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SMART TRANSPORTATION SYSTEMS

Master's Thesis

NECATİ KILIÇ

Thesis Advisor: ASSOC. PROF. TAŞKIN KOÇAK, PHD.

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Assoc. Prof., Tunç BOZBURA
Graduate School Director
Signature

I certify that this thesis meets all the requirements as a thesis for the degree of Master of Science.

Asst. Prof., V. Çağrı GÜNGÖR
Program Coordinator
Signature

This is to certify that we have read this thesis and we find it fully adequate in scope, quality and content, as a thesis for the degree of Master of Science.

Examining Comitee Members	Signature
Thesis Supervisor Assoc. Prof., Taşkın KOÇAK	----------------------------------
Member Assoc. Prof., Adem KARAHOCA	----------------------------------
Member Asst. Prof., K. Egemen ÖZDEN	----------------------------------

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ABSTRACT

SMART TRANSPORTATION SYSTEMS

Necati Kılıç

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Smart or intelligent transportation systems (ITS) have been around for some time. However, they are re-emerging again with the recent advances in wireless communications. This is made possible not only by the technological breakthroughs but also the widespread usage and affordability of the mobile communications based services. Contrary to the longevity of the experiences in ITS technologies, the road traffic in metropolitan areas is far cry from acceptable levels.

In order to have a deeper understanding of the aforementioned problem, the state-of-the-art in smart transportation systems has been studied. Many solutions in the literature that are offered by the range of top telecom companies, municipalities, corporations, universities and EU funded projects are reviewed. Communication technologies used in these solutions are discussed. A wide range of simulation tools in the literature are investigated which helped us choosing the right set of simulation tools.

The thesis covers the traffic theory background in detail that is investigated in this project. The meaning and the importance of several parameters which are common in all traffic applications such as density, flow, speed, gap, etc. are introduced. The relationship between flow, density and velocity is given and its significance is stated. The thesis also explored the mathematical traffic flow models that are widely mentioned in the traffic engineering discipline and are listed in two categories, namely Macroscopic and Microscopic traffic flow models. A segmented freeway system is simulated with several macroscopic traffic flow models introduced by Lighthill-Whitham-Richards, Payne, Papageorgiou and Daganzo. Some of the simulation results corresponding to Payne and Daganzo's Cell Transmission Model (CTM) which both utilize the hydrodynamic theory are given in the thesis. The fundamental diagram which is a significant concept that is used in both macroscopic and microscopic levels of traffic flow is studied, as well.

The thesis primarily focused on two steps to address the undying issue of recent decades which has lately become even more irritating. The first step described our efforts to construct and introduce a short-term prediction system. A simple yet effective simulation tool called CTMsim is presented. Two different case studies modeling a portion of TEM freeway ranging from Kavacık to Maslak have been carried out to demonstrate the abilities of the tool. Firstly, a traffic accident scenario is depicted and its effects both visually and statistically are displayed in the area of influence. In addition to it, second scenario interpreted and portrayed the prediction of the traffic states fifteen minute ahead of time which resulted in a slight difference from the real-time calculation. Briefly, the tool has been able to capture the traffic dynamics and present promising results.

The second step is comprised of presenting a real-time traffic monitoring system. On this sense, a simulator named BAU Traffic Simulator that is integrated with a smartphone application called TTraffic is developed from the scratch. The tool achieved to dynamically interpret the outputs of the client (android app) and represent the system in real-time. The outputs of the simulator can be fetched by the clients in order to get real-time traffic information, and hence calculate a dynamic routing plan to get to the destination within the possible minimum time. All analyses carried out during the development phase are presented in the thesis. Lastly three traffic scenarios simulating Regular Traffic, Free Flow Traffic, and Traffic Accident conditions are presented and analyzed thoroughly.

Keywords: Intelligent Transportation Systems, Microscopic Traffic Simulator, Traffic Prediction, GPS-based Traffic Estimation, Real-time Traffic monitoring

ÖZET

AKILLI ULAŞIM SİSTEMLERİ

Necati Kılıç

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Akıllı Ulaşım Sistemleri bir süredir araştırmacıların gözde konularından biri olarak çalışılmıştır. Ancak son zamanlarda özellikle kablosuz iletişim sistemlerinde gerçekleşen teknolojik gelişmeler bu çalışmalara son derece büyük bir hız kazandırmıştır. Gün geçtikçe ulaşımı kolaylaşan GPS sistemlerinin araçlarda bulunmaya başlaması ve öte yandan da akıllı cep telefonlarında bu iletişim sistemlerinin entegre halinde son kullanıcıya kadar ulaşması, gerçek zamanlı trafik bilgisi çıkarımını, izlenmesini ve tahmin edilebilmesine olanak tanımıştır.

Bu araştırma tezi GPS tabanlı akıllı telefonlar aracılığıyla gerçek zamanlı trafik izleme ve bilgilendirme sistemlerini ve yakın gelecek zamanlı trafik tahminlerini konu almaktadır. Araştırma sonunda on beş dakikalık kısa zamanlı tahminler yürütebilen bir sistemin yanı sıra cep telefonlarından gelen GPS bilgilerini yorumlayabilen bir simülatör geliştirilmiştir.

Anahtar kelimeler: Akıllı Ulaşım Sistemleri, Mikroskopik Trafik Simülatörü, Kısa süreli trafik tahmini, GPS tabanlı trafik durumu, Gerçek zamanlı trafik denetimi

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ABBREVIATIONS

ITS	:	Intelligent Transportation Systems
ATIS	:	Advanced Traveller Information System
POI	:	Point of Interest
GPS	:	Global Positioning System
GSM	:	Global System for Mobile Communications
RDS-TMC	:	Radio Data System – Traffic Message Channel
WiMAX	:	Worldwide Interoperability for Microwave Access
3G	:	Third Generation mobile telecommunications
Wi-Fi	:	Wireless Local Area Network (a.k.a WLAN or Wireless Fidelity)
DSRC	:	Dedicated Short Range Communication
LWR	:	Lighthill - Whitham - Richards
CTM	:	Cell Transmission Model
RFID	:	Radio Frequency Identification
LPR	:	License Plate Recognition
BAU	:	Bahçeşehir University

SYMBOLS

Flow in a section	:	q
Density in a section	:	ρ
Velocity in a section	:	v
Vehicle length	:	L
Vehicle spacing	:	s
Vehicle headway	:	h
Gap between consecutive vehicles	:	g
Free flow speed	:	V_f
Congestion wave speed	:	w
Maximum flow (capacity)	:	Q_{max}
Critical density	:	ρ_c
Jam density	:	ρ_j
Time increment (or unit time)	:	Δt
Time constant	:	τ
Length of the j^{th} section	:	l_j
Time constant	:	V_a
Anticipation constant	:	τ
Tuning parameter	:	K

1. INTRODUCTION

The traffic congestion is an undying problem since a few decades which has become even more irritating in the recent years. Traffic is one of the main parts of our lives. We are inside the system as soon as we leave the house. Vehicles, people, traffic lights, intersections, roadways, bridges, viaducts, tunnels and crosswalks are only some of the elements of the traffic. Traffic involves many vehicles, many people, spontaneity and randomness; this problem makes difficult to maintain the harmony and regulation. One of the most earth-shaking problems of the modern world is the impact of unbearable traffic congestion throughout the metropolitan cities.

Traffic congestion has become a serious issue that needs to be dealt with over the last years. Many more tires start to take place on roads as a result of rapid population growth, urbanization and swift drops in automobile prices. Long queues near traffic lights and junctions along the highways or freeways are the common discomfort. Problems arising from traffic congestion can be classified into three parts as economic, social and environmental impacts. For instance, people who wait at the heavy traffic start to get nervous. Stress has many negative effects on people such as heart attacks, high tension, and high blood pressure. We can add much more bad effects of stress but these are enough for to say that the traffic affects health of the people substantially. Other than the influences on our social life, in other words, wasting time being stuck in the traffic, a large amount of fuel is also wasted all around the world triggering the economic threats. Environmental effects due to more pollutant emissions are the other aspects of the issue that should not be underestimated.

It is often mentioned as a solution that can tackle the congestion is to construct new roads in order to increase the capacity of the infrastructure. However, it is a costly and a long-term solution. What these cities require is the implementation of ITS solutions which fulfill the requirements of being short-term and cost-effective in nature.

Smart or intelligent transportation systems (ITS) solutions have been around for some time. However, they are re-emerging again with the recent advances in wireless communications. This is made possible not only by the technological breakthroughs but also the widespread usage and affordability of the mobile communication based services. Contrary to the longevity of the experiences in ITS technologies, the road traffic in metropolitan areas is far cry from acceptable levels.

There are two main technical issues related to solving traffic related problems: Collecting real-time data and analyzing it. The former has been solved to an extent by deploying many sensor systems such as video, radar, induction-loop, etc. Though, mobile communications can play a critical role here, as well. The latter becomes more of an issue when there are massive amounts of data. Extracting the right set of data and using this to provide accurate suggestions to drivers is not a trivial task.

Conventional approaches, generally known as navigation systems, offer a static solution, in other words, shortest route in length. Knowing the shortest route to the destination does not solve any problems in today’s crowded cities. It only serves as the basic approach for supplying information such as travel length and travel time under free flow which is calculated with the speed limits of the corresponding roadway. Even knowing the real-time travel information cannot help the travelers since the traffic states are extremely unstable. None of the travelers that check the real-time traffic congestion can know what kind of surprises await them during a trip. What people need to and want to know are the answers to the questions like: “What is going to happen after 10 minutes?”, “Will the traffic that is occurring 10 km ahead affect my trip?”, and “How long it will take for me to go to home if I leave the office 15 min later from now?” Because the unstable characteristics of the road traffic may lead to traffic states which quite the opposite of what we see on are and expect from the real-time traffic screens.

Neither the last nor the least, short-term future prediction for the traffic status can also be done, noticing the drivers of an incoming wave of traffic congestion around their driving path. However, the reliability and the accuracy of such a prediction may vary depending on the different types of algorithms and the techniques. Research on this field still continues and it is not yet too clear which technique is better in general.

Fortunately, recent advances in mobile computing and wireless communication technologies have revealed many innovative solutions to urban traffic congestion. With the help of these solutions, the traffic congestion can be discovered and disseminated to others. In this sense, a smart traffic control system can direct the drivers to take less congested alternate paths. This direction can be done by a smart device on-the-go (e.g. mobile application that runs on a smartphone), by calculating the travel time according to the real-time traffic data coming from a centralized system.

On the other hand, some unnecessary delays can be eliminated by implementing adaptive control mechanisms near the traffic lights and/or signs. When the two systems intercommunicate, one can provide more accurate and efficient data to the other. So they help each other to achieve a better degree of quality of service. For example, consider a scenario that there is an adaptive traffic light control mechanism at a junction, and it gets informed by the traffic status system about re-adjusting the red light and green light durations according to its own traffic status analysis. Thus the congested direction may have a longer duration of green light and it helps the drivers to get to their destinations in less time.

Providing intelligence into the transportation system brings in the convergence of technologies providing a synergetic transformation in the commuter experience. The aim of this thesis is to address the critical issues of road congestion by offering new techniques and models in the fields of advanced traveler information systems. Hence the solution for such systems needs to deal with a number of main issues in the related field.

- **i.** Analyzing the current and the previous traffic pattern data
- **ii.** Development of new prediction paradigms and simulation environment
- **iii.** Extraction of the real-time congestion information
- **iv.** Investigation of dynamic traffic routing

In the literature, there exist a wide variety of scientific traffic models which help to analyze current and future condition of traffic. These models can be classified as microscopic and macroscopic levels. While macroscopic models use aggregate variables, microscopic models use individual vehicle dynamics. The role of traffic models in this sense is beyond the foreseen. They play quite an important part in both contemporary traffic research and traffic applications such as traffic control, incident detection and flow prediction. The biggest impact of the traffic models come from the fact that it provides the only possible way that can help not just to interpret the effects of the traffic congestion, but also to build up a mechanism to predict the near future congestion states of the system which are commonly up to 30 minutes. Predicting the future congestion states enables the users to optimize their departure time in advance, hence providing them an effective time management possibility. It serves as a short-term approach to solve, reduce or at least postpone the traffic problem. Moreover, testing the system in real life scenarios is a major problem. In order to overcome this problem, the current simulation environments are analyzed and a new simulation environment is developed. In our simulation systems, current traffic status estimation, in addition to the short-term traffic status prediction (e.g. 15 mins ahead in time) are demonstrated.

This is the first chapter of the thesis and it enables a general introduction to the smart or intelligent transportation systems. The chapter continues with the presentation of possible challenges vs. opportunities in the project and finishes with the introduction of the proposed system architecture. Remaining of the thesis is organized as follows; in Chapter 2 a survey for the state-of-the-art projects and the studies in the literature, as well as the communication technologies utilized in the ITS field are introduced. Chapter 3 presents the fundamentals of the mathematical traffic models which constructs a backbone structure for the traffic flow theory. The chapter continues by introducing the simulation tool CTMsim (modified for the prediction mechanism) as well as the experimental results for various case studies. Furthermore, the methods, the strategies, and the discussions about how to extract the congestion information are given in Chapter 4. The chapter also introduces BAU Real-time Traffic Simulator in great detail, from development to test. Three traffic scenarios simulated by the BAU Real-time Traffic Simulator are analyzed in detail. Finally, the thesis ends in Chapter 5 by presenting the conclusions.

1.1 CHALLENGES VS. OPPORTUNITIES

In recent years, the global positioning system (GPS) is widely used in technical products, such as navigation devices, GPS loggers, PDAs and mobile phones. At the same time, with the explosion of map services and local search devices, many GPS-related web services are built. Many research efforts have implemented GPS data collection platforms, which are based on client-server architectures (Kriegel et al., 2008), (Lo et al., 2008), (Yoon et al., 2007). Recent studies in (Kriegel et al., 2008), (Yoon et al., 2007), (De Fabritiis et al., 2008), (Sananmongkhonchai et al., 2008) utilized GPS data to estimate the traffic status. However, the challenge is that the GPS data reported along with a road segment may contain fewer amounts of GPS data for traffic estimation. As a result, the estimated driving speed cannot closely reflect the real traffic status (Wei et al., 2009). Thus, spatio-temporal (related to both space and time) features of road networks should be explored to obtain more GPS data from historical data for more accurate traffic status estimation.

Table 1.1: Challenges vs. opportunities

CHALLENGES	OPPORTUNITIES
Accuracy	Existing GSM network (support from Türk Telekom & Subsidiaries)
Some solutions require scalability	Municipality Support for Similar Systems
Swift changes in traffic environment: spatio-temporal features of road networks	Availability of historical data (IBB & Akıllı Durak)
Low system latency while providing reliable transmission	Availability of open source simulation tools
Testing in real life scenarios	Possibility of using ubiquitous GPS and other sensor systems to generate congestion information
Some solutions require costly hardware	Location Based Service Recommendation
High security: prevention of cyber attacks	Much attention / support from potential users

Source: Türk Telekom Technical Report, 2011; Robust Traffic Status Estimation and Adaptive Traffic Signaling, December 2011.

Dealing with dynamic changes in the traffic volume is one of the biggest challenges in Intelligent Transportation Systems. As the scale of the network gets larger, the better servers with greater processing power are needed. Dealing with huge amount of data coming from several car nodes will require more time-aware algorithms to prevent latency issues. Because of the system's inherent real-time nature, the entire job has to be done in a small interval of time. In other words, the centralized server should be able to overcome such performance and delay issues.

Moreover, testing the system in real life scenarios is another major problem. You cannot just deploy the traffic signaling system on a junction without getting legal permissions. Even if you could get the permissions, if something goes wrong it may cause a mess on the junction. Simulation tools, in this sense, will be our savior.

The system should also be protected against cyber-attacks. Signaling system requires high precision and one tiny attack on the system may give rise to catastrophic consequences.

Although many great challenges, the proposed system also may also provide some opportunities. For instance, the adaptive traffic signaling systems which can communicate with the vehicles or the central traffic status server based on the wireless technologies can employ greater flexibility than the conventional ones, since they are provided with more information for the signal decision process (e.g. vehicles positions and speeds). The cost is also significantly lower considering loop detectors are usually under each lane approaching the intersections and cameras require high processing power, not to mention visibility issues. If we assume that vehicles will be equipped with wireless communication devices - as current research suggests - then all that is needed are wireless devices with some processing power in intersections.

Furthermore, one of the biggest opportunities is the support from the massive network provider Türk Telekom and its subsidiaries, as well as the support from the municipality. Existing GSM network will help us a lot to test the system in real scenarios and the availability of historical data will benefit us in the simulation stage.

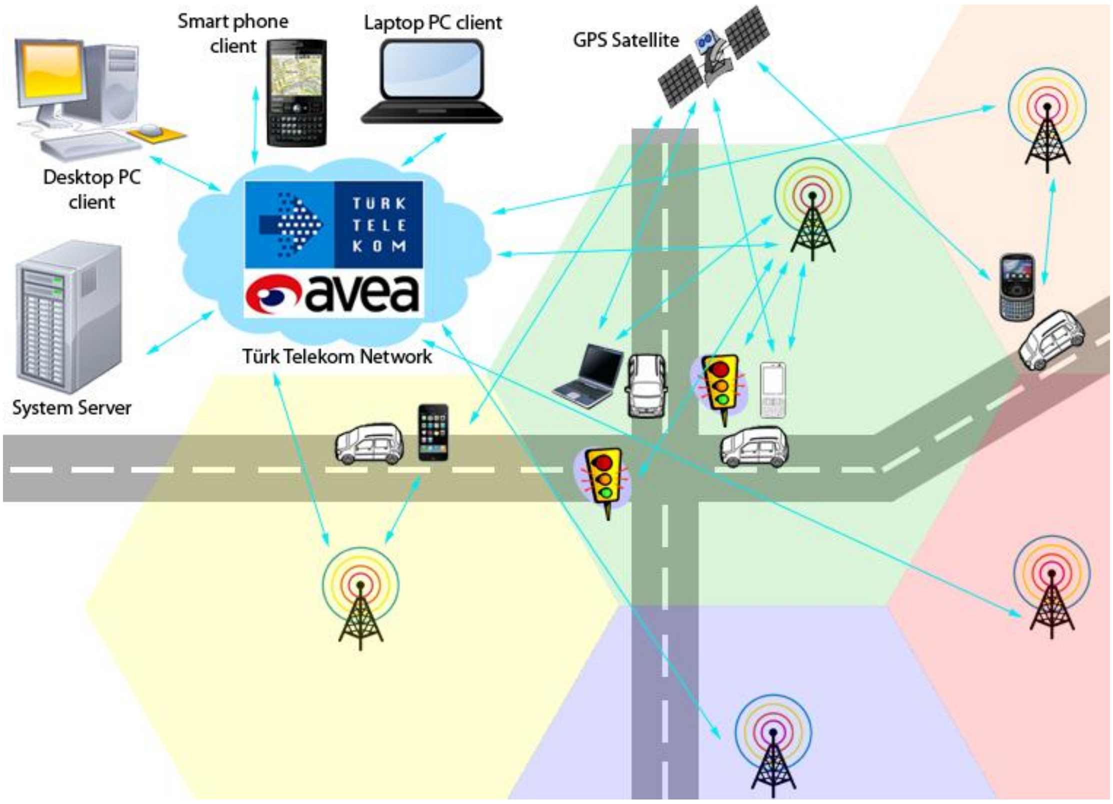
The existence of ubiquitous GPS devices and other sensor systems might make the extraction process of the congestion information relatively easier. More importantly, high attention/support from potential users is very exciting, and also seems quite promising.

Another awesome opportunity of the proposed system may be the recommendations for POIs (Points of Interest). Consider the case that you get stuck in a massive traffic jam, the time you need to spend to get to home takes the same as you stop by a coffee shop, relax a little and then take the road. Take into account that the calculation is done by your mobile client application and you are informed of this kind of scenarios automatically.

1.2 PROPOSED SYSTEM ARCHITECTURE

Overall system architecture is depicted in Figure 1.1. In this thesis, we first of all make a comprehensive background study, then continue with the introduction of the prediction system, and finally study how to extract the congestion information and thus provide a dynamic traffic routing mechanism.

Figure 1.1: System architecture for the technical approach



Source: Türk Telekom Technical Report, 2011; Robust Traffic Status Estimation and Adaptive Traffic Signaling, December 2011.

2. STATE-OF-THE-ART IN SMART TRANSPORTATION SYSTEMS

There are many projects carried out all around the world by top telecom companies, government authorities such as municipalities, privately funded corporations, universities, EU funded organizations and groups. All of these projects offered by variety of parties and the communication technologies used in smart transportation systems are needed to be surveyed to have a better understanding on the background.

Thus, in this section the state-of-the-art in Smart Transportation Systems is surveyed. The existing systems which are used in real-life scenarios in terms of traffic congestion solutions are covered in detail. Finally wireless technologies about these systems are discussed and the simulation tools are reviewed.

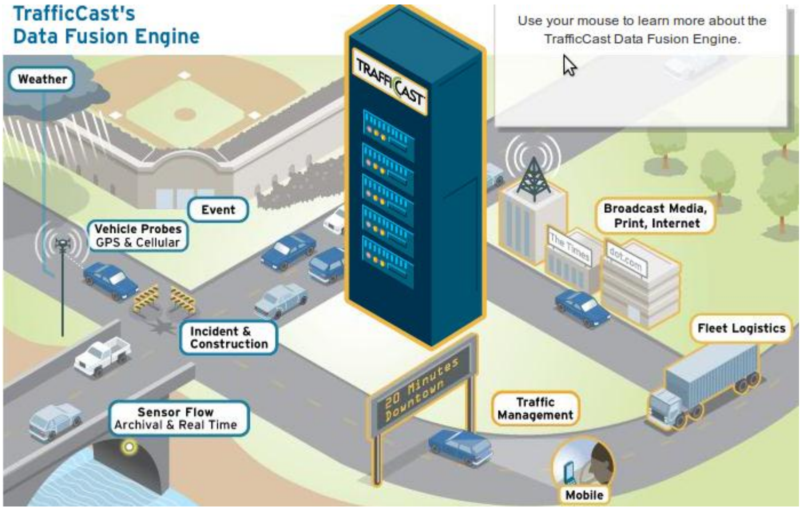
2.1 TRAFFIC SOLUTIONS OFFERED BY TOP TELECOM COMPANIES

Majority of the top telecom companies mention about their studies without giving detailed information due to confidentiality. This section covers the major telecom companies that studies on the smart or intelligent transportation systems.

2.1.1 China Mobile

China Mobile is the company that has the most number of subscribers in telecommunications market. The company has cooperated with TrafficCast. China Mobile and Traffic Cast have released a product called DynaFlow as a solution for travel time estimation and near term forecasting. Dynaflow gathers real-time information from 350 sources. 181 of them belong to the Westwood One's Metro Network; 30 of them are gathered from road sensors, GPS probes and a system called BlueToad (aggregated data from vehicles using Bluetooth), 3 of them are weather data sources which are obtained by Weather Central Inc., 90 of them are the event sources and the last 50 are the historical data sources which are obtained from sensor data and GPS tracks. System updates weather data for every 6 hours, incident and construction data for every 5 minutes (TrafficCast, 2009).

Figure 2.1: Traffic Cast's Data Fusion Engine

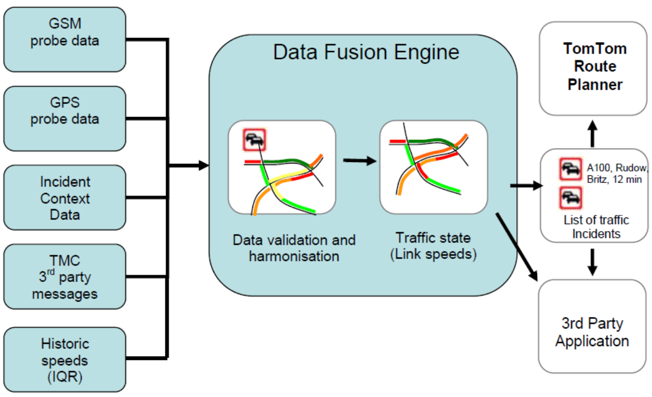


Source: TrafficCast, 2010. *TrafficCast data fusion engine*. [Online] Available at: http://trafficcast.com/technology-platform/data-fusion-engine/ [Accessed 13 January 2011].

2.1.2 Vodafone

TomTom navigation devices provide real-time traffic information to the drivers using RDS-TMC (Radio Data System – Traffic Message Channel), information providers (such as ITIS in UK), GPS probes and GPRS – EDGE technologies which are provided by Vodafone. Initially system gathers data from various information providers (which aggregate data from road sensors, cameras and public traffic sources). This data is being compared with GPS traces. Each vehicle with certain speed and certain direction sends information to the nearest base station with the beam signals from cellular phones.

Figure 2.2: Vodafone-TomTom HD Traffic data processing and delivery chain

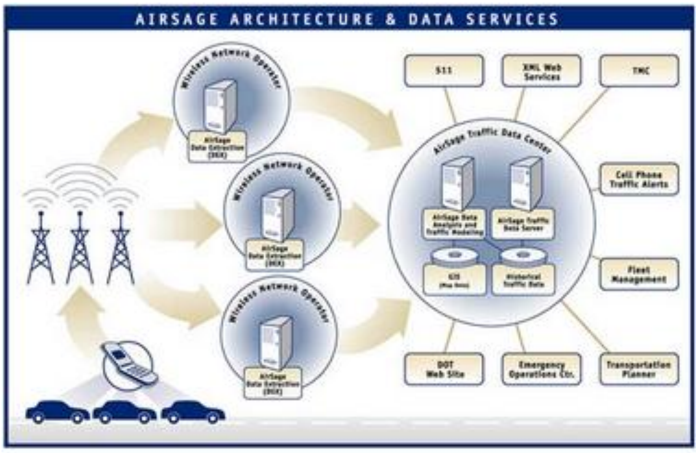


Source: TomTom Inc., 2009. *White paper: How TomTom's HD Traffic and IQ Routes data provides the very best routing*. [Online] Available at: http://www.tomtom.com/lib/doc/download/HDT_White_Paper.pdf [Accessed 15 October 2011].

2.1.3 Verizon

AirSage's patent-protected Wireless Signal Extraction technology aggregates, anonymizes and analyzes signaling data from individual handsets using the cellular network, determines accurate location information and converts it into real-time anonymous location data.

Figure 2.3: Airsage's WiSE Architecture



Source: AirSage Inc., 2011. *Airsage's WiSE Technology Overview*. [Online] Available at: http://www.airsage.com/site/index.cfm?id_art=46598&actMenuItemID=21674&vsprache/EN/AIRSAGE___WiSE_TECHNOLOGY__L.cfm [Accessed 5 May 2011].

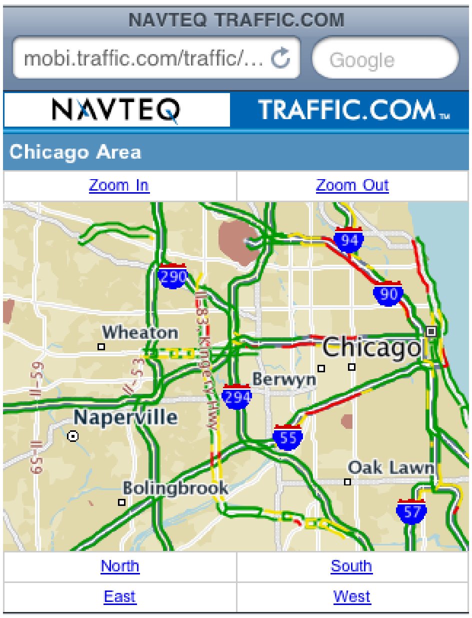
2.1.4 Nippon Telephone & Telegraph

Nippon Telephone & Telegraph uses radio tuning system, system's controller requests data from navigation unit and the data is sent to the base station via vehicle's telephone line.

2.1.5 Telefónica

NAVTEQ Traffic integrates comprehensive real-time content including sensor, GPS probe, and incident data, and anonymous cell-based probe data is extracted from Telefónica's mobile communications network.

Figure 2.4: Telefonica-NAVTEQ Traffic Solution

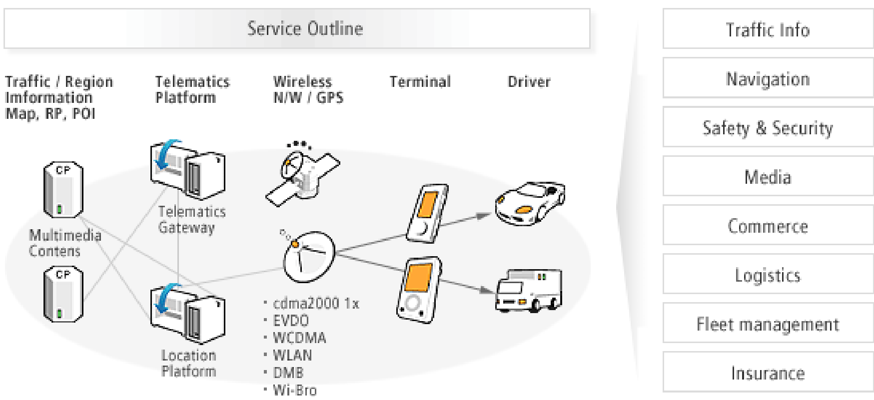


Source: Traffic.com, 2010. *Navteq Traffic.com* [Online] Available at: http://mobi.traffic.com/traffic/ [Accessed 10 October 2011].

2.1.6 SK Telecom

SK Telecom's Nate Drive service can be counted as another solution. NATE Drive is a cutting-edge wireless Internet service that provides drivers with hands-free function and vital navigation information such as driving routing guidance, real-time traffic situations, through Global Positioning System (GPS) technology and cellular phone wireless network.

Figure 2.5: SK Telecom's Nate Drive System Overview



Source: SK Telecom, n.d. *SK Telecom Nate Drive Telematics service*. [Online] Available at: http://www.sktelecom.com/eng/html/service/Ubiquitous/Telematics.html [Accessed 8 October 2010].

2.1.7 AT&T

AT&T partnered with InfoTek to provide hardware and software solutions to the Caltrans. System uses GPRS – EDGE networks for transferring information from vehicle to the base station. Cellular phones are used to estimate the current location of the vehicles and the data is transmitted to the nearest base station via beam signals (AT&T and CalTrans District 10, 2007).

2.1.8 Telecom Italia

Magneti Marelli and Telecom Italia developed a system which consists of two fundamental components: telematic box with a cell phone SIM card, they interacts with the driver by voice or via a dedicated display. The system connects the car to the high-speed UMTS network, ensuring on-the-move mobile broadband and access to infomobility services.

2.1.9 KDDI

KDDI's EZweb service can be counted as another solution; it provides drivers with driving direction assistance and information from VICS (Vehicle Information and Communication System). KDDI mobile phone subscribers can also access traffic information via the mobile phones.

2.1.10 NTT DoCoMo

NTT DoCoMo's i-mode services provide comprehensive information to mobile users and drivers. Under i-mode, "i-area" is a service that automatically selects and displays i-mode content related to the location of the i-mode user. Users do not select service areas since the base stations automatically recognize their locations.

2.1.11 LG Telecom

LG Telecom's EZ-Drive service can be counted as another solution. System collects vehicle location data from the nearest base station according to the beam signals and finds the fastest route and provides traffic updates by voice and maps displayed on mobile phones.

Table 2.1: Traffic solutions offered by top telecom companies

Company / Country	Purpose	Features
AT&T – InfoTek / USA	Improving California Department of Transportation Infrastructure	AT&T and InfoTek have formed a partnership to provide hardware and software solutions to the CalTrans. System uses GPRS – EDGE Networks
Verizon – AirSage / USA	Airsage applications	AirSage's patent-protected Wireless Signal Extraction (WiSE) technology aggregates, anonymizes and analyzes signaling data from individual handsets using the cellular network, determines accurate location information and converts it into real-time anonymous location data.
Nippon Telephone Telegraph / Japan	TelNav Navigation System's Information Provider	Using radio tuning system, controller requests data from navigation unit and the data is sent to the base station via vehicle's telephone line
Telefonica-Navteq / Spain	Information provider of NavTeq navigation devices.	NAVTEQ Traffic will integrate comprehensive real-time content including sensor, GPS probe, and incident data, and anonymous cell-based probe data is extracted from Telefonica's mobile communications network
Vodafone – TomTom / UK - Netherland	TomTom HD Traffic	Whenever a mobile phone is in motion at a certain speed and in a certain direction, reliable and useful traffic information becomes available. TomTom can access this anonymous data from millions of Vodafone customers, giving an accurate view of the traffic situation throughout the road network. This data is compared and merged with information from traffic authorities, road operators, and commercial third parties
China Mobile / China	Traffic Cast	It offers taxi fleet management solutions, allowing taxi operators to deploy vehicles, organize booking and monitor traffic situations
Telecom Italia Fiat Group company Magneti Marelli / Italy	Tema-Mobility Applications	Easy-to-install "telematic box" with a cell phone SIM card interacts with the driver by voice or via a dedicated display. The system connects the car to the high-speed UMTS network, ensuring on-the-move mobile broadband and access to infomobility services
KDDI / Japan	EZWeb Service	KDDI's EZweb service provides drivers with driving direction assistance and information from VICS (Vehicle Information and Communication System) KDDI mobile phone subscribers can also Access traffic information via the mobile phones.
NTT Do Co Mo – Nissan / Japan	I-mode Service	Its popular i-mode services provide comprehensive information to mobile users and drivers. Under i-mode, "i-area" is a service that automatically selects and displays i-mode content related to the location of the i-mode user. Users do not select service areas since the base stations automatically recognize their locations. It has a joint service with Nissan called Okutto-Keitai, allowing drivers to receive i-mode digital maps and restaurant information corresponding to the area in which their car is located.
SK Telecom / Korea	NATE Drive	Launched a Telematics service titled "Nate Drive". NATE Drive is a cutting-edge wireless Internet service that provides drivers with hands-free function and vital navigation information such as driving routing guidance, real-time traffic situations, through Global Positioning System (GPS) technology and cellular phone wireless network.
LG Telecom / Korea	EZ Drive	Launched a Telematics service "ez Drive". Enabling customers to find the fastest route to their destinations and provide traffic updates by voice and maps displayed on their mobile phones. To connect the navigation services with location-based data on fueling stations, restaurants, public facilities and other venues.

Source: Türk Telekom Technical Report, 2011; Robust Traffic Status Estimation and Adaptive Traffic Signaling, December 2011.

2.2 STATE-OF-THE-ART SOLUTIONS BY MUNICIPALITIES

In this section we explored two systems developed by the cooperation of İSBAK and İstanbul Municipality. These systems are developed for real-time traffic congestion status estimation. The names of these systems are İBB Trafik and Akıllı Durak (Smart Busstop).

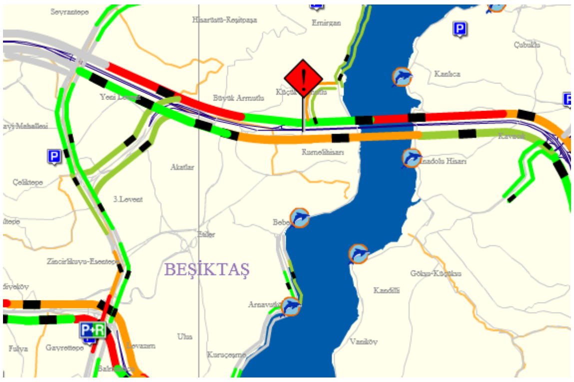
2.2.1 Smart Bus Stop (Akıllı Durak)

“Smart Bus Stop” is another project which is being developed by IBB and ISBAK. Bus priority is one of the key features of this project and their solution consists of on-board units for buses to provide the bus location information to the road side units and traffic light signalization systems. Once the information is obtained, traffic lights are adapted according to the bus location data. On the other hand bus speed, traffic density along the route, and predicted time to arrive to the next station is displayed via screen inside the bus. This service also provides information to the people on stations which include distance between bus and the current station and estimated time for arrival time of the bus to the current station.

2.2.2 IBB Traffic (IBB Trafik)

İstanbul Büyükşehir Belediyesi (IBB) Traffic which was designed as a mobile phone application is another existing solution for managing the traffic flow. Road cameras and radars which are being provided by traffic control station are used to identify congestion information of the road segments. Once the location data of the user is obtained, a specific map is provided to the user and traffic densities of each road segments are demonstrated. Also the place where the users want to go can be entered to the system and when the traffic conditions including average speed of vehicles, and average time for the indicated route are appropriate, the user is warned via message to notice that the traffic status is suitable. IBB Traffic status web interface is depicted in Figure 2.6.

Figure 2.6: The real-time traffic status demonstration from IBB Traffic



Source: IBB Traffic, n.d. *Istanbul Büyükşehir Belediyesi (IBB) Traffic web interface*. [Online] Available at: http://tkm.ibb.gov.tr/yolDurumu/YogunlukHaritasi.aspx [Accessed 5 October 2010].

2.3 STATE-OF-THE-ART SOLUTIONS BY CORPORATIONS

Private companies also take part in the development of smart transportation solutions. Actually, most of the literature is based on the solutions offered by the corporations. This section presents some of these technology giants and their projects.

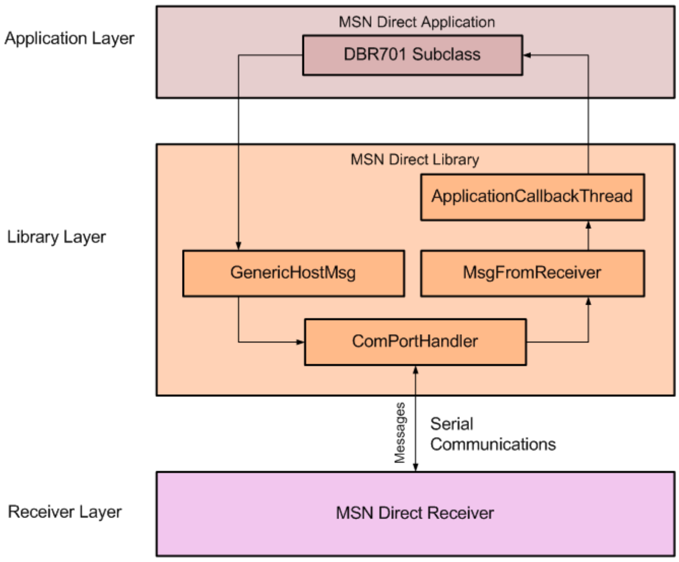
2.3.1 MSN Direct

Another system that is currently used in real-life scenarios is provided by MSN. The system is called as MSN Direct. MSN Direct is an FM radio-based digital service which allows Smart Personal Object Technology (SPOT) portable devices to receive information from MSN services. Devices that support MSN Direct include wristwatches, atomic desktop clocks, in-car GPS satellite navigation units, and even small appliances such as coffee makers. Information available through paid "channels" includes weather, horoscopes, stocks, news, sports results and calendar notifications. The service also allows users to receive notifications of new messages on Windows Live Messenger. Some Garmin GPS units, such as the nüvi 680, allow traffic notifications, weather forecasts, movie schedules and local gas prices to be received through MSN Direct.

MSN Direct has three-layered system architecture. You can see Figure 2.7 for further investigation. MSN Direct aggregates up-to-date data from various sources on back-end servers and then broadcasts the data over the Microsoft DirectBand Network to mobile devices that support it.

Push and Pull models are used for the implementation of the MSN Direct Service. With the push model the receiver pushes refreshed data to the MSN Direct application. With the pull model the MSN Direct application requests and pulls cached data from the receiver, such as when the Windows Embedded NavReady powered device starts up.

Figure 2.7: MSN Direct Architecture



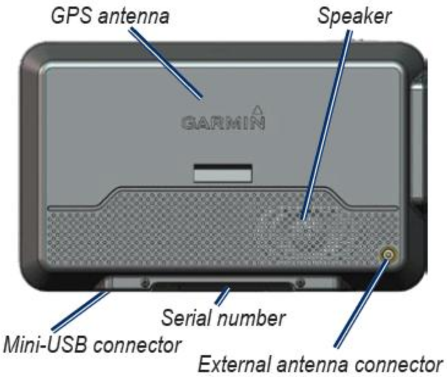
Source: MSN Direct, 2008. *MSN Direct Services Architecture*. [Online] Available at: http://msdn.microsoft.com/en-us/library/cc510579.aspx [Accessed 3 December 2010].

Figure 2.8 and Figure 2.9 show the hardware needed for MSN Direct services. MSN Direct receiver is connected to the GPS receiver which is specially designed to benefit from the service. Power outlet supplies the required power for both GPS unit and the MSN Direct Receiver from vehicle's own battery.

Figure 2.8: MSN Direct Receiver

Source: Garmin Ltd., 2008a. *MSN Direct Receiver/GDB 55 Instructions*. [Online] Available at: http://www8.garmin.com/manuals/MSNDirectReceiver-GDB55_Instructions.pdf [Accessed 3 January 2011].

Figure 2.9: Garmin GPS Unit designed for MSN Direct



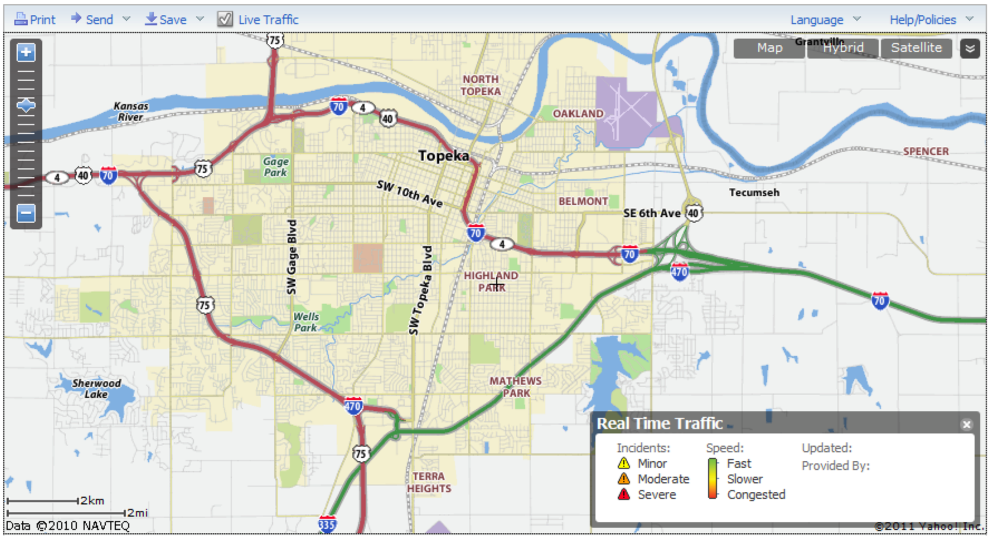
Source: Garmin Ltd., 2008b. *Garmin nüvi 780 quickstart manual*. [Online] Available at: http://www8.garmin.com/manuals/nuvi780_QuickStartManual.pdf [Accessed 19 February 2011].

