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Timetable Synchronisation for the First Trains in the Day According to Actual Transfer Times

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ABSTRACT

Non-synchronised timetables of the first hour trains can lead to longer waiting times for passengers wishing to transfer at the transfer station. This study aims to reduce the waiting time of passengers by synchronising the timetables of first hour trains using actual transfer times. The transfer times of the passengers are obtained from the observations and are used in this synchronisation study. The genetic and simulated annealing algorithms are implemented to solve the first train synchronisation model. Finally, a case study is conducted on a section of the Istanbul metro network to test the synchronisation model. The results show that the total waiting time of the first hour trains transfer passengers is reduced by 35% by applying the proposed model. Another result of the study shows that using the actual transfer time instead of the average transfer time of the passengers reduces the average waiting time of the passengers by 19%.

KEYWORDS

urban rail transit; timetable; synchronisation; first train; heuristic algorithms; transfer times.

1. INTRODUCTION

Urban rail systems are transportation systems that are integrated within themselves and with other types of public transport at some transfer stations and enable passengers to travel and transfer quickly and easily with their accessibility and integration. These integration opportunities make urban rail modes superior to other modes [1]. Especially in big cities, many passengers using urban public transport travel by transfer [2]. That's why, for those passengers, the waiting time, ease of access, and in-vehicle time are the parameters that have an impact on their choice of transportation mode [3].

The urban rail system network is growing, and its share in urban transportation is gradually increasing. For example, approximately 3 million passengers use urban rail systems daily in Istanbul [4]. The number of transfer passengers is also increasing with the growth and integration of urban rail system networks. Many urban railway passengers complete their travels by making one or more transfers [5]. For transfers, getting on the next train promptly and without waiting is a critical issue for the passengers. Therefore, the timetable of different train lines in the urban railway network should be synchronised in order to minimise waiting time. The aim of many studies on optimising timetables of urban rail systems is to reduce the travel time of passengers [6–8]. When it is done for integrated urban rail systems, there are some studies on synchronising the timetables of the same or different types of public transport at transfer points to reduce passengers' waiting time and travel time [2, 9–13].

Urban rail systems do not usually operate at night, and the first departures of urban rail systems are at around 6 a.m. Normally, in the first hours of the morning, the number of passengers using public transport is low. However, in big cities, the situation is a little different. People leave their homes early due to early working hours in some workplaces, passengers leave their homes early because of the long travel times, or passengers who will travel between cities want to go to terminals such as airports, bus stations and train stations in the early hours of the morning, etc. In addition, for passengers using urban rail systems and transferring between different urban rail systems, the waiting time for the first train at the transfer stations is more important because the headway time in the early morning is higher than at other times of the day. For these reasons, a fast, efficient and coordinated urban rail system is necessary [14]. Hence, the most important purpose of synchronising the timetables for the first train in urban rail systems is to reduce the waiting times of transfer passengers. This situation may lead to rescheduling timetables in urban public transportation and urban railway systems.

Although there are many studies about train timetables and synchronisation problems, few studies focus on the synchronisation of the first train. Typically, these studies concentrate on minimising the waiting time for transfer passengers [15–24]. Although the transfer time of passengers is one of the parameters used in the synchronisation of train timetables, all researchers have assumed a constant value for the transfer time in their studies on first train synchronisation.

The transfer time is a period that is affected by many conditions, such as the physical characteristics of the passengers and the behaviour and preferences of the passengers in the wagon, on the platform, and during the transfer process, and may differ for each passenger. Only Chen considered the effect of passengers' heterogeneous walking speed on the transfer process in their study on last train synchronisation. In this study, a model was developed to increase the number of successful transfers according to the heterogeneous walking times of the passengers. However, this study did not take into account the waiting time of passengers [25]. Specifically, the existing literature overlooks an important issue related to synchronising the first train timetable. Although all transferred passengers' speeds and transfer times are unequal, the transfer time is assumed to be a fixed and known value in all studies. Hence, the distribution of passenger transfer times should be considered in the synchronisation of the first train timetable to improve the reliability of the first train timetable. This study emphasises the importance of real transfer times in synchronising timetables and utilises these individualised times to synchronise first train timetables. Additionally, this research focuses on synchronising the first train timetables for real data between the Marmaray and metro systems in Istanbul, which are operated by different entities.

The rest of this paper is structured as follows. A literature review of the train timetable and first train timetable coordination and synchronisation are presented in Section 2. Section 3 describes the materials and methods, including variables, assumptions, heuristic algorithms and solution algorithms. Then, section 4 presents the testing of the developed model in a case study, and more detailed results and discussions are given in Section 5. Finally, comparative comments on results, limitations and future research are provided in section 6.

2. LITERATURE REVIEW

There is a wealth of literature on optimising and synchronising train timetable problems. Many studies in the literature aim to reduce the waiting time of passengers [2, 9–13, 26, 27]. In some studies, synchronisation of timetables has been done by considering operating costs and energy efficiency [28, 29]. In some studies have also tried to determine the optimal number of trips for rail system routes by considering the number of passengers and trying to produce an optimal solution for passengers and operators [30]. However, the most important objective of coordinating first and last train timetables is to minimise the travel and waiting time of passengers.

