TRAFFIC SIMULATION FOR TRAFFIC CONGESTION PROBLEM OF FATIH SULTAN MEHMET BRIDGE OF ISTANBUL TURKEY

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2014

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M.S., Industrial Engineering, Işık University, 2014

Submitted to the Graduate School of Science and Engineering
In partial fulfillment of the requirements for the degree of
Master of Science
In
Industrial Engineering

IŞIK UNIVERSITY
2014

IŞIK UNIVERSITY
GRADUATE SCHOOL OF SCIENCE AND ENGINEERING

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APPROVAL DATE: 21/01/2014

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Abstract

On a regular day, almost 200,000 cars use Fatih Sultan Mehmet Bridge of Istanbul to commute between European and Asian side of the Bosporus. This enormous volume causes the traffic congestion to become a problem not only endemic to the bridge, but also cascading some major arterial roads of the city. This study includes a simulation model to analyze the traffic congestion problem in Fatih Sultan Mehmet Bridge of Istanbul. The main focus of this research are to identify the bottlenecks of the system, to discover vehicle behaviors in these bottlenecks, and to create a simulation model to predict the level of congestion on the bridge that will occur with different arrival rates of the vehicles. Our simulation analysis shows that even though there is no significant difference between the number of cars arriving to the bridge from both directions in the evening rush hour, when both directions on the bridge have four lanes (without any counter-flow lane), east direction (Europe-to-Asia) suffers more from traffic congestion due to lane merging taking place after the electronic toll collection (ETC) plazas. The analysis also suggests that a counter-flow lane in favor of the east (Europe-to-Asia) direction significantly improves the average number of cars congested at the entrance of the bridge.

FATİH SULTAN MEHMET KÖPRÜSÜNÜN TRAFİK YOĞUNLUĞU PROBLEMİNİN TRAFİK SİMÜLASYONU YÖNTEMİYLE İNCELENMESİ

Özet

Ortalama bir günde İstanbul Boğazının Avrupa ve Asya yakası arasında seyahat etmek için neredeyse 200,000 araç Fatih Sultan Mehmet Köprüsünü kullanmaktadır. Bu miktarda araç sadece köprüde değil köprüye ulaşan ana arterlerde de trafik sıkışıklığı problemi oluşmasına neden olmaktadır. Bu çalışma Fatih Sultan Mehmet Köprüsündeki trafik sıkışıklığı probleminin analizi için oluşturulmuş bir simülasyon modelini içermektedir. Bu araştırmanın asıl odak noktası sistemin sahip olduğu darboğazların tespit edilmesi, araçların bu darboğazlardaki davranış biçimlerinin incelenmesi ve değişik araç geliş sıklıkları için trafik sıkışıklığı seviyesi tahmini yapılabilmesi için bir simülasyon modeli oluşturulmasıdır. Yapmış olduğumuz analizin önemli sonuçlarından bir tanesi köprünün her iki yakasına gelen araç sayısında önemli bir farklılık olamamasına rağmen akşam yoğunluğu saatlerinde her iki yöne 4 şerit ayrıldığında (ek şerit uygulaması olmadan) Doğu (Avrupa-Asya) yönüne giden araçlar trafik yoğunluğundan daha fazla etkilenmektedir. Bu yoğunluk farkı gişeler bölgesi sonrasındaki şerit birleşimi etkisinden kaynaklanmaktadır. Analizimizin önerisi Doğu yönüne (Avrupa-Asya) bir ek şerit verilerek köprü girişinde ortalama bekleyen araç sayısının azaltılması yönündedir.

Acknowledgements

There are many people who helped to make my years at the graduate school most valuable. First I thank all my department professors for their efforts for me having this level of education and knowledge on Industrial Engineering. Then I thank to my thesis Advisor Yrd.Doç.Dr. Burak Çavdaroğlu for all his support for this thesis comes true.

I also thank to M. Necip Ertaş head of Istanbul Metropolitan Municipality Traffic Department for all his kindness and helpfulness. My special thanks are for Esma Dilek and İbrahim Gökdere for all their efforts of providing data whenever I need.

Many thanks for Mr. Bahadır Şahin FSM bridge chief manager for all his contribution on early stages of thesis and his guidance.

I would also like to thank to my colleagues who helped me all through the years and especially in this stressful period of thesis writing. I deeply value their friendship.

The last words of thanks go to my family. I thank my parents Aysel Selçuk and Ufuk Selçuk for their patience and encouragement and understanding.

But most importantly I thank a lot to Justina Vaitiekūnaitė with all my heart for using a carrot stick with this rabbit to make it run and her endless encouragement through this long journey.

Dedication

To Justina Vaitiekūnaitė.
Myliu Tave...

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Chapter 1

Introduction

"Time is money"

Benjamin Franklin

1.1Opportunity cost of time

In the last century world started to turn much faster than ever before. All technological developments made our life easier and also made our time more valuable. Since the value of our time increased it gained more importance to minimize our non quality time. It is kind of time which can be transferred into productive and beneficial one. Time spent in traffic jams can be given as an example of this.

Possible delays or allocation of more travel time to avoid being late wastes our productive and efficient time. It will be more beneficial if we can minimize such kind of wasted time and turn it into quality time for working and production or just for ourselves. In that way we can increase either productivity or personal happiness.

1.2 Traffic congestion problem in the World

Traffic congestion is an important problem in today's populated world where most of the people are living in cities [1]. According to traffic index of Tom Tom, a manufacturer of automotive navigation systems [2], Moscow suffers the most traffic congestion in Europe. A typical resident of Moscow said to have 30 minutes of commute every day is facing 127 hours of traffic jam where the traffic does not flow at all. With this kind of traffic condition 30 minutes of typical daily commute in city center can be made in 74 minutes.

Istanbul comes second in European Congestion Scale. Drivers experience 118 hours of traffic jam during their annual commute. Thirdly Warsaw is the follower of first two cities where 30 minute typical commute takes 55 minutes that rounds 110 hours per year spent in traffic jams.

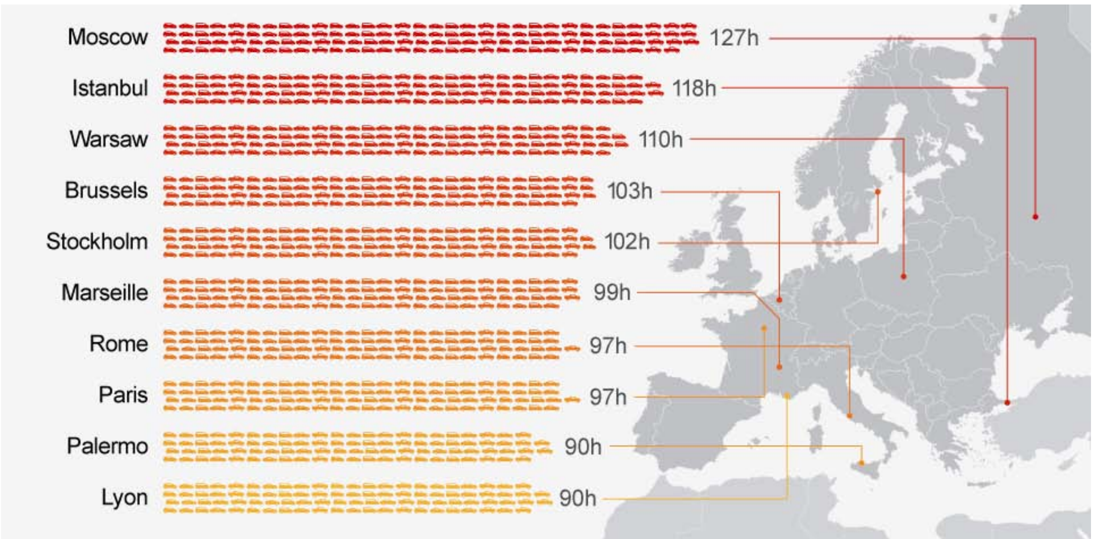


Figure 1.1 Annual hourly delays per commuter in Europe’s most congested cities.

Another study made by INRIX [3] UK’s one of the biggest in car data company which also provides real-time traffic information for car sat-nav companies. The research showed that UK has 5th bad traffic congestion level among European countries. British drivers are spending up to three days a year just waiting in their cars to move from a place to another.

The same problem also exists at the other side of the ocean. USA with their developed economy and production capabilities also facing great congestion problems and also it costs a lot for their economy. Congestion is not just stealing time but also money from driver’s pockets.

Texas A&M Transportation Institute’s (TTI’s) *2012 Urban Mobility Report* (UMR), [4] , showed hours spent in traffic and annual cost of that per commuter. The study introduced the index PTI which is the time multiplier for a half hour trip caused by traffic congestion. In cities with higher PTI level habitants needs to allocate much more extra time to catch their high priority events like catching their plane or any other urgency. This causes less efficient way of using time mentioned in chapter 1.1

Researchers say that the most effective way to address traffic congestion is creating more efficient traffic management and public transportation combined with new constructions to improve road infrastructure. Travel options such as flexible working hours and telecommuting should also be part of the solution.

1.3 Congestion, Jam, Rush Hour and Bottleneck

In this section, some important terminology related with our research is presented.

1.3.1 Traffic Congestion & Jam

Traffic congestion is the phenomena occurring on roads where increased demand causes slower speeds, longer travel times and vehicle queuing. Congestion effect can empower itself by the interactions between cars became more and more pronounced with increased demand on road. When the demand approaches the capacity of the road vehicles start to have periods of time in fully stopped position called *traffic jam*.

1.3.2 Rush Hour

Rush hours are the parts of the day where traffic levels on the roads reaches its peak because of extensive demand. Normally a day has 2 rush hours: one in the mornings when people are going for the work and other one are in the evening when work hours ended.

1.3.3 Bottleneck

A *bottleneck* is a localized disruption of traffic flow caused by physical conditions which can lead traffic congestion & jam. Some of the conditions creating bottlenecks are:

- Construction zones where one or more lanes became unavailable
- Accident sites blocking single or multiple lanes temporarily
- Lane merging points where available number of lanes decrease
- Terrain with steep climbs and sharp turns
- Poorly timed traffic lights
- City centers

- Rubbernecking (Slowing down to check an object of attraction)
- Existing lower capacity portion of road (bridges tunnels etc...)
- Slow vehicles interrupting traffic flow

These reasons can be classified in some general groups as follows:

Traffic interruption. These are the conditions where free traffic flow is obstructed by physical conditions. For example when traffic lights are not well synchronized with the direction and flow of traffic, significant delays may occur while traffic accumulates in one direction. Toll plazas can also be a major bottleneck, especially in urban areas, as significant time can be spent waiting to pay the manually collected fare.

Lane reduction. The merging required when the number of lanes is reduced can easily become a bottleneck, especially if the capacity of the lanes after merging point is lower than the lanes before. The unmet demand cumulates to create queues and traffic delays. Lane merges can be given as a bottleneck where vehicles are moving slower when they are coming to merging point and also for the need of giving way or changing lanes they need to slow their speed even more. This also influences the output rate.

Merging. Although highways are designed to provide an uninterrupted flow to traffic, merging can be a cause for bottlenecks as cars are slowing down and changing lanes. This is notably the case at the intersection of two major highways where a large amount of traffic shifts from one highway to another. In this kind of conditions cars are slowing down to better judge to give or take the way from merging on ramp lane.

Distraction. This type of bottleneck is created by a psychological reaction of drivers to an unusual event that, although does not directly influence the capacity, is distracting the traffic and causing a slowdown. Distractions can be as small as a car that was pulled over by police.

A bridge can be a very good example of physical bottleneck. Extensive demand on

Bridges overuse highway capacities. Also speed limits and junction ramp slows down traffic flows. Usually highway bridges have toll plazas to pay before or after bridge where cars usually stop and pay for the bridge. For all these reasons, bridge bottlenecks affect a huge volume of cars in the traffic network.

1.4 Scope and Limitations of the Research

In this research our aim is to discover characteristics of vehicle flow on FSM Bridge in different traffic conditions. As mentioned above bridges are bottlenecks of road infrastructure. One of the main goals of this research is to find out reasons of bottleneck creation.

In this research traffic congestion of toll plaza area and extended congestion on both sides of the bridges studied. Any kind of congestion that a driver facing after crossing the bridge is omitted. Traffic congestion caused by vehicles is considered to be the main reason of problem. Any kind of congestion caused by accidents, constructions or any kind of special actions is omitted.

The data for this research is taken from Istanbul Metropolitan Municipality Traffic Department Traffic Control Center. Demand levels, vehicle counting and average speed data is used as direct input for our simulation model. The data includes single day measurements. Thus it has daily characteristics that may lead biased input. Also the data omits some characteristics like vehicle types and their percentage in population.

1.5 Outline of the Thesis

The remainder of this thesis is organized as follows. A presentation of the problem in Fatih Sultan Mehmet Bridge of Istanbul is provided in Chapter 2. A review of the existing literature relevant to this work is presented in Chapter 3. In Chapter 4, data collection and modification stages are explained and then a simulation model is developed. After developing the model, Arena configuration is presented. Further, experiments and results are shown in Chapter 4. The thesis closes with conclusion and future research directions.

Chapter 2

Definition of Traffic Congestion Problem in Fatih Sultan Mehmet Bridge of Istanbul

2.1 Istanbul, the city with its own characteristics

Istanbul, unlike the general belief it is not the capital of Turkey but it is the biggest city with 15 millions of habitants. It is bigger than lots of other countries thus is facing a great traffic congestion problem every day.

Because it’s unique geographical location between Asia and Europe it has its unique traffic problems. Bosporus, the strait uniting Black Sea and Marmara Sea, divides city into two parts with huge amount traffic flow between them.

In the second half of 20th century Istanbul developed faster than ever before. As a consequence of this development, traffic flow between Europe and Asia increased with an enormous acceleration. To satisfy this traffic demand, the construction of Bosporus Bridge started in 1970 and it is completed on 10/29/1973.

In first year, on average, 30,000 cars per day were using the bridge. In 1987, with economic development of Turkey and Istanbul, this number passed normal capacity limit and reached 130,000 cars per day. The level of usage decreased the level of service, which also caused long delays in queues.

To overcome this congestion, to facilitate the traffic flow and also to connect Asia and Europe with a higher capacity highway, the second bridge on Bosporus, Fatih Sultan Mehmet Bridge, was built in 1988

The bridge is located 5km north of Bosporus Bridge, on the respectively narrower part of Bosporus (800 meters). The bridge has 1090 meters length and is located 64 meters above sea level. Fatih Sultan Mehmet Bridge was the 6th biggest bridge in the world of its kind at the time of its construction.

