USE OF BLUETOOTH TECHNOLOGY FOR TRAFFIC ANALYSIS IN URBAN ROAD NETWORKS

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ABSTRACT

USE OF BLUETOOTH TECHNOLOGY FOR TRAFFIC ANALYSES IN URBAN ROAD NETWORKS

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Bluetooth technology is a cheap and easy data collection method for traffic studies. It enables tracking of movements via detection of MAC addresses, unique to each Bluetooth device, without actually seeking any personal information. It is successfully used in traffic management in limited access corridors such as highway corridors. However, its potential in urban networks has to be evaluated to see the limitations, since it is more challenging in open networks, which is the main goal of this study. Within the scope of this study, we developed three case studies including;

- travel time/speed estimation along corridors
- Origin-Destination (OD) matrix estimation
- assessment of impact of electronic speed enforcement (ESE)

in Ankara urban layout using Bluetooth data from concurrently activated multiple Bluetooth readers. The results showed that many MAC addresses were observed at one place at one time without being observed at another observation location, as expected from the open network nature of an urban region. MAC-to-volume values suggested a penetration rate up to 10% for Bluetooth enabled devices in Ankara traffic. Travel time estimation for an urban corridor was very effective using Bluetooth data, in despite the small number of MAC matching. Moreover, Bluetooth data enables the realization of the expected speeding behavior before and after an ESE. Drivers before the ESE system location obeyed the speed limits, while they increased their speeds immediately after the ESE point. These results support the fact that ESE is a powerful way of forcing speed limit; however, it is not easy to assess their impact on increasing traffic safety. On the other hand, OD estimation for an open network is not reliable due to i) the currently low penetration rate of Bluetooth and ii) limited number of Bluetooth readers used. OD estimation process would benefit more from repeated data collection and verification via other data sources.

Keywords: Bluetooth Technology, MAC matching, Travel time estimation, Origin-Destination Estimation, Electronic Speed Enforcement

ÖZ

ŞEHİRİÇİ YOL AĞLARININ TRAFİK ANALİZİNDE BLUETOOTH TEKNOLOJİSİNİN KULLANIMI

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Bluetooth teknolojisi, trafik çalışmalarında kullanılan ucuz ve kolay bir veri toplama yöntemidir. Bu teknoloji, her bir Bluetooth aygıtına özel olarak kodlanmış MAC adresinin yakalanmasıyla, hiçbir kişisel bilgi gerektirmeden bu aygıtların hareketinin takibine imkan tanımaktadır. Özellikle otoyol gibi kısıtlı erişimi olan koridorlarda trafik yönetiminde başarıyla kullanılmaktadır. Ancak, bu teknolojinin şehiriçi yol ağlarında kullanımı daha zor olup bu tür kontrolsüz sistemlerdeki potensiyelini belirlemek bu tezin ana hedefi olarak belirlenmiştir. Bu çalışma kapsamında, birden fazla Bluetooth vericisi tarafından toplanan verilerin incelenmesiyle;

- Şehiriçi bölgelerdeki koridorlar üzerinde seyahat süresi/ hız tahmini
- Şehiriçinde Başlangıç-Varış (BV) tahmini
- Şehiriçi koridorlarda Elektronik Denetleme Sistemlerinin (EDS) etkisinin değerlendirilmesi

olmak üzere Ankara kentsel bölgesinde üç örnek çalışma yapılmıştır. Alınan sonuçlarda, okuyuculardan elde edilen verilerde, şehiriçi bölgelerde beklendiği gibi, yüksek oranda başka noktalardaki okumalarla eşleşmeyen MAC adresi gözlenmiştir. Az sayıda MAC eşleşmesine rağmen, şehiriçinde seyahat süresi tahmininden Bluetooth teknolojisinin kullanımı verimlidir. Ayrıca, EDS öncesinde ve sonrasında beklenen hız davranışı Bluetooth verisi ile gerçeklenmiştir. Sürücüler EDS'den önce hız limitine uyarken, EDS noktasından hemen sonra hızlarını artırmaktadır. Alınan sonuçlar, EDS'nin sürücüleri hız limitine zorlaması konusunda etkili olduğu gerçeğini desteklemektedir. Ancak, bu sistemlerin trafik güvenliği üzerindeki etkisini değerlendirmek çok kolay değildir. Diğer yandan, şehiriçi bölgelerdeki mevcut girim oranı ve sınırlı sayıda Bluetooth okuyucu düşünüldüğünde BV tahmini güvenilir değildir. BV tahmini, tekrarlanan veri toplama işlemi ve diğer veri kaynaklarını kullanan doğrulama yöntemleri ile geliştirilmelidir.

Anahtar Kelimeler: Bluetooth Teknolojisi, MAC eşleştirme, Seyahat süresi tahmini, Başlangı.-Varış tahmini, Elektronik Hız Denetimi

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CHAPTER 1

INTRODUCTION

Travel data collection is expensive and massive, especially using the traditional household surveys and modeling. Such surveys are even more impractical for local analysis in small urban regions, such as evaluation of traffic impact of business districts, large urban projects, etc. A relatively cheap alternative is to detect vehicles with Bluetooth via readers located at the major entry-exit points around the study region. As vehicles and/or travelers use this technology increasingly during their travels, this method may result more reliable data. Though it is really simple and straightforward in detecting movements along highways, use of this approach in urban locations is more challenging.

This study firstly aims to develop a methodology to distinguish vehicular movements and their travel characteristics from Bluetooth data, more specifically estimation of the OD matrix and corridor travel times. While there are example studies of Bluetooth use for access controlled corridors in the literature, use of this technology for open urban networks is the main focus of this study. Here, “open network” refers to a traffic network where all the possible traffic entry and exit points (streets, parking lot entrances, etc.) could not be surveyed, such an urban corridor or a neighborhood. As a result, the total entry and exit flows within the system do not necessarily match and could not be verified.

Secondly, detection of vehicular movements via Bluetooth technology may also help evaluation of other urban traffic phenomena, such as impact of speed management and enforcement. One of the most popular speed management techniques is “Speed Enforcement”, which aims to control vehicle speeds, enforce drivers to drive safe and increase the traffic safety. Besides the traditional manned speed limit enforcement (with radar, etc.), the advancements in technology led to development of applications for Electronic Speed Enforcement (ESE). However, as the definition of “speed” change from application to application, some ESE systems focused on spot speed limit enforcement while others aimed to control corridor speed (average) enforcement. Although spot speed limit enforcement is more preferred mostly due to easier and cheaper system requirements, it is equally important to analyze the impact of these systems in terms of travel characteristics, mainly travel speed. This needs speed data collection before and after an ESE application, which is possible with Bluetooth technology. The vehicular trip characteristics can be estimated by processing the detection information of the same Bluetooth device over multiple observation points at, before and after an ESE location.

Analysis of vehicular speed over consecutive segments before and after an ESE application point also enables us to measure the impact of an electronic speed limit enforcement application on vehicular travel speed. In the determination of speed profiles before and after an ESE application point, Bluetooth technology is employed, which itself is another innovative method for speed measurement in traffic studies. Though, the proposed methodology does not detect speed for every vehicle, a sample is created by detecting vehicles with active Bluetooth devices. The vehicular trip characteristics were estimated by processing the detection information of the same Bluetooth device over multiple observation points at, before and after an ESE location.

Layout of the manuscript is organized as follows: A brief literature on Bluetooth technology, use of Bluetooth in traffic analyses, travel time and OD estimation with Bluetooth, electronic speed enforcement and driver response to speed enforcement is given in Section 2. In Section 3, developed methodology is presented step by step. Section 4 deals with the numerical results of the developed approach, and Section 5 concludes the study with the shortcomings and recommendations.

CHAPTER 2

LITERATURE REVIEW

2.1 Bluetooth Technology

Bluetooth is basically a wireless technology using a special radio frequency (2.4 GHz) to transmit data in short distances, mainly because of low power consumption and the security issues. Bluetooth protocol uses electronic identifiers, MAC address, a unique signature of the device that enable re-identification of the device. MAC addresses can be logged and time stamped by a simple reading procedure; this requires a Bluetooth reader device, which has an antenna mounted to the scanner device. As a short range communication technology, one of the most important limitations of Bluetooth technology is communication distance of the devices, which depends on the class of the device (100m for Class 1; 10m for Class 2, and 1m for Class 3) (Chen and Chen, 2005; Meliton and Salcedo, 2010). However, these values can be increased using external antennas. Jiang et. al. (2004) presented the second important limitation as scan time of the Bluetooth reader devices, which is at 1.28 second intervals. Murphy et. al. (2002) stated that, since the time is very low, even for vehicles at a speed of 100 km/hr, for a Class 1 reader, there will be a 7.2 seconds of “in range time”, which makes it a quite reliable for traffic applications. Ahmed et. al. (2008) focused on other limitation, which is the number of active devices in the range of one Bluetooth reader at the same time and this value, named also as Bluetooth reader device capacity, can be up to 7. Dursch et. al. (2004) studied data transfer speed which is another limitation of Bluetooth technology, but it is not in the scope of this paper.

There are many studies focused on the reliability, feasibility, connection setup details and the other properties of the Bluetooth technology and Bluetooth networks. Dursch et al. (2004) focused on reliability and feasibility of Bluetooth technology and they proposed a framework to analyze various types of feasibility, such as technical, operational etc. Bluetooth device discovery procedure was analyzed in detail by Jiang et al. (2004) and Murphy et. al (2002). Inquiry and paging procedures, which are the main steps of device discovery, were discussed and a speed up mechanism was offered to reduce device discovery time and enhance the Bluetooth performance. Connection setup delay times regarding these discovery steps were analyzed by Chen and Chen (2005) and it indicated that Bluetooth technology is suitable for nonsafety-critical controls in-vehicle applications instead of wired connection.

Another way of analyzing Bluetooth performance is evaluating transmission delays within the personal area network (PAN) and master-slave concept. (Sugiura and Dermawan, 2005; Rozeha and Rohaiza, 2006) Results showed that, transmission delay depends on the size and the type of the file and 7,41s is an average needed time for a Bluetooth connection (for 10 m Bluetooth communication distance). A general comparison of Bluetooth and other wireless protocols (IEEE 802.11, ZigBee etc.) in terms of capacity, power consumption, security etc. was done by Durch et. al. (2004) and Ferro and Potorti (2005).

2.2 Use of Bluetooth in Traffic Analyses

Bluetooth monitoring has been used in different studies in transportation field already, including dynamic traffic management applications (Antoniouu& Koutsopoulos, 2010), Intelligent Transportation Systems (ITS) applications (Ahmet et. al., 2008). Especially time-stamping and fast data transfer properties make it a good data collection alternative for real-time traffic management (Boxel et. al., 2011; Van Der Ziip, 1997; Jiao and Huapu, 2005). Malinovskiy et. al. (2012) focused on another interesting application area of Bluetooth monitoring on pedestrian movements, their travel and dwell times, and waiting times within airports (Bullock et. al., 2010).

Some of the studies focused on travel time and OD estimation using Bluetooth data gathered from Bluetooth readers (Blogg et al., 2010 and Barcelo et al., 2010). They located Bluetooth readers which can capture Bluetooth enabled devices automatically by roadside; they concluded that, travel time analysis provides more reliable results, although OD estimation is more challenging and needs supplementary methods. Haghani et al. (2010) aimed to use Bluetooth data as travel time ground truth, instead of floating car data. They focused on filtering raw data, comparing results with floating car data and defining sampling rate for each Bluetooth reader. As a result of this study, Bluetooth technology was considered as a new alternative which can be used as especially travel time data source. Quayle et al. (2010) introduced a pilot study which aims to do arterial performance analysis using Bluetooth technology. They called Bluetooth sensor as Media Access Control (MAC) reader and emphasized that, MAC address is able to provide offline or real-time performance evaluation of various traffic applications, especially in intelligent transportation systems. Results showed that, larger data sets and more complex filtering algorithms are necessary to eliminate outliers, increase sampling rate and obtain more reliable results. Haseman et al. (2010) collected a comprehensive Bluetooth data and he concentrated on the evaluation of this data for work zones in real time. He tried to find a relation between crash rates and queuing in construction zones via the use of solar-powered Bluetooth readers.

2.3. Urban Travel Time Estimation using BT

Travel time measurement and estimation are key issues for real-time traffic management, which took advantage of Bluetooth technology, first. To estimate travel time of a corridor, using MAC addresses and time stamps obtained from Bluetooth sensors are generally filtered and matched. Two corridor applications of this nature were presented for i) a freeway corridor in Barcelona with 11 entry and 12 exit locations (Barcelo et. al., 2010; Jaime et. al., 2010) and ii) a motorway (with 6 MAC readers) and an arterial corridor (with 29 MAC readers) in Brisbane (Blogg et. al., 2010). As a consistency check, number of MAC addresses and total traffic volume at a station, called MAC-to-Volume ratio, was given by Blogg et. al. (2010). Jie et al. (2011) focused on the reliability of travel time measurements in urban locations by GPS-accessorized probe vehicle and Bluetooth readers. The study had two corridor segments of 600m and 935m with 1-hour data collection. The results of this rather limited control study showed that travel time estimations by Bluetooth monitoring has higher uncertainty, raising concerns about belonging of the captured MAC address to a vehicle, and possible existence of multiple Bluetooth devices in one vehicle.

Quality of travel time estimation based on Bluetooth technology was also assessed in a study by Haghani et al. (2010), in which more than 13,300 hours worth of travel time data was collected with Bluetooth; in the conclusion, Haghani et al. (2010) and Aliari and Haghani (2012) found this new technology a promising method to collect high quality travel time that could be used as ground truth. Richardson et. al. (2011) focused on network stratification based on the ground truth determination using Bluetooth. Looking at the issue from a reverse angle motivated some researchers to study travel time outliers on highways and arterials, measured by Bluetooth technology again (Boxel et. al., 2011).

Haseman et. al. (2010) focused on measuring travel time via Bluetooth to assess shifts in traffic assignments due to road closures, workzones, or even signal timing optimization (Quayle et. al., 2010; Day et. al., 2010). Travel time measurements made by Bluetooth probe vehicles were used to capture detour choices for an unexpected bridge closure northwest Indiana by Hainen et. al. (2011).

2.4 Urban O-D Estimation

Use of Bluetooth technology in OD estimation is rather new and limited, so far. In the Brisbane pilot study, Blogg et al. (2010) estimated demand for only two

OD pairs; one along the motorway and the other in the arterial network. The estimates for the motorway OD were compared with the automatic number plate recognition (ANPR) cameras and loop detector traffic volumes; for the arterial OD, control data was collected from traffic counts and a manual video OD survey at the two end stations. MAC address based estimates were found close to those with ANPR and video OD estimates, while further research on expansion methods from MAC based results was recommended. Authors concluded with the fact that MAC data collection was a cost effective way to collect OD in small and controlled networks, which could be used to supplement OD estimation in large complex networks. In the corridor study in Barcelona (Barcelo et. al., 2010; Jaime et. al., 2010), in addition to travel time estimation, a simulation experiment was conducted to estimate dynamic OD along an approximately 12 km corridor. OD estimation in urban locations is a more complex and challenging problem due to a) larger number of OD pairs, b) the availability and complexity of the alternative paths and c) larger number of Bluetooth device to identify all or the majority of the OD matrix. Barcelo et. al. (2012) also studied the problem of Bluetooth detector layout problem for urban location studies, which showed the complexity of the OD estimation from MAC address capturing. Carpenter et. al. (2012) also focused on the issue of detector locations to estimate route specific OD matrix, which is a more important issue for urban locations with more alternative and partially overlapping paths (Hainen et. al., 2011).

2.5. Electronic Speed Enforcement

It is important to measure the impact of ESE systems, which constitutes a rather small portion of the literature in traffic safety. Soole et al. (2013) gave a comprehensive literature review about average speed enforcement. They concluded that, all studies indicate the reduction in vehicle speeds and crashes via the use of average speed enforcement systems and it has an advantage of being a network-wide approach regarding spot speed enforcement. The stated studies had mostly used speed check services and consultations as the data source. Retting et al. (2008) provided an evaluation of the automated spot speed enforcement system which belongs fixed speed cameras located among a freeway in Arizona. They measured speeds via photo radar positioned between speed cameras and they concluded that, especially highly visible enforcement systems have a large effect in reducing the speed. Liu et al. (2010) compared the speed limit effects of two automatic enforcement equipment, camera and radar. They measured the speeds before, at and after the enforcement location using a MC5600 vehicle classifier system and they concluded that, the cameras are more durable and effective method than the radars. Zhang et al. (2011) aimed to evaluate effectiveness of automated speed enforcement systems in China. They used radar gun during data collection process, gathered speed data from road segments before and after enforcement point and it was concluded that, the automated enforcement system is still effective up to 1 km away by roadside. Tay (2009) compared the traditional and automated traffic enforcement considering the number of crashes and violations. He obtained the speed and the crash data from Queensland Transportation Department and automated and manned enforcement data separately. Results showed that, manned enforcement is more effective in number of crashes, while automated enforcement has a more general deterrence effect.