Urban railway systems do not operate for 24 hours for track or fleet maintenance purposes. Generally, these aims are allotted between 00:00 a.m. and 6:00 a.m. In addition, headways are higher in the morning and at night during operation hours. Hence, synchronising the first and last-hour train timetables is more important for transferring passengers as their options are limited. From this point of view, although the purpose of the synchronisation of train timetables is to reduce the waiting times of the passengers, in addition to this purpose, maximising the total number of passengers who can reach their destinations is another purpose of the last train timetable synchronisation. There are such efforts in the literature. For example, Li [31] and Chen [32] used a genetic algorithm (GA) to solve the last train coordination problem for the Shenzen and Shangai metro networks. Yang [33] formulated a tabu search algorithm to maximise the number of last train transfer passengers considering transfer demand in Beijing. Chen [25] proposed a branch and cut algorithm to increase transfer accessibility considering heterogeneous transfer time in the Shenzen metro.

For instance, Zhou [34] developed the first train coordination optimisation model using genetic algorithms to minimise passenger and transfer waiting times. Kang [15] proposed their optimisation model considering reducing the first train's waiting times at the transfer station. They tested the model using a simulated annealing (SA) algorithm on the Beijing metro line. They stated that the total waiting time of the passengers for the first train decreased from 705.1 minutes to 567.2 minutes. In another study, Kang [16] tested the developed first train optimisation model using mixed integer linear programming (MILP) model and heuristic algorithms on the Beijing metro line and found that the total waiting time of the passengers for the first train decreased from 1,605 minutes to 345 minutes. Guo [17] emphasised the importance of lines and stations in his model for synchronising the first train timetables. It aims to reduce passenger waiting times for the first train with the model using MILP, SA, GA and particle swarm optimization (PSO). Li [18] proposed a model that was solved by using a GA to coordinate the first train timetable to minimise passenger waiting time at transfer stations in the Beijing subway. This study also focused on passenger transfer quality. Guo [19] proposed a model that used a GA to synchronise the timetables of first hour trains and buses. Li [20] used the artificial bee colony algorithm in his study to increase the number of first train transfer passengers satisfied with the waiting time. Kang [21] arranged the first train timetable using the MILP model and developed a bus bridging model coordinated with the first train operator to reduce passenger waiting times. Chai [22] tried to synchronise the first train timetables in urban railways, considering origin-destination passenger demand. They used the Non-dominated Sorted Genetic Algorithm-II in the model to improve transfer coordination. Chen [23] proposed the model to reduce passenger waiting times for the first train. Unlike other studies, they obtain better results by adding additional train services. In all of the studies in the literature, it is an important shortcoming that the transfer times of the transferred passengers are assumed to be fixed.

In most of the studies, the coordination and optimisation of timetables are performed using deterministic and heuristic approaches. Moreover, for small networks, mathematical approaches are preferred since they can provide optimal results [24]. The branch and bound (B&B) algorithm and MILP models are the exact result methods used to obtain optimal timetable coordination [35–37]. Recently, heuristic solutions such as GA, SA and PSO have been used frequently in train timetable problems [11, 38–40]. In this study, PSO and GA, which are commonly used in the literature for synchronising the timetables of the first trains, have been developed.

As mentioned above, the transfer time has been taken as an average and fixed value for all passengers in other studies in the literature. However, unlike other studies, the first train transfer times of the passengers are determined as a result of observations, and these transfer times are used in the synchronisation of the first train timetables in this study. In this way, more successful first train timetables can be made, and the total waiting time of transfer passengers can be determined more realistically. In addition, the model is tested for a real-world case, and the first train timetables of Marmaray and connecting metro lines in Istanbul are synchronised. This case is important since the two urban rail lines are managed by different operators (Marmaray by Turkish Railways, metro by Istanbul Municipality).

3. MATERIALS AND METHODS

This section presents the first train timetable synchronisation model with assumptions, notations, objective function and constraints and the solution algorithms developed by genetic algorithm and simulated annealing algorithms.

3.1 First train synchronisation model

The first train synchronisation was developed in an effort to minimise the waiting time of passengers transferring to the first train in operation. *Figure 1* illustrates the scenario of transferring passengers arriving at the transfer station from the first train on line 1 to the first train on line 2. The arrival time of the train arriving at the transfer station, the transfer time of the transferred passengers and the departure time of the train departing from the transfer station are parameters that affect the waiting times of passengers. The developed model aims to reduce the waiting time of transfer passengers, as shown in *Equation 1*. Train departure and arrival times, as well as passenger transfer times, are used in calculating passenger waiting times, as shown in *Equation 4*. Therefore, taking the transfer times of passengers as real values may provide more realistic results. In this context, the methodology of the study consists of first determining the transfer times of passengers through observations and then optimising the departure times of trains in the first hour using heuristic algorithms to reduce passenger waiting times.

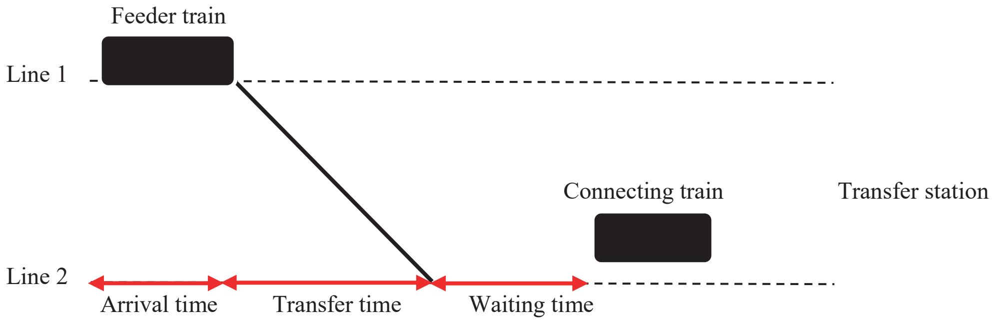

Figure 1 – First train synchronisation at a transfer station

The assumptions, notations, parameters, objective functions and constraints used in the first train synchronisation model are explained below.