Figure 2.1 Fatih Sultan Mehmet Bridge Istanbul

Fatih Sultan Mehmet Bridge in Istanbul, Turkey, is one of the two main bridges who handle over 200.000 cars per day (Figure 2.1).

The yearly demand data provided by Roads department of Turkey can be seen in Table 2.1. Yearly vehicle counts are stable over years and averages 200 thousands cars per day.

Vehicle counts by classes of Fatih Sultan Mehmet bridge over years									
YEARS	1.CLASS	2.CLASS	3.CLASS	4.CLASS	5.CLASS	6.CLASS	AVERAGE		SUM
	Units	Units	Units	Units	Units	Units	DAILY	MONTHLY	
2008	64.144.822	9.640.364	2.715.916	2.147.660	24.192	144.138	215.937	6.568.091	78.817.092
2009	64.080.688	9.571.764	2.532.486	2.020.398	17.954	155.938	214.738	6.531.602	78.379.228
2010	64.424.352	10.796.500	2.743.644	2.395.002	17.080	154.320	220.633	6.710.908	80.530.898
2011	65.670.476	11.695.142	2.790.562	3.137.066	36.308	149.482	228.710	6.956.586	83.479.036
2012	59.020.820	10.820.382	2.525.740	3.217.456	48.284	157.384	207.644	6.315.839	75.790.066

Table 2.1 Yearly utilization data of FSM Bridge

In the interview made with Mr. Bahadır Şahin, the chief engineer of Fatih Sultan Mehmet bridge management, it is stated that this 200.000 traffic volume is highly stable through a year. He also claimed that the daily traffic flow on each direction is almost equal and slightly over 100.000 vehicles per day.

Mr. Şahin explained after electronic toll collection (ETC) systems were introduced (called OGS Otomatik geçiş sistemi and HGS Hızlı geçiş sistemi); the need of traffic lanes has decreased drastically. Those lanes are built to compensate the flow stopped by toll plazas in old days when drivers are paying the fee with cash. He said a typical operation of payment takes 10-20 seconds per car with the older “cash payment” system. To be able to use bridge capacity efficiently they were taking 20 cars simultaneously in the paying process.

It can be calculated that the capacity of a toll plaza is nearly 4 cars per minute and the overall capacity was 80 cars per minute.

The bridge has 4 lanes and the toll plaza was built to supply nearly 80 cars per minute. Thus, a lane „serves“ 20 cars per minute, which gives us 3 seconds between cars and this level of supply obeys 2 seconds “chase distance rule” which will be explained in next chapter.

Today with fully ETC equipped toll plazas with nearly zero processing time; this payment process is not a bottleneck for bridge anymore. On the other hand even with nearly zero processing time, the plazas are experiencing arrival of way too much cars that the bridge can serve in a minute. This level of arrival rate now became a problem in the entrance of the bridge because of merging lanes. Furthermore, lots of small accidents between cars and trucks caused by this lane merges was happening which causes more delays on lane flows. Figure 2.2 shows a photo taken in 25 May 2013 at 17:30, which depicts the scale of the traffic jam occurring at the time of rush hours.

Figure 2.2 Traffic jam in toll plaza area “25/05/2013 17:00”

To overcome the merging problem mentioned, the bridge authorities have decided to decrease 20 lanes to 10, and in near future they are planning to re-decrease the number of lanes to 6.

Authorities also planning to retire electronic toll plazas and install overhead sensors which can scan both kind of ETC systems (OGS & HGS) [5] . This construction is planned to be finished in the beginning of 2014. Also in the near future, they plan to retire the OGS transponders and force all cars to use HGS stickers, which are easier to maintain.

With these developments, they can eliminate the time spent to choose and allocate correct plaza and prevent accidents caused by plazas and merging process.

Figure 2.3 Satellite views of FSM Bridge and peripheral roads

Fatih Sultan Mehmet Bridge (FSM) is a part of one of the two main land traffic roads on Bosporus. With the huge demand of these roads mentioned earlier, the importance of sustaining a smooth traffic flow on this bottleneck gains so much importance.

The congestion on the bridges or on the peripheral roads (Figure 2.3) has a cascading effect, and leads city wide congestion in a very short time. The analysis of data taken from Istanbul Municipality's traffic department showed that several factors affect both the capacity of the plaza and the traffic flow to plaza. Besides, the bridge authorities are applying some regulations for trucks and large scale vehicles to prevent them to enter the bridge at rush hours. On the other hand, the counter flow lane is being applied for Asia-Europe direction in the mornings, and Europe-Asia direction in the evenings.

Chapter 3
Literature Review

Traffic control is one of the biggest needs in modern metropolis. Efficiency should be sustained by successfully managing the infrastructure of the city. Traffic control systems and tools are being designed for this purpose. They can help to sustain higher level of service, decrease the number of traffic incidences, and provide a better CO2 emission levels and fuel economy.

To create a traffic control system, it is needed to have better estimation of traffic level on roads, road merges and other infrastructures like tunnels, bridges, and junctions. Such kind of data can be obtained by observation as well as sensors located on the roads.

Traffic congestion level is a very fragile issue and need to be followed on a regular basis. With small fluctuations in traffic level, an open free flowing road can easily turn into a populated one and eventually into a traffic jam.

Simulation is a commonly used methodology in the literature to understanding the nature of traffic congestion problem and the factors affecting the severity of traffic jams.

In recent years, there has been abundant work on the traffic simulations for traffic congestion problems. K.Balsys et al. [6] created a traffic simulation model for calculating optimality of traffic lights timing. In their study, they modeled the traffic at Karaliaus Mindaugo Avenue, which is one of the busiest streets in the Kaunas City of Lithuania. After opening a new shopping mall and amusement center with a car parking for 2500 cars, traffic flow on this avenue has been increased 26%. Also a new Sports arena with 15.000 seats for local team Žalgiris Kaunas will be built near this mall on the same street. They found out that the timing is good enough for average loads and also loads up to 1500 cars/hr. But when demand reaches 2000cars per hour the traffic lights are not sufficient enough.

In Abdul-Yasser Abd-Fatah et al. [7], time based system of traffic lights is compared with sensor based systems. In a time based system duration of traffic light's changing cycle is constant. In a sensor based system duration of the cycle is dynamic and it is determined by the data coming from sensors which counts number of cars waiting in front of the traffic light. A four way intersection is studied and ARENA simulation software was used. After collecting the parameters normal and busy road conditions have been simulated by the software. As the result, the program showed that average waiting time for sensor based system was 62.5% less than time based system in normal conditions and still 15% less than time based system in busy conditions.

Arena simulation is used in studies of Henrikas Panevičius and Tadas Kraujalis [8]. The parameters obtained from traffic detectors are used by the simulation model to obtain signal phase lengths for different traffic conditions. The study showed that the sensor based signal control system can provide better level of throughput in hours with higher traffic level.

These examples show that Arena Simulation tool is suitable for the simulation of traffic junctions. Also Arena's discrete environment provides simplification on complex queuing systems [9] [10] [11].

Another example that traffic simulation modeling used is lane merges like on ramp junctions to main roads, toll plazas and work zones [12] [13] [14]. These are the areas where the uncertainty occurs because of the decision of accelerating or decelerating to have a safe merge with other lanes. The time and capacity loss affects both main road flow rate and merging capacity [15] [16]. In some researches other than discrete modeling, fluid dynamics and kinematic wave theory is used to better simulate the continuous characteristic of traffic flow [17].

The main reason of congestion is that the traffic flow need to merge into less number of lanes than arriving lanes within limited space where arriving traffic flow exceeds downstream capacity, and as a side effect of congestion outflow is also reduced thus average speed of vehicles drops drastically or even reaches to zero. This scenario in very similar to what happens on Istanbul Fatih Sultan Mehmet Bridge especially on rush hours. The same principle mentioned in M. Papageorgiou et al. [18] is applicable for situations where no actual merging takes place but downstream capacity is lower than arriving traffic flow.

In the literature, there are also several studies concerning the toll plazas on highways and bridges. In these studies, the most common statistics collected for toll plazas is average delay time. Ivan Corwin et al. [19] searched for optimal number of toll booths in a toll plaza for a given number of arrival lanes. The study is conducted for low and high levels of traffic densities. It showed that for lower traffic density the same number of toll booths as lanes is enough. However, for high level of traffic, 50% more toll booths are needed than arrival lane number. It is also showed that average waiting time will be 20 times higher than optimal situation if the number of toll plazas is equal to number of lanes in high traffic congestion. This study is also important for modeling toll plaza usage in FSM Bridge where high traffic level condition is being observed for long rush hours in a day.

Toll plazas are one of the most fragile locations for traffic congestion occurrence. The congestion can be triggered by the physical design or operating characteristics of plazas. Vehicles approaching the plaza area usually encounter delays because of the need of fully stopping or obeying some speed limits. This declares toll plaza areas as bottlenecks of traffic system. The basic performance measures of plazas are generally chosen as average waiting time or average queue length. Traffic flow rate, single toll booth capacity, the number of plazas and toll collecting types are the key features affecting these performance measures.

Electronic Toll Collection (ETC) systems are being widely used in toll roads since 1980s [20]. It helps to decrease traffic congestion on toll plazas. With help of electronic devices, the fee is being collected by the system.

Different countries show different usage levels of these electronic systems but generally it is getting more and more popular in recent years. The application of electronic devices on toll booths lets road authorities use existing gates in spite of building new ones for existing toll plazas. Also this kind of plazas is being chosen when new roads or bridges with trespassing fee will be applied.

Converting cash plazas to ETC dedicated plazas has its own drawbacks. Dedicating one or more toll booth to a small part of population decreases the amount of resource (toll booth) available for majority. This increases traffic level in toll plaza area. In an environment where ETC systems are not popular, the huge percentage of cars not equipped with ETC devices will suffer from higher congestion level. Even traffic jam can reach to a point where lane blockage of these cars will not let ETC cars to reach their dedicated lanes [21] [22]. On the other hand dedicating one or very few number of booth is still creates congestion in ETC booths even the usage level is low. In this kind of situations the best solution has been found as switching ETC dedicated gates for both kind of usage. The simulation outcomes showed that this kind of decision will not increase ETC waiting times so much but it is efficient on clearing blockage in Toll plazas.

Chapter 4
Simulation Model & Experiments

4.1 Data Needs

In order to model the traffic flow on Fatih Sultan Mehmet Bridge, we need to have data about the vehicle’s behavior on the peripheral of the bridge.

One of the most needed types of data is about vehicle’s arrival into the system. To collect such kind of data, direct observation at a specific time interval cannot be the best way because the collected data can be affected by hourly and daily fluctuations. Measurements made in a single point can also be biased.

The best way of collecting the interarrival time between vehicles is measuring it in different locations simultaneously for a long period of time. As mentioned in chapter 2, Istanbul Municipality has sensors in strategic locations of FSM Bridge and Toll Plaza area. The sensors are capturing data continuously and sending it to traffic control center.

4.1.1. Data Collection

In this simulation project, the traffic flow of FSM Bridge is considered to be represented by the data taken from traffic control center of Istanbul Municipality. “Intelligent Transport Systems” are being used by this center since 2003. These systems are allowing authorities to watch and control the traffic flow of the city 24 hours in real time.

The system is being operated by the computer software with the data collected by 513 sensors all around the city. These sensors are located different locations of the city for surveillance, for taking measurements and also for spotting illegal actions.

The sensors are capable of providing live information about traffic conditions to the ITS system. The data that these sensors can provide are as follows:

- Vehicle Counts
- Vehicle Average Speed
- Vehicle type
- Flow density
- Estimated travel time

The data is used as input for the ITS system and stored for future projects and they are shared with educational institutions for research purposes.

After being processed by software, the output of the program is used on overhead electronic traffic signs that are located in strategic roads and informing drivers about the current status of the road ahead. The same output data is also made publically accessible via the road density maps on their website and smartphone applications.

The sensors are emitting magnetic waves and measuring the returning signal to identify the presence of an object in active area. The sensors are mounted 7.5 meters above road level with a 45 degree angle on a pole with 8 meters height. The pole is planted 5 meters away from road lane. Figure 4.1 and 4.2 show sensors mounted on pole and active scanning area of a typical sensor.

In Figure 4.3 you can see the locations of the sensors responsible for screening and scanning the FSM bridge traffic flow. Their ID numbers, their original names in Turkish and the English translations are represented In Table 4.1. All distances are in kilometers from the sensor to the center of the bridge. Four sensors per direction exist. For each direction, two sensors are located before the bridge and the other two are located after the bridge. First four rows represent Europe-Asia direction, where the others represent Asia-Europe direction. Last column represents the geographical location of the sensors with respect to bridge center.

Figure 4.1 Traffic Sensor mounted on pole

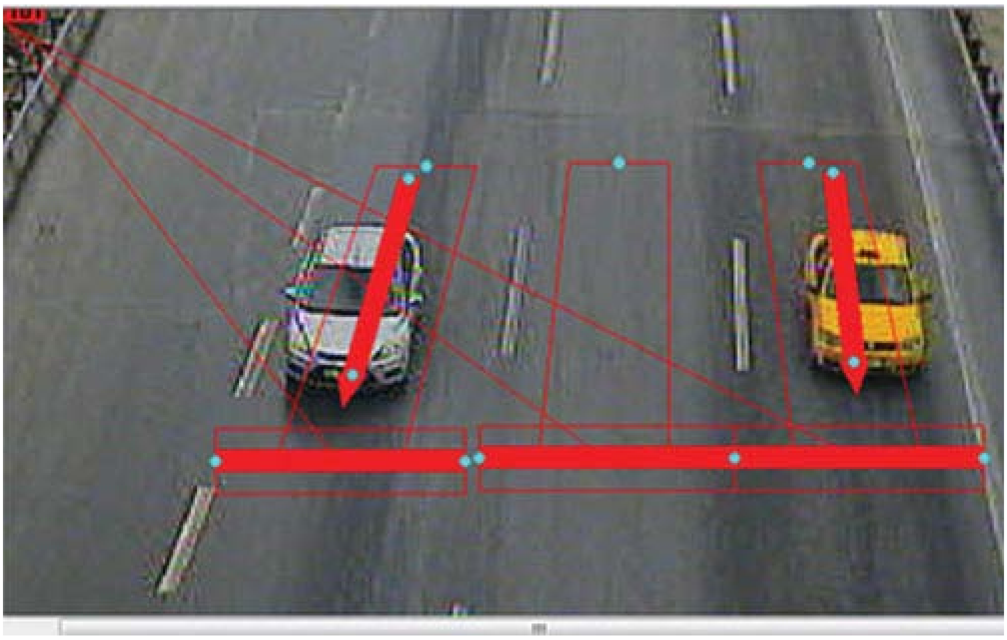


Figure 4.2 Scanning areas of sensors

Figure 4.3 Sensor locations

ID	Name (TR)	Name (ENG)	Distance (km)	East / West
417	TEM FSM Gişe Sahası Önce	Before FSM Toll Plaza Area	2,4	W
90	FSM Avrupa Girişi	FSM Europe Enterance	1,2	W
419	TEM FSM Köprü Çıkışı	FSM Asia Exit	0,8	E
72	Kavacık	Kavacık From FSM	1,8	E
3	Kavacık FSM	Kavacık To FSM	2,0	E
92	FSM Anadolu Girişi	Asia Enterance	1,5	E
154	FSM Avrupa Çıkışı	FSM Europe Exit	0,8	W
443	FSM Gişeler	FSM Toll Plza Area	1,8	W

Table 4.1 Sensor IDs names and distances to the bridge

4.1.2 Data Modification

As mentioned in Section 4.1.1, the sensors are emitting magnetic waves and collecting the magnetic echo of these waves to take measurements. From the shape of the wave received the sensor decides the size and speed of the vehicle.