2.6. Driver Response to Electronic Speed Enforcement

Studies show that people who drive cars through so many different ways and situations may represent same actions (speed variance, driving behavior, and psychological reaction). This means we can generalize or make some strong predictions about these scenarios. The study of Kweon and Kockelman (2006) included usual highway speed choice estimations depend on seat belt use and frequency of drunk driving which combines with age differences of drivers. Shortly; people who under age 50, support seat belt law less than older ones and they prefer higher speed limits while driving. Also drunk drive statistics of younger people showed that they have more unstable speed variance than the other drivers. Effectiveness, limitations and methods of speed enforcement were analyzed in SafetyNet (2009). In this work, they referred new vehicle technologies for more trusty data. Electronic vehicle identification (EVI) can be made part of the enforcement system and support it. When cars are equipped with black boxes, it is possible to enforce speeding at all times and places. In the long term, police enforcement as we know it may be largely replaced by new technological systems of speed control. Elliot (2004) specifically showed how halo effect with distance and duration variable influence the road and the driver. His study showed experimentally the effects of increased stationary enforcement of speed limits seem to last for a limited amount of time after the police presence has been removed. The largest time halo effects appear to be 8 weeks. However, sustained police presence is required to produce such large effects. They had seen the distance halo effects of stationary policing appear to be in the range of 1.5 miles to 5 miles of the enforcement site. Toledo (2003) examined that drivers are assumed to perform short-term plans to accomplish short-term goals. The short-term goal is defined by a target lane, which is the lane the driver perceives as best to be in. A target gap, which the driver intends to use to change lanes, defines the short-term plan. This brings; while driving, people generally make reactions for short-term plans to environmental parameters. Fitzpatrick (2013) explained the effects of roadside elements on driver in his thesis. The results of how strongly roadway environment factors affected people's speed choice are mainly about distraction and reaction time of driver. Also they assumed that parameters like clear zone size and vegetation density effect the driver's behavior.

CHAPTER 3

METHODOLOGY

3.1 Study Framework

To evaluate the use of Bluetooth technology in urban traffic management, we will focus on:

i. Travel time estimation
ii. OD estimation
iii. Evaluation of ESE impact via Bluetooth data

We developed three pilot studies a) in Etlik region b) along ESE corridor on Eskişehir Road and c) along ESE on Mevlana Boulevard. MAC-to-Volume analysis, travel time/speed estimation, OD estimation, determination of speed profiles and travel characteristics and lastly measure the impact of ESE were the main outputs of the pilot studies. We used Bluetooth data and traffic counts as the inputs for the study framework, which is shown in Figure 1. Pilot study regions were chosen as two main urban arterials and one urban area in Ankara city center (Figure 2).

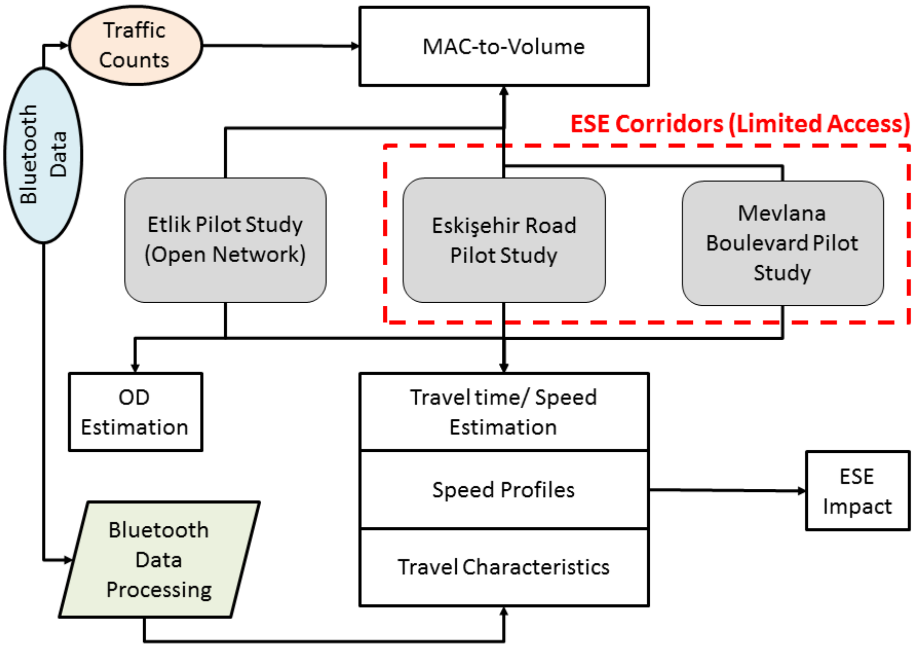

Figure 1 Study Framework

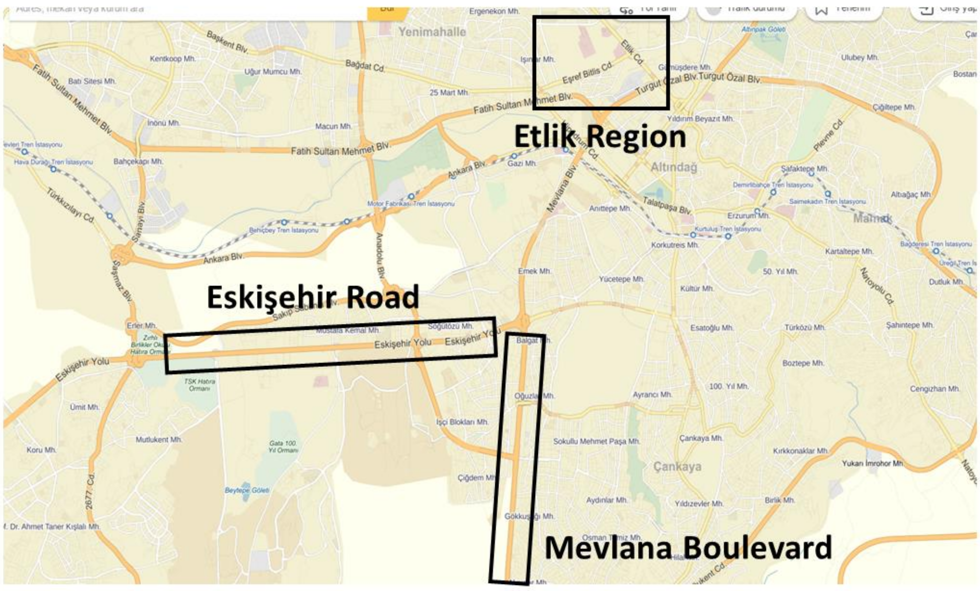

Figure 2 Pilot study locations

3.1.1 Etlik Region Study

In Etlik, an already developed urban region of Ankara, Turkey, construction of an integrated health campus with a capacity of 3500 beds has been proposed. The conceptual design of health complex required the estimation of existing traffic conditions at 10 major intersections and 4 main arterials around the block (see Figure 3). MAC address data from four Bluetooth devices located as shown in Figure 3 were analyzed to estimate travel time and OD matrix between 4 major intersections (J1, J4, J6 and J7) and two urban corridors, (J1-J4) and (J4-J6) with lengths of 1381m and 964 m, respectively, in the study region. Etlik region is an open urban network which includes primary and secondary arterials. This is the main challenge of this pilot study. Since it has many entries and exits (see Figure 4), it is very hard to manage data, make travel time and OD estimation.

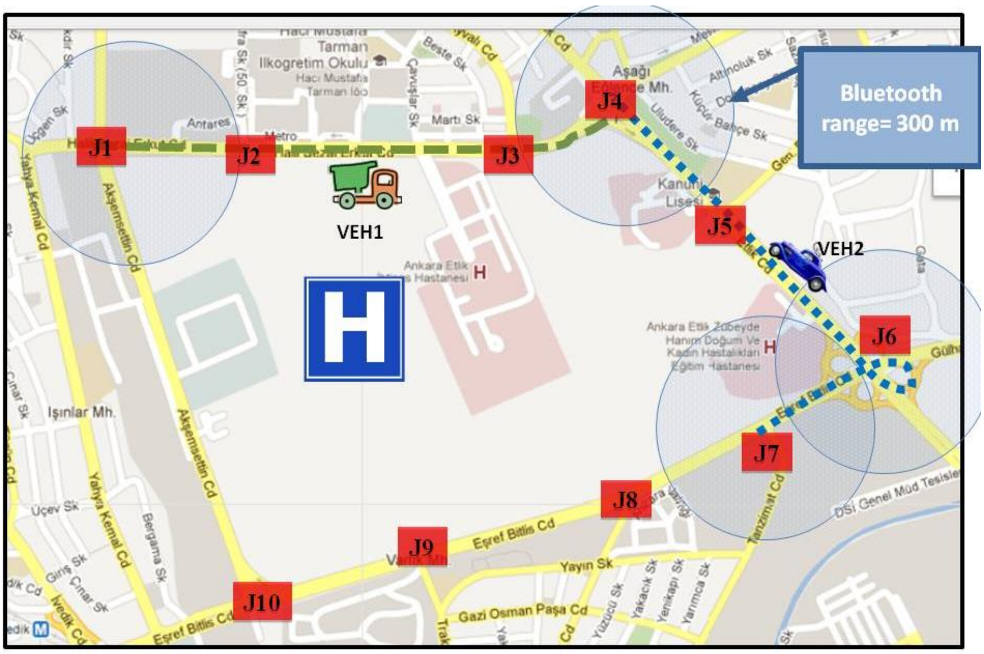

Figure 3 Locations of Bluetooth readers in the study region

Figure 4 Etlik study region and the analyzed corridors

3.1.2 ESE Corridor Studies

Two urban ESE corridors in the City of Ankara were used: Eskişehir Road and Mevlana Boulevard within the scope of ESE corridor studies. Since these corridors are main arterials which connects city center (Kızılay) to Çayyolu, Ulus and the other main districts, there is a huge demand for these corridors and traffic congestion during peak hours (see Figure 5). This situation increases the possibility of catching vehicles having active Bluetooth device.

The main goal of this case study is evaluating the ESE impact on driver behavior. At least two segments before and after ESE application location should be studied to detect the vehicular movements and speed changes along the study corridor. Bluetooth reader locations are shown in Figure 5.

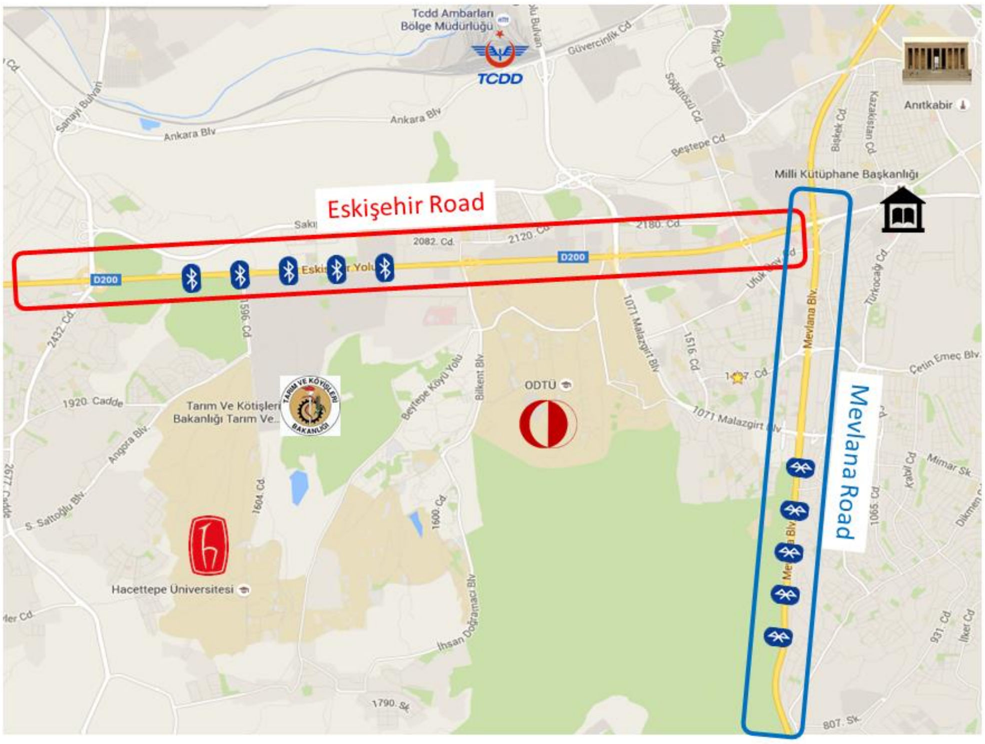

Figure 5 ESE Corridors and Bluetooth reader locations

Eskişehir Road and Mevlana Boulevard, with lengths of 2276 m and 2046 m respectively, were main arterial roads with at least 3-lanes in each direction and separated by a median. Satellite photographs along the study corridors show that they are limited access major arterials with very little and dispersed land use around them (see Figure 6). Each segment between two Bluetooth readers has approximately 500 m length.

a) Eskişehir Road   b) Mevlana Boulevard

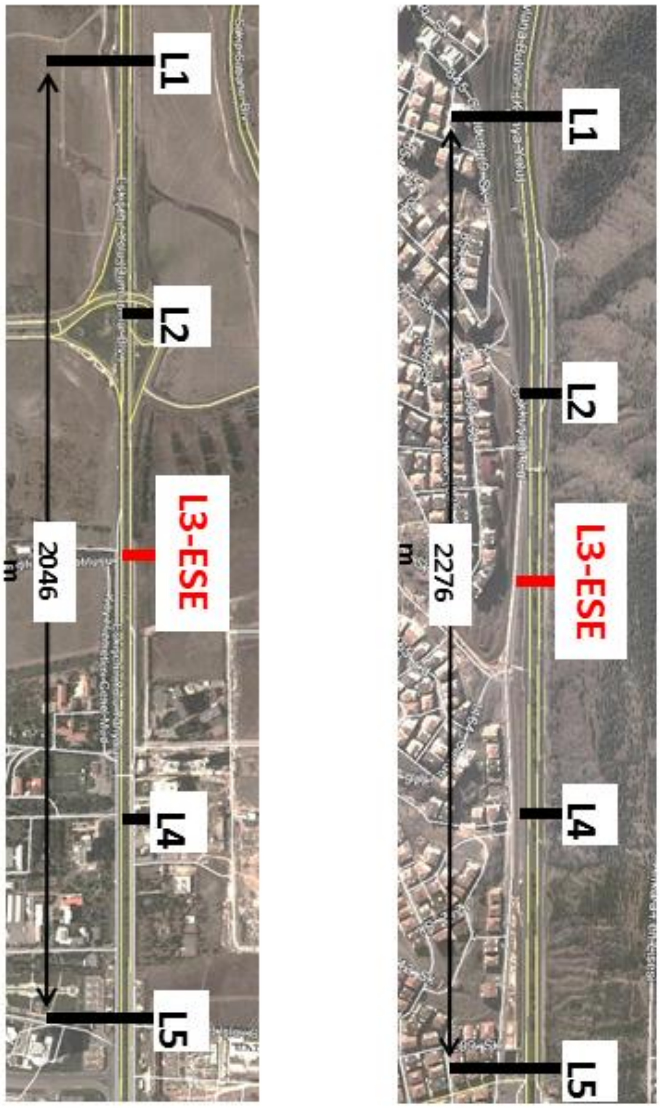

Figure 6 Study corridors: a) Eskisehir Road and b) Mevlana Boulevard

3.2 Bluetooth Data Processing

Due to the use of Bluetooth Technology in traffic applications, it is important to analyze Bluetooth data to eliminate non-vehicular movements, estimate travel time/speed precisely and manage the missing or unexpected data. Regarding the previous studies and presented methods in the literature, data processing steps can be summarized as follows:

i) MAC address matching
ii) Travel time/Speed calculation
iii) Detection of vehicular movements
iv) Determining trips and travel characteristics

The logic behind this methodology bases on use of i) redetection capability of a MAC address at different locations in a study area, and ii) regional travel characteristics (i.e. corridor speed) to distinguish potential vehicular movements from others and iii) travel patterns (travel routes, OD matrix and corridor travel times). The details of this procedure are presented in the next sections.

3.2.1 MAC Address Matching:

It is possible to analyze Bluetooth data gathered from only one single Bluetooth reader or multiple readers. The same device can be scanned multiple times as long as it is within the range of the reader. If a MAC address is observed multiple times within the range of a single Bluetooth reader, we can conduct performance analysis parameters for this reader via MAC matching, such as 'Rescan time' and 'Stay time'. The difference between the two consecutive readings of the same MAC Address is defined as the 'Rescan time'. Multiple readings within the range produce 'stay time' information. Single reader data analysis is not within the scope of this study, but it is important and necessary to analyze Bluetooth performance parameters as a future work.

If there are multiple Bluetooth readers, MAC address matching is used for inter-reader analysis. Use of multiple readers collects data about movements of vehicles/travelers in a network, such as average travel time/speed, trip detection, OD estimation etc. To estimate speed of a vehicle with an active Bluetooth device over a segment or multiple segments, it is necessary to observe the MAC address at two or more readers; however, the active device can be observed multiple times by a reader. Thus, it is important to i) the unique MAC addresses at a reader and then ii) match these recorded addresses across readers.