We use some assumptions to facilitate the model formulations. These assumptions of the proposed model are listed below.

- The capacity of each first train at transfer stations is sufficient to provide supply to passenger demand.
- All passengers want to transfer to the first train arriving at the platform.
- The dwell time of trains is known and fixed.
- Transfer passengers arriving at the transfer stations during the first train period pass directly to the trains without stopping.
- Weekend night timetables of some lines are not taken into account because they are not applied on all lines.

The proposed first train timetable model aims to minimise total transfer waiting time.

$$W = min \sum_{s_i \in S} \sum_{l_i \in L} N_{s,l_i-l_j} \cdot t^{w}{}_{s,l_i-l_j} \tag{1}$$

As seen in *Equation 1*, the objective function of the model is to minimise the total waiting time of transfer passengers at the transfer station between the first trains. The total waiting time of transfer passengers in *Equation 1* is obtained by multiplying the number of transfer passengers by the average waiting time per passenger. For simplicity, departure times, arrival times and transfer waiting times are shown in *Equations 2–4*, respectively.

$$t^{d}_{s,l1} = t^{d}_{s0,l1} + \sum_{s_i \in S} t^{r}_{s(s-1),l1} + \sum_{s_i \in S} t^{dw}_{s(s-1),l1} + t^{dw}_{s,l1} \tag{2}$$

The departure time of the train on line (l_1) departing from transfer station (s) is calculated as described in *Equation 2* by adding the travel time of the train from the starting station to transfer station s, along with the sum of dwell times at other stations and the dwell time at station s.

$$t^{a}_{s,l2} = t^{d}_{s0,l2} + \sum_{s_i \in S} t^{r}_{s(s-1),l2} + \sum_{s_i \in S} t^{dw}_{s(s-1),l2} \tag{3}$$

The arrival time of the train on line (l_2) arriving at transfer station (s) is calculated as shown in *Equation 3* by summing the travel time from the first station of line (l_2) to transfer station (s) and the dwell time at the intermediate stations, then adding this to the departure time of the train.

$$t^{w}_{s,l2-l1} = t^{d}_{s,l1} - t^{a}_{s,l2} - t^{tr}_{s,l2-l1} \tag{4}$$

The waiting time of passengers who wish to transfer from line (l_2) to line (l_1) at transfer station (s) is calculated as described in *Equation 4*.

The constraints of the proposed first train timetable model are as follows. The departure time of the first train must be within operating hours.

$$T_{operation\ start} < t^{d}_{s,li} < T_{operation\ end} \tag{5}$$

However, since our study has different train operators, the change of operating hours for the first train is also evaluated. Headway should not be less than the minimum headway determined by train operators.

$$t^{h}_{min\,li} < t^{h}_{li} < t^{h}_{max\,li} \tag{6}$$

3.2 SOLUTION ALGORITHM

Heuristic algorithms are widely used to solve optimisation and synchronisation problems [15, 38, 41]. In this study, GA and SA from the heuristic algorithms family will be used to solve the first train synchronisation model.

GA is a research algorithm based on and developed upon the genetic processes of living things. Genetic algorithms are a search technique based on parameter coding that tries to find solutions using random search techniques [42]. Below, the fundamental steps of the GA are described in detail.

Step 1: A solution group is created in which possible solutions are coded. Because of the similarities with biology, the population and the codes of the solutions are called chromosomes. We establish the initial population of individuals with n chromosomes in which the decision variables of the problem are encoded. The difference between the departure and arrival times of the first trains will be assumed to be the genes of chromosomes. The chromosome vector is as follows.

$$\begin{bmatrix} t_{s,l1}^{d1} - t_{s,l2}^{a1} & t_{s,l1}^{d2} - t_{s,l2}^{a2} & \dots & t_{s,l1}^{dd} - t_{s,l2}^{ad} \\ t_{s,l1}^{d1} - t_{s,l3}^{a1} & t_{s,l1}^{d2} - t_{s,l3}^{a2} & \dots & t_{s,l1}^{dd} - t_{s,l3}^{ad} \\ \dots & \dots & \dots & \dots \\ t_{s,l1}^{d1} - t_{s,ln}^{a1} & t_{s,l1}^{d2} - t_{s,ln}^{a2} & \dots & t_{s,l1}^{dd} - t_{s,ln}^{ad} \end{bmatrix}$$

The number of trains departing in the first train hour formed the gene number. The number of intersecting lines also constitutes the number of columns of the vector.

Step 2: Calculate each chromosome's objective function values. The aim function in our study is to minimise the waiting time.

Step 3: Individuals from the existing population to be crossed and mutated must be selected to create the new population. According to the theory, good individuals should continue their lives, and new individuals should be formed. Therefore, individuals with higher fitness values (f_v) are more likely to be selected in all selection methods. The roulette wheel method will make the selection in our model. For each individual, the probability of being selected (p_i) is calculated. i=(1,2,…,N) where N equals the number of individuals in *Equation 7*.

$$p_i = \frac{f_v}{\sum_{i=1}^{N} f_v} \tag{7}$$

Then, the cumulative probability (q_i) is calculated for each individual. If the randomly selected r number between 0–1 is less than q_1, we choose the value q_1. In this way, we will select individuals with big fitness values.

Step 4: The crossover function generates new individuals from individuals selected by the roulette wheel. The single-point crossover will be used in the study. The crossover probability will be taken as p_{cross}=0.95. Individuals obtained after crossover are expected to be better than crossover individuals, but this may not always be true. A mutation operation is performed if the similarity between individuals cannot be changed by crossover.