The drawback of this measuring system is that the magnetic echo is sensitive against metal objects. The signal can be affected by wrong metal objects such as barriers at the sides of the road. Especially the left side barrier is causing problems for the system. The system has tendency of measuring the barrier as a long and slow moving truck.

To overcome this problem, the sensors are adjusted to measure the lanes from right side of the road and totally omit the leftmost lane. In some extreme cases, two leftmost lanes are not counted by sensors but in general only the leftmost lane is omitted.

MsgTime	RtmsNo	S1	S2	S3	S4	V1	V2	V3	V4
14.11.2013 17:36:30	90	46	49	49	NULL	39	35	38	NULL

Table 4.2 Sample of data from sensor 90

An example of data from sensor 90 obtained on "14.11.2013" at "17:36:30" is presented in the Table 4.2. The sensor is located at 800 meters before the bridge entrance right after toll plazas & merging point. Sensor 90 is collecting data for 1 minute before sending it to the Traffic Control Center. The other sensors are sending data in every 2 minutes.

This part of the road has 4 lanes but only 3 of them measured and lane 4 (S4) has no data representation. (S is an abbreviation for the word "Şerit" in Turkish.) Average lane speed in each lane is calculated as 46, 49, 49 km/h, respectively. In this 1 minute interval the sensor 90 has counted 39, 35, and 38 vehicles from lane 1, 2 and 3, respectively.

In our simulation model, we need to use vehicle counting as an estimator of interarrival time. First, the sum of vehicles in 3 lanes (which are scanned by sensors) has been calculated. Then, the sum is multiplied by 1.33 to have an estimate of the total vehicles on 4 lanes. In other words, the average number of vehicles in 3 lanes is added to the data to represent lane 4 counting. Figure 4.4 shows corrected sensor 90 data in hourly basis. The same operations are conducted for other sensors to convert 3 lane data to 4 lanes.

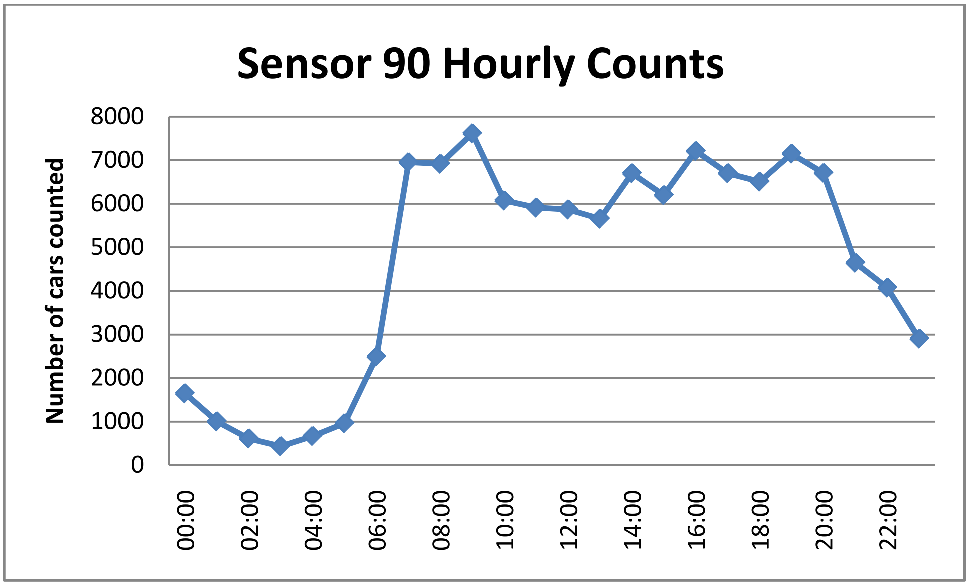


Figure 4.4 Sensor 90 corrected hourly demand rates

After converting the sensors data daily flow characteristics of bridge is studied. In Figure 4.5 daily flow rates are presented for Europe-to-Asia direction. Figure shows number of cars counted by different sensors in each 2 minute periods. Each color represents a different sensor. Figure 4.7 shows the flow on the opposite direction. Average speed data is also studied and outcomes are presented in Figures 4.6 and 4.7. The graph shows average speed changes within the day.

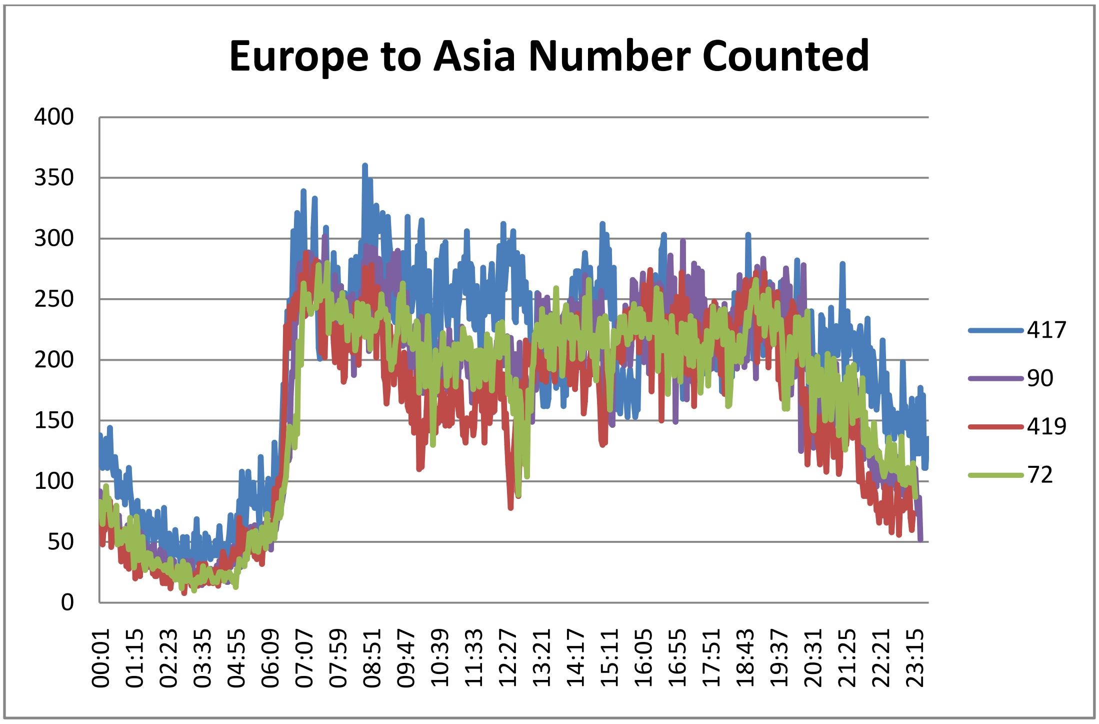


Figure 4.5 Europe to Asia number counted

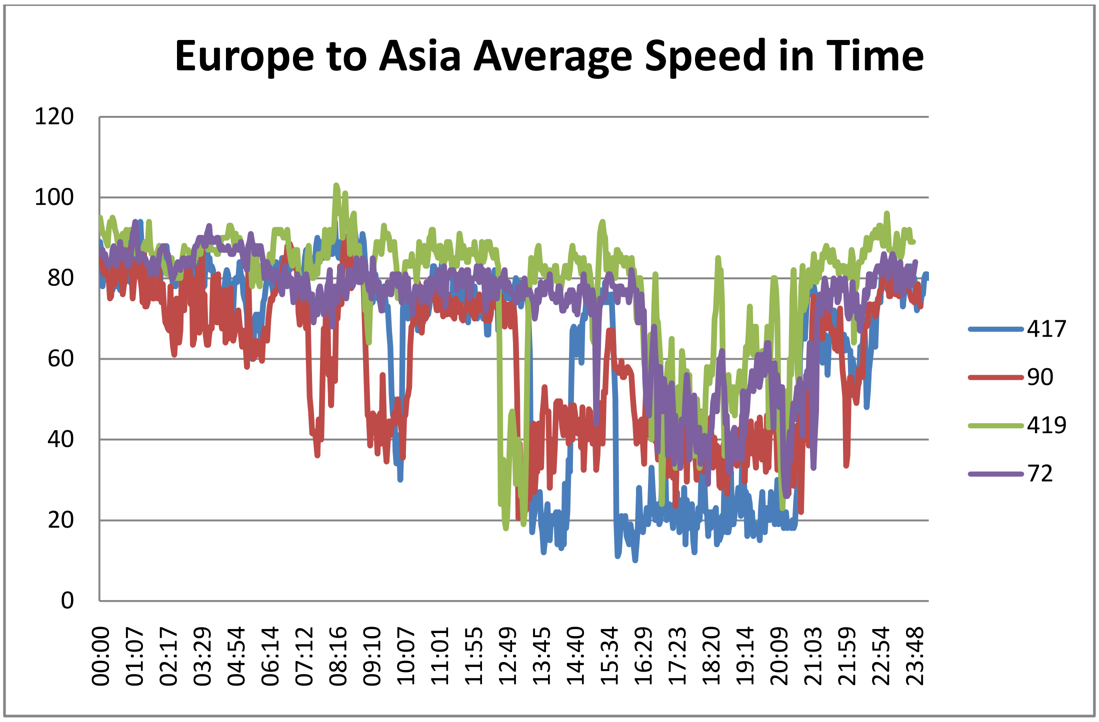


Figure 4.6 Europe to Asia average speed

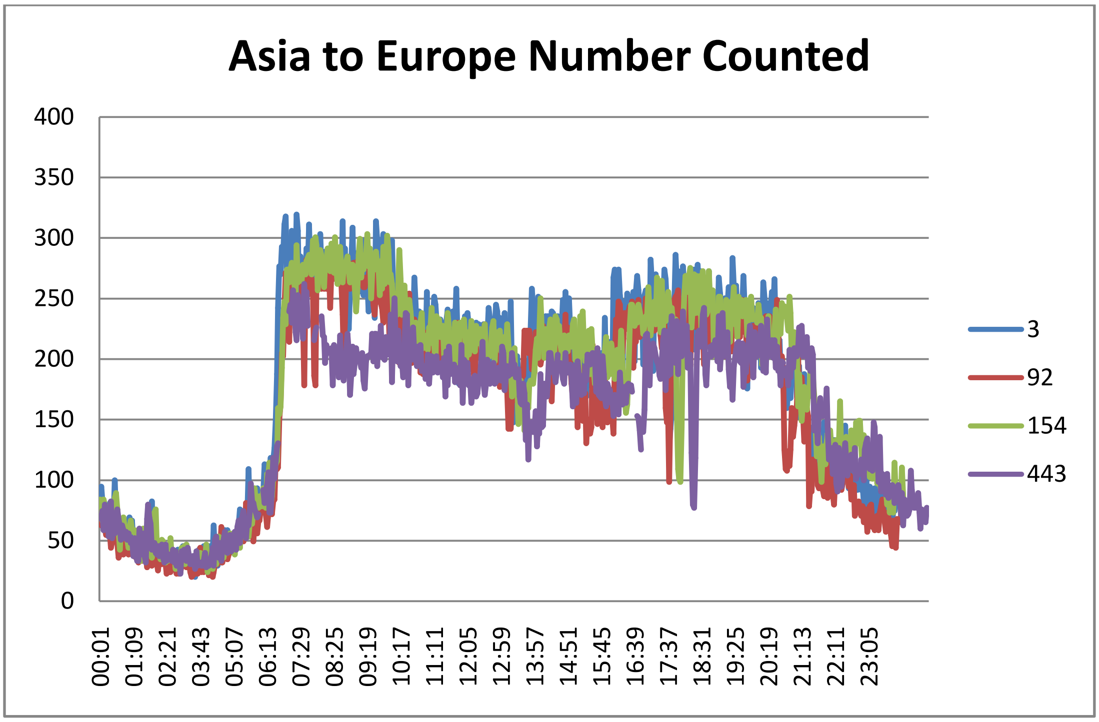


Figure 4.7 Asia to Europe number counted

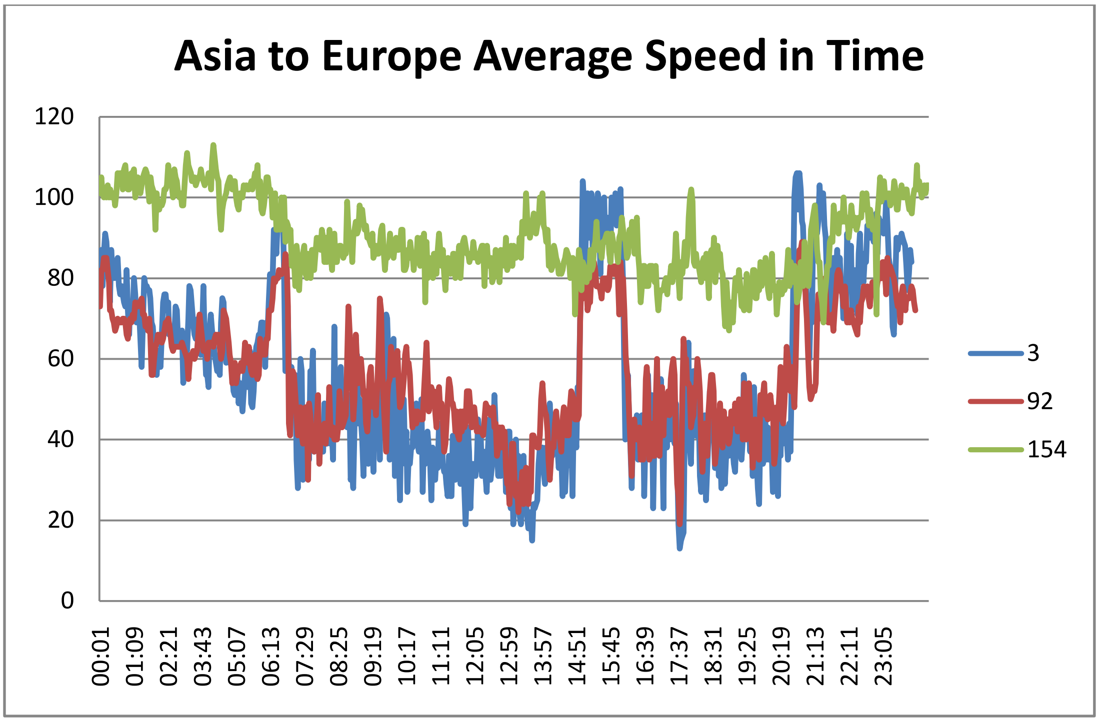


Figure 4.8 Asia to Europe average speed

4.2 Model Formulation

4.2.1. Assumptions

The simulation of the traffic flow is based on the assumption that vehicles do not face any traffic difficulties after taking a slot on the bridge. Once a vehicle could acquire the needed space on the bridge the vehicle is leaving out the system in our simulation.

