SIMULATION & ANALYSIS OF İZMİR METRO TRANSPORTATION SYSTEM

Güler ÖZTÜRK

Thesis Advisor: Asst.Prof.Dr.Adalet ÖNER

Department of Industrial Management and Information Systems

Bornova – İZMİR

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YAŞAR UNIVERSITY

GRADUATE SCHOOL OF NATURAL AND APPLIED SCIENCES

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This study titled "SIMULATION & ANALYSIS OF IZMIR METRO TRANSPORTATION SYSTEM" and presented as MSc Thesis by Güler ÖZTÜRK has been evaluated in compliance with the relevant provisions of Y.U Graduate Education and Training Regulation and Y.U Institute of Science Education and Training Direction and jury members written below have decided for the defence of this thesis and it has been declared by consensus / majority of votes that the candidate has succeeded in thesis defense examination dated August 08, 2012.

Jury Members :	**Signature:**
Head : ………………	…………….
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ÖZET

İZMİR METRO ULAŞIM SİSTEMİNİN BENZETİM YOLUYLA ANALİZİ

ÖZTÜRK, Güler

Yüksek Lisans Tezi, Endüstriyel Yönetim ve Bilişim Sistemleri Programı

Tez Danışmanı: Yrd. Doç. Dr. Adalet Öner

Ağustos 2012, 71sayfa

Bu tezde İzmir Metro ulaşım sisteminin büyük ölçekli bir benzetim modeli geliştirilmiştir. Model, kesikli-olay simülasyon yaklaşımı ile ARENA^{TM} programını kullanılarak oluşturulmuştur. Çalışmanın amacı metro operasyonlarının analizi ve etkinliğinin değerlendirilmesidir. Performans kriterleri enerji maliyeti, yolcuların ortalama bekleme süreleri ve konforudur.

Çalışma klasik simulasyon çalışmalarında olduğu gibi veri toplama, girdi analizi, modelin kurulması, geçerliliğinin sağlanması & doğrulama, deneysel tasarım ve çıktı analizi bölümlerinden oluşmaktadır.

Yolcuların istasyonlara gelişlerine ilişkin son 15 ayı içeren 50 milyondan fazla kayıt analiz edilerek ARENA^{TM} modeline girdi olarak kullanılmıştır. Yolcuların gelişleri "non-stationary" Poisson prosesine göre modellenmiştir. Model günde 135,000 den fazla yolcuyu yaratarak işlemektedir. Modelin koşturulması sonunda her seferde trenlerdeki ortalama yolcu sayıları, yolcuların istasyonlardaki ortalama bekleme süreleri gibi metro yönetiminin daha önce sahip olmadığı bilgiler edinilmiştir. Ayrıca operasyon etkinliğini arttıracak önerilerde bulunulmuştur.

Anahtar sözcükler: benzetim, modelleme, ulaşım sistemi

ABSTRACT

SIMULATION & ANALYSIS OF IZMIR METRO TRANSPORTATION SYSTEM

ÖZTÜRK, Güler

MSc in Industrial Management and Information Systems

Supervisor: Asst.Prof. Dr. Adalet Öner

August 2012, 71 pages

This study concerns with developing a large-scale simulation model of Izmir metro transportation system. The model is based on discrete-event simulation approach and it is developed using ARENA^{TM} simulation software. The goal is to make an analysis and evaluate the effectiveness of operations in metro line. The performance criteria of effectiveness are the cost of energy spent for operations, waiting time of passengers at stations and the comfort of the passengers.

The study is designed to be in accordance with the stages which a typical simulation study consists of: data collection, input analysis, model building, verification and validation, experimental design and output data analysis.

Historical data containing more than 50 million records about the arrivals of passengers have been analyzed, interpreted and compiled as an input to the simulation model. Arrivals of passengers are modeled as a non-stationary Poisson process. The model creates and processes more than 135,000 passengers daily. The simulation model delivers some useful information that the management didn't have before such as average number of passengers in the train across stations, average waiting time of passengers at stations etc. Some recommendations have been made to improve the efficiency of metro operations.

Keywords: Simulation, modeling, transportation systems

ACKNOWLEDGEMENTS

I would like to express my sincere appreciation to my supervisor Asst.Prof.Dr.Adalet Öner for his great guidance, criticism, encouragement and support.

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Finally, I would like to give my special thanks to my family for their understanding, support and patience.

TEXT OF OATH

I declare and honestly confirm that my study titled “SIMULATION & ANALYSIS OF IZMIR METRO TRANSPORTATION SYSTEM”, and presented as Master’s Thesis has been written without applying to any assistance inconsistent with scientific ethics and traditions and all sources I have benefited from are listed in bibliography and I have benefited from these sources by means of making references.

08 /08 / 2012
Güler ÖZTÜRK

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1. INTRODUCTION

Izmir Metro Inc. is affiliated with Great Municipality of Izmir. It runs a part of public transportation system having 12 km in length and carrying approximately 135,000 passengers a day in the average. The goal of the company is to provide comfortable, economical, and safe transportation for people of Izmir.

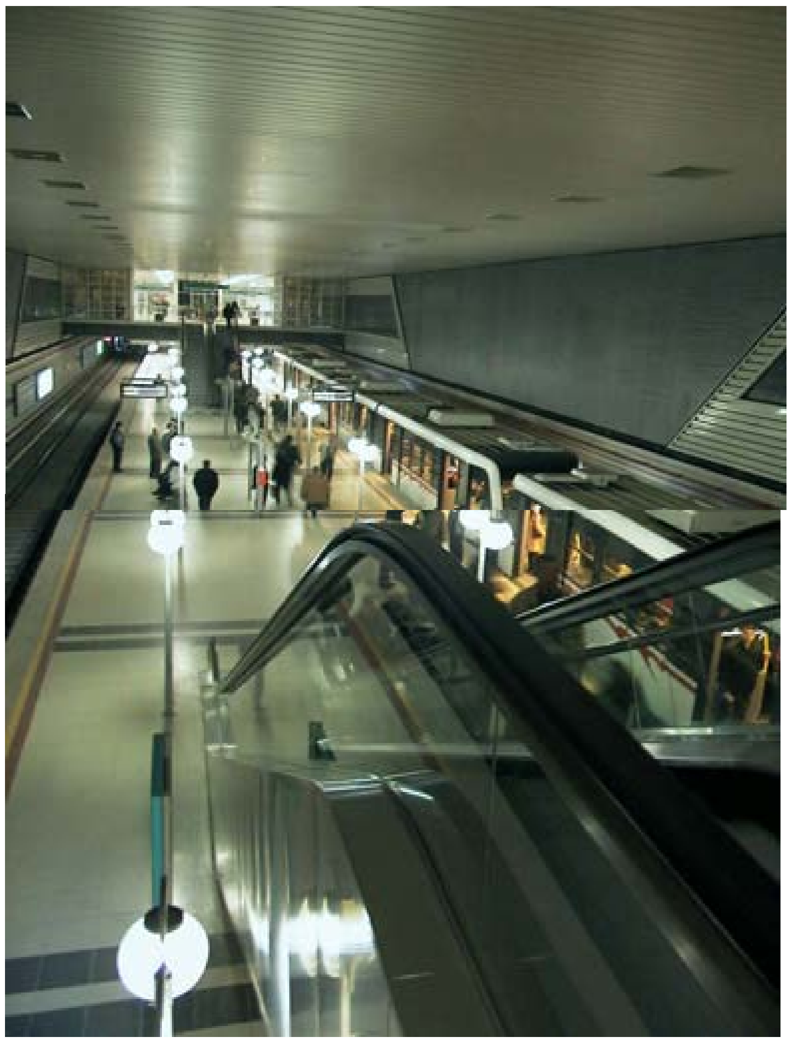

Figure 1.1 “Konak” station of Izmir Metro Line

The metro line has 10 stations. The names of stations are (“Üçyol”, “Konak”, “Çankaya”, “Basmane”, “Hilal”, “Halkapınar”, “Stadyum”, “Bölge”, “Bornova”) respectively in west-east direction. The first and last stations are terminuses where trains begin and finish their trips in the line. The distance between stations varies between 0.8 - 1.6 km. There are totally 30 escalators for easy access and 32 special elevators for disabled passengers. All station platforms have a 125 m long and are suitable to accommodate the operation of a train with up to 5 coaches.

Figure 1.2 “Halkapınar” station.

The company wants to improve its management system alongside with its technology and equipment in order to assure providing comfortable, economical, and safe transportation for people of Izmir. For this reason, the management wants to establish an integrated management system that is capable of assessing operations depending on measurable performance criteria. This study includes a simulation model of the metro line and it is a part of or a basis for the integrated management system to be established.

A typical simulation study consists of several steps such as data collection, input analysis, model building, verification and validation, experimental design and output data analysis. This study is designed to be in accordance with those stages and it consists of 8 chapters. The next chapter describes the operations of metro line and makes a formal definition of the problem. Chapter 3 includes literature survey on the simulation model of public transportation systems. Input analysis for the simulation model is provided in Chapter 4. The simulation model and its details are given in Chapter 5. Subsequently verification and validation is presented in Chapter 6. Output Analysis of the simulation model is the subject of Chapter 7. Finally the experimental results, outcomes of the simulation, discussions and recommendations are presented in Chapter 8.

2. STATEMENT OF THE PROBLEM

In this chapter, operations of metro line will be described first. The operational environment in which the problem arises will be mentioned and then the formal definition of the problem will be given.

2.1 Operations in Metro Line

Current metro line consists of 10 stations that are located in the southeast to northwest direction. The line has two tracks therefore trains can travel in both directions simultaneously. The layout of metro line is shown in Figure 2.1.

Figure 2.1 Layout of İzmir Metro Line.

"Halkapınar" station is the midpoint of this line which consists of management center and maintenance facilities. Besides, it serves as parking lot for trains. The trains access and leave the metro line at this station. There are 45 coaches and each coach has 44 seats. There is additional 34 m^2 of empty space for standing passengers who can't have a seat when the coach is crowded. Under congested situations, if the passengers take all seats in a coach, some additional passengers can still get in the coach as straphangers in the empty space. Maximum number of straphangers is physically limited to 6 persons per square meter. In such a case, each coach may have up to 248 passengers. This is the maximum capacity which creates uncomfortable voyage and it is not desirable. The company wants to provide a service not to exceed 3 standing passengers per square meter of empty space which means 146 passengers per coach.

A train which arrives at a terminus should be ready for the next trip on the opposite direction. However, there is not enough space to make a complete U-turn. Instead of that, it makes a simple manoeuvre to change the track and therefore to reposition itself such that its former tail becomes the head. It is now ready for the next trip in the opposite direction. In this way, trains keep travelling in cycles at the metro line. In order to keep the safety margins within limits, only 6 trains will be allowed to move in the same direction. Trains may consist of double, triple, quadruple or even more coaches. However, it is possible to change the number of coaches of a train only at “Halkapınar” station since other stations have no enough space and equipment.

The line consists of 2 tracks. The trains always use the “right” track relative to the direction they take. Except the emergency situations, trains are not allowed to change tracks.

Figure 2.2 Tracks of Metro Line.

Electrical energy is used to run the trains. A train with 4 coaches can have a maximum speed of 80 km per hour. However, average traveling speed is 40 km per hour because of the safety precautions and for the limited distances between stations. The cost of energy consumed is 0,70 TL/km per coach at the average speed.

The system begins operating at 6 o'clock of every day where trains start their daily tours. Traveling times between stations are known since the distances between stations are fixed. When a train arrives at a station, it waits for a specific period of time (dwell time) for passengers get in and get off the train. Dwell times are different for particular stations. The train closes its doors automatically when the dwell time ends and moves next station. The total time to complete a one-way trip is between 16 to 18 minutes. The travelling times between stations and dwell times are given in the following tables.

Table 2.1 Travelling times between stations (in seconds)

From	**To**	**Notes**	**Duration Time (Sec.)**
Üçyol	Üçyol	turning and preparing in the reverse direction	150
Üçyol	Konak	-	116
Konak	Çankaya	-	76
Çankaya	Basmane	-	64
Basmane	Hilal	-	84
Hilal	Halkapınar	-	97
Halkapınar	Stadyum	-	96
Stadyum	Sanayi	-	81
Sanayi	Bölge	-	81
Bölge	Bornova	-	79
Bornova	Bornova	turning and preparing in the reverse direction	90

Table 2.2 Dwell times at stations (in seconds)

Station	Duration (sec)
konak station	33
çankaya station	33
basmane station	30
hilal station	15
halkapınar station	20
stadyum station	20
sanayi station	15
bölge station	20

When system starts to operate at 06:00 A.M., the number of passengers is relatively small. The headway (time interval between consecutive trips at a station) is 10 minutes at the beginning. The arrival rate of the passengers gets higher as time advances to rush hours, therefore headway gets shorter and shorter. The duration of headway is controlled by the number of trains in the system. At the beginning there are 4 trains, but it becomes 5, 6, 7, 8, 9 and finally 10 trains at rush hours in the morning. The headway decreases to 4 minutes at that moment. The arrival rate of passenger decreases gradually after 9:00 A.M., and therefore the trains are pulled out of system one by one. It is responsive arrangement to the fluctuations of arrival rate. Similarly, the number of trains in the system increases again in the evening rush hours. There are 190 trips in each direction which means 380 trips in total a day. Current train schedule is given in the Table 2.3.

Table 2.3 Current schedule of trains

Train No	Time	Train No	Time	Train No	Time	Train No	Time
1	06:00:00	**3**	07:30:00	**8**	08:18:00	**5**	09:07:30
3	06:10:00	**9**	07:34:00	**2**	08:22:00	**4**	09:10:00
2	06:20:00	**8**	07:38:00	**5**	08:26:00	**10**	09:15:00
4	06:30:00	**2**	07:42:00	**4**	08:30:00	**7**	09:20:00
1	06:40:00	**5**	07:46:00	**10**	08:34:00	**1**	09:25:00
3	06:50:00	**4**	07:50:00	**7**	08:38:00	**3**	09:30:00
2	07:00:00	**10**	07:54:00	**1**	08:42:00	**9**	09:37:30
5	07:05:00	**7**	07:58:00	**6**	08:46:00	**8**	09:40:00
4	07:10:00	**1**	08:02:00	**3**	08:50:00	**2**	09:45:00
7	07:15:00	**6**	08:06:00	**9**	08:54:00	**4**	09:52:30
1	07:20:00	**3**	08:10:00	**8**	09:00:00	**10**	10:00:00
6	07:25:00	**9**	08:14:00	**2**	09:05:00	**1**	10:07:30

Table 2.3 Current schedule of trains(continued)

Train No	Time	Train No	Time	Train No	Time	Train No	Time
3	10:15:00	**51**	14:18:00	**61**	17:20:00	**2**	19:50:00
9	10:22:30	**2**	14:24:00	**1**	17:25:00	**4**	19:55:00
2	10:30:00	**4**	14:30:00	**3**	17:30:00	**10**	20:00:00
4	10:37:30	**10**	14:35:00	**71**	17:34:00	**61**	20:06:00
10	10:45:00	**61**	14:40:00	**9**	17:38:00	**1**	20:12:00
1	10:52:30	**1**	14:45:00	**51**	17:42:00	**3**	20:18:00
3	11:00:00	**3**	14:50:00	**2**	17:46:00	**9**	20:24:00
9	11:07:30	**9**	14:55:00	**4**	17:50:00	**51**	20:30:00
2	11:15:00	**51**	15:00:00	**81**	17:54:00	**2**	20:37:30
4	11:22:30	**2**	15:05:00	**10**	17:58:00	**4**	20:45:00
10	11:30:00	**4**	15:10:00	**61**	18:02:00	**10**	20:47:30
1	11:37:30	**10**	15:15:00	**1**	18:06:00	**61**	20:52:30
3	11:45:00	**61**	15:20:00	**3**	18:10:00	**1**	21:00:00
9	11:52:30	**1**	15:25:00	**71**	18:14:00	**3**	21:10:00
2	12:00:00	**3**	15:30:00	**9**	18:18:00	**5**	21:15:00
4	12:07:30	**9**	15:35:00	**51**	18:22:00	**2**	21:20:00
10	12:15:00	**51**	15:40:00	**2**	18:26:00	**4**	21:30:00
1	12:22:30	**2**	15:45:00	**4**	18:30:00	**1**	21:40:00
3	12:30:00	**4**	15:50:00	**81**	18:34:00	**3**	21:50:00
9	12:36:00	**10**	15:55:00	**10**	18:38:00	**2**	22:00:00
51	12:42:00	**61**	16:00:00	**61**	18:42:00	**4**	22:10:00
2	12:48:00	**1**	16:05:00	**1**	18:46:00	**1**	22:20:00
4	12:54:00	**3**	16:10:00	**3**	18:50:00	**3**	22:30:00
10	13:00:00	**9**	16:15:00	**71**	18:54:00	**2**	22:40:00
61	13:06:00	**51**	16:20:00	**9**	18:58:00	**4**	22:50:00
1	13:12:00	**2**	16:25:00	**51**	19:02:00	**1**	23:00:00
3	13:18:00	**4**	16:30:00	**2**	19:06:00	**3**	23:10:00
9	13:24:00	**10**	16:35:00	**4**	19:10:00	**2**	23:20:00
51	13:30:00	**61**	16:40:00	**81**	19:15:00	**4**	23:30:00
2	13:36:00	**1**	16:45:00	**10**	19:20:00	**1**	23:40:00
4	13:42:00	**3**	16:50:00	**61**	19:25:00	**3**	23:50:00
10	13:48:00	**9**	16:55:00	**1**	19:30:00	**2**	00:05:00
61	13:54:00	**51**	17:00:00	**3**	19:35:00	**4**	00:10:00
1	14:00:00	**2**	17:05:00	**7**	19:37:30	**1**	00:25:00
3	14:06:00	**4**	17:10:00	**9**	19:40:00		
9	14:12:00	**10**	17:15:00	**51**	19:45:00		

If the train schedule above is conducted, then the number of trains in the line over time can be tabulated as given in Table 2.4.

Table 2.4 Number of trains in the system

Time Interval	Number of trains in the system
06:00-06:52	4
06:52-06:55	5
06:55-07:02	6
07:02-07:05	7
07:05-07:18	8
07:18-07:21	9
07:21-09:14	10
09:14-09:16	9
09:16-09:47	8
09:47-09:49	7
09:49-12:26	6
12:26-12:28	7
12:28-17:18	8
17:18-17:20	9
17:20-19:43	10
19:43-19:49	9
19:49-20:54	8
20:54-20:57	7
20:57-21:21	6
21:21-21:24	5
21:24-00:00	4

2.2 Definition of the Problem

The goal of this study is to build a simulation model in order to make an analysis and evaluate the effectiveness of operations in metro line. The performance criteria of effectiveness are identified as follows:

a. cost of energy spent for operations (0.7 TL / coach / km)
b. average waiting time of passengers at stations
c. comfort of the passenger (number of standing passengers in each square meter of the empty space devoted to straphangers in the coach)

It is desirable to decrease cost of energy. It is possible by decreasing the number of coaches and trains in the line which leads the headways to become longer and longer. Average waiting time of passengers gets higher then. Furthermore the trains would be much more crowded and it would not be convenient for the comfort of the passengers. Hence we have some contradicting objectives derived from performance criteria on hand.

3. LITERATURE SURVEY

There are many studies in literature about transportation systems. Some studies concerns with the analysis of the system whereas the other includes also the improvement and optimization of some performance criteria in the system.

Goverde (1998) dealt with synchronization control of scheduled train services to minimize passenger waiting times. This model can be utilized to review the optimal synchronization control policy from the point of view of expensed arrival delays. The objectives are to minimize of the total generalized passenger waiting time and to resolute of substantial buffer times related with the passenger waiting times in service network timetables.

Chang et al (1999) concerned a multi-objective model for passenger train services planning which is applied to Taiwan's high speed rail line. The goal is to improve a multi-objective programming model for optimal assignment of passenger train services on an intercity high speed rail line without branches. There are two objectives: minimizing the operator's total operating cost and minimizing the passenger's total travel time loss. This model assisted to improve train service planning in general. The train stop schedule plan, service frequency and fleet size are parameters that are few to mention that involves in the model.

Li (2000) built up a simulation model of a train station and its passenger flow. Simulation model consists of the processes, equipment and queues which a passenger comes across from entering the station. All these parameters directly affect the total passenger travel times. Minimizing the total passenger travel times and increasing the service quality are the purpose of this study, and that is to develop existing condition and upgrade for the future, and to review station design.

Martinez (2002) denoted application of Siman ARENA™ that is a discrete event simulation tool in the operational planning of a rail systems. This model also involves in an animation of a Siman simulation. The simulation model gives the capability to use a realistic model of the rail network and calculated waiting time in platform and on time performance for special system performance parameters.

Sheu and Lin (2011) denoted optimization of train regulation and energy usage of metro lines using an adaptive – optimal - control algorithm. The automatic train regulation system involves in service quality, transport capacity and energy usage of a metro line operations. The train regulator has a purpose of maximizing the schedule and headway commitment while minimizing the energy depletion.

Lindner and Zimmermann (2005) presented an optimization model of train schedule in public rail transport system to reduce cost and increase resource utilization.

Finally, Yalcinkaya and Bayhan (2009) described modeling and optimization of average travel time for a metro line by simulation. They present a modeling and solution approach based on simulation and response surface methodology for optimization. The aim is to find the optimum headways, and to minimize the average passenger time spent in the metro line with a satisfactory rate of carriage fullness. Actually their study is conducted on the same transportation system as in our model. There are some discrepancies in that study such that the arrival rates of passengers are assumed to be fixed during the day. However, it is shown that the arrival rates are non-stationary (See Chapter 4 and 5.1). On the other hand, the objective is to find the optimal headways (time interval between consecutive trips at a station). They assume that there are infinite numbers of trains available at the end of the metro lines. In fact, there are limited numbers of trains available and the headways are limited by some other factors.