2.3.2 Yahoo Maps

Yahoo Maps is a web site which provides real-time traffic information to the drivers by demonstrating the current traffic status on live maps. It uses many sources: such as historical traffic information, public web sites etc. In 2008, Yahoo made an agreement with TrafficCast for providing more accurate live information to the drivers. TrafficCast is obtained real-time traffic data from 116 sources and these can be subcategorized into 6 parts: weather, incident data, road cameras, sensors, GPS probe data, GSM probe data, and historical data. TrafficCast and its features are given in detail on the next section. The main challenge for using a web site such as Yahoo Maps to obtain real-time information is the update time interval. Such web sites usually update their information for every 15 minutes, which is really long to estimate the current traffic (Yahoo Maps, n.d.). Interface of the system can be seen in Figure 2.10.

In a competitive ITS Market, Pioneer Information Services released a real time, voice activated navigation device which has many useful features for the drivers. Tele Atlas map database is used in the system and it also obtains information from a lot of sources such as RDS, Municipality sources, Cellular Network Information etc., and all of the information coming from different sources are fused on the engine. It has 12 million points of interest for America, Canada and Hawai in its database. Speech recognition is one of the key features of the system which is used for establishing connection between navigation hardware and mobile phone. Users can access to contacts by voice and phone calls can be done just by saying the contact’s name. Also notification of the fuel consumption which is called as Eco-drive is another essential specification for drivers (Pioneer, 2010).

Figure 2.10: Yahoo Maps!



Source: Yahoo Maps, n.d. *Yahoo Maps Real-time Traffic Flow System*. [Online] Available at: http://maps.yahoo.com/ [Accessed 13 August 2011].

2.3.3 Pioneer Information Services

In a competitive ITS Market, Pioneer Information Services released a real time, voice activated navigation device which has many useful features for the drivers.

Figure 2.11: Pioneer GPS navigation device

Source: Pioneer, 2010. *Pioneer Information Services*. [Online] Available at: http://www.pioneerelectronics.com/PUSA/Car/GPS-Navigation/ [Accessed 16 December 2010].

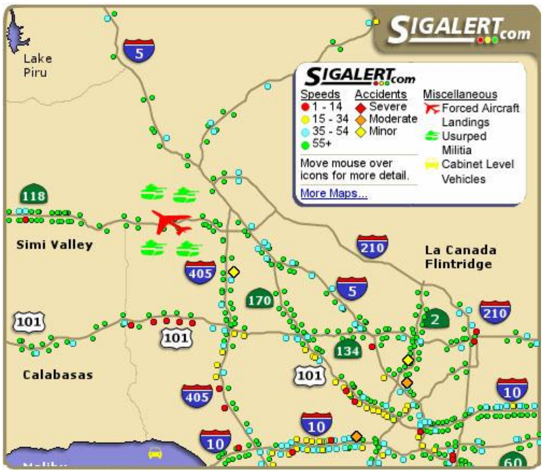
Tele Atlas map database is used in the system and it also obtains information from a lot of sources such as RDS, Municipality sources, Cellular Network Information etc., and all of the information coming from different sources are fused on the engine. It has 12 million points of interest for America, Canada and Hawai in its database.

Speech recognition is one of the key features of the system which is used for establishing connection between navigation hardware and mobile phone. Users can access to contacts by voice and phone calls can be done just by saying the contact's name. Also notification of the fuel consumption which is called as Eco-drive is another essential specification for drivers (Pioneer, 2010).

2.3.4 Sigalert

Sigalert is another web site for the drivers to calculate arrival times for different roads on their way. It has live maps which are updated approximately every 15 minutes. The difference of the system from other web sites such as Google Maps, Yahoo Maps is the demonstration of every alternative routes and calculation of arrival time for each routes. Another feature is the sigalert account for the drivers. So drivers are warned according to the instant changes on the road conditions via sums messages. The main challenge for such systems can be described as a low accuracy rate (Sigalert, 1998-2012).

Figure 2.12: Sigalert Maps



Source: Sigalert, 1998-2012. *Lane closure and traffic status monitoring system*. [Online] Available at: http://www.sigalert.com/Map.asp [Accessed 1 March 2011].

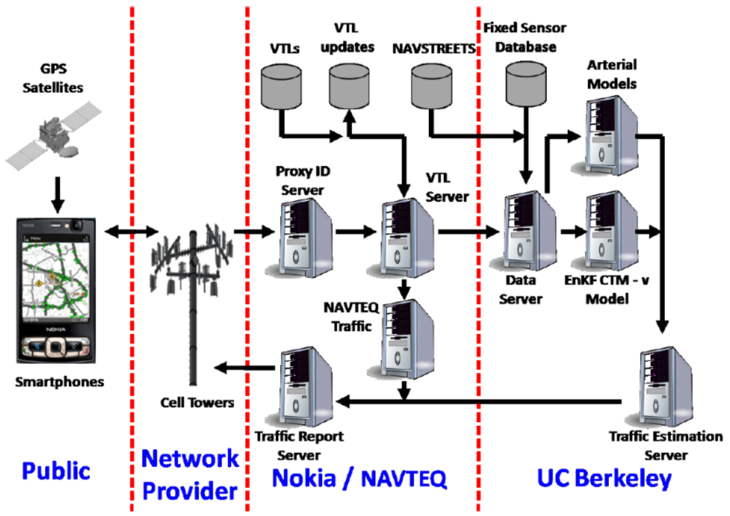
2.4 STATE-OF-THE-ART SOLUTIONS BY UNIVERSITIES

This section briefly describes the projects conducted by universities that aimed for improving the traffic flow. Some of these projects are also supported by various companies and/or government authorities.

2.4.1 Mobile Millennium

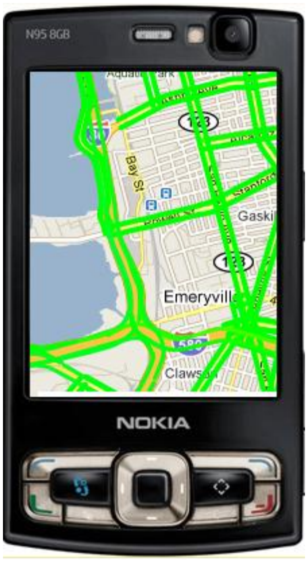
Mobile Millennium is a research project conducted by UC Berkeley, Nokia Research Center, and NAVTEQ, with sponsorship from the California Department of Transportation. Its main purpose has been to design, test and implement a system to collect traffic data from GPS-equipped mobile phones and estimate traffic status in real-time. It demonstrates a real-time permanent monitoring system capable of using GPS data from thousands of vehicles in a metropolitan area to construct velocity fields and travel time estimates. The system is able to monitor not only freeways, but also arterials and secondary highways. The system is scalable, requires low bandwidth, protects the privacy of its participants, and has the highest quality of information when compared with existing traffic monitoring systems. During the development timeline, it conducted a six month pilot deployment of GPS technology, where thousands of GPS mobile phones were placed in vehicles within a focus area.

Figure 2.13: Mobile Millennium system architecture overview



Source: Work, D., Tossavainen, O.-P., Jacobson, Q. & Bayen, A., 2009. Lagrangian Sensing: Distributed Traffic Estimation with Mobile Devices. In *Proceedings of the 2009 American Control Conference*., 2009, pp. 1536-1543.

Figure 2.14: Mobile Millennium Traffic Status



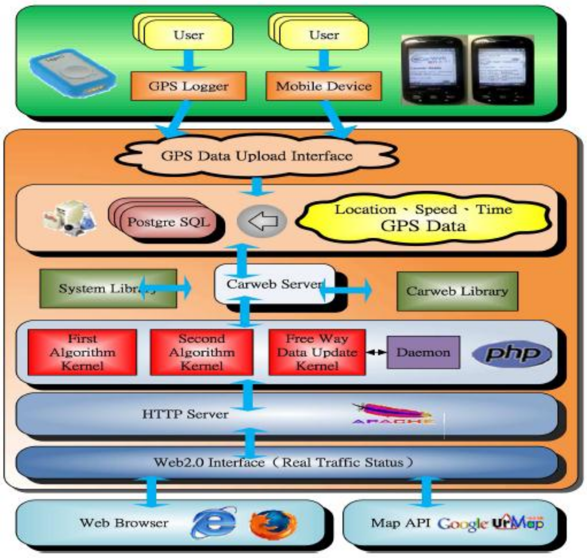
Source: UC Berkeley, 2008-2011. *Mobile Millennium*. [Online] Available at: http://traffic.berkeley.edu/ [Accessed 5 February 2011].

The Mobile Millennium traffic-monitoring system, reportedly, integrates numerous feeds into traffic models, which broadcast highway and arterial traffic information in real-time. The feeds include data obtained from GPS-enabled mobile phones, all of San Francisco's taxis (through GPS), plus radar, loop detectors, and historical database (UC Berkeley, 2008-2011). The smart phone data is collected in a privacy-by-design environment, using spatially aware sampling. Using data assimilation, the probe data is fused with existing sensor data, to provide real-time estimates of traffic. See Figure 2.14 and Figure 2.13 for a better understanding on the system.

2.4.2 CarWeb

One other existing system is called CarWeb. This system was implemented in Taiwan by National Chiao Tung University. CarWeb system was developed based on a client-server architecture in which clients refer to cars equipped with GPS receivers and the floating car data which includes location and speed information of clients is collected by the server, and wireless networks such as 3G and WiMax are used to upload client's data for the stated time intervals. Also a software module was implemented to the client's mobile devices for accessing GPS data from GPS receivers and at the server side of this system information was collected in the database and traffic status is estimated for each road segment.

Figure 2.15: Architecture of CarWeb



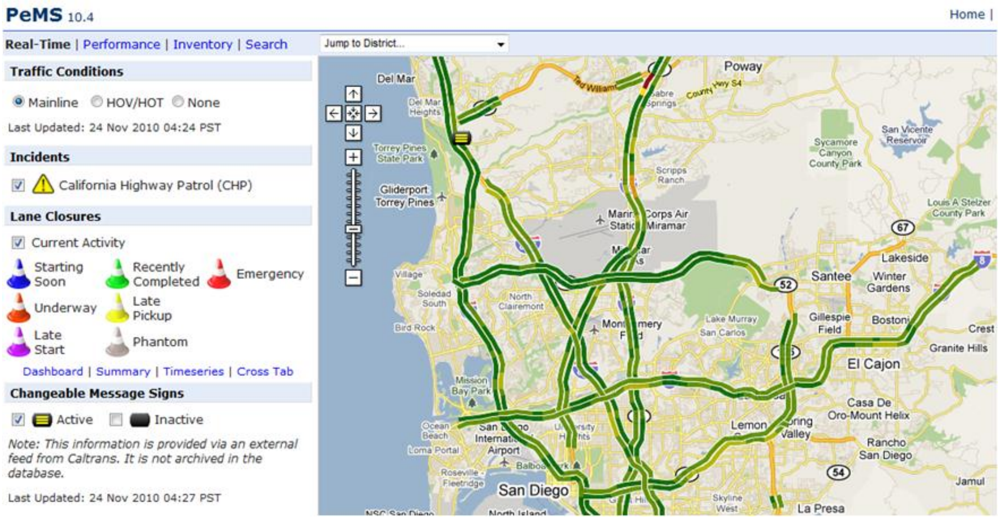
Source: Chang, Y.-M. et al., 2009. Exploring GPS Data for Traffic Status Estimation. In *Tenth International Conference on Mobile Data Management: Systems, Services and Middleware*., 2009, pp. 369-370.

2.4.3 Performance Measurement System (PeMS)

A project to investigate various performance measures on the freeway system is called Freeway Performance Measurement System (PeMS), conducted by University of California, at Berkeley, with the cooperation of the California Department of Transportation, California Partners for Advanced Transit and Highways, and Berkeley Transportation Systems.

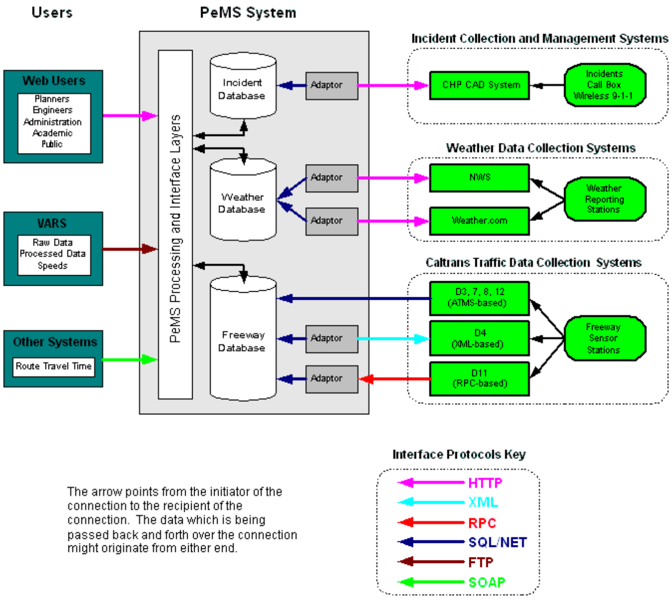
PeMS collects raw detector data in real-time, stores and processes this data, and reports this data through a number of web pages such that engineers can analyze the performance of freeway segments or of the overall freeway system. PeMS collects loop detector data (over 25k individual detectors) from District 3, 4, 7, 8, 11, 12 and stores them online. PeMS is also an Archived Data User Service (ADUS), contains 2 TB of historical data (belongs to past 10 years) online, and adds 2 GB of data each day. The data is available for research analysis.

Figure 2.16: PeMS real-time traffic conditions map



Source: PeMS, 2010. *Performance Measurement System (PeMS) by Caltrans, UC Berkeley, and PATH*. [Online] Available at: https://pems.eecs.berkeley.edu [Accessed 2 May 2011].

Figure 2.17: PeMS System Overview



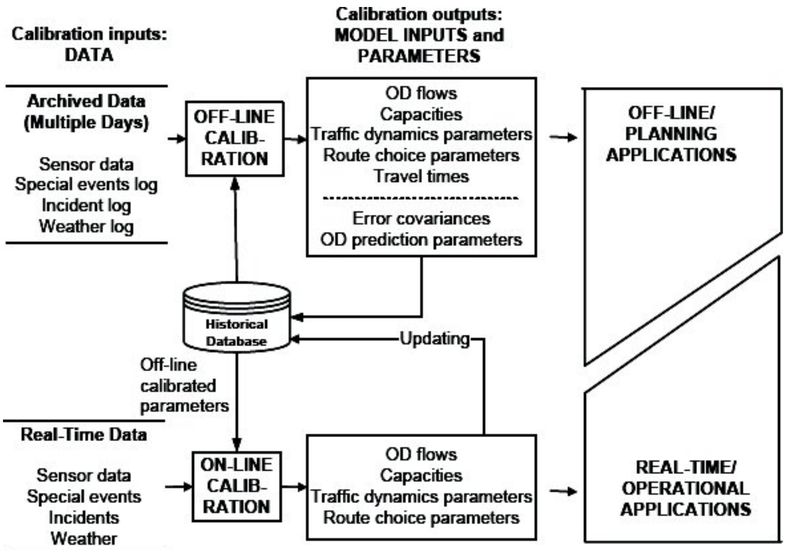
Source: PeMS, 2010. *Performance Measurement System (PeMS) by Caltrans, UC Berkeley, and PATH*. [Online] Available at: https://pems.eecs.berkeley.edu [Accessed 2 May 2011].

PeMS is accessed via a standard Internet browser and contains a series of built-in analytical capabilities to support a variety of uses. In order to use PeMS site, one must apply for an account. The most important capabilities of the system are real-time traffic estimation map, and travel time prediction on pre-defined routes. Prediction system is based on the historical data. Moreover, the date range for the historical data can be chosen by the users (PeMS, 2010).

2.4.4 DynaMIT

DynaMIT can be described as another solution for Advanced Traveler Information Systems (ATIS) which is conducted by Massachusetts Institute of Technology (MIT). The system is composed of two sub-systems: State Estimation and State Prediction.

Figure 2.18: DynaMIT state estimation and prediction processes using real-time traffic data



Source: Antoniou, C.R., Balakrishna, H., Koutsopoulos, N. & Ben-Akiva, M.E., 2009. Off-line and online calibration of dynamic traffic assignment systems. In *Proc. 12th IFAC Symposium on Control in Transportation Systems*., 2009,

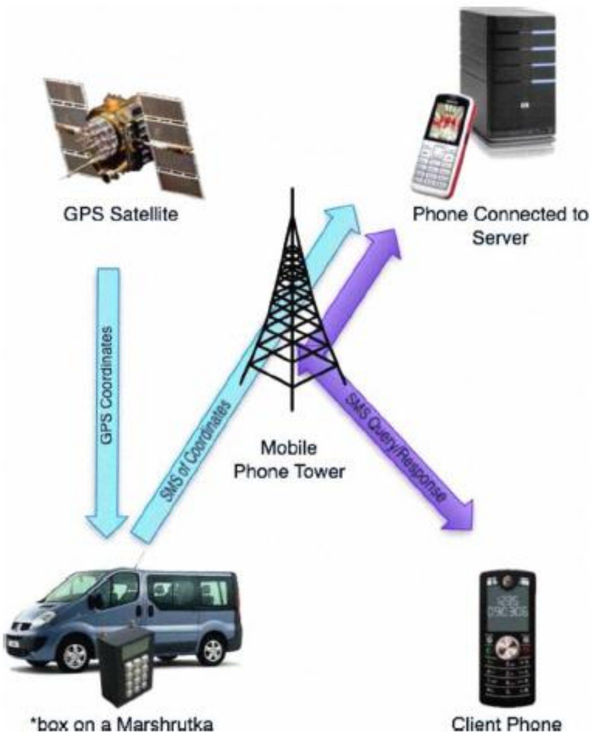
State estimation combines the available surveillance with historical information to estimate the current state of the entire network. Pre-trip demand is simulated, allowing drivers with different characteristics to dynamically change their departure time and travel mode. This is followed by OD (Origin-Destination) flow estimation and network estimation. The estimated network condition is then compared to surveillance information. Inconsistent estimations are unaccepted and a new iteration of estimation is initiated.

After the state estimation process, state prediction is done by first indicating the pre-trip predictions then followed by OD (Origin-Destination) prediction and network state prediction. DynaMIT system architecture is demonstrated in Figure 2.18.

2.4.5 *bus (Starbus)

Another research interest is developing a multi-functional box which can be used as a part of bus arriving systems, which is developed by University of Washington. This box can be implemented to the bus and passenger information system can be designed via SMS. Box hardware consists of two components: GPS module for gathering location information and GSM modem which can be combined in a single package using a local SIM card. GSM modem is used for connecting central server via SMS messages.

Figure 2.19: Use of in-vehicle multi-functional box systems for receiving / transmitting floating car data



Source: Anderson, R. et al., 2009. Building a transportation information system using only GPS and basic SMS infrastructure. In *International Conference on Information and Communication Technologies and Development (ICTD).*, 2009, pp. 233-242.

Central server updates and stores GPS data for indicated time intervals and the components of the server can be declared as: a laptop computer which is connected to GPS-enabled mobile phone and serves as an SMS gateway. Server uses MySMS which is an application framework for implementing a system that connects via SMS.

Table 2.2: Comparison of existing traffic solutions I

Name / Partner	Subcategory	Requirements	Providers	Approach	Challenges	Prediction	Real-Time Data
MSNDirect USA 2004-2010	Location Based Services	MSNDirect is widely used with GPS devices. Each company should design their own software for implementing the system	Microsoft	The system provides real-time traffic information by Microsoft Directband channel	Microsoft DirectBand can be used only with one FM channel and additional hardware is required. Also data feeds are required for the system	✗	✓
TomTom HD Traffic Netherlands - Portugal	Advanced Traveler Information System (ATIS) Navigation Device	TomTom navigation device has to be implemented to the car for using the system which is widely called as TomTom HD Traffic	Vodafone - TomTom	TomTom has a data fusion engine for estimating the current status of traffic. The engine takes 5 inputs from different sources to provide more accurate information. Vodafone's GSM probe data is the one of this sources which is taken by calculating the traffic status by counting the mobile phones along the route and displays alternative routes according to the TomTom's IQ technology.	Providing real-time information from GSM Probe Data has many challenges : such as identifying the irrelevant probes, decide the direction and speed of the vehicle and identifying whether the signals are coming from the same vehicle or not	✗	✓
CarWeb Taiwan 2008-2010 Chiao Tung University	Advanced Traveler Information System (ATIS)	GPS Data Logger 3G Smart Phone Web Server Database Server	Chiao Tung University	System collects real-time data from GPS Probes via 3G and WiMax	Challenges can be divided into two subcategories as network challenges of 3G and WiMAX and the accuracy of using single data source such as GPS.	✗	✓
IBB Traffic Turkey 2009-2010	Advanced Traveler Information System (ATIS)	No additional hardware is required.	IBB-Microsoft	IBB Traffic is the mobile application that uses cameras, sensors and real-time information data which is provided by IBB, as the sources. Image processing is used for estimating the current status of traffic	System mainly uses cameras for the estimation but traffic cameras are located	✗	✓

Source: Türk Telekom Technical Report, 2011; Robust Traffic Status Estimation and Adaptive Traffic Signaling, December 2011.

Table 2.3: Comparison of existing traffic solutions II

Name	Subcategory	Requirements	Providers	Approach	Challenges	Prediction	Real-Time Data
Smart Bus Stop Turkey 2009-2010 / Istanbul Technical University	Road Side Unit – ATIS(Advanced Traveler Information System)	Sensors for buses, and screens for the stations are required	IBB – ISBAK	Smart Bus Stop can be categorized as a road site unit which is stated at every bus stations and provides real-time bus information such as arrival time of the bus, current traffic status, current location of the bus etc.	Network challenges on road side units such as broadband limitations are main challenges of the system	✗	✓
RDS Link China 2008-2010 / Rice University	ATIS(Advanced Traveler Information System)	FM Receiver	Motorola Qualcomm Inc.	RDS Link is a system which provides an interface to implement RDS-TMC channel sources to the existing software	The main challenges of using RDS-TMC channel as a real-time information provider are the broadband challenges and the implementation of RDS to the existing software	✗	✓
DynaMIT USA 2009-2010 / MIT	ATIS(Advanced Traveler Information Systems)	GPS enabled cell phones	Massachusetts Institute of Technology	DynaMIT collects real-time traffic data from GPS Probes, and evaluation of the information is done on the simulation layer of the system and MITSIM is used as a simulation tool	Complexity of the algorithms causes a low-speed system	✓ Short Term Prediction	✓
Mobile Millennium USA 2008-2010 / UC Berkeley	ATIS(Advanced Traveler Information System)	GPS enabled cell phones	Nokia – UC Berkeley	System architecture is based on using GPS enabled cell phones to provide real-time information and demonstrating the estimation of the current traffic status on live maps in a mobile application	Mobile Millennium uses GPS probe data for estimation and usage of one kind of data as a source decreases the accuracy of the system	✗	✓

Source: Türk Telekom Technical Report, 2011; Robust Traffic Status Estimation and Adaptive Traffic Signaling, December 2011.

Figure 2.20: Multi-functional box developed for the research in Kyrgyzstan

Source: Anderson, R. et al., 2009. Building a transportation information system using only GPS and basic SMS infrastructure. In *International Conference on Information and Communication Technologies and Development (ICTD).*, 2009, pp. 233-242.

2.5 EU PROJECTS

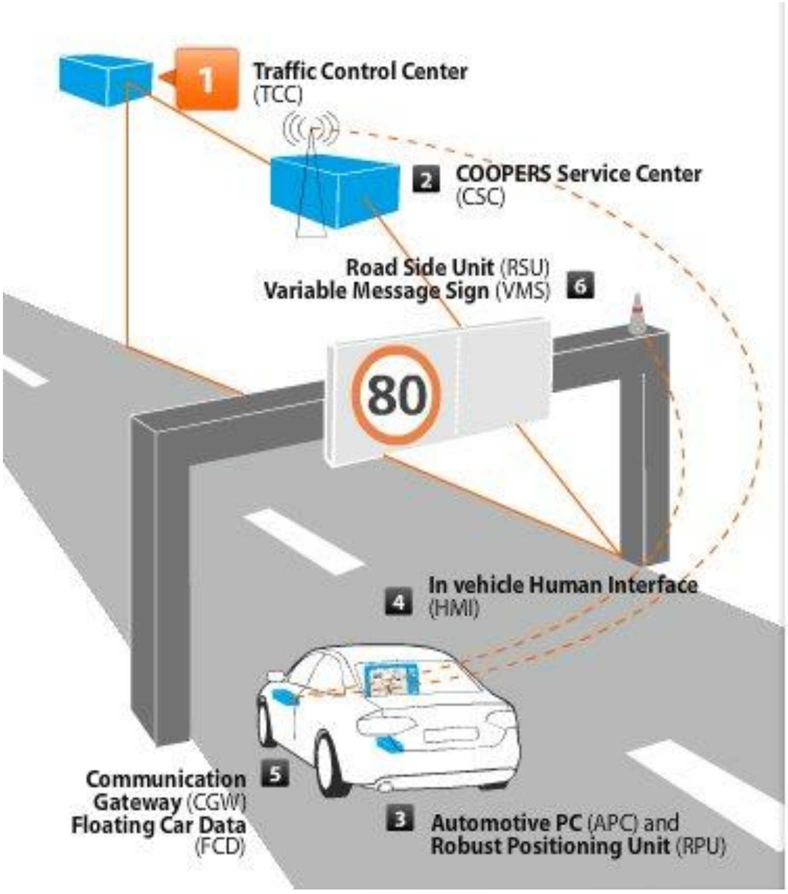
Some other existing projects funded by European Union (EU) are also investigated. These solutions were compared according to the same metrics; namely, subcategory, requirements, providers, approach and challenges. See Table 2.4 for the comparison of EU projects which are COOPERS, CVIS, NOW and HAVE-IT.

Currently, eighteen projects are funded by European Union 7th Framework Programme. These projects can be categorized according to their objectives such as: traffic management systems, road safety, energy efficiency, autonomous driving, toll collection etc. But we mainly focus on traffic management systems in our research so we have investigated existing solutions in 7th Framework Programme, which are related with traffic management systems.

2.5.1 COOPERS (2006-2009)

COOPERS is an EU funded project which offers solution for managing traffic congestion, road safety, and also autonomous driving. System provides information by I2V communication via TMC RDS channel. Traffic information is obtained via road sensors, and tolling systems, then data is forwarded to the road side units via TMC RDS channel, Road Side Units process data and forwards to traffic control center, decisions are made and processed-data is sent back to the road side units and road side units forward data to the Human Machine Interface System in cars to display safety warnings and alternative routes.

Figure 2.21: System architecture of COOPERS solution



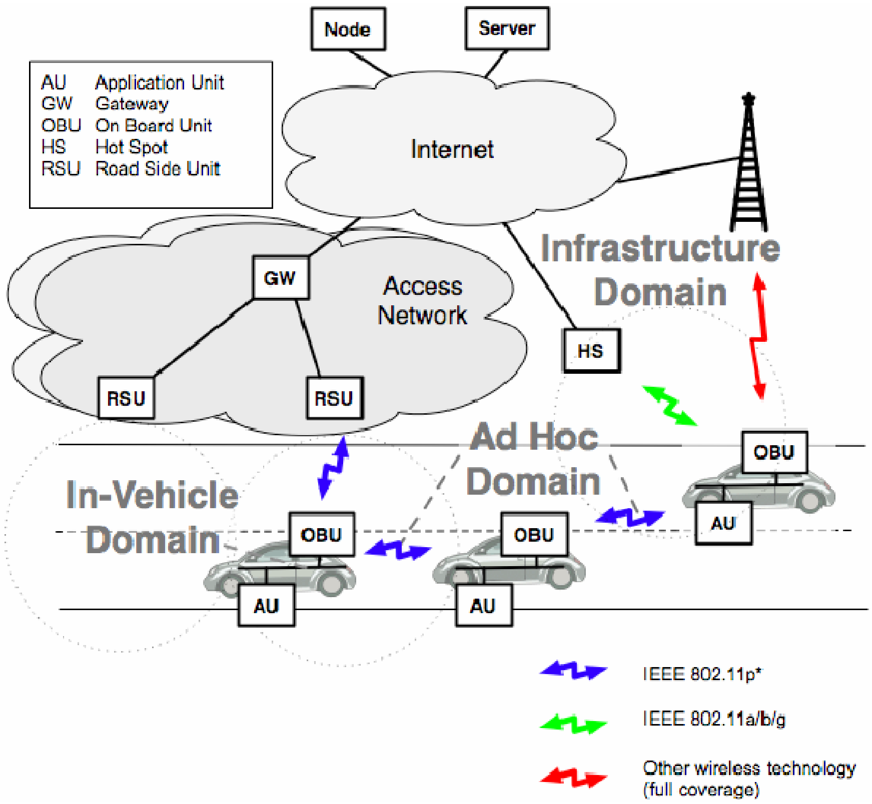
Source: COOPERS, 2006-2010. *European Union ITS Project: COOPERS*. [Online] Available at: http://www.cooper-eu.org [Accessed 13 October 2010].

2.5.2 NOW (2008-2009)

Another project which is funded by EU is "Network on Wheels" (NOW). The objective of this project is to provide car-to-car and car-to-infrastructure communications for traffic management. System mainly has 3 elements: On-board Units (OBU), Application Units (AU) which are in cars on roads and Road Side Units (RSU) on roads. Two different technologies are used for establishing the connection between OBU's and RSU's and these are: GPS and Wireless LAN IEEE 802.11. Two different OBU's are communicated via ad hoc networks and OBU's and RSU's are communicated using

IEEE 802.11, other technologies such as TMC RDS channel is used for forwarding data from RSU's to the central server.

Figure 2.22: System Architecture of NOW



Source: NOW, 2004-2008. *European Union ITS Project: NOW*. [Online] Available at: http://www.network-on-wheels.de/ [Accessed 21 November 2010].

2.5.3 HAVEit (2008-2010)

In the scenario of driving from point A to point B:

a. Select Optimal Route

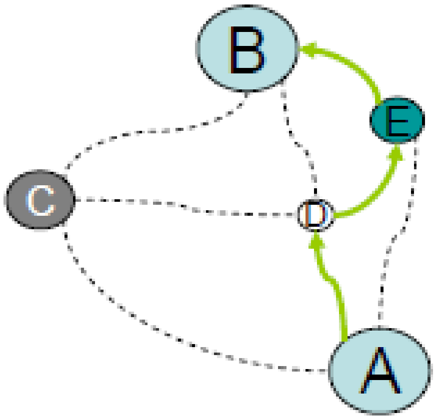
- **i.** Fuel consumption
- **ii.** Duration, start time
- **iii.** Topology, weather
- **iv.** Road costs

b. Take into account

- **i.** Obey Rules
- **ii.** Avoid/minimize risks
- **iii.** Experience
- **iv.** Digitized map
- **v.** Traffic information

HAVEit is an EU-funded project, and it provides a scalable vehicle architecture, by means of smart sensors, standard fail silent Electronic Control Units (ECU) and smart actuators, will be defined to cope with the needs for highly automated driving, based on conventional actuators up to fail tolerant integration of drive-by-wire to allow autonomous driving (HAVEit, 2008-2011). Various sensors in cars are used for traffic management applications, and human machine interface is designed for driving assistance system.

Figure 2.23: HAVEit - Decision Mechanism & Optimum path from source A to destination B



Source: HAVEit, 2008-2011. *European Union ITS Project: HAVEit*. [Online] Available at: http://www.haveit-eu.org [Accessed 20 December 2010].

2.5.4 CVIS (2007-2010)

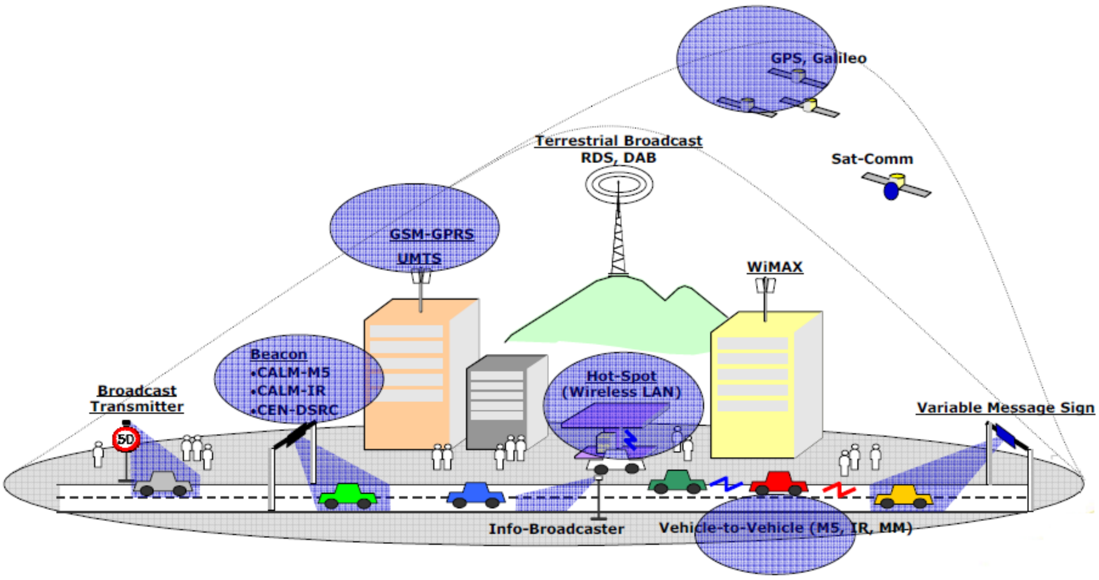
CVIS is the another existing solution which is funded by EU, and its objectives include providing real-time information to the drivers, establishing car-to-car and car-to-infrastructure communications, providing parking slot management and developing adaptive traffic light system and VMS (Vehicle Message System). CVIS collects floating car data via GPS and broadcasts this data using TMC RDS channel.

Table 2.4: Comparison of European Union projects and solutions

Name & Period	Subcategory	Requirements	Providers	Approach	Challenges
COOPERS (2006-2010)	Vehicle to vehicle and vehicle to Infrastructure communication	The implementation of this project requires road side units.	European Car-to-Car Consortium.(Austria Tech) Supported by EU 6th Framework Programme	This project focuses on the advance of telematics applications on the road.	The system requires in-vehicle units, road side units. Lots of hardware implementation is required.
CVIS (2006-2010)	Advanced Traveler Information System (ATIS) V-2-V and V-2-I communication	System provides communication between cars and infrastructure by especially using “Wi-Fi for mobiles”. It also uses 3G and DSRC for communication	European Car to Car Consortium (EU funded project)	To create a technical solution allowing all vehicles and infrastructure elements to communicate with each other in a continuous and transparent way using a variety of media and with enhanced localization	The network limitations of Wi-Fi and 3G. Also network violence can be explained as another challenge.
NOW (Network on Wheels) (2008-2012)	Car-to-Car Communication	On-board Units are required	European Car to Car Consortium EU Funded Project	System collects data via ad hoc networks and IEEE 802.11	Specification of position based routing and forwarding protocols, adaption of wireless LAN under realistic radio conditions
HAVE-IT (2008-2012)	Advanced Traveler Information System (ATIS) ADAS joint system	On-board Units are required	European Car to Car Consortium EU Funded Project	Design of the task repartition between the driver and co-driving system (ADAS) in the joint system	Designing of HMI's (Human Machine Interface) and complexity of DSU algorithm

Source: Türk Telekom Technical Report, 2011; Robust Traffic Status Estimation and Adaptive Traffic Signaling, December 2011.

Figure 2.24: CVIS system architecture



Source: CVIS, 2004-2010. *European Union ITS Project: CVIS*. [Online] Available at: http://www.cvisproject.org/ [Accessed 17 October 2010].

The system provides car-to-car communication (DSRC), hot-spots (wireless LAN) and also WiMAX communications. Park Slot Management is one of the key features of this project and the data related to parking is obtained using DSRC connection.

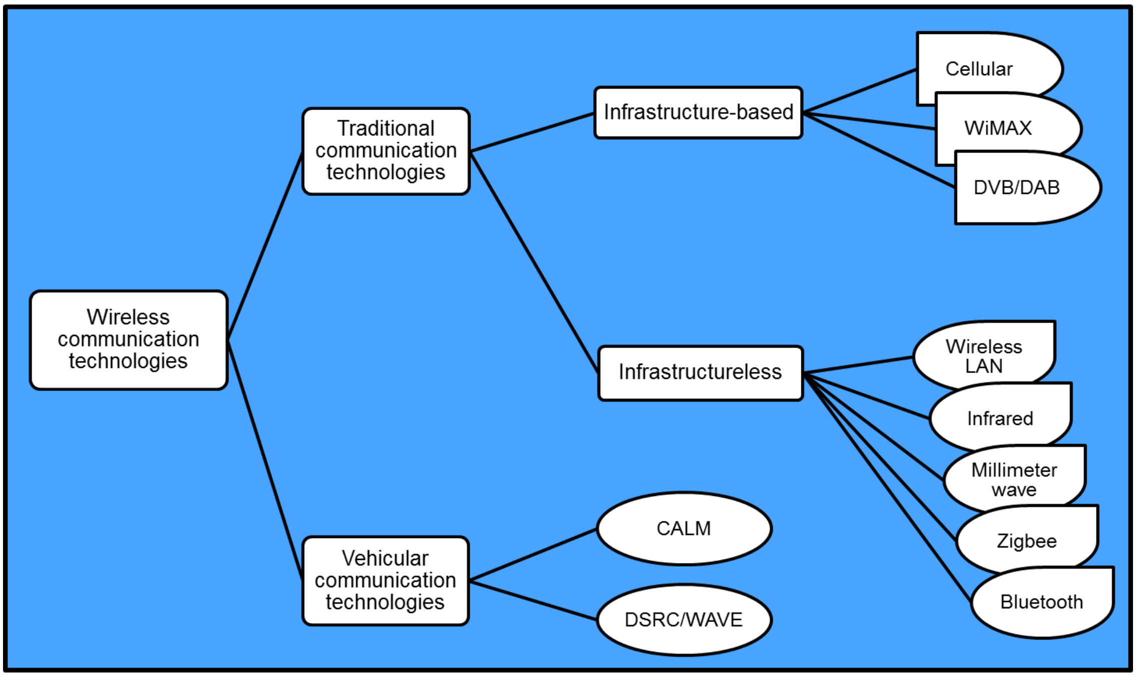
2.6 COMMUNICATION TECHNOLOGIES

This section briefly explains the possible communication services that can be used in the smart transportation systems. Communication technologies which are used in many ITS researches, can be subcategorized into two parts: Traditional Communication Technologies and the Vehicular Communication Technologies. Each of these technologies that have advantages on their own is provided below.

2.6.1 Traditional Communication technologies

Traditional Communication technologies can be divided into two subcategories as Infrastructure based and infrastructure-less according to their communication ranges. Infrastructure based technologies have a long communication range while infrastructure-less technologies have less than 1km communication range. These technologies can be listed as Cellular Communications (GPRS, 3G, LTE, EVDO), WiMAX, DVB, WLAN, Infrared, Bluetooth, ZigBee, Millimeter-wave (MMWAVE) (Dar et al., 2010), (Huang & Chen, 2009).

Figure 2.25: A classification of Wireless Communication Technologies used in ITS



Source: Dar, K. et al., 2010. Wireless communication technologies for ITS applications [Topics in Automotive Networking]. *IEEE Communications Magazine*, **48** (5), pp.156-162.

2.6.2 Vehicular Communication Technologies

Since ITS market improves, the need for special communication technologies increases. Vehicular communication specific networks were developed to satisfy the increased sensor based applications requirements. These are basically, DSRC (Dedicated Short Range Communication), WAVE (Wireless Access in the Vehicular Environment), CALM (Communication Air interface for Long and Medium range) (Huang & Chen, 2009).

Table 2.5: Comparison of wireless communication technologies for Smart Transportation Systems

	Data Rate	Range	Mobility	Operating Band	Latency	Usage Area in ITS
GSM/GPRS	80-384 Kb/s	10km	Yes	0.8-1.9 GHz	1.5-3.5 sec	• Incident Management • Traffic Management • Infotaintment
WiMAX	1-32 Mb/s	15km	Yes	5.x GHz	110 ms	• Contextual Applications
DVB/DAB	1.73 Mb/s	40km	Yes	6-8 MHz	10-30 sec	• Traffic Management • Contextual Applications
WLANs(a/b/g/n)	54-600 Mb/s	250m	Limited	2.4-5.2 GHz	46 ms	• In Vehicle Connection
MMWAVE	1 Gb/s	10m	Limited	60-64 GHz	150 µs	• In Vehicle Connection
IR	1 Mb/s	10m	No	2.6 GHz	Very Low	• Road Monitoring
ZigBee	20-250 Kb/s	100m	Yes	2.4-2.5 GHz	16 ms	• Road Monitoring
Bluetooth	1-3 Mb/s	10 m	Limited	2.4 GHz	100 ms	• On Board Applications
DSRC/WAVE	6-27 Mb/s	1 km	Yes	5.8-5.9 GHz	200 µs	• Collision Avoidance • Road Sign Notifications • Incident Management • Traffic Management • Contextual Applications • Road Monitoring
CALM (M5)	6 Mb/s	1 km	Yes	5-6 GHz	200 µs	• Road Sign Notifications

Source: Türk Telekom Technical Report, 2011; Robust Traffic Status Estimation and Adaptive Traffic Signaling, December 2011.

3. ROBUST TRAFFIC STATUS ESTIMATION

It is often mentioned as a solution that can tackle the congestion is to construct new roads as well as enlarge current motorways in order to increase the capacity of the infrastructure (Bellemans et al., 2003). However it is a costly work and a long-term solution. What these cities require is a cost-effective and short-term solution.

Knowing the shortest route to the destination does not solve any problems in today's crowded cities. It only serves as the basic approach for supplying information such as travel length and travel time under free flow which is calculated with the speed limits of the corresponding roadway. Even knowing the real-time travel information cannot help the travelers since the traffic states are extremely unstable. None of the travelers that check the real-time traffic congestion can know what kind of surprises await them during a trip. What people need to and want to know are the answers to the questions like: "What is going to happen after 10 minutes?", "Will the traffic that is occurring 10 km ahead affect my trip?", "How long it will take for me to go to home if I leave the office 15 min later from now?" Because the unstable characteristics of the road traffic may lead to traffic states which are quite the opposite of what we see on and expect from the real-time traffic screens.

The role of traffic models in this sense is beyond the foreseen. They play quite an important part in both contemporary traffic research and traffic applications such as traffic control, incident detection and flow prediction. The biggest impact of the traffic models come from the fact that it provides the only possible way that can help not just to interpret the effects of the traffic congestion, but also to build up a mechanism to predict the near future congestion states of the system which are commonly up to 30 minutes. Predicting the future congestion states enables the users to optimize their departure time in advance, hence providing them an effective time management possibility. It serves as a short-term approach to solve, reduce or at least postpone the traffic problem.