In Figure 4.9 general congestion characteristics of both bridges are shown. The peripheral roads are divided into sections, each of which is controlled by a different sensor. The data collected from sensors are represented in colors of red, orange, yellow, and green. The bridge on the north is FSM Bridge and the one on the south is Bosporus Bridge of Istanbul. Although in the figure it seems the congestion still exists on the bridges, it is just because of this section representation. After reaching the bridge, it can be seen in the figure that that traffic congestion disappears. This assumption is also supported by average speed graph of Asia to Europe direction (Figure 4.8). Sensor 154 with green lane color is located 800 meters away from the end of the bridge on the European side. According to Figure 4.8, Average speeds of the vehicles measured by sensor 154 are much higher than the cars trying to get the bridge on Asian side (measured by sensor 92).

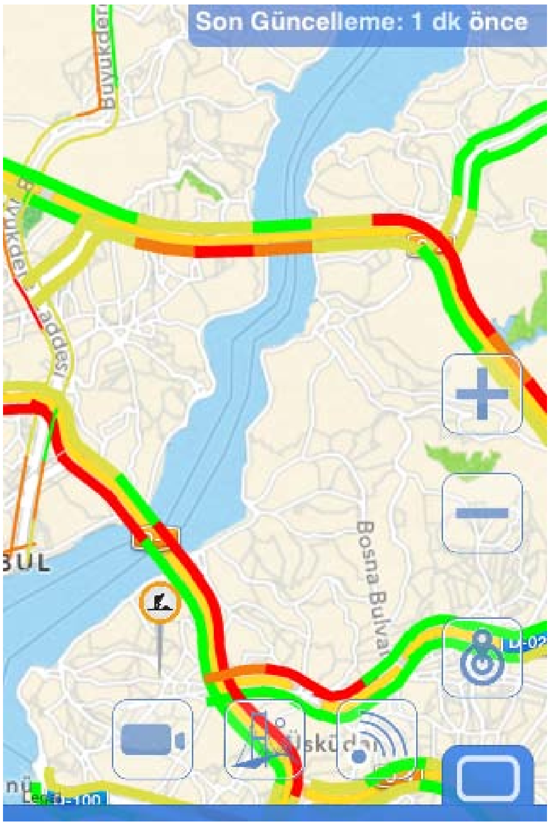


Figure 4.9 Traffic control center illustration of 23/12/2013 18:00

4.2.2. Model Design

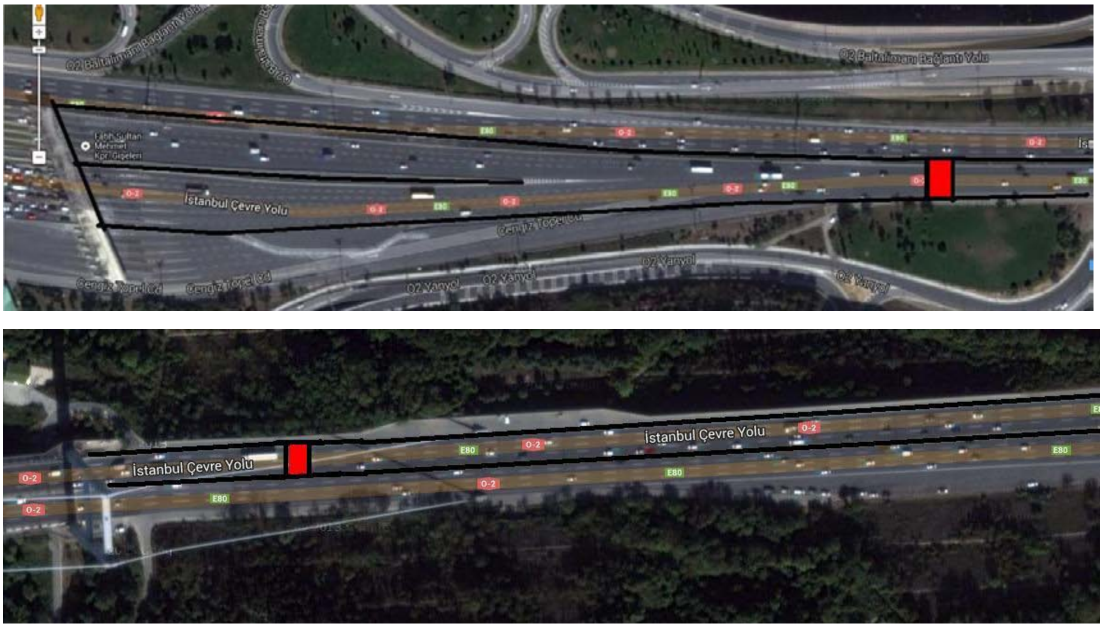


Figure 4.10 Borders of the simulation model

The core service areas in our simulation model are represented in the Figure 4.10. The red rectangles represent our *Service* in the simulation model. This space is where the lane merging has just been completed. Once a vehicle is cleared off this area, the other vehicle on the lane allowed using it. As an analogy, our simulation's service area look like a funnel filled by vehicles coming from the wider side of the funnel and when a vehicle leaves the bottom end of funnel it is discarded from the simulation system.

In both sides of the bridge, vehicles try to acquire the necessary gap for safe driving. In traffic terminology this distance is called chasing distance and defined as ”the minimum distance needed between two cars in the same lane to have a safe driving”. The chasing distance should be at least the half of the vehicle's km/h speed in meters. Second parameter of this distance is the vehicle's length. A typical full-sized passenger car's length is accepted as 5 meters by US Government [23].

In Table 4.3, this required space is calculated for different speeds. Speeds are starting from 90 (legal maximum) and gradually decreases until 1. Also in the same table the time needed to travel this safety distance is presented in seconds. All time values are rounded to upper decimal point.

From our calculations we see that required gap in terms of time averages are around 2-3 seconds and from the Figure 4.11 we can say that it is pretty stable for moving traffic.

This calculations showes us another explanation of chasing distance : The “Two second rule”. The two-second rule is a rule of thumb by which a driver may maintain a safe following distance at any speed. The rule is that a driver should ideally stay at least two seconds behind any vehicle that is directly in front of the driver's vehicle [24].

kmh	m	sec	Lane Capacity	Total Capacity	Utilization
90	50	2	1800	7200	100
85	47,5	2,02	1782	7128	99
80	45	2,03	1773	7092	99
75	42,5	2,04	1764	7056	98
70	40	2,06	1747	6988	97
65	37,5	2,08	1730	6920	96
60	35	2,1	1714	6856	95
55	32,5	2,13	1690	6760	94
50	30	2,16	1666	6664	93
45	27,5	2,2	1636	6544	91
40	25	2,25	1600	6400	89
35	22,5	2,32	1551	6204	86
30	20	2,4	1500	6000	83
25	17,5	2,52	1428	5712	79
20	15	2,7	1333	5332	74
15	12,5	3	1200	4800	67
10	10	3,6	1000	4000	56
5	7,5	5,4	666	2664	37
1	5,5	19,8	181	724	10

Table 4.3 Chasing distance in terms of meters and the time needed to travel this safety distance in seconds

4th and 5th column of Table 4.3present the lane capacity and the total capacity of the road with 4 lanes for different speed levels. Lane capacity is the number of cars that can pass in one minute trough our service area. The capacity is calculated under the asumption of the drivers are chasing each other without violating the required gaps calculated for various traffic flow speeds.

The last column represents the lane capacity and how it changes with respect to the inbound traffic flow speed. We can see how traffic congestion empowers itself by not just reducing average speed on the road but also reducing lane capacity of vehicles. Figure 4.12 shows how lane capacity changes with different inbound speed levels.

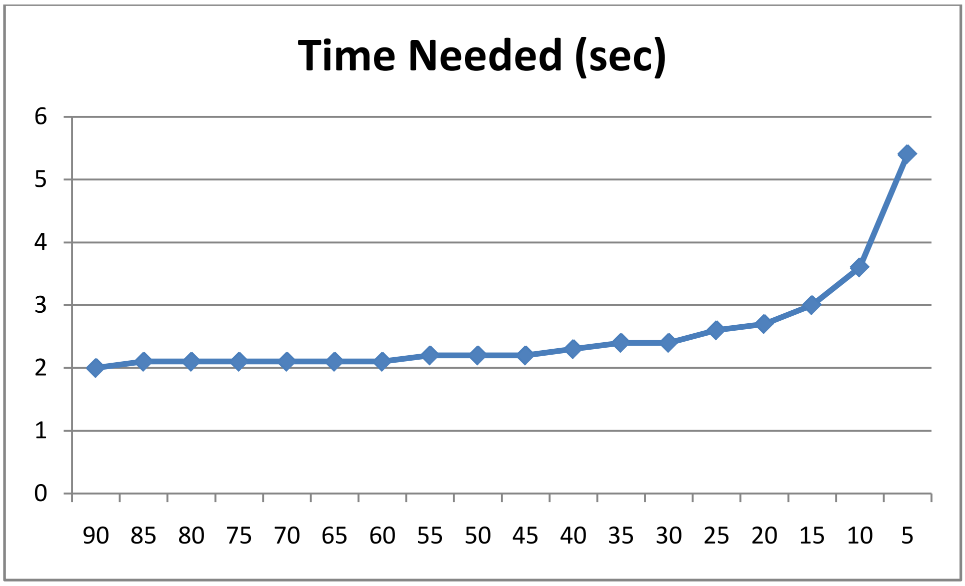


Figure 4.11 Time to travel the Chasing distance for different speeds

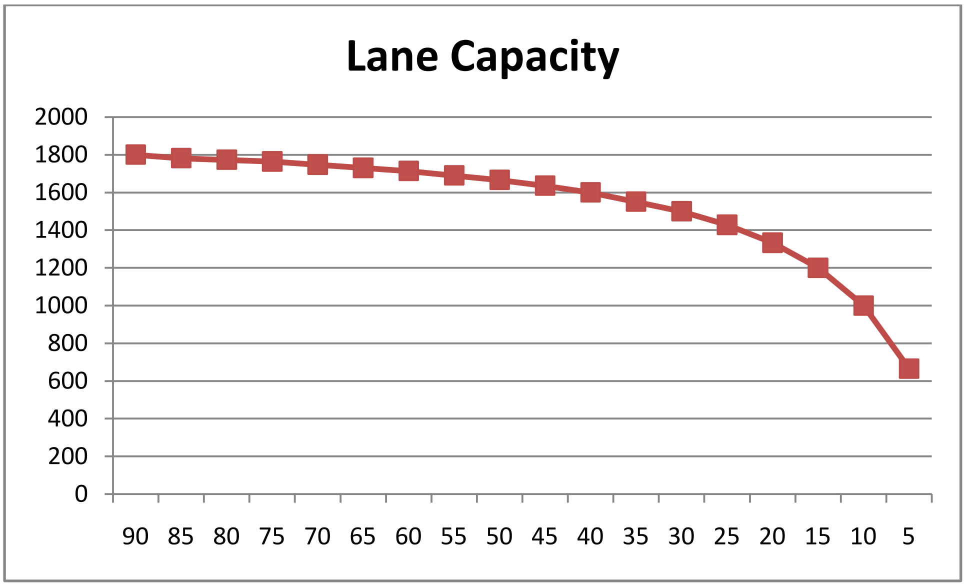


Figure 4.12 Lane capacity change with speed.

To simulate the congestion of the bridge, rush hours are selected for the simulation time interval where the real congestion occurs. From our data and common knowledge, we know that rush hours of the bridge is between 17:00 and21:00 . However, a warm up period to reach steady state is defined between 16:00-17:00. Because collecting statistics at the start of the simulation may effect the results, we prefer to add this warm up period in our analysis.

Before and after this time interval (17:00-21:00), number of cars arriving to the bridge decreasesdrastically, and the average speed increases letting cars to achieve free flow speed.

On both sides of the bridge enterance, there is one sensor located: sensor 90 for Europe-Asia direction and Sensor 92 for Asia-Europe direction. These sensor's data is used as system inputs.

Figure 4.13 and 4.14 represent the number of cars arriving to the system and the average speed measured by the sensors. Furthermore, comparison of arrival rate and speed is made to check the relationship between arrival rate and achieved speed level. On Figure 4.15 it is clear that the speed achieved from both sides of the bridge is nearly 40 km/h.

In our simulation study, the performance parameters of average number in queue, maximum number in queue and average waiting time will be collected from the simulation model.