Step 5: The presence of identical individuals in the community can be prevented with the mutation function. It is also expected to obtain an individual with a better score than the mutated individual. We will take the mutation probability as $p_{mutation}$=0.01.

Step 6: We will form the intermediate population with the best individuals. If the criterion is met, the algorithm is terminated.

Step 7: The calculations are repeated from Step 1 until the termination criterion is met.

A simulated annealing algorithm generally consists of an initial solution, a neighbour solution generation method, and an annealing program. The function of the annealing process is to cycle between good and bad solutions and find the best solution, starting with a solution at a sufficiently high temperature and gradually decreasing the temperature [43]. The values created according to the passenger waiting times obtained by *Equation 4* will be cooled by the annealing simulation algorithm, and the best solution will be found in our study. The steps of the simulated annealing algorithm in synchronising the first train timetables are as follows.

Step 1: Form our initial solution with the passenger waiting times of transfer passengers.

Step 2: Cool the initial algorithm with the cooling efficient (C_C=0.90) from the starting (T=1000) to the ending T_{end}=1 temperature.

Step 3: Then, we have two objective values. If $v_{new}>v_{old}$, we will accept v_{new} as a solution; if $v_{new}<v_{old}$, we will calculate the acceptance probability with *Equation 8.*

$$P = e^{-\Delta/T} \tag{8}$$

$$\aleph \quad v_{new} \quad v_{old} \tag{9}$$

Step 4: When the cooling process is finished, the algorithm ends. Thus, we will find the best solution.

4. A CASE STUDY

In this study, the proposed model is tested in synchronising the timetables of Marmaray and the M1, M2, M4 and M5 lines integrated with Marmaray in Istanbul. According to Stoilava et al. [44], Istanbul, which had a 138 km rail network in 2013, currently has a 303 km rail network and is planned to increase further. More than 3 million passengers in Istanbul travel daily on the 303 km rail network. The selected lines are among the most demanded lines in the city, with a total ridership of approximately 2 million passengers per day. A schematic presentation of the structure and connection points of selected lines is given in *Figure 2.* The M1 light rail system consists of the M1A and M1B lines. M1A Yenikapı-Atatürk airport line serves between Yenikapı-Şirinevler stations after the closure of Atatürk airport. The total number of stations is 15, and the travel time is 30 minutes, with the first departure at 06:00 a.m. The minimum headway time on the daily timetable is 6 minutes. The M1B Yenikapı-Kirazlı line also consists of 13 stations and has a travel time of 25 minutes. The minimum headway time for this line is given as 4 minutes. The M2 Yenikapı-Hacısoman line consists of 16 stations and is 23.5 km long with a travel time of 32 minutes. The first service of the line is at 05:57 a.m. and the minimum headway time is 3 minutes. The M4 Kadıköy-Tavşantepe line is 34 km long. There are 23 stations on the line with a journey time of 50 minutes. The line has a minimum headway time of 4 minutes; the first service is at 06:00 a.m. The 20 km long M5 Üsküdar-Çekmeköy line consists of 16 stations and has a journey time of 32 minutes. The minimum headway time of the line is 4 minutes, with the first departure at 06:00 a.m. Marmaray is a suburban line that connects Asia and Europe and crosses the Bosphorus. The line has 43 stations and its length is 76 km. Trains are operated at intervals of 8 and 15 minutes on the line with a running time of 115 minutes. Marmaray is integrated with the M1 and M2 lines at Yenikapı station, with the M4 line at Ayrılıkçeşme station, and with the M5 line at Üsküdar station [4].

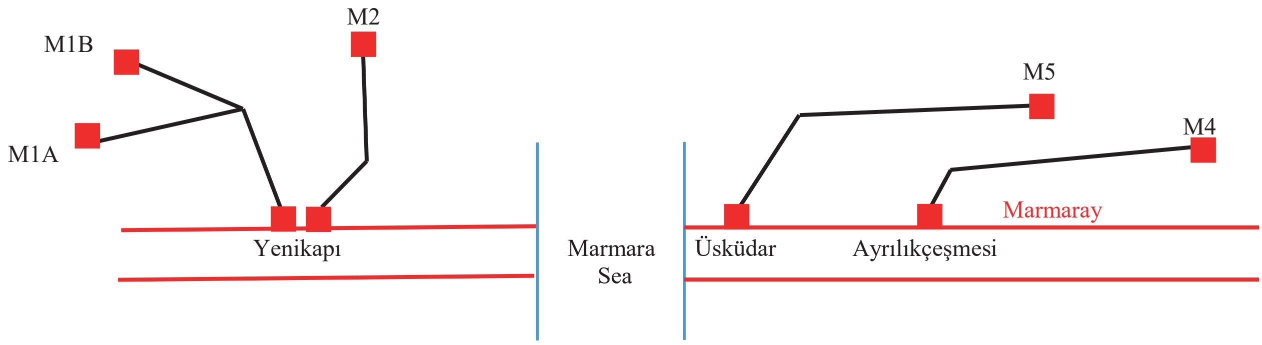

Figure 2 – Schematic map of the sample network

4.1 Transfer times

The transfer time of the passengers is one of the important parameters in the model. Therefore, the varying transfer times are collected through observation of passengers in the Yenikapı, Ayrılıkçesmesi and Üsküdar stations. All observations are made for 100 passengers. Marmaray is integrated into three metro lines in Yenikapı. In Yenikapı, fifty observations were made during daytime and first train hours when the passenger density was not high between January and June 2023 for Marmaray-M1A, Marmaray-M1B and Marmaray-M2. Furthermore, 100 passengers were used for all measurements. The histograms of the transfer times of the passengers obtained from the observations are given in *Figure 3*, *Figures 4 and 5*. The histograms in *Figures 3–7* show the average transfer times and standard deviations between the indicated lines for 100 transfer passengers.