4. INPUT ANALYSIS

There are two stochastic inputs of the system. The first one is the arrivals of the passengers into the system, the other one is the destination station of the passengers. The details of input analysis are given in the following sections.

4.1 Arrivals of Passengers

When a passenger arrives at station, he/she uses an electronic pass card or a token to access the system. Therefore arrival information including the time stamp and station is automatically stored in an ORACLE^{TM} database.

The records of passengers served by the system within last 15 months have been considered for the analysis in order to determine arrival rates. There are more than 50 million of such records in the database. Since the size of the file is huge, an interface and an analysis tool have been designed to interact with the database in place at the corporate IT department. Only then it was possible to make statistical analysis of arrivals. Both the interface and the analysis tool have been coded using VBA tools.

Raw data has been investigated, and average number of passengers has been determined for every minute of a day, for each day of the week and for each station. The idea is to identify the differences, if any, in arrival rates for different stations and hours in a day. We are also interested in whether there is a difference between days of a week (working days vs weekend) and between winter and summer seasons.

It has been observed that every station has its own characteristic pattern for arrival rates. It is not surprising since the stations are established at different parts of the city. Some stations are at the neighborhood of business center whereas some others are settled at residence area. The arrival patterns for different stations are given in Figure 4.1 through 4.10. The graphics depicted in those figures represent the average number of passengers per minute that arrives to the corresponding station over time during the day. Numerical data is supplied in a DVD attached to the thesis and also stored at http://aoner.yasar.edu.tr/?page_id=723

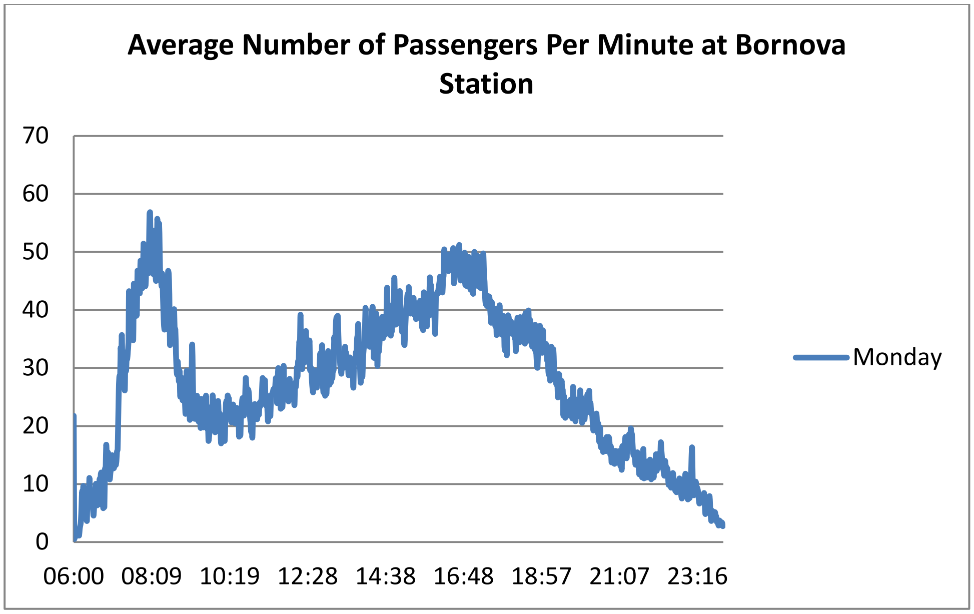

Figure 4.1 Average number of passengers per minute at “Bornova” station for monday.

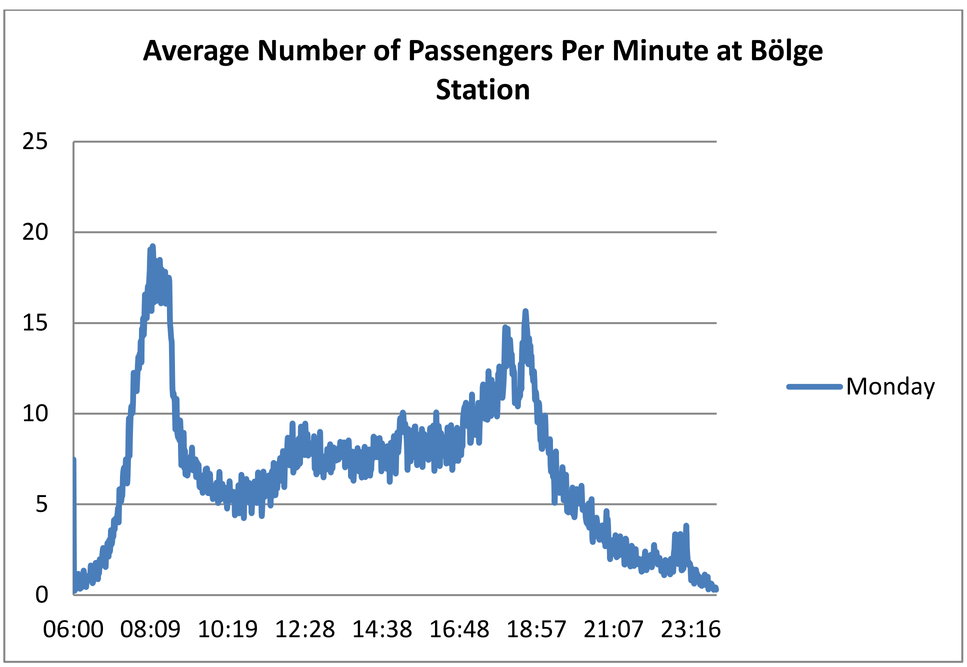

Figure 4.2 Average number of passengers per minute at “Bölge” station for monday.

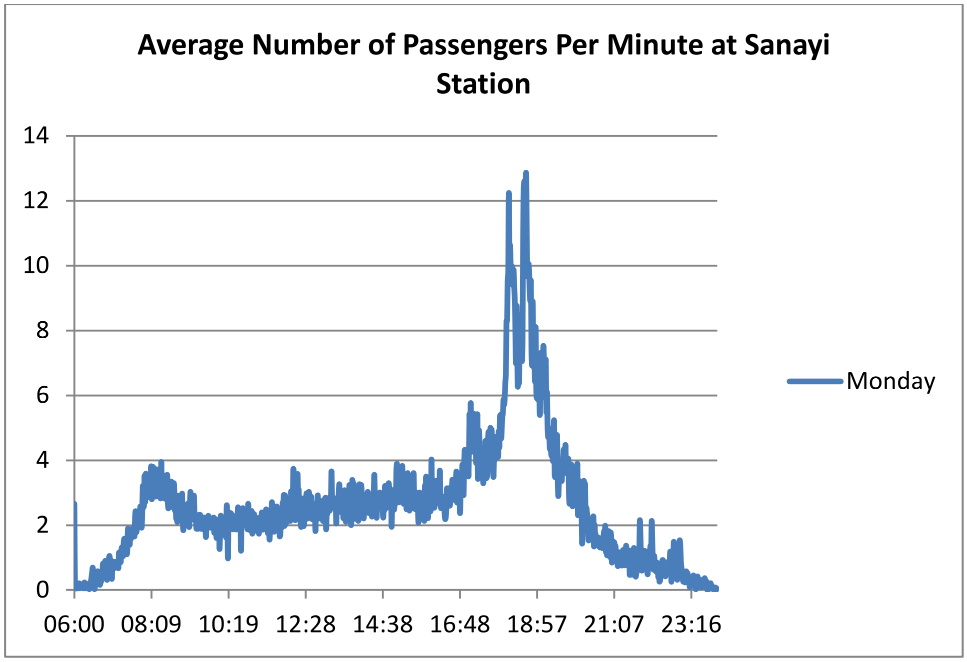

Figure 4.3 Average number of passengers per minute at “Sanayi” station for monday.

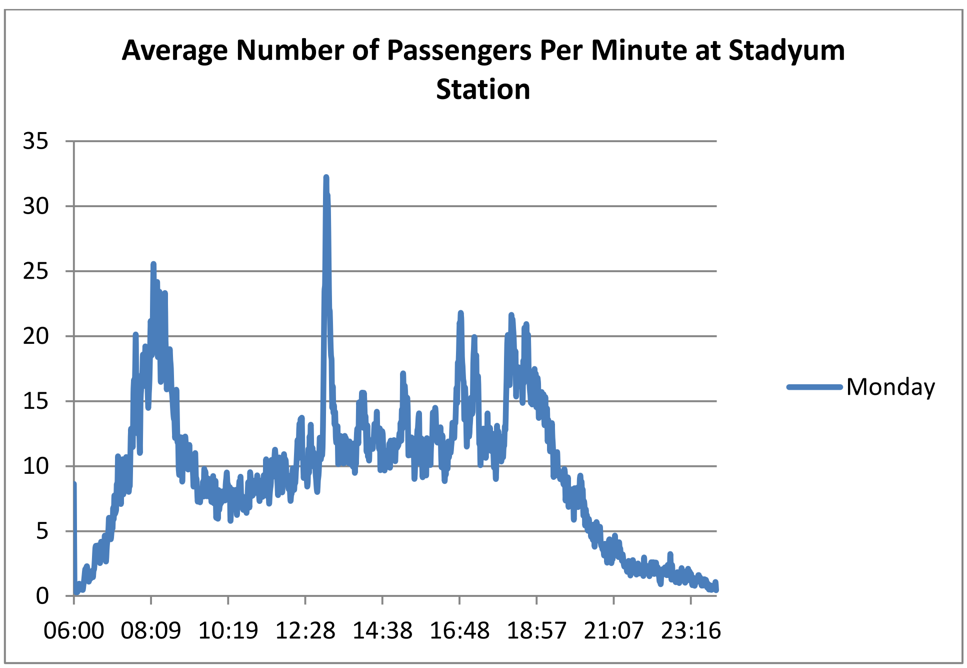

Figure 4.4 Average number of passengers per minute at “Stadyum” station for monday.

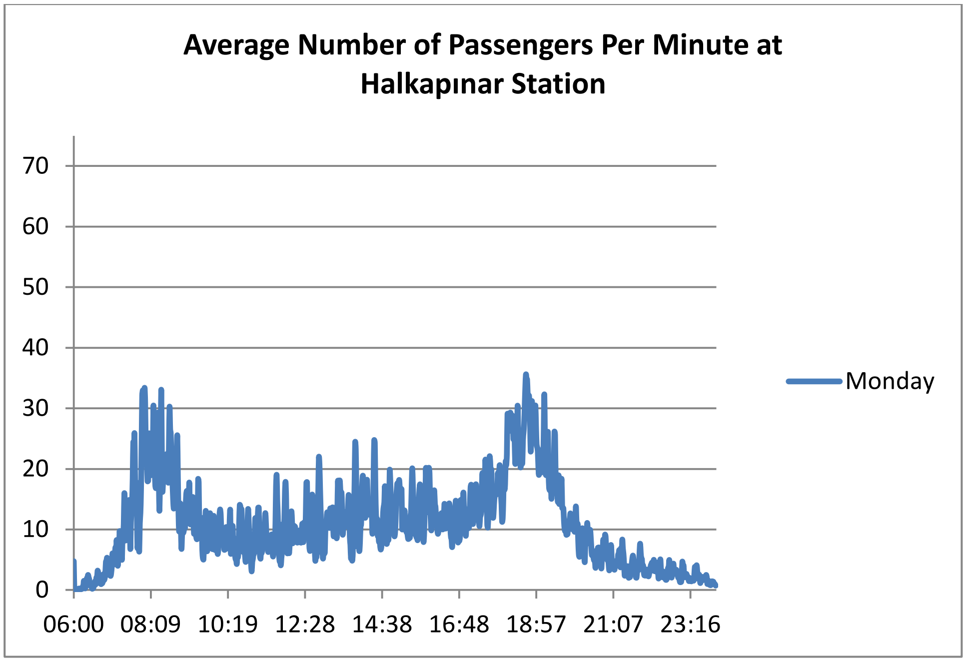

Figure 4.5 Average number of passengers per minute at “Halkapınar” station for monday.

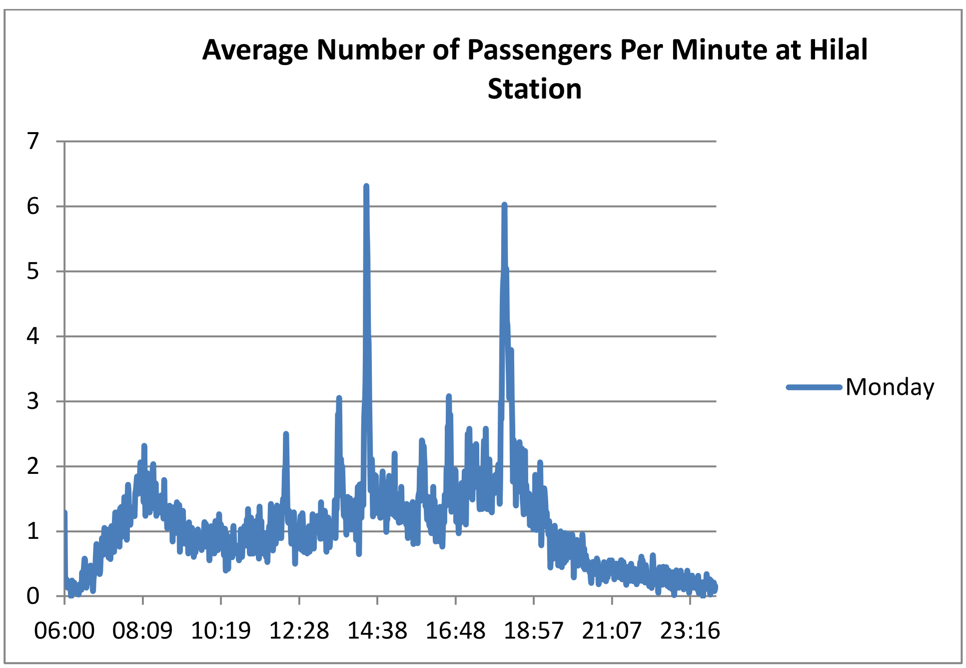

Figure 4.6 Average number of passengers per minute at “Hilal” station for monday.

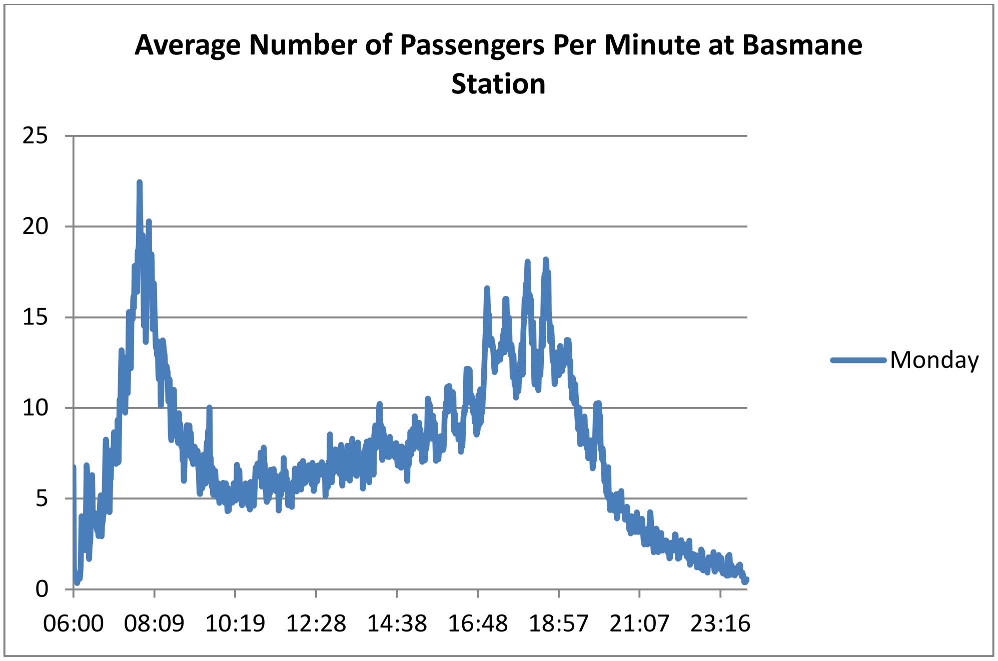

Figure 4.7 Average number of passengers per minute at “Basmane” station for monday.

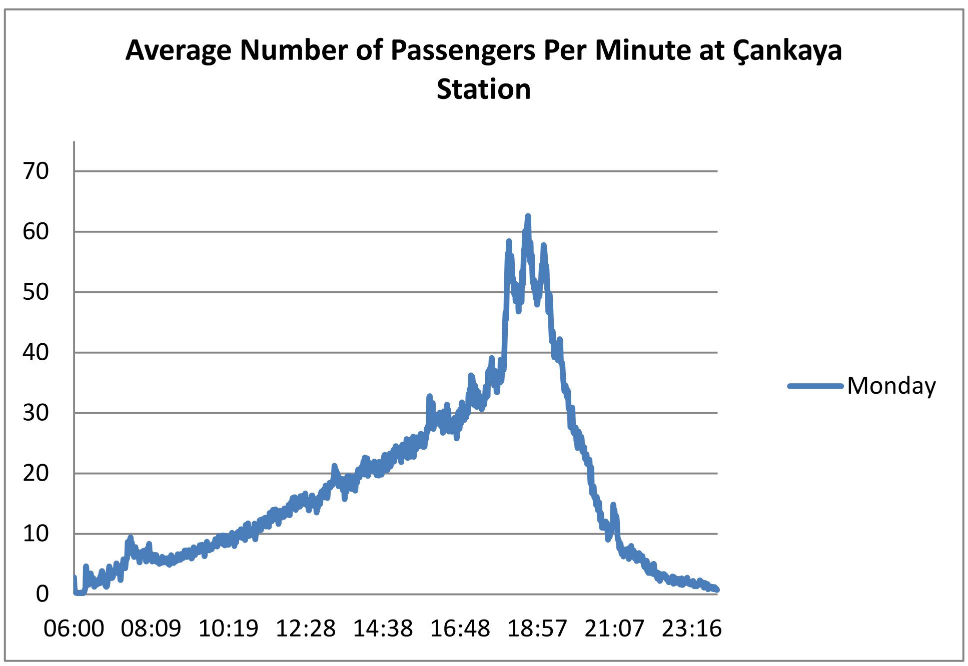

Figure 4.8 Average number of passengers per minute at “Çankaya” station for monday.

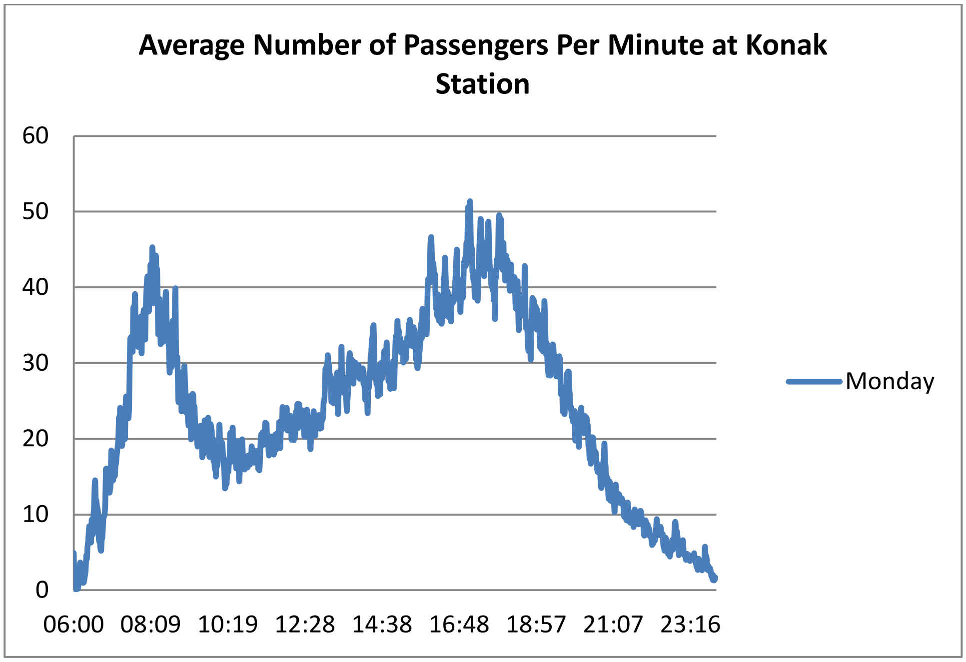

Figure 4.9 Average number of passengers per minute at “Konak” station for monday.