If a MAC address is read only at one reader, it is not possible to know whether it is from a Bluetooth device on a stationary point or a moving object traveling through the region. Thus, to generate travel information , the same MAC address has to be read at least at two locations within the study zone; for example, MAC address “00:0D:18:A0:0C:68” in Figure 7 was observed at J1 and J4 intersections.

@J1 "2012-04-07 16:22:05","A0:71:A9:42:84:C2","- "2012-04-07 16:22:07","00:0D:18:A0:0C:68","- "2012-04-07 16:22:08","6C:83:36:2E:08:20","- VEH1	**@J4** "2012-04-07 16:24:43","00:E0:0C:57:4B:3D"," "2012-04-07 16:24:43","00:0D:18:A0:0C:68"," "2012-04-07 16:24:49","00:2F:6D:6D:00:66"," VEH1 "2012-04-07 16:23:14","28:D1:AF:4F:F8:A1"," "2012-04-07 16:23:15","00:02:C7:F7:75:B5"," "2012-04-07 16:23:15","78:CA:04:09:C6:8D"," VEH2
@J6 "2012-04-07 16:19:24","60:A4:C1:70:66:12","- "2012-04-07 16:19:26","00:02:C7:F7:75:B5","- "2012-04-07 16:19:28","00:07:80:9B:8C:AB","- VEH2	**@J7** "2012-04-07 16:18:46","3C:8B:FE:4E:FE:1F"," "2012-04-07 16:18:49","00:02:C7:F7:75:B5"," "2012-04-07 16:18:52","04:A8:2A:E6:C8:71"," VEH2

Figure 7 Excerpts of MAC reading data from four readers

3.2.2 Travel Time/ Speed Calculation:

Detection time of the matched MAC addresses can be used to estimate travel times of each vehicle which is equipped with a Bluetooth-enabled device. Travel time for a MAC address matched at two consecutive reader locations is basically calculated by taking difference of detection times. Travel time estimation using Bluetooth data was discussed in Yucel et. al. (2013).

Averaging the vehicular speeds arithmetically, it is possible to get “average travel speed (Time mean speed)” of a vehicle over the segment (Equation 1). However, “space mean speed” is a more meaningful definition in terms of transportation engineering. Space mean speed is calculated as dividing the segment distance by average travel time (Equation 3).

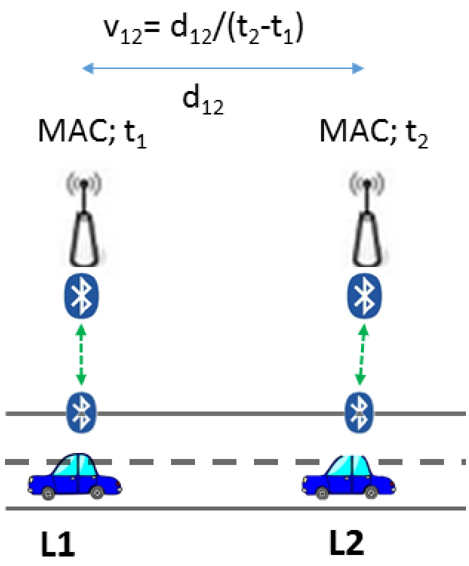

Figure 8 Individual speed definitions for L1-L2 segment

v_{12} in Figure 8 is individual speed of the vehicle which travels between L1 and L2. “Time mean speed” for n vehicles is calculated as follows:

$$\overline{u_t} = \frac{\sum v_{ij}}{n} \tag{1}$$

“Average travel time” and “Space mean speed” are calculated as follows:

$$\Delta t_{avg} = \frac{\sum \Delta t_k}{n} \tag{2}$$

$$\overline{u_s} = \frac{L}{\Delta t_{avg}} = \frac{nxL}{\sum \Delta t_k} \tag{3}$$

If segment length is short and we assume constant travel speeds, “Space mean speed” is equal to “Harmonic mean speed” which is shown in Equation 4.

$$\overline{u_s} = \frac{L}{\Delta t_{avg}} = \frac{nxL}{\sum \Delta t_k} = \frac{n}{\sum \frac{1}{u_k}} \tag{4}$$

As it is possible to determine direction of the vehicle movements by comparing the detection time of the same Bluetooth device, vehicle speeds for both directions can be calculated separately. Since Bluetooth data may include outliers of very low value that may belong to pedestrians, bikes, parked vehicles or detours, it is necessary to eliminate them to get more reliable results. Elimination methods are presented in the next section.

3.2.3 Detection of Vehicular Movements

Observance of a MAC address at consecutive locations reveals a movement. However, in urban locations, the movement of a device with Bluetooth technology can be attributed different occasions (potential pedestrian or bikers with active Bluetooth device) and only some of them will be related to vehicular movements. To distinguish the vehicular ones from the others, the easiest way is to get average corridor travel speeds between consecutive MAC reader locations and used an appropriate lower speed (or an upper travel time) limit to mark vehicular ones. For example, the first example in Figure 3(VEH1) was observed at J1 and J4 with time stamps 16:22:07 and 16:24:43, respectively. Considering the distance of 1381 m between J1 and J4, this suggests a speed of approximately 32 km/hr, which is more likely to happen in a vehicular movement.

To eliminate non-vehicular movements, an appropriate speed limit is needed to filter raw data and distinguish only the vehicular ones instead of intuitive filtering. In addition, we need to manage unexpected Bluetooth data caused range overlapping, reading problems, antenna problems etc. For this situation, it is also necessary to eliminate abnormal high speeds (very short travel times) which is impossible to happen in a vehicular movement. In conclusion, appropriate lower and higher speed limits are both necessary to detect vehicular movements.

There are many statistically approved filtering approaches which are all developed to filter any kind of data and get rid of outliers. Bluetooth data gathered in this study was filtered by using most common filtering approaches given below:

i) Gaussian Filter:

At first, calculated travel time and speed values were filtered statistically by eliminating those 2-standard deviations lower and higher than the segment mean. However, because of the high variation in Bluetooth data, this method was insufficient to eliminate all non-vehicular movements. Chi-Square error calculation was used to evaluate the efficiency of this method.

Secondly, lognormal distribution was chosen instead of normal distribution (Gaussian) because of the absence of the negative values in travel time and speed data. filtered statistically by eliminating those, lower and higher than the segment mean by 2-sigma. Chi-Square error calculation was used to evaluate the efficiency of this method. Although error was much more lower than normal distribution, this method was also not efficient enough to eliminate outliers.

ii) Interquartile Range Filter

Interquartile Range Filter is a common statistical filtering approach which based on eliminating outliers outside the range of median value. Both travel time and speed values were filtered by interquartile range filter. While high travel time values were filtered to eliminate pedestrian/ bike movements or parking cars, high speed values were filtered to eliminate unexpected data including very fast movements.

3.2.4 Determination of Trips and Travel Characteristics

Looking at two consecutive Bluetooth reader data at a time does not always produce the real vehicular trip information in the region; a vehicle may follow a route visiting more than two reader locations, as in the example of the second vehicle (VEH2) in Figure 3.

For urban areas like Etlik Region, to detect the real OD locations of a vehicular trip in the region, it is important to detect route of a vehicle with an active MAC address. To detect a trip, time stamps of a MAC address at consecutive reader locations along the possible route must be checked for continuity: if the speeds between consecutive readings are above the selected threshold, the vehicle can be assumed to have a continuous trip. If the estimated travel times are lower than the threshold, the vehicles must have stopped in between or traveled a longer route, either case suggesting trip chaining within the study zone or with an out-of-study zone destination. Only after this careful check of trip continuity in space and time, it is possible to identify possible start (origin) and end (destination) points of vehicular trips in the region. Eventually, total number of trips with the same OD points is summed up to get the OD Matrix for the locations with Bluetooth readers. The size of the OD matrix also determines the minimum number of Bluetooth readers needed in a study; thus, in OD estimation of highway corridors, it is necessary to locate Bluetooth readers at all on- and off-ramps.

For urban corridors like ESE corridors (Eskişehir Road and Mevlana Boulevard), detecting trips is useful to understand travel characteristics and driver behavior along the corridor. It is possible to track individual vehicles if Bluetooth readers are located at, before and after ESE location. This may reveal if there are drastic changes before or after ESE application. Looking at the segments before the ESE, it may be possible to comment on the "slowing down" behavior of drivers; similarly, speed change over the segments after the ESE may reveal insights on the "beyond enforcement" behavior.

It is possible to see ESE impact along the corridor by two approaches: travel speed profiles and individual speed track along consecutive segments. For travel speed profiles, we calculate space mean speeds along consecutive segments. Space mean speeds for Figure 9 are shown in Equation 5 (L1-L2), Equation 6 (L2-L3) and Equation 7 (L3-L4).

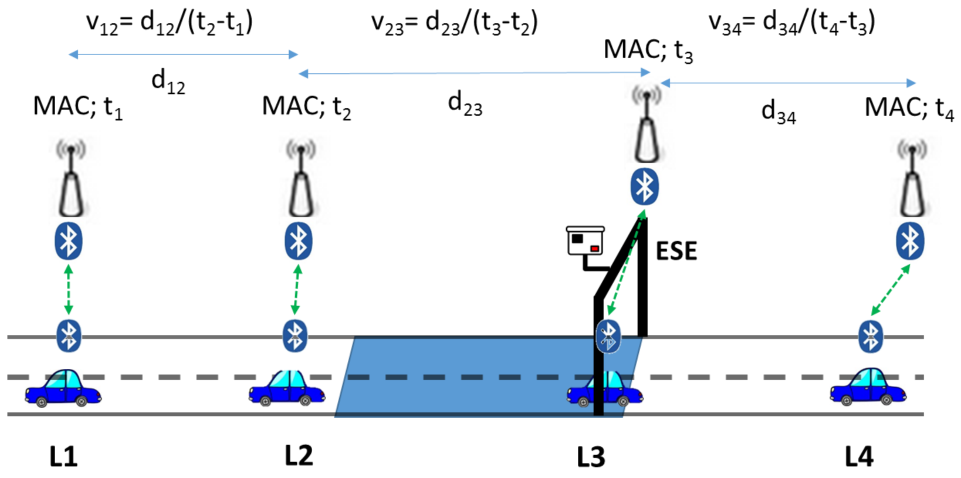

Figure 9 Individual speed definitions for consecutive segments

$$\overline{u_s}^{L1-L2} = \frac{nxd_{12}}{\sum \Delta t_k} = \frac{n}{\sum \frac{1}{v_{12}}} \tag{5}$$

$$\overline{u_s}^{L2-L3} = \frac{nxd_{23}}{\sum \Delta t_k} = \frac{n}{\sum \frac{1}{v_{23}}} \tag{6}$$

$$\overline{u_s}^{L3-L4} = \frac{nxd_{34}}{\sum \Delta t_k} = \frac{n}{\sum \frac{1}{v_{34}}} \tag{7}$$

For speed change profiles, we calculate individual vehicular speeds along consecutive segments. It is possible to define travel patterns as shown in Figure 10. They cover all the possible driver behaviors along the corridor. Each vehicle is tracked via MAC matching and the speed differences between two consecutive segments are calculated. In this way, it is possible to see how many vehicles fit into one of the defined patterns.

	v_{12}		v_{23}		v_{34}	# of patterns
Pattern 1		→		→		n_1
Pattern 2		→		↗		n_2
Pattern 3		→		↘		n_3
Pattern 4		↗		↗		n_4
Pattern 5		↗		→		n_5
Pattern 6		↗		↘		n_6
Pattern 7		↘		→		n_7
Pattern 8		↘		↗		n_8
Pattern 9		↘		↘		n_9

Figure 10 Speed Pattern definitions and the number of trips

3.3 Data Collection Patterns

In this study, Bluetooth data was collected for two different case studies: ‘Etlik Region’ and ‘ESE Corridors: Eskişehir Road and Mevlana Boulevard’. In the first case study, four Bluetooth readers were located in the intersections on two urban corridors in Etlik region. In the second case study, two urban corridors which have ESE application were used to locate the same Bluetooth readers, two before, one at, and one after ESE location. Additionally, traffic videos were recorded at the same reader locations simultaneously.

3.3.1 Etlik Region

Before the Bluetooth observations, traffic counts at 10 intersections around the block with the proposed health campus were taken for two weekdays during morning, noon and evening periods. These studies showed that major in and out flows were observed at J1, J4, J5, J6, J7 and J10. Total travel time around the block was approximately 8 minutes (for 5.5 km), which corresponds to an average speed of 40 km/hr during off-peak periods. As for the non-motorized travel, while there were significant pedestrian activities at the intersections of the study areas, there was limited pedestrian movement between intersections due to long walk distances and lack of pedestrian attraction points in between. There is almost no bicycle use in the City of Ankara.

For Thursday and Saturday evenings, four available Bluetooth reader devices were located in the center of the junctions J1, J4, J6 and J7, to capture the major flows expected between these points. The two major corridors that were studied, (J1-J4) and (J4-J6), and were respectively. These corridors were main arterial roads with at least 3-lanes in each direction and separated by a median.

Bluetooth readers were employed during evening peak hour on both Thursday and Saturday. At the same time, simultaneous traffic videos were recorded at the same locations to get traffic counts. Traffic videos were deciphered to detect different vehicle types: cars, dolmus (a public transit mode with minibuses), minivan/buses, large vehicles such as trucks, tankers, etc.).

3.3.2 ESE corridors

In 2013, enforced speed limits were 70 km/h for private cars and 50 km/h for others in this area (Currently speed limits are 82 km/h for private cars and 60 km/h for others). Therefore, five observation points (ESE application, 500 m and 1000 m before and after the ESE) were chosen as the reader locations, named L1, L2,L3, L4 and L5 as shown in Figure 6 (Elliot, 2004). Because of the availability of only 4 Bluetooth readers, a more dynamic plan was developed to get data for these 5-reader measurement plan; for a 2-hour observation period, three of them were located on ESE location, 500 m before and after permanently; the remaining one was located 1000 m before the ESE location for an hour and 1000 m after the ESE location for the next hour. Bluetooth readers recorded reader ID, MAC address, time stamp and signal strength information of the captured device together for the duration of the observation.

The technology that they use is fixed traffic cameras located on the top of the roads. Bluetooth readers were employed during two-hour off-peak noon and afternoon (11:00-13:00 and 16:00-18:00 on Tuesday; 12:00-14:00 and 17:00-19:00 on Wednesday) periods to eliminate the peak-hour factors. Data collection process was repeated on the next day to handle with the missing data.

Most popular headset models and vendors discovered in ESE corridors case study (for three days) are given in Appendix F.

3.4 Bluetooth Reader Device

All the devices were Class 1 type Bluetooth sensors (UD 100) from Sena Technologies, Inc., and were accessorized with stub antenna (see Figure 11) providing an approximately 300 meters range (see Figure 3). This reading range was appropriate to capture vehicle movements on roads in the study regions where curb-to-curb widths and even at the grade-separated interchange laid out in an area of approximately 400mx300m.

Figure 11 Class 1 type Bluetooth reader device with antenna (range 300m) used in the Etlik and ESE corridors case studies

CHAPTER 4

CASE STUDIES

4.1 Travel Time estimation in Etlik Region

Before applying the methodology explained in Chapter 3, it is useful to answer the question ‘How many of the vehicles have active Bluetooth device?’. To have an idea of the sampling capability with Bluetooth technology, it is helpful to see the MAC-to-volume ratios (unique MAC address number divided by traffic count) at the observation points. During the 90-minute observation period, traffic counts and MAC address detections were studied to generate MAC-to-Volume ratios as done by Blogg et. al. (2010). For Saturday, 5 minute was used as the time interval. As expected, the high traffic counts at J6 resulted in also higher MAC detections, with a MAC-to-Volume ratio of 9.9%. This ratio is close to those observed at J4 and J7. There were slightly more MAC addresses detected at J1 with an MAC-to-Volume ratio of 14.4%. These rates are not much different than reported penetration rates in other studies (Blogg et. al., 2010).

For Thursday, because of the lack of traffic counts, 15 minute was used as the time interval. As the opposite of Saturday results, J6 had the lowest MAC-to-Volume ratio of 3.2% and 8% of the vehicles had active Bluetooth device in J1. There were slightly more MAC addresses detected at J4 with an MAC-to-Volume ratio of 8.7%.

MAC-to-volume ratio graphs for Thursday and Saturday are given in Appendix A.