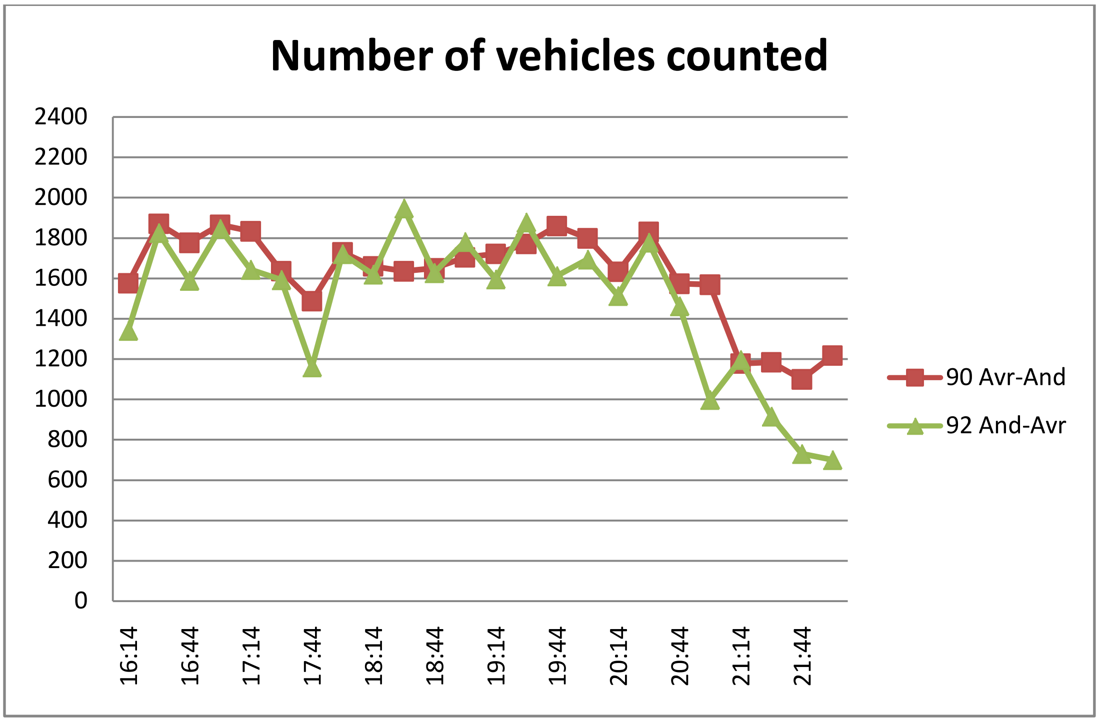


Figure 4.13 Vehicle counts of sensors 90 & 92

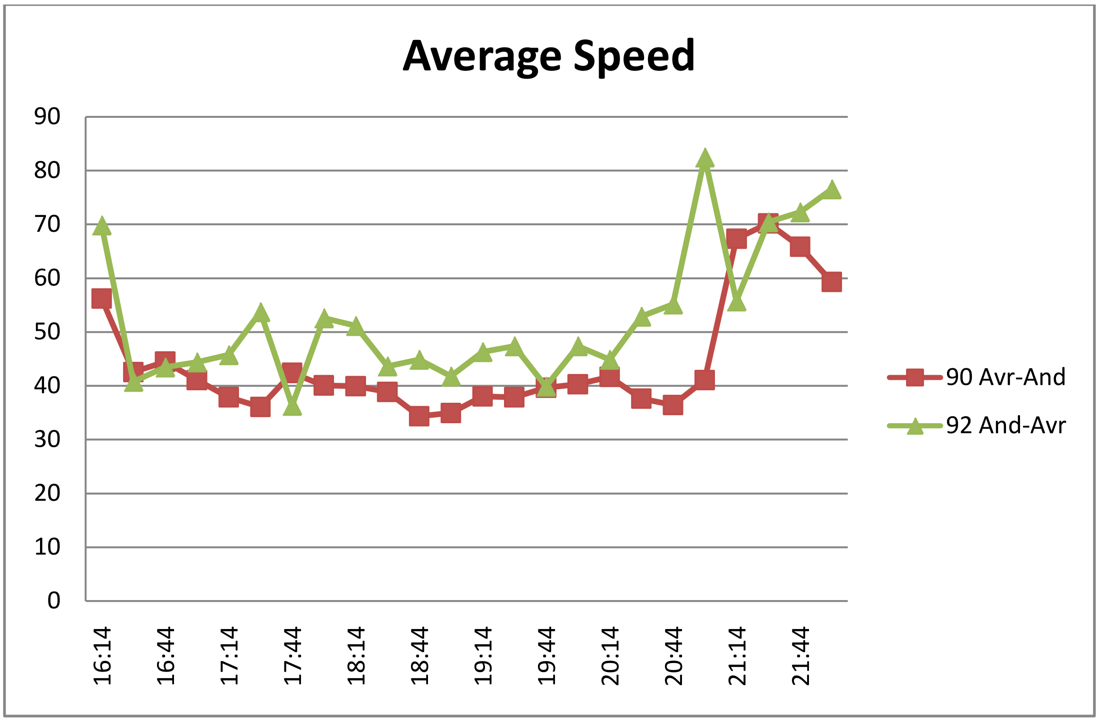


Figure 4.14 Average speed calculated from sensors 90&92

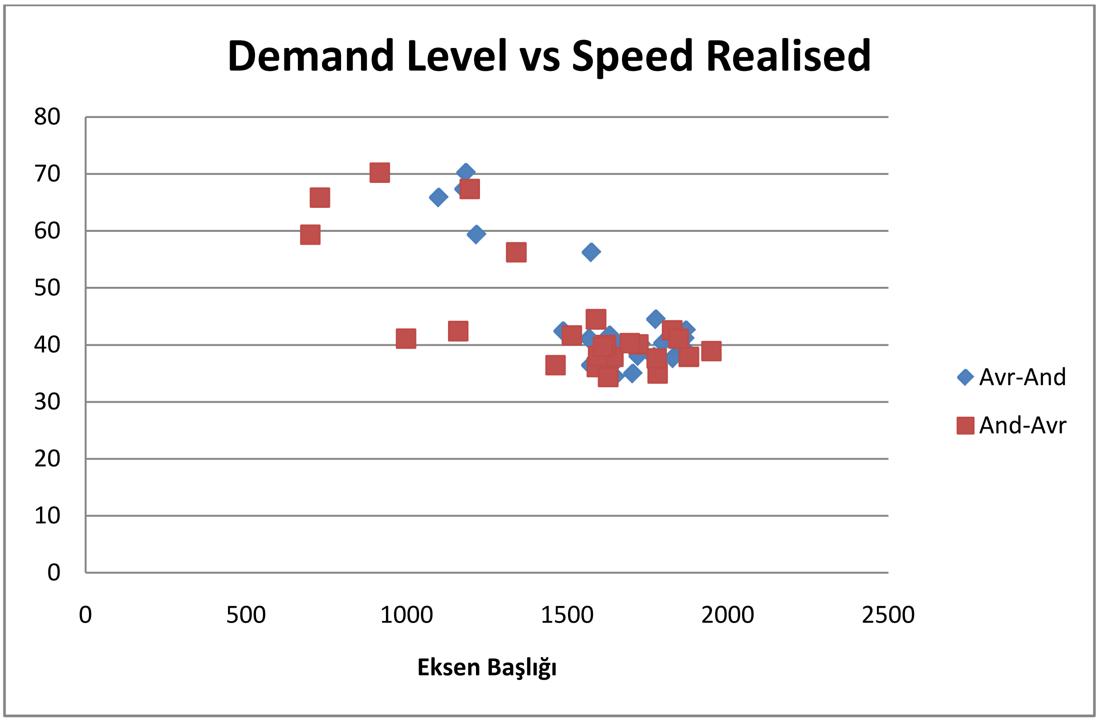


Figure 4.15 Demand level vs. Speed realized

4.3 Simulation Model in Arena

Arena simulation software is used for the simulation of traffic flow on Fatih Sultan Mehmet Bridge. Arena is discrete event simulation software developed by Rockwell Automation INC. [25]. In Figure 4.16 the ARENA modules of the simulation model are shown.

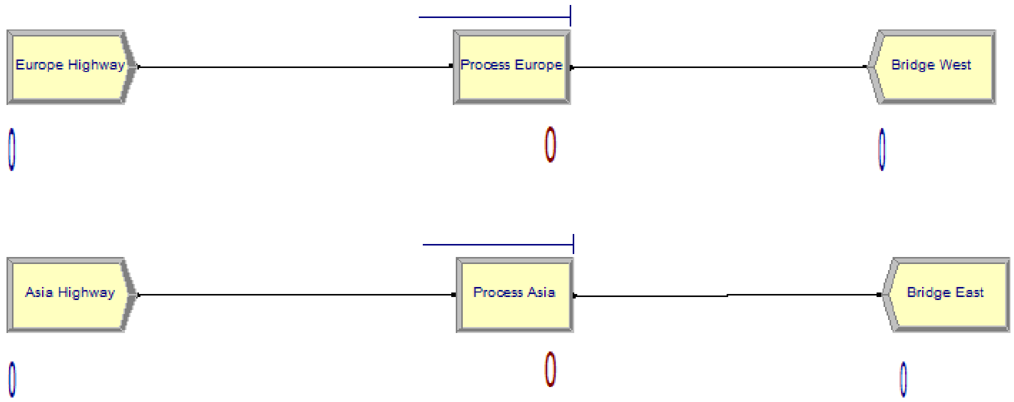


Figure 4.16 Arena simulation model

For each direction (Asia-Europe and Europe-Asia), the entities as vehicles are generated by a *create* module, then processed by a *process* block. Finally, entities leave the system by passing through a *dispose* module.

4.3.1 Entity Creation

Entity creation is performed with *Create* blocks named as Europe Highway & Asia Highway (Figure 4.17)

Two types of entities exist in our model.

- Vehicle Europe: Vehicles travelling to East direction. They are coming from European side (Europe Highway) and heading to Asian side.
- Vehicle Asia: Vehicles travelling to West direction. They are coming from Asian side (Asia Highway) and heading to European side.

Entity generation is made according to their own schedule created separately. (Schedule Europe & Schedule Asia). Figure 4.18-19 shows how schedules are defined inside each *Create* block. Schedule Europe and Schedule Asia is declared as "Arrival" schedules to the system. (Figure 4.20)

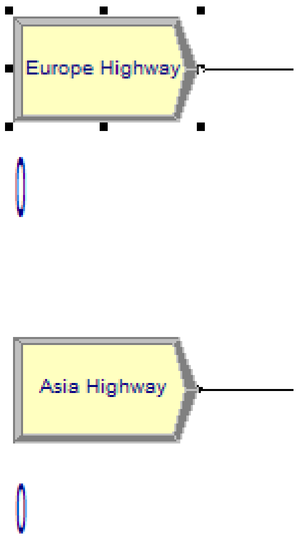


Figure 4.17 Create Blocks

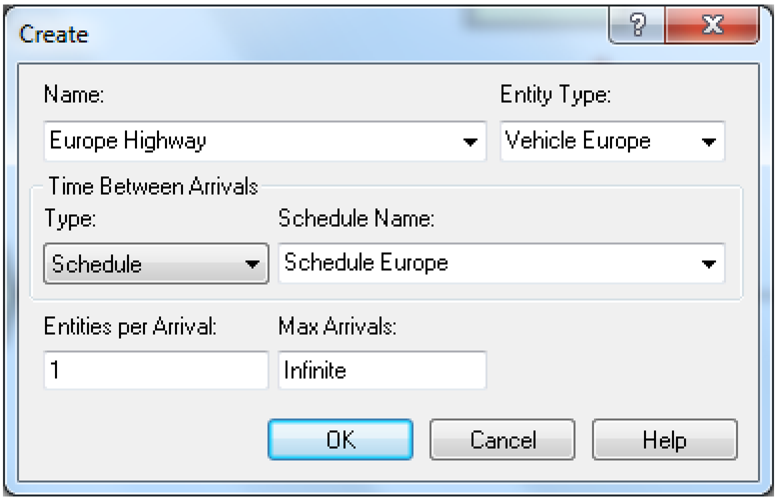


Figure 4.18 Europe Schedule declaration

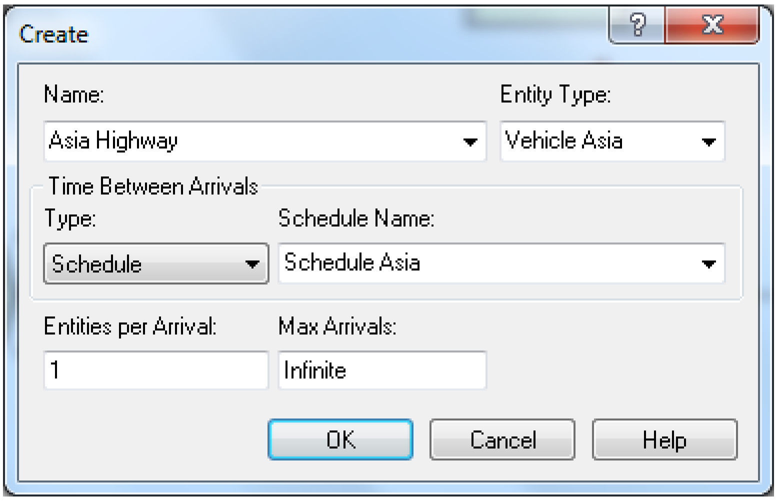
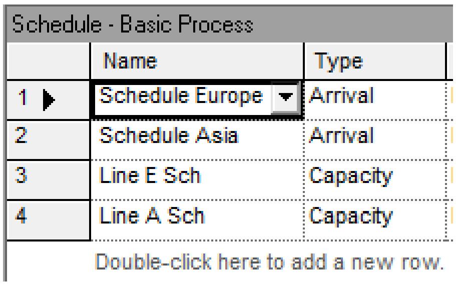


Figure 4.19 Asia Schedule declarations



Schedule - Basic Process

	Name	Type
1	Schedule Europe	Arrival
2	Schedule Asia	Arrival
3	Line E Sch	Capacity
4	Line A Sch	Capacity

Double-click here to add a new row.

Figure 4.20 Schedules of the system

4.3.2 Entity Processing

Entity processing is done with *process* blocks named as Process Europe & Process Asia (Figure 4.21)

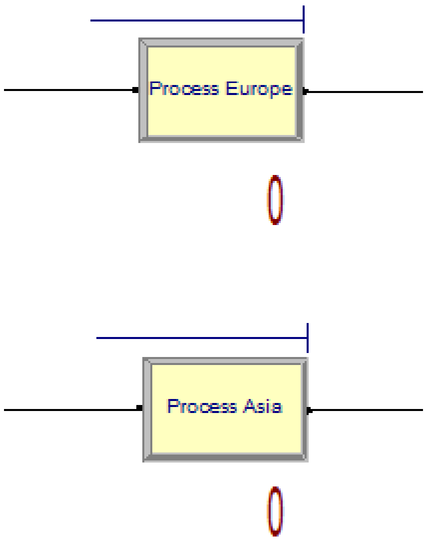


Figure 4.21 Process Blocks

Process Europe and Process Asia are the processes that entities has to pass trough to be able to defined as processed item. In this simulation model a processed item is defined as “a vehicle which managed to obtain required space on the surface of bridge” then the entity becomes ready to be disposed from the system.