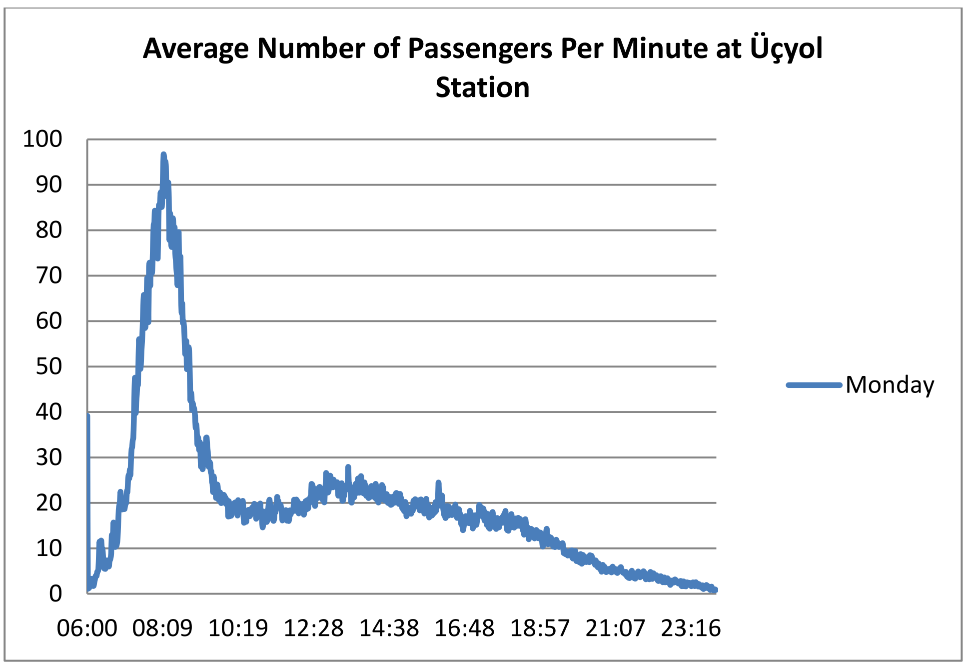

Figure 4.10 Average number of passengers per minute at “Üçyol” station for monday.

Another remarkable observation is that the patterns repeat themselves at each particular station during the weekdays but differ only weekends, Saturday and Sunday namely. It leads to an important result such that there should be three scenarios in the model; one for weekdays, the other one for Saturdays and finally the last one for Sundays. The following figures indicate differences between weekdays, Saturdays and Sundays.

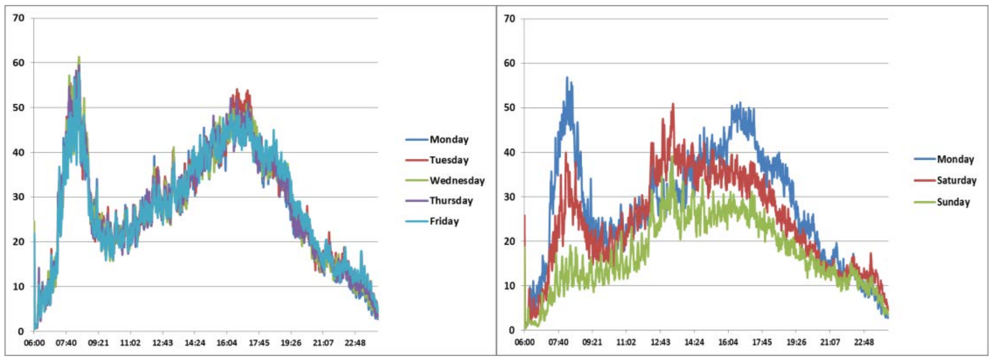

Figure 4.11 Average number of passengers on weekdays vs. weekends at “Bornova” st.

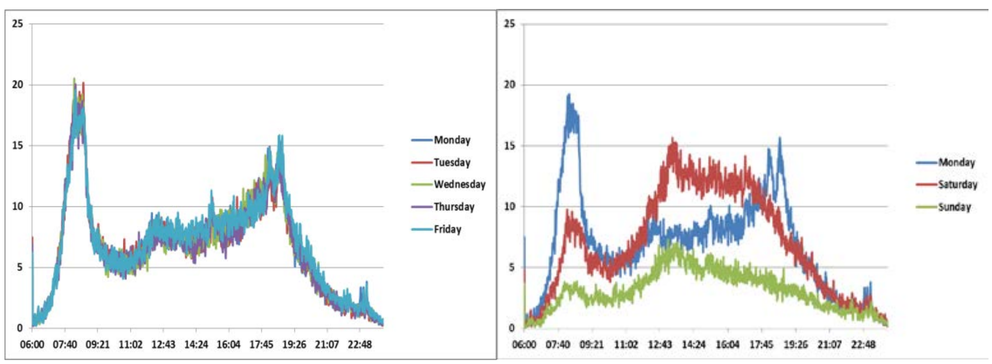

Figure 4.12 Average number of passengers on weekdays vs. weekends at “Bölge” st.

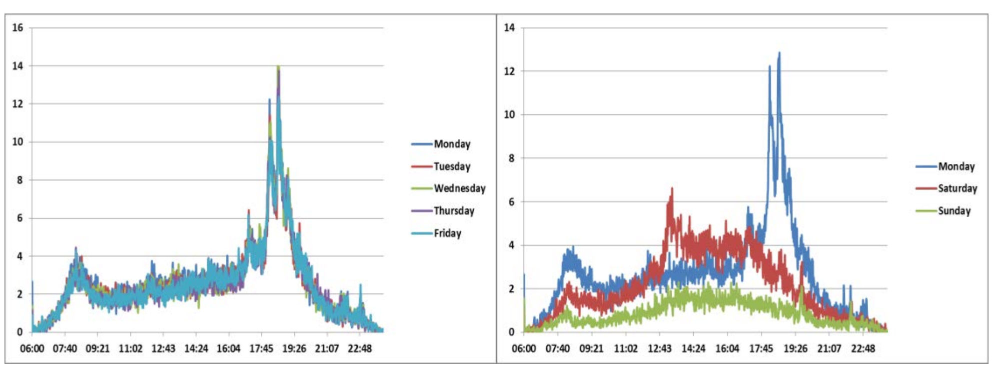

Figure 4.13 Average number of passengers on weekdays vs. weekends at “Sanayi” st.

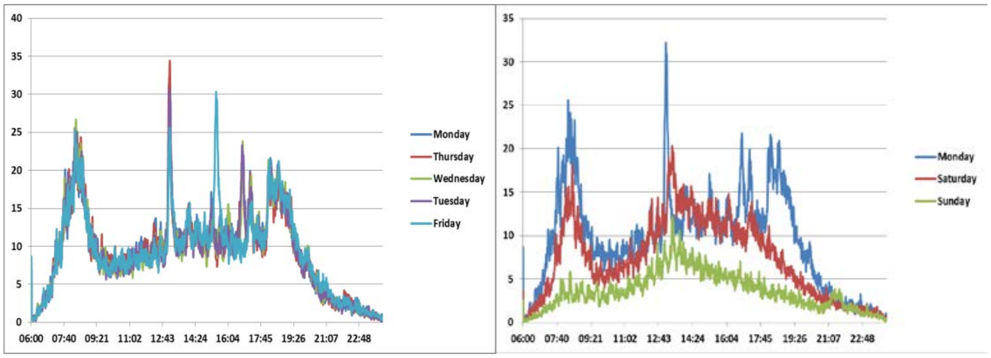

Figure 4.14 Average number of passengers on weekdays vs. weekends at “Stadyum” st.

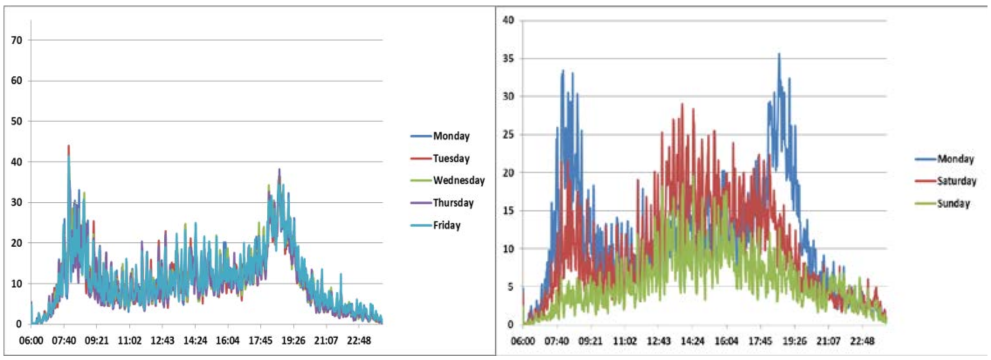

Figure 4.15 Average number of passengers on weekdays vs. weekends at “Halkapınar” st.

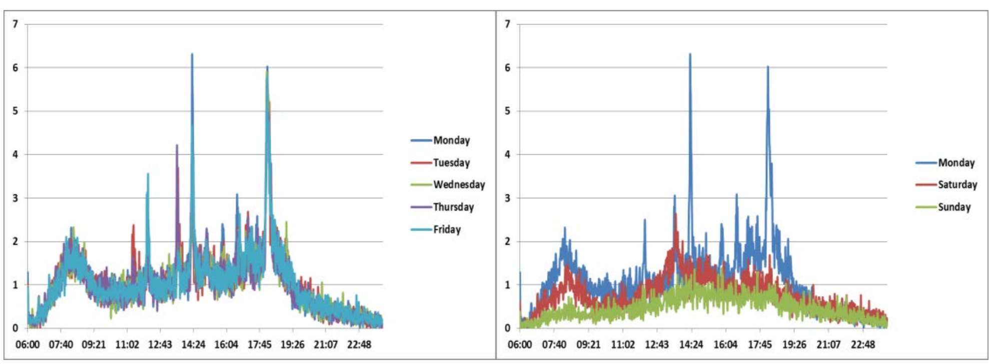

Figure 4.16 Average number of passengers on weekdays vs. weekends at “Hilal” st.

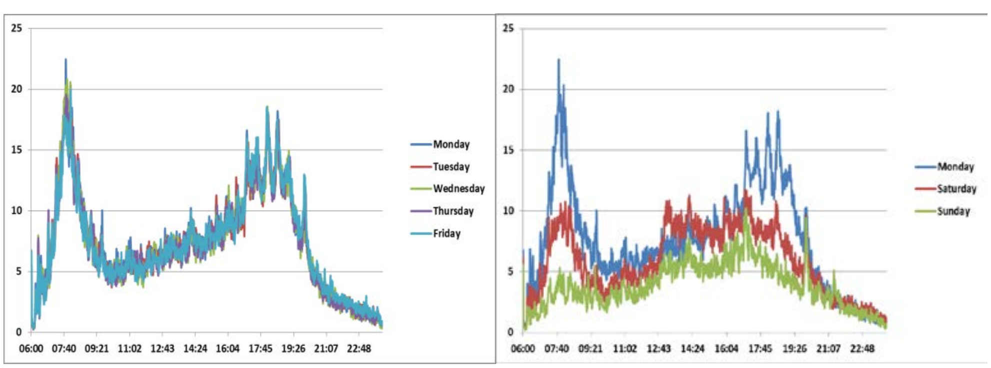

Figure 4.17 Average number of passengers on weekdays vs. weekends at “Basmane” st.

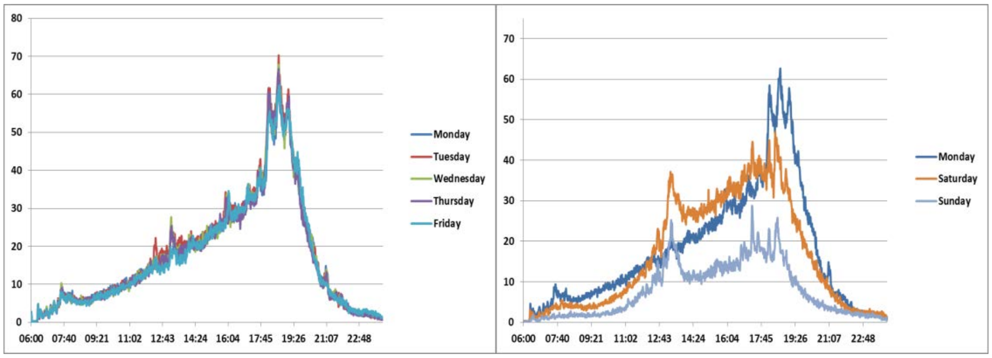

Figure 4.18 Average number of passengers on weekdays vs. weekends at “Çankaya” st.

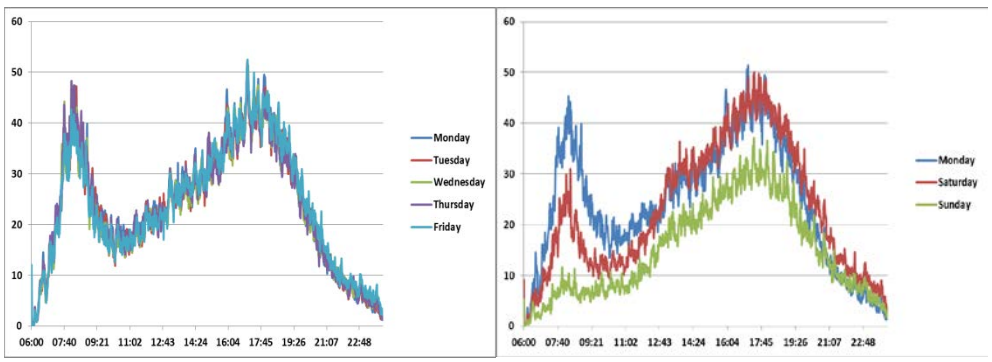

Figure 4.19 Average number of passengers on weekdays vs. weekends at “Konak” st.

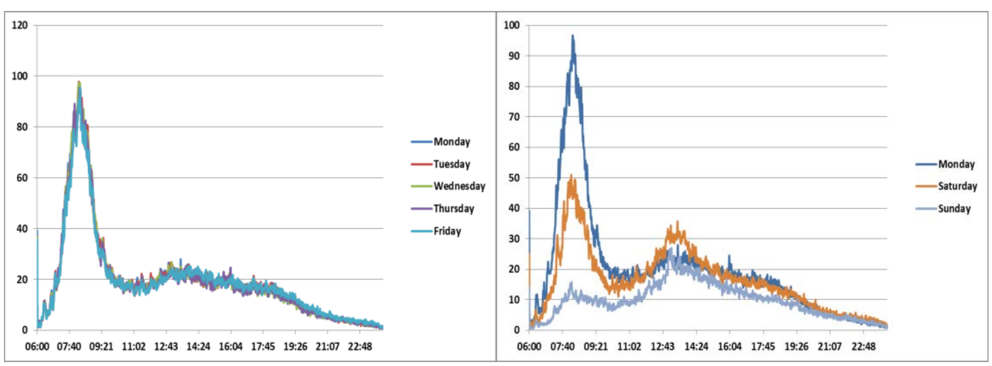

Figure 4.20 Average number of passengers on weekdays vs.weekends at “Üçyol” st.

The final observation is that only the magnitudes change whereas the shapes of the patterns do not change when the seasonal changes come into question. All those observations provide valuable information that the company has not have before.

4.2 Destination Stations of Passengers

When a passenger accesses in the system at a particular station, there is no information available about at which station he/she leaves the system. However, it is important to have this information in order to assess the performance of the system.

One-week lasting public surveys have taken place twice during winter and summer seasons in order to provide information about destination stations of the passengers. Surveys are conducted by the assistance of security personnel. At each station, security men have questioned arriving passengers about their destination station. The answers including time stamps have been automatically recorded with their hand counters. Each survey covers more than 500,000 passengers in total. Collected data has been organized and analyzed to produce probability tables for destination stations. The outcomes are assumed to be confident and consistent since sample spaces are pretty big for each station.

Destination probabilities are organized in two complementary tables for each station. Because when a passenger arrives at a station, first of all it is required to identify the probability of the direction which he/she will take. The probability of destination station should be determined next. If the station is a terminus, it is obvious that the passenger will travel in either west or east direction depending on the terminus which he/she arrives. However if the station is an intermediate one, a preliminary probability should be assigned for the direction, and then a probability table should accompany for the destination stations.

Due to socio-economical behavior of the passengers and the attributes of the stations in the line, destination probabilities may change over time during the day. Therefore the tables should be prepared as a function of time to represent those fluctuations. The following two tables indicate the probabilities of direction and destination station if a passenger enters into the system at “Basmane” station.

Table 4.1 Probability of directions for passengers at “Basmane” station

Direction	Hours								
	06-07	07-08	08-09	09-10	10-11	11-12	12-13	13-14	14-15
WEST	0.241	0.250	0.251	0.291	0.296	0.326	0.339	0,314	0,294
EAST	0.759	0.750	0.749	0.709	0.704	0.674	0.661	0,686	0,706

Table 4.1 Probability of directions for passengers at “Basmane” station (Continued)

Direction	Hours								
	15-16	16-17	17-18	18-19	19-20	20-21	21-22	22-23	23-24
WEST	0,303	0,339	0,362	0,333	0,364	0,328	0,385	0,338	0,358
EAST	0,697	0,661	0,638	0,667	0,636	0,672	0,615	0,662	0,642

Table 4.2 Probabilities of destination station for passengers at “Basmane” station

	Destination Stations	Hours								
		06-07	07-08	08-09	09-10	10-11	11-12	12-13	13-14	14-15
WEST	**ucyol**	0.558	0.489	0.472	0.415	0.441	0.428	0.391	0,412	0,520
	konak	0.383	0.326	0.354	0.426	0.417	0.460	0.451	0,442	0,343
	cankaya	0.058	0.184	0.172	0.157	0.141	0.111	0.157	0,144	0,135
	basmane	0	0	0	0	0	0	0	0	0
EAST	**hilal**	0.004	0.012	0.009	0.018	0.005	0.008	0.009	0,008	0,008
	halkapinar	0.247	0.188	0.204	0.163	0.241	0.253	0.256	0,287	0,291
	stadyum	0.109	0.143	0.178	0.141	0.091	0.112	0.096	0,105	0,121
	sanayi	0.050	0.056	0.081	0.056	0.037	0.038	0.039	0,038	0,051
	bolge	0.073	0.069	0.070	0.067	0.059	0.062	0.063	0,061	0,062
	bornova	0.513	0.529	0.455	0.551	0.564	0.523	0.534	0,499	0,463

Table 4.2 Probabilities of destination station for passengers at “Basmane” station (Continued)

	Destination Stations	Hours								
		15-16	**16-17**	**17-18**	**18-19**	**19-20**	**20-21**	**21-22**	**22-23**	**23-24**
WEST	**ucyol**	0,449	0,521	0,571	0,614	0,575	0,639	0,561	0,610	0,564
	konak	0,471	0,383	0,351	0,323	0,334	0,331	0,351	0,303	0,301
	cankaya	0,078	0,095	0,077	0,062	0,089	0,029	0,086	0,085	0,133
	basmane	0	0	0	0	0	0	0	0	0
EAST	**hilal**	0,009	0,003	0,018	0,010	0,020	0,001	0,013	0,009	0,030
	halkapinar	0,300	0,312	0,331	0,307	0,309	0,327	0,296	0,263	0,246
	stadyum	0,082	0,071	0,096	0,080	0,082	0,066	0,078	0,069	0,077
	sanayi	0,026	0,031	0,038	0,031	0,033	0,005	0,036	0,041	0,027
	bolge	0,062	0,043	0,087	0,131	0,079	0,047	0,075	0,084	0,116
	bornova	0,519	0,535	0,427	0,439	0,474	0,550	0,500	0,531	0,501

It is noticeable that the passengers arriving at “Basmane” station usually travel in east direction. “Bornova” station is the most popular destination at the east wing of metro line probably due to hospitals and universities located nearby.

The destination probabilities for passengers arriving at other stations are supplied in a DVD attached to the thesis and also stored at http://aoner.yasar.edu.tr/?page_id=723

5. SIMULATION MODEL

Simulation model is created by ARENA software which uses discrete-event simulation methodology. An animation model is also established to accompany the model. Main structure of the model and an overview of the animation are shown in the following figures.