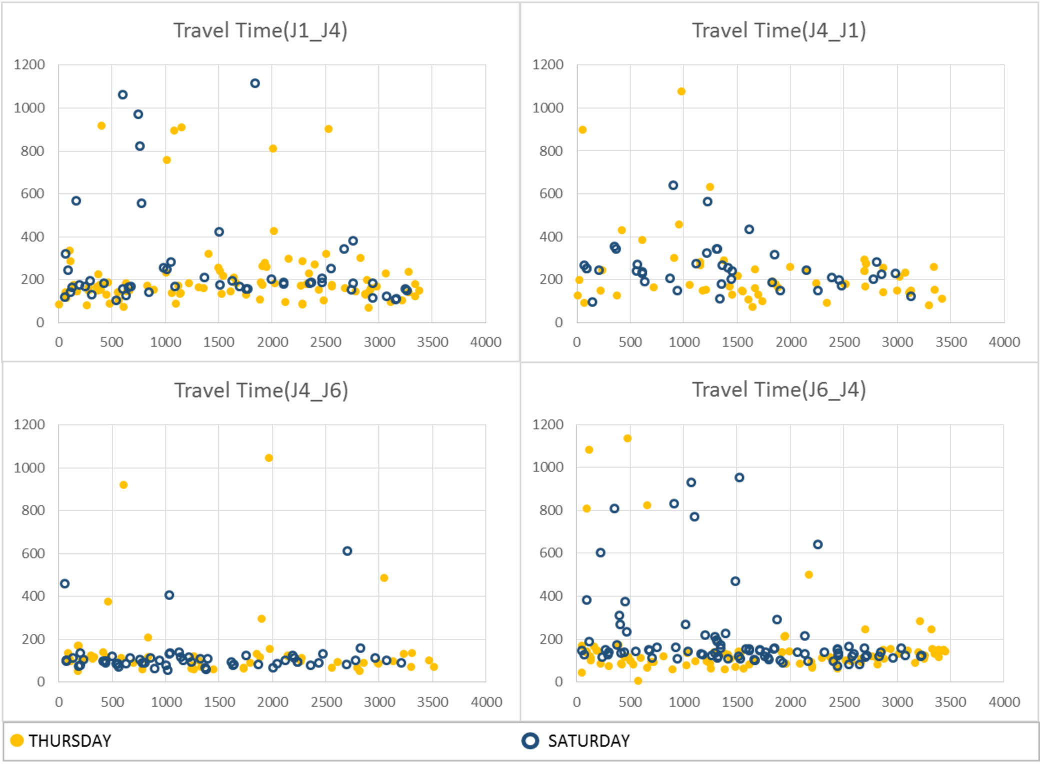

Figure 12 Travel time distributions on Thursday and Saturday for the analysis corridors between J1 and J4, and J4 and J6

As the lengths of the two corridors are rather short, most of the travel times were less than 300 seconds (5 minutes). The average travel times along (J4->J6) and (J6->J4) directions were found as 97 and 144 seconds for Saturday, and 103 and 118 seconds for Thursday. For weekend (Saturday), considering the 964m corridor length, this corresponds to the space mean speed of 35 and 24 km/hr. Similarly, space mean speed of (J1->J4) and (J4->J1) segments were calculated as 28 and 20 km/hr. Vehicle speeds in weekday were higher than weekend as an unexpected result. For Thursday, average space mean speed of (J4->J6) and (J6->J4) directions were found as 34 and 30 km/hr. Similarly, space mean speed of (J1->J4) and (J4->J1) segments were calculated as 31 and 25 km/hr.

Travel time histogram graphs with lognomal curve fitting for Thursday and Saturday for both directions of each corridor is given in Appendix B. Therefore, travel time values were sorted out increasingly after data cleanup. The generated graphs showed that after data cleanup (Chapter 3), approximately 15% of the data was evaluated as outliers and eliminated. Sorted travel time graphs are given in Figure B.2.

At last but not least, to estimate OD matrix, trip detection in the methodology presented in Chapter 3 was applied to Etlik data. Considering the 8 minutes travel time to drive around the block, a conservative upper limit of 5-minute travel time is accepted to identify potential moving vehicles along study corridors. The 5-minute threshold corresponds to minimum vehicular speed limits of 16.5 km/hr and 11.5 km/hr for the J1-J4 and J4-J6 corridors. The appropriateness of the 5-minute (300 seconds) threshold value can be verified by analyzing the travel times of all the selected movements between the reader locations as shown in Figure B.2. In the percentile graphs, vertical axis shows the travel time of the captured movements in seconds and horizontal axis shows percentage. The graphs show that 75-80% of the movements on (J1-J4) and (J4-J6) corridors took much less than 5 minutes for weekend and weekday.

Travel times larger than this were regarded as out-of-region trips between the locations or non-motorized trips; and were eliminated from the OD estimation. The remaining MAC address matchings were reviewed manually to seek trip continuity to get the routes of the vehicles with active Bluetooth. For Saturday, a total of 444 vehicle trips were identified; 394 of them were indicating travel between two reading points, and only 50 of them traveled through 3 reading points, and none were capture traveling all four station points. For Thursday, a total of 589 vehicle trips were identified; majority of the movements were between J1-J4) and (J4-J6) corridors, as expected. The estimated OD matrices are presented in Table B.1 in Appendix B.

4.2 Evaluation of ESE Impact

As stated in Section 4.1, it is important to know MAC-to-Volume ratios before starting to apply data processing steps. During the ESE Corridors case study, total number of 4338 unique MAC addresses were captured in the first day, while 5520 unique MAC addresses were captured in the next day. Unique MAC address counts and traffic counts were used to calculate MAC-to-Volume ratios for each location. Results show that, MAC-to-Volume ratios are approximately 8-12% and they are very close each other. This is an expected result, because study region is urban corridors with less entry and exit points, not an open network like Etlik region. As an example, MAC-to-Volume ratios of Eskişehir Road are given in Appendix A.

To evaluate driver behavior along the segments on ESE corridors, travel time and speeds were calculated and the outliers were eliminated via data cleanup. Results show that, a majority of vehicles had less than 50 seconds travel time in Eskişehir Road, while it was 40 seconds in Mevlana Boulevard. Another important result is that vehicles getting closer to ESE application point had higher travel times than they had after ESE. Travel time distributions of ESE corridors for both directions and each segment are presented on in Appendix C (Eskişehir Road) and Appendix D (Mevlana Boulevard).

Since this case study includes ESE corridors, it is more meaningful to evaluate speed results rather than travel time values. From the viewpoint of Traffic Engineering, space mean speed is commonly used in various traffic studies and it is more meaningful to evaluate driver speed behavior along the corridor. Since segment lengths are short, we can use harmonic mean speed as space mean speed. For this reason, harmonic mean speeds were obtained as discussed in Chapter 3 and displayed in Figure 13 (first day) and Figure 14 (second day). Figure 13 and the first half of Figure 14 shows the change of segment mean values over the ESE study corridors. The numbers supported the common expectation of sudden slow-downs (almost in the first 500 m before the ESE) to obey the speed limits, which are mostly increased suddenly after the ESE. Similar behavior is observed on both Eskişehir and Mevlana corridors.

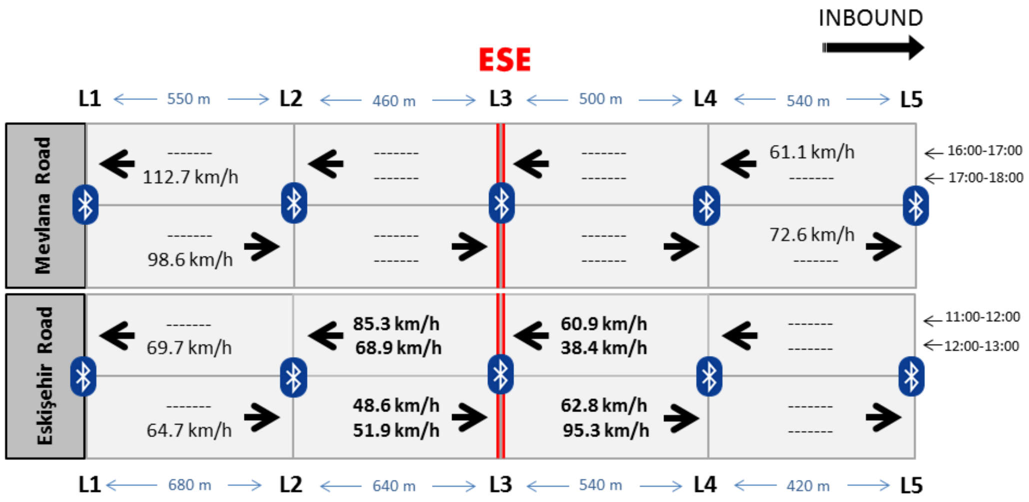

Figure 13 Harmonic mean speeds of each segment on ESE Corridor (2.7.13)

To give more insights, speed distribution at the two segments right before and after the ESE location (L3) on Eskişehir Road are provided in the second half of the Figure 14. This graph suggests that vehicles flow at almost similar speeds with small variations before an ESE but display a more dispersed pattern right after it. This may be due to the fact that some aggressive drivers temporarily slow down right before an ESE but speed up right after as opposed to those which follow a more uniform speed through an ESE point. The rest part of segment speed profiles is given in Appendix E.

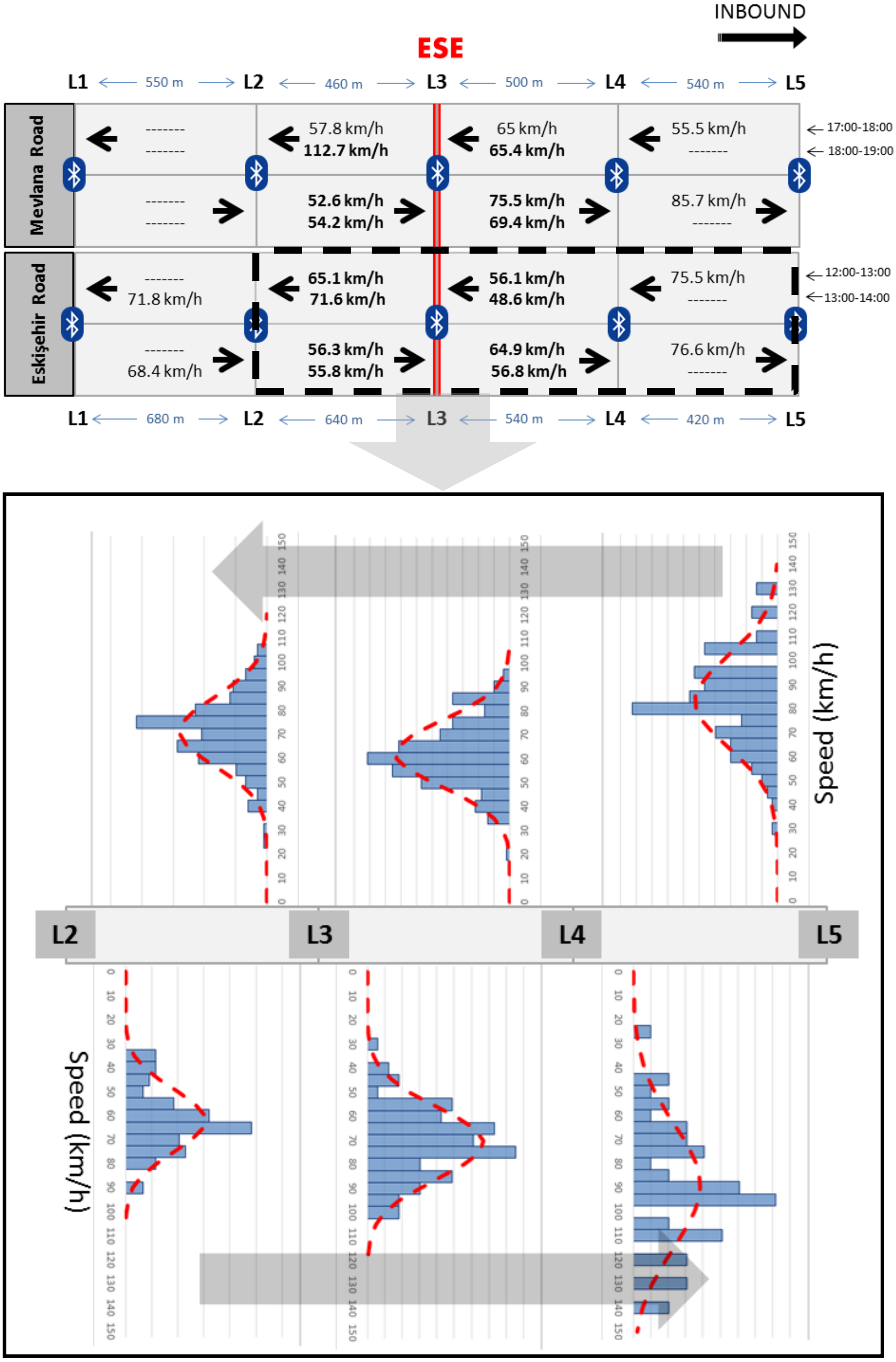

Figure 14 Harmonic mean speeds of each segment on ESE Corridors (3.7.13) and segment profiles for Eskişehir Road

The last evaluation was about individual vehicle movements along the ESE corridors. It is possible to track each vehicle which has Bluetooth enabled device as discussed in the methodology in Chapter 3. 9 patterns were defined to describe all the possible driver behaviors along the corridor. Then, each vehicle was tracked via MAC matching and the speed differences between two consecutive segments were calculated. In this way, it is possible to see which pattern fits into the tracked driver behavior.

Results show that, a big majority of drivers preferred Pattern 7-8-9, which include decreasing speed before ESE location. 30 of them followed Pattern 7 and 20 of them followed Pattern 9, while 36 of them prefer to increase their speeds right after ESE location (Pattern 8). Speed patterns and individual average travel speed graphs are given in Figure 15-16-17.

	v_{12} or v_{54}		v_{23} or v_{43}		v_{34} or v_{32}	from L1 to L5	from L5 to L1
Pattern 1		→		→		3	0
Pattern 2		→		↗		0	1
Pattern 3		→		↘		3	4
Pattern 4		↗		↗		0	0
Pattern 5		↗		→		1	0
Pattern 6		↗		↘		7	3
Pattern 7		↘		→		**17**	**13**
Pattern 8		↘		↗		**12**	**24**
Pattern 9		↘		↘		**13**	**7**

Figure 15 Average travel speeds of the trips which follow most popular patterns (Pattern 7-8-9)

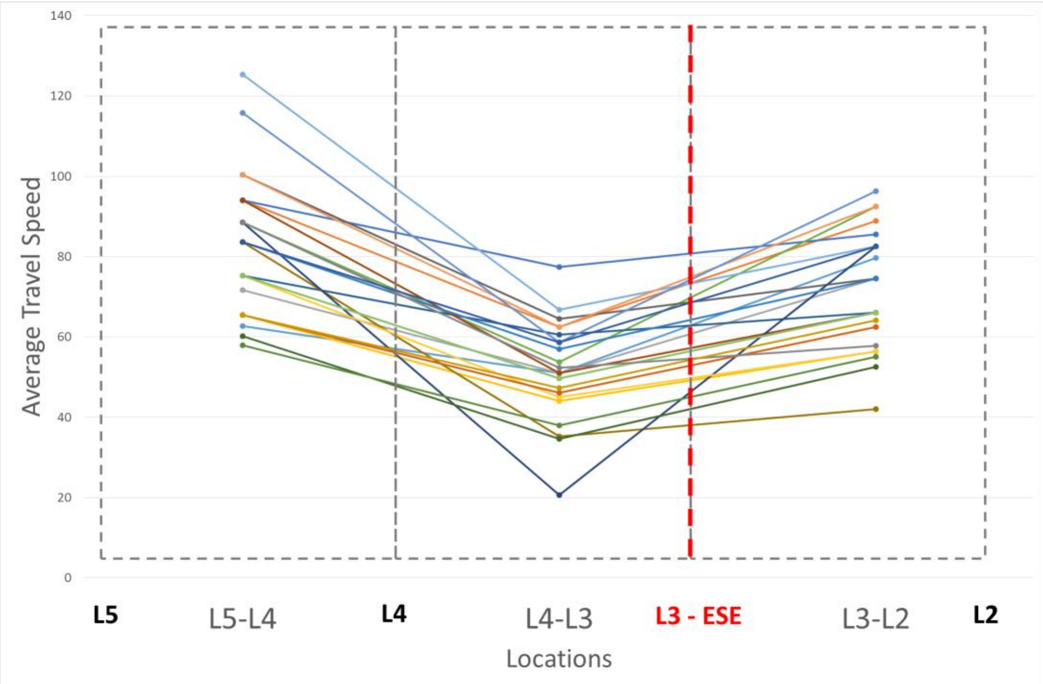

Figure 16 Average travel speeds of the trips which follow Pattern 7-8-9 (From L5 to L1)

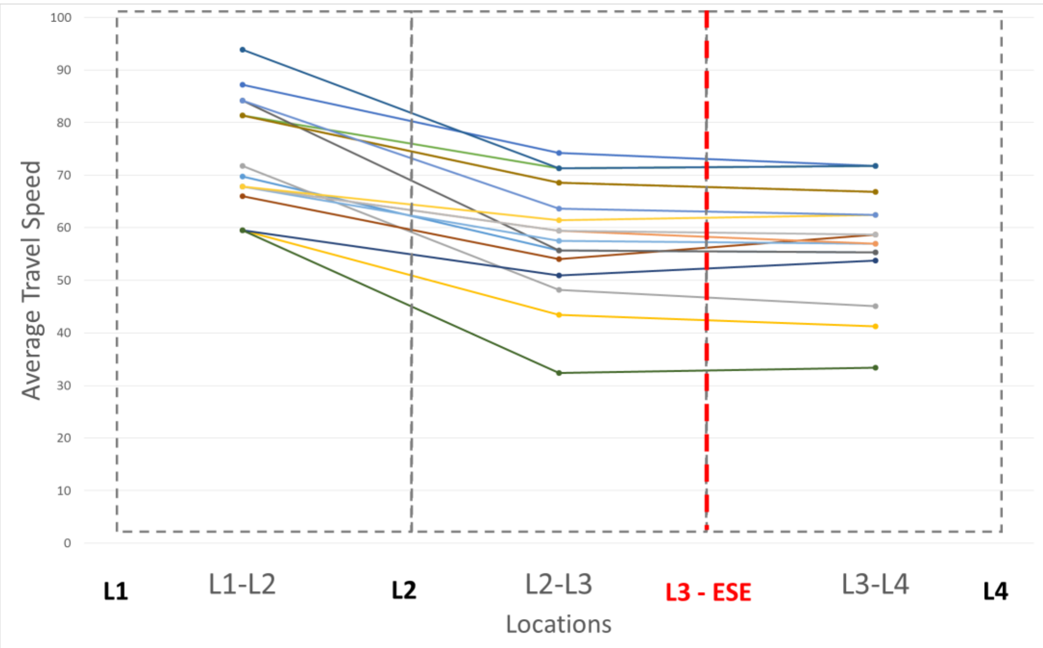

Figure 17 Average travel speeds of the trips which follow Pattern 7-8-9 (From L1 to L4)

CHAPTER 5

CONCLUSIONS AND FURTHER RECOMMENDATIONS

The main challenge of using Bluetooth in this study was using it to study an urban traffic region, which is an open-system. Here, “open system” refers to traffic network where all the possible traffic entry and exit points (streets, parking lot entrances, etc.) could not be surveyed. As a result the total entry and exit flows within the system do not necessarily match and could not be verified. This would reflect on the Bluetooth readings such that all detected MAC addresses would not be utilized to estimate travel patterns. Secondly, in an urban region all matched trips would not necessarily be vehicular ones; thus, a filtering approach has to be included in the methodology to the vehicular ones.