3.1 TRAFFIC THEORY EQUATIONS AND BASICS

The most common equation used in the traffic theory is the one that introduces the relationship between Flow (q), Density (ρ) and Velocity (v):

$$q = \rho \, . \, v \quad , \; \textit{Flow = Density . Velocity} \qquad \textbf{(3.1)}$$

Density can also be expressed as the reverse of spacing between the vehicles. That is.

$$\rho = 1/s \quad , \; \textit{Density = 1 / Spacing} \qquad \textbf{(3.2)}$$

3.2 TRAFFIC THEORY PARAMETERS

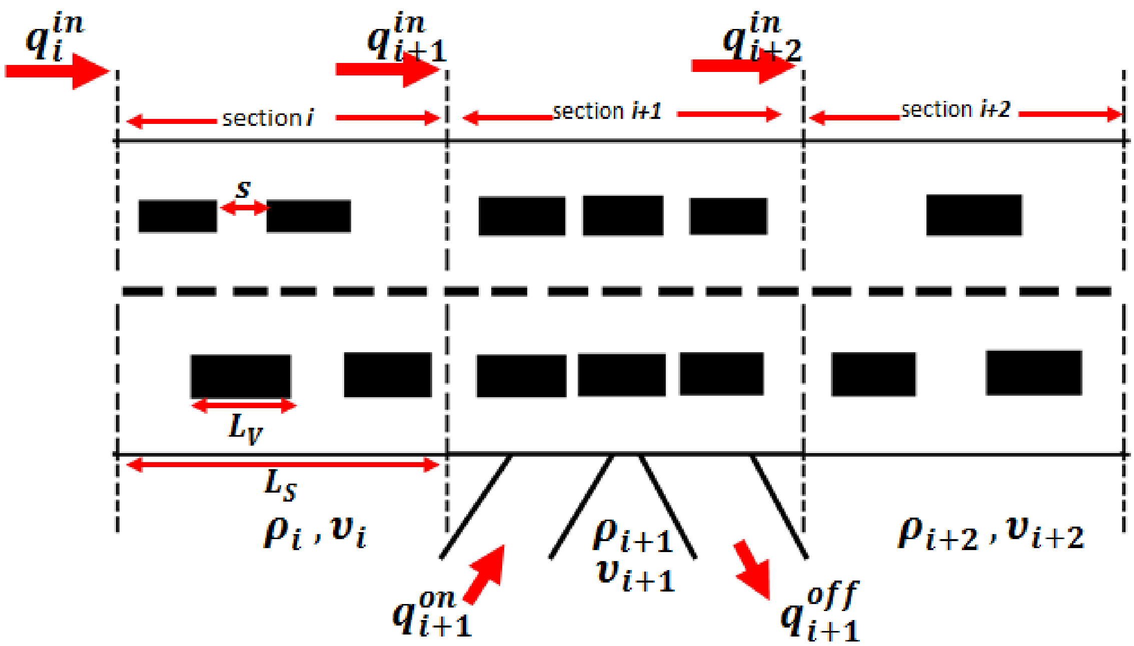
Traffic theory is a hard to handle and explain phenomenon without the help of some specific set of parameters. The most common terms used in equations and discussions are explained in this section.

i. ***q*** : is the parameter that is also known as flow variable. Flow is determined as the number of vehicles that pass from a fixed point per hour and is given in terms of vehicles per hour (veh/h). It is the most common parameter in traffic theory. A 10 min volume can be converted to flow by multiplying its value with 6, since 10 min is the one sixth of an hour. For instance, if a 10 min volume of a road segment is 100 vehicles then its equivalent rate in terms of flow is 600 veh/h.

ii. ***ρ*** : is the parameter that is also known as density variable. Density is determined as the number of vehicles present on a given length of roadway, and is reported in vehicles per km (veh/km) or mile at a particular time instant. Higher densities imply that the vehicles are quite close to each other while low densities indicate long distances (spacing) between vehicles.

iii. $\boldsymbol{v}$: stands for the speed (velocity) of a vehicle at a given time instant. It is defined as the distance traveled within a certain amount of time, e.g. km/h. Since the speed of vehicles will differ from each other, the average speed should be taken into account in traffic flow calculations. In our calculations we take the average speed of many vehicles inside a road segment.

Figure 3.1: Basic parameters of Traffic Flow shown on a three segment roadway



Source: Türk Telekom Technical Report, 2011; Robust Traffic Status Estimation and Adaptive Traffic Signaling, December 2011.

iv. ***space mean speed***: The arithmetic mean of the speed of those vehicles occupying a given length of road at a given instant. It is calculated as $v_s = (n / \sum_{i=1}^{n} (1/v_i))$

v. ***time mean speed*** : The arithmetic mean of the speed of vehicles passing a point during a given time interval. It is calculated as $v_t = \left(\frac{1}{m}\right) \sum_{i=1}^{m} v_i$

vi. $\boldsymbol{L_v}$: This is the vehicle length which is used to calculate both jam density ρ_j and critical density ρ_c. We take it as approximately 5.5 meters in our calculations.

vii. $\boldsymbol{s}$: Spacing is the physical distance (space) between two vehicles and is the inverse of density. The space referred here is measured between the front bumper of the leading vehicle and the front bumper of the following vehicle. Space is the product of speed and headway and generally given in unit of meters.

viii. $\boldsymbol{c}$: Clearance is similar to spacing. However, clearance indicates the distance between the rear bumper of the leading vehicle and the front bumper of the following vehicle. In this sense, clearance equals the spacing minus the length of the leading vehicle. Again similar to spacing, its unit is in meters.

ix. $\boldsymbol{h}$: Headway stands for the temporal space between two consecutive vehicles. To get into more detail, it is the time which elapses during the arrival of leading vehicle and the following vehicle at a fixed point. Headway variable is generally determined as in seconds.

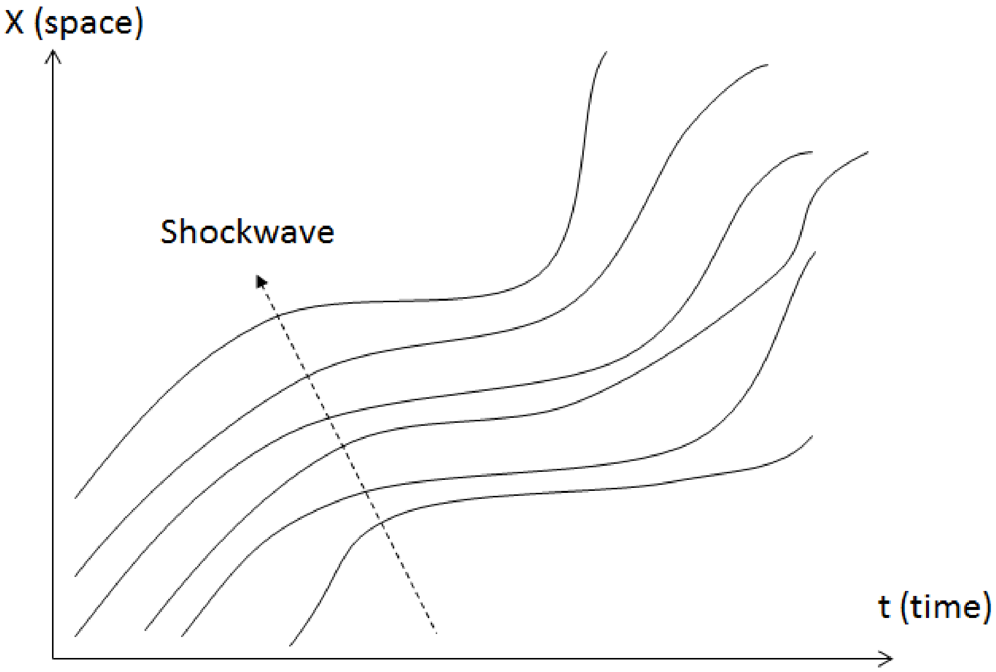
x. $\boldsymbol{g}$: Gap is a similar to headway parameter. It is the measure of time that elapses during the departure of the first vehicle and arrival of second vehicle at a given point. It is measured between the rear bumper of the lead vehicle and the front bumper of the second vehicle, where headway refers to front to front bumper times. Unit of gap is in seconds.

xi. $\boldsymbol{volume}$: It is the number of vehicles that pass a given point on the roadway in a specific period of time. For instance, a 10 minute volume means the counted number of vehicles that passed the fixed point on the roadway during a 10 minute period. Usually, volume is directly converted to flow (q) for convenient calculations.

xii. $\boldsymbol{peak\ hour\ factor}$: This describes the relationship between hourly volume and the maximum rate of flow within the hour: PHF = hourly volume/maximum rate of flow. For the 15 minute periods, PHF = volume/4 x (maximum 15 minute volume within the hour). PHF = q_{60}/q_{15} (Wei et al., 2009).

xiii. $\boldsymbol{shockwaves}$: Shockwaves occur as a result of differences in flow and density which occur when there are constrictions in traffic flow. These constrictions are called bottlenecks. The speed of growth of the ensuing queue is the shockwave, and is the difference in flow divided by the difference in density. For instance, when a crash occurs and one or more of the lanes are closed to traffic a bottleneck occurs right at that crash zone. This bottleneck will cause a shockwave traffic along the crash zone.

Figure 3.2: Shockwave analysis on a time-space diagram



Source: Türk Telekom Technical Report, 2011; Robust Traffic Status Estimation and Adaptive Traffic Signaling, December 2011.

xiv. $\boldsymbol{interrupted\ flow}$: It occurs when the flow is periodically interrupted by the external entities, primarily by the traffic control devices.

xv. $\boldsymbol{uninterrupted\ flow}$: It occurs when vehicles traveling on a route are not affected by external conditions such as traffic signaling devices that might possibly interrupt their normal cruise.

xvi. $\boldsymbol{travel\ time}$: The total time spent between when vehicle starts traveling from source point and reaches to destination point over a specified route under regular conditions.

3.3 FUNDAMENTAL DIAGRAM

Fundamental diagram is used to show the basic relationship between the flow (vehicle/h) and density (vehicle/km) at a given location or section of the motorway. In other words, it describes the behavior of traffic in aggregated variables (average speed, average density, and average flow). Fundamental diagram is one of the basic concepts in traffic theory because of the comprehensive insight it provides. In addition, the determination of the traffic dynamics such as maximum traffic flow (Q_{max}, a.k.a. capacity, measured in vehicle per hour), critical density (ρ_c, measured in vehicle per km), jam density (ρ_j, measured in vehicle per km), free flow speed (V_f, measured in km per hour) and congestion wave speed (w, measured in km per hour) for a particular segment of a roadway are found by the fundamental diagram.

The relationship between density and velocity can be explained as the more vehicles on the road, the slower the velocity. Fundamental diagram can play the role of a controller where the vehicles entering a road should be equal to vehicles leaving the road. Hence the traffic flow can be kept stable. State of the flow changes to unstable when a critical density is reached.

3.4 TYPES OF THE FUNDAMENTAL DIAGRAM

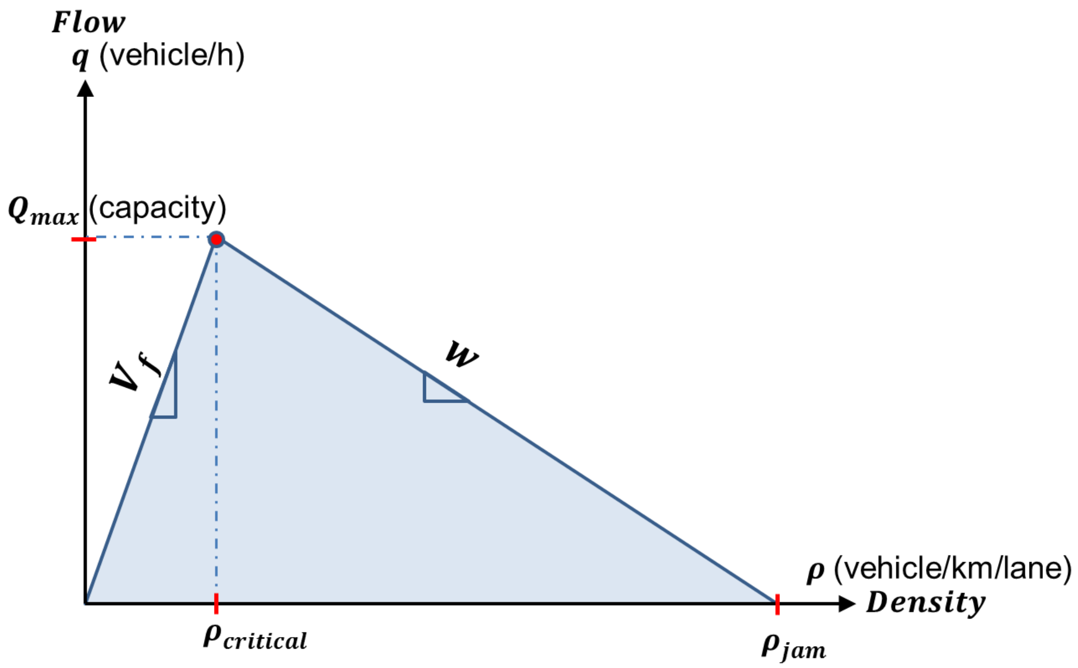
There are three types of Fundamental Diagram in traffic systems. These can be listed as:

- **a.** Flow-Density
- **b.** Speed-Density
- **c.** Speed-Flow

The one most related to our research is the flow-density diagram. Flow density diagram is used to give the traffic conditions of a roadway. With the help of pre-determined traffic conditions, time-space diagrams can be created to give travel time, delay, and queue lengths of a road segment.

If we observe the traffic for a segment over the roadway and plot the flow (veh/h) versus the density (veh/km/lane) for the related segment a curve similar to that in Figure 3.3 occurs. This curve has a characteristic shape which is the same for every roadway section.

Figure 3.3: Flow-Density Fundamental Diagram in traffic theory



Source: Türk Telekom Technical Report, 2011; Robust Traffic Status Estimation and Adaptive Traffic Signaling, December 2011.

When the density is zero which means there are no vehicles in the road, then flow is definitely zero, as well. Traffic flow increases with increasing traffic density. Increasing the traffic density more will result a slowing down effect on the increment rate of traffic flow. After a specific point, the flow reaches a maximum for a density that in the literature called the critical density (ρ_c). When the density is greater than the critical density, the traffic flow on the roadway starts decreasing. As the density increases further, the flow converges to zero for a density that is called the jam density (ρ_j) in the literature.

There are two types of flow-density graphs. One of them is the triangular shaped flow-density curve, which is in the context of our research and also viewed as the more realistic one by the academia. The other one is the parabolic shaped flow-density curve.

The triangular shaped fundamental diagram consists of two vectors. The first one represents the free flow (V_f). It starts from the origin and goes up until the capacity point designated by Q_{max} and calculated via the slope of the corresponding vector. The other vector represents the congested situation of the road. It is named as congestion wave speed vector which is placed between Q_{max} and the point representing the zero flow and jam density ρ_j. At the congested part of the diagram, there is a negative slope which introduces the fact that the higher the density the lower the flow. Intersection of these two vectors is the maximum possible flow that can be achieved under free flow speed.

3.5 PARAMETERS OF THE FUNDAMENTAL DIAGRAM

Parameters that appear on the Flow-Density fundamental diagram are explained in this sub-section. Each of these parameters is essential for obtaining the fundamental diagram, and hence a realistic road network configuration. Obtaining the right diagram lets us to get better real-time simulation and prediction results because of the realistic input.

i. $\boldsymbol{V_f}$: *Free flow speed*, meaning in the speed in an uncongested section. Most of the time equals to the speed limit in the corresponding section.

ii. $\boldsymbol{w}$: *Congestion wave speed*, meaning in the speed that the traffic starts to slow down after reaching the maximum flow on the road section. Most of the time, it is seen along the bottlenecks where the shockwaves occur.

iii. $\boldsymbol{Q_{max}}$: *Maximum flow (capacity)*, meaning in the traffic condition at which the maximum # of vehicles can pass by a point within a given time period.

iv. $\boldsymbol{\rho_c}$: *Critical density* stands for the threshold that the change in density does not affect the free flow speed. It is the maximum density achievable under free flow.

v. $\boldsymbol{\rho_j}$: *Jam density* stands for the minimum density achievable under congestion.

3.6 CALIBRATION OF THE FUNDAMENTAL DIAGRAM

There are two equations corresponding to the relations between maximum flow Q_{max}, critical density ρ_c, jam density ρ_j, free flow speed V_f and congestion wave speed w.

$$V_f = \frac{Q_{max}}{\rho_c} \quad , \quad Free\ Flow\ Speed = \frac{Capacity}{Critical\ Density} \tag{3.3}$$

$$w = \frac{Q_{max}}{\rho_j - \rho_c} \quad , \quad Congestion\ Wave\ Speed = \frac{Capacity}{Jam\ Density - Critical\ Density} \tag{3.4}$$

However, there are more than one unknown parameter. We calculate some of the unknown parameters with the equations below:

$$\rho_c = \frac{Section\ Length}{Vehicle\ Length + \frac{V_f}{2}(spacing)} \tag{3.5}$$

$$\rho_c = \left(\frac{Section\ Length}{Vehicle\ Length}\right)/7 \quad \textbf{(3.6)}$$

We assume the free flow V_f on freeways equals the pre-determined value by the "Karayolları Genel Müdürlüğü", which is implemented as 120 km/h. Another known parameter is the section length which is determined during the segmentation process of the freeway. We take the vehicle length as approximately 5.5 m.

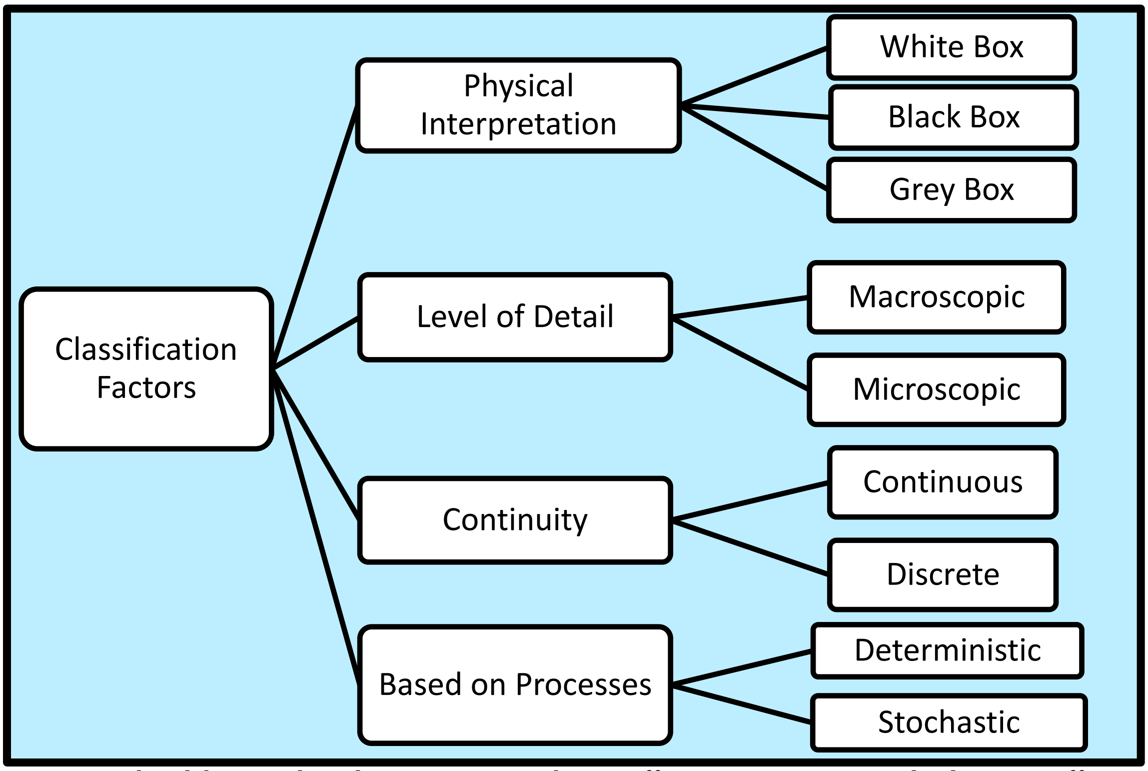
Section Length / Vehicle length stands for the Jam Density (ρ_j) and is the seven times of Critical Density (ρ_c) in the traffic theory.

3.7 MATHEMATICAL TRAFFIC FLOW MODELS

There exists a wide variety of traffic models. The models are classified based on their specific attributes. There are four different factors used in the classification process, 1) Physical interpretation, 2) Level of detail, 3) Discrete versus continuous, 4) Deterministic versus stochastic.

Physical interpretation consists of three major approaches, namely white box, black box, and grey box. In black box modeling, input and output data are recorded and a generic parameterized model is fitted to the data. In white box modeling, physical equations describe the relationships between the different states of the traffic system. In the middle of these models, an intermediate model is the grey box modeling, which is the combination of the other two, and comprised of two phases. In the white box phase, parameterized equations of the motorway states are described; whereas in the black box phase, input/output relation of the traffic model are fitted to input/output measurements, thus the parameters are calibrated. LWR model (Richards, 1956), (Lighthill & G.B., 1955) and Payne model (Payne, 1979), (Payne, 1971) are the products of such a method.

Figure 3.4: Classification of the Traffic Flow Models



Source: Türk Telekom Technical Report, 2011; Robust Traffic Status Estimation and Adaptive Traffic Signaling, December 2011.

Another way of classifying the traffic models is to determine whether it is a deterministic or a stochastic approach. Deterministic models provide a deterministic relation between the states of the system, as well as the inputs and outputs of the related system. In a deterministic approach, simulating a traffic situation more than once with not only the same initial and boundary conditions but also the same input parameters, the results of the simulation will exactly be the same. For instance, the macroscopic model developed by Payne is a deterministic model. On the other hand, stochastic traffic models contain one or more stochastic variable(s). Having at least one stochastic variable means that the results of the two separate simulations of the same model run with the same initial and boundary conditions and the same inputs might yield different results which is directly affected by the stochastic variable's value in each simulation. Paramics simulation tool is an example of such a model. The tool is a microscopic model that requires the distribution function of the level of patience over different drivers to be defined. In every new simulation, this parameter is found by a new sampling of the distribution. Considering large traffic networks, stochastic models have a major drawback in terms of computational power requirements. This project aims at an online prediction mechanism which increases the impact of the computational requirement which makes the stochastic models even more undesirable.

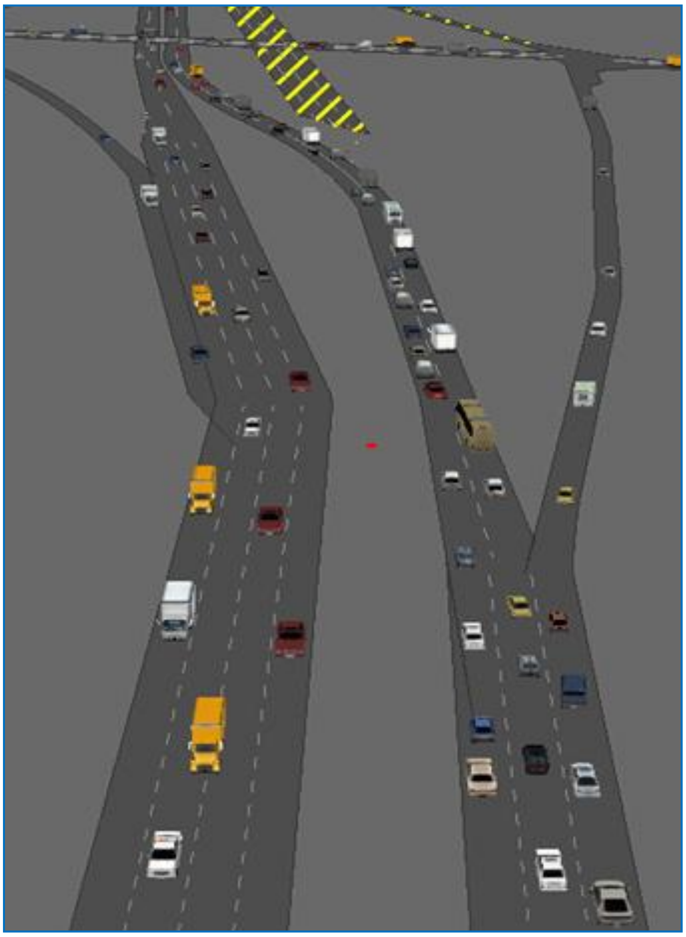
All of the traffic flow models are based on describing the evolution of variables on the corresponding roadway – also known as state variables – over time. Obviously, it consists of two independent variables, namely, time and space. These independent variables can be considered to be either discrete or continuous. For example, the Payne model is continuous in nature. However, the continuous models are too complex that for proper calculation they are discretized. It would not be possible to solve them in real-time if the size of the road network is huge. Payne model is also discretized in both time and space (15 seconds and 500 meters in common) to be able to be simulated by a computer.

The most known model classification is done according to level of detail. Level of detail based classification is composed of two types of traffic flow approaches, one of which is in macroscopic level; the other is in microscopic level. The microscopic flow approach resulted in car-following theory which studies the interactions of one vehicle following the other. On the other hand, macroscopic approach studied the similar behaviors of the fluid dynamics or continuum theories. Unlike microscopic models that studies the individual vehicle dynamics, macroscopic models lack a big level of detail, however gain the ability of monitoring and dealing with the issues of a large scope. What is making a significant difference in macroscopic models is the conservation law of vehicles just like in the fluid mechanics. Conservation law is quite useful especially in describing the waves in a traffic stream, vehicles passing through the waves, and their speed (Haefner & Li, 1998).

3.7.1 Microscopic

Microscopic simulators refer to simulations of all vehicles or particles of the system that are individually identified. Each vehicle's position and velocity define the state of the systems as dependent variables of time. The systems are mathematically represented with ordinary differential equations. The models defined for every single vehicle are the interactions between the vehicles or between the vehicles and the terrain (roadway). In such a system, all the vehicles and their interactions with the environment are calculated and in the end the whole system is shown as a snapshot.

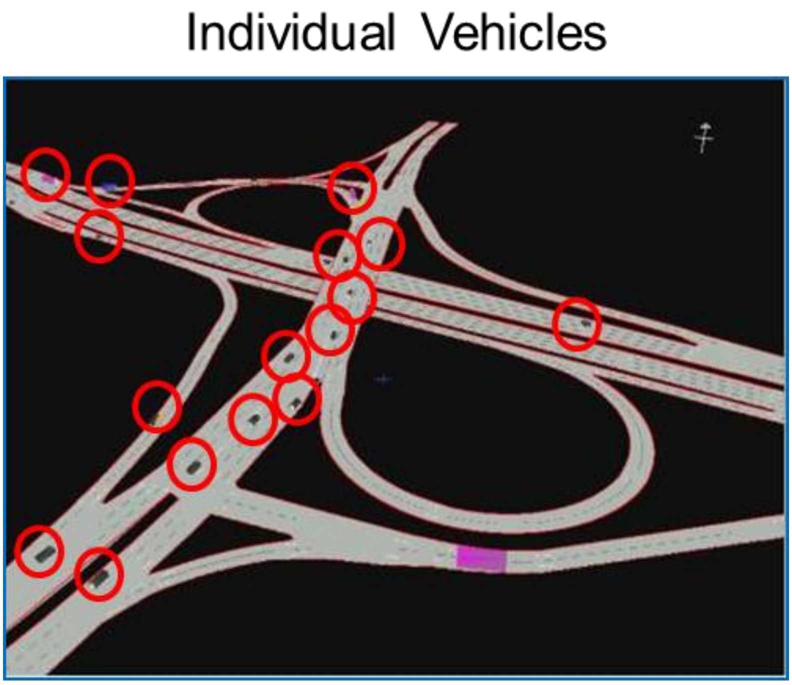
Figure 3.5: Microscopic Model Simulation



Source: Paramics, n.d. *Paramics Traffic Simulator*. [Online] Available at: http://www.paramics-online.com/ [Accessed 23 July 2011].

In Microscopic models the roadway setup is described in terms of fundamental parameters such as overtaking rules, speed limits, number of lanes, etc. In addition to the environmental setup, the vehicles are described one by one in terms of individual parameters such as driver's patience, aggressiveness, reaction time, acceleration, deceleration behaviors; the vehicle's origin, type (bus, minibus, van, etc.) , destination, etc. Both the driver parameters and the vehicle parameters are sampled from a predefined stochastic function that is supposed to be based on the measurements of real life traffic. Each vehicle tries to reach its destination according to the model defined individually for its own. During the whole trip starting from the origin, they interact with each other by overtaking moves and interact with the environment such as obeying the speed limits according to their own microscopic vehicle models.

Figure 3.6: Individually defined vehicles in a system that form the concept of Microscopic Traffic Models and Simulation



Source: Paramics, n.d. *Paramics Traffic Simulator*. [Online] Available at: http://www.paramics-online.com/ [Accessed 23 July 2011].

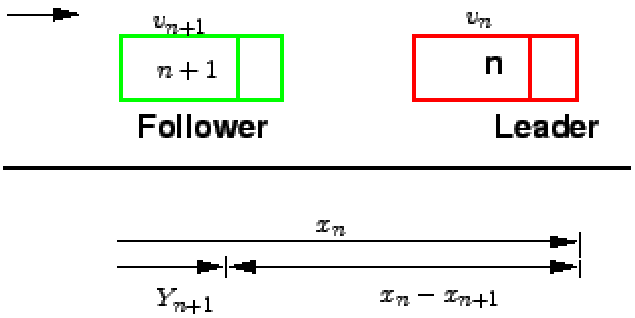
Microscopic traffic flow models are able to yield more accurate and detailed representation of a traffic system, however they require intensive computational power which makes them typically not suitable for real-time implementations. Nonetheless, such implementations are vital for the development of advanced transportation solutions (Zhang et al., 2000) since they help to analyze very small changes in the traffic stream over time and space.

The most known microscopic models are 1) the car following model, 2) the overtaking model.

3.7.1.1 Car following model

Car following model (Kesting & Reiber, 2008) tries to determine how the vehicles tend to follow one another. The model describes the headway (distance) a driver preserves between the own vehicle and the preceding vehicle, in addition to how the driver reacts on traffic in front of its own, in other words the reaction to the acceleration and deceleration of the preceding vehicle. There are two types of parameters defined for the model. The first type introduces vehicle related parameters such as aggressiveness of the driver, size (mass) of the vehicle, acceleration and deceleration. Second type introduces the roadway-setup specific parameters such as speed limit, number of lanes affecting the way a vehicle follows the one in its front.

Figure 3.7: Notation for Car Following Model



Source: Mathew, T.V., n.d. *Microscopic Traffic Flow Modeling*. [Online] Department of Civil Engineering, Indian Institute of Technology Bombay Available at: http://www.civil.iitb.ac.in/tvm/1100_LnTse/509_lnTse/plain/plain.html [Accessed 10 November 2011].

3.7.1.2 Overtaking model

Overtaking model studies the way a driver decides whether or not to overtake the vehicle in the front. In this microscopic model the key attributes are the driver’s desired speed and the vehicle’s acceleration capabilities. Besides, vehicle’s interactions with other vehicles and the number of lanes on the road are the other properties that have influence on the overtaking model. Subject vehicle’s driver decides to overtake depending not only on the speed difference of the own lane and the lane adjacent to it, but also on the available gap on the adjacent lane that determines whether or not it is possible.

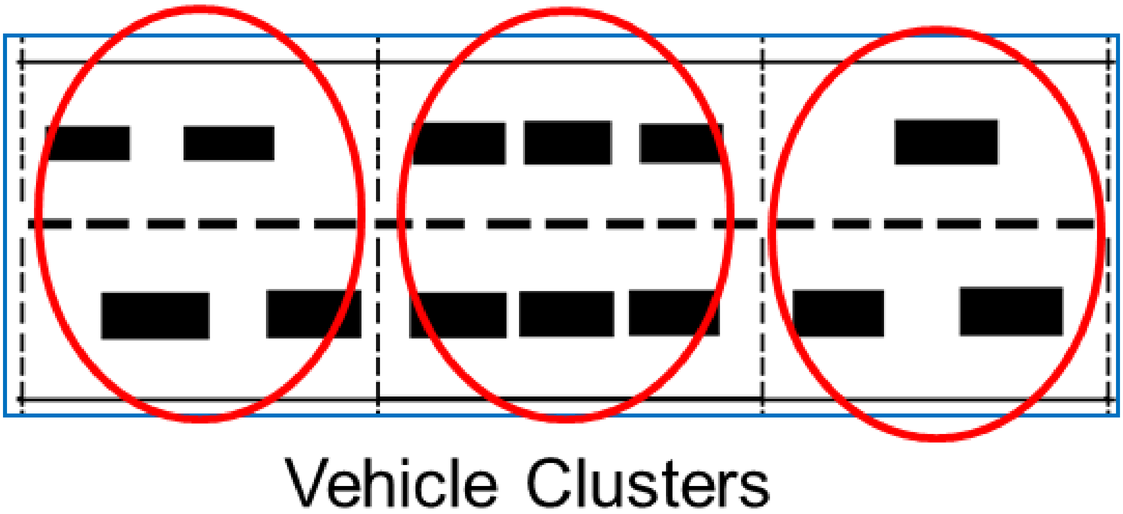
3.7.2 Macroscopic

Unlike microscopic models that represent individual vehicle interactions, macroscopic models have the ability to deal with problems related to a larger scope by sacrificing a decent deal of detail. Macroscopic traffic flow approaches follow the fundamentals similar to that of fluid dynamics or continuum theories. Macroscopic traffic models are often derived using the analogy between traffic flows and fluid flows where the movements of the vehicles exhibit the attributes of the fluid motion (Javed et al., 2010). The most prominent feature of the macroscopic models is the conservation law of vehicles which states that the number of vehicles entering the traffic system must be equal to the vehicles leaving the system.

Macroscopic traffic flow models are characterized in terms of the aggregate variables such as traffic density, space mean speed and traffic flow. Aggregate traffic variable stands for a variable that summarizes information about multiple vehicles. For example, average speed is comprised of the speed of all vehicles present in a given section of the road (Bellemans et al., 2003). In other words, the state of the traffic system is described by the averaged gross quantities regarded as dependent variables of both time and space. The traffic flow is defined as the number of vehicles passing a fixed point per hour and the traffic density is defined as the number of vehicles per kilometer and per lane. Being the functions of two dimensional space (x,y) and time (t) is one of the prominent features of Macroscopic traffic models. Moreover, dynamics of the macroscopic models are described using partial differential equations.

A classification based on the order of the models can be made within the class of macroscopic models. The first macroscopic model developed is LWR (Lighthill-Whitham-Richards) and is a first-order model. The model described by Payne (Payne, 1979), (Payne, 1971) is a second order model since it has two different state variables, namely density and average velocity. Another higher order model is developed by Papageorgiou (Papageorgiou et al., 1990). These three models are the most used ones in practice. Although we have investigated these approaches thoroughly, our project is based on another macroscopic model called CTM (Cell Transmission Model) which is going to be discussed in detail later on. But note that the CTM is also based on the same density calculation approach. Thus it can be said that the CTM is not far cry from these models.

Figure 3.8: Aggregated variables and vehicle clusters that form the basis of Macroscopic Traffic Models and Simulation



Source: Türk Telekom Technical Report, 2011; Robust Traffic Status Estimation and Adaptive Traffic Signaling, December 2011.

Macroscopic models require less computational power compared to microscopic models since they do not describe the traffic situation on the level of independent variables like microscopic models do. Thus it is possible to quickly simulate a with the macroscopic traffic flow models which is a compulsory requirement for online prediction mechanisms. The fact that the macroscopic models have fewer parameters to estimate allows easier calibration and identification of such models. Hence they are better suited for optimal predictive mechanisms.

Furthermore in this section, we will give some insight on three macroscopic models, namely, LWR, Payne and Papageorgiou.

3.7.2.1 LWR model (Lighthill – Whitham – Richards) (first order)

Macroscopic models mimic the analogy between the fluid flows and traffic flows. There exists a law of conservation of vehicles similar to the law of conservation of mass in fluid dynamics literature.

The first macroscopic model is developed by Lighthill and Witham (1955) and later modified by Richards (1956) and its current form was developed. In LWR model there exist only one state variable (density) that resulted in poor momentary behavior. Payne later on (1971) coped with the problem by introducing another partial differential equation that represents the dynamics of the mean speed onto the existing LWR model (Javed et al., 2010), (Bellemans et al., 2003), (Haefner & Li, 1998), (Papageorgiou et al., 1990), (Payne, 1979), (Payne, 1971).

Conservation of vehicles in traffic context can be represented as

$$\frac{n(x)\partial\rho(x,t)}{\partial t} + \frac{\partial q(x,t)}{\partial x} = 0 \qquad \textbf{(3.7)}$$

where $n(x)$is the number of lanes at position *x*, $\rho(x,t)$denotes the traffic density in vehicle/lane/km at location x and time *t*, $q(x,t)$stands for the traffic flow in vehicle/hour at location *x* and time *t*. Among the aggregated variables both $\rho(x,t)$ and $q(x,t)$ are the continuous functions of time and space. However the system is actually not continuous, in the contrary, it is a discrete system since the vehicles on the roadway are discrete. The equation of conservation states that none of the cars can appear suddenly out of blue nor they can vanish, which complies with the law of physics.

The analytical solution as well as the implementation on the computer of the partial differential equations is extremely hard. In order to cope with both complications a discretization process is needed. Discretizing the differential equation for flow yields the fundamental equation that describes the flow in terms of density and velocity. The equation tells that the average flow in each section is average velocity times the traffic density times the number of lanes of that section:

$$q(x,t) = \rho(x,t)\,.\,v(x,t).\,n(x) \qquad \textbf{(3.8)}$$

LWR model observed that the average velocity of vehicles can be expressed as a function of traffic density.

$$v(x,t) = f\big(\rho(x,t)\big) \qquad \textbf{(3.9)}$$

There is several velocity calculations expressed as a function of density. The idea behind these equations tries to represent the relationship of velocity and density such that the average velocity will drop until zero when the roadway becomes congested. One of the empirical velocity formulas is:

$$v_j(t) = V^e\left(\rho_j(t)\right) = v_f.\left[1 - \left(\frac{\rho_j(t)}{\rho_{jam}}\right)^{\alpha}\right]^{\beta} \qquad \textbf{(3.10)}$$

where v_f stands for the free flow speed expressed as the average velocity of all the vehicles belong to section j, V^e is the average speed in equilibrium, ρ_{jam} is the jam density which where the average velocity is zero, α and β are parameters to be calibrated. Parameters that require calibration are needed to be fitted on the traffic data (Bellemans et al., 2003).

LWR is a continuum flow model in both time and space. In order to practically solve this continuum model in a computer simulation the equations are discretized in both time and space which is illustrated in Figure 3.1. Discretization of time is represented with Δt (in our case 10 second intervals). The discretization of space is done in terms of kilometers and represented by either Δx or l_j (length of section j usually in 0.5km to 1km where the main requirement is defined as $\Delta x > v\,\Delta t$. In other words, the minimum space discretized should be greater than the space that can be traveled within one time step under free flow speed condition.

The difference equation represents the LWR model is found by discretizing the conservation Equation (7) is given as:

$$\rho_j(t+1) = \rho_j(t) + \frac{\Delta t}{l_j n_j}\left(q_{in,j}(t) - q_{out,j}(t)\right) \quad \textbf{(3.11)}$$

where $\rho_j(t)$ is the average traffic density in section j and at time period t, n_j is the number of lanes in section j, l_j is the length of section j. $q_{in,j}(t)$ minus $q_{out,j}(t)$ describes the net inflow in section j. The equation tries to describe the density at time $t+1$ and states that it equals the density at previous time interval $t$plus a slight difference in density arises from the net inflow in section j.

Defining the Equations (8), (10), and (11) for each of the sections of a roadway it is possible to implement a simulated model. With the help of the model, it is possible to demonstrate the possible changes in density, flow and speed values of each section for each time interval.

3.7.2.2 Payne model (second order)

Another popular macroscopic simulation model is developed by Payne (Payne, 1979), (Payne, 1971) and named after its developer, Payne model. This model is of second order and includes two partial differential equations whereas LWR model had only one. The first differential equation is the same as LWR's which describes the law of conservation of vehicles. According to the observations the average velocity in a section is not only dependent on the traffic density but also affected by the state of the adjacent sections and the dynamics of the average velocity. The second partial differential equation tries to address these other influential factors.

According to Payne, three factors that influence the change in average velocity can be listed as convection (term 1), relaxation (term 2), and anticipation (term 3). The following differential equation describes the system (actually it is a new form of the velocity calculation used instead of Equation 10):

$$\frac{\partial v}{\partial t} + \overbrace{v\frac{\partial v}{\partial x}}^{1} = \overbrace{\frac{V^e(\rho) - v}{T}}^{2} - \overbrace{\frac{c_0^2}{\rho}\frac{\partial \rho}{\partial x}}^{3} \quad \textbf{(3.12)}$$

where c_0 is the anticipation constant, V^e is the average speed in equilibrium, T is the relaxation constant. Equation 12 describes the change in average velocity as a partial differential equation and is later on discretized for implementation on a computer.

Overall Payne model consists of two state variables, namely traffic density and traffic velocity. The partial differential equation can be discretized similar to how it is done in LWR model which yields the difference equation:

$$v_j(t+1) = v_j(t) + \underbrace{\frac{\Delta t}{l_j} v_j(t)\left[v_{j-1}(t) - v_j(t)\right]}_{term\ 1}$$

$$+ \underbrace{\frac{\Delta t}{\tau}\left[V\left(\rho_j(t)\right) - v_j(t)\right]}_{term\ 2} - \underbrace{\frac{V_a \Delta t\left[\rho_{j+1}(t) - \rho_j(t)\right]}{t l_j\left[\rho_j(t) + K\right]}}_{term\ 3} \quad \textbf{(3.13)}$$

where,

- **a.** t : Time index
- **b.** j : Section index of the roadway
- **c.** $v_j(t)$: Average velocity at time t and in section j
- **d.** Δt : Time increment
- **e.** τ : Time constant
- **f.** l_j : Length of the j^{th} section
- **g.** V_a : Anticipation constant
- **h.** K : Tuning parameter
- **i.** $V\left(\rho_j(t)\right)$: Actual speed at equilibrium defined as a function of density, which is introduced by Equation 10.

Equation 13 says that the speed in section j at time $t+1$ equals the speed in the section j at time t plus a correction for convection anticipation, and relaxation. We refer to Figure 3.1 for an explicit representation of the discretization for both time and space. The average speed in equilibrium is an empirical function of traffic density and needs to be calibrated for the roadway in question. Several formulas for estimating the equilibrium speed are proposed in the literature (Bellemans et al., 2003).

The major difference between LWR and Payne models is the introduction of dynamic equation for the speed in Payne model.

3.7.2.2.1 *Convection term (term 1)*

In reality, it is not possible for vehicles moving from section j-1 to section j to adapt their speed instantaneously. Consider a driver driving from section j-1 to section j will gradually slow down the vehicle's speed as it reaches to section j. This implies that the driver was actually driving the vehicle faster than the desired equilibrium speed of the section j. For the other way around when the vehicle moves in section j-1 slower than the desired equilibrium speed of section j, driver will gradually speed up to adapt to the desired speed in section j as it reaches to that section.