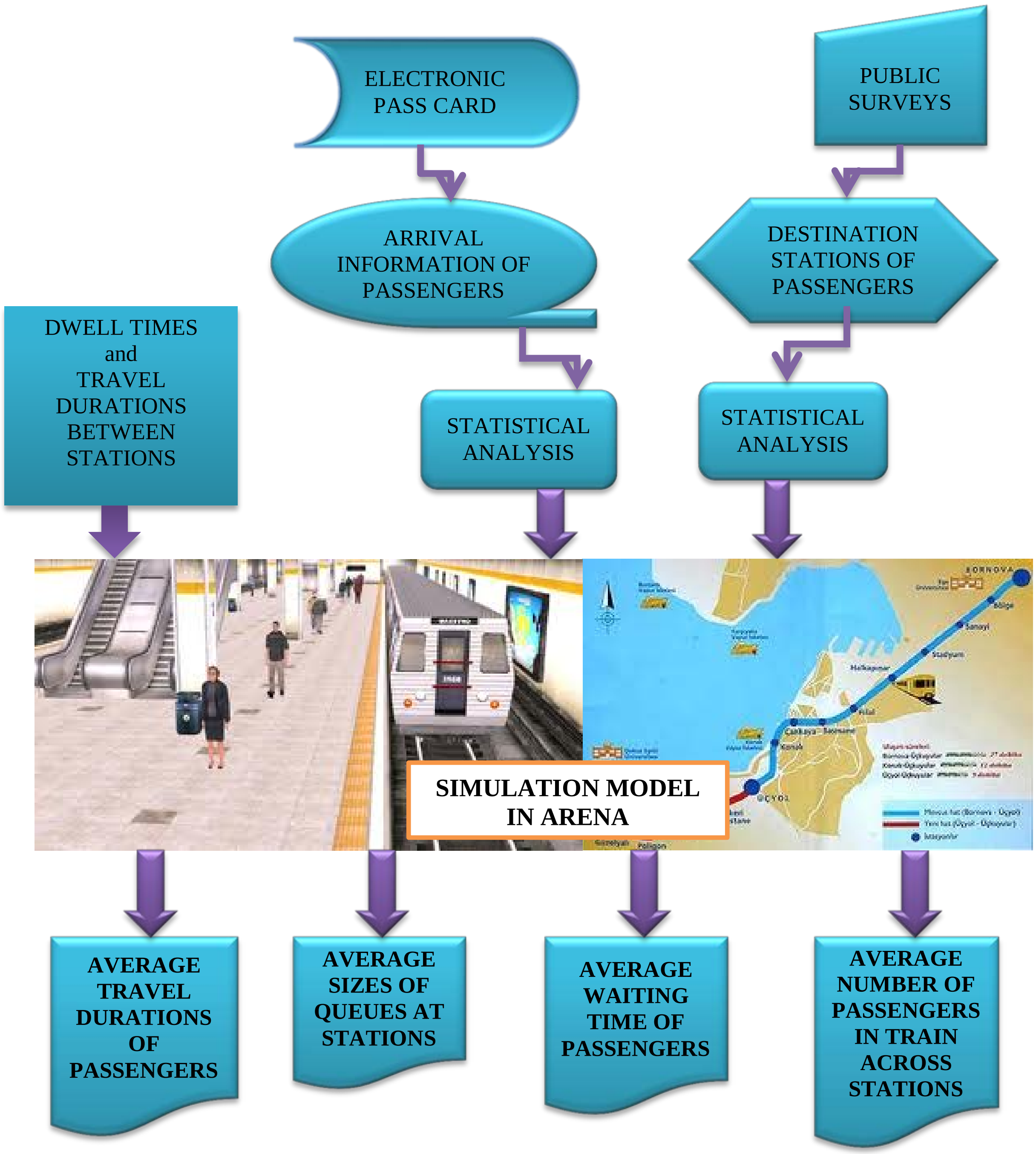

Figure 5.1 Main structure of the model

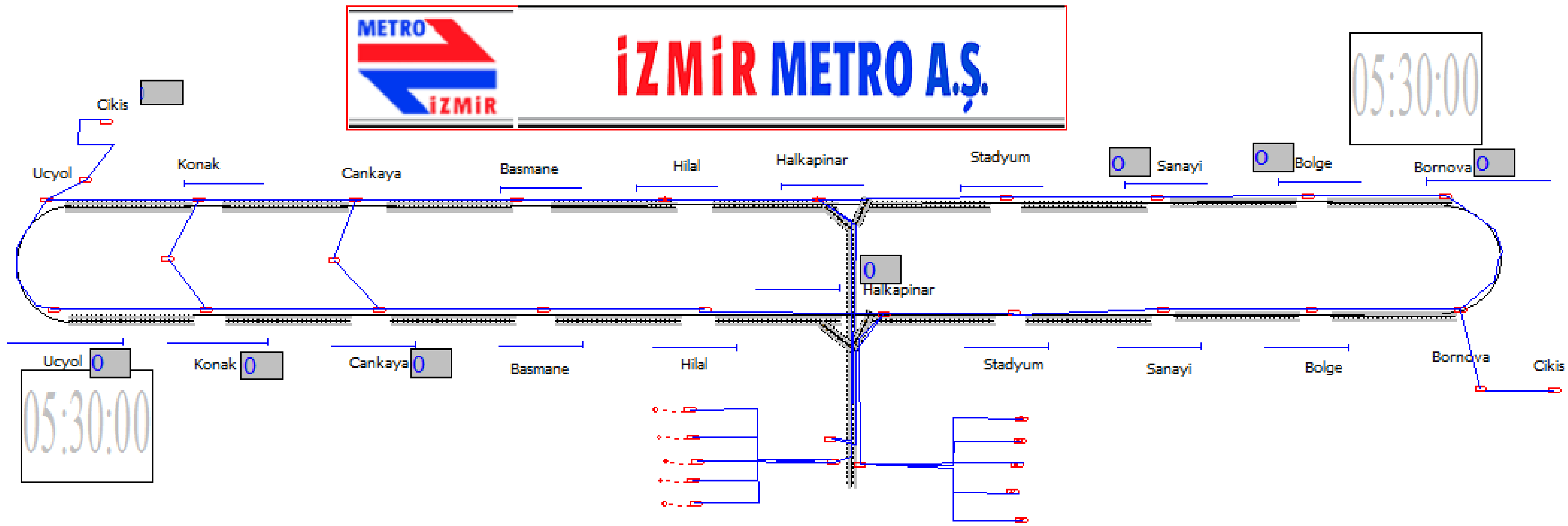

Figure 5.2 Animation overview

The model is accompanied by two external files, one for inputs and the other one for outputs of the simulation. Both of them are MS Excel™ files. The input file includes the following data:

- Travel durations for trains between stations
- Dwell times at stations
- Current train schedule
- Arrival rates at each station at each minute
(an array of real numbers with dimensions 10 stations x 1080 minutes)
- The probabilities of direction and destination stations of passengers arriving at each station as function of time (an array of real numbers with dimensions 10 stations x 10 stations x 18 hours)
- The number of trains in the system over time during the day

The model is developed in a modular structure that includes several sub-models. For example a sub-model simulates train motions and their entrance into and exit from the system. It also controls time, distance between stations and speed of the trains. Another sub-model controls special statistical counters and system parameters. Some other several sub-models simulate arrivals of the passengers to the stations. Finally a sub-model that controls the train and passengers interaction has been developed for each station. The details of sub-models are explained in following sub-sections.

5.1 Arrival of Passengers

Statistical analysis of passenger arrivals reveals that the arrival rates are constantly changing during a day. It means that it is not appropriate to investigate a single probability distribution to fit for inter-arrival times. Instead of that, arrivals of the passengers should be modeled as a (non-stationary) Poisson process.

Poisson process is probably the most commonly used model for the arrival process of passengers to a queueing system. Çınlar(1975) defined the stochastic process $\{N(t),\ t \geq 0\}$ is said to be a Poisson process if;

1. Passengers arrive one at a time.

2. $N(t+s) - N(t)$ (the number of arrivals in the time interval $[t,\ t+s]$) is independent of $\{ N(u),\ 0 \leq u \leq t \}$.

3. The distribution of $N(t+s) - N(t)$ is independent of t for all $t, s \geq 0$.

Properties 1 and 2 are characteristic of many actual arrival processes. Property 1 would not hold if customers arrived in batches. The passengers in metro model don't arrive in batches therefore this property is not violated in our model. Property 2 says that the number of arrivals in the interval $[t,\ t+s]$ is independent of the arrivals in the earlier time interval $[0,t]$ and also of the times at which these arrivals occur. This property could be violated if, for example, a large number of arrivals in $[0,t]$ caused some passengers arriving in $(t,\ t+s)$ to balk, i.e., to go away immediately without being served, because they find the system highly congested. Property 2 holds for our model since violation conditions don't exist. The passengers don't go away once they arrive at a station. Property 3, on the other hand, is violated by many real-life arrival processes since it implies that the arrival rate of passengers does not depend on the time of day, etc. The arrival rates in metro model are constantly changing during a day, which means Property 3 does not hold. Therefore regular Poisson process can't be used in metro model, but instead a non-stationary process should be considered. The theoretical background is explained in following theorems proved in Çinlar (1975). First the theorems on Poisson process are given, and then non-stationary process will be explained.

Theorem 5.1. If $\{N(t),\ t \geq 0 \}$ is a Poisson process, then the number of arrivals in any time interval of length s is a Poisson random variable with parameter λs (where λ is a positive real number). That is,

$$P[\ N(t+s) - N(t) = k\ ] = \frac{e^{(\lambda s)}(\lambda s)^{\ k}}{k!} \quad for\ k=0,1,2,\ldots\ and\ t,\ s \geq 0$$

Therefore $E[N(s)]= \lambda s$ and in particular $E[N(1)]= \lambda$. Thus, λ is the expected number of arrivals in any interval of length 1. The parameter λ is called the rate of the process. The theorem leads a practical result such that the inter-arrival times for a Poisson process are independent, identically distributed (IID) exponential random variables.

Theorem 5.2. If $\{N(t),\ t \geq 0\ \}$ is a Poisson process with rate λ, then its corresponding inter-arrival times $A_1, A_2, \ldots$ are IID exponential random variables with mean $1/\lambda$.

On the other hand, if the arrival rate in Poisson process changes over time as in metro model, we need to consider non-stationary Poisson process, which is often used as a model of the arrival process to a system when the arrival rate varies with time. Non-stationary Poisson process is defined as follows (Kelton and Law, 2000):

Let $\lambda(t)$ be the arrival rate of passengers to some system at time t. If passengers arrive at the system in accordance with a Poisson process with constant rate λ, then $\lambda(t)= \lambda$ for all $t \geq 0$. However, for many real-world systems, $\lambda(t)$ is actually a function of t. For example, the arrival rate of passengers to a metro transportation system will be larger during the morning rush hour than in the middle of the afternoon. If the arrival rate $\lambda(t)$ does in fact change with time, then the inter-arrival times $A_1, A_2, \ldots$ are not identically distributed; thus, it is not appropriate to fit a single probability distribution to the A_i's by using the distribution fitting techniques. The properties of non-stationary Poisson process are listed as follows :

1. Passengers arrive one at a time.

2. $N(t+s) - N(t)$ is independent of $\{N(u), 0 \leq u \leq t\}$.

Thus, for a non-stationary Poisson process, passengers must still arrive one at a time, and the numbers of arrivals in disjoint intervals are independent, but now the arrival rate *λ(t)* is allowed to be a function of time.

In our model, average number of arrivals per minute has been determined for each station that corresponds to parameter *λ(t)* for non-stationary Poisson process at minute *t* . Each minute *λ(t)* takes a different value as in real life. Creation of the passengers in "Basmane" station is shown in the following figure.

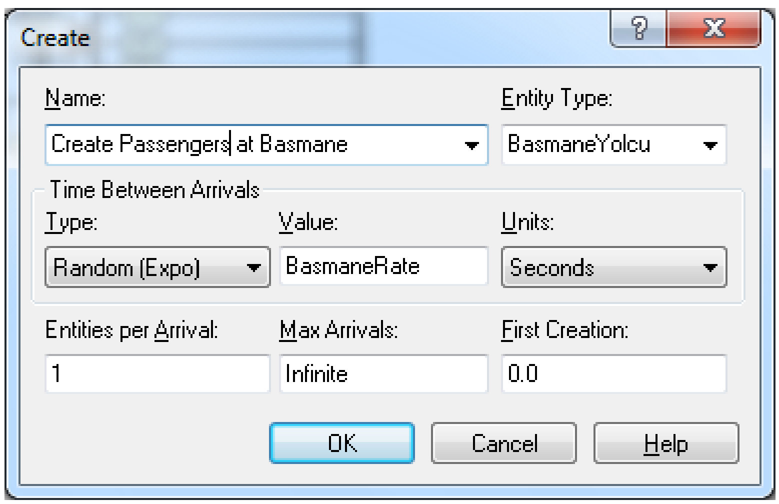

Figure 5.3 Creation of passengers at "Basmane" station

Since the passengers are created using "Poisson process", the time between arrivals should come from Exponential distribution with mean (*1 / λ(t)*). It is represented by the value "BasmaneRate" in the model. The simulation model reads the average number of passengers from the input file that corresponds to parameter *λ(t)* for that particular minute. Each minute the parameter *λ(t)* changes and its value is assigned to "BasmaneRate". Creation of passengers at other station is handled by similar structures, but some details and the numerical parameters change correspondingly.

When a passenger arrives at an intermediate station, first of all, it is required to identify the probability of the direction which he/she would take. The probability of destination station should be determined next. Furthermore, those probabilities may change over time during the day. Therefore they have to be determined depending on the hours of the day. The following two figures indicate how these issues have been implemented in ARENA.

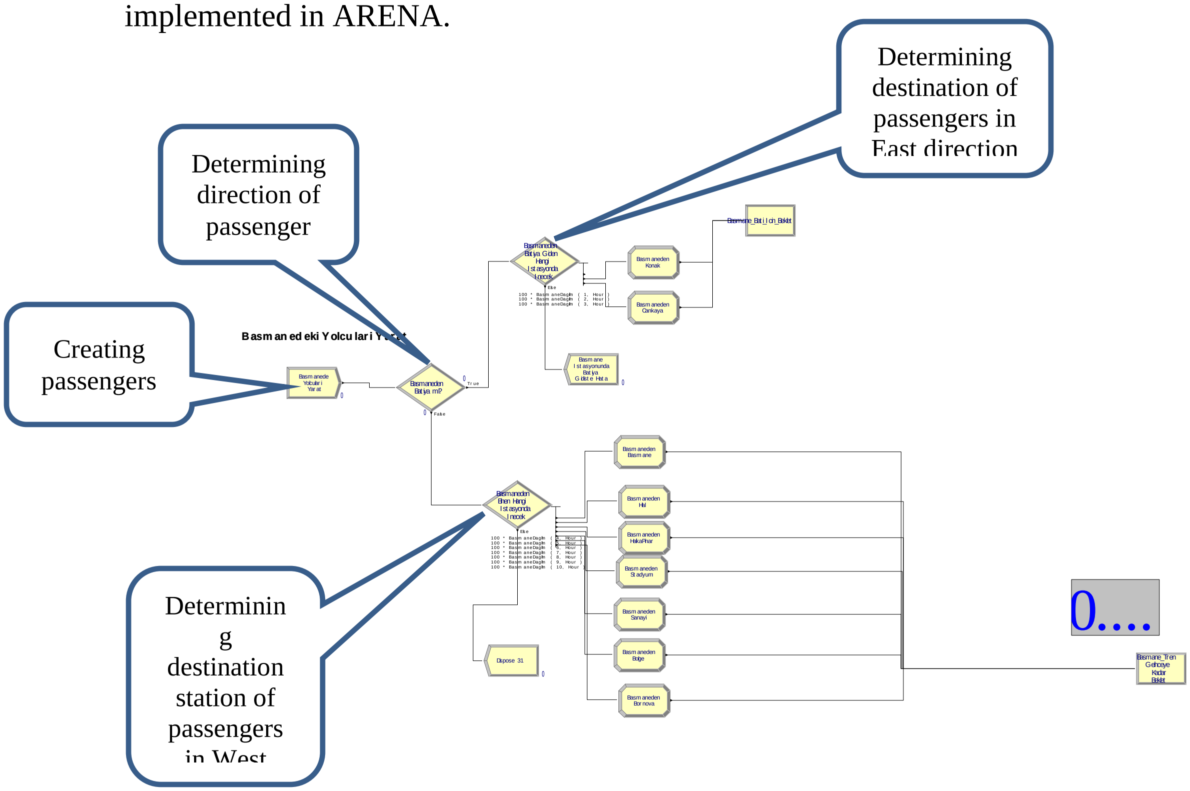

Figure5.4 Management of passengers at “Basmane” station

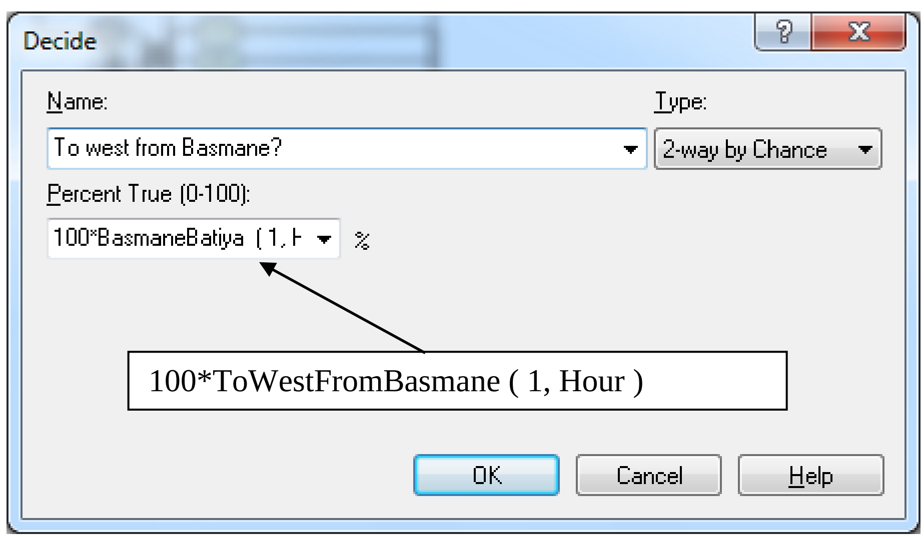

Figure 5.5 Determining the direction of passengers at “Basmane” station

A two dimensional array "ToWestFromBasmane" contains the probabilities of direction in an hourly basis. The probability changes as the hour changes during the day. Values of probabilities are read from input file.

Following the direction, the destination station is assigned to the incoming passenger as an entity attribute depending on the corresponding probabilities. The name of the attribute is "destination". Related probabilities are read from the input file to an array "BasmaneDistribution". The following two figures indicate how it is implemented in ARENA

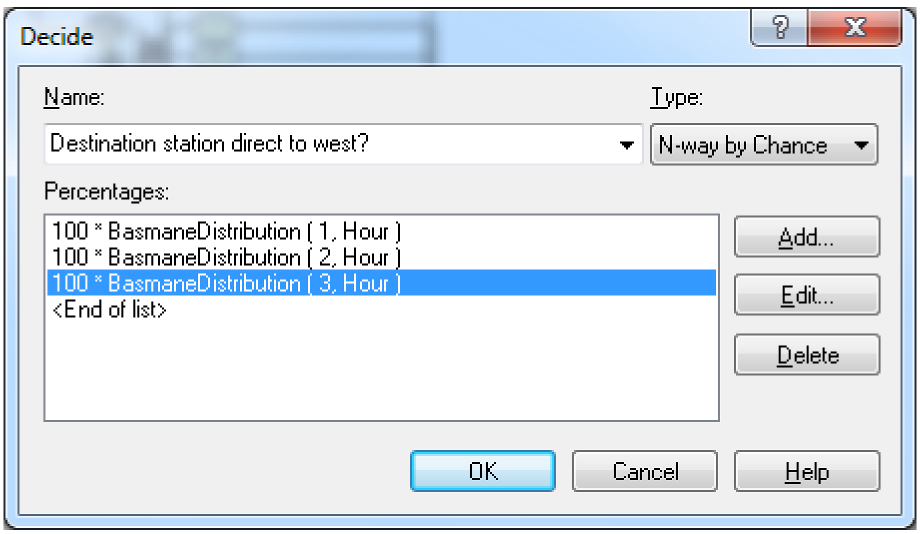

Figure 5.6 Determining destination station of passengers arriving at "Basmane" station.

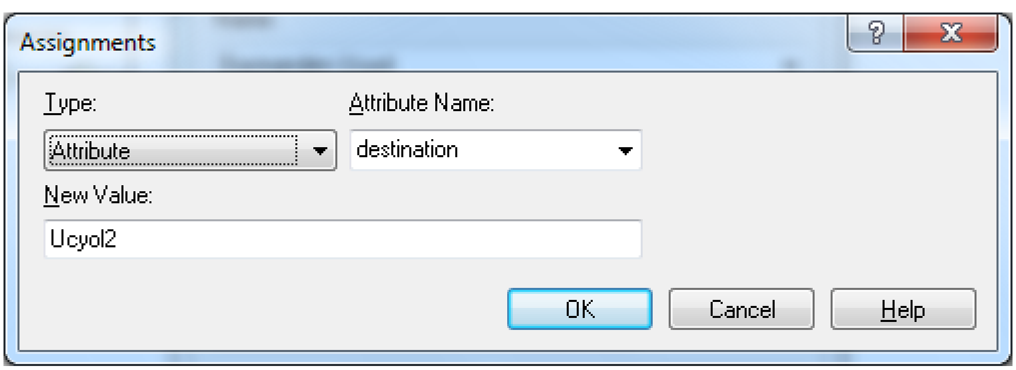

Figure 5.7 Assigning destination stations to passengers

Once the direction and the destination station are assigned to a passenger, he/she begins waiting for the train at the proper side of the station. In ARENA, passenger is put into a "HOLD" queue.

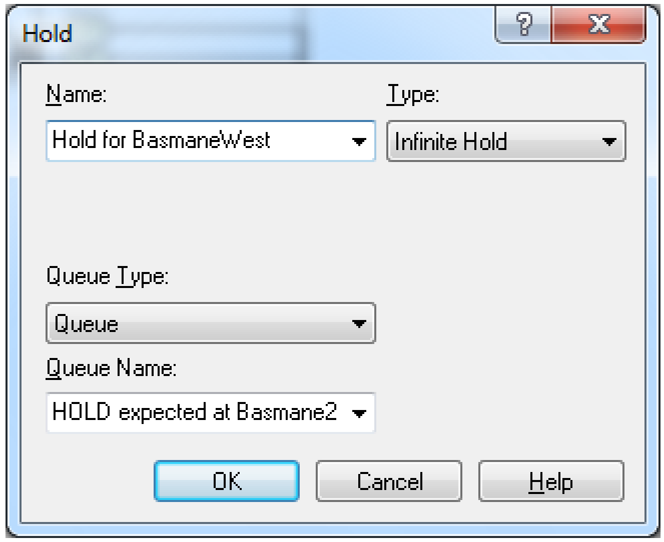

Figure 5.8 Waiting passengers at "Basmane" station

5.2 Train – Passenger Interactions

When a train arrives to a station, it is expected to drop off some passengers whose destinations are that station, and then takes the waiting passengers whose direction is the same with the train. In ARENA, passenger exchange is implemented using "DropOff", "PickUp" and "Search" modules in a coordinated way. The following figure shows the main structure of the passenger exchange.