Two-second rule mentioned earlier in this section is applied for *process* blocks for initial entry. Figure 4.22 and 4.23 shows the intialization of *process* blocks.

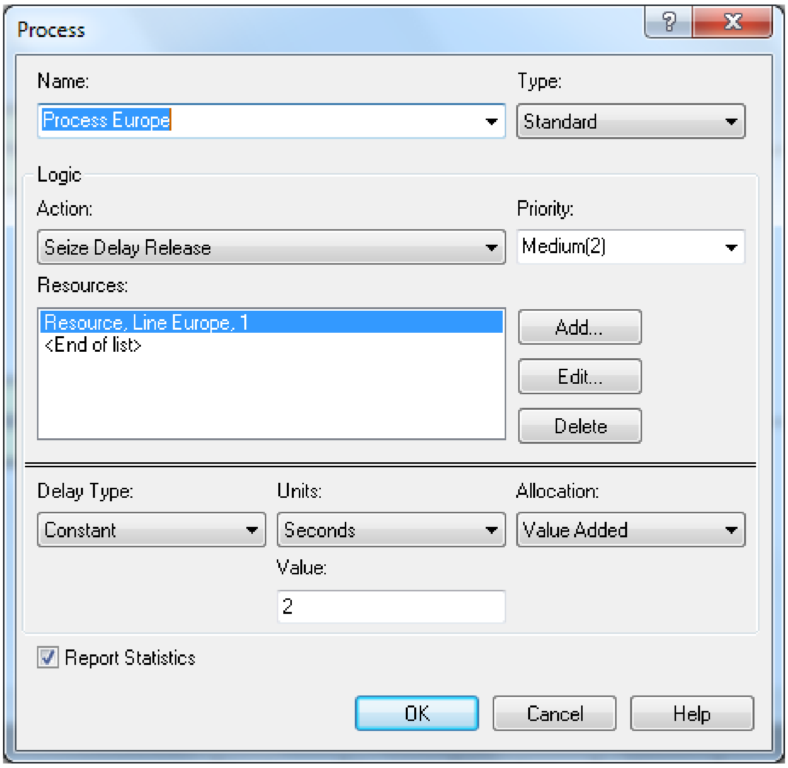


Figure 4.22 Process of Europe-Asia travel

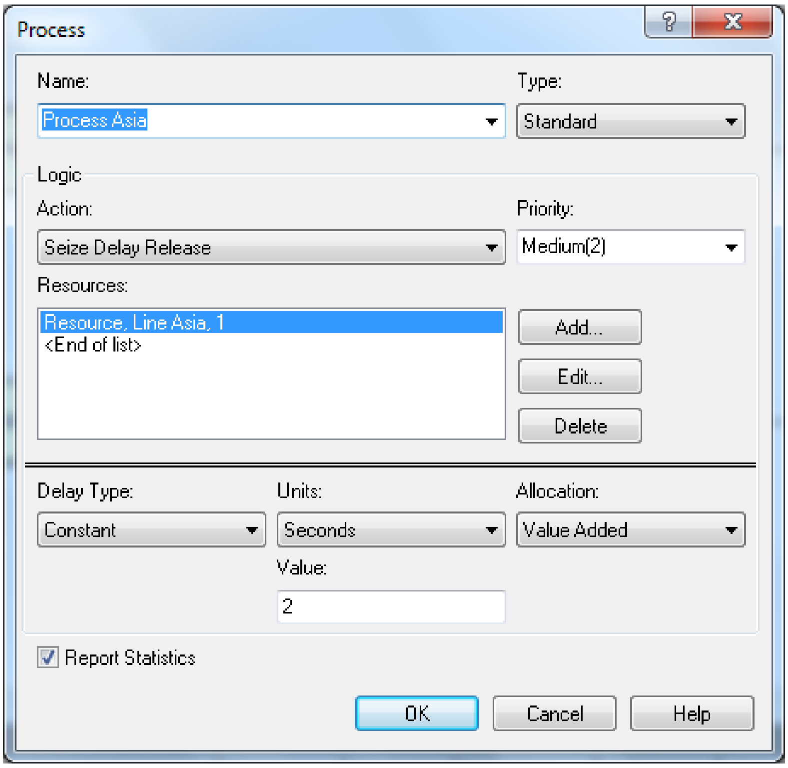


Figure 4.23 Process of Asia-Europe travel

In FSM Bridge, there are four lanes for each direction. All entities are occupying a single lane for 2 seconds to complete the process. In Figures 4.24-25 you can see definition of resource usage for entities.

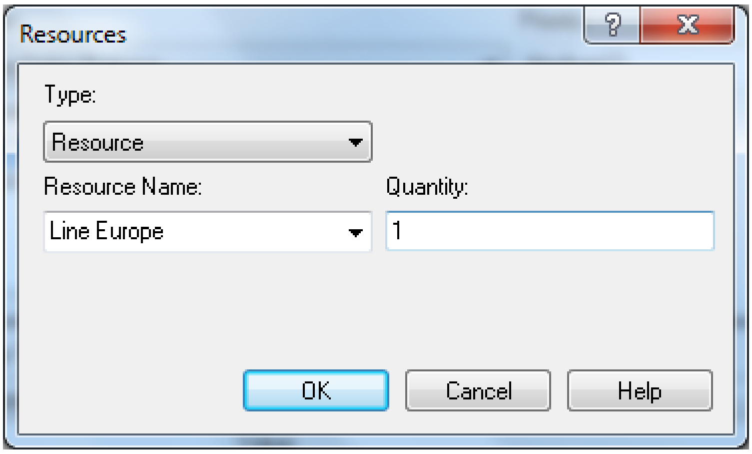


Figure 4.24 Lane occupancy European side

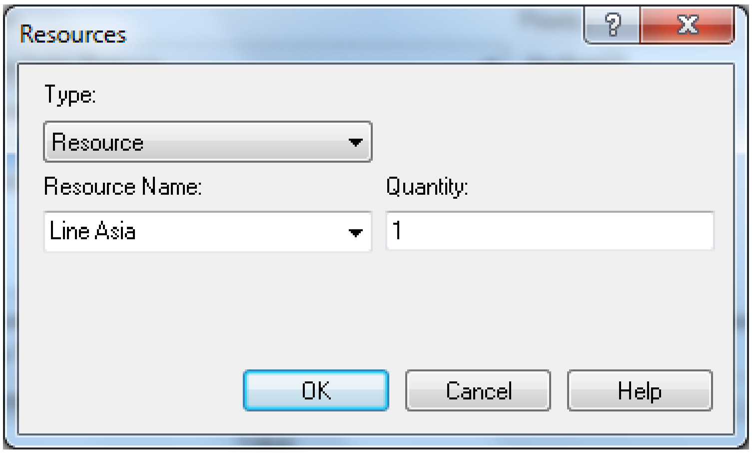
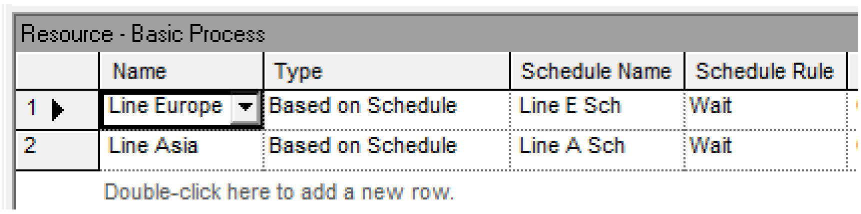


Figure 4.25 Lane occupancy Asian side

Resources (in our case the lanes) are defined in Arena's resource sheet as shown in Figure 4.26.

Their capacity is based on schedules named as "Lane E Sch" and "Lane A Sch"



Resource - Basic Process

	Name	Type	Schedule Name	Schedule Rule
1	Line Europe	Based on Schedule	Line E Sch	Wait
2	Line Asia	Based on Schedule	Line A Sch	Wait

Double-click here to add a new row.

Figure 4.26 Lane resouce based on schedule

Depending on the traffic congestion and traffic estimates, authorities on FSM bridge can decide to create counter traffic lane in favour of one direction. (Mornings for westbound and evenings for eastbound traffic). To be able to have this flexibility on the program,we defined number of the lanes with a schedule. Schedules "Lane E Sch" and "Lane A Sch" are declared as capacity to show the number of lanes assigned for each direction in a time interval.(Figure 4.27)

Schedule - Basic Process

	Name	Type
1	Schedule Europe	Arrival
2	Schedule Asia	Arrival
3	Line E Sch	Capacity
4	Line A Sch	Capacity

Double-click here to add a new row.

Figure 4.27 Lane Schedules

4.3.3 Entity Discarding

Entity discarding is done with *discard* blocks named as Bridge West & Bridge East (Figure 4.28). Entities declared as processed item leaves the system by passing through a *dispose* block. Vehicles that rolled on the bridge are considered to be a processed item because the boundary of the system ends where vehicles started to roll continuously and regularly with free flow speed.

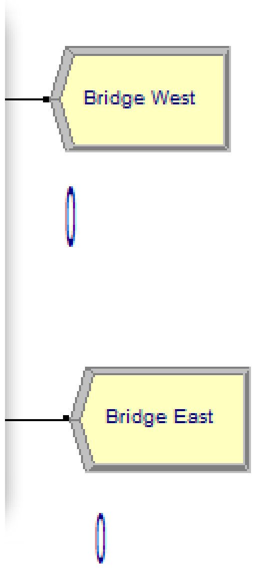


Figure 4.28 Dispose blocks

4.4 Experiments and Results

4.4.1 Current Situation

First experiment will be for the current situation of the traffic on the bridge. Although the rule of 2 seconds usually ensures a safe driving, when congestion starts to occur drivers have tendency to drive closer to the car in front. To have a model working accurately, first we need to update this 2 seconds with a more realistic estimate.

Because traffic congestion level on the bridge is high enough to create stop-and-go traffic, sensor 90's data does not provide real arrival rates of the vehicles. The same problem also occurs for the other sensors. In the time of rush hours, these sensors cannot represent the correct interarrival time data due to the queues going beyond these sensors.

On the other hand the vehicle counts collected from the sensors can be used as "process time" data. For instance, if a vehicle is managed to pass in front of sensors 90 to east direction, then we know that that car becomes a processed item for our simulation. Therefore, for rush hours, sensor counts are output rates of system. In other words, they count the number of vehicles the system managed to give service.

Currently, the traffic control center of Istanbul Municipality assigns a counter-flow lane for the east direction (Europe-to-Asia) of the bridge in the evening rush hours. Therefore, the number of lanes assigned to each side is not equal, but 5 on the east direction and 3 on the west direction in the evening rush hours.

Before proceeding in our analysis, we first refine the data gathered from sensors 90 and 92 by aggregating them for "15 minutes" intervals and insert them in *schedule* datasheets. (Figure 4.29). In Arena, schedules need to be filled with hourly rates. In the figure, hourly rates of traffic flow represented in 15 minute intervals in input window of Schedules module (Figure 4.30).

Schedule - Basic Process

	Name	Type	Time Units	Scale Factor	Durations
1	Schedule Europe	Arrival	Quarterhours	1.0	20 rows
2	Schedule Asia	Arrival	Quarterhours	1.0	20 rows
3	Line E Sch	Capacity	Quarterhours	1.0	1 rows
4	Line A Sch	Capacity	Quarterhours	1.0	1 rows

Figure 4.29 Arrival and capacity schedules with 15 slots

After inputting the arrival rates, the system is tested for different processing times. With various repetitive test runs, we tried to reach a high utilization level for the resources (close to 100% as much as possible) which also provides a low level of queue size for the *process* block (close to zero as much as possible). This utilization level mostly turns out to be 95%. Any level significantly below 95% is an indicator of short processing time and any level above that level is likely to create an excessive queue size.

Outcomes of test runs are shown in Figure 4.31. It is visible that 1.8 and 1.9 seconds of process time are way below 95% utilization level for European side. On the other hand, 2.1 seconds is creating an excessive queue size (239) and fails to exactly represent the processing time. 1.95 second of process time, however, creates on average of 14 cars of queue which is low enough to be credited to the randomness of the arrival rate. The same analysis is also conducted for Asian side. The only point satisfying the utilization level with low queue sizes for Asian side is 1.25 seconds with 35 cars of queue. In Figure 4.32, upper and lower limits of the utilization level are represented with horizontal green lines. It is visible that there is only one point falling into the interval for Asian side and two points for Europe side. In Figure 4.33, average queue lengths are represented, and it is visible that 4th data point in European side has better output level (utilization: 94%, queue size: 40).

