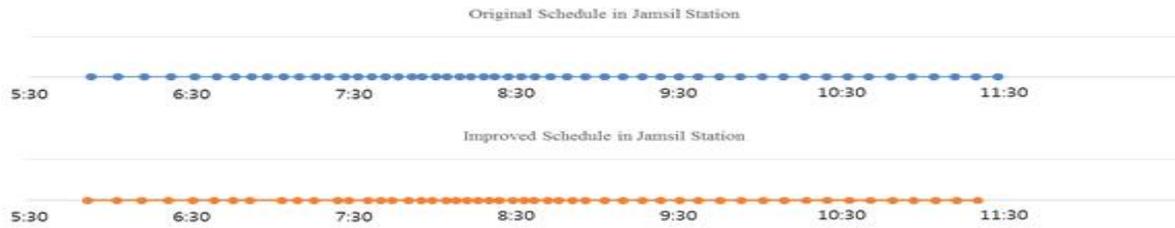


Fig. 11. Schedules at the Jamsil Station in Problem 1 and Removing the Randomly Selected Train

were no Type II passengers as well, which shows that the operating efficiency improved. Due to the characteristics of the non-periodic schedule, the maximum waiting time increased by 1.5 minutes.

For both these methods where trains were removed, the average waiting time decreased. As shown in figures 8 and 10, the waiting time at the transfer station decreased a larger amount compared to that at the non-transfer station. This may be because of the characteristics of the genetic algorithm. The average

randomness. Usually, the genetic algorithm provides better results with higher randomness. Thus, fewer trains give a wider range of scheduling because each train not only has running time but also has platform wait time and headway. However, this result may change if we run a genetic algorithm infinitely. In problem 1, removing the lowest demand train shows a better result because of our waiting time focused objective.

1.3 Problem 2 and Removing the lowest demand level train

	Total Cost	Type I Average Waiting Time	Number of Type I	Type II Average Waiting Time	Number of Type II	Number of Trains	Max Demand	Min Demand	Average Demand	Max Waiting Time	Average Waiting Time in Transfer Station	Average Waiting Time in Non-Transfer Station
Original Solution	131,793,570	182.53	34,547	0	0	51	1,102	36	587.61	599	184.77	181.37
Improved Solution	126,455,974	203.82	34,547	0	0	45	1,355	155	665.16	779	206.73	202.31

Fig. 12. Result of Problem 2 and Removing Lowest Demand Level Train

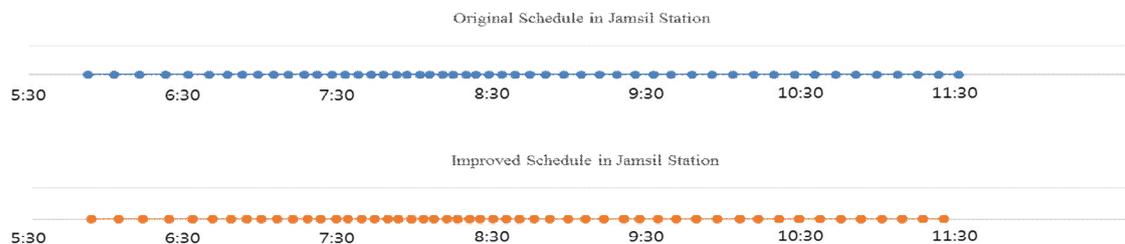


Fig. 13. Schedules at the Jamsil Station of Problem 2 and Removing the Lowest Demand Level Train

number of boarding passengers at the transfer stations was greater than at the non-transfer stations (an average of 540 passengers). Since the genetic algorithm seeks the solution that fits better, it chooses to decrease the larger wait time at the transfer station. The number of trains in the second method stayed the same, while it decreased in the first method. This may be because of the objective. The objective of problem 1 was very focused on the average waiting time. Thus, the objective would not improve if we removed trains without considering passenger flow. Notably, the first method removing the train gave us a better result than the second method. With one less train used, the average waiting time was smaller in the first method. This may be because of the limitation of

With a different objective, minimizing total cost, the improved schedule saves two million won (1.8 thousand USD). The average passenger waiting time decreases by 1.5 seconds and the number of trains decreases by one. As maximum demand decreases and minimum demand increases, the schedule is well distributed to the passenger flow.