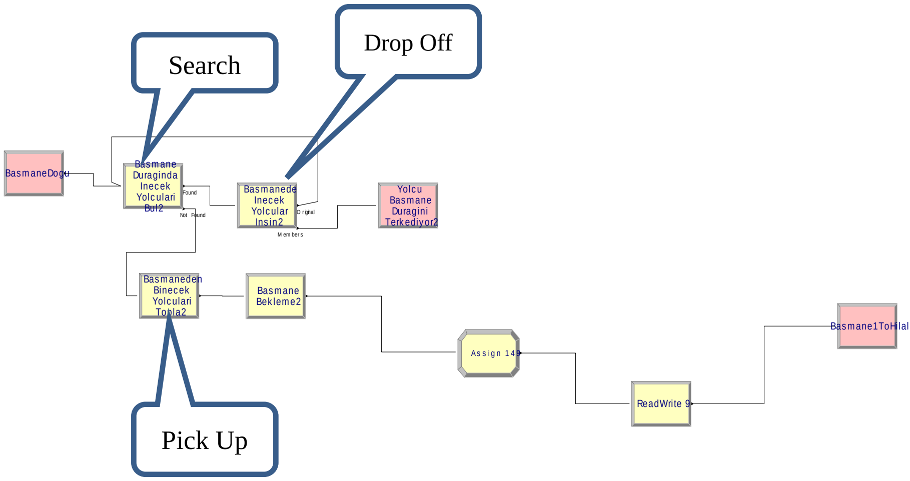

Figure 5.9 Passenger exchange at “Basmane” station

When a train arrives at a station, “Search” module checks all the passengers in the train and determines the ones who will get off the train at that station. The details of the module are given in Figure 5.10. The parameter in the “Ending Value” field is NG which stands for “Number in Group”

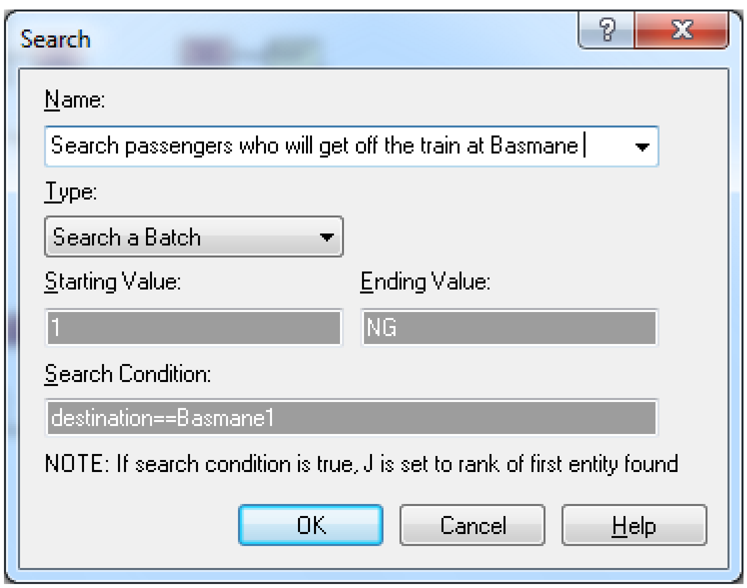

Figure 5.10 Search module

On the other hand, the “DropOff” module opens a drain hole for the entities representing passengers to get off the train. The details of “DropOff” module is given in Figure 5.11.

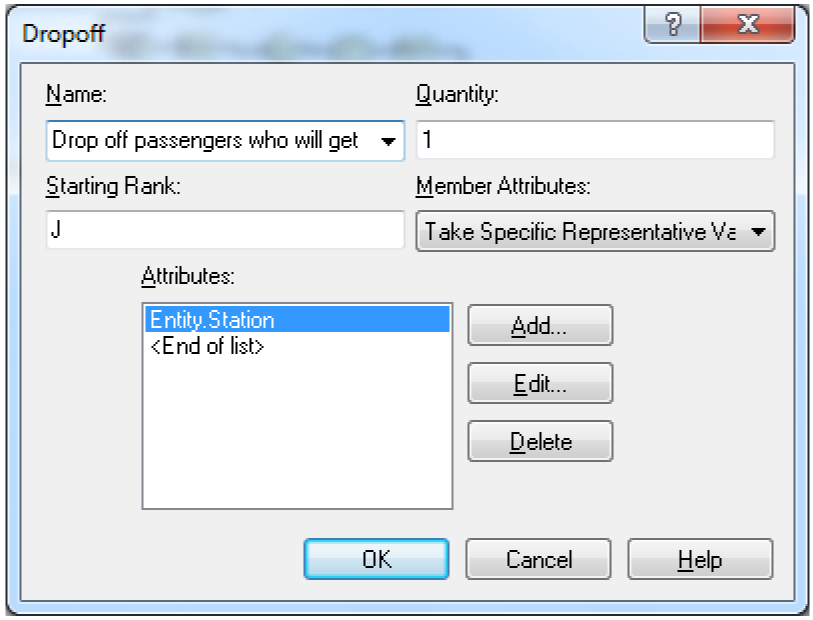

Figure 5.11 Dropoff passengers at “Basmane” station

After the passengers get off, waiting passengers at the station get in the train. The “PickUp” module handles that process. Technically it inserts new entities into an existing group of entities. New entities represent the new passengers that are getting in the train. Existing entities represent the train and the passengers in that train.

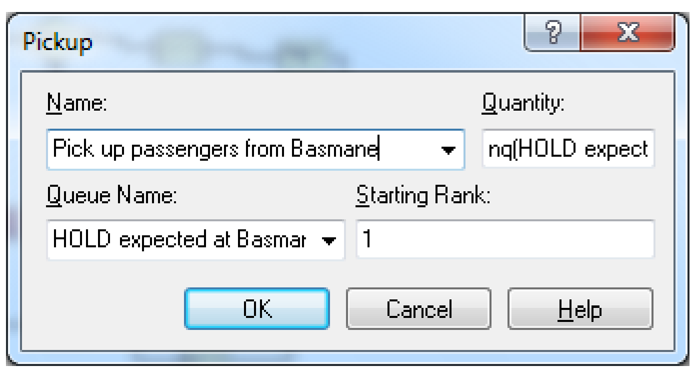

Figure 5.12 Pick up passengers from “Basmane” station

There is a “Delay” module after “PickUp” module to represent dwelling time of the train at that station. Dwell time is read from the input file into an array named “Dwell (Station No)”

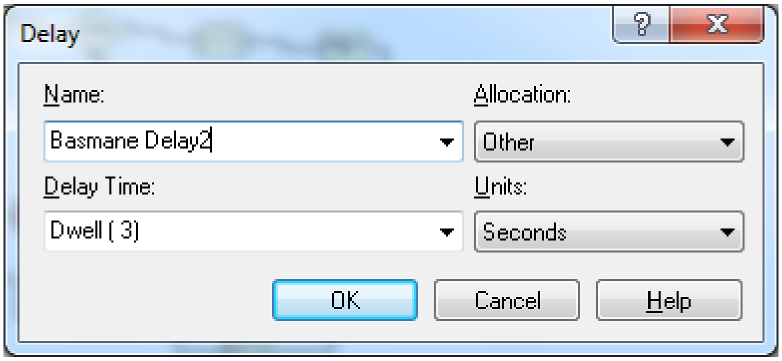

Figure 5.13 Dwell time

When dwell time ends at a station, it means that the train is ready to leave. Simulation model tallies the number of passengers in the train whenever the train leaves a station. Two dimensional arrays "YolcuSayilariBatiya" & "YolcuSayilariDoguya" are defined as tallies to update the current number of passengers in the train. The following figure shows how the model implements it using an "Assign" module. The first index of the array is the trip number, the second one is the station number.

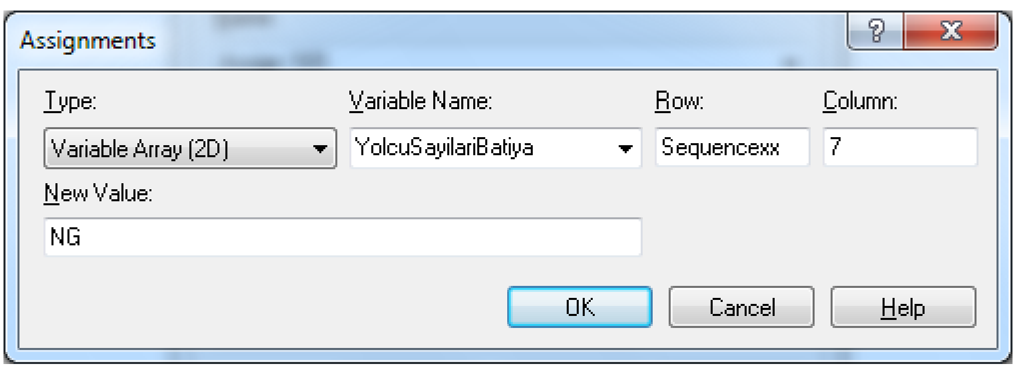

Figure 5.14 Updating the number of passengers when the train leaves "Basmane" station

The number of passengers is then immediately written into an external file as one of the outcomes of the simulation model. The module "ReadWrite" is used for this purpose, and the details are given in the following figure.

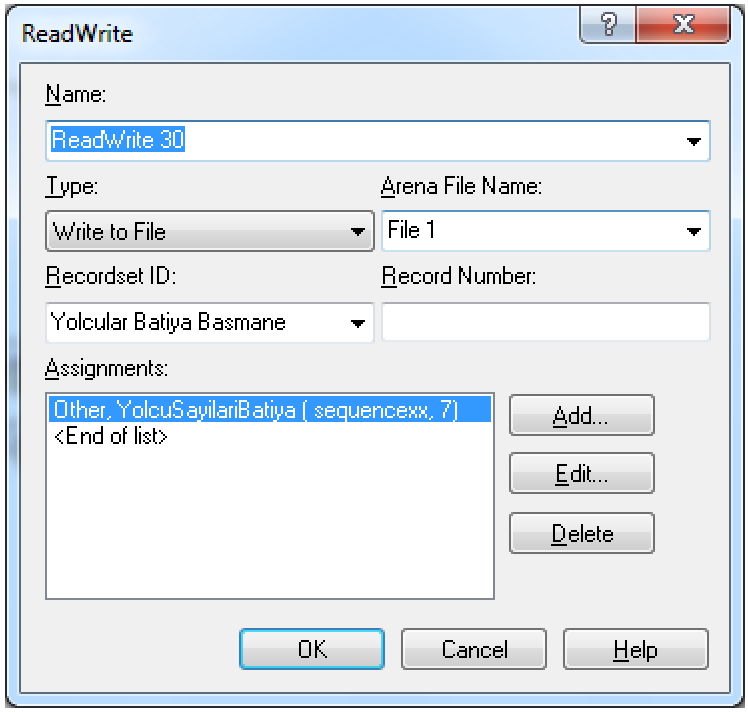

Figure 5.15 ReadWrite passengers at “Basmane” station

When the train leaves a station, it is moved to the next one using “Station” – “Route” module pair. The travel durations between stations are read from the input file.

The structure of the train-passenger interactions described above is the same for the platform in the opposite direction of the same station. Furthermore, the structure is similar for all stations with some minor differences such as station numbers and the next stations etc.

5.3 Movements of the Trains

A sub-model is devoted for creating and controlling the movements of the trains. Details of creating trains are given in the following figures.

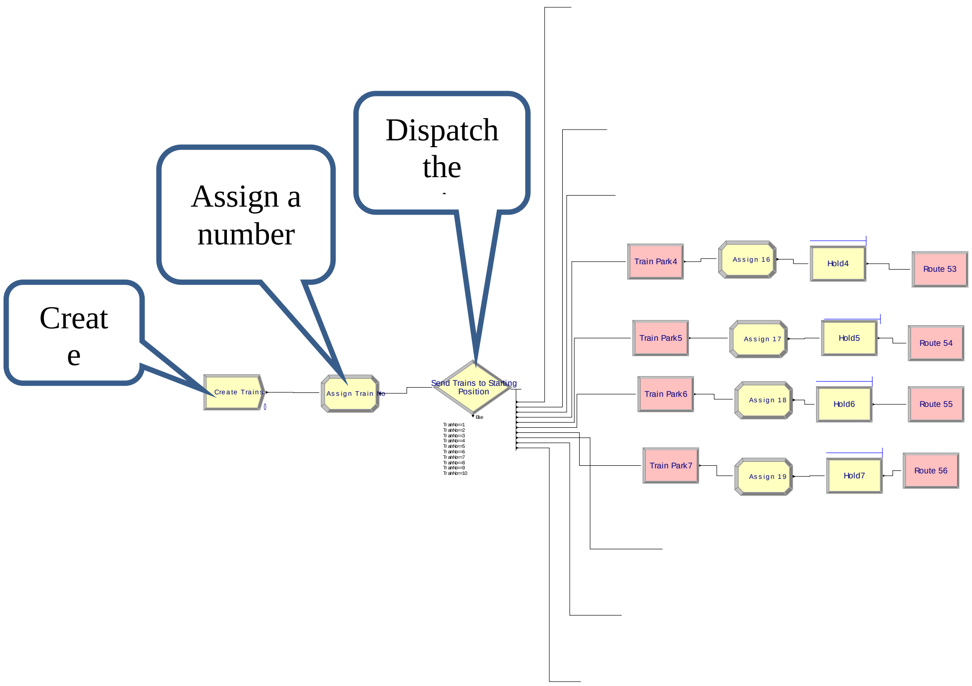

Figure 5.16 Creating and controlling the movements of trains.

Ten entities are created to represent the trains at the beginning of the simulation. These entities are never disposed, they move in the system continuously until the end of the day.

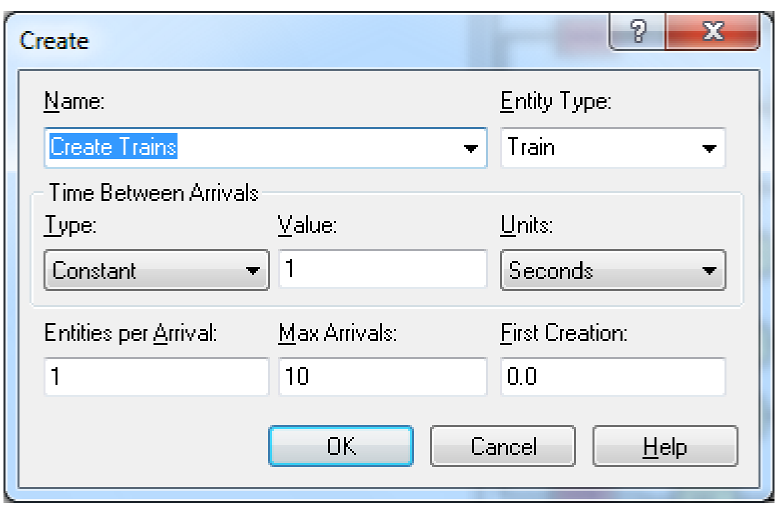

Figure 5.17 Create trains

A specific number is assigned to each train and that number is required to keep track of the trains. The attribute “TrainNo” is assigned using the built-in ARENA function “EntitiesIn”

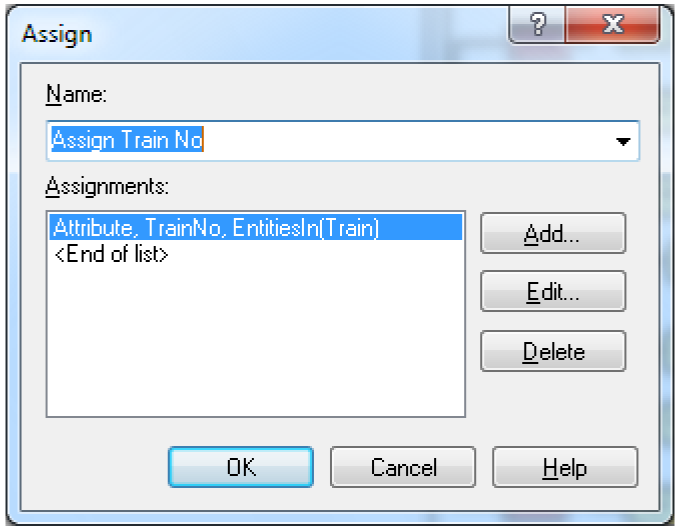

Figure 5.18 Assign train number

Once the trains are created, they are sent to starting positions at “Halkapınar” station.

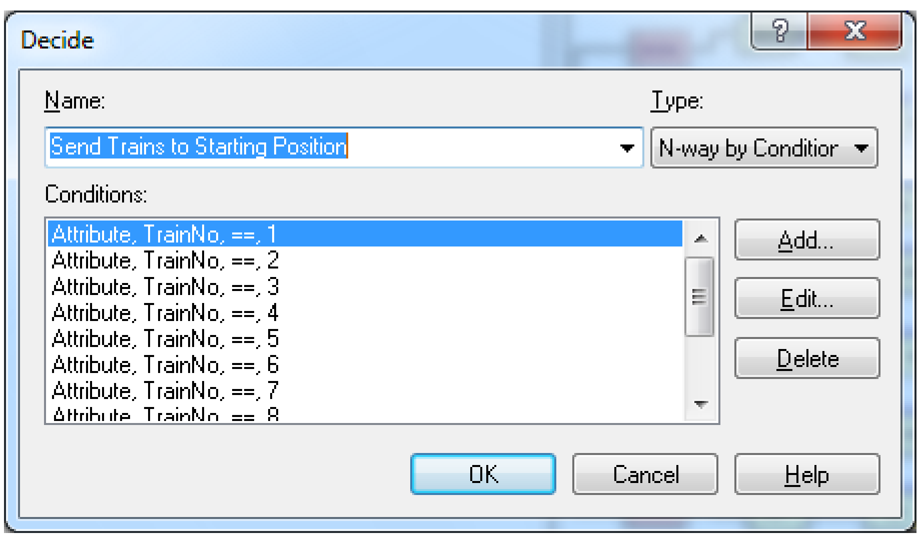

Figure 5.19 Dispatching the trains to starting positions.

The trains wait at their starting positions until a specific signal is sent to move and enter in the system. The module "Hold" is used in ARENA to make trains wait for their turn to enter in the system. The following figure depicts the "Hold" module for train number 4. It waits until a signal with the value 4 is sent.

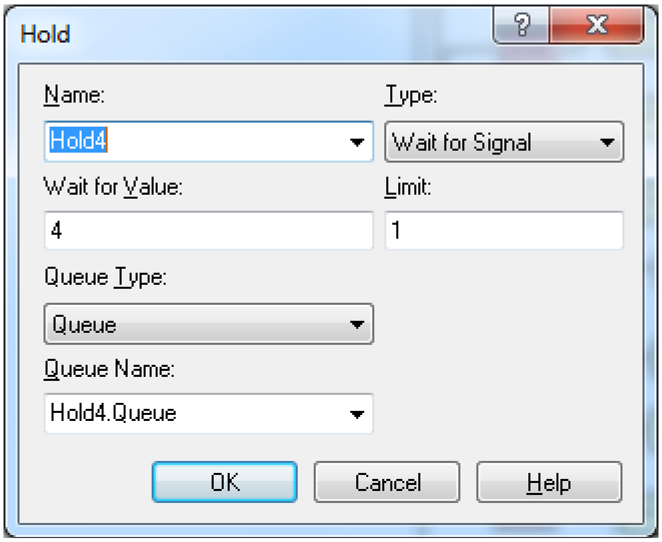

Figure 5.20 Hold trains

A time control unit is designed to control when trains enter into the system. The following figure shows the control unit. A ghost entity is created for this reason, and it checks the simulation clock in every 30 seconds in order to decide whether the time comes for a specific train to enter in.

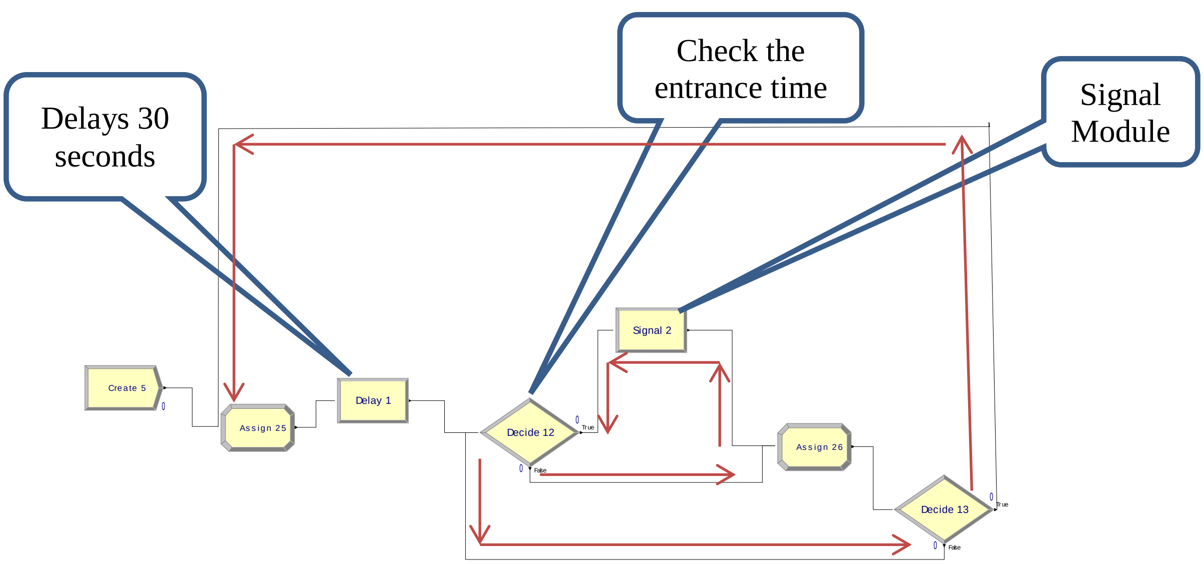

Figure 5.21 The control unit for inserting trains into the Metro Line

The trains enter into and leave the metro line during the day. Therefore they conduct several rounds inside the system. The entrance, exit and re-entrance times of each train are known and stored in the input file. A two dimensional array "EntranceTime" in ARENA reads the entrance times of trains for each round from the input file. The first index stands for the train number and the second index represents the number of round for that train. The following figure shows the "If" block to decide whether the time of entrance for a specific train comes. By the way, it is known that manoeuvering time from the starting position to the entrance of the systems takes 90 seconds.