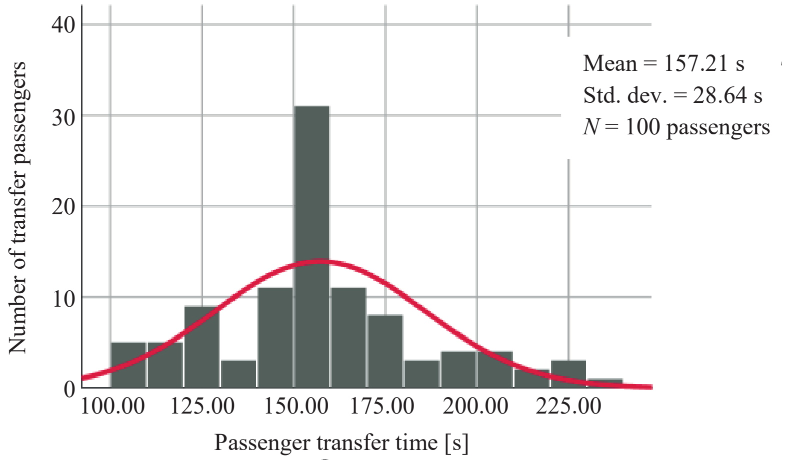

Figure 3 – Passenger transfer time between Marmaray and M1A

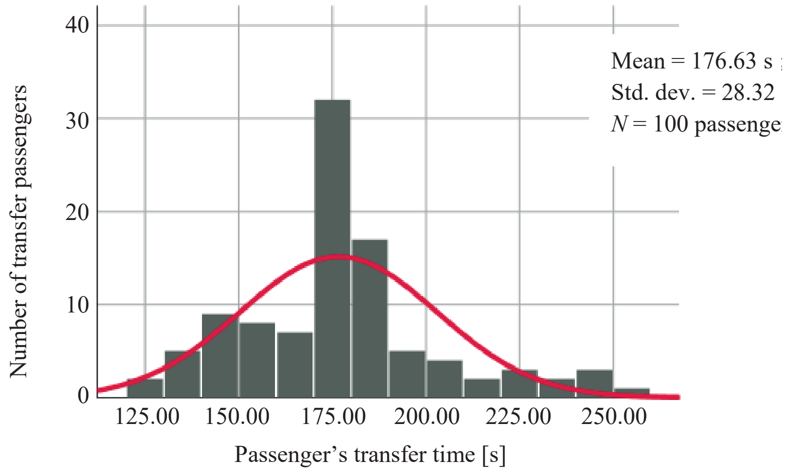

Figure 4 – Passenger transfer time between Marmaray and M1B

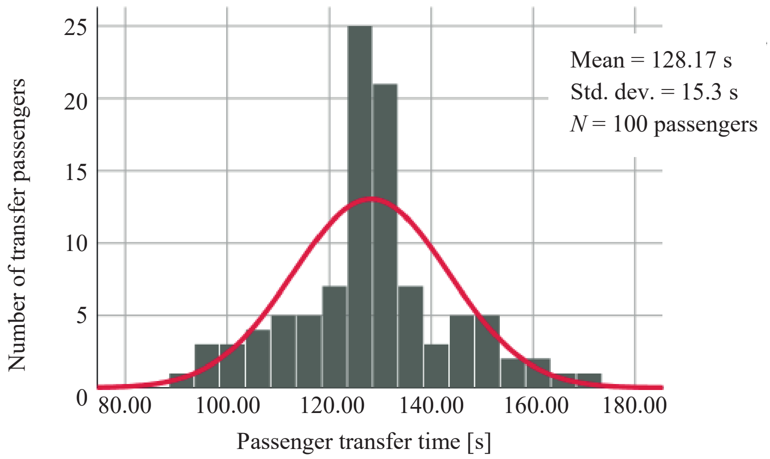

Figure 5 – Passenger transfer time between Marmaray and M2

Ten observations were made in June 2023 for Marmaray-M4 and Marmaray-M5 in Ayrılıkçeşmesi and Üsküdar. The histograms of the transfer times of the passengers obtained from the observations are given in *Figures 6 and 7*. All observations were made during off-peak hours.

Table 1 gives the minimum, average, and maximum transfer times of the five transfers for which the normal distribution graphs of the passenger transfer times are given.