1.4 Problem 2 and Removing the Randomly Selected Train

With the method removing the selected train randomly, six fewer trains are used to operate the metro. This results in 5,337,596 won cost saving, which is about 4.8 thousand USD. Without any Type II passengers, average waiting time increases by 20 seconds.

	Total Cost	Type I Average Waiting Time	Number of Type I	Type II Average Waiting Time	Number of Type II	Number of Trains	Max Demand	Min Demand	Average Demand	Max Waiting Time	Average Waiting Time in Transfer Station	Average Waiting Time in Non-Transfer Station
Original Solution	131,793,570	182.53	34,547	0	0	51	1,102	36	587.61	599	184.77	181.37
Improved Solution	129,616,999	181	34,547	0	0	50	1,098	155	599	675	183	179

Fig. 14. Results of Problem 2 and Removing the Randomly Selected Train

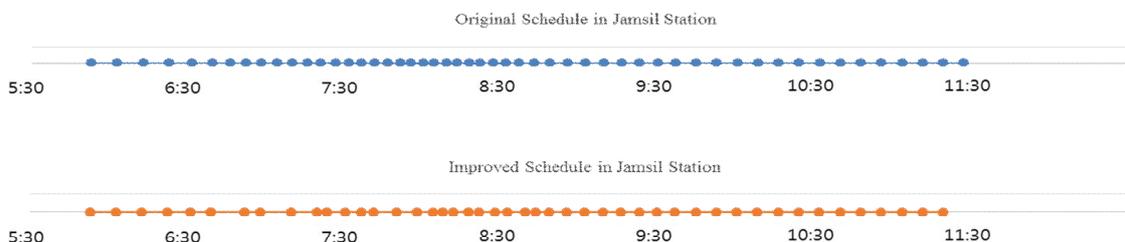


Fig. 15. Schedules at the Jamsil Station of Problem 2 and Removing the Randomly Selected Train

A big difference between the two methods is the change in average waiting time and the number of trains. The first method decreases the average waiting time, while the second method increases it. However, as shown in the total cost change, randomly removing the train shows a better result with a fewer number of trains used. This may be because the number of trains has a bigger influence on the objective 2, minimizing total cost. Moreover, in the first train removal method, if the result does not improve after the removal, the genetic algorithm will not decrease the number of trains at all. Therefore, decreasing passenger waiting time is the only way to improve the solution. Decreasing waiting time, however, has a smaller impact than decreasing the number of trains. In the random removal method, it keeps trying to decrease the number of trains randomly. Therefore, for objective 2, the second method of removing trains shows a better result due to the higher chance of removing a train.

VI. Conclusion and Future Study

In all of the experiments, using a non-periodic schedule shows a much better result, not only in terms of passenger convenience but also in operating cost. Thus, we can conclude that flexible scheduling is more effective than standard scheduling. Moreover, there are no type II passengers in any solution. Thus, we can also conclude that subway line 8 currently being under utilized is an issue. In this research, we reflect not only on the transferring passengers but also on the non-transferring passengers. Moreover, this study suggests precise estimation of transfer time. Although those topics are not new, we combine related studies into one topic to find more precise solutions. Seoul

metro periodically updates its schedule; in the case of line 8, the latest update was four or five years ago. In the next update, our findings can be applied so that the metro can consider both types of passengers as well as the adoption of a non-periodic time table. Moreover, Seoul metro faced a huge subway union strike in 2016. During that time, six or less trains were used before noon. Even with fewer trains and highly saturated conditions, Seoul metro continued to use regular scheduling. As this study proves, non-periodic schedule can give a better result and the metro should consider a more flexible scheduling in various situations.

This study has some limitations as well. We only consider trains traveling one way and with a cutoff time due to computation time. Thus, we should improve this to include both ways and a full day schedule so that methods and results can be closer to the real world. For future study, real time scheduling dependent on dynamic capacity and passengers incoming will be one possible field of research. Since real time scheduling can reflect real time or stochastic passenger data, it can be flexible in responding to any kind of situation such as an emergency or an unexpected oversaturation of the number of passengers. Additionally, updating the schedule of the first and last train by considering passenger demand could be another field of research. This study should also consider the cost for people who are unable to ride the train due to the shift in schedule.

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