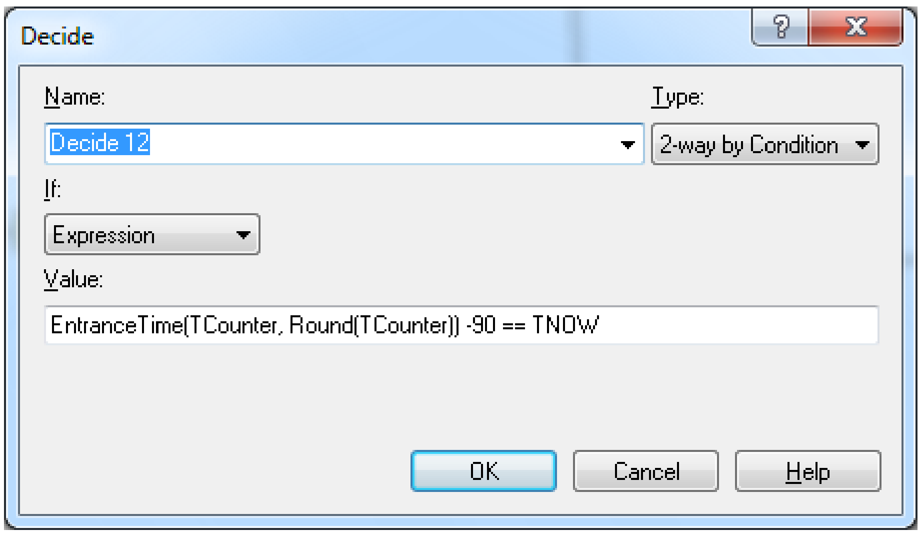

Figure 5.22 Checking entrance times of trains

When the time of entrance comes, the "Signal" block sends a specific signal for a specific train to move and enter into the system.

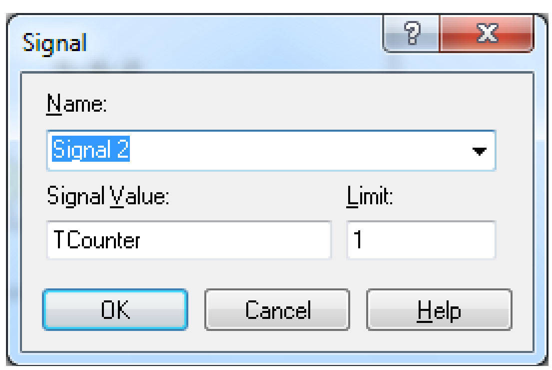

Figure 5.23 Signal block

As the arrival rate of passengers decrease after rush hours, some trains are pulled out from the metro line. The trains leave the line at Halkapınar station. Line-leaving train enters in the parking lot and directed to an appropriate waiting area. The following control unit handles the returning trains at Halkapınar station.

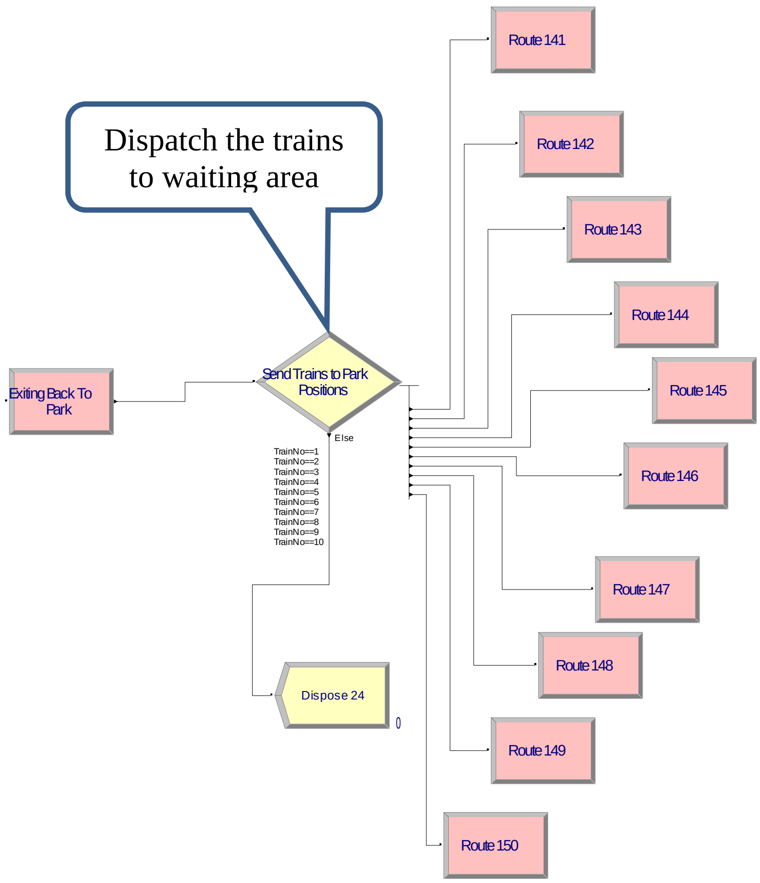

Figure 5.24 Handling the trains pulled out from the line

5.4 Supplementary Modules

There are two additional control mechanisms to manage changes in parameters over time such as the arrival rates of passengers, probability tables for destination stations etc. The following unit makes it possible to change the arrival rates at each minute.

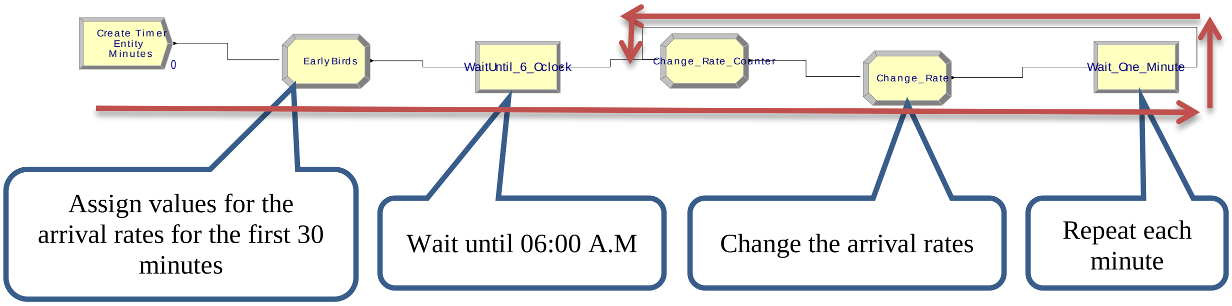

Figure 5.25 Control mechanism to change the arrival rates of passengers

The simulation clock starts at 05:30 A.M. in the morning as the system open doors at stations for the passengers. However the daily train tours begin at 06:00 A.M. and therefore passengers accumulate in stations for 30 minutes. Arrival rates are measured separately for that first half hour. Numerical values are read from the input file and assigned to arrival rates for the first 30 minutes.

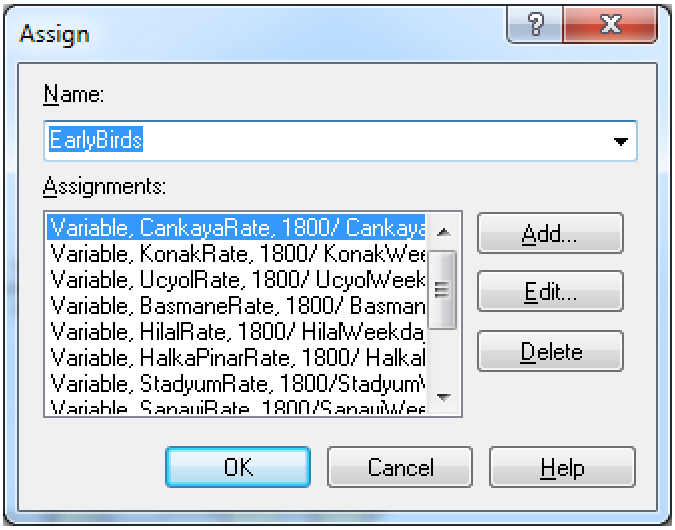

Figure 5.26 Assigning arrival rates for early birds

When the daily routine begins, arrival rates are changed on a minute basis by the help of the ghost entity.

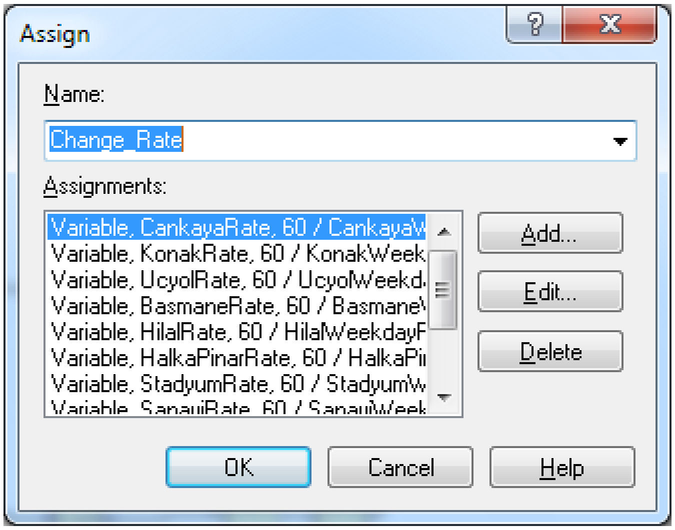

Figure 5.27 Assigning arrival rates on a minute basis.

On the other hand, the probability tables for the destination stations should be changed on an hourly basis. The following control unit handles that issue. A ghost entity moves in a loop repeatedly for each hour and forces to change the probability tables of destination stations.

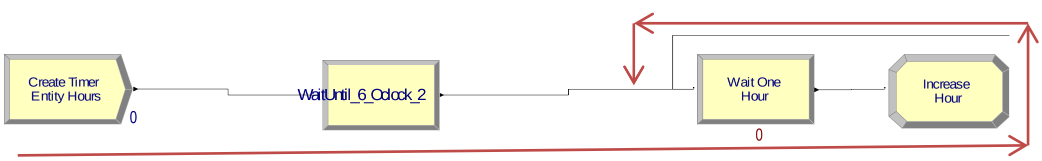

Figure 5.28 Control unit to change probability tables.

6. VERIFICATION & VALIDATION

In simulation studies, the concept of "verification" concerns with building the ***model right***. It is utilized in the comparison of the conceptual model to the computer representation. It asks the questions: "Is the model implemented correctly in the computer? Are the input parameters and logical structure of the model correctly represented?"

In order to verify the model, each module and unit has been tested using the debugging tools of ARENA software during the model development process. The movements of particular passengers are tracked upon arrival at the system. The selection of direction and destination station and then putting the passenger into the appropriate queue has been verified by tracking random passengers at each station. Furthermore especially the train-passenger interactions are investigated carefully. Technically train and passengers are two different kinds of entities in ARENA. When a train is ready to move from a terminus, the entities representing the passengers getting in the train and the entity representing the train are merged into a group and they are moved together to the next station. Upon arriving at the next station, some of the entities should be separated from the group to represent the leaving passengers. Some new entities are then merged to the group to simulate the passengers getting in the train. The movements of trains are tracked over time whether they comply in the regulations and time schedule.

On the other hand "validation" concerns with building the ***right model***. It is utilized to determine that a model is an accurate representation of the real system. Validation is usually achieved through the calibration of the model, an iterative process of comparing the model to actual system behavior and using the discrepancies between the two, and the insights gained, to improve the model. This process is repeated until model accuracy is judged to be acceptable.

Some comparisons have been prepared in order to validate the model. Actual and simulated numbers of passengers arriving at the stations are compared and it is found that the fidelity of arrival process in simulation model is pretty high. The following table shows the comparison related with the total passengers at each station.

Table 6.1 Comparison of total number of passengers arriving at stations

Station Name	**Simulation Average**	**Actual System Average**
Basmane	7904	7930
Bolge	7296	7321
Bornova	29943	30028
Cankaya	18735	18780
HalkaPinar	11460	11503
Hilal	1118	1132
Konak	25446	25516
Sanayi	2706	2722
Stadyum	10048	10059
Ucyol	21257	21267
Total	135912	136258

Furthermore, the numbers of arriving passengers are also compared in an hourly basis at each station. The following tables present the comparisons for stations at different hours of the day.

Table 6.2 Comparison of hourly number of passengers arriving at stations

Hours	Ucyol			Konak		
	Generated by Simulation	Actual	Deviation	Generated by Simulation	Actual	Deviation
05:30-07:00	547	531	3%	393	394	0%
07:00-08:00	2985	2920	2%	1571	1547	2%
08:00 09:00	4390	4419	-1%	2094	2109	-1%
09:00-10:00	1688	1712	-1%	1260	1271	-1%
10:00-11:00	1085	1083	0%	1000	998	0%
11:00-12:00	1038	1033	1%	1139	1137	0%
12:00-13:00	1238	1229	1%	1298	1293	0%
13:00-14:00	1344	1345	0%	1605	1602	0%
14:00-15:00	1252	1252	0%	1687	1684	0%
15:00-16:00	1138	1139	0%	2004	1986	1%
16:00-17:00	1048	1055	-1%	2322	2315	0%
17:00-18:00	997	1000	0%	2567	2573	0%
18:00-19:00	890	887	0%	2299	2304	0%
19:00-20:00	642	645	0%	1762	1781	-1%
20:00-21:00	411	412	0%	1129	1142	-1%
21:00-22:00	281	282	-1%	665	670	-1%
22:00-23:00	202	202	0%	442	445	-1%
23:00-00:00	117	121	-3%	255	265	-4%

Hours	Çankaya			Basmane		
	Generated by Simulation	Actual	Deviation	Generated by Simulation	Actual	Deviation
05:30-07:00	99	103	-4%	212	214	-1%
07:00-08:00	337	335	1%	793	788	1%
08:00 09:00	342	343	0%	659	671	-2%
09:00-10:00	422	420	0%	384	384	0%
10:00-11:00	546	540	1%	310	308	1%
11:00-12:00	716	714	0%	332	335	-1%
12:00-13:00	939	935	0%	375	374	0%
13:00-14:00	1153	1154	0%	411	413	0%
14:00-15:00	1260	1259	0%	450	449	0%
15:00-16:00	1507	1499	1%	499	497	0%
16:00-17:00	1735	1736	0%	590	586	1%
17:00-18:00	2114	2095	1%	781	781	0%
18:00-19:00	3283	3269	0%	832	836	0%
19:00-20:00	2518	2549	-1%	609	611	0%
20:00-21:00	1052	1071	-2%	313	321	-2%
21:00-22:00	462	466	-1%	166	167	-1%
22:00-23:00	181	185	-2%	119	118	1%
23:00-00:00	103	108	-5%	73	76	-4%

Table 6.2 Comparison of hourly number of passengers arriving at stations (Continued)

Hours	HalkaPinar			Stadyum		
	Generated by Simulation	Actual	Deviation	Generated by Simulation	Actual	Deviation
05:30-07:00	81	85	-5%	135	135	0%
07:00-08:00	727	714	2%	665	653	2%
08:00 09:00	1166	1174	-1%	1065	1073	-1%
09:00-10:00	611	615	-1%	531	535	-1%
10:00-11:00	484	483	0%	453	455	0%
11:00-12:00	509	510	0%	516	516	0%
12:00-13:00	574	577	0%	580	573	1%
13:00-14:00	676	677	0%	821	831	-1%
14:00-15:00	757	749	1%	686	687	0%
15:00-16:00	747	746	0%	720	718	0%
16:00-17:00	698	696	0%	747	747	0%
17:00-18:00	892	892	0%	745	740	1%
18:00-19:00	1542	1535	0%	1016	1012	0%
19:00-20:00	1025	1035	-1%	663	671	-1%
20:00-21:00	441	450	-2%	353	354	0%
21:00-22:00	270	274	-1%	173	174	0%
22:00-23:00	178	180	-1%	124	126	-1%
23:00-00:00	104	109	-5%	56	58	-3%

Hours	Bolge			Bornova		
	Generated by Simulation	Actual	Deviation	Generated by Simulation	Actual	Deviation
05:30-07:00	73	76	-4%	453	441	3%
07:00-08:00	490	481	2%	1939	1907	2%
08:00 -09:00	923	930	-1%	2549	2566	-1%
09:00-10:00	397	402	-1%	1356	1363	-1%
10:00-11:00	323	325	-1%	1279	1281	0%
11:00-12:00	365	362	1%	1482	1473	1%
12:00-13:00	467	466	0%	1768	1759	1%
13:00-14:00	446	448	0%	1861	1854	0%
14:00-15:00	441	440	0%	2218	2217	0%
15:00-16:00	497	498	0%	2477	2465	1%
16:00-17:00	516	514	0%	2774	2771	0%
17:00-18:00	622	620	0%	2576	2590	-1%
18:00-19:00	745	746	0%	2226	2227	0%
19:00-20:00	433	438	-1%	1693	1713	-1%
20:00-21:00	255	260	-2%	1213	1214	0%
21:00-22:00	139	140	-1%	920	924	0%
22:00-23:00	105	106	-1%	755	757	0%
23:00-00:00	64	66	-3%	490	505	-3%

Please note that actual and simulated numbers of passengers arriving at the stations are very close to each other which enable us to be confident with verification and validation of the model.

Furthermore, the animation model also provides a visual tool for validating the model. It is especially very helpful to present the model to the management of the company.

7. OUTPUT ANALYSIS

The purpose of simulation studies is to estimate system parameters under consideration. If some of the input processes driving a simulation are random, then the output data are also random and runs of the simulation program only result in estimates of system performance measures. Unfortunately, a simulation run does not usually produce independent, identically distributed (i.i.d.) observations; therefore it is required to run the simulation more than once and apply convenient techniques of output analysis.

The model developed in this study is a “terminating simulation” model since the metro operations are stopped at midnight each day and starts with an empty state in the next day. It is required to collect data across some replications and analyze them statistically to construct confidence intervals for performance measures in the model. The performance measures in consideration are the number of passengers in train across stations for each trip and the average waiting times of passengers at stations.

Assume that n replications have been made and $X(n)$ is the average of a performance measure across replications. $X(n)$ is said to be an unbiased point estimator for the real system response μ, and an approximate 100(1-α) percent ($0 < \alpha < 1$) confidence interval (CI) for μ is given by

$$CI = X(n) \pm t_{n-1,\ 1-\frac{\alpha}{2}} * \frac{s^2(n)}{\sqrt{n}}$$

$$where\ s^2(n)\ is\ the\ sample\ variance\ and\ \alpha\ is\ the\ confidence\ level$$

The number of replications is determined as 10 at the beginning as proposed in Kelton and Law (2000). The following tables indicate the confidence intervals for the number of passengers in train across stations for selected trips. There are 380 trips in total during a day, the rest of the information is supplied in a DVD attached to the thesis and also stored at < http://aoner.yasar.edu.tr/?page_id=723 >

Table 7.1 Confidence intervals for the number of passengers in train across stations (Number of replications =10)

Trip Time	Bornova	Bölge	Sanayi	Stadyum	Hlkpinar	Hilal	Basmane	Çankaya	Konak
06:00	21,8 ± 3,61	26,1 ± 3,18	27,8 ± 2,99	33 ± 4,19	26,9 ± 3,36	26 ± 3,16	23,5 ± 3,02	19,1 ± 3,34	9,5 ± 2,55
06:10	10,8 ± 2,33	14,1 ± 1,95	14,4 ± 2,13	16,9 ± 3,06	13,4 ± 2,50	13,5 ± 2,26	16,9 ± 2,39	14,9 ± 2,59	11,6 ± 2,78
…..	…..	…..	…..	…..	…..	…..	…..	…..	…..
08:02	189,1 ± 10,8	227,3 ± 7,97	229,5 ± 9,02	265,7 ± 11,8	271,4 ± 14,2	265,8 ± 14,1	245,2 ± 13,6	169,3 ± 12,7	79,6 ± 5,57
08:06	184,8 ± 7,39	232 ± 9,53	237 ± 10,8	278,9 ± 8,96	281,4 ± 8,04	274,1 ± 8,35	252,3 ± 10,3	175,6 ± 9,13	80,8 ± 3,67
08:10	205,4 ± 10,1	254,5 ± 10,5	255,6 ± 9,13	303,9 ± 12,5	311,2 ± 15,1	304,3 ± 14,2	279,5 ± 11,6	187,8 ± 5,64	80,9 ± 3,06
….	…..	…..	…..	…..	…..	…..	…..	…..	…..
13:18	220,2 ± 10,1	246,8 ± 12,0	251,5 ± 12,4	299,3 ± 13,2	273,1 ± 14,3	270,4 ± 14,4	251,8 ± 14,6	222,2 ± 10,2	106 ± 8,98
13:24	195,9 ± 10,9	220,1 ± 9,64	229,3 ± 10,4	269,2 ± 10,9	269,5 ± 12,6	266,5 ± 12,9	253,2 ± 13,1	221,8 ± 14,0	113 ± 7,22
….	…..	…..	…..	…..	…..	…..	…..	…..	…..
17:42	161,3 ± 11,6	184,9 ± 13,0	192,3 ± 12,5	215,7 ± 13,9	203,3 ± 13,1	201,3 ± 12,7	200 ± 12,0	214,2 ± 11,7	137 ± 4,53
…	…..	…..	…..	…..	…..	…..	…..	…..	…..
20:47	50 ± 5,48	55,5 ± 6,03	58,3 ± 7,66	62,7 ± 6,79	73 ± 0,01	73 ± 0,02	71 ± 0,01	88 ± 0,03	65 ± 0,04
..	…	…..	…..	…..	…..	…..	…..	…..	…..