Increased speed differences between consecutive sections will cause a longer period for acceleration or deceleration and eventually result in a greater impact on the average speed in the section. The impact of convection on the average speed is proportional to the speed difference of two consecutive sections and inversely proportional to the length of the section. Consequences of the convection term can be summarized in two: 1) The bigger the speed difference between the sections, the longer it will take for vehicles to accelerate or decelerate in order to adapt their speed due to kinetic energy and the greater the influence on the average speed in the section. 2) The longer the section the longer the vehicles move with their desired speed.

3.7.2.2.2 *Relaxation term (term 2)*

Payne also wanted to describe another fact that the drivers all the time tend to reach their desired speed. In order to reflect this within the mathematical model Payne used the relaxation term. As long as the average speed differs from the desired speed, the average speed will tend to evolve towards the desired speed.

If the actual speed is higher than the desired speed of the road due to generation of traffic congestion, the driver will apply brakes. If the actual speed is lower than the desired speed, then the driver will accelerate. Moreover, an increase in the difference between the actual and the desired speeds indicates an increase in driver's action and thus an increase in relaxation term. In addition to these effects, the driver's swiftness which is denoted by the time constant τ will determine the driver's reaction to deviating speeds. The larger the time constant τ, the slower the drivers reaction and the smaller the relaxation term.

3.7.2.2.3 *Anticipation term (term 3)*

Anticipation term tries to mimic the fact that the driver will anticipate the density of the traffic ahead since the driver looks ahead all the time while driving. If the traffic ahead is congested then the driver will slow down, conversely if the traffic ahead is free then the driver will accelerate more. Anticipation constant $V_a$is proportional to the relative density difference between two sections. Parameters V_a and Kappear in the term are used for tuning purposes. Time constant τ is again used for describing the driver's swiftness of response as in relaxation term.

3.7.2.3 Papageorgiou (second order)

Papageorgiou extended the Payne model by adding two more terms (Papageorgiou et al., 1990). One of the terms describes the effects of the lane drop. The other term takes into account of a merging effect in the presence of on-ramps within the section (Zhang et al., 2000). The ultimate momentum equation is discretized as:

$$v_j(t+1) = v_j(t) + \underbrace{\frac{\Delta t}{l_j} v_j(t)\left[v_{j-1}(t) - v_j(t)\right]}_{term\ 1}$$

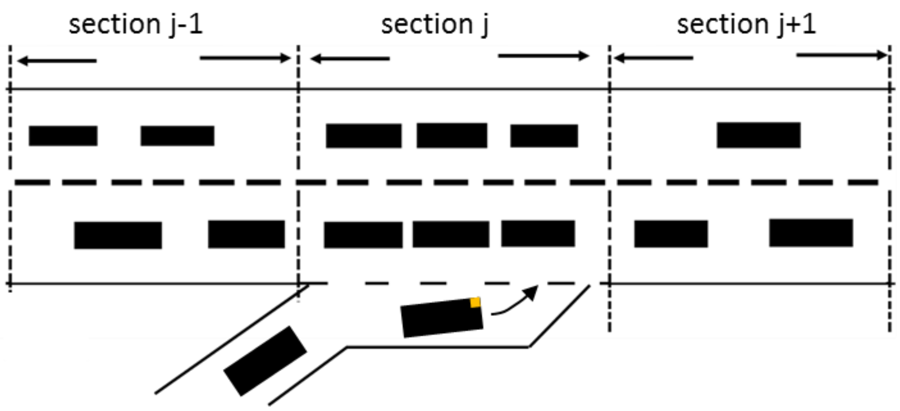
$$+ \underbrace{\frac{\Delta t}{\tau}\left[V\left(\rho_j(t)\right) - v_j(t)\right]}_{term\ 2} - \underbrace{\frac{V_a \Delta t\left[\rho_{j+1}(t) - \rho_j(t)\right]}{t l_j\left[\rho_j(t) + K\right]}}_{term\ 3}$$

$$\underbrace{-\left(\frac{\delta \Delta t}{l_j \lambda_j}\right)\frac{r_j(t) v_j(t)}{\rho_j(t) + L}}_{term\ 4} - \underbrace{\frac{\phi \Delta t}{l_j \lambda_j}\left(\frac{\left(\lambda_j - \lambda_{j+1}\right)\rho_j(t)}{\rho_{jam_j}}\right) v_j^2(t)}_{term\ 5} \qquad \textbf{(3.14)}$$

where the terms 1, 2 and 3 have the same parameters as in Payne model, δ and L are the tuning parameters in term 4 which stands for the merging term, ϕ is used as a tuning parameter and $\lambda_j - \lambda_{j+1}$ indicates the number of lanes dropped while moving from section *j* to section *j+1* in term 5 which is the weaving term that examines lane dropping effects.

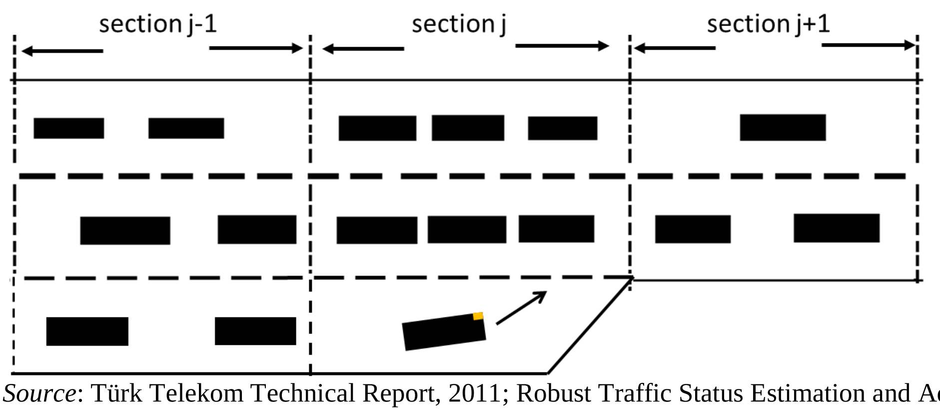
The effects of merging and weaving cases are illustrated relatively in Figure 3.9 and Figure 3.10. For more details on the model we refer the curious reader to Papageorgiou (Papageorgiou et al., 1990).

Figure 3.9: Illustration of a merging case (term 4)



Source: Türk Telekom Technical Report, 2011; Robust Traffic Status Estimation and Adaptive Traffic Signaling, December 2011.

Figure 3.10: Illustration of a weaving case (term 5)

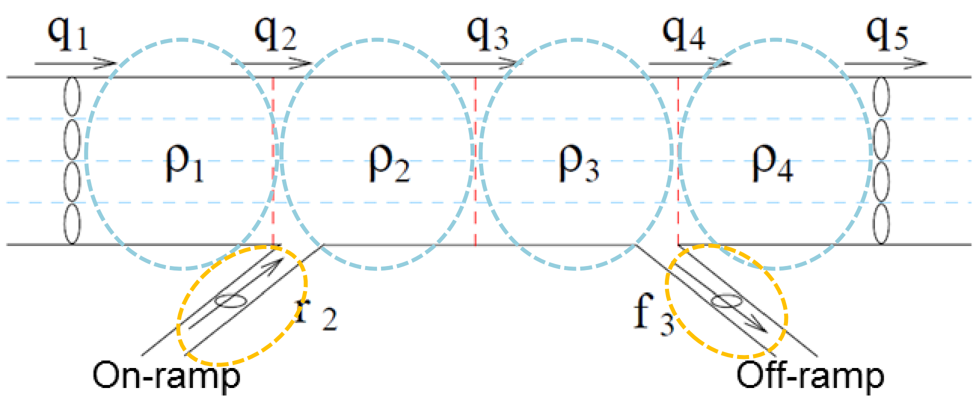


Source: Türk Telekom Technical Report, 2011; Robust Traffic Status Estimation and Adaptive Traffic Signaling, December 2011.

3.7.2.4 Cell Transmission Model (CTM)

The cell transmission model (Munoz et al., 2004), (Munoz et al., 2003), (Daganzo, 1993) as a macroscopic traffic model was selected for this research due to its analytical simplicity and ability reproduce congestion wave propagation dynamics. In the idea of CTM, road is divided into several cells and numbered consecutively starting with the upstream end of the road, from i=1 to N. The lengths of the cells are homogenous and chosen such that they are set equal to the distance traveled by free-flow traffic in one clock tick. The first cell transmission model has been designed for a single freeway link without on-ramps or off-ramps. To iteratively evaluate traffic behavior of each cell in CTM, initial and boundary conditions are required. Initial conditions can be defined as occupancy and flow of each cell. Boundary conditions can be specified by means of input and output cells. The traffic behavior is evaluated every time step starting at t=1,2,....,m due to defined conditions. These fundamentals of CTM are modified to improve flexibility in portioning road. Some of the modifications are a) using non-uniform cell lengths, b) using on-ramp and off-ramps and using cell densities as a state variable instead of cell occupancies. Evaluating the flow and density of each cell at different time step gives us to predict macroscopic traffic condition of each cell. The traffic density of cell i at any time step can be found by conservation of vehicles rules.

Figure 3.11: Cell Transmission Model approach



Source: Türk Telekom Technical Report, 2011; Robust Traffic Status Estimation and Adaptive Traffic Signaling, December 2011.

$$\boldsymbol{\rho_i(k+1) = \rho_i(k) + \frac{T_s}{l_i}\left(q_{i,in}(k) - q_{i,out}(k)\right)} \qquad \textbf{(3.25)}$$

where $q_{i,in}$ *(k)* is total entering flows to cell *i* in vehicles per unit time during k^{th} time interval, $q_{i,out}(k)$ is total leaving flows from cell i, T_s is time interval, *k* is the time index, l_i is the length of cell *i*, $p_i(k)$ is the density in cell *i*, in vehicles per unit length at time $k.T_s$. Results of above equation are affected by some parameters which should be defined for each cell of road. Maximum cell density, flow, critical density, free flow speed and congestion wave speed are important parameters which they can be uniform over all cells or can be different from cell to cell. These parameters are depicted in the fundamental diagram Figure 3.3.

In CTM, connection between cells can be occurred in variety ways as simple, merge and diverge.

Simple Connection: If connection between two cells is occurred without any on-ramp or off-ramps, then we can call them as an example of simply connected. In such case, flow entering from *i-1* to *i* can be calculated by below equation.

$$q_i(k) = min\{S_{i-1}(k), R_i(k)\} \qquad \textbf{(3.26)}$$

where $S_{i-1}(k) = \min\{v_{i-1} * p_{i-1}(k), Q_{M,i-1}\}$, is the maximum flow that can be supplied by cell *i-1* during k^{th} time interval. $Ri(k) = \min(Q_{M,i-1}, w_i(p_j - p_i(k)))$, is the maximum flow that can be accepted by cell i which is sent by cell *i-1* during k^{th} time interval.

Merge: If an on-ramp intervenes between two cells, then the cells can be an example of merge connection. On-ramp can be connected with first cell, second cell or both of them. If it is connected with first cell, flow entering second cell should be sum of first cell mainline flow and on-ramp flow. These case affects downstream of first cell. The second case, on-ramp can be connected with second cell, in such case second cell density will increase by on-ramp flow. The increasing affects congestion wave speed which is important for flow leaving from first cell. Assume that $OR_{d,i}$ is measured demand at on-ramp i, and that OR_i is the actual flow that enters the main line from the on-ramp.

$$q_i = \begin{cases} S_{i-1}, \; S_{i-1} + OR_{d,i} \leq R_i \\ max(0, R_i - OR_{d,i}), \; otherwise \end{cases} \quad \textbf{(3.27)}$$

In such a case $S_{i-1} + OR_{d,i} > R_i(k)$, total flow entering downstream cell (q_i) is equal to R_i (k).

$$OR_i = \begin{cases} OR_{d,i}, \; S_{i-1} + OR_{d,i} \leq R_i \\ R_i - q_i, \; otherwise \end{cases} \quad \textbf{(3.28)}$$

Diverge: When the outflow from a cell is split between the following cell and the off-ramp, a diverge connection is occurred. Diverge connection equation

$$q_{i-1,out}(k) = min\{S_{i-1}(k), R_i(k)/(1 - B_{i-1}(k))\} \quad \textbf{(3.29)}$$

where $q_{i-1,out}$ (k)= q_i (k)+ f_i (k) is the total flow exiting cell i-1, and f_i (k) is the off-ramp flow. The flow entering the downstream cell is then given by (1-B_{i-1}(k)) $q_{i-1,out}$(k), and the flow exiting through the off-ramp is B_{i-1}(k) $q_{i-1,out}$(k), where B_{i-1}(k) is the split ratio for off-ramp i-1, the fraction of vehicles leaving cell i-1 which exits through the off-ramp during k^{th} time interval.

3.8 SIMULATION TOOL: CTMSIM

In order to provide traffic experiments that are safe, fast, cost effective and reproducible we utilize the simulators that best fit the model(s) we have investigated so far. It is possible to simulate specific traffic conditions and situations using the available traffic models. These models can also be used in a simulation tool and run in such a way that becomes a lot faster than real-time to allow for future state predictions. It helps not only to predict but also to evaluate the future states of the traffic in real-time for the purposes of determination and the selection of the alternative routes for certain origin-destination trip that would not be possible otherwise. In addition to the aforementioned potential benefits, simulation tools also allow for the evaluation of the dangerous traffic conditions – e.g. traffic accidents – that would otherwise compromise the safety of the passengers.

CTMsim is an interactive tool and is based on the ACTM model of Gomes and Horowitz (Gomes & Horowitz, 2006). The interface of the tool is intuitive. It is possible to watch the evolution of the traffic temporally and pause it whenever the user wants to change the value of the parameters defined in the fundamental diagram or the flow values in the demand profile to simulate a specific incident/event. CTMsim offers the opportunity to evaluate the effects of traffic situations such as extreme congestion, lane closures due to a crash, and also the prediction of future traffic states with the help of modifications applied on the tool. When the changes are done, the simulation can be continued to see the impacts of the new conditions. Both the original tool and the modified tool were implemented in Matlab environment.

3.8.1 Segmentation Rules

The important issues that needed to be considered during the cell (segment) division process are as follows:

- **i.** Any cell contains no more than one on-ramp, and if there is one, it is located in the beginning of the cell
- **ii.** Any cell contains no more than one off-ramp, and if there is one, it is located at the end of the cell
- **iii.** In ordinary conditions, any cell should contain at most 1 vehicle detector (radar).
- **iv.** Cells are not too long, ideally not longer than 1 km in order to provide realistic traffic dynamics.
- **v.** Cells are not too short, ideally not shorter than 0.33 km to ensure that the length that can be traveled with V_f in one sampling time (Δt) is not larger than the cell length itself.

vi. If two or more on-ramps are very close to each other, we choose to treat them as one with the demand equals to the sum of them.

vii. Similarly two close off-ramps can be collapsed into one with double capacity.

viii. If one on-ramp is closely followed by an off-ramp, we place them in two separate neighboring cells.

ix. The number of cells should also not to be too many, in order to ensure faster execution of the simulation.

3.8.2 Coloring the Segments

Segment colorization is the primary metric that is perceived by the user of the real-time traffic congestion system and the predicted congestion maps. Factors affecting the colorization used in our project are defined as shown in Table 3.1. Most of the conventional systems use only the velocity output as the colorization metric whereas in our system both the flow and the density parameters are the key identifiers of the color scale that varies between green, yellow, orange and red colors.

Table 3.1: Our method's congestion spectrum

State	Cofactor	Flow	Density	Output	Color
1	$.95$	$< Qmax$	$<= \rho_{crit}$	Free	Green
2	$.95$	$>= Qmax$	$<= \rho_{crit}$	Synchronized	Yellow
3	$.95$	$> Qmax$	$> \rho_{crit}$	Congested	Orange
4	$.95$	$<= Qmax$	$> \rho_{crit}$	Jammed	Red

Source: Türk Telekom Technical Report, 2011; Robust Traffic Status Estimation and Adaptive Traffic Signaling, December 2011.

Observations suggest that up to a maximum flow, velocity does not decline while density increases, but above a threshold, increased density reduces flow as well. In light of these observations, optimal coloring of the segments can also be done as in the Table 3.2.

Table 3.2: Theoretical congestion spectrum of road segments

State	Speed	Flow	Density	Output	Color
1	High	Low	Low	Free	Blue
2	Medium	Low	Low	Free	Blue
3	High	Medium	Low	Impeded Free	Green
4	High	High	Medium	Impeded Free	Green
5	Medium	High	Medium	Synchronized	Yellow
6	Medium	Medium	Medium	Synchronized	Yellow
7	Medium	Low	Low	Synchronized	Yellow
8	Low	Medium	High	Congested	Orange
9	Low	Low	High	Jammed	Red

Source: Türk Telekom Technical Report, 2011; Robust Traffic Status Estimation and Adaptive Traffic Signaling, December 2011.

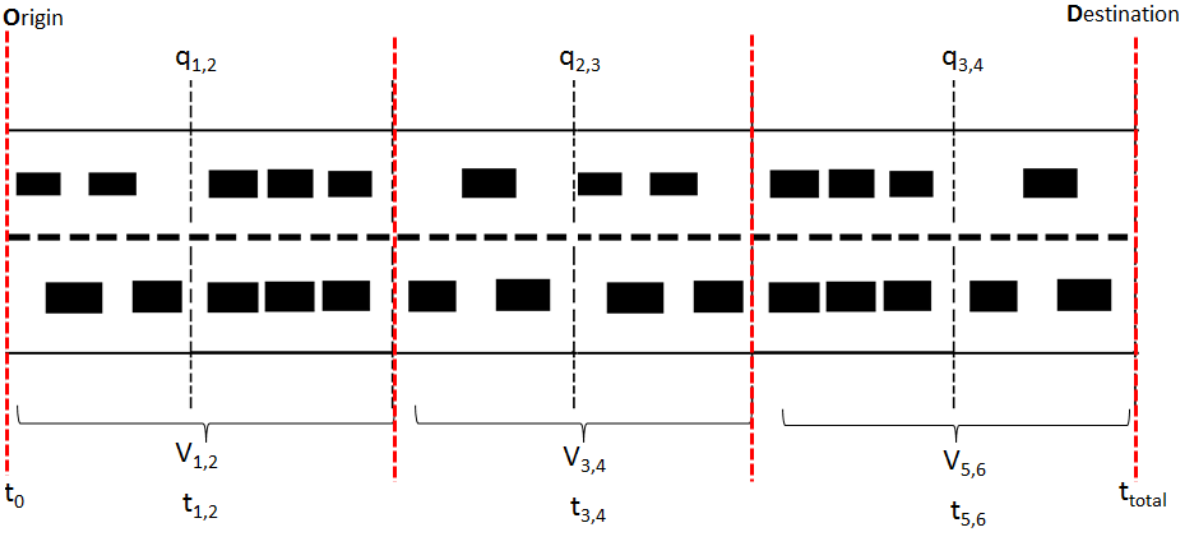
3.8.3 Travel Time Calculation

Travel time calculations are done with the fundamental theory of

$$t = \frac{X}{V} \quad , \quad Time = \frac{Distance}{Velocity} \qquad \textbf{(3.30)}$$

in the simulation tool. It can easily be understood that this type of a calculation would not give realistic results since the traffic dynamics are not reflected as it is in real life. Because in this way, there is no adaptation dynamics included in the equation while going from any section to the next one. Here, considering a case where the vehicles in the current section moves slower compared to the vehicles in its downstream (successor) section, adaptation dynamics stands for the fact that it will take some time to speed up and blend to the next section's mean speed and/or flow values.

Figure 3.12: Sketch used during the equation modification to increase the precision



Source: Türk Telekom Technical Report, 2011; Robust Traffic Status Estimation and Adaptive Traffic Signaling, December 2011.

We have explored how to reflect a more realistic merge of the vehicles and their mean speed at the section boundaries as shown in Figure 3.12 and come up with the following modifications. Thus we ultimately ended up using a density based approach. Density based calibration and the resultant equations can be listed as below:

$$t_1 = \frac{x_1}{v_1} \tag{3.31}$$

$$t_2 = \frac{x_2}{v_2'} \tag{3.32}$$

$$v_2' = v_1 \frac{q_2}{q_1} \tag{3.33}$$

$$t_3 = \frac{x_3}{v_3'} \tag{3.34}$$

$$v_3' = v_2' \frac{q_3}{q_2} = v_1 \frac{q_3}{q_1} \tag{3.35}$$

$$v_2' = v_1 \frac{q_2}{q_1} = \frac{q_1}{\rho_1} \frac{q_2}{q_1} = \frac{\rho_2 v_2}{\rho_1} \quad \textbf{(3.36)}$$

$$v_2' = \frac{\rho_3 v_3}{\rho_2} \quad \textbf{(3.37)}$$

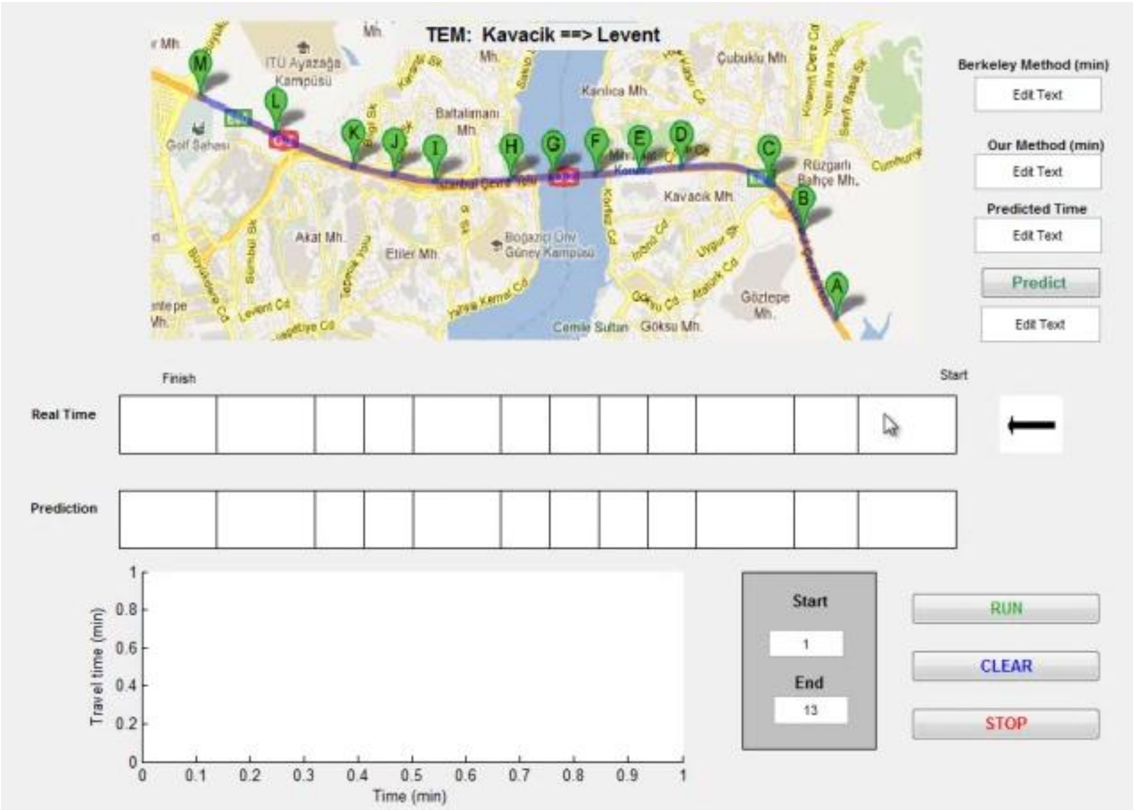
$$t_1 + t_2 + t_3 = \frac{x_1}{v_1} + \frac{x_2 \rho_1}{v_2 \rho_2} + \frac{x_3 \rho_2}{v_3 \rho_3} \quad \textbf{(3.38)}$$

The vehicles do not change their speed instantaneously while moving from a congested section to a free flowing section, i.e. from 20- km/h to 100+ km/h, so the calibration on the travel time is done by taking the ratio of the densities into account, including some exceptions. To get an optimum solution, we handled some exceptions where some unrealistic situations occurred by using a control mechanism. In this control mechanism there are two conditions: 1) Use Berkeley method for the first section of the roadway since there is no section -1 and 2) Use our method when both densities of the following sections are higher than the critical density since under the critical density the vehicles can be driven by free flow speed. 3) Use Berkeley method if the ratio of the densities results in a value bigger than some specific multiplier where it may cause enormous leaps in the travel time.

3.8.4 Simulation Environment

The simulation tool allows us to analyze the instantaneous states of the current traffic states. The overall interface of the simulation tool is illustrated in Figure 3.13. The current traffic states for each segment at each time step of the simulation will be shown by the upper bar graphics object which is denoted by “Real Time” label to its left. The color of the segments switches from green to red including the intermediate colors such as yellow and orange while the state of the traffic evolves from free flow to congested. The state of the road which is going to be predicted for a specific post time to the future will be shown in the lower bar graphics object which is denoted by “Prediction” label. In this roadway configuration the direction of the traffic stream is from right to left, hence the starting segment which corresponds to the interval between the boundary points A and B is the one to the right on the bar graphics object, and the last segment is the one to the left of the bar graphics object which corresponds to edge between the boundary points M and L.

Figure 3.13: Overall interface of the Simulation Tool



Source: Türk Telekom Technical Report, 2011; Robust Traffic Status Estimation and Adaptive Traffic Signaling, December 2011.

On the lower right corner of the interface screen there are three generic buttons, namely “RUN”, “CLEAR”, and “STOP”. The “RUN” button is used for two purposes. First is for starting the simulation if it is pressed for the first time and the second is for resuming the simulation when it was paused. The “CLEAR” button has two purposes, as well. One use is for initializing the whole configuration, in other words resetting the simulation to its initial state if the STOP button was pressed before the CLEAR button is pressed. The second use is for clearing the plot on the lower left corner of the simulation to make it look clearer or to make it plot the data with a bigger scale since the previous data will be cleaned from the plotting area. The “STOP” button has only one purpose and that is for pausing the simulation.

To the left of the generic buttons (RUN, CLEAR and STOP) there are two text boxes. These text boxes are used to determine the range of the sections on the roadway that will be evaluated during the calculation and the plotting processes. The upper text box is used for determining the starting point of the calculation range and the bottom text box is used for determining the ending point of the calculation range within the configured roadway. The point *A* is indicated by the value 1, and the point *M* is indicated by the value 13 since there are *(number_of_sections + 1)* points for our case study shown in Figure 3.13. For example, if the upper text box has the value of 3 (point *C*) and the lower text box has the value of 7 (point *G*), then the information about the roadway interval between section 3 and section 7 will be picked among the complete calculation of the whole configuration and the output will be given accordingly on the interface screen. The user can select any point of the roadway as the start and the finish points. An example is given in Figure 3.18. However there are some logical restrictions. The tool prevents the user to choose the section number of start point lower than the finish point. Other similar restricted cases are handled by the tool.

On the upper right corner of the interface screen there are 4 text boxes and an extra button. The text boxes labeled as “Berkeley Method” and “Our Method” will give the results of the calculated travel times using the Berkeley method *(30)* and our method *(31)*, respectively. Berkeley method uses the standard travel time calculation whereas our method includes the ratio between the density of the current and the next section into the calculation.

Berkeley method calculates the travel time using the equation:

$$Travel\,Time = \sum_{i=start}^{Finish} \frac{X_i}{V_i} \tag{3.39}$$

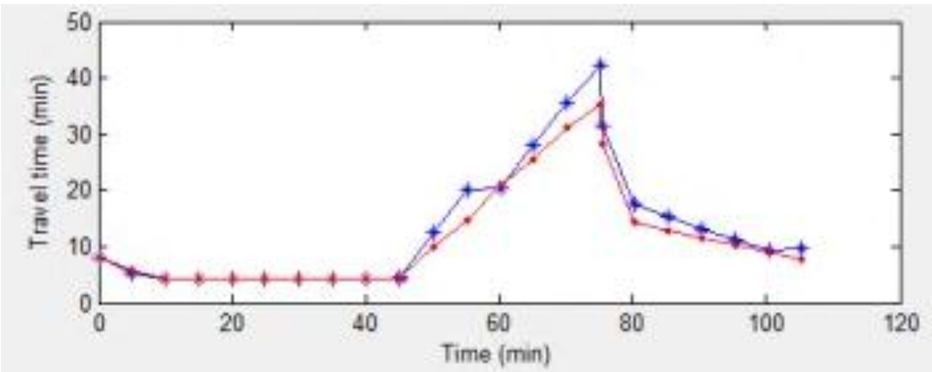
where X_i(*km*) and V_i (*km/h*) stands for the length of the section *i* and average speed of the section *i*, respectively. On the other hand, our method calculates the travel time using the equation:

$$Travel\ Time = \sum_{i=start}^{Finish} \frac{X_i}{V_i} \frac{\rho_i}{\rho_{i-1}} \quad \textbf{(3.40)}$$

where X_i(*km*) and V_i (*km/h*) are the same as in Berkeley's method, ρ_i and ρ_{i-1} are the density of section *i* and section *i-1*, respectively.

The travel times given by both methods are calculated for the range of the sections specified by the user in the textboxes labeled as start and finish. Moreover, how many minutes ahead in time the user wants to predict is specified inside the text box labeled as "Predicted Time". The button "Predict" will perform the prediction process when activated. According to this specified value inside "Predicted Time" text box, the prediction process will be carried out and the numeric value in minutes for the travel time predicted is given in the textbox right below the "Predict" button. The state of the predicted traffic will be colored accordingly in the lower bar graphic object. An example is given in Figure 3.22.

Figure 3.14: The plotting of the data calculated by our method (blue line) and Berkeley method (red line)



Source: Türk Telekom Technical Report, 2011; Robust Traffic Status Estimation and Adaptive Traffic Signaling, December 2011.

The calculated travel time (min) data are plotted in the plot area that appears on the lower left corner of the screen. There will be two lines drawn in this area. The first one is the red line that represents the data calculated by Berkeley method, and the second one is the blue line indicating the data calculated by our method as illustrated in Figure 3.14.

3.9 CASE STUDY

We start by extracting the freeway geometry from the Google Maps for the stretch of the roadway which is given in Figure 3.15. The number of lanes, coordinates of the on-ramps and off-ramps and segment lengths are designed with the help of Google Maps tools considering the segmentation rules.

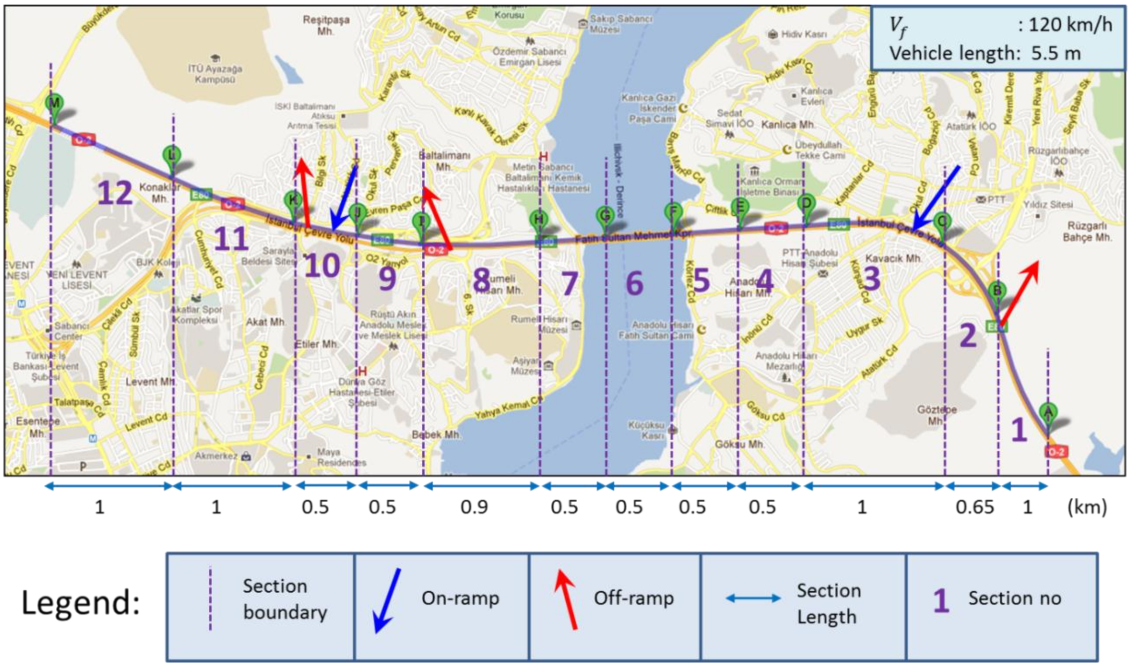
Our case study is established on the TEM motorway beginning at the point denoted by A (Kavacık) and lasting at the point denoted by M (Maslak). The road stretch studied is depicted in both Figure 3.13 and Figure 3.16, andFigure 3.19 is 8.55 km long. It is divided into 12 segments for the purpose of simulation according to the segmentation rules which are given previously in this chapter.

Figure 3.15: The area of interest to be simulated (TEM: Kavacık → Maslak direction, 8.5 km ~ 11 mins)

Source: Türk Telekom Technical Report, 2011; Robust Traffic Status Estimation and Adaptive Traffic Signaling, December 2011.

Additional information about the segmented road can be found in Figure 3.16 and Table 3.3. Each number designates the section number. Moreover, the free flow speed is determined as 120 km/h, and vehicle length is considered as 5.5 m.

Figure 3.16: Final Road Network Configuration of the Test Site



Source: Türk Telekom Technical Report, 2011; Robust Traffic Status Estimation and Adaptive Traffic Signaling, December 2011.

Table 3.3: Section Properties

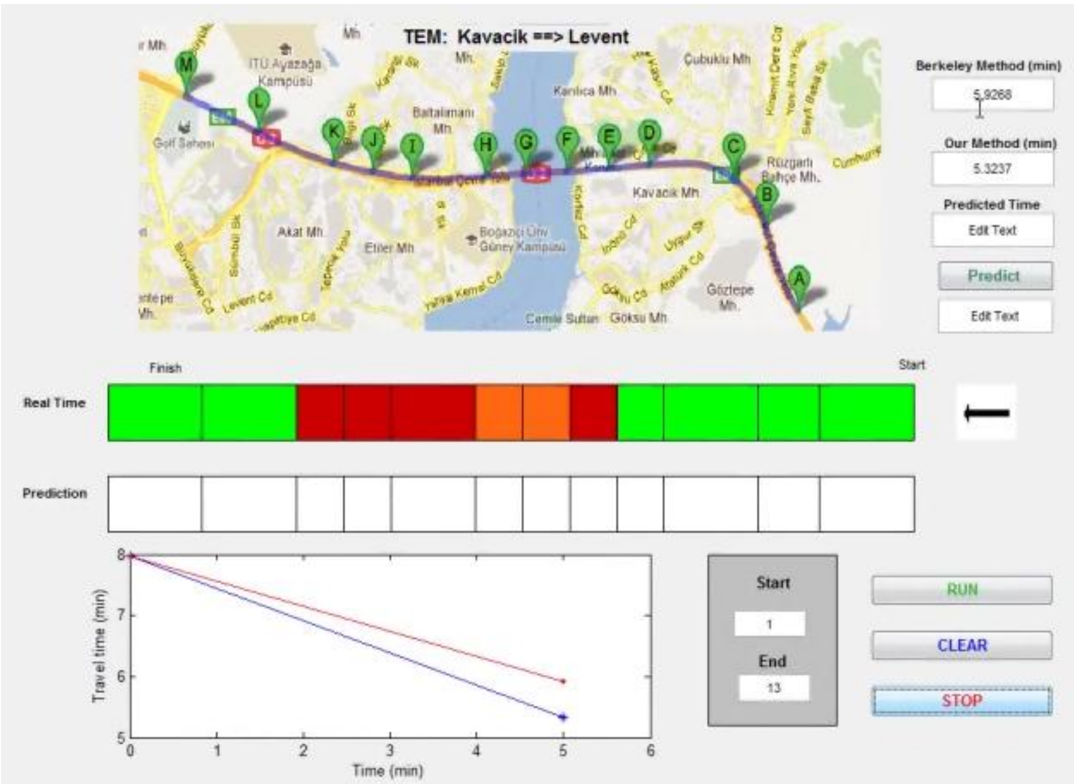
Section Number	Section Length	On-Ramp	Off-Ramp
1	1 km		
2	0.65 km		✓
3	1 km	✓	
4	1 km		
5	0.5 km		
6	0.5 km		
7	0.5 km		
8	0.5 km		✓
9	0.9 km		
10	0.5 km	✓	✓
11	0.5 km		
12	1 km		

Source: Türk Telekom Technical Report, 2011; Robust Traffic Status Estimation and Adaptive Traffic Signaling, December 2011.

The segmentation rule number 3 is inherently taken care of by the initial placement of the detectors. Detectors do not very often seem to be located close to each other. It is a rare case in other words. What is more likely to be come across is the case that some cells don't have any detectors at all. And if right after an off-ramp is an on-ramp, the way to satisfy the corresponding segmentation rules 1, 2, 5 and 9 is to place the off-ramp into upstream cell and on-ramp into downstream cell.

When we run the simulation for 5 minutes for our case study setup, the travel time of the current traffic for the whole roadway (sections 1 to 12) is calculated as 5.92 min for Berkeley method and 5.32 min for our method. The resultant system is given in Figure 3.17.

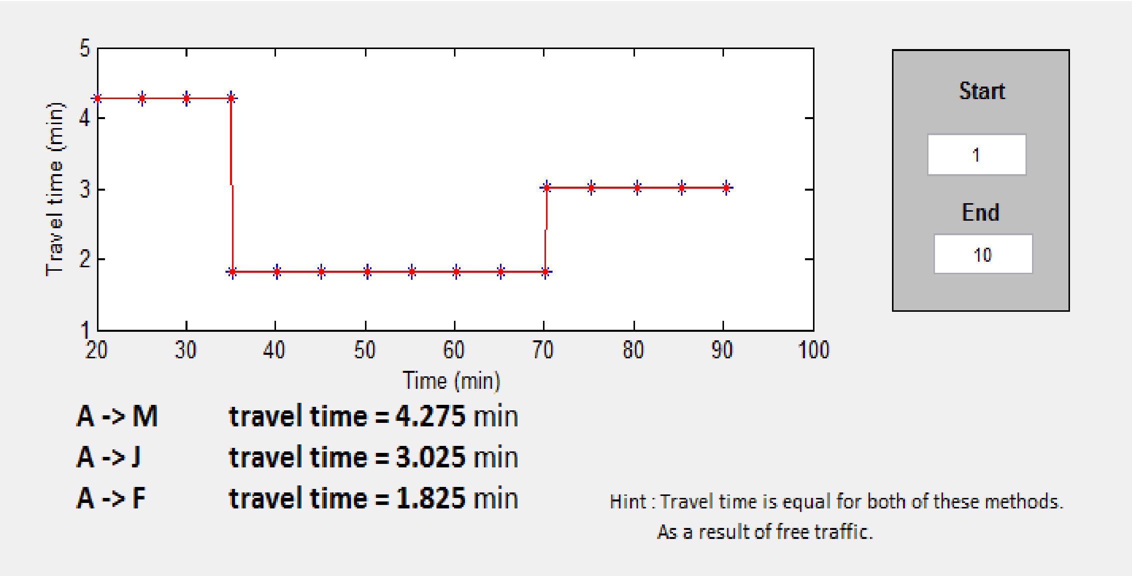
Figure 3.17: The results of the simulation calculated for the first 5 mins of the whole roadway



Source: Türk Telekom Technical Report, 2011; Robust Traffic Status Estimation and Adaptive Traffic Signaling, December 2011.

When the range from the points *A* to *J* (1 to 10) was selected, the travel time was 3.025 min, on the other hand when range was from the points *A* to *F* (1 to 6) the travel time became 1.825 min, and for the last case when the range was between *A* and *M* (1 and 13) the travel time was calculated as 4.275 min, as shown in Figure 3.18.

Figure 3.18: Selection of the start and the finish points and the corresponding change on the calculated time



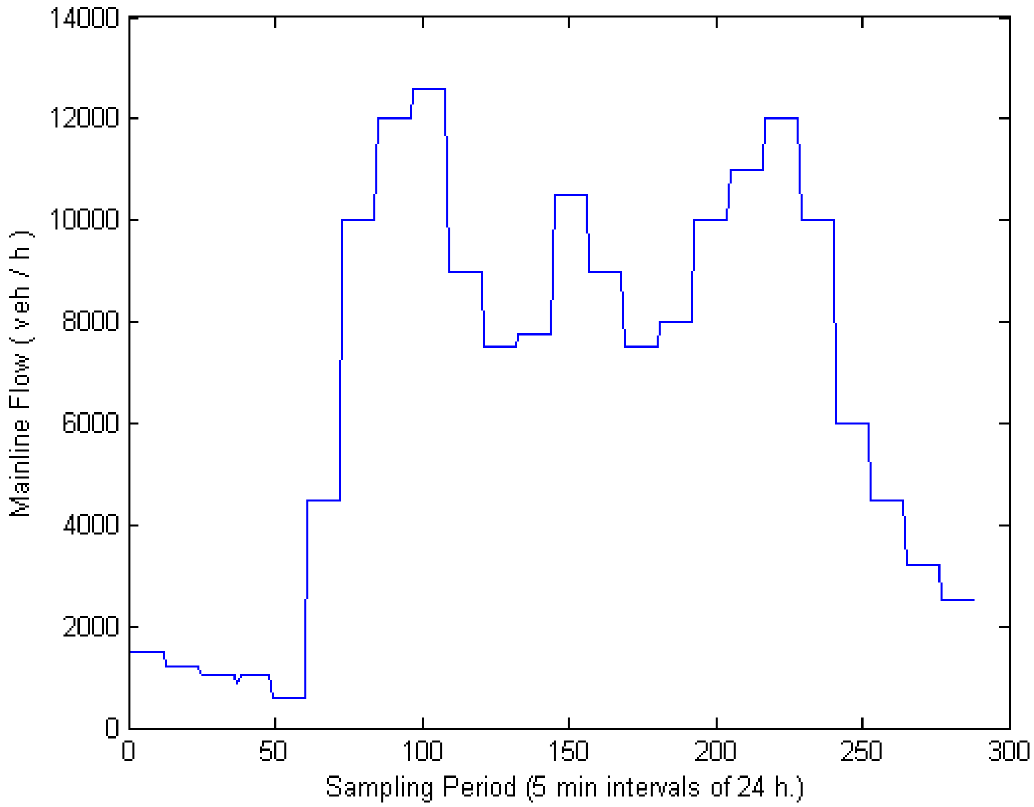
Source: Türk Telekom Technical Report, 2011; Robust Traffic Status Estimation and Adaptive Traffic Signaling, December 2011.

Figure 3.19: Case study on motorway "TEM: Kavacık -> Maslak" simulated by CTMsim simulation tool

Source: Türk Telekom Technical Report, 2011; Robust Traffic Status Estimation and Adaptive Traffic Signaling, December 2011.

We have added a demand profile which helps us to randomize the incoming demand expressed in flow, in other words vehicles/hour, from each of the on-ramps and also on the mainline. Hence, the simulation is able to reflect a more realistic scenario. The mainline flow demand profile is given in Figure 3.20. The data set that belongs to the main line in-flow demand is given in the first column of the on-ramp demand profile.