5.1 Overview of Etlik Region Study

In the Etlik region, traffic flows on two arterials, one serving north-south direction while the other serving east-west direction, were observed via sampled vehicular movements equipped with GPS. While most of the results are same for weekend and weekday, there are also some different results. For example; on Saturday, the major arterial served a heavy demand from the northern part of the study region destined to the city center in the south. However, for Thursday the major flow was on the arterial which connects the east part of the region to the west. The travel times of observed vehicles were mostly within a narrow range, which excluded very slow movements –or stop-and-go situations within the corridors. The characteristics of flows on opposite directions were also visible in the average corridor speed values and speed distributions, which proved the appropriateness of the use of Bluetooth data for urban travel time measurement.

Even though it was possible to calculate average speed of a vehicle over an arterial corridor, detection of travel time enabled the estimation of space mean speed for the corridors, which is more often needed in traffic studies.

5.2 Overview of the ESE Study

This study showed the potential of a Bluetooth-based methodology to evaluate the impact of ESE. Although the Bluetooth data is a sample of the total flows on the corridor, it was possible to observe main trends in the traffic behavior via Bluetooth based data. Also, since the vehicles are not directly identified, this methodology does not violate privacy rights, and Bluetooth Technology is a cheap and timesaving alternative for traffic related studies. Such monitoring systems should be implemented to evaluate ESE impacts at low costs. However, it is important to create further level data processing to understand the Bluetooth activation (whether multiple active Bluetooth device in the vehicle, etc.) to shed light on the randomness of the Bluetooth-based sampling. It is also more informative if the MAC-to-volume ratios calculated to have an idea of the sampling ratio. Considering the increasingly use of this technology, this method may provide more significant results. The Bluetooth data collection plan is important in the reliability of the assessments; if the segments are taken too long, calculated average travel speeds may not reflect the slowing down or speeding up segments properly. Missing Bluetooth data, unexpected mean speed values, limited number of Bluetooth readers may be considered as the major shortcomings of the study. To deal with these shortcomings and limitations, more complicated filtering techniques, verification with supportive data collection techniques like probe vehicle and GPS should be applied. Moreover, the use of Bluetooth technology in speed estimation should be studied in detail and the ways of getting more reliable speed results should be discussed.

Plotting the segment-wise speed distributions, it is possible to see the change in the mean and standard deviation values over the segment. This may reveal if there are drastic changes before or after ESE application. Looking at the segments before the ESE, it may be possible to comment on the “slowing down” behavior of drivers; similarly, speed change over the segments after the ESE may reveal insights on the “beyond enforcement” behavior. These patterns may be compared to those that would be obtained from a “corridor enforcement”, if available. However, the real effect of ESE systems should be certainly interpreted by traffic safety experts. Randomness and sampling ratio issues should be also considered during the impact evaluation process, since non-random data or low sampling ratio directly affects the reliability of the results.

5.3 Bluetooth Data Quality in Ankara

Travel time estimation is more efficient limited access corridors, because there are not so much entries and exits. However, open networks like Etlik are more challenging and require more Bluetooth readers to catch vehicle movements. However, installing lot of Bluetooth reader is not an economical approach. Before a city level macro implementation, it is very important to design Bluetooth reader locations and warn drivers to enable their Bluetooth devices when they arrive a major entry or exit point.

To summarize, the strength of this method is the tracking capability of a movement including Bluetooth device over time and space. In uncongested traffic conditions, looking at the corridor speeds, moving vehicles can be distinguished from the others. However, filtering based on a simple corridor speed (or travel time) value may not be correct for peak hours. Instead, time-dependent speed thresholds can be selected to represent traffic regime during different periods. A key issue is the sampling ratio of vehicles using Bluetooth based estimations; this depends on the penetration ratio of Bluetooth technology in a region. Sampling ratio is around 10% in this study, this ratio is enough for travel time estimation, but not enough for OD estimation. If more vehicles are accessorized with Bluetooth devices, more reliable travel data can be generated. On the other hand, a potential problem is having multiple Bluetooth devices active in one vehicle: while this may not be a high probability in single-occupant vehicles, it can be critical in high-occupancy ones, such as transit buses, shuttles, etc. Both cases would harm estimation of OD matrices, but not corridor travel times. This can constitute a bigger problem in the future, when the use of Bluetooth devices in the vehicles and by the travelers increases drastically. It is important to create further level data processing to understand the Bluetooth activation (whether multiple active Bluetooth device in the vehicle, etc.) to shed light on the randomness of the Bluetooth-based sampling. Although it is possible to get an estimate of the OD matrix between reader locations, it is hard to know the reliability of the data without any other supportive data.

5.4 Future Reccommendations

Despite all shortcomings, Bluetooth technology certainly presents an alternative and relatively easy-and-cheap way of travel study, even for an urban region. For large area applications, such as travel time monitoring for all the main arterials in a city, trip detection step of the Bluetooth data processing must be automated to handle complex traffic networks. Layout of the Bluetooth readers over the network must be designed with care, which would capture corridors carrying major traffic flows reliability. This requires equipping of the critical intersections along the main urban corridors via readers. However, traffic monitoring via Bluetooth data should be verified with another traffic data source, such as Floating Car Data (FCD) to test the reliability of Bluetooth data. Idealistically, all these data from different sourcers have to be fused by a central control unit, such as urban traffic management authority, which would not only monitor the traffic but also start broadcasting real-time traffic status to the drivers.

From the techonological point of view, to understand the efficiency and usability of Bluetooth technology in traffic studies, it is necessary to perform more detailed analysis, such as rescan time and stay time analysis. Detection of vehicles with active Bluetooth devices at different operating speeds and road widths should be analyzed carefully with an interdisciplinary team including electrics and electronics engineers and traffic engineers.

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APPENDIX A

MAC-TO-VOLUME RATES

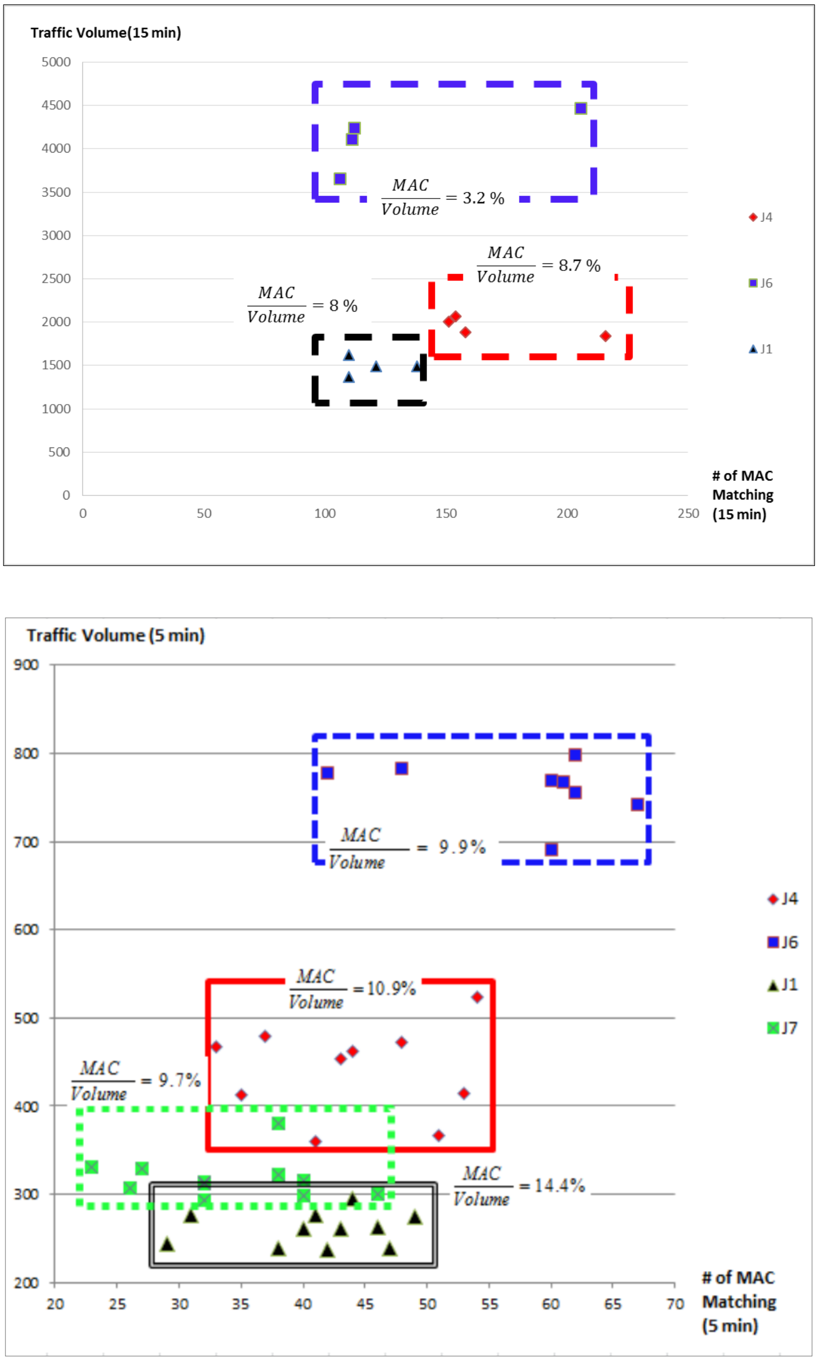
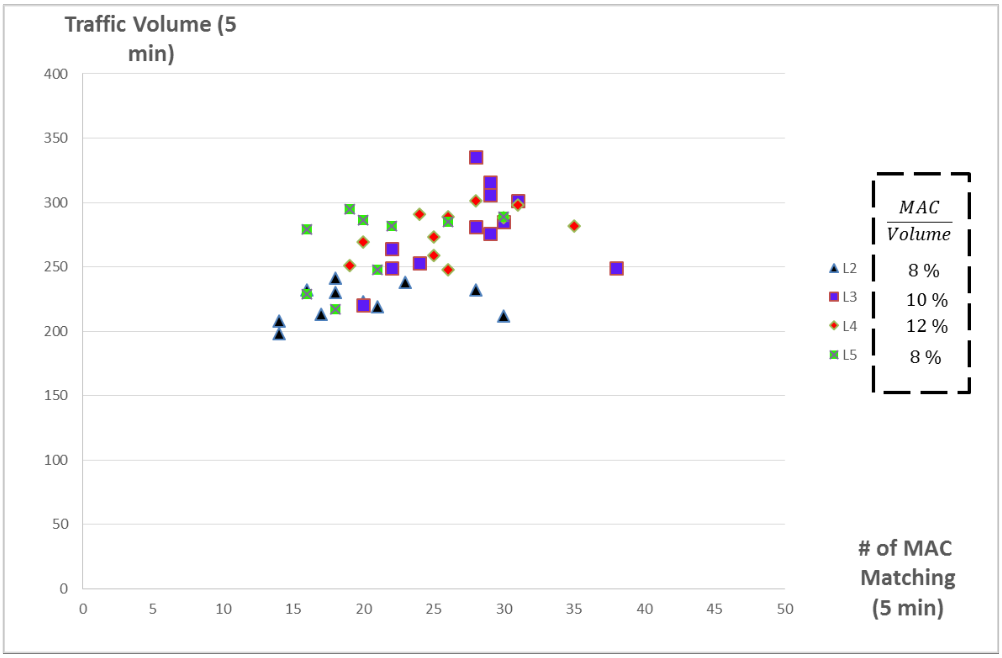


Figure A.1 MAC-to-Volume rates at the four junctions in Etlik Region (Above: Thursday, Below: Saturday)



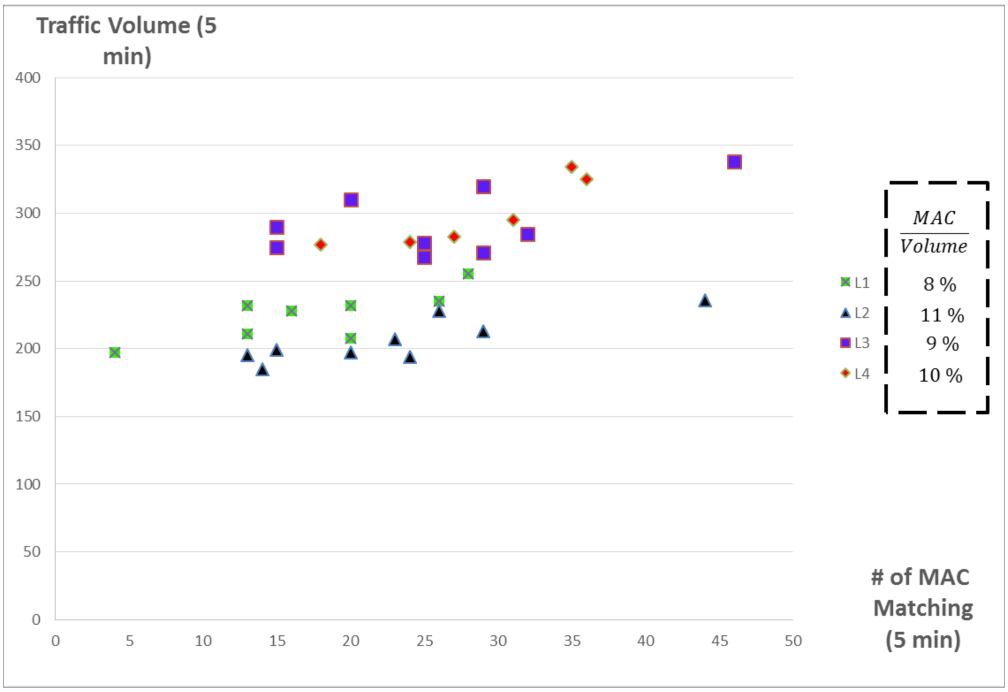


Figure A.2 MAC-to-Volume rates at Eskişehir Road Above: 12:00-13:00, Below: 13:00-14:00)

APPENDIX B

ETLIK STUDY RESULTS

B.1 OD ESTIMATION RESULTS FOR ETLIK REGION

Table B.1 Estimated OD matrix and Percent Distribution at Origins for Etlik Study

OD (by counts) - Saturday						**OD (by percent distribution at the origin)**					
O\D	**J1**	**J4**	**J6**	**J7**	Row sum	**O\D**	**J1**	**J4**	**J6**	**J7**	Row sum
J1		44	15	7	66	**J1**		**67**	23	11	100
J4	35		63	8	106	**J4**	33		**59**	8	100
J6	21	69		91	181	**J6**	12	38		**50**	100
J7	6	19	66		91	**J7**	7	21	**73**		100
Column sum	**62**	**132**	**144**	**106**	**444**						

OD (by counts) - Thursday						**OD (by percent distribution at the origin)**					
O\D	**J1**	**J4**	**J6**	**J7**	Row sum	**O\D**	**J1**	**J4**	**J6**	**J7**	Row sum
J1		101	17	4	122	**J1**		**83**	14	3	100
J4	72		59	12	143	**J4**	**50**		41	8	100
J6	15	79		110	204	**J6**	7	39		**54**	100
J7	3	35	82		120	**J7**	3	29	**68**		100
Column sum	**90**	**215**	**158**	**126**	**589**						