The averages and half-widths of confidence intervals differ substantially with respect to the trip time. In order to compare the tightness of the confidence intervals in a common ground, the estimates of “relative error” are calculated for each trip. The estimate of relative error is defined as the division of half width by the average (Kelton and Law, 2000). Table 7.2 shows the estimates of relative errors for the same trips given in Table 7.1

Table 7.2 Estimates of relative errors (Half width divided by average)

Trip Time	Bornova	Bölge	Sanayi	Stadyum	Hlkpinar	Hilal	Basmane	Çankaya	Konak
06:00	0,17	0,12	0,11	0,13	0,13	0,12	0,13	0,18	0,27
06:10	0,22	0,14	0,15	0,18	0,19	0,17	0,14	0,17	0,24
…..	…..	…..	…..	…..	…..	…..	…..	…..	…..
08:02	0,06	0,04	0,04	0,04	0,05	0,05	0,06	0,08	0,07
08:06	0,04	0,04	0,05	0,03	0,03	0,03	0,04	0,05	0,05
08:10	0,05	0,04	0,04	0,04	0,05	0,05	0,04	0,03	0,04
….	…..	…..	…..	…..	…..	…..	…..	…..	…..
13:18	0,05	0,05	0,05	0,04	0,05	0,05	0,06	0,05	0,08
13:24	0,06	0,04	0,05	0,04	0,05	0,05	0,05	0,06	0,06
….	…..	…..	…..	…..	…..	…..	…..	…..	…..
17:42	0,07	0,07	0,07	0,06	0,06	0,06	0,06	0,05	0,03
…..	…..	…..	…..	…..	…..	…..	…..	…..	…..
20:47	0,11	0,11	0,13	0,11	0,0001	0,0002	0,0001	0,0003	0,0006
…..	…..	…..	…..	…..	…..	…..	…..	…..	…..

Estimates for relative errors are pretty small for all trips except the ones which are the early trips in the morning and the late trips in the evening. It is not surprising since the numbers of passengers arriving at those hours are relatively small for every station which leads smaller averages.

Confidence intervals and estimates of relative errors are also determined for the average waiting times of passengers at different stations. The following table presents the corresponding outcomes for 10 replications.

Table 7.3. Confidence intervals and estimates of relative errors for average waiting time (in seconds)

Stations	Confidence Interval	Estimate of Relative Error (Half Width divided by Average)
Bornova	232±4.32	0.018
Bolge	227±5.02	0.022
Sanayi	220±10.49	0.047
Stadyum	228±7.06	0.030
HalkaPinar	161±0.81	0.005
Hilal	217±26.86	0.123
Basmane	223±9.01	0.040
Cankaya	186±2.77	0.014
Konak	221±4.45	0.020
Ucyol	211±4.82	0.022

Notice that the estimates of relative errors are also quite small for average waiting times of the passengers. The highest value in this table is observed for the station “Sanayi” due to larger half width which is an indication of higher variability in the average waiting times of passengers arriving at that station.

The estimates of relative errors derived from 10 replications are reviewed for all system parameters and it is observed that the highest relative error occurs for the number of passengers in the train at trip with time 06:00 A.M in west direction (See Table 7.2). This parameter will be used as the reference point in order to find the number of replications required to provide a smaller relative error level which is determined as 0.05. In other words, we need to figure out the number of replications in order to decrease the half widths such that relative error is less than 0.05 for each system parameter.

The concept of relative error is defined in Kelton and Law (2000). If the estimate $X(n)$ is such that $\frac{|X(n)-\mu|}{|\mu|} = \gamma$, then we say that $X(n)$ has a relative error of γ. Suppose that we make replications of a simulation until the half-width of the confidence interval divided by $|X(n)|$ is less than or equal to γ (0< γ <1). This ratio is an estimate of the actual relative error. Then :

$$
\begin{aligned}
1\text{-}\alpha \;&\approx P\left(\frac{|X(n)-\mu|}{|X(n)|} \le \frac{half\ width}{|X(n)|}\right) \\
&\le P(|X(n)-\mu| \le \gamma * |X(n)|) && \left(\frac{half\ width}{|X(n)|} \le \gamma\right) \\
&= P(|X(n)-\mu| \le \gamma * |X(n)-\mu+\mu|) && \text{(add, subtract } \mu\text{)} \\
&\le \mathrm{P}\left(|X(n)-\mu| \le \gamma * (|X(n)-\mu| + |\mu|)\right) && \text{(triangle inequality)} \\
&= \mathrm{P}\left((1-\gamma) * |X(n)-\mu| \le \gamma * |\mu|\right) && \text{(algebra)} \\
&= \mathrm{P}\left(\frac{|X(n)-\mu|}{|\mu|} \le \frac{\gamma}{1-\gamma}\right) && \text{(algebra)}
\end{aligned}
$$

Thus, $X(n)$ has a relative error of at most γ / (1- γ) with a probability of approximately 1-α. In other words, if we construct 100 independent 90 percent confidence intervals using the above stopping rule, we would expect $X(n)$ to have a relative error of at most γ / (1- γ) in about 90 of the 100 cases; in about 10 cases the relative error would be greater than γ / (1- γ). Note that we get a relative error of γ / (1- γ) rather than desired γ, since we estimate |μ| by $|X(n)|$.

$$\frac{|X(n)-\mu|}{|\mu|} \xrightarrow{\quad estimator \quad} \frac{half\ width}{|X(n)|}$$

$$\frac{|X(n)-\mu|}{|\mu|} \le \frac{\gamma}{1-\gamma} \xrightarrow{\quad estimator \quad} \frac{half\ width}{|X(n)|} \le \gamma$$

$$\frac{|X(n)-\mu|}{|\mu|} \le \gamma \xrightarrow{\quad estimator \quad} \frac{half\ width}{|X(n)|} \le \frac{\gamma}{1+\gamma} = \gamma'$$

since $$\frac{\gamma'}{1-\gamma'} = \frac{\frac{\gamma}{1+\gamma}}{1-\frac{\gamma}{1+\gamma}} = \frac{\frac{\gamma}{1+\gamma}}{\frac{1}{1+\gamma}} = \gamma$$

Suppose once again that we have constructed a confidence interval for μ based on a fixed number of replications n. If we assume that our estimates of both the population mean and population variance won't change as the number of replications increases, an approximate expression for the number of replications n_r (γ), required to obtain a relative error of γ is given by

$$n_r(\gamma) = Min \left\{ i \geq n : \frac{t_{i-1,1-\frac{\alpha}{2}} * \frac{s(n)}{\sqrt{i}}}{X(n)} \leq \gamma' \right\} \; where \; \gamma' = \frac{\gamma}{1+\gamma} \; is \; the \; adjusted \; relative \; error$$

n_r (γ) is approximated as the smallest integer *i* satisfying $i \geq s^2(n) \left[\frac{z_{1-\frac{\alpha}{2}}}{\gamma' * X(n)}\right]^2$

If n_r (γ) > n and if we make [n_r (γ) – n] additional replications of the simulation, then the estimate $X(n_r)$ based on all n_r (γ) replications should have a relative error of approximately γ.

Recall that we have already made 10 replications and the confidence intervals and estimates of relative errors have been presented earlier. Let's use the knowledge explained above for the system parameter with highest relative error (i.e. the number of passengers in the train at trip with west direction and time 06:00 A.M) in order to find the number of replications to be made.

X(10) = 9.50 (See Table 7.1)
s (10) = 3.57 (See Table 7.1)
γ = 0.05
α =0.10

$$i \geq s^2(n) \left[\frac{z_{1-,\frac{\alpha}{2}}}{\gamma' * X(n)}\right]^2 = (3.57^2) \left[\frac{1.64}{\frac{0.05}{1+0.05} * 9.5}\right]^2 \geq \ldots \approx 168 \text{ replications}$$

It means that if we conduct 158 additional replications of the simulation, then the estimate $X(168)$ based on all 168 replications should have a relative error of approximately 0.05.

In ARENA software, there are some useful global functions that can handle confidence intervals and half-widths across replications. The built-in function "ORUNHALF (*parameter*)" delivers half-width of a system parameter after *n* replications. Furthermore, it is possible to develop an experimental design in ARENA such that the model itself makes replications sequentially until a desired level of half-width is attained and then it stops making further replications. Unfortunately there is not such a function to work with relative errors. However it is possible to translate desired level of relative error into desired level of half-width as follows:

$$\frac{half\ width}{|X(n)|} \leq \frac{\gamma}{1+\gamma} = \gamma' \quad \longrightarrow \quad half\ width \leq \gamma' * |X(n)|$$

$$half\ width \leq \frac{0.05}{1+0.05} * (9.5) = 0.452381$$

It means that if we make replications of the simulation until half-width ≤ 0.452381, then we get the desired level of relative error $\gamma = 0.05$ for the system parameter under consideration.

A sub-model is developed in ARENA which is a trapping mechanism such that it checks the decreasing half-width after each replication, and it shuts down the model whenever the half-width becomes equal or less than the desired level. Before presenting the details, it is required to show some definitions as follows:

MREP: Built-in ARENA variable that stands for *maximum number of replications* to be run for the simulation. When you fill out Run > Setup dialog and specify the number of replications, MREP is set to the value specified. At the beginning, MREP should be set to arbitrarily a large value such as 500.

NREP: Built-in ARENA variable that holds *current number of replications*. When NREP equals 1, no replication has been completed yet. When NREP equals 2, the first replication has been completed and the second replication is in progress. When NREP equals 3, two replications have been completed. It is required at least two replications completed to form a confidence interval. The ARENA model and its details are given in the following figures.

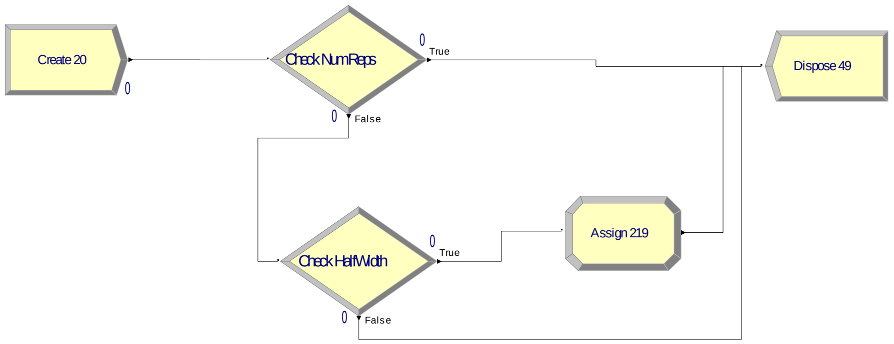

Figure 7.1 The mechanism to stop replications when desired level is attained

The create module creates a single entity at time 0.0 for each replication. That entity then proceeds to a “Decide” module where it checks whether NREP is greater or equal to 2. Once the simulation is past two replications, the entity will then begin checking the half-width of the parameter under consideration

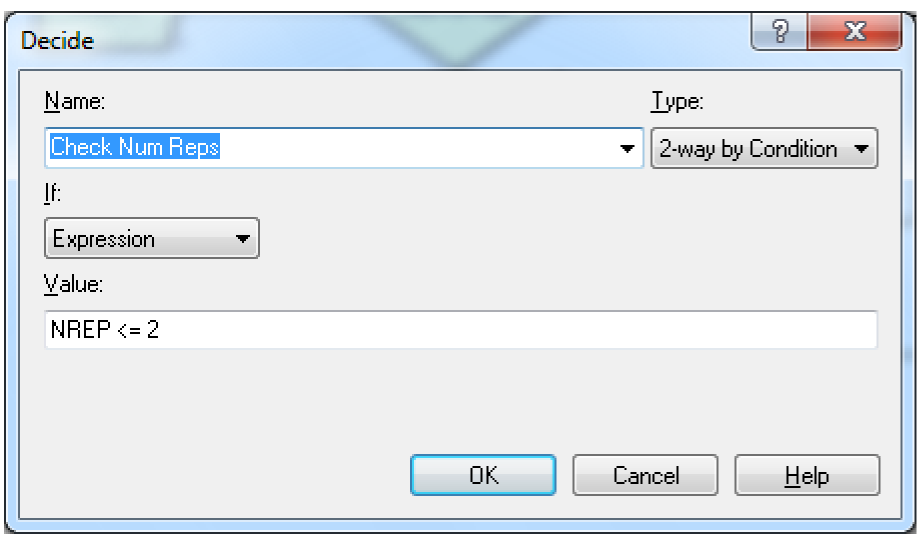

Figure 7.2 Checking current number of replications

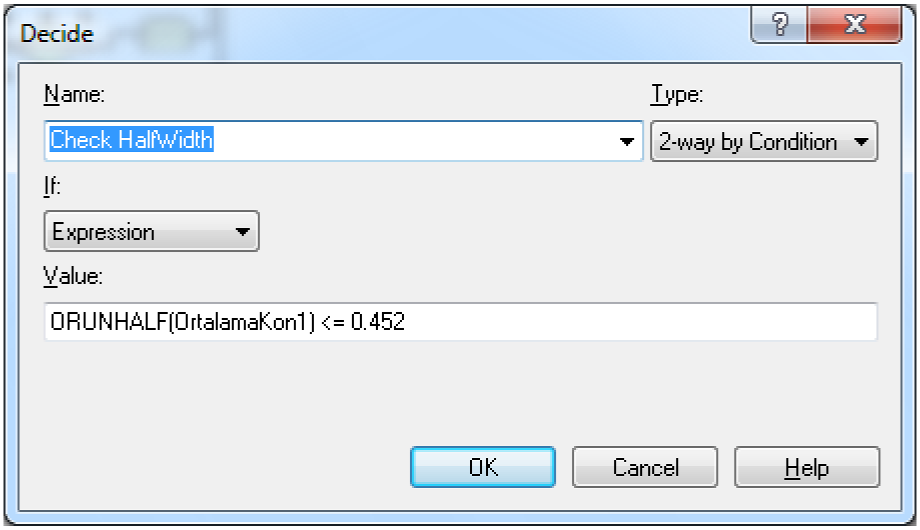

Figure 7.3 Checking half-width for the system parameter

At the end of a particular replication, if desired level of half-width is not attained yet, then MREP is set equal to NREP in order to force make one more replication.

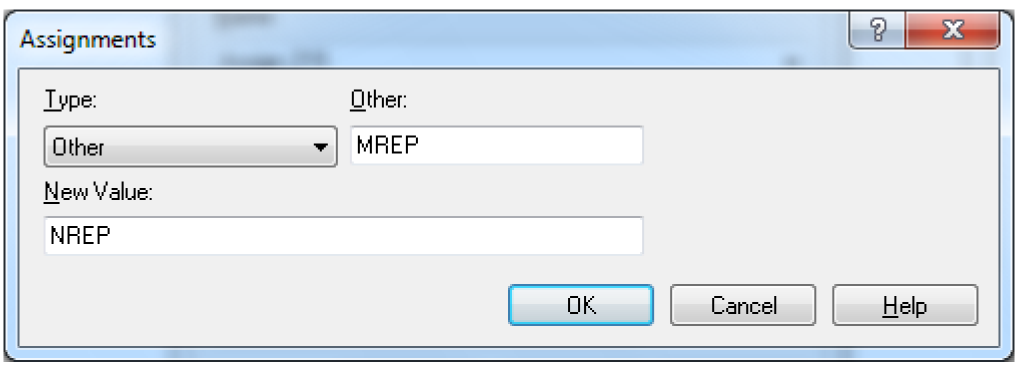

Figure 7.4 Assignments module

The model has been run with the construct explained above, and it had stopped after 217 replications. Number of replications here is very close to the one found earlier using the procedures described in Kelton and Law (2000). The relative errors have been calculated then and the results are indicated in following tables.

Table 7.4 Estimates of relative errors for the number of passengers across stations (Number of replications =217)

Trip Time	Bornova	Bölge	Sanayi	Stadyum	Hlkpinar	Hilal	Basmane	Çankaya	Konak
06:00	0,04	0,04	0,04	0,03	0,04	0,03	0,04	0,04	0,05
06:10	0,05	0,05	0,05	0,05	0,05	0,05	0,05	0,05	0,05
…..	…..	…..	…..	…..	…..	…..	…..	…..	…..
08:02	0,02	0,01	0,01	0,01	0,01	0,01	0,01	0,01	0,02
08:06	0,01	0,01	0,01	0,01	0,01	0,01	0,01	0,02	0,02
08:10	0,01	0,01	0,01	0,01	0,01	0,01	0,01	0,02	0,02
….	…..	…..	…..	…..	…..	…..	…..	…..	…..
13:18	0,01	0,01	0,01	0,01	0,01	0,01	0,01	0,01	0,02
13:24	0,01	0,01	0,01	0,01	0,01	0,01	0,01	0,01	0,02
….	…..	…..	…..	…..	…..	…..	…..	…..	…..
17:42	0,02	0,02	0,01	0,01	0,01	0,01	0,01	0,01	0,02
…	…..	…..	…..	…..	…..	…..	…..	…..	…..
20:47	0,03	0,03	0,03	0,03	0,02	0,02	0,02	0,01	0,02
…..	…..	…..	…..	…..	…..	…..	…..	…..	…..

Table 7.5. Estimates of relative errors for average waiting time of passengers (in seconds) (Number of replications =217)

Stations	Confidence Interval	Estimate of Relative Error (Half Width divided by Average)
Bornova	225±1,65	0,0073
Bolge	229±1,87	0,0081
Sanayi	234±0,94	0,0040
Stadyum	184±0,69	0,0037
HalkaPinar	161±0,13	0,0008
Hilal	211±3,87	0,0183
Basmane	221±1,01	0,0046
Çankaya	216±2,49	0,0115
Konak	230±1,64	0,0071
Ucyol	216±1,01	0,0047

It is observed that the confidence intervals and half-widths are all much narrower than the previous ones and the relative errors are all less than or equal to 0.05. The rest of analysis results not presented above is supplied in a DVD attached to the thesis and also stored at < http://aoner.yasar.edu.tr/?page_id=723 > . From now on, the results derived after 217 replications will be used as the formal outcomes of the simulation model.

8. RESULTS & DISCUSSION

8.1 Simulation Outcomes

The primary outcome of the simulation model is the average number of passengers in the train across the stations for each trip. It serves an indication for the comfort of the passengers. The management had no numerical information on this indicator prior to this study. The following figures present the average number of passengers in the train across stations for some selected trips.

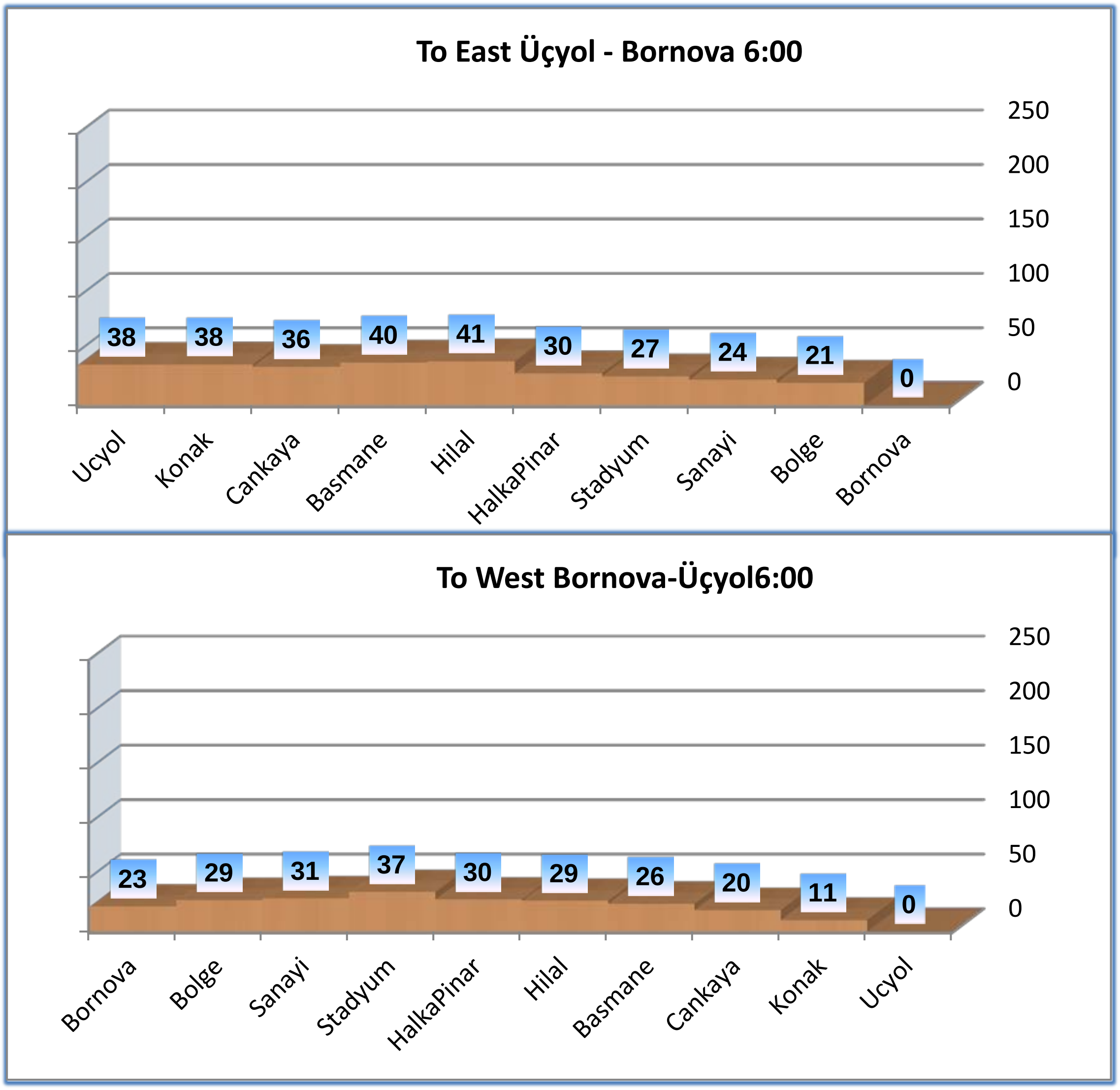

Figure 8.1 The average number of passengers in train across stations for trip at 06:00

The numbers in the figures represent the number of passengers in the train whenever the train leaves a station. Please remember that each train is comprised of 4 coaches and each coach has 44 seats plus 34 m^2 empty spaces for standing passengers. The first suggestion may be to use only two coaches for trip conducted at 06:00 A.M. This issue will be discussed again later in section 8.2. The following figures present the situation for the trips conducted in rush hours.