Figure 3.20: Main line flow demand profile sampled in 5 min intervals within a day



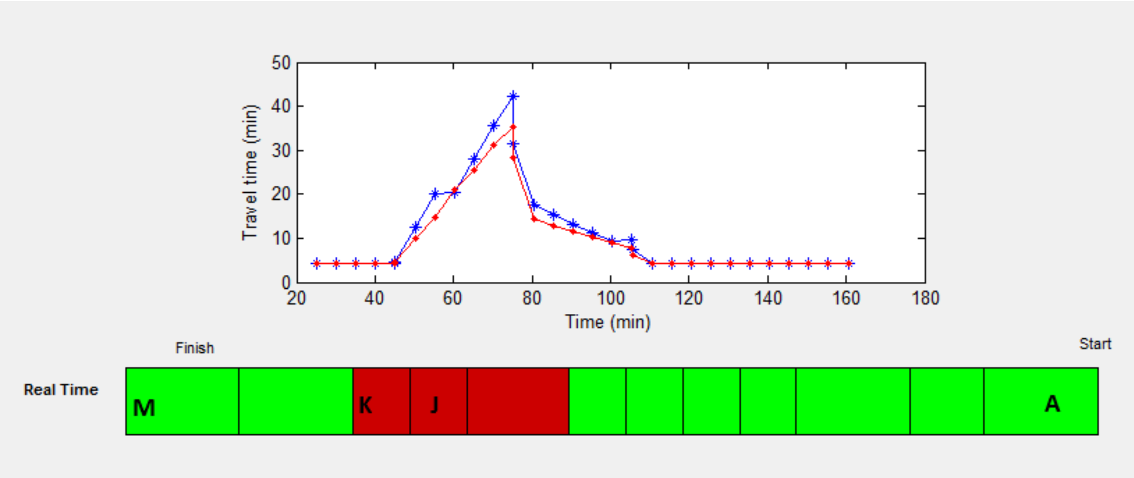
Source: Türk Telekom Technical Report, 2011; Robust Traffic Status Estimation and Adaptive Traffic Signaling, December 2011.

Data points are retrieved by the samples of 5 min intervals within a day, which are in total 288 samples (24*60/5=288 data points). There are 2 more sets similar to this data set that contains 288 data samples which are defined for the 2 on-ramps in the order of appearance on the case study map (TEM: Kavacık --> Maslak) represented in Figure 3.19. All of these three data sets together generate the on-ramp demand profile. There is also the off-ramp demand profile which contains 3 sets of sampled data that belongs to each of the three off-ramps, plus set that belongs to the main line out-flow demand. Mainline out-flow demand is given by the last column of the off-ramp demand profile.

3.9.1 Scenario 1: Traffic Accident in Section 10

In order to simulate the effects of a case where a traffic accident occurs we simulated an accident scenario in section 10 (between points *J* and *K*). The section normally contains 4 lanes, but due to the accident we created in this section, it drops to only 1 lane which causes an extreme bottleneck. We chose this section to simulate the accident case because the existence of both an on-ramp and an off-ramp increase the likelihood of such an incident.

Figure 3.21: Traffic accident scenario between points *J* and *K* (section 10)



Source: Türk Telekom Technical Report, 2011; Robust Traffic Status Estimation and Adaptive Traffic Signaling, December 2011.

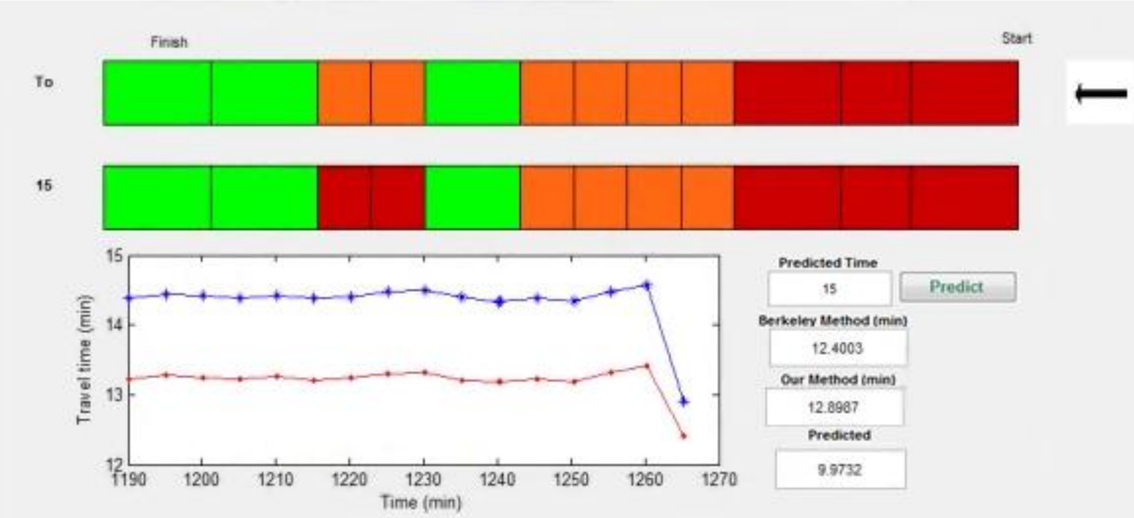
The accident occurs at 50^{th} minute of the simulation and the 3 out of 4 lanes in this section were closed. After 30 minutes, i.e. at 80^{th} minute one of the lanes are opened and so the traffic congestion diminished a little. Then after next 30 minutes all the lanes are opened and the traffic state became normal. The recovery of the road in such a case took approximately 1 hour. The illustration of the scenario is given in Figure 3.21.

3.9.2 Scenario 2: Prediction of the Traffic State 15 Min Ahead

One of the scenarios simulated with the modified CTMsim is the prediction of the state of traffic congestion 15 min ahead of the current time (t_0). The prediction tool is configured to 15 min and then the prediction process is activated with the help of prediction button. The current traffic state had a travel time from source to destination as 12.4003 min for Berkeley method and 12.8967 for our method at the moment the prediction button is pressed. The process is illustrated in Figure 3.22.

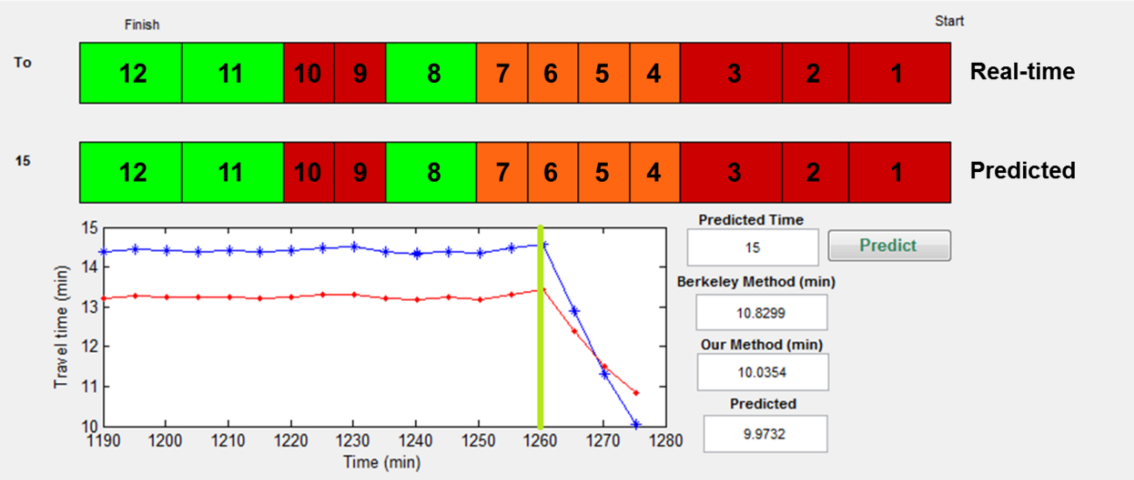
The prediction color bar (lower bar) has run in fast forward mode and found the traffic state that belongs to 15 min later. At the same time the upper bar continues to show the current (real-time) traffic state, which corresponds to the 1260th minute in the simulation, and the numeric value related to it is given in both “our method” textbox and “Berkeley Method” textbox.

Figure 3.22: The state of the simulation at the moment the predict button is pressed



Source: Türk Telekom Technical Report, 2011; Robust Traffic Status Estimation and Adaptive Traffic Signaling, December 2011.

Figure 3.23: Travel time estimation of real-time traffic and the 15 min prediction coincides



Source: Türk Telekom Technical Report, 2011; Robust Traffic Status Estimation and Adaptive Traffic Signaling, December 2011.

Figure 3.23 shows the results of the simulation run where the real-time color bar and the travel time calculated by our method gives similar outputs with a slight difference to the predicted color bar and predicted travel time which are calculated and then drawn 15 minutes prior to the current time. Our simulations look promising at the moment. What we need to further investigate is the results of the simulation run by the real data collected by the sensors for a specific time and date, and then compare the predicted congestion with the real data of the same predicted time of the day. This step is planned to be carried out in the next phase of the project.

4. EXTRACTION OF CONGESTION INFORMATION

Before the wide usage of mobile internet the traffic network was monitored using dedicated equipment such as radars, loop detectors, and cameras. However, using such equipment for the monitoring infrastructure cost much in terms of both deployment and maintenance processes. Thus the dedicated equipment technologies cannot be deployed for the entire arterial network in many countries, not even for highways in many regions. In addition to the costs of such technologies, the errors and malfunctions in the equipment prevent the efficient usage. For instance, it is reported in (Herrera et al., 2010) hat approximately 30% of all loop detectors in the state of California do not work properly every day.

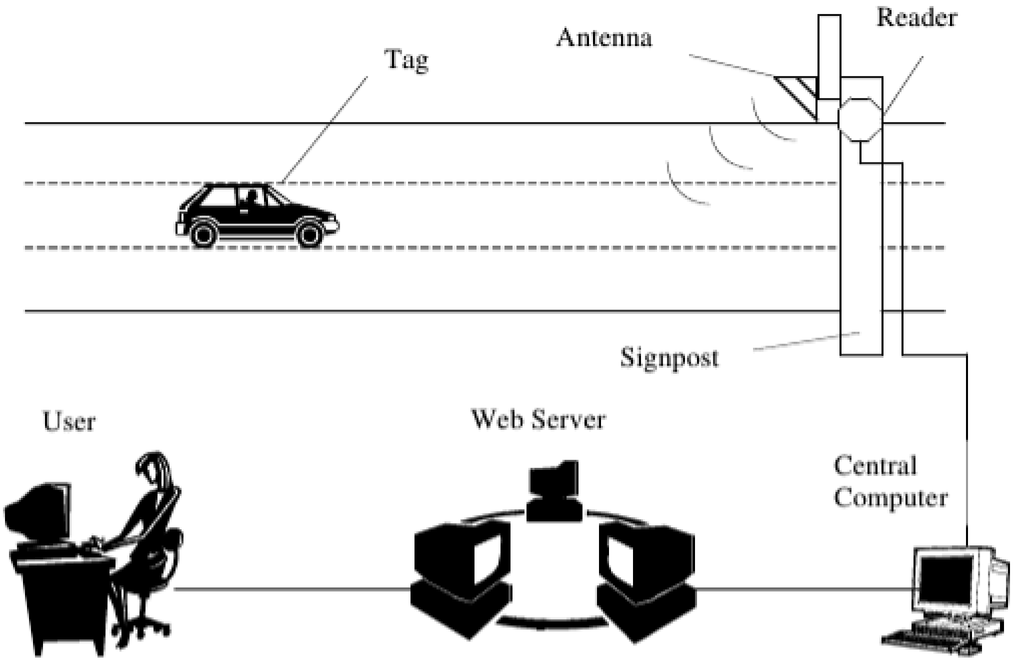
4.1 NEW WAYS FOR TRAFFIC MONITORING

Experts in the transportation community started to seek for improved technologies to overcome the common issues related to conventional equipment. In order to collect the data to monitor the states of the road traffic, some new ways which consist of electronic devices carried on-board the vehicles were discovered. These devices can be classified under several categories: 1) Radio Frequency Identification (RFID) transponders, 2) License Plate Recognition (LPR) systems, 3) Global Positioning System (GPS) devices, etc.

4.1.1 Radio Frequency Identification (RFID)

There are several systems that utilize the Radio frequency identification (RFID) technology. One example is the Fastrak in California and the other is EZ-Pass on the east coast in United States. In both of these systems the RFID transponders are used to obtain the individual travel times based on re-identification of the vehicles. Figure 4.1 illustrates the RFID usage in estimating the travel times in traffic systems. As shown in the figure, the RFID readers deployed near the roads record the time when the vehicles equipped with RFID transponders passes the fixed location. Next reader located at another fixed point measures the time the vehicle spent during the distance traveled between two consecutive readers. The main disadvantage of such a system is the cost to deploy the fixed point readers, as well as its limited range. Another limitation of the system is that it is only able to capture the travel time between two fixed places.

Figure 4.1: Using RFID tags on probe vehicles to estimate travel times



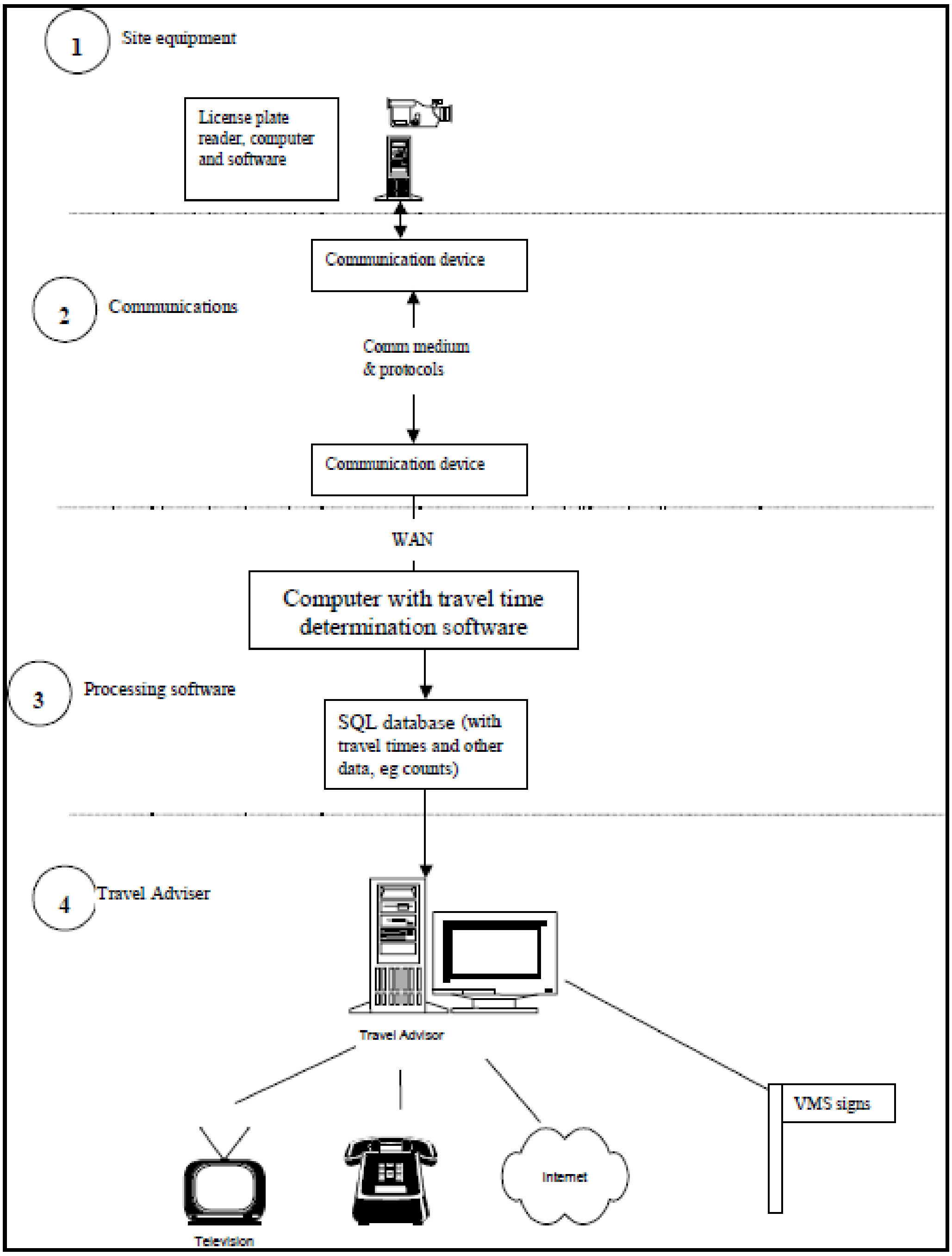
Source: Wright, J. & Dahlgren, J., 2001. *Using vehicles equipped with toll tags as probes for providing travel times*. Working paper. California PATH Program, Institute of Transportation Studies University of California, Berkeley CA.

4.1.2 License Plate Recognition (LPR)

The second technology that is used instead of the conventional approaches is the License Plate Recognition (LPR) systems which exploit the image processing techniques. In this system, there are several cameras located near/on the roads that capture many snapshots and explore them in order to identify the vehicles from their license plate. The travel time calculation concept is similar to that in RFID systems. Two consecutive cameras capture the images of the same vehicles, identify them, and after the successful identification the travel time is obtained for the vehicle that was identified. Related works using LPR systems include the Passive Target Flow Management (PTFM) developed by Traffic Master (Traffic Master, n.d.) in United Kingdom. In addition, Frontier Travel Time project (Bertini et al., 2005) by Oregon

DOT also used cameras to estimate travel times. The fundamental limitation of the system is the deployment costs just like in RFID systems.

Figure 4.2: LPR system used by Frontier Travel Time project



Source: Bertini, R., Lasky, M. & Monsere, C., 2005. Validating predicted rural corridor travel times from an automated license plate recognition system: Oregon's frontier project. In *Proceedings of the 8th International IEEE Conference on Intelligent Transportation Systems*., 2005, pp. 706-711.

4.1.3 Global Positioning System (GPS) devices

Another way is the use of Global Positioning System (GPS) devices. These devices are able to obtain varying readings of position and velocity values and also readily available in the market. The high accuracy provided within the GPS devices enable the possibility of using them as traffic information probes to obtain traffic data. The study in (Sanwal & Walrand, 1995) addressed the substantial problems related to using probe data such as instantaneous speed, latitude, longitude, travel time, etc. reported from a vehicle to monitor the traffic states. According to the study, GPS devices can be used as a feasible source for monitoring the traffic states.

Figure 4.3: Traffic Master's live travel time estimation system that utilizes LPR

Source: Traffic Master, n.d. *Traffic Master's Passive Target Flow Management (PTFM) system*. [Online] Available at: http://trafficmaste.co.uk [Accessed 6 February 2011].

Another study in (Zito et al., 1995) also investigated the GPS devices to be used as a source to provide traffic data and evaluated the GPS accuracy in terms of velocity and acceleration data. The study had good results for the accuracy of GPS. The only problem with this technology is the low penetration rates in the population that makes it insufficient to provide large coverage on the road network. Dedicated probe vehicles if could have been applied at a global scale would provide viable traffic data for the monitoring systems. HICOMP program in California used dedicated probe vehicles equipped with GPS devices at a small scale. The vehicles are used to monitor some freeways and major highways in California. However the penetration rate of this program was too low (Kwon et al., 2007) that could not provide reliable travel times.

Some other approaches consist of using dedicated vehicle fleets equipped with GPS devices or black-boxes which exploit the Automatic Vehicle Location (AVL) technology to monitor the traffic. Such an approach is used in the truck fleets by logistics companies like UPS and FedEx or by taxi fleets, bus fleets, etc. Particularly in large cities the use of dedicated fleets provided substantial amount of data, for instance Inrix, and have been quite successful. Nonetheless, due to operational constraints and specific travel patterns the issues like coverage, penetration and bias are inevitably encountered.

4.1.4 Base Station Signals & Cellular Phones

Using mobile phones as traffic probes has been the latest technology trend in the field of monitoring vehicle motion. Before the rapid emergence and penetration of GPS technology within the mobile devices, cellular phone based monitoring consisted of identifying the cellular devices via the base station signal information. The technique behind the technology is based on triangulation, trilateration, hand-offs between the base stations or a hybrid of these techniques. Cell tower signals are used to estimate the approximate location of vehicle probes as well as the vehicle speeds from the distance traveled and the time passed between consecutive samplings. Authors in (Caceres et al., 2008), (Hongsakham W., 2008), (Sohn, 2008), (Bar-Gera, 2007), (Fontaine & Smith, 2007), (Hsiao & Chang, 2006), (Lovell, 2001), (Bolla & Davoli, 2000), (Ygnace et al., 2000), (Westerman et al., 1996) studied this technique for traffic monitoring by using the base station signals and the mobile phones as a beacon. The major problem in the method of using base stations for obtaining the probe vehicle information is the natural lack of precision for estimating the location. When the precision of the location information is low, considerable difficulties arise in the process of computing the vehicle speed. Especially the company named Airsage which used the base station signals as the data extraction infrastructure for their traffic monitoring system back in time, developed some solutions to cope with the inherent problems of the method (Herrera et al., 2010), (Airsage Inc., 2006). Approximate travel time and average speed between an origin-destination pair based on the time difference of these two locations is possible to be estimated.

A field operational test was carried out by Yim *et. al.* in (Yim & Cayford, 2001) in order to compare the efficiency of GPS devices and cell phones to be used as a traffic monitoring approach. According to the study, using base station signals for determining the location and tracking the vehicles pose significant inaccuracy issues compared to GPS equipped vehicles method. Specifically in the roads that have complicated geometry the inaccuracy of the methods except the GPS based ones prevents their wide use in traffic monitoring applications. Even though it is possible to get travel time reports for large scale networks using these methods, obtaining some other traffic variables such as instantaneous speed of vehicles are difficult to accomplish in an accurate way.

4.2 THE METHOD: TRAFFIC MONITORING BASED ON GPS-ENABLED SMARTPHONES

Together with the fact that mobile communications has developed immensely in the last decade and become readily available all over the world, decreasing costs and increased accuracy of GPS attracted the attention of the transportation authorities for probe based traffic monitoring. Moreover, as the smart phone usage increases rapidly within the population, they become more attractive as traffic sensors. Using GPS-enabled smart phones is especially appropriate to be used in developing countries (Herrera et al., 2010), where the penetration rate of smart phones in the population is increasing at a huge pace and the wide deployment of the traffic monitoring infrastructure are costly. GPS-enabled smartphones allow obtaining more reliable position information, and hence providing more dependable traffic data, namely instantaneous velocity, travel time, acceleration/deceleration, direction and so forth. Calculation of reasonable travel time estimations requires a high level of accuracy on the vehicle's position information as mentioned in (Fontaine & Smith, 2007) which emphasizes the importance of accurate position information for reliable traffic monitoring purposes. Some other studies mention that the wide-use of GPS-enabled mobile phones will constitute a better alternative for traffic monitoring (Yim & Cayford, 2001), (Yim, 2003). Furthermore, the study in (Menard et al., 2011) presents a comparison between three different smart phones that run a vehicle tracking application (named FreeSim Mobile) and concludes that the GPS-enabled smart phones are potential alternative to tracking devices installed in the probe vehicles. They also show that all the phones around 95% of the time had an accuracy of 10 meters along the real points on the road. They prove their findings of smart phones being a reliable traffic data source by presenting a case study in which 10 test vehicles driving in a congested section of the road at different times throughout a day (Menard et al., 2011).

4.2.1 Concerns of the Technology

There is no doubt about the accuracy and the spatio-temporal extensive coverage provided by GPS-enabled smart phones. However, there are some other concerns related to privacy of the users, energy consumption of the phone and overload on the communication network. Since the traffic data coming from a GPS-enabled smartphone are needed to be sent to a central server, the communication load may become extremely high and it can be hard to maintain the system. Other than the communication load, frequent updates of the vehicle’s traffic data to the central server will also cause the battery to be drained relatively faster which will emerge the question of a specifically designed handset. Knowing the almost exact position information and the speed of the users may lead to infringing privacy (Herrera et al., 2010). Thus all these concerns regarding to traffic monitoring based on the GPS-enabled smart phones need to be taken care of.

4.2.2 Sampling Strategies

At least two strategies can be listed to deal with these concerns that have substantial influence on the communication network, the user privacy and the battery life. One is the temporal sampling strategy, and the other is the spatial sampling strategy.

4.2.2.1 Temporal Sampling

In this strategy, the device equipped within the vehicle reports its traffic information such as longitude, latitude, velocity, direction, acceleration, timestamp, etc. to the central server at predetermined time intervals regardless of its spatial status. This specific update time interval is called the sampling time and is denoted by Δt in many traffic monitoring systems and applications.

4.2.2.2 Spatial Sampling

In this strategy, the vehicles report their traffic information such as time, velocity, direction, acceleration, etc. to the central server as they pass by each fixed locations on the roadway independent of the time. This sampling strategy uses a similar method as the inductive loop detectors, LPR readers or RFID transponders do. In all of them the data is obtained as the vehicles cross a fixed point. The advantage of spatial sampling over the temporal sampling is that it forces the mobile phone to send the vehicle's traffic data at spatially important locations.

Although having small sampling time Δt or frequently placed fixed points will provide a rich amount of available traffic data, and hence increase the accuracy of traffic monitoring and estimation systems, the existence of large amount of data will cause complications in terms of battery life of the phone, communication load on the cellular network, as well as well as privacy protection of the users who participate in the system. So a good optimization process on both determining of Δt and the fixed location frequency is needed in order to overcome such challenges.

4.3 DISCUSSIONS, CONSIDERATIONS, AND FACTS

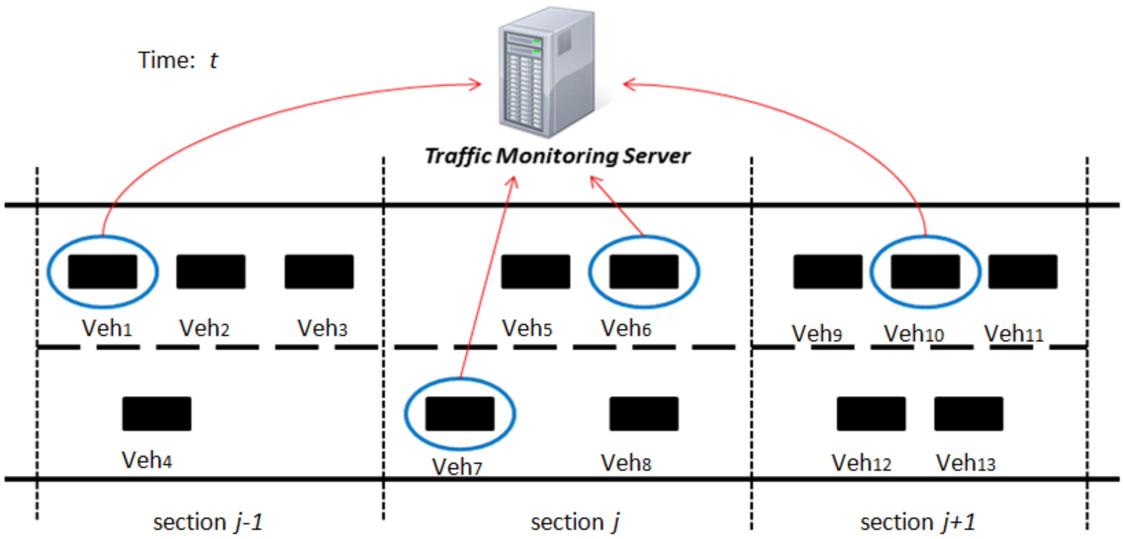
First of all, the data to be extracted are clear.

- **a.** Time stamp
- **b.** Location information (longitude, latitude, and maybe even altitude)
- **c.** Direction

However the way these data will be processed is yet to be defined. On this sense, our biggest contribution in this study will be the methods we are going to use for processing the spatio-temporal vehicle data.

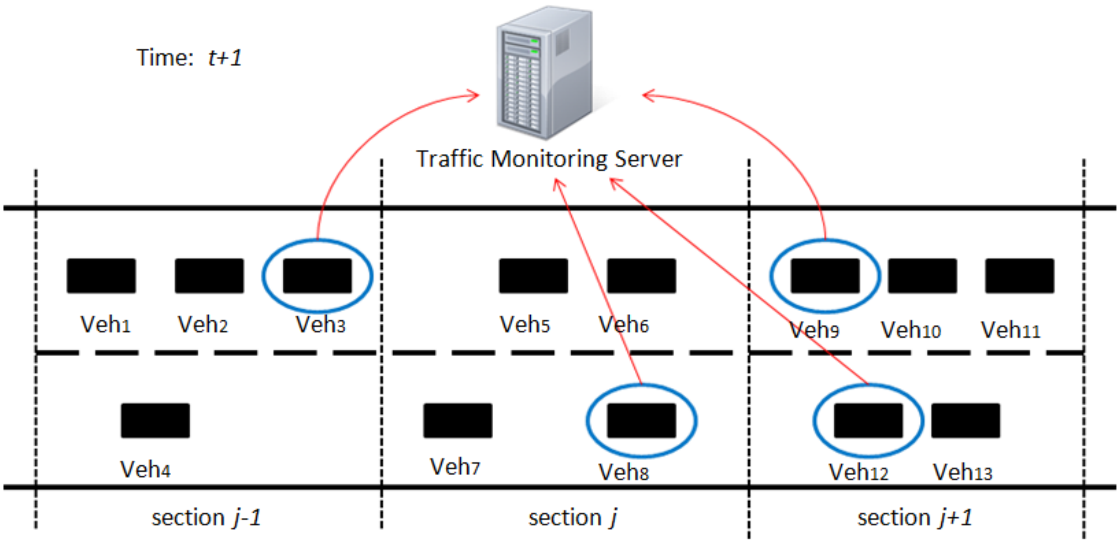
There is the fact that the data might not be coming from the same source (floating vehicle nodes) for a specific segment of the road at successive time intervals. At a certain time instant t while the marked vehicles in Figure 4.4 are sending the data that belongs to their segments to the traffic monitoring server, at the next time instant $t+1$ some other vehicles in Figure 4.5 may send the data. Considering that such scenarios are strongly possible, appropriate action must be taken during the data processing phase of the extracted vehicle data.

Figure 4.4: At time instant *t* vehicles denoted by Veh1 for section *j-1*, Veh 6 and Veh 7 for section *j*, and Veh 10 for section *j+1* are sending their traffic data to the central server



Source: Türk Telekom Technical Report, 2012; Extraction of Congestion Information and Dynamic Route Planning, May 2012.

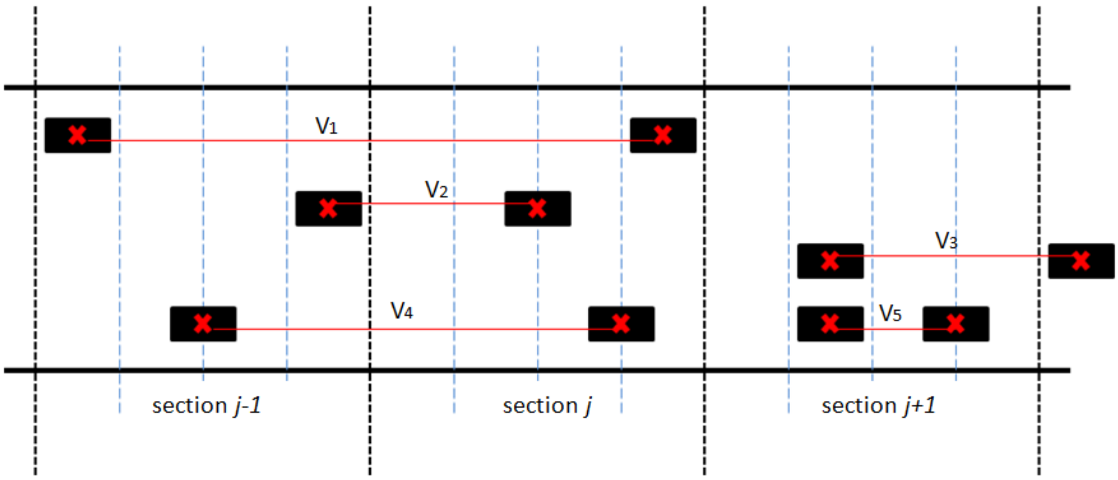
Figure 4.5: At time instant *t+1* vehicles denoted by Veh3 for section *j-1*, Veh8 for section *j*, and Veh 9 and Veh 12 for section *j+1* are sending their traffic data to the central server. The data sources changed.



Source: Türk Telekom Technical Report, 2012; Extraction of Congestion Information and Dynamic Route Planning, May 2012.

A contribution in this research can include the determination of which segment the velocity information belongs to if two location points used for the velocity calculation are situated in different segments as shown in Figure 4.6. It is good to have a grid inside each segment to create sub-segments. Thus higher accuracy can be achieved for velocity calculation and segment determination of the vehicle. Vehicle 1 sends its first location in the first subsegment of segment *j-1*, then sends its second location information in segment *j* 's last subsegment. According to these two locations the vehicle's speed is calculated, but it is uncertain that to which segment this velocity information should be assigned. Our contribution will include this determination phase.

Figure 4.6: Processing the location data for velocity calculation in case that vehicles report their successive data in different road segments.



Source: Türk Telekom Technical Report, 2012; Extraction of Congestion Information and Dynamic Route Planning, May 2012.

Another question is about how we should store the data coming from vehicles equipped with GPS-enabled smartphones. We could use a table like below but it is still an essential question how to fill the data in the table. Segment specific velocity values can be calculated by using the interpolation methods on the data coming from different vehicles for each segment and/or sub-segment.

Table 4.1: Storing the data coming from the smartphones in floating cars

	t_1	L_1	t_2	L_2	t_3	L_3	t_4	L_4	t_5	L_5
Car 1	0	5	75							
Car 2	0	35	60							
Car 3	0						30			
Car 4	0									
Car 5	0									

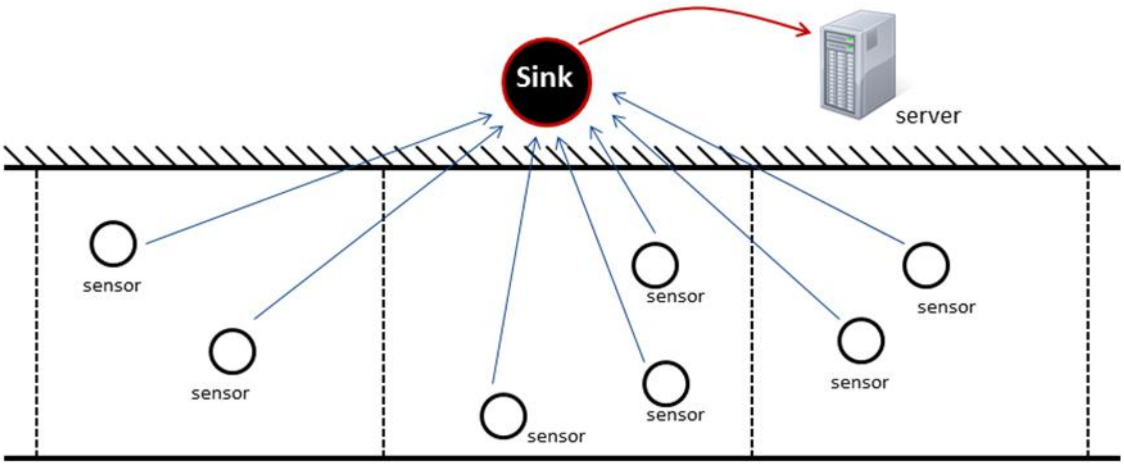
Source: Türk Telekom Technical Report, 2012; Extraction of Congestion Information and Dynamic Route Planning, May 2012.

The design introduced here resembles in many ways to that in wireless sensor networks. We could use the simulation environments in sensors networks with a few modifications applied. In sensor networks the sensors or the actuators report their data in three ways:

- **a.** Periodic: E.g. 1 min time intervals (Δt)
- **b.** Threshold: E.g. 20 meters distance (Δd)
- **c.** Combined: E.g. (10 min, 20 meters)

In these networks, there is a sink node that every sensor or actuator forwards its data to be processed or further sent to a central server. Figure 4.7 illustrates a sample scenario in sensor networks where every sensor node sends its data to the sink, and the sink forwards the data to the server.

Figure 4.7: Resemblance of the floating vehicle reports with the Wireless Sensor Networks



Source: Türk Telekom Technical Report, 2012; Extraction of Congestion Information and Dynamic Route Planning, May 2012.

It is also possible to address the average velocity calculation issue utilizing the micro-grids in each section, as depicted in Figure 4.6. There are three methods considered for the calculation process.

4.3.1 Methods for Average Velocity Calculations

This section presents the studies in order to address the average velocity calculation issue utilizing the micro-grids in each section, as depicted in Figure 4.6. There are three methods considered for the calculation process.

4.3.1.1 First method

The method consists of dividing the known velocity into micro-grids, and then finding the overall velocity by averaging the velocities identified by each micro-grid.

The method includes the following considerations:

- **a.** The incoming data must correspond within a time interval denoted by T and a ± *threshold* which can provide a specific precision in time.
- **b.** If the data does not belong to this time interval, then the data is obsolete, thus must be retired.

The model and an example are depicted in Figure 4.8. In this example, the average velocity that belongs to the first section of the road is tried to be calculated, where there are three vehicles associated with the first section and their velocity are 60 km/h, 70 km/h, and 65 km/h for V1, V2, and V4, respectively. However all of the cars are also associated with section 2, as well. This situation pops up the question that which section does the vehicle velocities belong to. The method tries to address the problem by:

- **i.** Divide the section into micro-grids.
- **ii.** Determine which vehicles are located in which micro-grid.
- **iii.** For each micro grid, calculate the average velocity using the vehicles' velocities in the micro-grid.
- **iv.** Calculate the overall velocity by averaging the velocities calculated for each micro-grid.

The mathematical representation of the method is as following:

$\boldsymbol{i}$: Micro-grid index

$\boldsymbol{j}$: Section index

$\boldsymbol{k}$: Vehicle index

$\boldsymbol{\chi_k}$: k^{th} vehicle's traveled distance ($\Delta x = x_2 - x_1$)

$\boldsymbol{T_k}$: k^{th} vehicle's traveled time ($\Delta T = T_2 - T_1$)

$\boldsymbol{L}$: Length of the micro-grid

$$\overline{V_J} = \sum_{i,k}\left(C_{i,j,k} \, . V_{i,j,k}\right) \quad \textbf{(4.1)}$$

$$\overline{V_J} = \sum_i \frac{\sum_k \left(C_{i,j,k} \, .V_{i,j,k}\right)}{\sum_k \left(V_{i,j,k} \neq 0\right)} \quad \textbf{(4.2)}$$

$$V_{i,j,k} = \frac{\chi_k / T_k}{\frac{\chi_k}{L}} = \frac{L}{T_k} \quad \textbf{(4.3)}$$

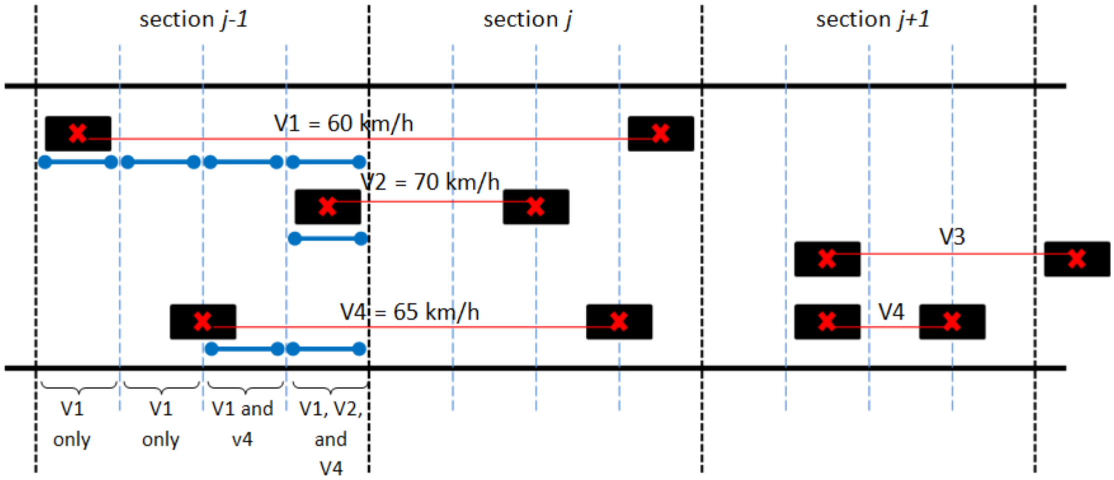
For example in the first micro-grid there is only one vehicle (V1), in the second micro-grid again only one vehicle (V1), in the third micro-grid there are two vehicles (V1 and V4), in the fourth micro-grid there are three vehicles (V1, V2 and V4). Hence we follow the calculations that are given in Table 4.2.

Table 4.2: Calculation steps for the example

Micro-Grid ID	1	2	3	4
Micro-Grid Velocity	$\frac{60}{1}$	$\frac{60}{1}$	$\frac{60+65}{2}$	$\frac{60+65+70}{3}$
Overall Velocity	$\dfrac{\frac{60}{1}+\frac{60}{1}+\frac{60+65}{2}+\frac{60+65+70}{3}}{4} = 61.875$			

Source: Türk Telekom Technical Report, 2012; Extraction of Congestion Information and Dynamic Route Planning, May 2012.

Figure 4.8: The modeling of the first method



Source: Türk Telekom Technical Report, 2012; Extraction of Congestion Information and Dynamic Route Planning, May 2012.

4.3.1.2 Second method

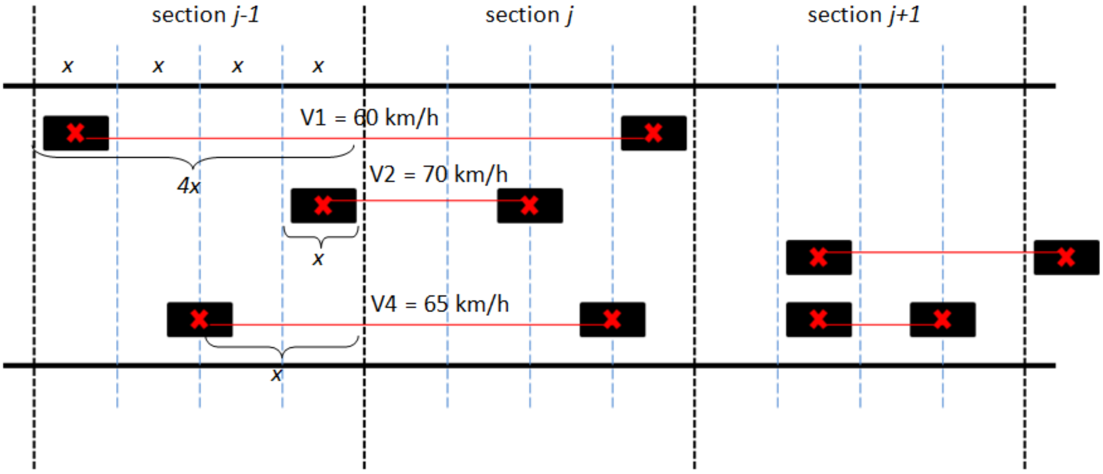
Second method employs the same considerations explained in the first method. According to the method, the total distance traveled by each vehicle in the section divided by total time traveled.

$$\overline{V_j} = \frac{4x+x+2x}{(\frac{4x}{V1}+\frac{x}{V2}+\frac{2x}{V3})} \tag{4.4}$$

Suppose that each micro grid in section *j-1* is 15 unit long, and V1, V2 and V4 are 60 km/h, 70 km/h and 65 km/h, respectively. Then according to the second method, the total distance traveled by all of the vehicles equals 60+15+30 unit, divided by the sum of each individual vehicle's travel time depicts the scenario, explicitly. If the Equation 5.4 applied to these parameters, the result will be the following:

$$\frac{60+15+30}{(\frac{60}{60}+\frac{15}{70}+\frac{30}{65})} \cong 62.1\ unit/h$$

Figure 4.9: Model and an example for the second method



Source: Türk Telekom Technical Report, 2012; Extraction of Congestion Information and Dynamic Route Planning, May 2012.