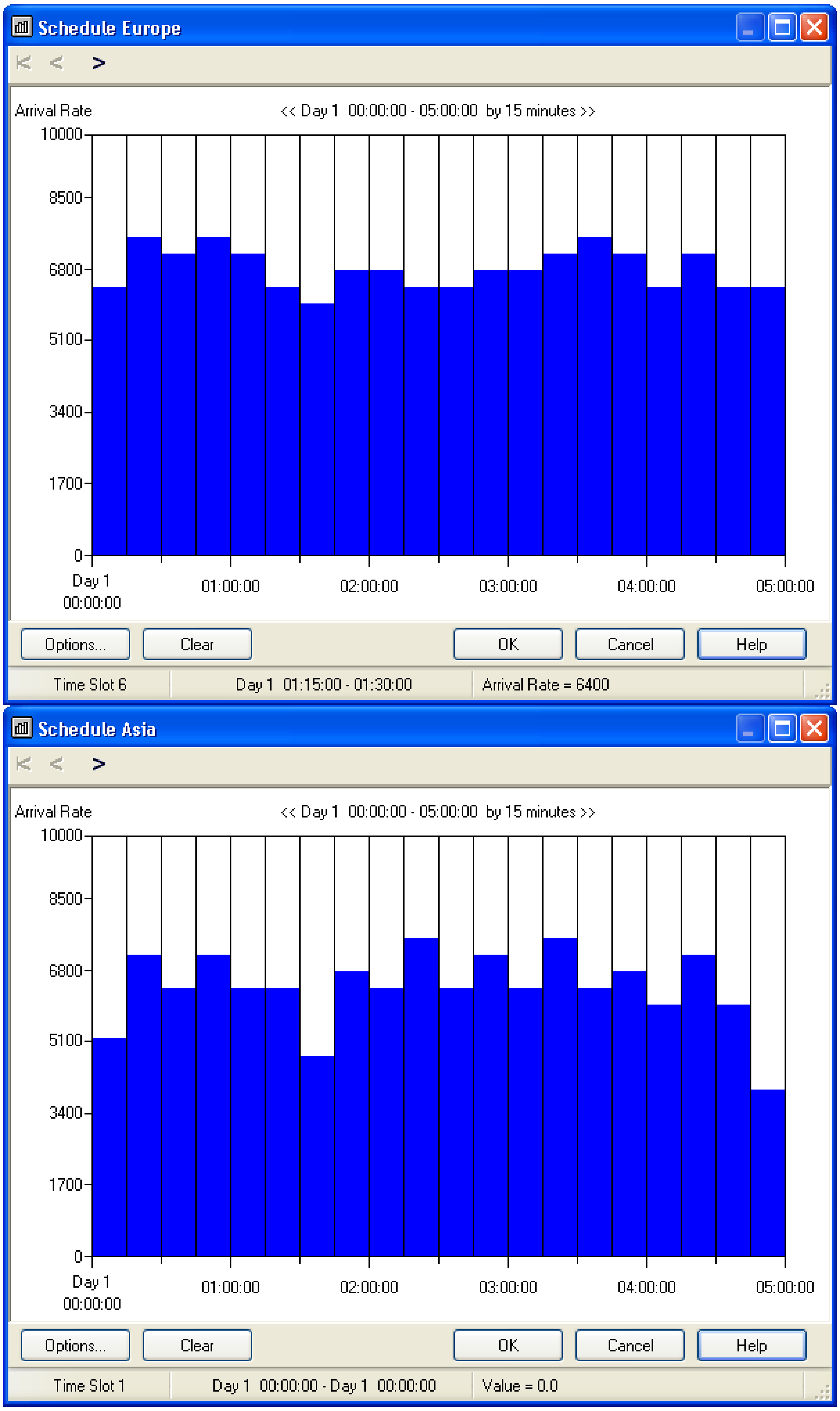


Figure 4.30 Arrival rates input within schedules.

Europe Side 5 Lanes		
Pros. Time	**AVG. Util.**	**Number**
1,80	84%	2
1,90	88%	6
1,95	91%	14
2,00	94%	40
2,10	99%	239

Asia Side 3 Lanes		
Pros. Time	**AVG. Util.**	**Number**
1,10	81%	2
1,20	88%	14
1,25	92%	35
1,30	96%	193
1,40	100%	1234

Figure 4.31 Process times and utilization levels with average queue length

Because of these reasons, processing times of 1.25 seconds for Asia-to-Europe direction and 2 seconds for Europe-to-Asia direction are selected. The reason of having longer processing time on the European side compared to Asian side is the merging of lanes in toll plaza area. In Asian side, vehicles are flowing on straight lanes without any merging just before the bridge. The last junction before the bridge is “Kavacık” junction and it is 2 kilometers before the bridge entrance. Thus, the vehicles have enough time to reach a stable flowing speed before the bridge entrance.

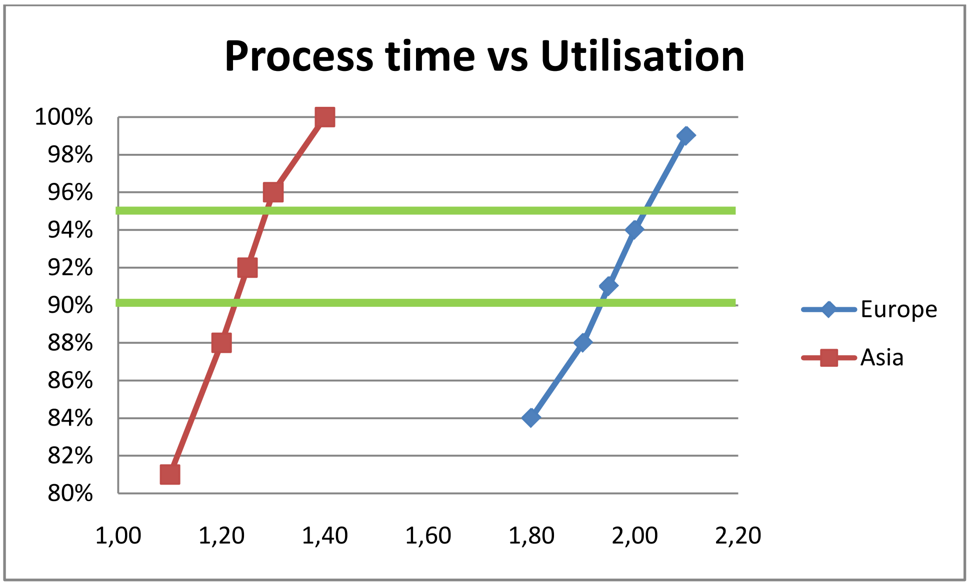


Figure 4.32 Process time vs. Utilization level

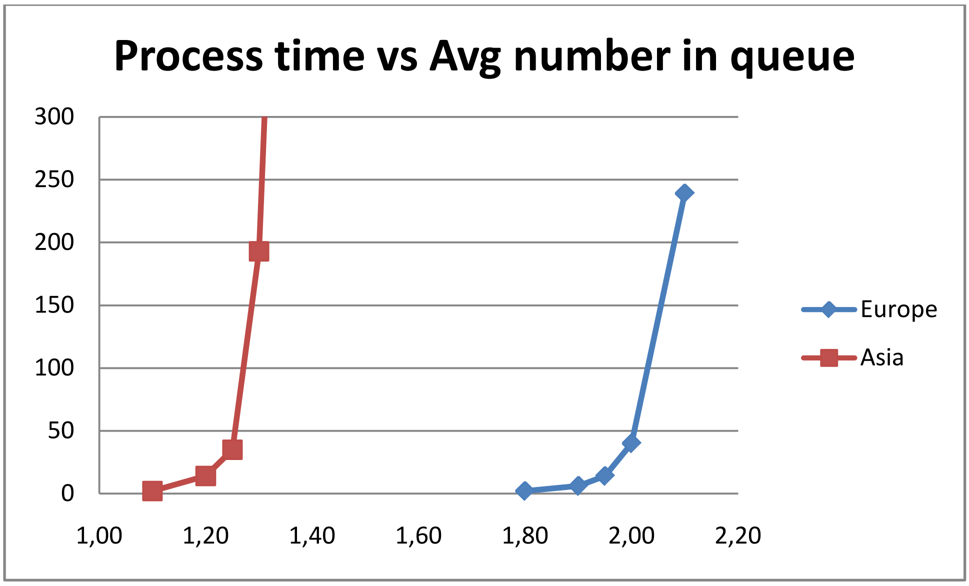


Figure 4.33 Process time vs. average number in queue

With these process times, it is seen that there is no significant difference between the number of cars counted by the sensors 90 (and sensor 92) and the number of entities processed on European side (and Asian side) by the simulation. This shows us that our simulation is now consistent and accurately matches with the real sensor data with respect to processing times.

4.4.2 Arrival Rate Scenarios with counter-flow lane in favor of eastbound traffic

After tuning the processing times of *process* blocks, it is needed to run simulation for various arrival rates. Since the bridge traffic gets stuck in front of the sensors at the rush hours, and the real arrival rate data cannot be collected from these sensors, the arrival rates has to be estimated by the help of vehicle counts collected from the sensor in the proximity of the bridge. To be able to test the effect of different traffic flow densities on the bridge traffic, the simulation runs with various arrival rates ranging from the exact vehicle counts collected from sensor 90 on east direction (sensor 92 on west direction) to 200% of the counts collected from the same sensor.

As noted before, currently in the evening rush hours, a counter-flow lane is assigned for the east direction (Europe-to-Asia) of the bridge. This means when the counter-flow lane in favor of eastbound traffic exists, our simulation has to assume 5 lanes for the east direction and 3 lanes for the west direction. The outcomes of this simulation run can be seen in Tables 4.4 and Table 4.5. For the "counter-flow lane" scenario, both Asia and European side average waiting times become around 0.25 minutes when %100 of the vehicle counts collected from sensors are used as arrival rate.

In %100 arrival rate scenario, unsurprisingly, our simulation is giving the same queue sizes that we have found in Figure 4.31. If we select the arrival rate 50% higher, then the average waiting time per vehicle becomes 53 minutes for Europe-to-Asia direction and 51 minutes for Asia-to-Europe direction. For instance if we expect a high volume traffic on an exceptional day, such as the day before a prolonged holiday (say, arrival rates 80% higher than the vehicle counts of sensor 90 and 92), then the vehicles will wait more than an hour on average to pass the bridge.

Outcomes of the simulation runs show us that the bridge system has reached its peak service level and remained incapable in serving the vehicles within a reasonable time especially when high arrival rates are inevitable. With every 10% increase in arrival rate (nearly 4000 cars), the average waiting time of the vehicles increases approximately 10 minutes. Figures 4.34, 4.35 and 4.36 show the percentage of the vehicles, which waits 0-30 minutes, 30-60 minutes, and more than 60 minutes, for Europe-to-Asia direction, Asia-to-Europe direction, and cumulative of both directions, respectively.

	Europe-Asia						
	Number Arrived	Avg. Number in Queue	Max. Number in Queue	Avg Wait Time (min)	Percentage Waited 0-30 min	30-60 min	60+ min
100%	33712	40	247	0,29	1,00	0,00	0,00
110%	36878	1407	2151	9,13	1,00	0,00	0,00
120%	40202	3719	5926	22,00	0,83	0,17	0,00
130%	43835	6415	10444	34,82	0,51	0,49	0,00
140%	47286	8962	14704	44,86	0,37	0,47	0,17
150%	50399	11331	18714	53,40	0,31	0,37	0,32
160%	53674	13812	22867	61,08	0,28	0,31	0,41
170%	57551	16714	27716	69,21	0,25	0,25	0,49
180%	60590	19217	31705	75,69	0,23	0,22	0,55
190%	64336	22066	36388	81,95	0,22	0,20	0,58
200%	67794	24769	40807	89,26	0,20	0,18	0,63

Table 4.4 Europe-Asia direction simulation output

	Asia-Europe						
	Number Arrived	Avg. Number in Queue	Max. Number in Queue	Avg Wait Time (min)	Percentage Waited		
					0-30 min	30-60 min	60+ min
100%	31821	35	221	0,26	1,00	0,00	0,00
110%	35327	1087	2153	7,34	1,00	0,00	0,00
120%	38340	3357	5600	20,49	0,81	0,19	0,00
130%	41542	5680	9390	31,78	0,59	0,41	0,00
140%	44468	7912	12947	41,41	0,48	0,37	0,15
150%	48273	10748	17566	51,52	0,34	0,36	0,30
160%	51245	13068	21172	59,03	0,30	0,33	0,37
170%	54221	15369	24851	65,53	0,28	0,30	0,43
180%	57601	17672	28862	71,08	0,26	0,24	0,50
190%	60648	20032	32724	76,51	0,24	0,22	0,54
200%	63826	22334	36569	82,53	0,23	0,17	0,60

Table 4.5 Asia-Europe direction simulation output

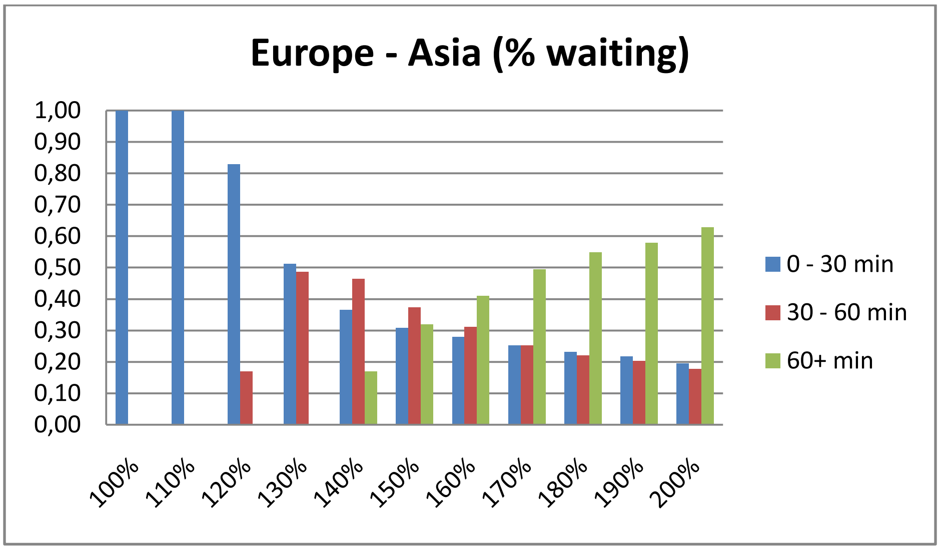


Figure 4.34 Percentage of cars waited Europe-Asia (5-3)

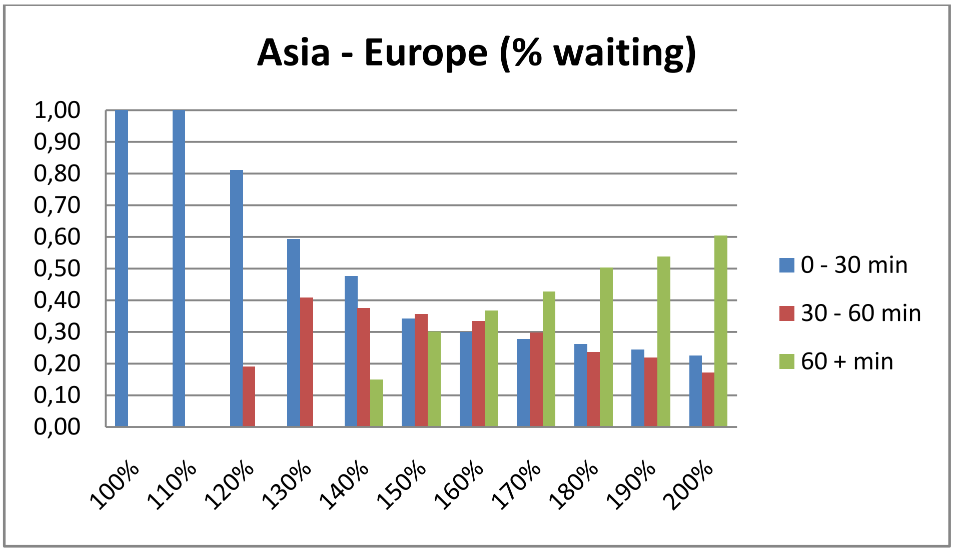


Figure 4.35 Percentage of cars waited Asia-Europe (5-3)

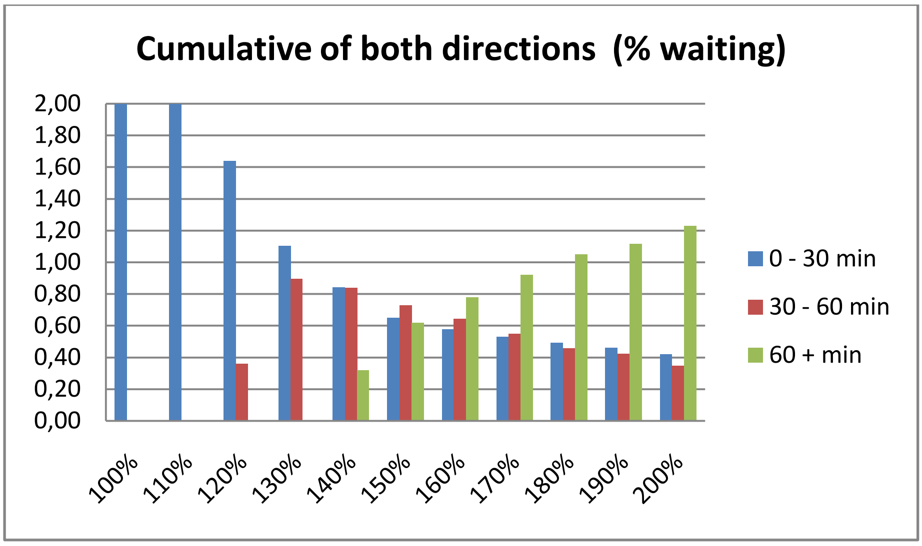


Figure 4.36 Cumulative percentage values (5-3)

4.4.3 Arrival Rate Scenarios without any counter-flow lane

Another experiment is conducted to compare the "counter-flow lane" scenario of Section 4.4.2 with a scenario where there is no counter-flow lane in evening rush hours. Although arrival rates of Asian and European sides seems to be very close to each other, the effect of lane merges on the Europe-to-Asia direction influences the waiting times of the vehicles. To show this influence, lane resources inside the *process* blocks are changed from 5 and 3 to 4 and 4 for east and west directions, respectively.