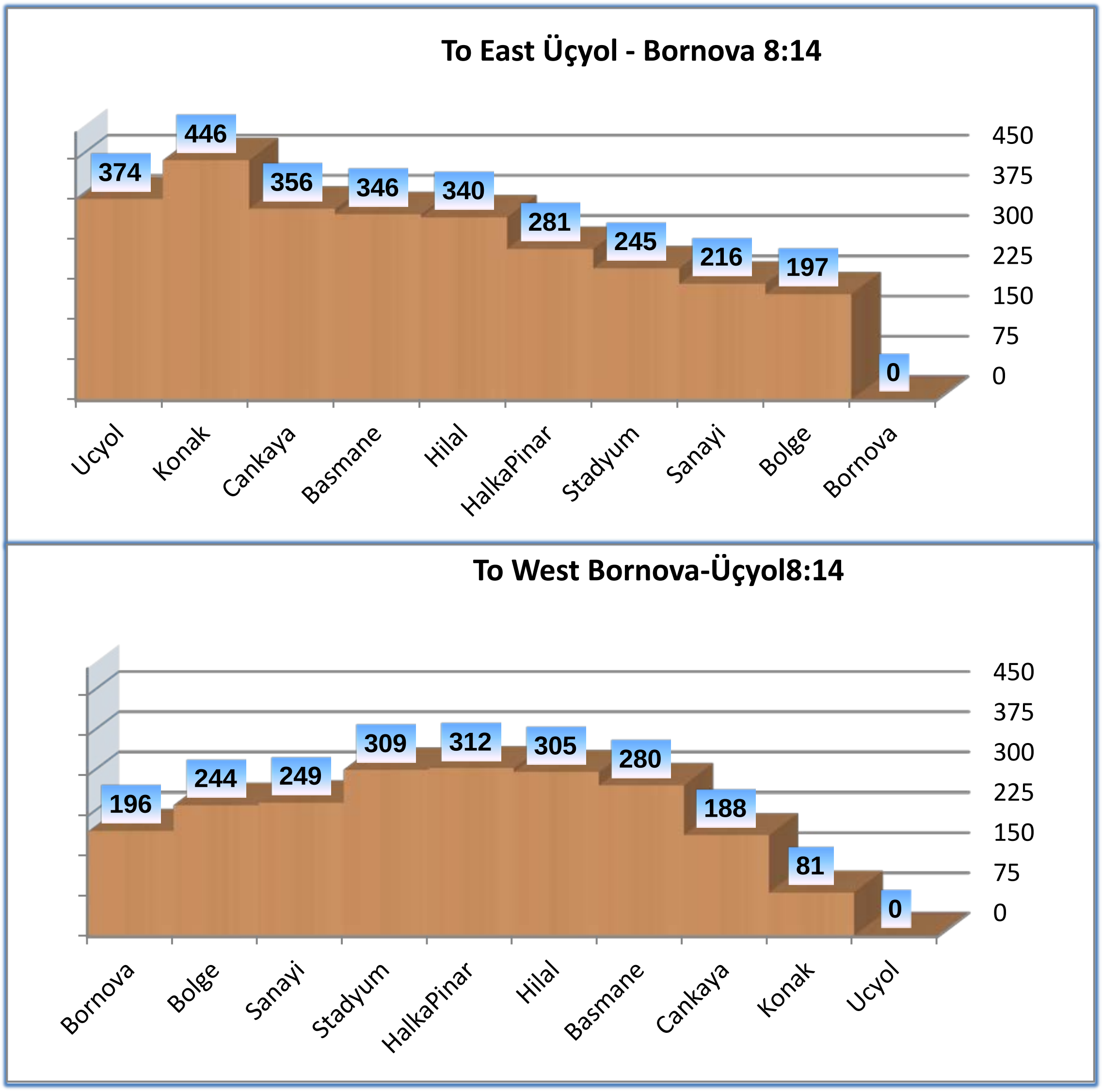

Figure 8.2 The average number of passengers in train across stations for trip at 08:14

Note that the maximum numbers of passengers in the trains are 446 and 312 for the east and west rounds respectively. Since the train has four coaches, it means that the train is a little bit crowded, all seats are occupied and there are approximately 2 straphangers per square meter. In order to define the service quality clearly, let us make some definitions before proceeding further:

$CoI_{i.d}$: Comfort Index. the number of straphangers per square meter for trip i to direction d. i=1.2.…190; d= East, West

$MNP_{i.d}$: Maximum number of passengers in the train for trip i

NS : Number of seats per coach

$NC_{i.d}$: Number of coaches

ES : empty space for straphangers per coach in terms of square meter

$$CoI_{i.d} = \frac{MNP_{i.d} - (NC_{i.d} * NS)}{(NC_{i.d} * ES)}$$

Currently, there are four coaches for the trip to east at 08:14 and therefore the comfort index can be calculated as (446– 4*44) / (4*34) = 1.98. Since the comfort index does not exceed 3, it is convenient to use 4 coaches for this trip. However, the efficiency of using 4 coaches may be a question here. For the sake of saving energy costs, it is required to find the minimum number of coaches to be used without exceeding the comfort index. Let's investigate whether it is convenient to use 3 coaches for this trip:

$$CoI_{08:14\,,\ east} = \frac{446-(3*44)}{(3*34)} = 3.078 \qquad for\ \ 3\ coaches$$

Since comfort index exceeds 3.00 for three coaches, the minimum number of coaches within comfort limits is 4 coaches. Therefore it is convenient to use 4 coaches with respect to both comfort index and the cost of energy. Figure 8.3 below shows the situation at noon hours in which the arrival rates are moderate compared to rush hours. If we consider the maximum number of passengers for the trip to west at 13:00, the comfort indexes for different number of coaches are measured as follows:

$$CoI_{13:00.\ west} = \frac{304 - (4 * 44)}{(4 * 34)} = 0.94 \qquad for\ \ 4\ coaches$$

$$CoI_{13:00.\ west} = \frac{304 - (3 * 44)}{(3 * 34)} = 1.68 \qquad for\ \ 3\ coaches$$

$$CoI_{13:00.\ west} = \frac{304-(2*44)}{(2*34)} = 3.17 \qquad for\ \ 2\ coaches$$

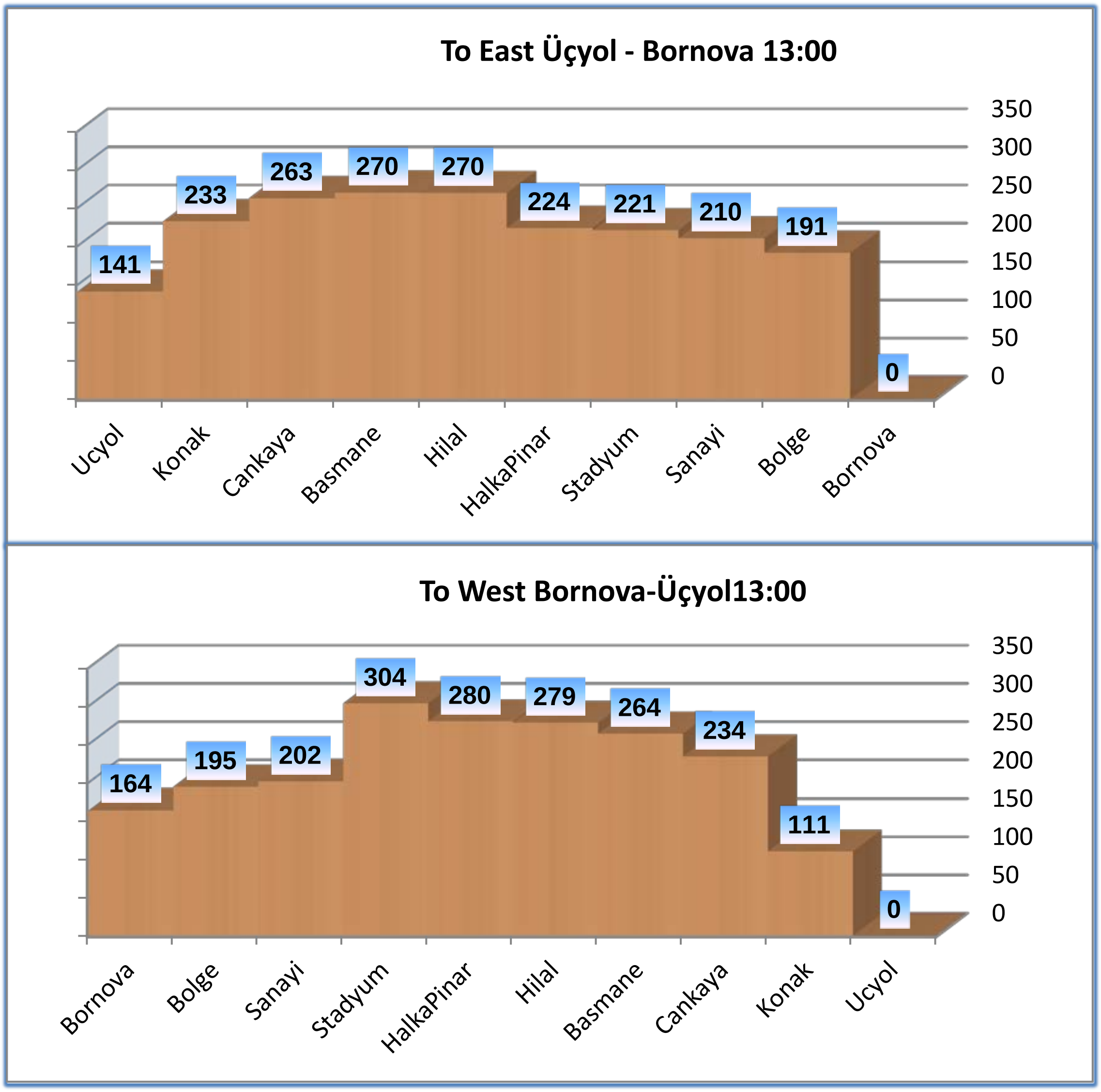

Figure 8.3 The average number of passengers in train across stations for trip at 13:00

The minimum number of coaches within comfort limits is determined as 3 coaches which means 3 coaches may be used for this trip instead of using 4 coaches. Therefore there is an opportunity to save one coach for this trip which might decrease the energy cost by 8.4 TL (=12 km x 1 coach x 0.7 TL).

Another performance measure is the average waiting times of passengers at stations. Confidence intervals have been constructed and relative errors have been calculated for this measure. The following table summarizes the outcomes about the average waiting times.

Table 8.1 Daily Average Waiting Time of Passengers at Different Stations (in seconds)

	Number of Replications =10			Number of Replications =217		
Stations	**Average**	**Half Width**	**Relative Error**	**Average**	**Half Width**	**Relative Error**
Basmane	223	9,01	0,040	225,32	1,65	0,0073
Bolge	227	5,02	0,022	229,69	1,87	0,0081
Bornova	232	4,32	0,018	234,58	0,94	0,0040
Cankaya	186	2,77	0,014	184,25	0,69	0,0037
HalkaPinar	161	0,81	0,005	161,10	0,13	0,0008
Hilal	217	26,86	0,123	211,54	3,87	0,0183
Konak	221	4,45	0,020	221,90	1,01	0,0046
Sanayi	220	10,49	0,047	216,38	2,49	0,0115
Stadyum	228	7,06	0,030	230,16	1,64	0,0071
Ucyol	211	4,82	0,022	216,11	1,01	0,0047

Notice that the confidence intervals and half-widths are all pretty tight and the highest relative error in table is 0.018 for 217 replications. It is by far smaller than 0.05. It is observed that the highest value is 232 seconds ≈ 4 minutes for "Bornova" station.

The average queue sizes have also been observed and the outcomes are given in the following table for the respective platforms at stations.

Table 8.2 Average queue sizes

	Number of replications =10			Number of replications =217		
Stations	**average**	**half width**	**relative error**	**average**	**half width**	**relative error**
BasmaneWest	13	0,17	0,0126	14	0,03	0,0022
BasmaneEast	6	0,11	0,0177	6	0,02	0,0032
BolgeWest	3	0,09	0,0266	3	0,01	0,0030
BornovaEast	78	0,45	0,0057	78	0,07	0,0009
CankayaWest	31	0,19	0,0061	31	0,04	0,0013
CankayaEast	15	0,12	0,0080	15	0,03	0,0020

Table 8.2 Average queue sizes (continued)

	Number of replications =10			Number of replications =217		
Stations	**average**	**half width**	**relative error**	**average**	**half width**	**relative error**
HalkapinarWest	11	0,15	0,0136	11	0,03	0,0028
HalkaPinarEast	17	0,23	0,0132	17	0,03	0,0017
HilalWest	2	0,06	0,0361	2	0,01	0,0061
HilalEast	1	0,06	0,0507	1	0,01	0,0083
KonakWest	52	0,31	0,0058	53	0,06	0,0011
KonakEast	12	0,19	0,0163	12	0,03	0,0026
SanayiWest	1	0,03	0,0237	1	0,01	0,0079
SanayiEast	5	0,04	0,0074	5	0,02	0,0037
StadyumWest	5	0,07	0,0137	5	0,02	0,0039
StadyumEast	20	0,17	0,0084	20	0,03	0,0015
UcyolWest	53	0,23	0,0043	53	0,06	0,0011

Another interesting observation is the transfer times of the passengers which indicate the average travel times for the passengers by the stations. The outcomes are given in the following table.

Table 8.3. Average travel times of passengers (in seconds)

	Number of replications =10			Number of replications =217		
Stations	**10 times average**	**10 times half width**	**10 times**	**217 times average**	**217 times half width**	**217 times**
Basmane	471	2,22	0,004	472	0,44	0,0009
Bolge	489	1,47	0,003	488	0,32	0,0007
Bornova	585	1,58	0,002	586	0,2	0,0003
Cankaya	431	1,62	0,003	432	0,27	0,0006
HalkaPinar	425	1,84	0,004	425	0,24	0,0006
Hilal	408	6,43	0,015	411	0,94	0,0023
Konak	555	1,45	0,002	555	0,27	0,0005
Sanayi	445	3,77	0,008	445	0,52	0,0012
Stadyum	432	1,18	0,002	433	0,26	0,0006
Ucyol	484	1,42	0,002	484	0,33	0,0007

8.2 Discussion and Recommendations

Using the outcomes of simulation, the number of coaches to be used will be discussed in this section. The aim is to improve the efficiency of metro operations and the idea is to minimize the energy cost while ensuring the comfort index is below a predetermined value (CoI < 3). It is possible to decrease the cost of energy by decreasing the number of coaches and the number of trips which leads the headways to become longer and longer. Average waiting time of passengers gets higher then. Furthermore the trains would be much more crowded and it would not be convenient for the comfort of the passengers.

Comfort indexes are calculated for each trip to each direction and the minimum numbers of coaches whose comfort index is less than 3 are determined. The results are given in the following table.

Table 8.4 Current and suggested number of coaches

Trip No	Trip Time	Maximum number of passengers in train	Current number of coaches	Current CoI	Suggested number of coaches	Suggested CoI
1	06:00:00	41	4	0	2	0,00
2	06:10:00	27	4	0	2	0,00
3	06:20:00	71	4	0	2	0,00
4	06:30:00	150	4	0	2	0,91
5	06:40:00	162	4	0	2	1,09
6	06:50:00	187	4	0,00	2	1,46
7	07:00:00	284	4	0,79	2	2,88
8	07:05:00	157	4	0,00	2	1,01
9	07:10:00	176	4	0,00	2	1,29
10	07:15:00	216	4	0,29	2	1,88
11	07:20:00	241	4	0,47	2	2,24
12	07:25:00	269	4	0,68	2	2,66
13	07:30:00	328	4	1,11	3	1,92
14	07:34:00	288	4	0,83	2	2,94
15	07:38:00	322	4	1,07	3	1,86
16	07:42:00	341	4	1,21	3	2,04
17	07:46:00	341	4	1,21	3	2,05
18	07:50:00	357	4	1,33	3	2,21
19	07:54:00	384	4	1,53	3	2,47
20	07:58:00	405	4	1,68	3	2,68
21	08:02:00	409	4	1,71	3	2,71

Table 8.4 Current and suggested number of coaches (continued)

Trip No	Trip Time	Maximum number of passengers in train	Current number of coaches	Current CoI	Suggested number of coaches	Suggested CoI
22	08:06:00	418	4	1,78	3	2,80
23	08:10:00	441	4	1,95	4	1,95
24	08:14:00	446	4	1,99	4	1,99
25	08:18:00	432	4	1,88	3	2,94
26	08:22:00	405	4	1,68	3	2,68
27	08:26:00	378	4	1,49	3	2,41
28	08:30:00	378	4	1,49	3	2,41
29	08:34:00	377	4	1,47	3	2,40
30	08:38:00	365	4	1,39	3	2,29
31	08:42:00	340	4	1,21	3	2,04
..	…	…	….	…	…	…
110	16:25:00	317	4	1,04	3	1,81
111	16:30:00	304	4	0,94	3	1,69
112	16:35:00	301	4	0,92	3	1,65
113	16:40:00	307	4	0,97	3	1,72
114	16:45:00	309	4	0,98	3	1,74
115	16:50:00	308	4	0,97	3	1,73
116	16:55:00	320	4	1,06	3	1,84
117	17:00:00	351	4	1,28	3	2,14
118	17:05:00	378	4	1,49	3	2,42
119	17:10:00	349	4	1,27	3	2,13
120	17:15:00	346	4	1,25	3	2,09
121	17:20:00	346	4	1,25	3	2,10
122	17:25:00	355	4	1,31	3	2,18
123	17:30:00	351	4	1,29	3	2,15
124	17:34:00	299	4	0,90	3	1,63
125	17:38:00	296	4	0,88	3	1,60
126	17:42:00	283	4	0,78	2	2,86
127	17:46:00	275	4	0,73	2	2,75
128	17:50:00	285	4	0,80	2	2,90
129	17:54:00	298	4	0,90	3	1,63
130	17:58:00	307	4	0,97	3	1,72
131	18:02:00	323	4	1,08	3	1,87
132	18:06:00	340	4	1,21	3	2,04
133	18:10:00	332	4	1,15	3	1,96
134	18:14:00	317	4	1,04	3	1,81
…	…	…	…	…	…	….

Remember that there are 380 trips in total during a day; the rest of the information which is missing in table above is supplied in a DVD attached to the thesis and also stored at < http://aoner.yasar.edu.tr/?page_id=723 >

The daily cost of energy for the current mode of operations which uses 4 coaches for every trip can be calculated as follows:

$$\text{Cost (current)} = (0.7\ \text{TL/km/coach}) * (380\ \text{trips}) * (4\ \text{coaches/trip}) * (\approx 12\ \text{km/trip})$$

$$\text{Cost (current)} \approx 12{,}750\ \text{TL}$$

On the other hand, if suggested numbers of coaches are used for the corresponding trips, then the daily cost of energy would be :

$$\text{Cost (suggested)} = (0.7\ \text{TL/km/coach}) * [\ (448+408)\ \text{coaches in 380 trips} * (\approx 12\ \text{km/trip})$$

$$\text{Cost (suggested)} \approx 7{,}190\ \text{TL}$$

It is clear that daily saving in cost of energy would be 5560 TL and yearly saving could reach up to 1,389,000 TL. It implies remarkable improvement in the efficiency of the metro operations. However, the management had been surprised with this suggestion and they hesitated to apply the recommendations about the number of coaches. Because they believe that it is subject to a political decision since the trains would seem always congested or perceived like that by people of Izmir. However, they appreciated the details of the study and begin to use as a benchmark since most of the information exposed was not available for them before.

The next step of this study would be to study optimization via simulation in order to determine optimal headways and the number of coaches to be used for each trip. The optimization model should incorporate the costs of trips with the objectives of minimum waiting times and maximum comfort of the passengers which is measured by the number of passengers per square meter of the train in each trip.

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