4.3.1.3 Weighted moving average method

The weighted moving average method consists of assigning a weight factor on the average velocity calculation:

$$\overline{V_J} = x_{t-1}.\alpha + x_t.(1-\alpha) \qquad \textbf{(4.5)}$$

4.4 ANDROID APPLICATION: TTRAFFIC

We need real-life data to be used in our simulations. For this purpose, we decided to develop an Android application named TTraffic that will do the following tasks:

a. Saving the location information (longitude, latitude, altitude) and timestamp for each successive data received from the GPS satellites in a file. In addition, it also calculates the velocity for each pair of data using the simple equation (distance traveled divided by time difference) and saves it into the same file.

b. Get the speed values using the android.location.Location.getSpeed() method (along with hasSpeed()) in our LocationListener implementation. Then these values will be compared with the values from conventional speed calculation.

This mobile application (TTraffic) is developed by the same research group as part of the Türk Telekom R&D Projects and presented as the capstone project of an undergraduate student. However it is not mentioned in detail within the scope of this thesis.

4.5 OPTIMIZATION AND CALIBRATION PHASE

4.5.1 Determining the Fixed Time Interval for Data Transfer

We will let the user to select the frequency of sending the GPS data to the central server. The more frequent the user sends data to the system, the more frequent updates about the traffic congestion status he/she will get from the system. This way the users will be motivated to participate actively on the evolution of the system.

4.5.2 Sending the Data When the Speed Band Changes

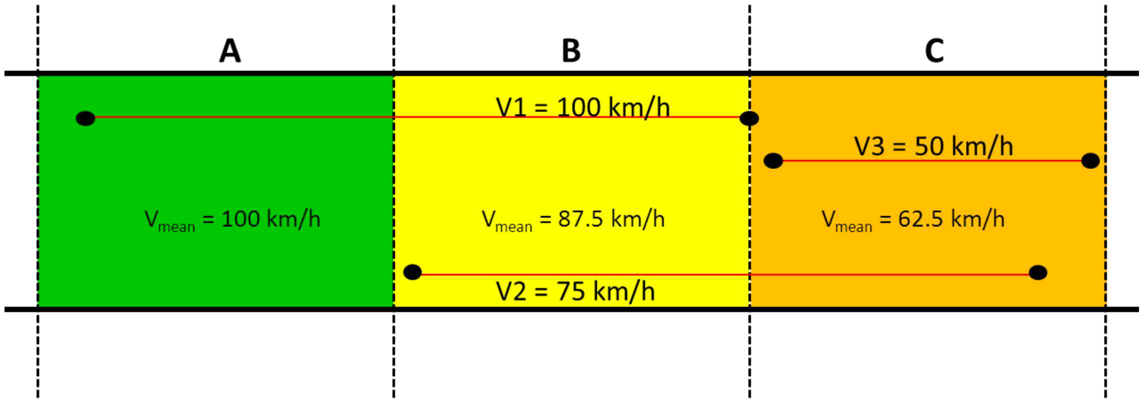
Another option to determine when to send the data to the central server is to inspect the significant changes in speed of the vehicle. Consider that there are pre-determined speed bands A, B, C, D and E as shown in color-speed scale in Table 4.3. The vehicle might send its data to the traffic monitoring server only if its speed band changes. In other words, if the change in the vehicle's speed reflects a significant amount then the vehicle should send the data, or vice versa.

Table 4.3: Color-Speed scale

Speed	90+	89-70	69-50	49-30	29-0
Color Scale	A	B	C	D	E

Source: Türk Telekom Technical Report, 2012; Extraction of Congestion Information and Dynamic Route Planning, May 2012.

Figure 4.10: Link Speed and Coloring



Source: Türk Telekom Technical Report, 2012; Extraction of Congestion Information and Dynamic Route Planning, May 2012.

4.5.3 Keep multiple data in the memory, send after

In order to avoid the rapid battery drain, hold several GPS data in the smartphone's memory, and when a decent amount of data are collected send them to the traffic monitoring server all together.

4.6 PRELIMINARY INVESTIGATION FOR THE MICROSCOPIC TRAFFIC SIMULATOR

After the background investigation we needed a microscopic simulation framework to model and test our system. However we could not find a suitable simulator that can meet our needs, and then we decided to develop our own traffic simulation environment.

Our simulation environment to be developed will be covering the following properties:

a. The board of the simulation environment will be large enough to simulate many vehicles at the same time while providing efficiency in terms of performance.

b. The board will be divided into micro-grids where a vehicle will be able to pass a grid in unit time while moving with the minimum speed such as 1km.

c. E.g. consider that with minimum speed 1km/h the number of grids that is traveled in unit time is 1 grid, and then with 80km/h the distance traveled will be 80 grids.

$$\Delta x = 1_{\,grid} = t\,.V_{min}$$

d. If the board size is 600x600 pixel, then the number of pixels a single micro-grid corresponds to will be evaluated and scaled accordingly. Because otherwise, it would take only a few unit times to travel the whole board from beginning to the end, even for the vehicles that move slowly. Scaling, in this way, will allow for a zoomed-out board display.

e. E.g. Considering a micro-grid would correspond to 0.01 pixel, then the whole road for a 600 px wide board would be 60000 micro grids, and that can be traveled in 60000 unit times with the velocity of V_{min}.

f. The board will have a variable that will control the number of lanes in sections.

Figure 4.11: Demo of vehicles' micro-grid positions at times t1, t2, t3, t4, t5 depending on their varying speed at each unit time

	g1	g2	g3	g4	g5	g6	g7	g8	g9	g10	g11	g12	g13	g14	g15	g16	g17	g18	g19
Veh1	t1							t2		t3 t4					t5				
Veh2	t1				t2						t3			t4					t5
Veh3	t1		t2 t3						t4		t5								

Source: Türk Telekom Technical Report, 2012; Extraction of Congestion Information and Dynamic Route Planning, May 2012.

g. The vehicles will be arbitrarily generated at random lanes (y coordinates) and at random times.

h. The lanes will have 3 meters width; hence random lanes that the vehicles will be in will be having fixed differences of 3 meters and multiples of 3.

i. The vehicles will move with varying speeds, so there will be a possibility of collision. When collision occurs they will stop.

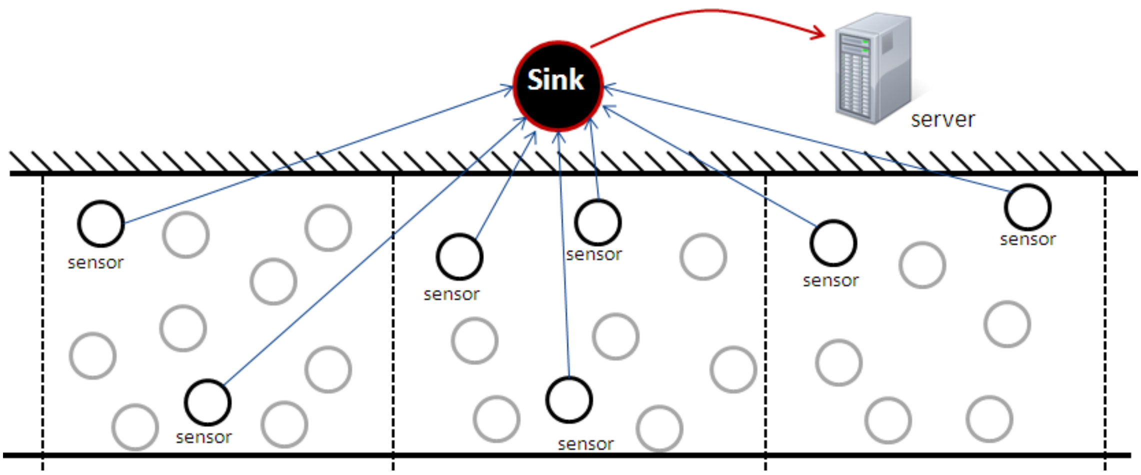
j. The number of vehicles that will start moving on the roadway will also be another simulation parameter.

4.7 SENSOR NETWORK ANALOGY AND DATA ACQUISITION FROM EACH SEGMENT

Improving the sensor model described in Figure 4.7 we introduce the case where there may be many sensors in each segment, however we are not able to receive data from some of them or they would not send their data due to following reasons:

i. Battery is depleted
ii. Does not prefer sending the data
iii. Forgot to or did not want to run the application
iv. Only a few have the application in the segment

Figure 4.12: The case where many nodes are unable to send the data by the analogy of sensor networks



Source: Türk Telekom Technical Report, 2012; Extraction of Congestion Information and Dynamic Route Planning, May 2012.

4.7.1 Exploiting Base Station Hand-Offs

There is also another notion that is based on exploiting the cell phone signals during the hand-offs between the base stations. In such systems the users need not know about an application or trigger a device. Their cell phone signals are automatically recognized by the base stations, interpreted accordingly and suitable actions are taken.

Some important points we should mention about are listed below:

4.7.1.1 Base station ranges

The range of base stations will be varying such that it will be short within the urban areas whereas it will be getting larger while traveling along the rural parts of the city. Note that the cells will be covering a smaller scope and their numbers will be many since the cellular users are much more in number in urban areas, and vice versa. The range of the cell towers will also affect the distance in each segment. In order to know the distance for each segment the actual size of each base station must be known in advance. Hence required calculations can be made to approximate the segment distances which is a must for traffic status estimation and monitoring purposes

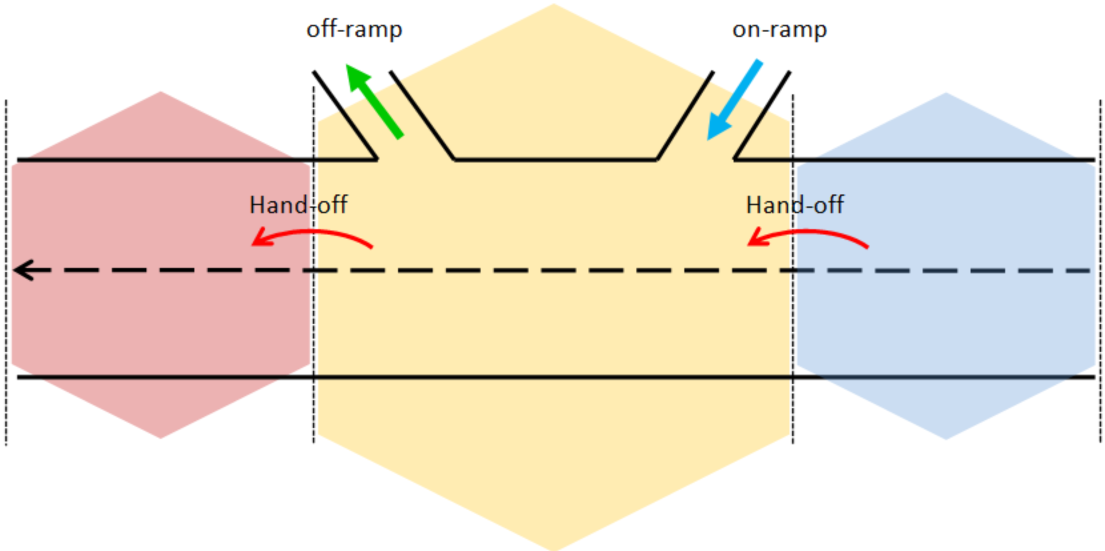
4.7.1.2 Base station hand-off boundaries

This is the major input that is to be used in order to determine the average speed in each segment or the flow from one segment to another. All the calculations will take place according to these boundary points.

4.7.1.3 Off-ramps

The vehicles moving out of a road segment using the off-ramps may lead to errors in the calculation. Because it may not be possible to capture the number of cars moving from the off-ramps since the off-ramp is also contained by the base-station itself.

Figure 4.13: Depiction of hand-offs between base stations and the off-ramp / on-ramp problem



Source: Türk Telekom Technical Report, 2012; Extraction of Congestion Information and Dynamic Route Planning, May 2012.

4.8 BAU REAL-TIME TRAFFIC SIMULATOR

In the second phase of the research, a microscopic traffic simulator is needed to be developed in order to provide both a test and a display mechanism of the traffic system. The name of the simulator is BAU Real-time Traffic Simulator. This simulator will not only provide the required data to be used in the research analyses, but also play the role of the research method.

Simulator is written in Java development environment since it handles the threaded software development quite well and the ability to run in multi-platform, i.e. in multiple operating system platforms.

4.8.1 Motivation

The main reason that leads to the idea of a Smart Transportation Simulator is to develop a framework to analyze and test our GPS data retrieved from the test vehicles on the field that use our Android application. The simulation will allow us the possibility to create road sections with specified number of lanes in each of them. Hence we will be able to find out the average velocity and density for each section on the roadway that is to be simulated.

The traffic simulator is focused on achieving several aims as listed below:

- **a.** Test the data collected by the android smartphone app *TTrafic.*

- **b.** Generate random runtime data for various setups (e.g. Dynamic random 100 vehicles in each section of a four section roadway with varying lengths) and plot them for analysis purposes.

- **c.** Calculate the traffic conditions according to the data received from the built-in GPS sensors within the smartphones.

- **d.** Simulator's output is the smartphone app's input: Use these data to determine the section traffic congestion weights and paint the section colors on the map displayed in the smartphone app.

- **e.** Simulator's input is the smartphone app's output: Display the output of the end-user data transmitted by the android app TTraffic from within the user vehicles (display vehicle locations on the traffic map)

- **f.** Simulate the battery model

4.8.2 The System Architecture

The simulator is based on 7 classes. These classes can be listed as:

i) Vehicle, ii) Battery, iii) Section, iv) RandomVehiclesThread, v) Board, vi) Configuration, vii) Simulation.

This section presents the class tasks and the smart phone battery model implemented in the system, as well as the class diagrams that show the interactions between the classes.

4.8.2.1 The Battery Consumption Model

a. The battery will be shown as a percentage level for each vehicle.

b. Each phone may have different percentage of initial battery power when the mobile application is run. In the simulation scenarios the battery level will either be randomly chosen or set as 100 percent in the start.

c. The mobile application will consume a constant amount of power in the background even though it is in the idle state.

d. The battery model in the simulator will have another consumption state where the user is having a call at the same time the mobile application is running. A real test is run in order to find out the approximate level of battery power the phone consumes during this state.

e. When the mobile application is run by a smart device it will require a constant amount of start-up power, e.g. 1 percent.

f. Each data transmission by the smart devices in the floating vehicles will drain an approximate amount of power from the battery, e.g. 0.01 percent. In other words, such an amount of power is consumed in each iteration of the traffic simulator.

g. Real-time or predicted map requests from the server will drain 0.5 percent battery power.

h. If the vehicle charger connection is established it will not drain the battery. On the contrary it will charge the battery with a certain amount of replenishment rate, e.g. 0.8 percent per minute, as long as the battery level is lesser than 100 percent.

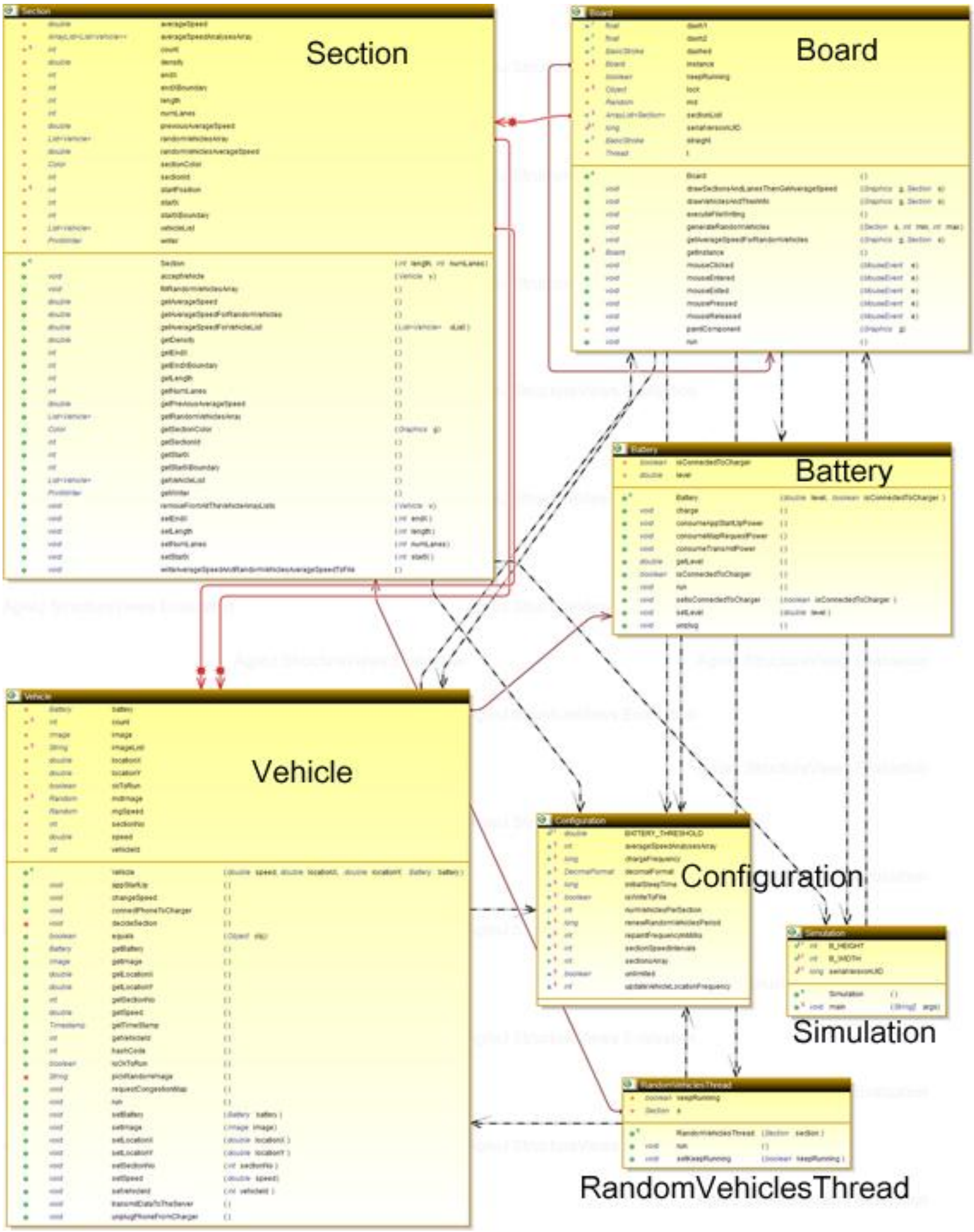
4.8.2.2 Classes

The classes and their distinct responsibilities together with their interaction are presented in great detail in this section. The classes are designed according to the known design principles and design patterns to provide desirable features such as reusability, readability, extendibility, etc. However, further abstraction on these classes are possible to be implemented if required.

4.8.2.2.1 *Class Diagram*

Seven classes are developed in this simulator software. The structure of the software is designed in such a way that it is open for extension instead of modification. The software can be equipped with further tasks to perform when it is desired. The scope of the simulator suggests a class diagram as shown in Figure 4.14.

Figure 4.14: Comprehensive class diagram of the BAU Traffic Simulator



Source: Türk Telekom Technical Report, 2012; Extraction of Congestion Information and Dynamic Route Planning, May 2012.

4.8.2.2.2 *Vehicle*

Vehicle class is basically responsible of creating a vehicle to be painted on the main panel as well as keeping track of the vehicle's most important attributes such as its id, x and y coordinates, speed and the current section at any time instant. Other major roles include the operational steps to be executed during the vehicle movement, application startup, charger connection and disconnection, congestion map requests, data transmission to the server, section decisions, speed changes, and picking the random vehicle display image.

Vehicle class extends the Thread class as its parent class. Hence a run() method is implemented for the Vehicle class. The task of the thread is determined within this method. This is the point where the vehicle will not only move (i.e. set its new location) according to its instantaneous speed, but also will decide what section it is in after the movement. Moreover the thread will help the vehicle change its speed randomly, i.e. accelerate or decelerate. Such operations implemented as the thread task will be executed in each time interval that is specified by the static field updateVehicleLocationFrequency in the Configuration class.

Vehicle class has 12 fields of varying types. These fields can be listed as below:

a. **battery**: It is a reference on a Battery object. With the help of this field, the battery is consumed or charged according to the operation performed by the Vehicle. These operations can be one of the following i) appStartUp(), ii) transmitDataToTheServer(), iii) requestCongestionMap(), iv) connectPhoneToCharger().

b. **count:** This field is responsible for counting the vehicle objects created during the simulation and is of the primitive type int. It is a static field of the Vehicle class, hence the id of the vehicle can be assigned on the vehicleId field.

c. **image:** image is a reference on an object of the type Image. It is assigned with a randomly chosen image that displays the vehicle on the simulator panel.

d. **imageList:** this field is a static string array that has the names of the vehicle images present in the simulator. It is used by the pickRandomImage() method.

e. **locationX:** This field keeps the pixel value for the x coordinate of the vehicle as the double primitive type. Actually this value is scaled according to the simulator screen and the vehicle's reported coordinate on the road. It is then used as the upper-left corner coordinate of the randomly chosen vehicle's bounding rectangle.

f. **locationY:** This field keeps the pixel value for the y coordinate of the vehicle as the double primitive type. Actually this value is set according to the lanes in which the vehicle is located at the time being. It is then used as the upper-left corner coordinate of the randomly chosen vehicle's bounding rectangle. Its value is specifically assigned in such a way that the vehicle will eventually appear within one of the lanes of the current section.

g. **okToRun:** There is a Thread assigned for each vehicle that is started to run on the creation time. When it is true, the thread task operation will continue. When it is false, the thread will stop and hence the vehicle movement will stop.

h. **rndImage:** This static field is of a Random type and is used in pickRandomImage() method to pick the random image from the imageList string array.

i. **rngSpeed:** This is also of the type Random and is used for deciding how the vehicle will move in the current iteration of the thread. The vehicle can accelerate and decelerate. Both acceleration and deceleration can happen at three levels, i.e. plus or minus 1 or 2 or 3 magnitudes of speed change on the current speed.

j. **speed:** The speed level is the primitive type double and is determined to be between 1 km/h and 120 km/h. If somehow the speed drops below 1 km/h or exceeds 120 km/h it will then be set to minimum or maximum values appropriately by the changeSpeed() method. Each vehicle has its own speed randomly set on the object (vehicle) creation process. The speeds are determined for each vehicle according to the section it is in at the time it is created. For example if the vehicle is in first section and the first section's initial speed interval was set as between 40 km/h and 60 km/h in the Configuration class, then the speed will be randomly chosen between these values as the minimum and the maximum limits.

k. **sectionNo:** This field is initially set when the vehicle is created anywhere on the screen. The section is determined according to the creation location or the section that uses the Section class's accept(Vehicle v) method. When a section gets the vehicle as the parameter inside the accept(Vehicle v) method, that vehicle's sectionNo is set with the id of that specific section. This is an important field that plays a key role on the section decision operations throughout the simulator software.

l. **vehicleId:** This field also plays a key role on the vehicle list updates for each section. The vehicles are added in or removed from a section according to the unique vehicleId. Actually hascode() and equals() methods are overriden according to the "vehicleId" field of the Vehicle class, so that the predefined methods that utilizes equals() or contains() methods will behave according to this criteria.

Other than the 12 fields, there are 9 getter methods and 7 setter methods. Getter methods are comprised of getBattery(), getImage(), getLocationX(), getLocationY(), getSectionNo(), getSpeed(), getVehicleId(), isOkToRun(). On the other hand, the setter methods can be listed as setBattery(), setImage(), setLocationX(), setLocationY(), setSectionNo(), setSpeed(), setVehicleId().

Furthermore, the constructor and the remaining methods are explained below in detail:

i. **Vehicle(double speed, double locationX, double locationY, Battery battery):** There is just a single constructor for Vehicle class and it gets four parameters in it. It simply sets the vehicleId field according to the count static field by increasing this value every time the constructor call is made, i.e. every time a vehicle object is created. After that, the vehicle's speed field, locationX and locationY fields, battery field are set according to the incoming parameters. The vehicle's image is also set with the random image returned by the pickRandomImage() method.

ii. **void run():** It is an @Override method specified by the Thread class and is implemented by the child class, namely Vehicle. According to the run() method, what kind of tasks the implementing class should carry out is determined. Vehicle's thread is responsible for the specific vehicle's movement operation according to its instantaneous speed. A Boolean variable, namely okToRun is used in order to stop this thread or make it keep running, in other words keep the vehicle moving. Other than the movement task, the thread also commands the vehicle to decide its new section if it has changed, and change the vehicle's speed. These tasks are performed in each time interval the Configuration class specified with updateVehicleLocationFrequency field. The thread actually sleeps for the amount designated by that field. The thread also sleeps only once when it is started() for the very first time.

iii. **void appStartUp():** This method is responsible of doing everything specifically needed at the smart phone application startup time. Other than that, it executes the consumeTransmitPower() method located in Battery class which is accessed from its battery field, if and only if the battery is not docked into the vehicle charger.

iv. **void transmitDataToTheServer():** Do whatever is needed in the transmission to the server process. Morever, as long as the vehicle charger connection is not established consume the battery for the amount needed in battery.consumeTransmitPower() method of the Battery class. There will be no battery consumption if the smartphone, and thus the battery, is connected to the charger.

v. **void requestCongestionMap():** Execute the operations to request the congestion snapshot from the server. In addition, if the smartphone is not being charged then consume the battery for the amount needed in battery.consumeMapRequestPower() method of the Battery class. Of course again, no battery consumption is performed if it is connected to the charger.

vi. **void connectPhoneToCharger():** Execute the charge method implemented within the Battery class. Use the vehicle's battery field to access to the method.

vii. **void unplugPhoneFromCharger():** This method simply calls the battery.unplug() method which stops the thread responsible of the charging task within the Battery class.

viii. **void changeSpeed():** This method uses a switch that generates a random number over six states. According to the number, it decides at which level the vehicle should accelerate or decelerate. It is performed by increasing the speed value by +1 or +2 or +3; or similarly decreasing the speed value by -1 or -2 or -3. Check if the speed value is between 1 and 120 km/h. If not set the value to 1 if it is lower than 1 or 120 if it is greater than 120.

ix. **void decideSection():** This method is called after each movement in the vehicle's thread. When the location is updated, check to see if the new section is different than what the current sectionNo shows. It is decided by the section boundary locations that are dynamically determined according to the number of sections and their lengths present in the simulation setup. If the section was changed, remove this vehicle from the previous section's vehicle list and all the other vehicle lists related to that section. After that, check if it is the last section in the simulation setup, if it is then stop this vehicle's thread so it will stop and disappear on the simulation screen. If it is not the last section then accept this vehicle to the next section, i.e. to the new section.

x. **boolean equals() & int hashCode():** These are the overridden hashCode() and equals() methods that use the vehicleId in order to override the comparison mechanism for the vehicle objects. These are java specific implementations modified for the Vehicle class.

xi. **String pickRandomImage():** Decides on a random image from the image list. Thus the created vehicle will have that specific image to depict the vehicle on the simulation screen.

As it is also shown in the class diagram in Figure 4.15, Vehicle class depends upon Board class and Board class depends upon Vehicle class. Vehicle also depends upon Configuration class that has just static fields. Another class that depends upon Vehicle is RandomVehiclesThread.

Besides, Vehicle class references one Battery object, whereas both Section.randomVehiclesArray and Section.vehicleList references many Vehicle objects.

Figure 4.15: Vehicle class's structure

Vehicle

Vehicle

Battery	battery	
int	count	
Image	image	
String	imageList	
double	locationX	
double	locationY	
boolean	okToRun	
Random	rndImage	
Random	rngSpeed	
int	sectionNo	
double	speed	
int	vehicleId	
	Vehicle	(double speed, double locationX, double locationY, Battery battery)
void	appStartUp	( )
void	changeSpeed	( )
void	connectPhoneToCharger	( )
void	decideSection	( )
boolean	equals	(Object obj)
Battery	getBattery	( )
Image	getImage	( )
double	getLocationX	( )
double	getLocationY	( )
int	getSectionNo	( )
double	getSpeed	( )
Timestamp	getTimeStamp	( )
int	getVehicleId	( )
int	hashCode	( )
boolean	isOkToRun	( )
String	pickRandomImage	( )
void	requestCongestionMap	( )
void	run	( )
void	setBattery	(Battery battery)
void	setImage	(Image image)
void	setLocationX	(double locationX)
void	setLocationY	(double locationY)
void	setSectionNo	(int sectionNo)
void	setSpeed	(double speed)
void	setVehicleId	(int vehicleId)
void	transmitDataToTheServer	( )
void	unplugPhoneFromCharger	( )

Source: Türk Telekom Technical Report, 2012; Extraction of Congestion Information and Dynamic Route Planning, May 2012.

4.8.2.2.3 *Battery*

Battery class plays the role of a smartphone battery which is consumed by the operations done on the client side. Using the battery class aims at simulating the battery consumption model while transmitting and receiving data during the communication processes.

Every vehicle has a smartphone and hence a battery integrated with it. The Board class creates the vehicles using the generateRandomVehicles(Section s, int min, int max) method for the specified section within random speeds bounded by the lower and upper limits defined by the min and max values. Every vehicle is created with the random speed range specified, at the specified X and Y coordinates (Y coordinate stands for the lane number) including a battery with arbitrary level of energy stored in it. Thus it makes the Vehicle class dependent on the Battery class.

Battery class extends the Thread class that makes it responsible of executing a task in its run() method. The task is based on the charge() method. The charge method starts the charging process that increases the battery level by 0.8 percent in each charge frequency defined in the Configuration.chargeFrequency static field. When the battery level is greater than or equal to100 percent it simply keeps the charging without increasing the battery level. The other major roles are composed of unplugging from the charger, consuming the application startup power, consuming the transmission power, and lastly consuming the energy needed for real-time map requests.

Vehicle class has only two fields. These fields are listed below:

a. **level:** The field is of a double type and is used for keeping the battery state in terms of percentage levels. Every method uses this level field such that they either decrease or increase the value by a certain percentage determined during the battery analyses using an android phone.

b. **isConnectedToCharger:** This field is the type of a boolean. It is used to check the state of the charger connection. The actual purpose it has is to either stop the loop in the run() method that is responsible for charging the battery when the charger connection is established, or to keep the thread (charging operation) running.

Moreover, the class has both setter and getter methods assigned to each fields. These methods have the name: getLevel(), setLevel(double level), isConnectedToCharger(), setIsConnectedToCharger(Boolean isConnectedToCharger).

Furthermore, the class has one parametric constructor as well as 6 other methods including the thread’s run() method. The methods are comprehensively explained below:

i. **Battery(double level, Boolean isConnectedToCharger):** the Battery objects are instantiated using the parametric constructor Battery(double level, Boolean isConnectedToCharger). The constructor simple sets the initial battery level (in the simulation runs it is set as 100 percent in vehicle creation phase) and checks if the isConnectedToCharger field is true or not, and if it is true the charge() method is called.

ii. **void charge():** The charge() method simply starts the thread’s run() method that increases the battery level by 0.8 percent in every minute. Right before the thread is started, isConnectedToCharger field is set as true since the charge() method can be called arbitrarily outside the constructor.

iii. **void unplug():** The method actually acts as a setter method. It simply sets the value of isConnectedToCharger field to false, hence the thread stops running.

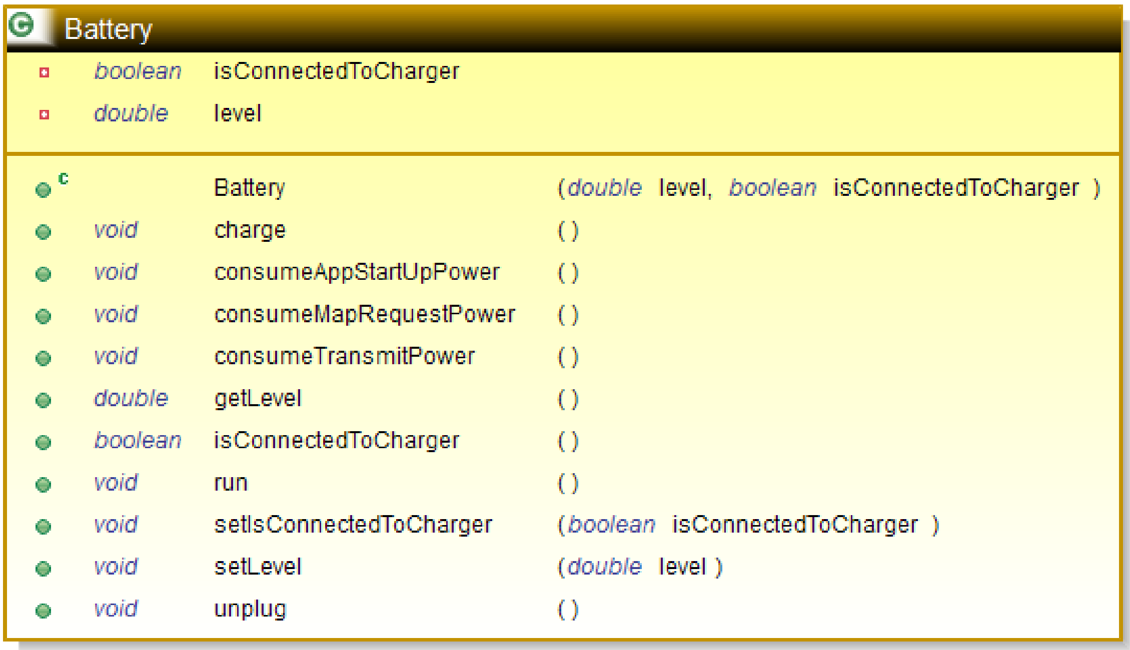
iv. **void consumeAppStartUpPower():** The method is used to decrease the battery level by the amount specified within the method. This method is used when the RandomVehiclesThread's run() method is executed in every n (renewRandomVehiclesPeriod) seconds. This means that the vehicles will only consume app startup power whenever they start their applications in every n (renewRandomVehiclesPeriod) seconds. If the battery level is somehow decreased to a level lesser than zero, it will set the remaining battery level to zero, hence prevent the possibility of setting negative values.

v. **void consumeTransmitPower():** The method decreases the value assigned to level field by an amount defined in the method, e.g. 0.01 percent**.** consumeTransmitPower() method is called in each repaintFrequencyInMillis, i.e. the frequency of the time which the vehicles transmit their data. By design, the transmission to server occurs whenever the vehicles' new locations are updated, in other words repainted. It guarantees that the remaining level is greater than or equal to zero.

vi. **void consumeMapRequestPower():** This method is also responsible of decreasing the battery level by an amount defined in the method, e.g. 0.5 percent**.** consumeMapRequestPower() is used in each repaintFrequencyInMillis, i.e. the frequency of the time which the vehicles transmit their data, as well. Because the system tries to reward the user and hence keep their congestion map up-to-date whenever the user contributes in the system by transmitting its GPS data (location and speed) to the server. This method also guarantees that the remaining level is greater or equal to zero.

Figure 4.16 introduces the class diagram for the Battery. Battery class depends upon Configuration class since it uses the static field chargeFrequency defined in it.

Figure 4.16: Battery class's structure



Source: Türk Telekom Technical Report, 2012; Extraction of Congestion Information and Dynamic Route Planning, May 2012.

4.8.2.2.4 *Section*

Section class has a very active role in the simulator software. It has several important responsibilities. Besides, many of the other classes depend upon the vehicle lists saved by the section objects.

Section class helps to create the virtual boundaries drawn on the simulation field, as well as keeping track of the starting and ending coordinates and distances of each section iteratively created. Basically, the whole simulator waits for the average speed calculations done and then saved in each section object. The class accepts the vehicles that enter from the objects starting boundary, and removes the vehicles that are passing from the ending boundary point of the corresponding section object. Hence the vehicle list is properly determined and is provided to dependent methods and classes for further operations.

Major roles of the Section class are accepting a vehicle into the section, removing the a vehicle from all the vehicle lists saved in the section, calculating the density in the section, calculating the real average speed in the section, calculating the average speed of the transmitting vehicles in the section at a specific time instant, calculating the average speed of a specific vehicle list given as an input, writing the average speed of all vehicles as well as the average speed of randomized vehicle lists into a file for the section, filling the random vehicles arrays as well as the average speed analyses arrays, determining the section color according to the average speed of the vehicles in the section, and saving the latest available section speed in order to show it in case a problem occurs.

The Section class has 18 fields of varying types of which two of them are static. The fields are explained thoroughly below:

a. **startPosition:** This is a static field of the type integer. It basically starts with the value of zero and increased by the length of the latest section object created. This way the starting and the ending distances of the next section to be created can be determined easily on the complete roadway.

b. **count:** Every section has a sectionId to make the sections unique. The count field is a static field and increased by one every time a new section object is created, and thus the sectionId is determined using this static integer field named count.

c. **density:** Every section can have not only different lengths but also different number of vehicles present in it. The field density is used to provide a statistical ratio that keeps track of the number of vehicles per kilometer (vpk) in a section as a double type value. The field is one of the key parameters used in the traffic theory which provides an approximate comparison metric.

d. **averageSpeed:** The users in a real-time traffic system wonder how congested the sections are and evaluate the congestion levels according to the average speed measurements given for the sections. For this reason, the average speed field in a section is quite important. This field is of the type double and is responsible for keeping track of the average speed of all vehicles present in the section. This is the real average speed that describes the section and can be compared with the average speed calculated for the vehicles contributing into the system by transmitting their locations and speeds to the server. The average speed is kept in terms of km/h.

e. **previousAverageSpeed:** This field saves the latest average speed of all vehicles in the section in case a problem occurs during the calculation and thus the latest average speed value can be shown instead. It is also of the type double and is saved in terms of km/h.

f. **randomVehiclesAverageSpeed:** It is basically the same as averageSpeed field. The type of the field is double and keeps the value in terms km/h. But this average speed is calculated using the random vehicles list that stands for the vehicles that are selected for transmitting data to the server.

g. **sectionId:** The field is of the type integer and its value is assigned by the static field count. This field is used to determine the unique sections.

h. **startX:** This field is an integer type, as well. The field saves the actual starting point of the section in the x axes in terms of real distances in a straight roadway. Its value is assigned by the startPosition static field which is updated everytime a section is created.

i. **endX:** This field has exactly the same properties as startX. The only difference is that it saves the meter value of the actual ending point of the section in the x axes in terms of real distances in a straight roadway. Its value is determined by the sum of startX and the section length.

j. **startXBoundary:** It keeps track of section's starting vertical boundary as exact pixel coordinates on the painted area (Board JPanel). The values are scaled accommodate the drawing area. Thus startXBoundary is assigned with the value calculated by Simulation.B_WIDTH static field minus the half of the startX.

k. **endXBoundary:** It keeps track of section's ending vertical boundary as exact pixel coordinates on the painted area (Board JPanel). A scaling process which is the same as in startXBoundary calculation is done. Thus endXBoundary value is determined by Simulation.B_WIDTH value minus the half of endX value.

l. **sectionColor:** This field is of the type Color and is responsible for saving the color state of the section. The color of the section is assigned by the getSectionColor(Graphics g) method located in the Section class. It simply checks the average speed of the section and assigns the appropriate color according to the the average speed value. The details are given in getSectionColor(Graphics g) method.

m. **writer:** writer keeps a reference to a PrintWriter object. The field than instantiated with a PrintWriter object that takes a new file object as a parameter whose name is determined by the sectionId, in the Section's constructor. In short, every section creates its own file to log the average speed calculations in. It is used in the writeAverageSpeedAndRandomVehiclesAverageSpeedToFile() method.

n. **vehicleList:** This is the most important field in the whole program. Because the output of the simulator totally depends on this List of the type Vehicle. The field has a reference to a synchronized array list and is instantiated in the same line it is defined. According to the vehicles accepted in or removed from the section, the corresponding vehicleList field is updated. The average speed calculations are done in each iteration according to the vehicles present in the section's vehicleList field. This field is the key to many classes and methods written in the simulator software.

o. randomVehiclesArray: This field has the same properties as vehicleList field. But this array list contains the vehicles that are selected randomly for transmitting their data to the server. The upper average speed labeled as “Rnd Avg Speed” in the simulator interface is calculated using this List of the type Vehicle.

p. **averageSpeedAnalysesArray:** This field is an Array List containing multiple Lists of the type Vehicle. The field actually keeps a reference to the Lists of dynamic random 20, dynamic random 40, dynamic random 60 and dynamic random 80 vehicles, which are mentioned throughout the dynamic random analyses. These average speeds are calculated and written in to the section files in the third, fourth, fifth and sixth columns for dynamic random 20, dynamic random 40, dynamic random 60 and dynamic random 80 vehicles, respectively.

Moreover, the class has 15 setter and getter methods in total. Some fields have only getter method while some others have both getter and setter methods. These methods are, namely: getLength(), setLength(int length), getNumLanes(), setNumLanes(int numLanes), getStartX(), setStartX(int startX), getEndX(), setEndX(int endX), getStartXBoundary(), getEndXBoundary(), getSectionId(), getWriter(), getPreviousAverageSpeed(), getRandomVehiclesArray(), getVehicleList().