B.2 TRAVEL TIME EVALUATIONS FOR ETLIK REGION

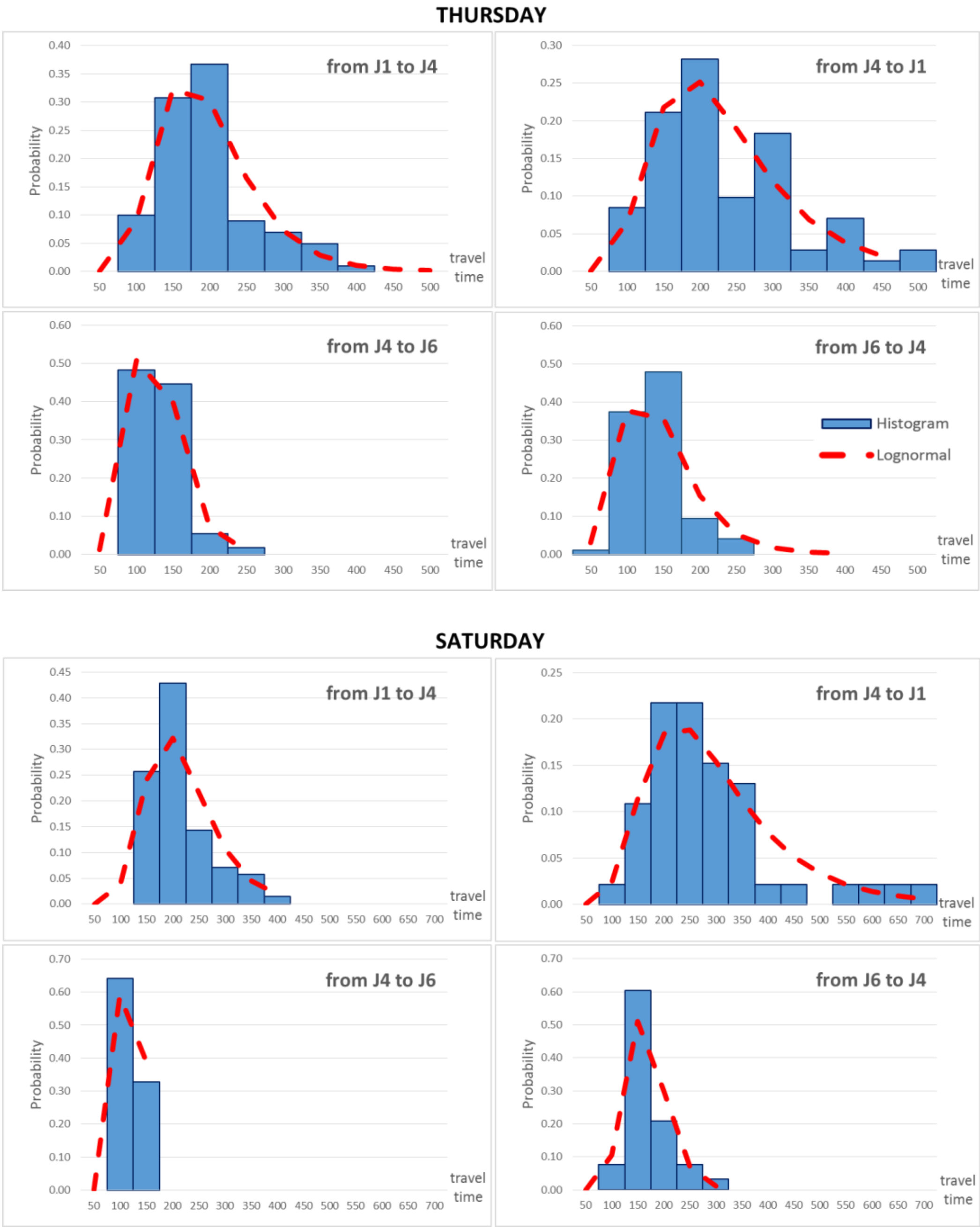
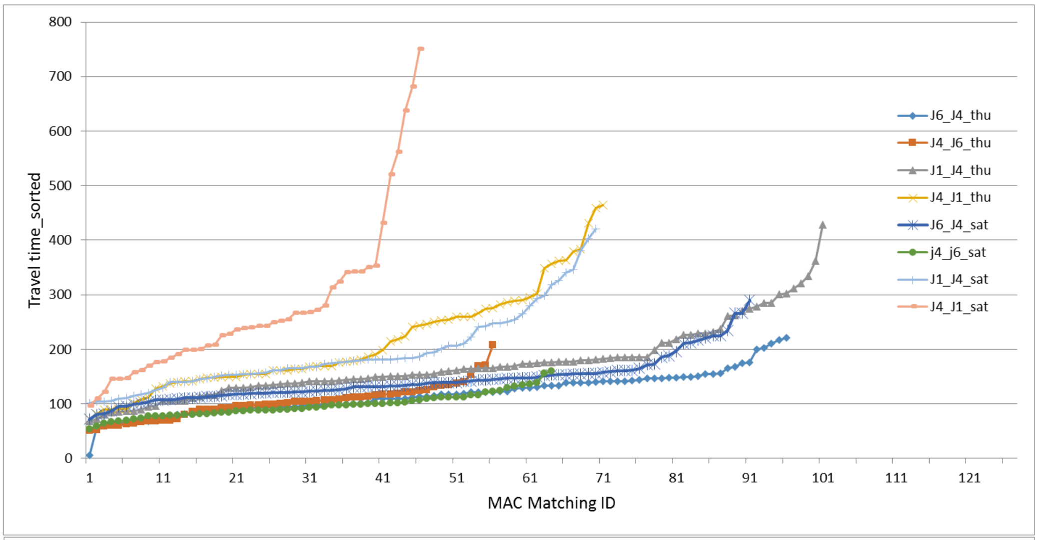
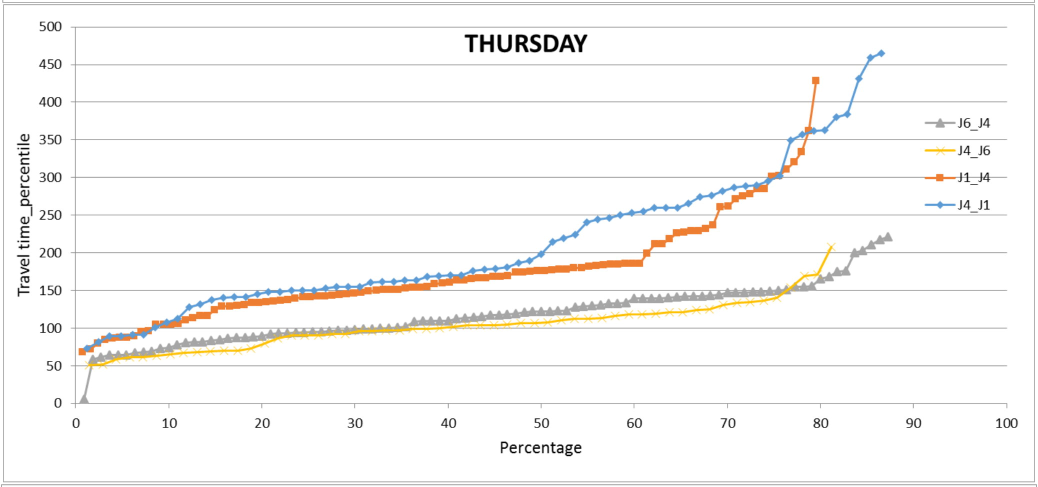


Figure B.1 Travel time histogram graphs and Lognormal curve fitting for Etlik Region