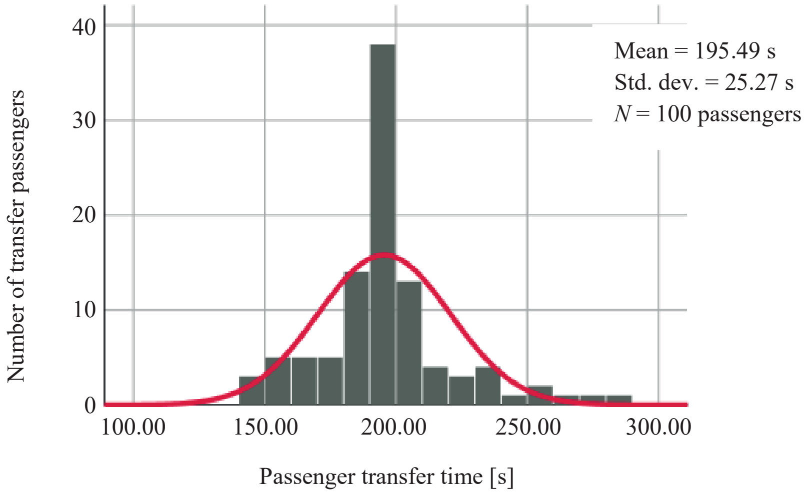

Figure 6 – Passenger transfer time between Marmaray and M4

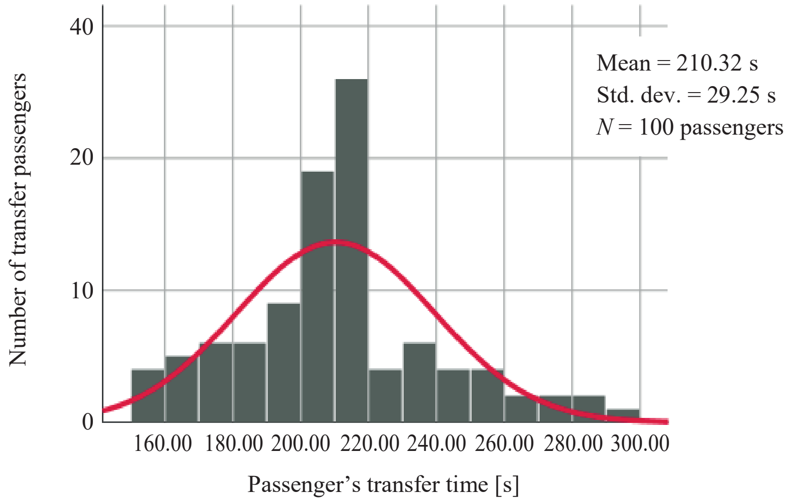

Figure 7 – Passenger transfer time between Marmaray and M5

Table 1 – Passenger transfer time

Transfer station	Transfer direction	Transfer times [s]			Standard deviation [s]
		Minimum	Average	Maximum	
Yenikapı	Marmaray↔M1A	100	158	230	26
	Marmaray↔M1B	120	177	250	25
	Marmaray↔M2	91	128	170	15
Ayrılıkçeşmesi	Marmaray↔M4	140	195	280	25
Üsküdar	Marmaray↔M5	152	210	295	29

The transfer time of each passenger can be a separate value. Taking the transfer times of all passengers as the same and the average value in synchronising the timetables may lead to unrealistic results in practice. Therefore, the waiting time of the passengers in synchronising the first train timetables will be calculated by considering the transfer times shown between *Figures 3 and 7*.

4.2 Timetables

This section contains original and optimal first train timetables for our sample lines.

Table 2 – Original timetables

Transfer station	Transfer direction	Arrival time	Departure time	Number of transfer passenger	Average waiting time per passenger for transfer [s]	Total waiting time [min]
Yenikapı	Marmaray–M1A	06:06:00	06:10:00	25	72	30.0
	Marmaray–M1A	06:00:00	06:10:00	25	442	184.2
	M1A–Marmaray	06:29:00	06:36:00	20	262	87.3
	M1A–Marmaray	06:29:00	06:38:00	40	382	254.7
	Marmaray–M1B	06:06:00	06:15:00	25	363	151.3
	Marmaray–M1B	06:00:00	06:05:00	25	123	51.3
	M1B–Marmaray	06:23:00	06:29:00	20	183	61.0
	M1B–Marmaray	06:23:00	06:30:00	40	243	162.0
	Marmaray–M2	06:06:00	06:12:00	20	232	77.3
	Marmaray–M2	06:00:00	06:04:00	20	112	37.3
	M2–Marmaray	06:29:00	06:36:00	25	292	121.7
	M2–Marmaray	06:29:00	06:38:00	50	412	343.3
Ayrılıkçeşmesi	Marmaray–M4	06:10:00	06:20:00	10	405	67.5
	Marmaray–M4	06:11:00	06:20:00	50	345	287.5
Üsküdar	Marmaray–M5	05:59:00	06:09:00	10	330	55.0
	Marmaray–M5	06:07:00	06:18:00	30	450	225.0
	M5–Marmaray*	06:33:00	06:37:00	20	39	13.0
	M5–Marmaray	06:33:00	06:45:00	5	458	38.2
	M5–Marmaray*	06:33:00	06:36:00	5	14	1.2
	M5–Marmaray	06:33:00	06:44:00	20	442	147.3

Table 2 shows the first train timetable information for the lines in the case study, the number of transfer passengers, the average waiting times and the total waiting time of passengers who can be transferred. In the row indicated with * in *Table 2*, some passengers could transfer to the first train, and the rest could be transferred to the next train. The average waiting times of the passengers here are calculated considering this situation. Furthermore, the total waiting times presented in *Tables 2–4* were calculated by multiplying the number of passengers wishing to transfer between the specified lines and times by the waiting time of these passengers.

Table 3 was obtained by optimising the first train timetables and passenger information in *Table 2* with the model we developed using a GA for first train synchronisation. In the algorithm, the number of population was 50, the crossover probability was 0.9 and the mutation probability was 0.01. *Table 3* is the optimisation result with GA for synchronising the first train timetables. The departure times presented in *Table 3* were obtained by optimising the train departure times listed in *Table 2* using a GA to minimise the waiting times of passengers transferring to the first trains. Based on the arrival and departure times of the trains in *Table 3*, the average waiting times of passengers were multiplied by the number of transferred passengers, resulting in the calculation of the total waiting times for passengers in *Table 3.*

Table 4 shows the data obtained from the first train synchronisation with the SA. In the algorithm, we started the temperature at 1000 degrees and cooled it down to 1 degree. We also took the cooling coefficient as 0.9 and the number of iterations as 100. *Table 4* shows the average waiting time per passenger and the total waiting time of the passengers transferring at the first train time on the sample lines after optimisation with SA.