In the scenario without any counter-flow lane, process times found in Section 4.4.1 are also valid because behavior of the vehicle in lane merging area is still the same. The only difference is that now Europe-to-Asia direction can serve one less vehicle, and Asia-to-Europe direction can serve one more vehicle simultaneously. Although there exists different number of resources (lanes), vehicles still need the same amount of time on this part of the road to securely clear this area.

The simulation runs with various arrival rates (ranging from 100% to 150% of vehicles count obtained sensor 90 and sensor 92 are presented in Tables 4.6 and 4.7. Figures 4.37, 4.38 and 4.39 show the percentage of the vehicles, which waits 0-30 minutes, 30-60 minutes, and more than 60 minutes, for Europe-to-Asia direction, Asia-to-Europe direction, and cumulative of both directions, respectively.

	Europe-Asia						
	Number Arrived	Avg. Number in Queue	Max. Number in Queue	Avg Wait Time (min)	Percentage Waited 0-30 min	30-60 min	60+ min
100%	33712	4144	6675	29,14	0,66	0,34	0,00
110%	36878	6762	10833	43,34	0,37	0,49	0,13
120%	40202	9101	14907	53,59	0,31	0,38	0,31
130%	43835	11804	19432	64,19	0,27	0,29	0,44
140%	47286	14355	23697	72,32	0,24	0,24	0,52
150%	50399	16728	27710	79,39	0,22	0,22	0,56

Table 4.6 Europe-Asia direction 4-4 lane scenario simulation output

	Asia-Europe						
	Number Arrived	Avg. Number in Queue	Max. Number in Queue	Avg Wait Time (min)	Percentage Waited 0-30 min	30-60 min	60+ min
100%	31821	1	15	0,00	1,00	0,00	0,00
110%	35327	1	29	0,01	1,00	0,00	0,00
120%	38340	6	170	0,04	1,00	0,00	0,00
130%	41542	15	263	0,23	1,00	0,00	0,00
140%	44468	411	919	2,21	1,00	0,00	0,00
150%	48273	2498	4314	12,19	1,00	0,00	0,00

Table 4.7 Asia-Europe direction 4-4 lane scenario simulation output

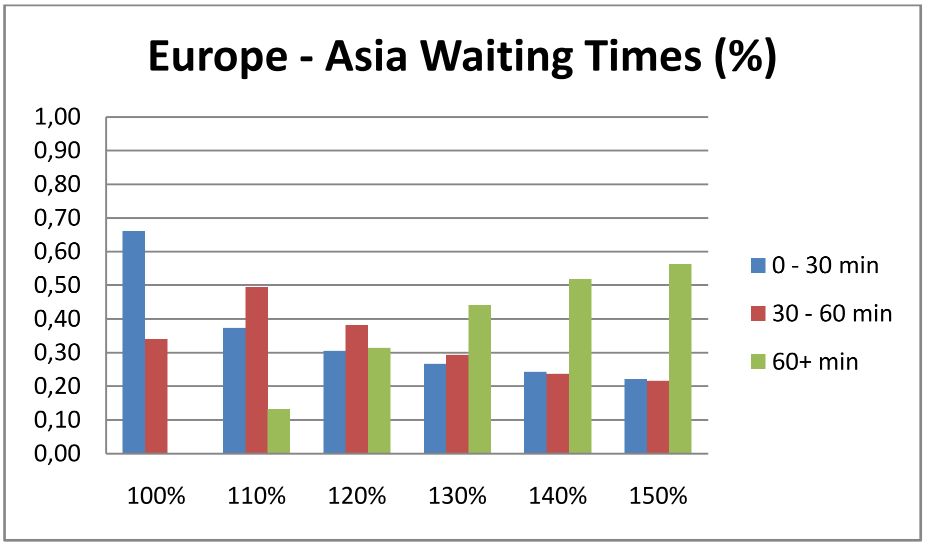


Figure 4.37 Percentage of cars waited Europe-Asia (4-4)

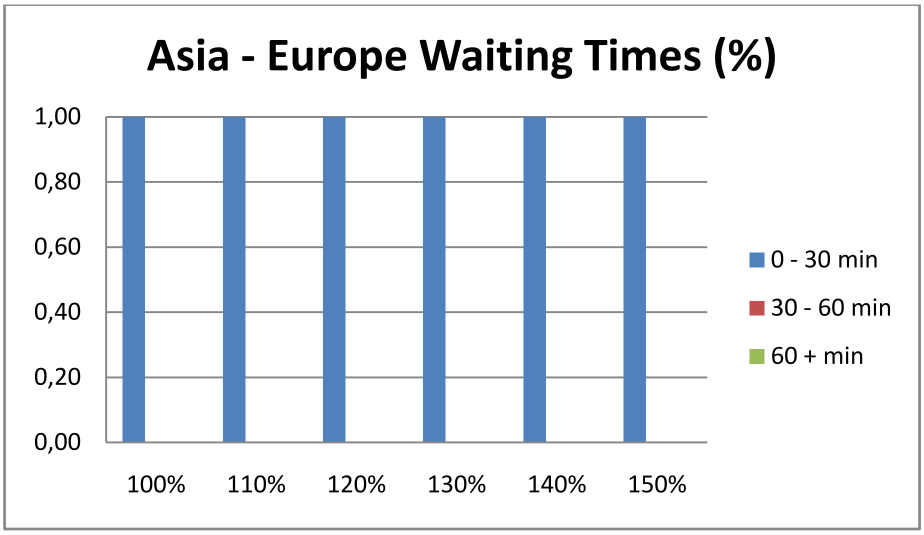


Figure 4.38 Percentage of cars waited Asia-Europe (4-4)

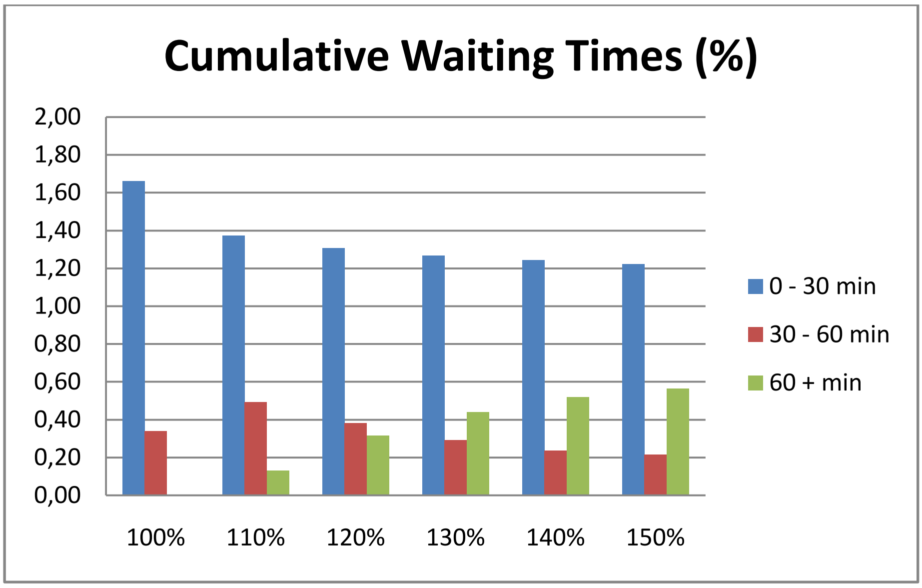


Figure 4.39 Cumulative percentage values (4-4)

Table 4.6 and 4.7 show that even though there is no significant difference between the number of cars arriving to the bridge from both directions in the evening rush hour, when both directions on the bridge have four lanes (without any counter-flow lane), east direction (Europe-to-Asia) suffers much more from traffic congestion due to lane merging taking place after the electronic toll collection (ETC) plazas. When the “average number in queue” values of Table 4.4 with Table 4.6 are compared, it can be noticed that a counter-flow lane in favor of the east (Europe-to-Asia) direction significantly improves the average number of cars congested at the entrance of the bridge.

Chapter 5
Conclusion

5.1 Summary of Research

One of the world's biggest problems in efficiency loss is about time and money spent on traffic jams. In this project an ARENA simulation model is created to simulate the traffic on Fatih Sultan Mehmet Bridge of Istanbul.

Some of the important outcomes of the simulation study can be listed as follows: Firstly, the traffic level on bridges of Istanbul is now reaching over capacity limits not just for rush hours but longer periods during the day. Secondly, any traffic jam caused by the merging lanes on the bridge can affect all traffic flow in and around the city. That is why keeping a continuous flow on bridges is extremely important. Finally, in safety point of view relying on 2 overused bridges for all traffic flow is not a good strategy when redundancy is taken into consideration. Any kind of construction needs or temporary happenings can affect traffic flow deeply.

Building a third bridge outside from city and diverting heavy vehicles may help to decrease the load on FSM Bridge. This relaxation on traffic congestion can help to achieve more fast and stable traffic flow all around the city. In addition, the third bridge may increase redundancy of the road system in case of failures or if construction needs appear.

5.2 Opportunities for Future Work

5.2.1 Further Improvements in Current ARENA model

The main drawback of current model is the lack of accuracy in interarrival time measurements caused by traffic jam. The jams prevent drivers to drive with their free flow speed. When queues reach sensors active area sensor readings will show incorrect results. Future studies can be made to acquire more data from sensors located further away from the bridge compared the current sensors. These sensors will be capable of both measuring more accurate arrival rates and developing better queue characteristics. With the help of those data an ARENA simulation can be set up with better measurements which can take the junctions of the peripheral road and their traffic flows into consideration. Such kind of simulation model can be capable of distinguish the differences between vehicles coming from different junctions.

The model that mentioned above was created in early stages of the thesis. The outline of the model can be seen on Figure 5.1.

The model given in Figure 5.1 simulates the traffic flow on the peripheral road with junctions. In and out flows from junctions are also taken into consideration. The model is also able to simulate traffic jam on peripherals. It simulates toll plaza area lane closings and our focused area of lane obtaining. The lack and inaccuracy of traffic data around the junctions prevented us from using this proposed ARENA model in our study. With a better estimation of arrival and departure rates on the junctions (entrances and exits), the proposed model can be used in a future study.

5.2.2 Discrete vs. Continuous Simulation

Discrete simulation environment is not always suitable for the traffic simulation modeling because of the continuous characteristic of the traffic flow. As mentioned in literature review chapter, many simulations on traffic flow are designed with the help of fluid dynamics and kinematic wave theory. These methodologies may help future researchers to better simulate the continuous nature of the traffic flow. Continuous event modeling is especially beneficial in slow moving jams when vehicles are moving close to each other with low speeds.

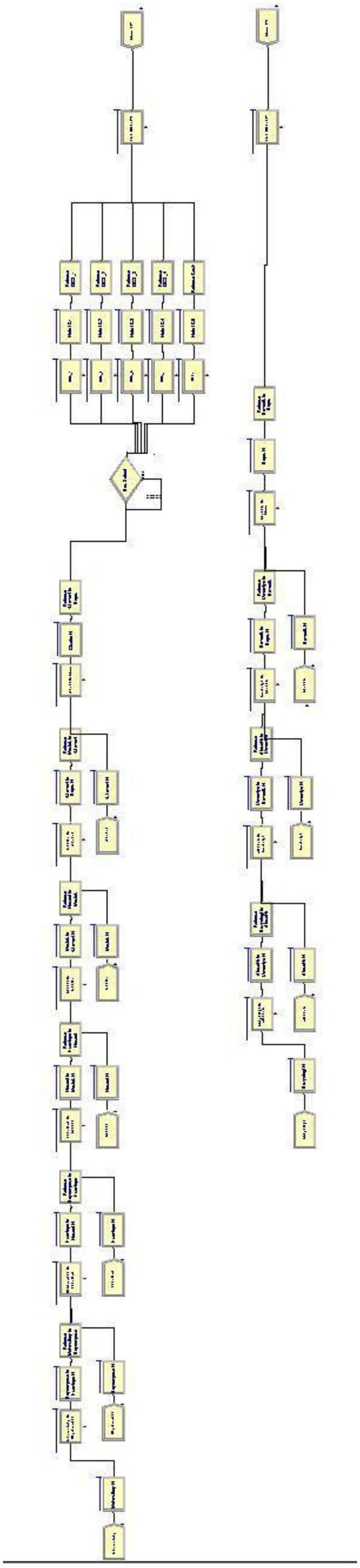


Figure 5.1 ARENA model with junctions and toll plaza metering

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Curriculum Vitae

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