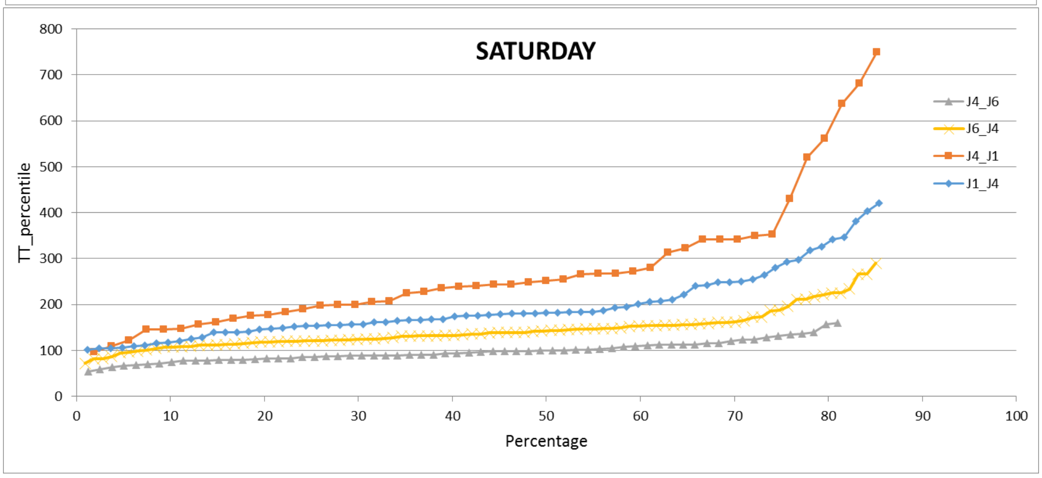


Figure B.2 Sorted travel time results for Etlik Region

APPENDIX C

RESULTS OF ESE CORRIDOR ON ESKİŞEHİR ROAD

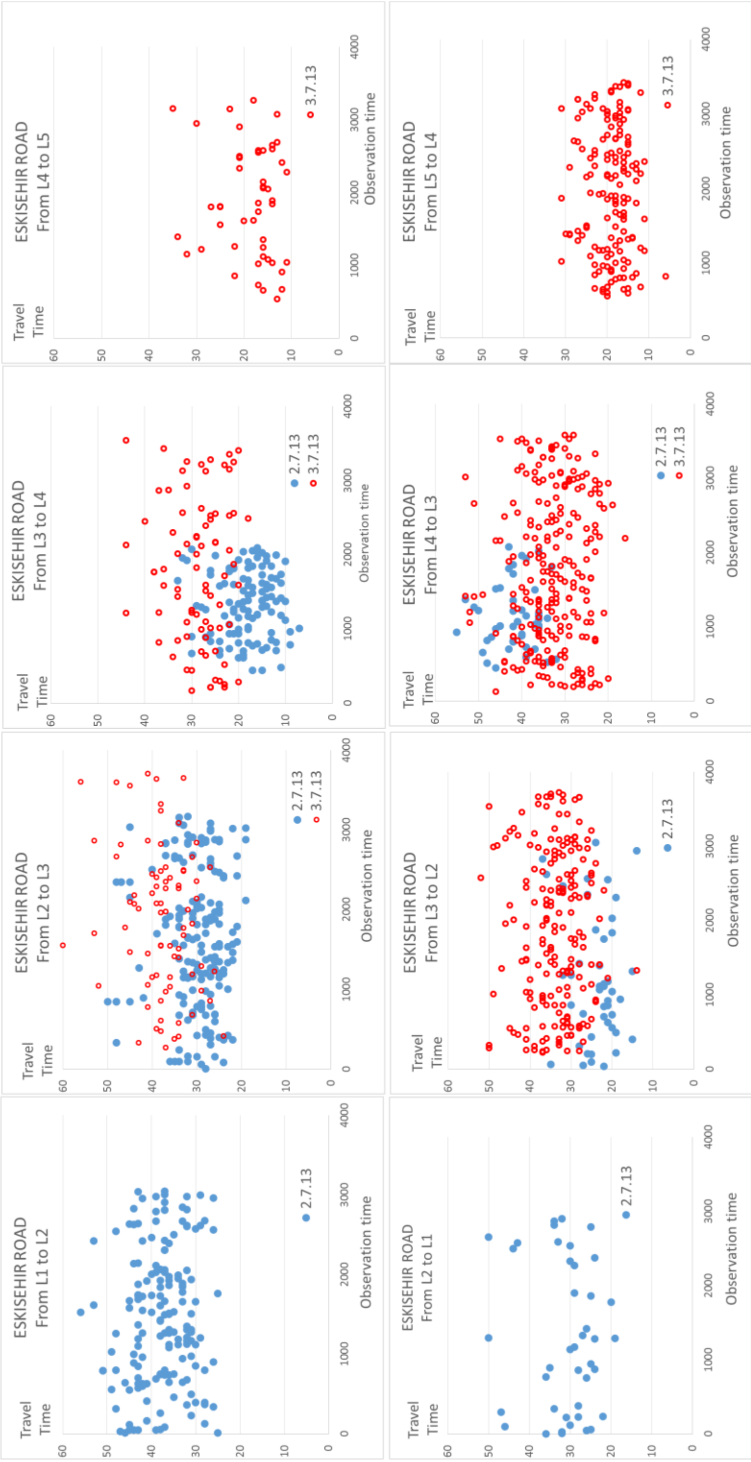


Figure C.1 Travel time distributions for Eskişehir Road

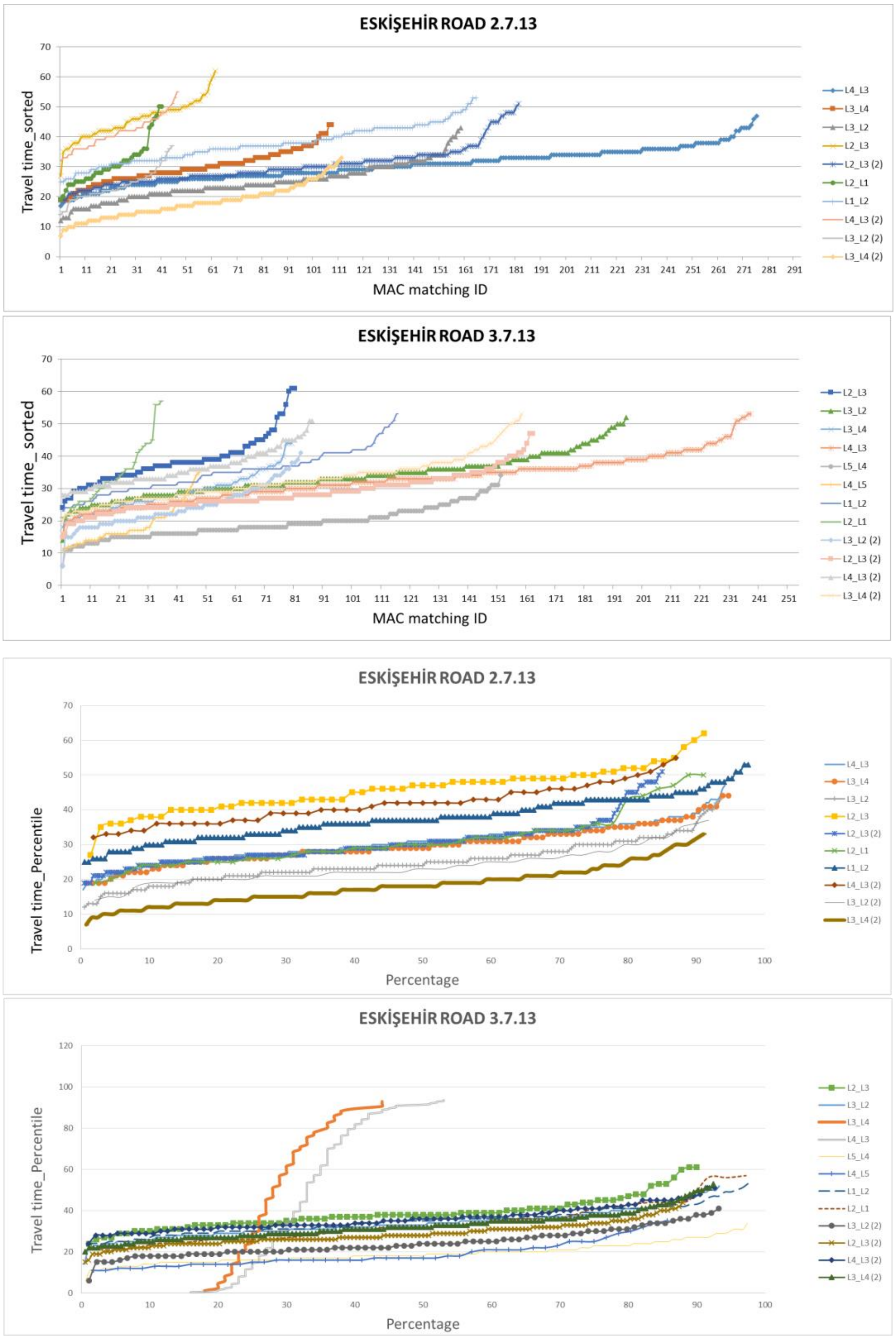


Figure C.2 Travel time results for Eskişehir Road

APPENDIX D

RESULTS OF ESE CORRIDOR ON MEVLANA BOULEVARD

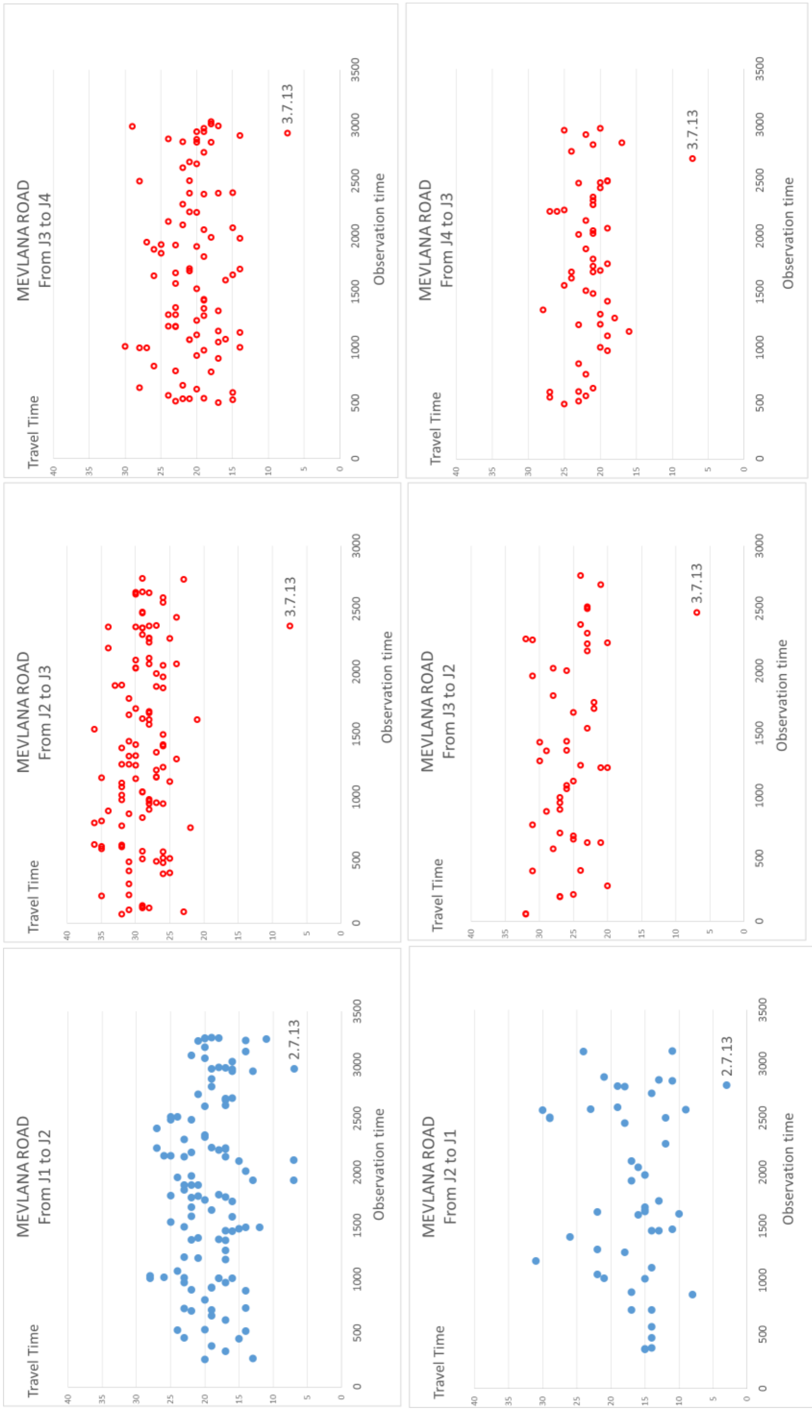


Figure D.1 Travel time distributions for Mevlana Boulevard

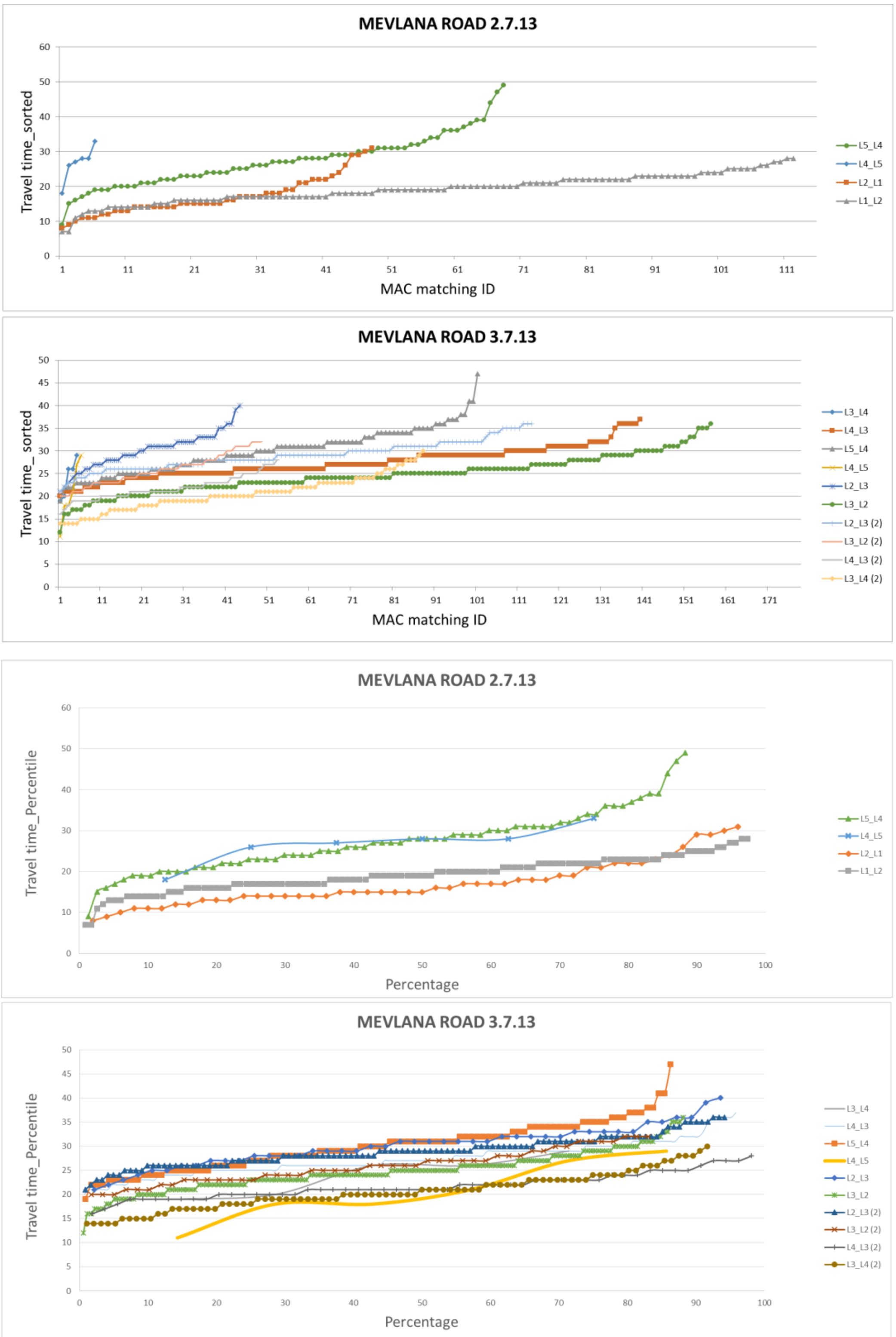


Figure D.2 Travel time results for Mevlana Boulevard

APPENDIX E

SPEED PROFILES FOR ESE CORRIDORS

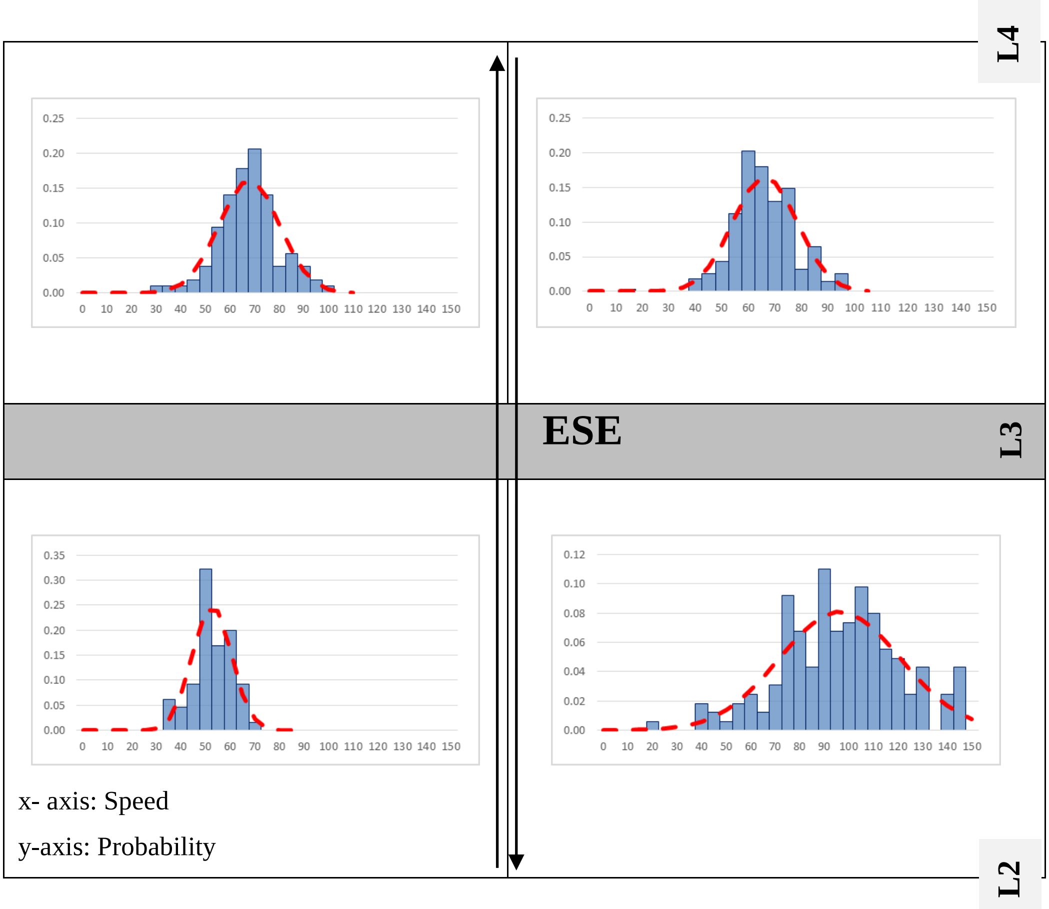


Figure E.1 Segment Profiles for Eskişehir Road in ESE Study - 2.7.13/ 11:00-12:00

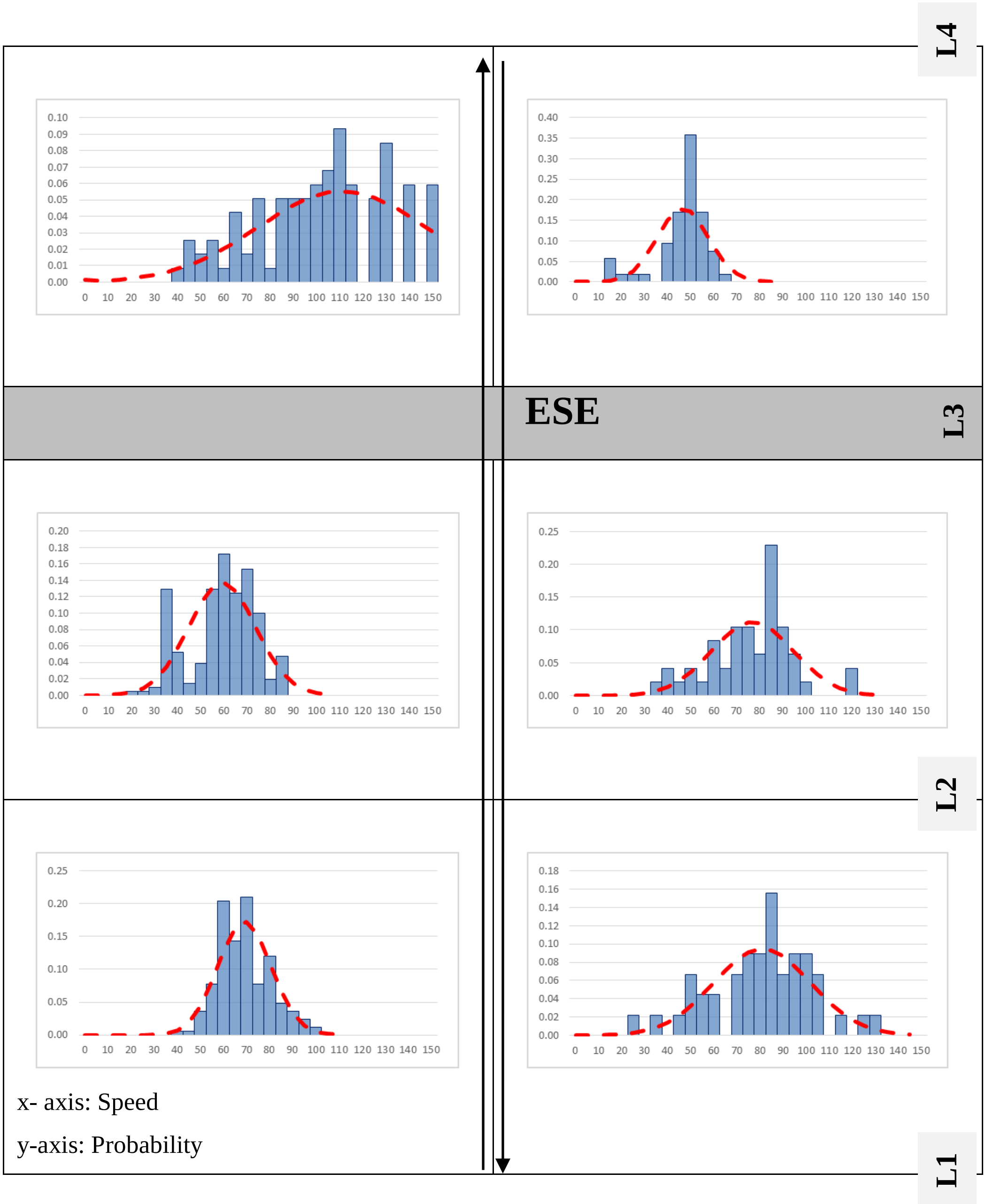


Figure E.2 Segment Profiles for Eskişehir Road in ESE Study - 2.7.13/ 12:00-13:00

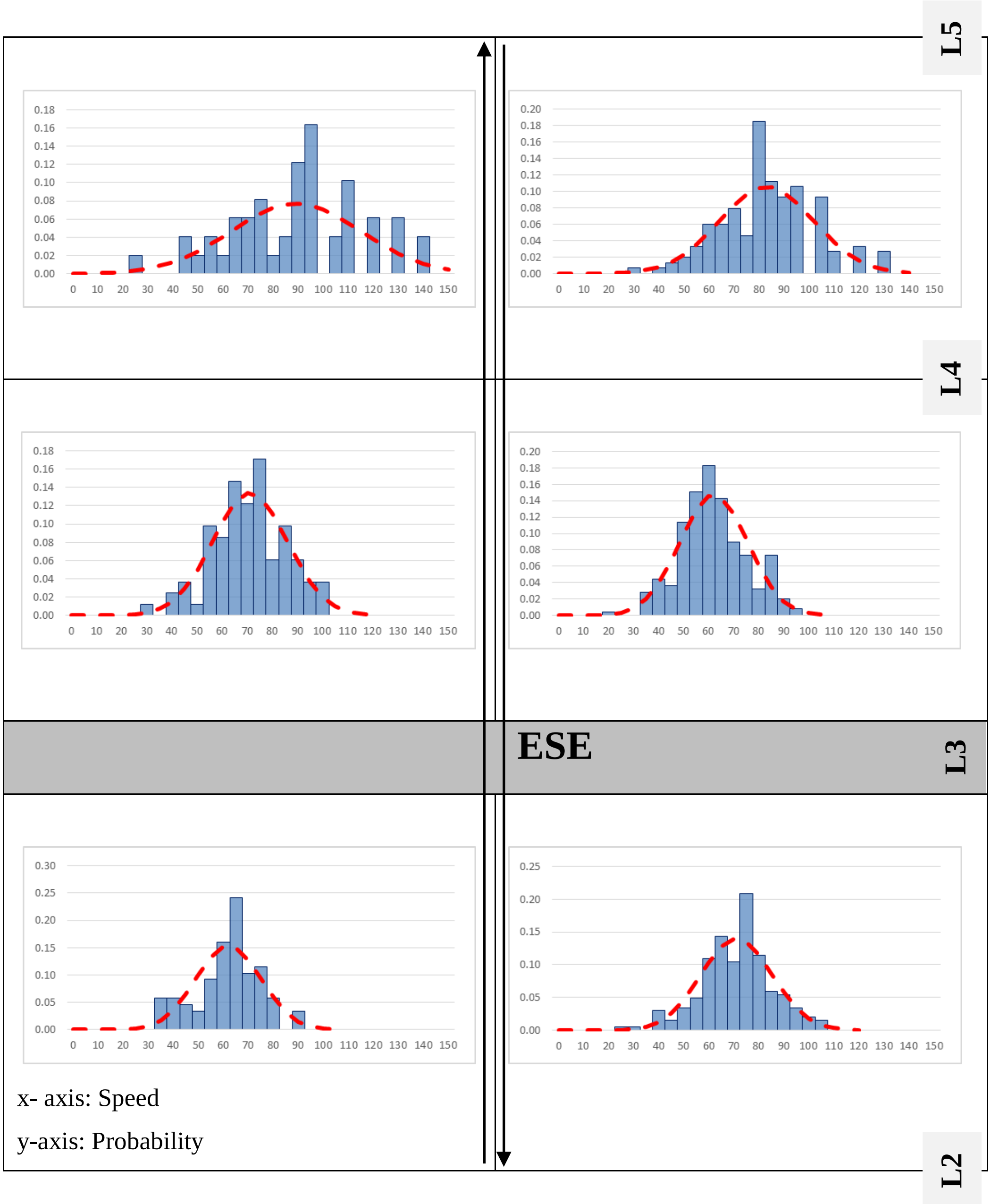


Figure E.3 Segment Profiles for Eskişehir Road in ESE Study - 3.7.13/ 12:00-13:00