Table 3 – Optimal timetables with GA

Transfer station	Transfer direction	Arrival time	Departure time	Number of transfer passenger	Optimal waiting time per passenger for transfer [s]	Total waiting time [min]
Yenikapı	Marmaray–M1A	06:06:00	06:10:10	25	62	25.8
	Marmaray–M1A	06:00:00	06:05:10	25	152	63.3
	M1A–Marmaray	06:30:00	06:36:00	20	202	67.3
	M1A–Marmaray	06:30:00	06:37:30	40	272	181.3
	Marmaray–M1B	06:06:00	06:13:10	25	253	105.4
	Marmaray–M1B	06:00:00	06:04:40	25	103	42.9
	M1B–Marmaray	06:23:30	06:29:00	20	153	51.0
	M1B–Marmaray	06:23:30	06:29:45	40	198	132.0
	Marmaray–M2	06:06:00	06:11:30	20	202	67.3
	Marmaray–M2	06:00:00	06:03:45	20	97	32.3
	M2–Marmaray	06:30:00	06:36:00	25	232	96.7
	M2–Marmaray	06:30:00	06:37:30	50	282	235.0
Ayrılıkçeşmesi	Marmaray–M4	06:10:00	06:18:30	10	275	45.8
	Marmaray–M4	06:11:10	06:18:30	50	265	220.8
Üsküdar	Marmaray–M5	05:59:00	06:07:55	10	265	44.2
	Marmaray–M5	06:07:00	06:13:00	30	150	75.0
	M5–Marmaray*	06:33:10	06:37:00	19	31	9.8
	M5–Marmaray	06:33:10	06:38:40	6	76	7.6
	M5–Marmaray*	06:33:10	06:36:00	4	9	0.6
	M5–Marmaray	06:33:10	06:38:50	21	130	45.5

Table 4 – Optimal timetables with SA

Transfer station	Transfer direction	Arrival time	Departure time	Number of transfer passenger	Optimal waiting time per passenger for transfer [s]	Total waiting time [min]
Yenikapı	Marmaray–M1A	06:06:00	06:10:00	25	72	30.0
	Marmaray–M1A	06:01:20	06:10:00	25	362	150.8
	M1A–Marmaray	06:29:40	06:35:00	20	162	54.0
	M1A–Marmaray	06:29:40	06:37:00	40	282	188.0
	Marmaray–M1B	06:06:00	06:13:40	25	263	109.6
	Marmaray–M1B	06:00:00	06:04:40	25	103	42.9
	M1B–Marmaray	06:23:00	06:27:40	20	103	34.3
	M1B–Marmaray	06:23:00	06:28:20	40	143	95.3
	Marmaray–M2	06:06:00	06:10:30	20	142	47.3
	Marmaray–M2	06:00:00	06:03:10	20	62	20.7
	M2–Marmaray	06:29:00	06:34:30	25	202	84.2
	M2–Marmaray	06:29:00	06:37:00	50	352	293.3
Ayrılıkçeşmesi	Marmaray–M4	06:10:00	06:19:00	10	345	57.5
	Marmaray–M4	06:11:30	06:19:00	50	255	212.5
Üsküdar	Marmaray–M5	05:59:00	06:07:30	10	240	40.0
	Marmaray–M5	06:07:00	06:17:10	30	400	200.0
	M5–Marmaray*	06:33:10	06:36:05	3	39	2.0
	M5–Marmaray	06:33:10	06:45:00	22	448	164.3
	M5–Marmaray*	06:33:00	06:35:40	1	3	0.1
	M5–Marmaray	06:33:00	06:42:30	24	352	140.8

5. RESULTS AND DISCUSSION

Table 5 shows the total and average waiting times of the first train transfer passengers due to the optimisation we have done to reduce the waiting times of the first train transfer passengers. According to these results, it is seen that we obtained the best result with the GA for the first train synchronisation model.

Table 5 – Comparison of algorithms with real transfer times

Number of transfer passengers	Total waiting times for transfer passengers [min]			Average waiting time per passenger for transfer [s]		
	Original	GA	SA	Original	GA	SA
485	2396	1550	1968	296	192	243

In *Table 5*, while the total waiting time of the transfer passengers was 2396 minutes, this time decreased to 1550 minutes with the GA and 1968 minutes with the SA thanks to the first train synchronisation model. Thus, it can be seen that the average waiting time of the first train passengers is reduced by 104 seconds per passenger with the GA synchronisation model.

Many studies on timetable synchronisation use transfer times as a fixed and average value. The most commonly used transfer times are 2 and 3 minutes [16, 22, 23, 34]. All transfer passengers are assumed to travel at the average transfer time in these studies. If the transfer times were taken as an average value for each passenger in our study, for example, if we had taken the most commonly used 2 and 3 minutes, the total waiting times for the first train passengers as a result of our study would be as shown in *Table 6.*

Table 6 – Comparison of algorithms with fixed transfer times

Number of transfer passengers	Total transfer waiting times [min]			Average waiting time per passenger for transfer [s]		
	Original	GA	SA	Original	GA	SA
485	2426	1910	2422	300	236	300

Table 6 shows that when we take a fixed and average value as transfer time, the reduction in total transfer times is less, thanks to the first train synchronisation model. It can also be seen that the average waiting time per passenger is reduced by 64 s with the GA, while there is no reduction with the SA.

Table 7 – The sensitivity analysis of the results

Transfer time	Average waiting time per passenger for transfer [s]			Improvement		
	Original	GA	SA	Original	GA	SA
Fixed	300	236	300			
Real	296	192	243	1%	19%	19%

Table 7 shows that the average waiting time of passengers is reduced by 35% with the GA synchronisation model using the real transfer time. *Table 7* also shows a 19% reduction in average passenger waiting times in the GA and SA synchronisation models when the real transfer time is used instead of the average transfer time.