Furthermore, the class has one parametric constructor as well as 9 other methods. The methods are explained comprehensively below:

i. Section(int length, int numLanes): The parametric constructor gets two parameters in total, one of which is to set the length of the section (given in meters) and the other is to set the number of lanes. The constructor first of all sets its sectionId according to the value taken from the static field count. After that the average speed and the previous average speed values are initialized to zero, and then the writer is instantiated to a PrintWriter that writes into a file corresponding to the same section id. Then the length of the section is checked and tuned. The sections must be larger than 300 meters in order to assure that the distance that can be travelled within a cycle of update time does not exceed the minimum section length. In the following lines, the number of lanes is checked. The number of lanes for a section cannot be lesser than 1 and greater than 8. If the number of lanes is outside of this range appropriate adjustments are done. Then the startX and endX values are set using the startPosition static field and the length field. Furthermore the startXBoundary and endXBoundary values are scaled and set according to the aforementioned calculations. Lastly the startPosition static field is updated with the latest value of endX field, and required number of new synchronized array lists of the type Vehicle are added on the averageSpeedAnalysesArray field.

ii. **void acceptVehicle(Vehicle v):** This method is responsible for the operation of adding the Vehicle v taken as a parameter into the section's vehicleList. Besides the vehicle's section id is set with the value coming from the getter method this.getSectionId().

iii. **void removeFromAllTheVehicleArrayLists(Vehicle v):** This method is called in the Vehicle class's decideSection() method. When a vehicle changes its section during the movement process, it takes action to determine its new section using the decideSection() method. Firstly vehicle must be removed from all the vehicle lists it appeared previously, and then the new section is determined appropriately. These vehicle lists are namely the vehicleList, and all the lists in the averageSpeedAnalysesArray.

iv. **double getDensity():** The method basically checks the section's vehicleList if it is empty or not. If it is empty it return zero, and if not then it sets the density by dividing the number of the vehicles in the list by the length of the section, and returns this value.

v. **double getAverageSpeed():** Average speed calculation of all the vehicles present in the section is performed by this method. The method first of all checks if the vehicleList is empty, if not it sums up the vehicle speeds and divides it to the number of vehicles and return the result. Meanwhile the value of previousAverageSpeed is also assigned. If there are no vehicles the average speed is set to zero. Thus in case there are no vehicles in the section the previous average speed can be shown.

vi. **double getAverageSpeeForRandomVehicles():** The logic executed inside the method is completely the same as it is in getAverageSpeed() method. The difference lies on the list the inputs are taken from. The list used as the input source is the randomVehiclesArray that keeps track of the transmitting vehicles at any time.

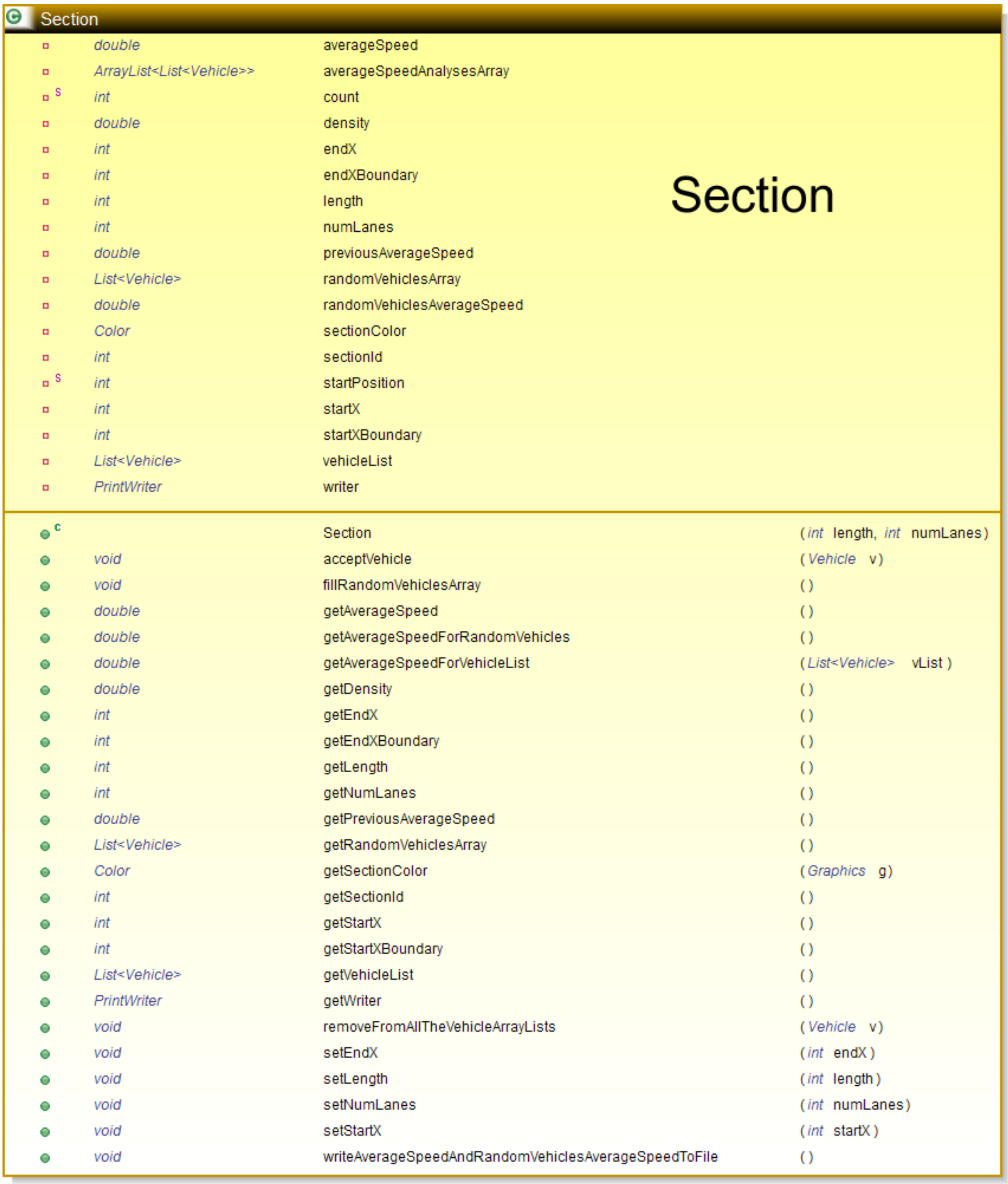
vii. **double getAverageSpeedForVehicleList(List<Vehicle> vlist):** The method works the same way as the other average speed calculation methods. But this method gets its input source as a List type parameter that saves vehicle objects in it.

viii. **void writeAverageSpeedAndRandomVehiclesAverageSpeedToFile():** The method acts as a writer. Actually the field writer of the type PrintWriter initialized in the Section objects is used to print various average speeds calculated for the section. The average speeds are written in the file column by column, in other words they are delimited by a space character. The average speeds are averageSpeed, randomVehiclesAverageSpeed, average speed averageSpeedAnalysesArray(0), average speed averageSpeedAnalysesArray(1), average speed averageSpeedAnalysesArray(2), average speed averageSpeedAnalysesArray(3), written in the order of appearance inside the file.

ix. **void fillRandomVehiclesArray():** This method is executed by the thread of RandomVehiclesArray class. The thread's run method simply fills randomVehiclesArray in each time determined by Configuration's renewRandomVehiclesPeriod. The method first of all clears the randomVehiclesArray, and then creates a random number generator to pick a random number of vehicles out of vehicleList's size plus 1. This randomly determined number sets the number of vehicles which are to be transmitting their data. A for loop is created to pick as many vehicles as this random number says. As long as the vehicleList is not empty, the method picks an individual vehicle among the vehicleList. After that the Lists in the averageSpeedAnalysesArray are cleared, and as many vehicles as it is stated for each List is picked randomly from the vehicleList and added into the appropriate list. For example 20 random vehicles are picked to be added into the random dynamic(20) array, 40 vehicles are picked to be added into the random dynamic(40) array, and goes so on for random dynamic (60) and (80).

x. **Color getSectionColor(Graphics g):** This method is responsible for determining the section color according to the average speed and returns it. Beside the method draws a string to show traffic congestion level such as 1 heavily congested, 2 congested, 3 dense flow, 4 smooth flow, 5 free flow, and 6 highly free flow. According to the returned color a colored bar above the section in the simulator screen is drawn by the Board class. The method is called in drawSectionsAndLanesThenGetAverageSpeed(Graphics g, Section s) method in the Board class. The speed intervals that determine the color and the traffic congestion level are [0-20], (20,40], (40,60], (60,80], (80,100], and (100,120] for 1 heavily congested, 2 congested, 3 dense flow, 4 smooth flow, 5 free flow, and 6 highly free flow, respectively.

Figure 4.17: Section class's structure



Source: Türk Telekom Technical Report, 2012; Extraction of Congestion Information and Dynamic Route Planning, May 2012.

Figure 4.17 introduces the structure of the Section class. As it can be seen from the class structure, both Section.vehicleList and Section.randomVehiclesArray references many Vehicle objects. Furthermore, the Section class depends upon Configuration class since it uses the static variables defined in that class. Section also depends upon the

Simulation class since it uses B_WIDTH static final field that defines the JFrame's width. Lastly, the Board.sectionList references many sections whereas the RandomVehiclesThread.s references one section.

4.8.2.2.5 *RandomVehiclesThread*

The RandomVehiclesThread extends the Thread class and called in the Board class's constructor. What the constructor of Board class does is to create a section and give that section to RandomVehiclesThread in order to instantiate an object. The constructed RandomVehiclesThread object fills the randomVehiclesArray of the Section it references to. This operation is repeated in each renewRandomVehiclesPeriod. In short this class is responsible for renewing the randomVehiclesArray and the Lists in the averageSpeedAnalysesArray.

The class fields are given below:

a. **s:** The class references a Section object. The tasks of the thread are done via this section and its fillRandomVehiclesArray() method.

b. **keepRunning:** This field is a Boolean type and is used to stop the infinite while loop in the run() method.

The class has only one setter method to change the value of keepRunning field and has no getter method. The setter method is implemented for keepRunning boolean. Other than the setter method, it has only one method, namely the thread's run() method. The purpose of the method is given below:

c. **void run():** The run() method simply fills the arrays containing random vehicles by calling fillRandomVehiclesArray() method of the Section class using the Section reference s, e.g. s.fillRandomVehiclesArray(). The sections random arrays are renewed in each milliseconds defined in Configuration.renewRandomVehiclesPeriod. After each renewing operation, the vehicles in the randomVehiclesArray, i.e. the vehicles that are transmitting data, are told to call their appStartUp() method. Thus it is simulated that every randomly chosen vehicle starts up its smart app and consume startup power from the battery.

Figure 4.18: RandomVehiclesThread class's structure

Source: Türk Telekom Technical Report, 2012; Extraction of Congestion Information and Dynamic Route Planning, May 2012.

Figure 4.18 introduces the structure in the class RandomVehiclesThread. The class references one section in each object. Beside the RandomVehiclesThread class depends upon Configuration class for the two static fields named initialSleepTime and renewRandomVehiclesPeriod. It also depends upon the Vehicle class since it executes the randomly picked vehicle's appStartUp() method. On the other hand, Board class depends upon the RandomVehiclesThread.

4.8.2.2.6 *Board*

Board class is a singleton due to the fact that the simulator software will have only one instance of the Board class. The class extends the JPanel class and implements both MouseListener and Runnable interfaces. The Board is mainly responsible of repainting the simulator panel, dynamically creating the sections according to the Configuration class fields, namely two dimensional arrays sectionSpeedIntervals and sectionsArray, and save these Section objects in an array.

Other major roles include generating random vehicles according to speed intervals given for each section, creating a thread of the type RandomVehiclesThread to handle the filling operation on the randomVehiclesArray and the lists contained in averageSpeedAnalysesArray.

Meanwhile it executes several related operations to perform the tasks defined in the repaint(Graphics g) method, (i.e. paintComponent(Graphics g), that is called by the class's own thread, such as the operational steps to draw section lanes and the texts that show the average speed calculations, commanding the section objects to calculate and return the random vehicle array's average speed, drawing the vehicle images and so on.

Board class extends the JPanel class and implements both Runnable and MouseListener interfaces. Using the Runnable interface the repaint() method is called to refresh the graphics components over and over again. The MouseListener interface, on the other hand, lets the mouse functions to be implemented in the simulator. For example a mouse function that displays the vehicle information in an information balloon or pop-up screen when right clicked.

The Board class has 11 fields in total. The fields are explained below:

a. **dash1:** This field is of the type float. It is used as a global variable and to determine the array representing dashing pattern in a dashed BasicStroke. This is used to draw the dashes that limit the width of each lane in both sides and the vertical borders of each section. It has the value of 10.0f for the float array. It is called in the final field named "dashed" of the type BasicStroke.

b. **dash2:** The field acts the same way as dash1 field does. It has the float value of 1.0f for the float array representing the dashing pattern and is used to draw the green rectangle encloses the vehicles transmitting data. It is called in the final field named "straight" of the type BasicStroke.

c. **dashed:** This field is of the type BasicStroke and used as the parameter to set the stroke of the graphics objects, both for the graphics object that draws the vertical section borders depicted by the blue dashed lines, and for the graphics object that draws the hortizontal section lanes depicted by the gray dashed lines.

d. straight: This is the same as dashed field except a few different attributes. The width is 1.0f instead of 2.0f and uses dash2 field as the dashing pattern attribute.

e. instance: This field is a static instance of Board class. It is null at first but then initialized as a new Board() object in the static method getInstance(). This way the class is assured to act like a singleton that has a double locking mechanism. This is due to the fact that the simulator software will have only one instance of the Board class. The board class is called from outside using the getInstance method that returns the instance field to the caller.

f. keepRunning: This field is of the type boolean and serves to the purpose of keeping the thread running or making the thread stop if required (for example in case the simulator is paused by the user). The thread of the Board class, as mentioned earlier, refreshes the display screen in the simulator software by calling the repaint method in each specified time interval.

g. lock: This field is the type of a plain Object. It is used in the getInstance method to perform the singleton mechanism work. The singleton mechanism has a synchronized block that uses the lock field to restrict the simultaneous access. The field is initialized before the object creation at the point it is defined.

h. rnd: The field is of a Random type and is used inside the method generateRandomVehicles(Section s, int min, int max) while creating the vehicles. The field determines where to put to image on the display screen. Since there are lanes and the vehicles need to be located inside these lanes a calculation in the pixel level is done. The vehicles are located at the pixel 200 plus the randomly chosen lane number times 20 in the y axes. The x axes coordinate is calculated differently.

i. **sectionList:** The field is of the type ArrayList that takes Section objects in it. The sections created in the constructor of the Board class are added inside this statically accessible field.

j. **t:** This field references a Thread type object. The field is initialized in the Board constructor using the class itself, e.g. t = new Thread(this), since the class implements the Runnable interface. The field is started at the last line of the constructor and is responsible of starting the run() method that executes the repaint() task.

k. **serialVersionUID:** The Board class is a serializable and hence it should declare a static final serialVirsonUID field of type long. It has the value of 1L. The field is required by default.

The class has neither setter nor getter methods. But it has 12 methods except the constructor. The details about the methods are given below:

i. **Board():** The constructor of the Board has the access type of private. The constructor makes the screen focusable (coming from JPanel) and sets the background color to black in the beginning. Right after that, a loop generates as many sections as the length of the array named sectionsArray declared in Configuration class. According to the values of the Configuration.sectionsArray[i][j], the section objects are created. This field of the Configuration class gives the section parameters that stand for the length and the number of lanes of each section. Then for each section as many vehicles as it is specified in Configuration class are created. The vehicles are created with random speeds where the speed values are between the specified ranges. The speed ranges are also declared in Configuration class's sectionSpeedIntervals field that is a two dimensional array. After the vehicles are created and added into one section, the RandomVehiclesThread object is created for that section and its task is started. As the last thing to do, the Board class's own thread that is responsible of repainting the screen and repeating the calculations is initialized and started.

ii. **Board getInstance():** This method ensures the class is a singleton, in other words it is initialized using this static method and the it can be initialized only once from the outside using the static instance field of type Board. The method implements a double locking mechanism to assure the object creation is done only once even in multicore systems. The method first of all checks if the private static field of type Board named instance is null or not. If it is null that means no instance of the class is created yet. Then the method gets into a synchronized block to prevent simultaneous access to the line below by multi-threaded systems. A robust singleton implementation should work in any conditions. This is why it is needed to ensure it works when multiple threads uses it. Inside the synchronized block, the instance field is checked to see if it is instantiated, for the second time. If it is not, then the instance can be instantiated with a new Board() object and returned in the end.

iii. **void generateRandomVehicles(Section s, int min, int max):** This method is responsible of creating as many vehicles as specified by the field Configuration.numVehiclesPerSection with the random speeds that is in the range of the parameters min and max. First of all a Battery object with 100 percent energy level and the isConnectedToCharger field set to false. A local random variable is instantiated. The difference between the min and max values are calculated in order to generate a random value between zero and the difference value plus 1. And then this random value is summed up with min value to be able to set a speed value between min and max parameters for the vehicle to be created. The vehicle is created at the coordinates; one of which is defined by Simulation.B_WIDTH minus the half of the startX location of the section, and the other is defined such that the vehicle image fits in one of the randomly chosen lanes in the section. The battery object is given as the last parameter of the vehicle into its constructor. When the vehicle is created, it is ensured that the section given as the first parameter, accepts this vehicle. Lastly the vehicle's thread is started that accomplishes the movement task.

iv. **void paintComponent(Graphics g):** The method acts completely the same way as paint() method implemented in a JPanel class. It is possible to use the paint() method instead. The method works whenever the repaint() method is called. The method clears the screen by calling the super.paintComponent(g). The graphics parameter "g" is used to draw the components on the JPanel. What the method does after the cleaning process is that it first of all scans each section in a loop and calls the method that draws the section and its lanes and gets the average speed of the section and also draws the value as a string above the section. After that it gets the average speed for random vehicles that are transmitting their GPS data and draws it as a string component above the section, as well. Lastly it calls the method that draws the each vehicle's images. The method is also responsible of drawing dashed green lines around the vehicles that are transmitting GPS data to the server. Further information about the individual vehicles can also be drawn within this method. Lastly the method synchronizes the default toolkit's graphics state and disposes of the graphics context "g" and releases any system resources that it is using.

v. **void drawSectionsAndLanesThenGetAverageSpeed(Graphics g, Section s):** This method draws not only the vertical dashed lines to determine the section boundaries as well as the horizontal lines that determine the number of lanes in the section. In addition, it gets the sections average speed and the previous average speed and assigns these values to its local variables latestAverageSpeed and currentAverageSpeed of type double, respectively. In case there is no available average speed data, the method shows the average speed using the latestAverageSpeed local variable, which is in fact the previous average speed taken from the section. If nothing is out of order then the average speed is drawn above the section as a string graphics component. In the following step, the section color is taken from the section type parameter named "s" using the

Section’s getSectionColor(g) method. This method of the Section class not only returns the suitable section color according to the section’s average speed, but also draws the congestion weight (an integer value between 1 and 6 such that 1 stands for the heavily congested and 6 stands for the free flow) as a string graphics component. And then a rectangular area is filled with the color return from the getSectionColor(g) method via the graphics “g” reference. This colored rectangular shape is positioned on the simulator screen at an appropriate above the corresponding section. And then the color of graphics “g” is set to gray and the required number of lanes is drawn using the dashed lines. Furthermore the color of “g” is set to blue and then the vertical dashed lines are drawn to indicate the section borders. In the last line the color of “g” is set back to gray.

vi. **void getAverageSpeedForRandomVehicles(Graphics g, Section s):** The method gets the average speed calculation for random vehicles and then draws the string component to show the value taken for the specific section object. The drawing operation is done via the Graphics g parameter, and the section reference is used to determine which section’s average speed for random vehicles to get and where to draw the string component. After the calculation is done and the string component is drawn above the appropriate section, lastly for each vehicle transmitting their GPS data it calls each individual vehicle’s transmitDataToTheServer() and requestCongestionMap() methods.

vii. **void drawVehiclesAndTheirInfo(Graphics g, Section s):** At the first step the stroke type of graphics “g” is set to straight and then the color is set to green. After that the randomVehiclesArray is copied on a new List<Vehicle> from section referenced with “s” using the getRandomVehiclesArray() defined in Section class. And then the image of each vehicle that appear in the section is drawn in a “for each” loop. After that it is check that if the drawn vehicle is also contained by the randomVehiclesArray. If it is, then a green rectangular dashed border is drawn around the image of that vehicle. The vehicle with the green dashed lines around it means that the vehicle is transmitting at that moment.

Lastly when the loop is over, the stroke is set to “dashed” named BasicStroke type.

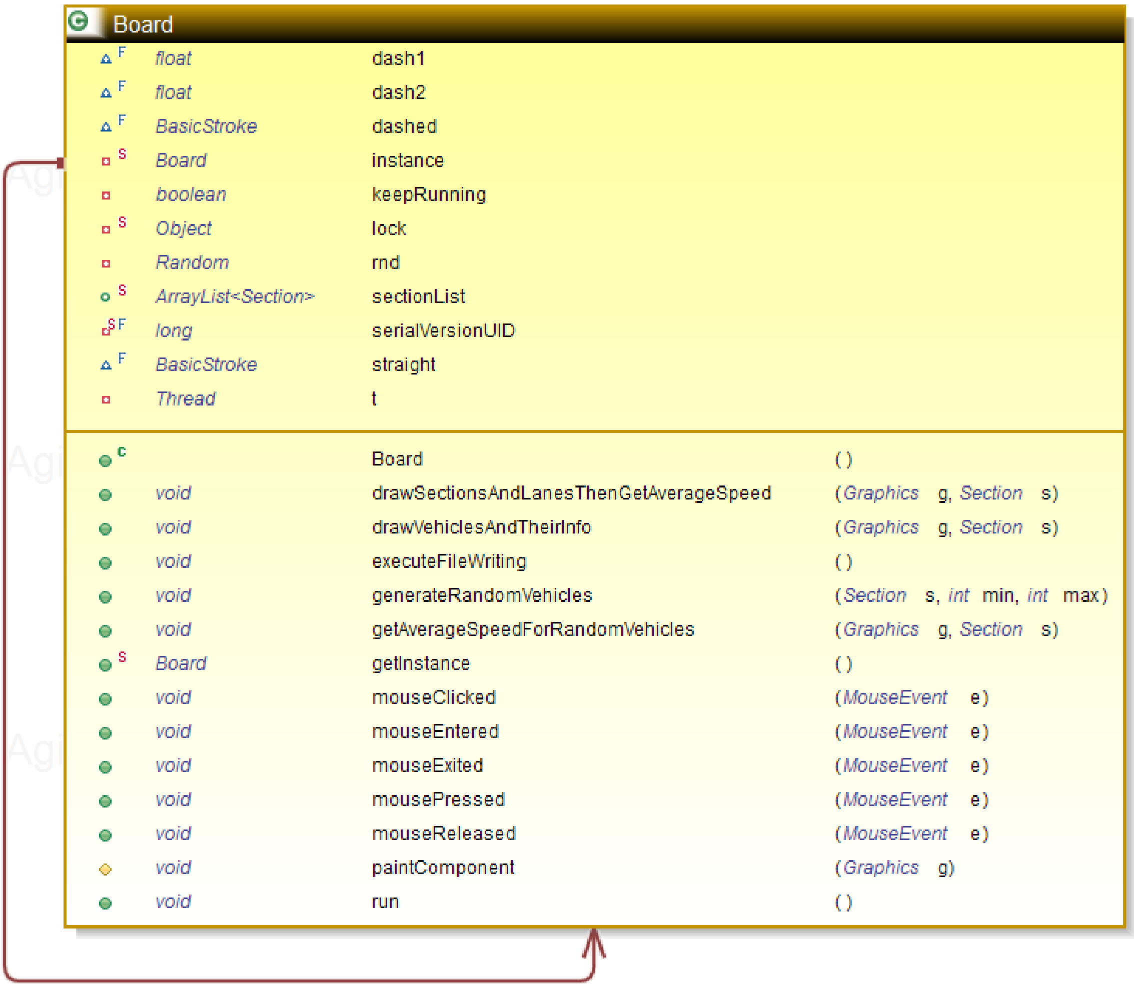
viii. **void run():** This method must be overridden by the implementing class of the Runnable interface. It has an infinite while loop that iterates as long as the keepRunning field is true. It calls the repaint(), then checks if the Configuration.isWriteToFile field is true, if it is then calls the executeFileWriting() method. These steps are repeated in each millisecond defined by repaintFrequencyInMillis static field in the Configuration class.

ix. **void executeFileWriting():** The method simply calls the method writeAverageSpeedAndRandomVehiclesAverageSpeedToFile() for each specific section in a “for each” loop.

x. **void mouseClicked(MouseEvent e):** Since the Board class implements the MouseListener interface it must implement all of the mouse events. When mouse is clicked this method is called. Its job is to check where the mouse is clicked and show the info of the clicked vehicle in a box or a pop-up window. Remaining mouse events defined by void mousePressed(MouseEvent e), void mouseReleased(MouseEvent e), void mouseEntered(MouseEvent e), void mouseExited(MouseEvent e) are left empty.

Figure 4.19 depicts the class structure of the Board class. As it can be seen, the Board class depends upon several other classes. The dependent classes are Configuration, RandomVehiclesThread, Battery, Vehicle and Simulation. On the other hand the classes that depend upon the Board are Vehicle and Simulation. Moreover, Board.sectionList references many Section objects and Board.instance references one Board object.

Figure 4.19: The class structure of Board



Source: Türk Telekom Technical Report, 2012; Extraction of Congestion Information and Dynamic Route Planning, May 2012.

4.8.2.2.7 *Configuration*

The Configuration class is written to define a central access point for the static fields. Hence the configuration can be handled directly from one generic class. This is why there are only fields in this class but no methods.

The fields that exist in this class as well as their purposes are given below:

a. **BATTERY_THRESHOLD:** This field is a static final double and holds the value that determines the battery threshold. As in battery threshold, it is meant that the lower limit required to be selected for transmitting data to the server. If the battery energy level is below this constant value then the vehicle that has this battery is not selected. If it is above this limit, everything works as intended.

b. **NUM_VEHICLES_PER_SECTION:** It is in fact quite easy to understand what most of these static final fields stand for, and this field is one of them. It is basically defining the number of vehicles that must be created in each section during the initialization of the simulation board. For instance, when the value assigned to this field is 10, that means there will exist 10*n* vehicles in total for the simulation run, where "*n*" stands for the number of sections. The field is used by the Board class during the vehicle creation with random attributes.

c. **SECTIONS_ARRAY:** This field is of type static final integer array with two dimensions. The first dimension of the array determines the section numbers. The second dimension has two indexes where the first index determines the section length and the second index determines the number of lanes in the section to be created. The field is called in the Board class in the sections creation process.

d. **SECTION_SPEED_INTERVALS:** This field is of the type static final integer. It is a two dimensional array, which the first dimension stands for the section id and the second dimension stands for the min and max speeds for 0^{th} and the 1^{st} indexes, respectively. According to the min and max values defined in the Configuration, the initial speed values that the vehicles can have in the creation process are limited in a specific interval for each section. The field is used by the Board class during the vehicle creation for each section.

e. **AVERAGE_SPEED_ANALYSES_ARRAY:** It is the field that determines the number of vehicles to be randomly picked and analyzed. Each index of the array determines a different number of vehicles that has the proportion of 2:10, 4:10, 6:10, 8:10 to the total number of vehicles defined for each section, i.e.

NUM_VEHICLES_PER_SECTION constant. Thus when the value of number of vehicles per section is 10, the four different set of vehicles will have 2, 4, 6, 8 number of vehicles to be analyzed, respectively. According to length of this array, constructor of the Section class creates required number of different arrays. And then the fillRandomVehiclesArray() method fills these arrays with as many vehicles as these numbers determine.

f. **REPAINT_FREQUENCY_IN_MILLIS:** This field is of the type static final int and determined as 30 millisecond in most cases. It is used by the Board class to find out how frequently to refresh the screen and repaint it. It is done by sleeping the Board's thread for the number of milliseconds specified by this field. The smaller the value the smoother the vehicle motions. The sleep time also affects the frequency of writing calculated average speeds for each array into the files.

g. **UPDATE_VEHICLE_LOCATION_FREQUENCY:** This field is also of the type static final int. It is used by the Vehicle class. The value of the field affects the movement frequency of vehicles since it makes the Vehicle thread sleep. In each iteration the vehicle moves and changes its speed. It is good to assign the same value as the REPAINT_FREQUENCY_IN_MILLIS constant in order to avoid the repeating average speed calculations written into the files.

h. **INITIAL_SLEEP_TIME:** This field is of the type static final long. It is used as a waiting mechanism in vehicle threads. It gives time to the program to generate all other vehicles before starting to vehicle movements and related calculations. It is set as 50 millisecond in most simulation runs.

i. **RENEW_RANDOM_VEHICLES_PERIOD:** The field is of the type static final long and is used by the class RandomVehiclesThread. The purpose of this field is to set the frequency which both the random vehicles array and the random average speed analyses arrays are renewed, in other words filled with newly selected vehicles, in the run method. Other than filling the random arrays, the randomly selected vehicles start their applications using the appStartUp() method. The vehicles with green dashed rectangles around them are identified in each interval defined by this value, which is in terms of milliseconds. The value of the constant field is usually 3 seconds in terms of simulation time.

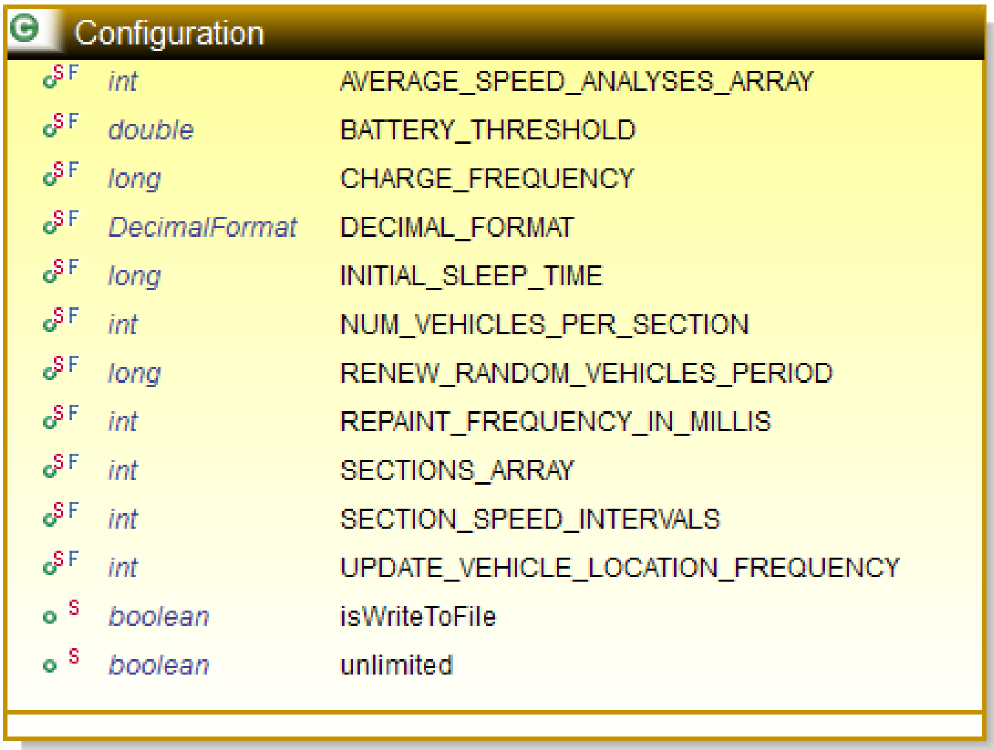
j. **CHARGE_FREQUENCY:** The field is of the type static final long. It is used by the Battery class. Since the Battery class is a thread, it has a run method(), this run method is responsible for the battery charging when the phone is connected to the charger. The charging operation is done in each cycle of time defined by this field. Normally the charging operation is done in every 60 seconds for +0.8 percent energy level. However the charge frequency is scaled into 2000 milliseconds in terms of the simulation time.

k. **DECIMAL_FORMAT:** This field is of the type static final DecimalFormat. It defines a decimal format that has a precision up to two digits. This field is used by the Board class, in both drawSectionsAndLanesThenGetAverageSpeed(…) method and getAverageSpeedForRandomVehicles(…) method, in order to format the incoming double values to two digit precision level, or just truncate to two digits.

l. **unlimited:** This field is a static boolean type variable. It is used in Vehicle's run() method to stop the thread of the vehicles which pass a specific location in the simulation field. For example in one simulation setup, the vehicles which were passing the "x coordinates" lesser than -50 were stopped. If it is assigned with "true" value, then that means the vehicles can move as long as it is possible, i.e. without a limit on the road.

m. isWriteToFile: This field is also of a static boolean type. Its initial value is false in the simulation setups. Its purpose is to decide whether to write the average speed results to the files or not. Set true if want the data to be written in the files. The default value is false. It is used in the run() method of the Board class which if true executes the method called executeFileWriting().

Figure 4.20: The class structure of Configuration



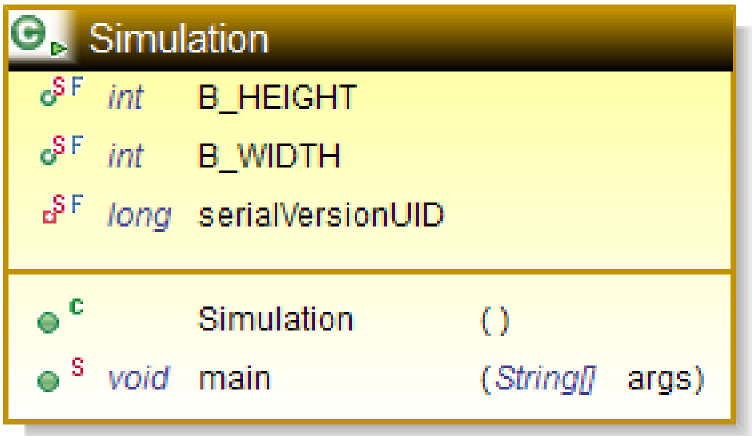
Source: Türk Telekom Technical Report, 2012; Extraction of Congestion Information and Dynamic Route Planning, May 2012.

Figure 4.20 portrays the class structure modeled for the Configuration class. The class has no references to other classes. But instead, it has lots of classes which depend on itself. The depending classes can be listed as RandomVehiclesThread, Vehicle, Section, Board, and Battery.

4.8.2.2.8 *Simulation*

The Simulation class extends the JFrame class and is basically responsible of displaying all the graphical contents of the system within the JFrame. It has two static constant fields B_WIDTH abd B_HEIGHT, as well as a static final long field that determines the serialVersionUID.

Figure 4.21: The class structure of Simulation



Source: Türk Telekom Technical Report, 2012; Extraction of Congestion Information and Dynamic Route Planning, May 2012.

The class has a main method to launch the application. It simply creates a Simulation object and sets its visibility to true. The constructor of the class is explained below:

Simulation(): The constructor has no parameters, it is just the default constructor. It first of all creates a Dimension reference that references to the default toolkit's screen size. From there the X and Y screen coordinates where the simulation frame will be drawn is taken. X coordinate is defined by getting the half of the screen width minus the half of B_WIDTH constant. The same goes for the Y coordinate, and it is calculated by getting the screen's height minus the half of B_HEIGHT constant. And then the default close operation of the frame is set to EXIT_ON_CLOSE. The title of the simulator is set as "Smart Transportation Simulator by BAU". The bounds of the frame is set via the calculated X and Y integer type coordinates, with a height of B_HEIGHT and a width of B_WIDTH+20. The frame's layout is set to BorderLayout(), then an instance is got using the static method of the Board, namely the Board.getInstance() which instantiates a Board class object and returns it (it is done this way since the class is a singleton), and lastly the Board instance is placed in the BorderLayout.Center region.

Figure 4.21 represents the Simulation's class structure. The Simulation class depends upon Board class since it adds the Board panel into its center region in the border layout. Likewise, the Board class depends upon Simulation class, as well. Board class uses the static final fields B_WIDTH and B_HEIGHT that are defined in the Simulation class. On the other hand, the Section class depends on Simulation class since it uses the same constant fields defined in Simulation, as well.

4.8.3 CALCULATIONS

All the average speed calculations are performed according to the vehicles generated randomly using the void *generateRandomVehicles(Section s, int min, int max)* method. What the method does is to generate random vehicles for the designated section with speeds between min and max values. These randomly generated vehicles are put into the designated section's vehicle list, to be more precise, into the Section object's vehicleList field. Generated vehicles are put into this vehicleList field of type synchronized ArrayList using the section object's accept(Vehicle v) method. After each vehicle creation the vehicle's thread is started to run. Thus the vehicle starts moving and changing its speed in every cycle denoted by the updateVehicleLocationFrequency field in the Configuration class.

The change in the speed of the vehicles leads to varying average speeds for each section. Board class is responsible for displaying these varying speeds for the sections and if specified in the Configuration class, writing them into a distinct file for each of the sections.

4.8.3.1 Average Speed Calculation

As mentioned before, void *generateRandomVehicles(Section s, int min, int max)* method has three parameters. The Section s is a reference given to the method as a parameter that stands for the section to be filled with as many number of randomized vehicles as stated in numVehiclesPerSection static field of the Configuratiın class. Changing vehicle speeds in every section causes the average speed in the section to vary in designated time cycles.

Board class extends JPanel class and implements Runnable class. This means that the Board class can display the change in average section speeds visually. Thus it should have a paint(Graphics g) method, or paintComponent(Graphics g) as suggested by the

Java gurus. It also should implement the run() method since the class implements the Runnable interface. The simulator screen can be repainted as frequent as it is specified by repaintFrequencyInMillis static field in the Configuration class. Everytime the screen is repainted, the average speed calculations can be performed again to show the change in the section speed values.

In the method paintComponent(Graphics g), the method that draws the sections and lanes in the simulator screen, and then gets the average speed values for each section in the section list is called. The method also does the similar average speed calculations for the vehicles transmitting their information to the server. The details for this operation can be found in the next sub-section.

The average speed calculation is done using the well-known averaging method that simply sums up the vehicle speeds and divides the sum of these speeds to the number of vehicles present in the vehicle list. This operation is done separately for each section since the section list is unique for each of them.

4.8.3.2 Randomization Process and Calculations

Randomization process is determined by two factors. One of them is the fact that in each vehicle location update frequency, the vehicles change their speed, either by accelerating or decelerating. This process is performed randomly for every vehicle appearing in the simulator.

On the other hand, the second randomization effect is due to the randomly selected vehicles among the vehicle list of a section. This randomization process is carried out by the fillRandomVehiclesArray() method. The method is explained in detail under the Section class part. Briefly, the method fills the field named randomVehiclesArray which is of the type synchronized ArrayList in every cycle defined by the renewRandomVehiclesPeriod in Configuration class. The process is random not only in terms of determining the number of vehicles to be selected, but also in terms of determining which individual vehicles among the all vehicles in the section are going to be selected for transmitting their GPS data to the server. For example, 13 vehicles may be the random number of vehicles selected in an iteration, whereas 4 vehicles may be the random number of vehicles selected in another iteration. Moreover the vehicle with the vehicle id of 5 may be selected in an iteration but not in the next iteration, and instead the vehicle with the vehicle id 17 may be the selected one.

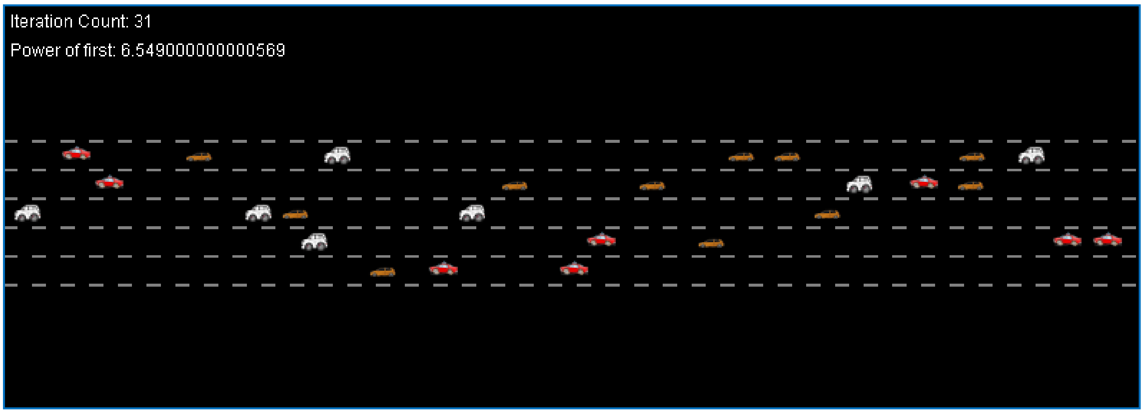
There are also some other ArrayLists that perform the quite similar randomization process, but this time the number of randomly selected vehicles differ in each such as 20 vehicles, 40 vehicles, 60 vehicles, 80 vehicles out of 100 vehicles in each section. These random lists are gathered under an ArrayList named averageSpeedAnalysesArray. The inner lists are the type of synchronized ArrayList objects that have Vehicles in them.

Average speed calculations are performed for all the array lists that are made of randomly chosen vehicles in every section, as well. The simulation screen shows the average speed information of each section for randomly determined number of vehicles which are also randomly selected, in addition to average speed calculated from the whole vehicle list. The remaining information is written into the files. Thus in the analyses phase we use all of these outputs to plot and analyze the average speeds.

4.8.4 The Interface

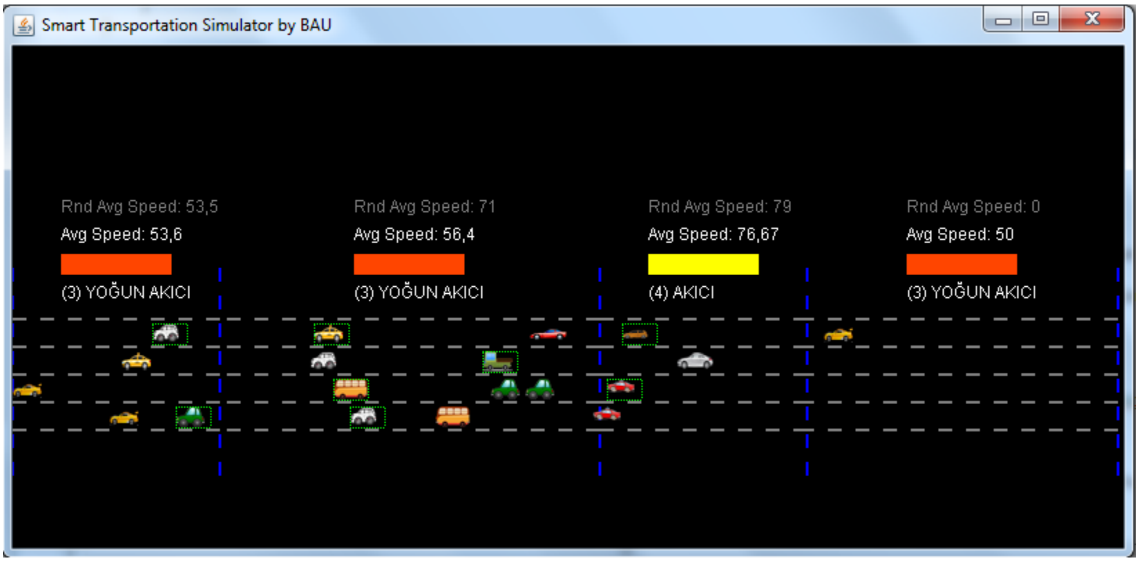
The screenshot in Figure 4.22 that depicts a simulation setup of a single section roadway with 50 vehicles spread within 5 lanes on-the-go. Each of the vehicle that appears in the simulation starts from the right hand side of the roadway in a random lane and drives on the same lane from beginning to the end.

Figure 4.22: The very first look of the simulation environment



Source: Türk Telekom Technical Report, 2012; Extraction of Congestion Information and Dynamic Route Planning, May 2012.

Figure 4.23: Snapshot from a newer version of the simulator



Source: Türk Telekom Technical Report, 2012; Extraction of Congestion Information and Dynamic Route Planning, May 2012.