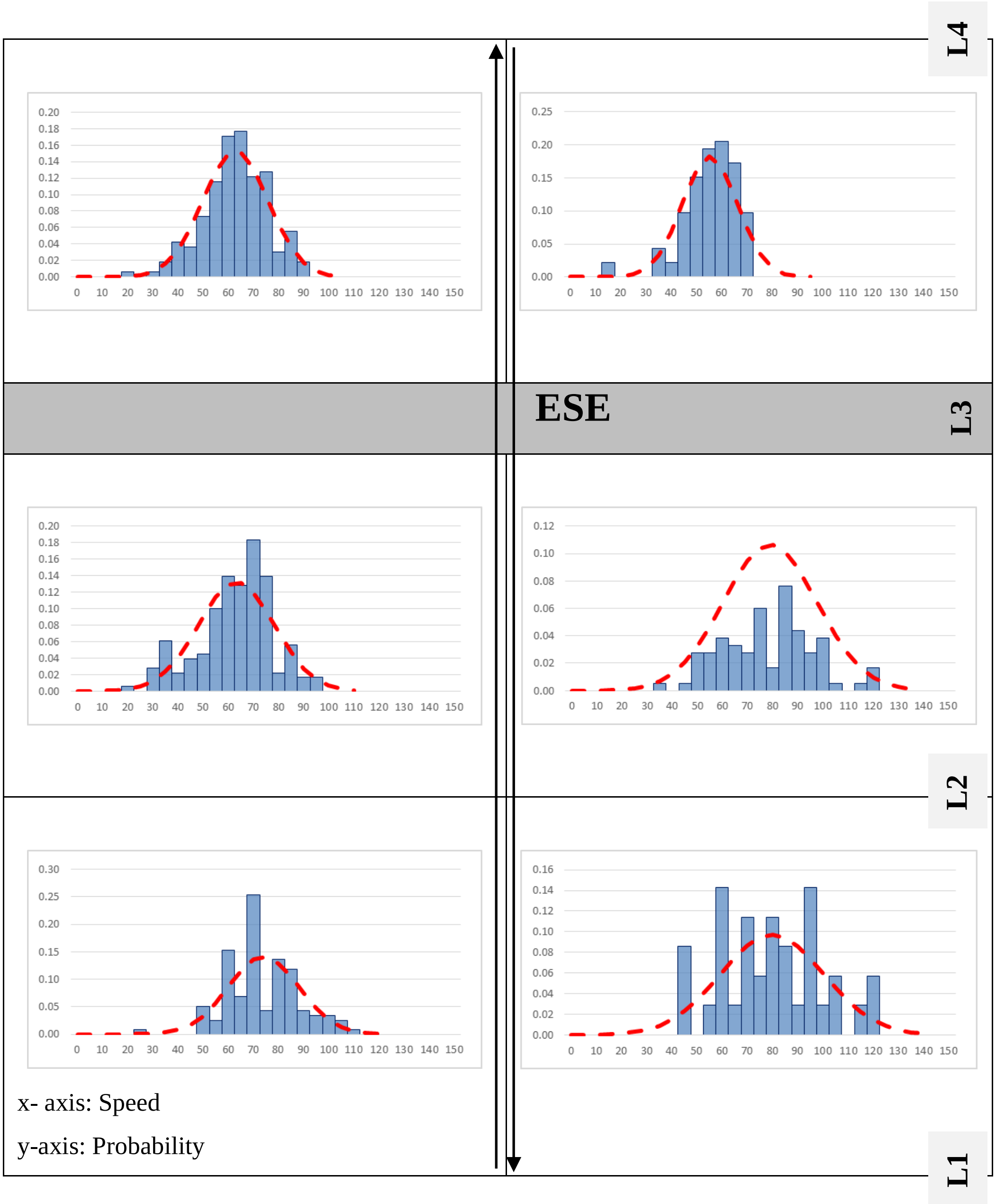


Figure E.4 Segment Profiles for Eskişehir Road in ESE Study - 3.7.13/ 13:00-14:00

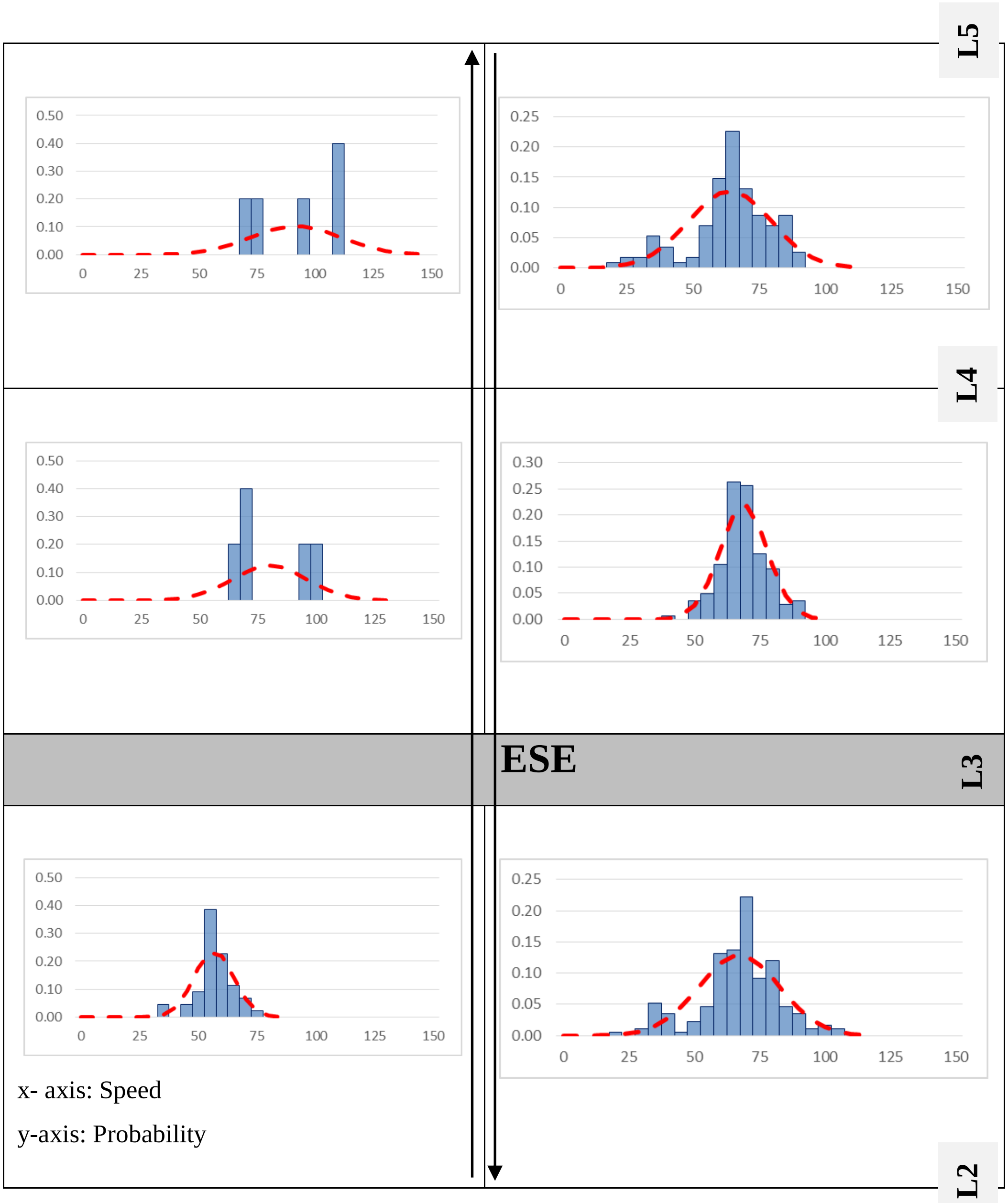


Figure E.5 Segment Profiles for Mevlana Boulevard in ESE Study - 3.7.13/ 17:00-18:00

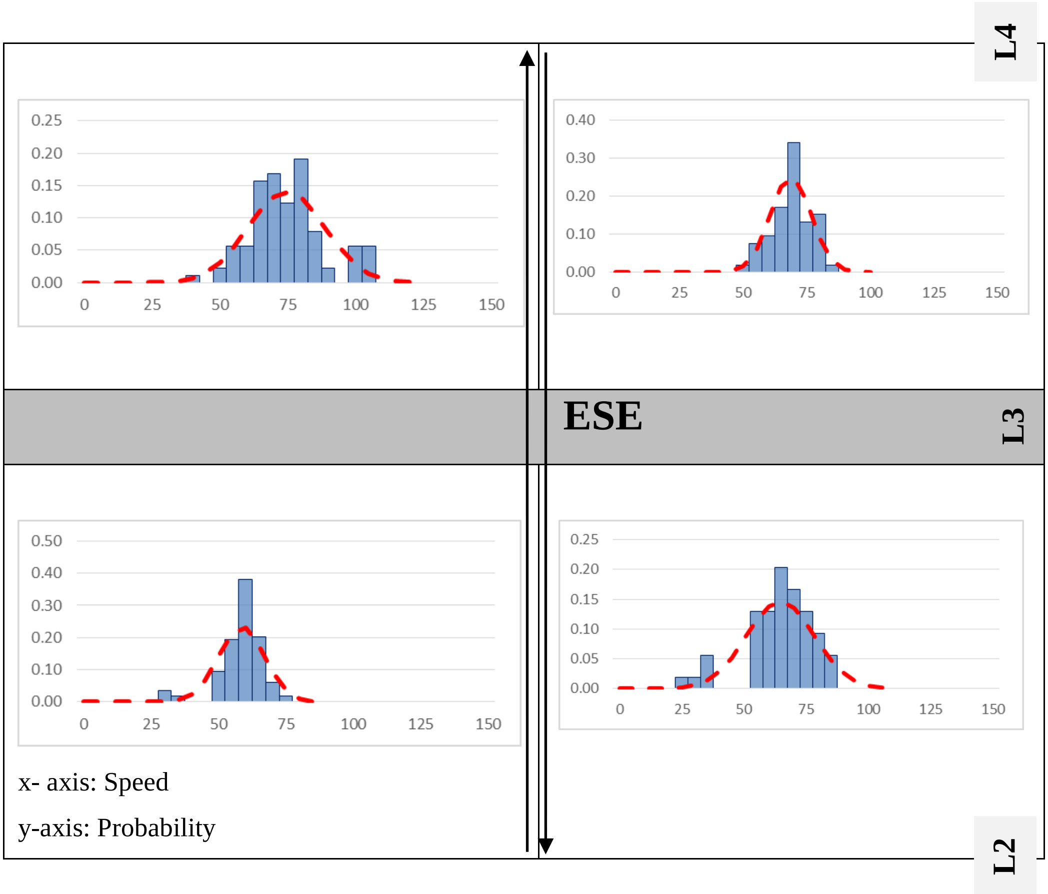


Figure E.6 Segment Profiles for Mevlana Boulevard in ESE Study - 3.7.13/ 18:00-19:00

APPENDIX F

STATISTICS BY BLUETRACE

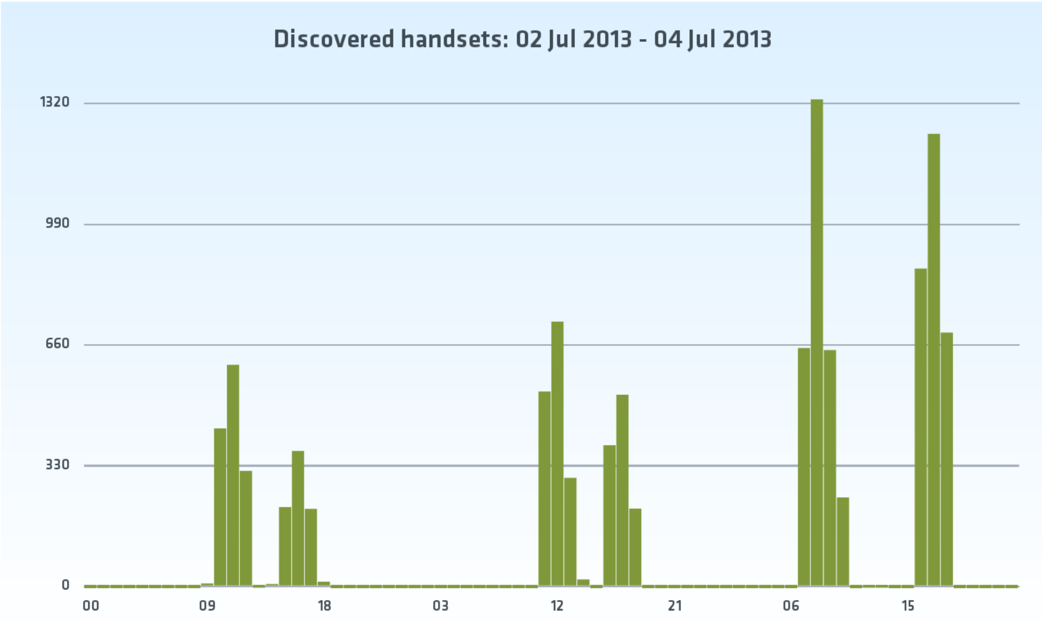
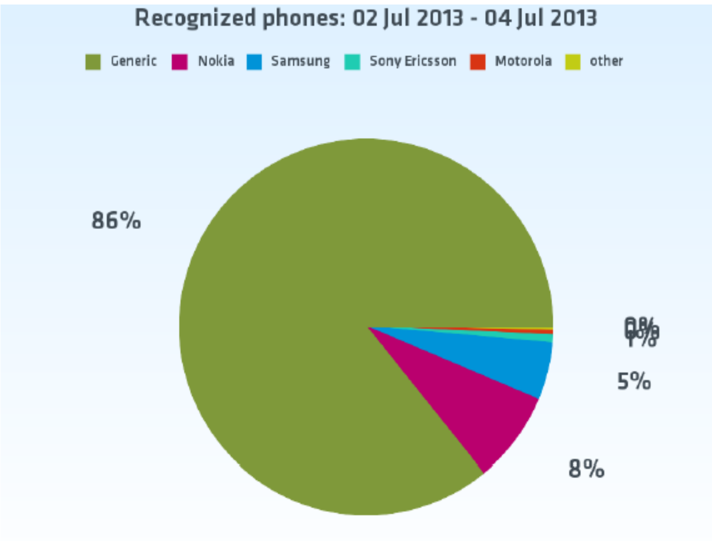
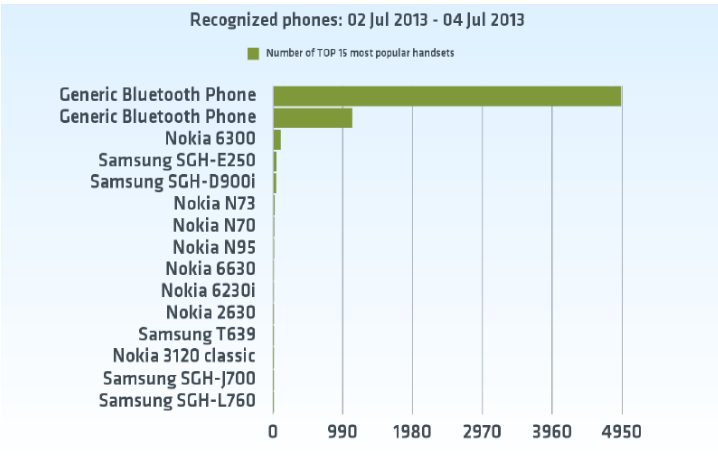


Figure F.1 Number of unique handsets discovered in ESE Case Study



Vendor name	Total
Generic	6124
Nokia	561
Samsung	354
Sony Ericsson	49
Motorola	28
LG	11
BlackBerry	2
Vertu	1
Alcatel	1
Sharp	1
	7132

Figure F.2 Most popular vendors of discovered handsets in ESE Case Study



Model name	Total
Generic Bluetooth Phone	4980
Generic Bluetooth Phone	1145
Nokia 6300	121
Samsung SGH-E250	61
Samsung SGH-D900i	57
Nokia N73	38
Nokia N70	33
Nokia N95	30
Nokia 6630	23
Nokia 6230i	23
Nokia 2630	21
Samsung T639	20
Nokia 3120 classic	19
Samsung SGH-J700	18
Samsung SGH-L760	18
	6607

Figure F.3 Most popular handset models discovered in ESE Case Study