The average waiting time of the passengers as a result of the optimisation according to the actual and fixed transfer times is shown in *Figure 8*. When the actual values of the transfer times of the passengers are taken instead of the average value, it is seen in *Figure 8* that there is a decrease in the passenger waiting times. The results in *Figure 8* show the importance of the purpose of the study.

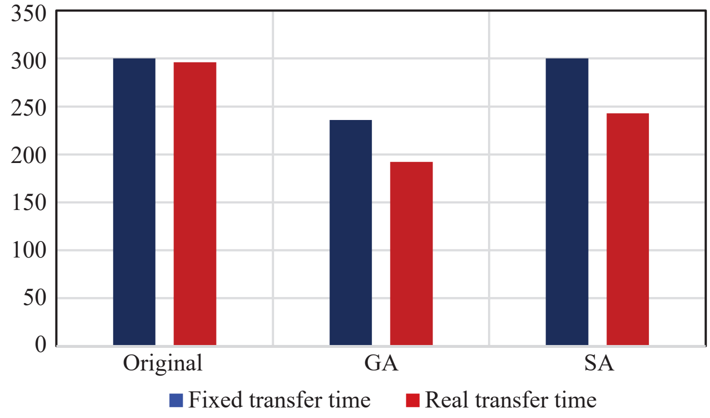

Figure 8 – Comparison of average waiting time of passengers

6. CONCLUSION

The problem of synchronisation of first train timetables has become an inevitable optimisation problem that needs to be solved in the integrated urban rail system network. In recent years, studies have been carried out to solve this problem and the general aim of these studies is to minimise the waiting time of transfer passengers. This study emphasises that in most of the literature, passenger transfer times are assumed to be constant and represented as an average value, as highlighted in some references [16, 22, 23, 34]. However, it is important to emphasise that considering transfer times as a constant and average value for all passengers is not in line with real data. For example, *Table 1* shows that the average transfer time for 100 passengers on the Marmaray and M4 lines varies between 140 and 280 seconds, resulting in an average transfer time of 195 seconds. If an average transfer time of 195 seconds is assumed and schedules are synchronised accordingly, it is presumed that all 100 passengers can be transferred in 195 seconds. However, based on the data available for this sample, it is understood that only 59 out of 100 passengers can be transferred in 195 seconds. Therefore, it is important to determine passenger transfer times more accurately and based on real data. This approach is crucial for optimising transportation systems more effectively. Hence, it is important to use more realistic and data-driven approaches for determining transfer times instead of assuming a fixed average.

As the example shows, defining the transfer time with realistic data is crucial to synchronise the timetables. Therefore, the transfer time distributions of the passengers shown in *Figures 3–7* were obtained from approximately 50 measurements in the last 6-month period to use the actual transfer time data in the synchronisation of the first train timetables. This paper emphasises the importance of incorporating actual passenger transfer times into the synchronisation of the first train timetables. For this purpose, the transfer processes of passengers on selected train lines were observed, and the transfer times of passengers were recorded. When synchronising the first train timetables using heuristic algorithms like GA and SA, it was found that there was a 35% reduction in average waiting times per passenger with the GA and an 18% reduction with the SA when real transfer data were utilised. Additionally, both algorithms achieved a 19% reduction in waiting time per passenger by employing real transfer time data instead of the average transfer time assumed in some literature [16, 22, 23, 34]. This study contributes to the synchronisation literature by using actual passenger transfer times to improve the synchronisation of train timetables.

It is important to note that although measurements were made on sample lines to collect actual transfer data, the specific passengers present during the transfer are unknown. Therefore, longer-term observations of passenger transfer processes can provide valuable insights.

In future studies, it may be useful to model passenger behaviour during the transfer process. This modelling could help assess the impact on the transfer process and the synchronisation of train schedules. Understanding passenger behaviour and its impact on transfers can lead to more efficient and precise optimisation of urban railway systems.

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Gerçek Transfer Sürelerine Göre Günün İlk Trenleri için Zaman Çizelgesi Senkronizasyonu

Özet

İlk saat trenlerinin zaman çizelgelerinin senkronize olmaması, aktarma istasyonunda aktarma yapmak isteyen yolcular için daha uzun bekleme sürelerine neden olabilir. Bu çalışma, gerçek transfer sürelerini kullanarak ilk saat trenlerinin zaman çizelgelerini senkronize ederek, yolcuların bekleme sürelerini azaltmayı amaçlamaktadır. Yolcuların transfer süreleri gözlemler sonucunda elde edilmiş ve bu senkronizasyon çalışmasında kullanılmıştır. İlk tren senkronizasyon modelini çözmek için genetik ve benzetilmiş tavlama algoritmaları uygulanmıştır. Senkronizasyon modelini test etmek için İstanbul metro ağının bir bölümünde bir vaka çalışması yapılmıştır. Sonuçlar, önerilen modelin uygulanmasıyla ilk saat trenlerine transfer olan yolcularının toplam bekleme süresinin %35 oranında azaldığını göstermektedir. Çalışmanın bir diğer sonucu ise yolcuların ortalama aktarma süresi yerine gerçek aktarma süresinin kullanılmasının, yolcuların ortalama bekleme sürelerini %19 oranında azalttığını göstermesidir.

Anahtar kelimeler

kentsel raylı ulaşım; zaman çizelgesi; senkronizasyon; ilk tren; sezgisel algoritmalar; transfer süreleri.