In time, the simulator software has evolved such that it depicts every section divided with vertical blue dashed lines which is also shown in Figure 4.23. In addition, an information panel appears for each section that gives the numeric values for the average speed of all vehicles, another average speed of randomly chosen vehicles, a color bar that gives an idea about the section speed, and the related congestion weight.

4.8.5 The Analyses

The analyses in this research are done with the data retrieved from various simulation runs with randomized setups. These simulation setups are classified in two categories named static random and dynamic random. This section explains what these categories actually mean, furthermore explains and depicts the several plotted analyses related to these categories.

4.8.5.1 Static random

In the initial average speed analyses a specific number is set for the number of vehicles to be randomly chosen, and this number as well as the already chosen vehicles do not change during the simulation.

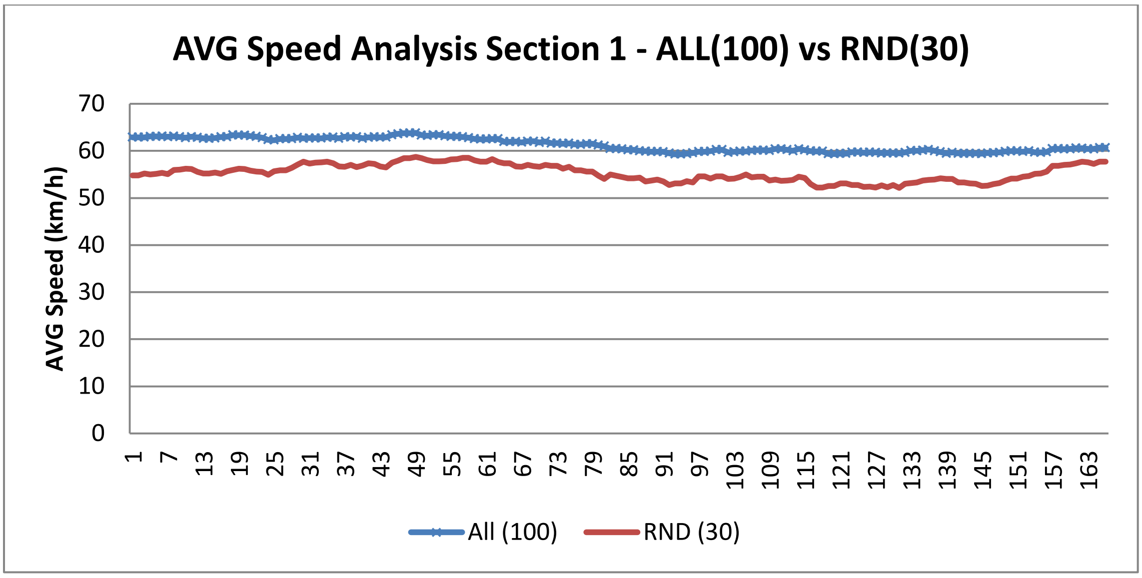
The simulation runs deployed using such configurations does not reflect a real case. Because in the real-life, vehicles do not continuously send GPS data to the server. The mobile application may be closed or run arbitrarily which leads to randomized effects in terms of simulating such real-life conditions. Hence the number of vehicles as well as the individual vehicles sending GPS information to the server will keep varying in real-time.

Three different setups are run in terms of static random analyses. These are 10 vs. 3, 50 vs. 10, and lastly 100 vs. 30. The analyses are performed separately for each section in the simulation, and for each different setup.

4.8.5.1.1 *100 vs. static random 30*

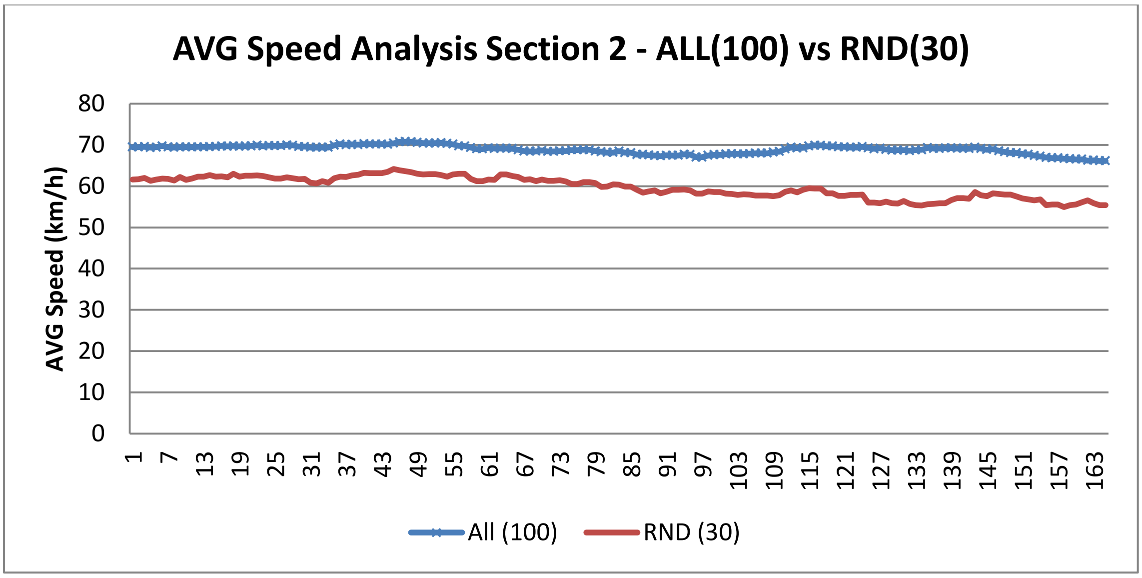
Figure 4.24 to Figure 4.27 shows the average speed calculated with 100 vehicles (blue line) versus the average speed calculated with 30 random vehicles initially chosen (red line) for each section. The randomly chosen vehicles are static in this analysis. The speed of the vehicles created in this setup are random values between 1 km/h and 120 km/h. The speed differences between two lines representing the mentioned setup are lower than 12 km/h. Sometimes the difference is at around 2 km/h. However the difference may be much greater in consecutive simulation runs with exactly the same setup since the speed differences between the vehicles can be quite big in such a configuration. In some other analyses the speed difference between the vehicles of the same section will be lowered to prevent such unrealistic situations.

Figure 4.24: Average speed of 100 vs. static random 30 vehicles for section 1



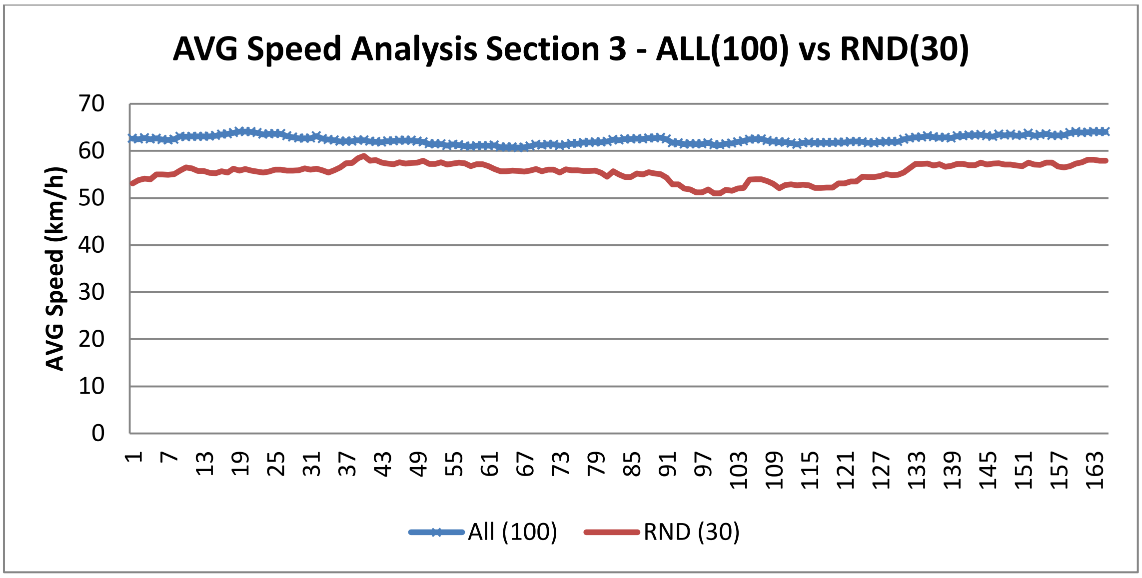
Source: Türk Telekom Technical Report, 2012; Extraction of Congestion Information and Dynamic Route Planning, May 2012.

Figure 4.25: Average speed of 100 vs. static random 30 vehicles for section 2



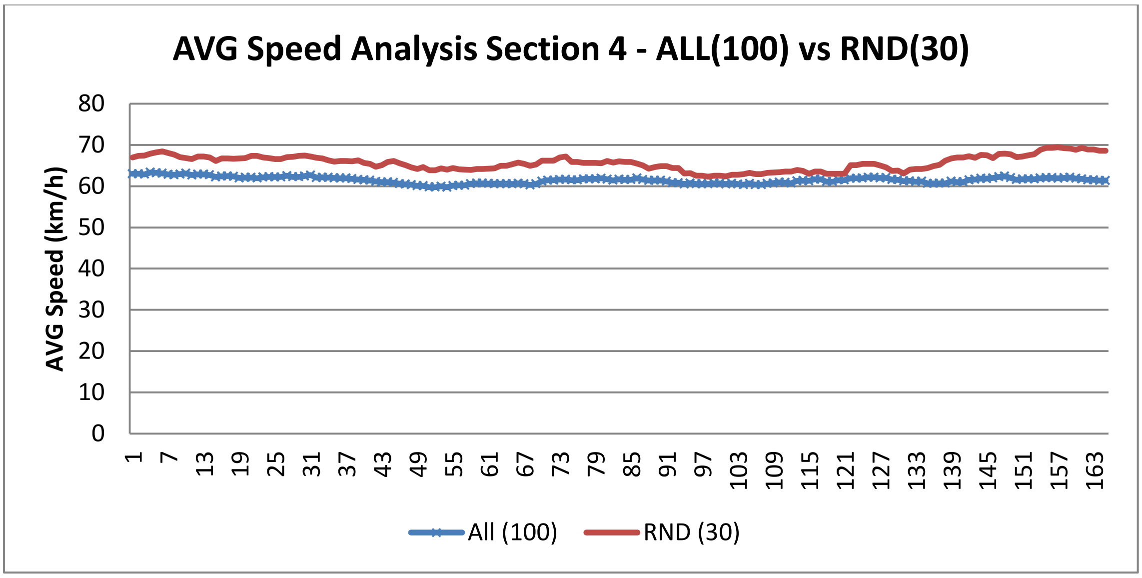
Source: Türk Telekom Technical Report, 2012; Extraction of Congestion Information and Dynamic Route Planning, May 2012.

Figure 4.26: Average speed of 100 vs. static random 30 vehicles for section 3



Source: Türk Telekom Technical Report, 2012; Extraction of Congestion Information and Dynamic Route Planning, May 2012.

Figure 4.27: Average speed of 100 vs. static random 30 vehicles for section 4

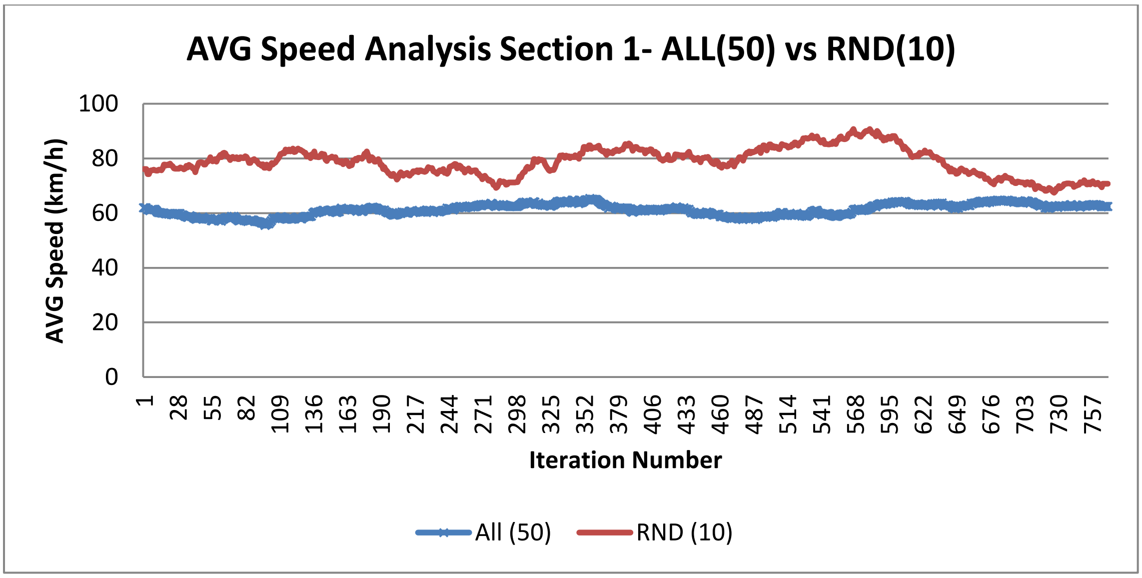


Source: Türk Telekom Technical Report, 2012; Extraction of Congestion Information and Dynamic Route Planning, May 2012.

4.8.5.1.2 *50 vs. static random 10*

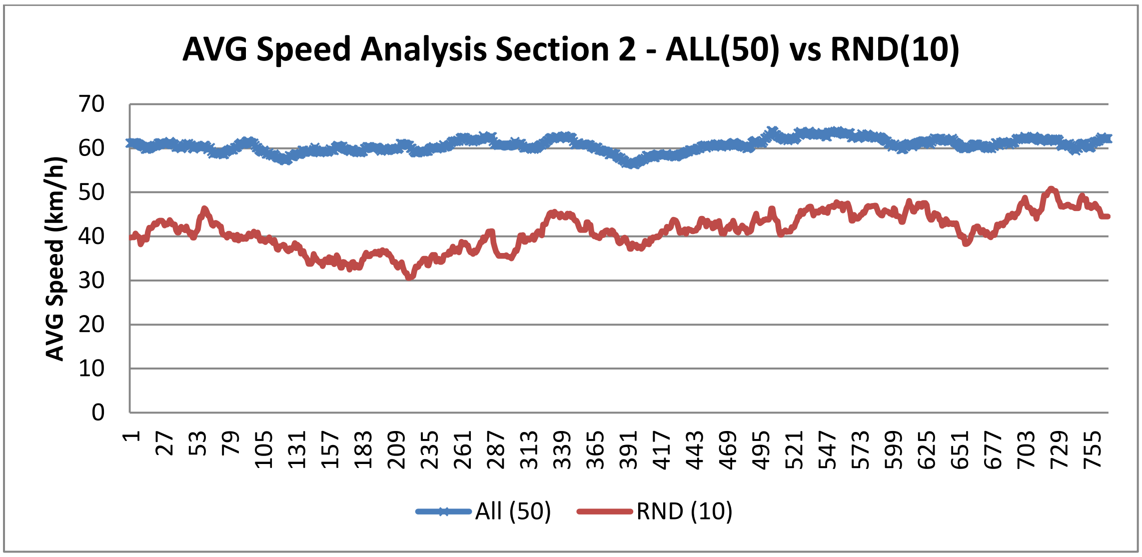
From Figure 4.28 to Figure 4.31 another random static analysis is plotted. This time the analyzed simulation setup is composed of 50 vehicles in each section. The plotting is done for the average speed of 50 vehicles (blue line) versus average speed of static randomly chosen 10 vehicles (red line). In this analysis the difference between the lines at the same iterations (i.e. time instants) is much bigger. This is due to the fact that the vehicles in the sections are able to have quite different speed values of between 1 km/h - 120 km/h, and the fact that the randomly chosen vehicles are the ones which move really slowly compared to the average of all the vehicles. There is another statistical reason that the randomly chosen vehicles ratio is 1/5, whereas in the previous setup it is 3/10. Hence the difference will be definitely bigger, no matter the average speed of randomly chosen vehicles is greater or lesser than the average speed of all. The average speed differences in the sections go beyond 20 km/h and even 30 km/h in some time instants. Overall, the difference is a lot bigger than the 100 vehicles versus 30 vehicles case.

Figure 4.28: Comparison of average speed for all 50 vehicles vs. static random 10 vehicles for section 1



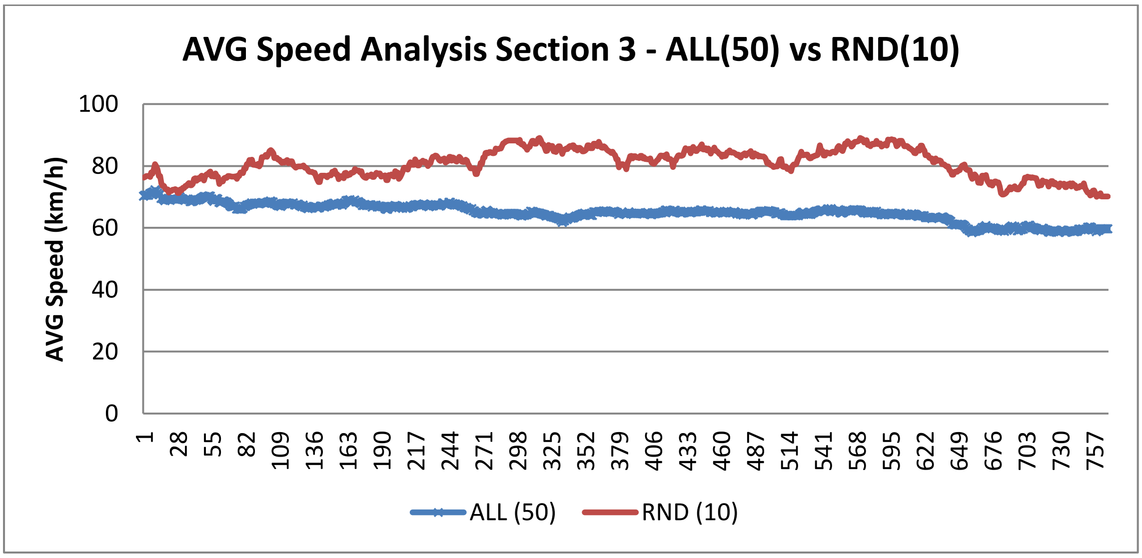
Source: Türk Telekom Technical Report, 2012; Extraction of Congestion Information and Dynamic Route Planning, May 2012.

Figure 4.29: Comparison of average speed for all 50 vehicles vs. static random 10 vehicles for section 2



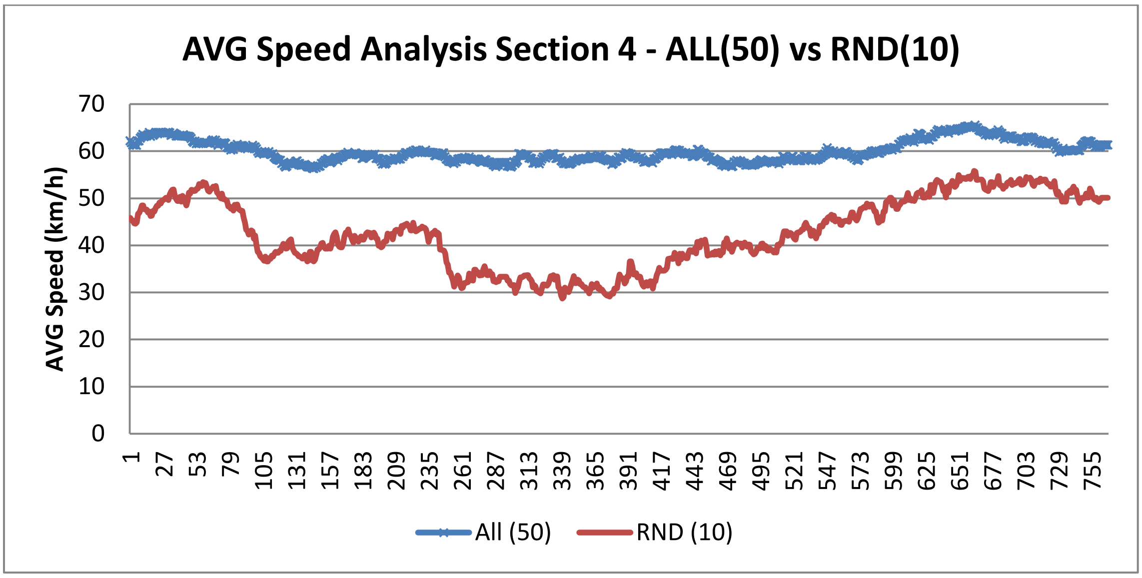
Source: Türk Telekom Technical Report, 2012; Extraction of Congestion Information and Dynamic Route Planning, May 2012.

Figure 4.30: Comparison of average speed for all 50 vehicles vs. static random 10 vehicles for section 3



Source: Türk Telekom Technical Report, 2012; Extraction of Congestion Information and Dynamic Route Planning, May 2012.

Figure 4.31: Comparison of average speed for all 50 vehicles vs. static random 10 vehicles for section 4



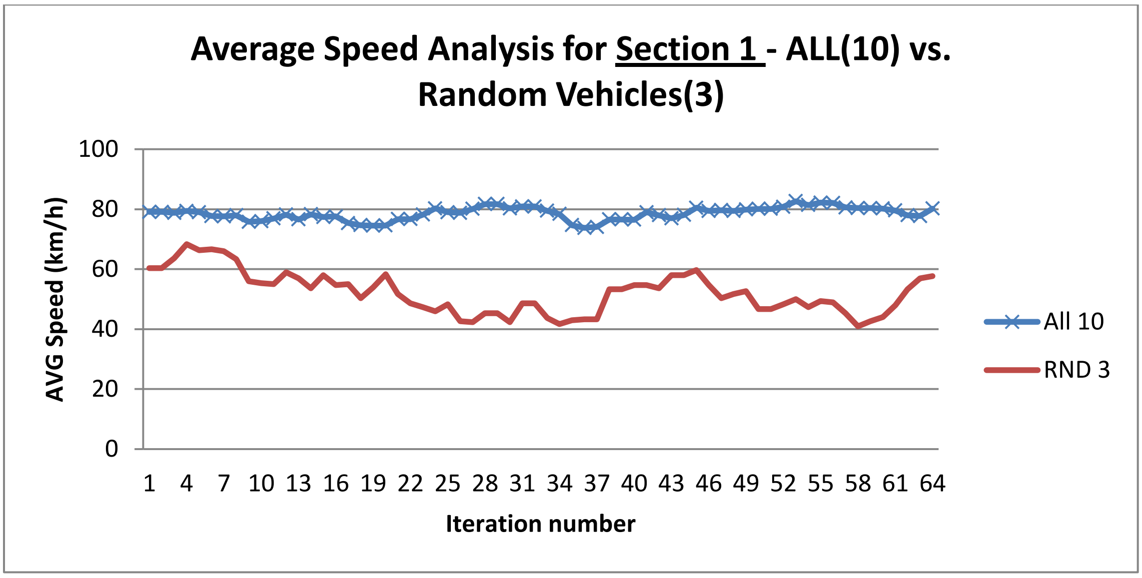
Source: Türk Telekom Technical Report, 2012; Extraction of Congestion Information and Dynamic Route Planning, May 2012.

4.8.5.1.3 *10 vs. static random 3*

One last analysis in the static random category is carried out by the comparison of 10 vehicles per section versus random statically chosen 3 vehicles. The objective with this analysis is to test the difference when the ratio between the number of randomly chosen vehicles and all vehicles is kept the same but the number of the vehicles in a section is reduced substantially. In other words, the test aims at observing the difference between "10 vs. 3" and "100 vs. 30" static random vehicles scenarios.

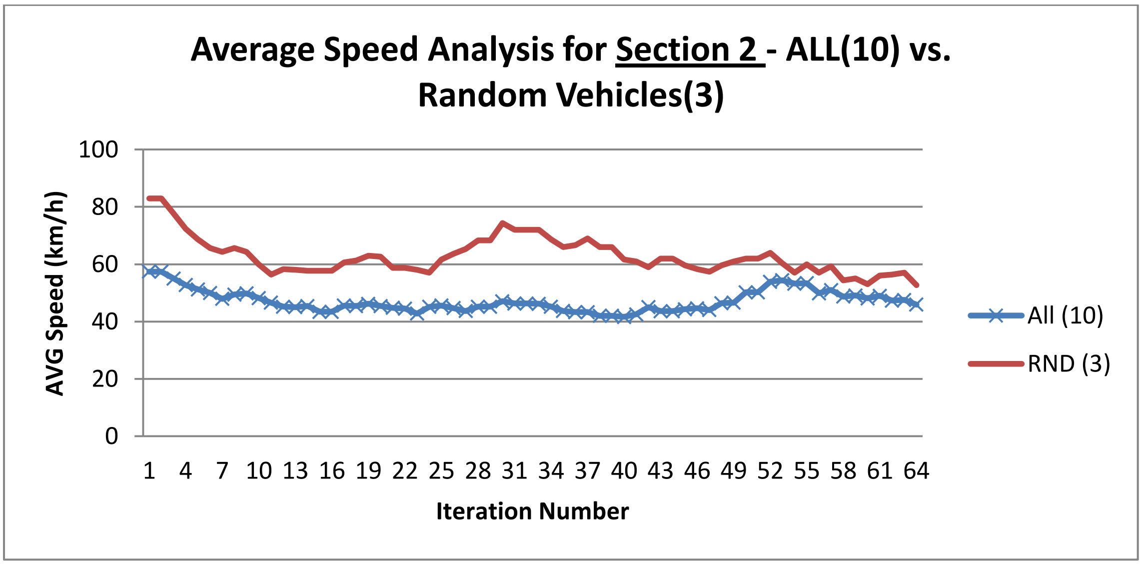
As it can be observed from Figure 4.32 to Figure 4.35, the gap between two average speed lines become larger compared to the analysis done for 100 vs. 30 static random vehicles setup.

Figure 4.32: Section 1 average speed differences for 10 vs. 3 static random setup



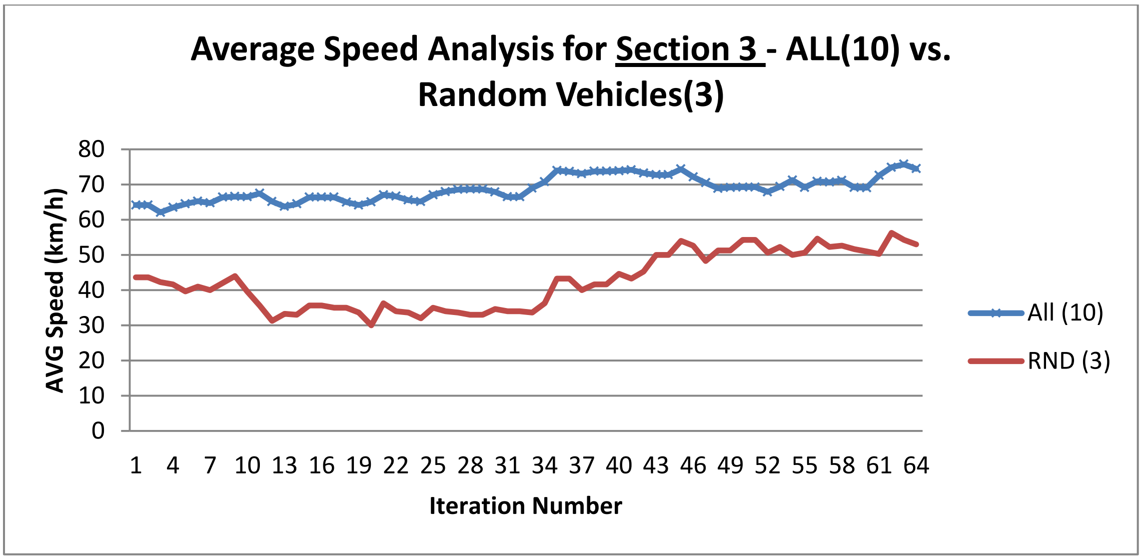
Source: Türk Telekom Technical Report, 2012; Extraction of Congestion Information and Dynamic Route Planning, May 2012.

Figure 4.33: Section 2 average speed differences for 10 vs. 3 static random setup



Source: Türk Telekom Technical Report, 2012; Extraction of Congestion Information and Dynamic Route Planning, May 2012.

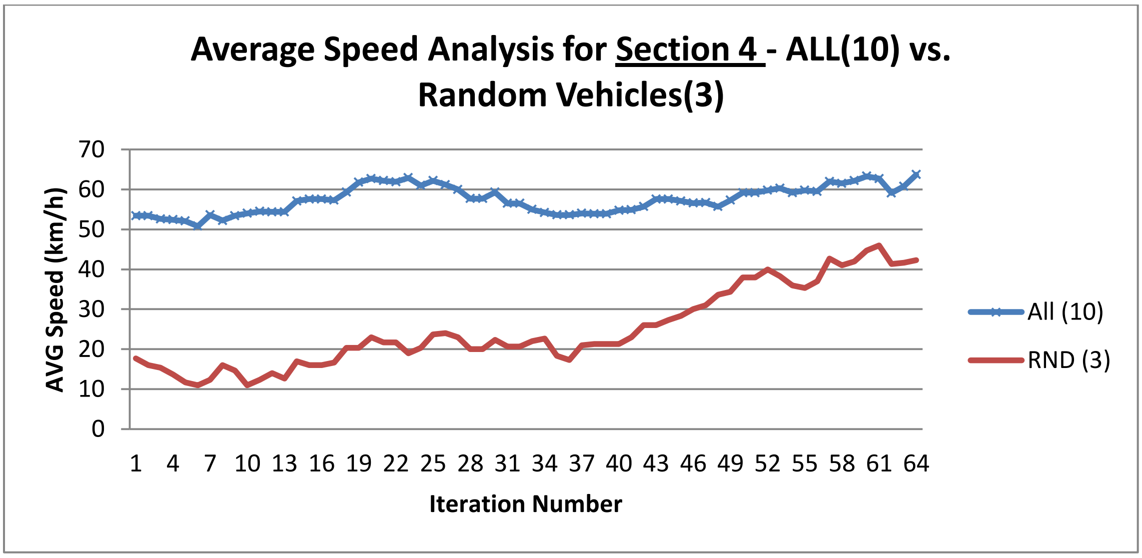
Figure 4.34: Section 3 average speed differences for 10 vs. 3 static random setup



Source: Türk Telekom Technical Report, 2012; Extraction of Congestion Information and Dynamic Route Planning, May 2012.

The decrease in number obviously causes the difference become larger, hence the error becomes greater. The average speeds difference is really immense specifically in Figure 4.35 where the minimum difference is 16 km/h, and it even goes up to 40 km/h at some point.

Figure 4.35: Section 4 average speed differences for 10 vs. 3 static random setup



Source: Türk Telekom Technical Report, 2012; Extraction of Congestion Information and Dynamic Route Planning, May 2012.

4.8.5.2 Dynamic random

This section introduces the dynamic random analyses done in the simulator development phase. It is called dynamic random or random dynamic in some cases, since it reflects a dynamic mechanism on the randomization of vehicle selection process.

The random selections of individual vehicles as well as determination of the random number of vehicles that are assigned to execute the task of transmitting GPS data (location, speed and time) to the server are repeated in every specified time interval. This time interval is defined in the Configuration class with the static field named renewRandomVehiclesPeriod. Because vehicles that are transmitting GPS data will keep changing in real-life scenarios. This might happen in some cases where phone battery is depleted or the user doesn't want to send the data and/or closes the application. In the simulator we have taken into account such conditions and hence implemented the mechanism to renew the random vehicles lists.

The analyses presented in this sub-section reflect more realistic scenarios than the previous ones thanks to the mechanism that renews the random vehicle lists, which is the key difference of the random dynamic analyses from the previous analyses. As mentioned earlier, in the real life scenarios, the vehicles don't send GPS data continuously since the smartphone app might be closed arbitrarily by the user or the phone battery might be low or completely drained. Hence the renewed random vehicles list provides the same arbitrary conditions occurred in the real life scenarios.

This part of the study includes four different dynamic random analyses for the vehicle lists in every section. These are 10 vs. dynamic random 10, 20 vs. dynamic random 20, 50 vs. dynamic random 50, and 100 vs. random dynamic 100 vehicles.

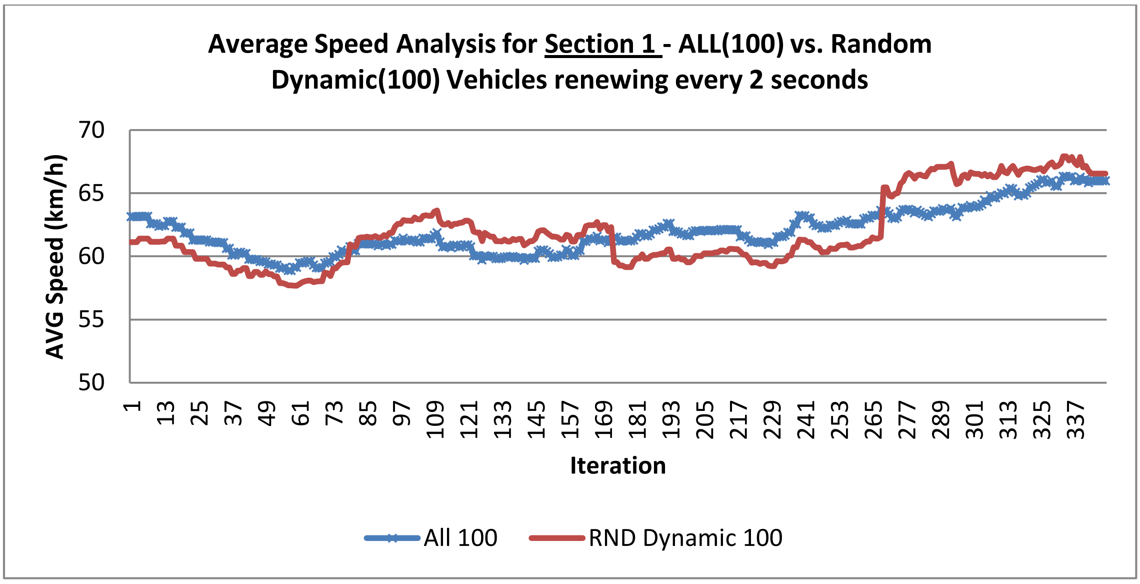
4.8.5.2.1 *100 vs. random dynamic(100) vehicles*

The average speed calculated with 100 vehicles indicated with the blue lines versus the average speed of the random number of vehicles chosen among this 100 vehicles indicated by the red lines are plotted in Figure 4.36, Figure 4.37, Figure 4.38 and Nevertheless, it is still quite obvious to observe the rapid leaps (occurring in a single iteration) at around the iterations mentioned before. This is due to the sudden change in the random vehicles list at these iterations. Yet, the differences between the real average speed of the section one and the average speed of the randomly chosen vehicles in the section one at the same time instant are quite low, namely 3.6 km/h at most. The biggest average speed difference in the analyses occurs in the second section which is depicted in Figure 4.37 with and amount of 7 km/h. Briefly, the analyses provide quite convenient results.

Figure 4.39 for section 1, 2, 3 and 4, respectively.

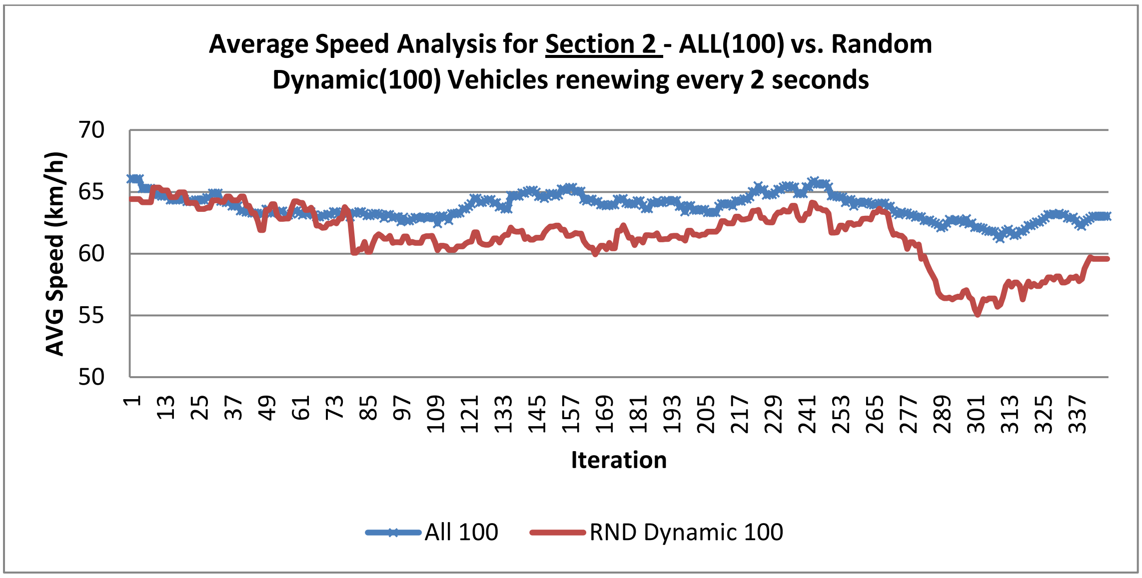
The random vehicles lists are renewed three times in the analyses generating four different random vehicles lists in every section. Every new randomization process can be seen in each figure. For example in Figure 4.36, the renewing processes occur at around 80th, 170th and 270th iterations. The first section (that is the right most section and can be observed in Figure 4.36) has relatively closer values of average speeds in each renewal.

Figure 4.36: Section 1 average speed analysis for 100 vehicles vs. dynamic random 100 vehicles, changing every 2 seconds in terms of simulation time



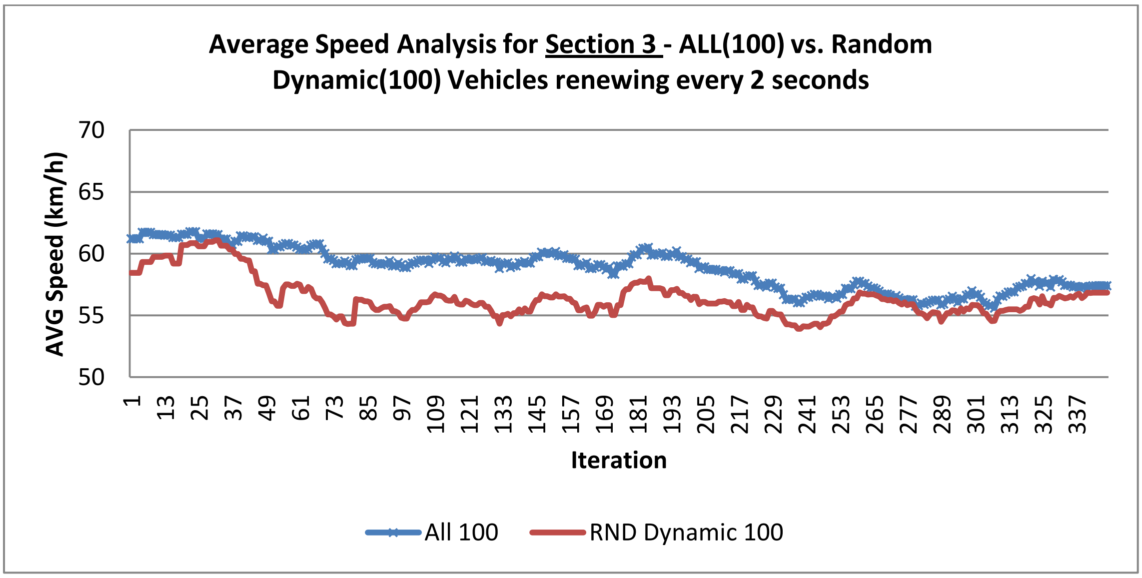
Source: Türk Telekom Technical Report, 2012; Extraction of Congestion Information and Dynamic Route Planning, May 2012.

Figure 4.37: Section 2 average speed analysis for 100 vehicles vs. dynamic random 100 vehicles, changing every 2 seconds in terms of simulation time



Source: Türk Telekom Technical Report, 2012; Extraction of Congestion Information and Dynamic Route Planning, May 2012.

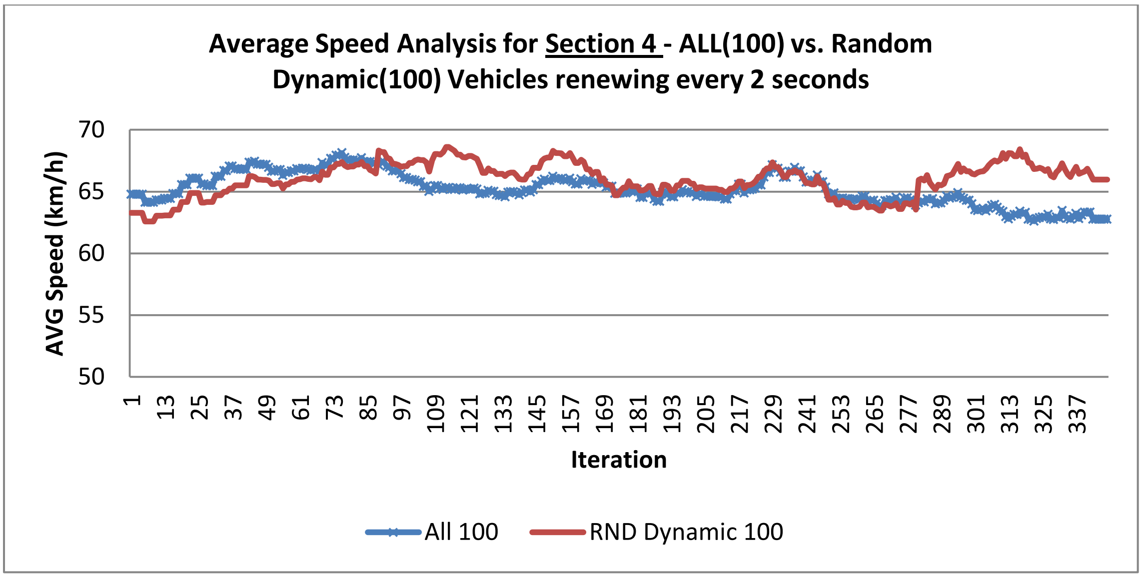
Figure 4.38: Section 3 average speed analysis for 100 vehicles vs. dynamic random 100 vehicles, changing every 2 seconds in terms of simulation time



Source: Türk Telekom Technical Report, 2012; Extraction of Congestion Information and Dynamic Route Planning, May 2012.

Nevertheless, it is still quite obvious to observe the rapid leaps (occurring in a single iteration) at around the iterations mentioned before. This is due to the sudden change in the random vehicles list at these iterations. Yet, the differences between the real average speed of the section one and the average speed of the randomly chosen vehicles in the section one at the same time instant are quite low, namely 3.6 km/h at most. The biggest average speed difference in the analyses occurs in the second section which is depicted in Figure 4.37 with and amount of 7 km/h. Briefly, the analyses provide quite convenient results.

Figure 4.39: Section 4 average speed analysis for 100 vehicles vs. dynamic random 100 vehicles, changing every 2 seconds in terms of simulation time

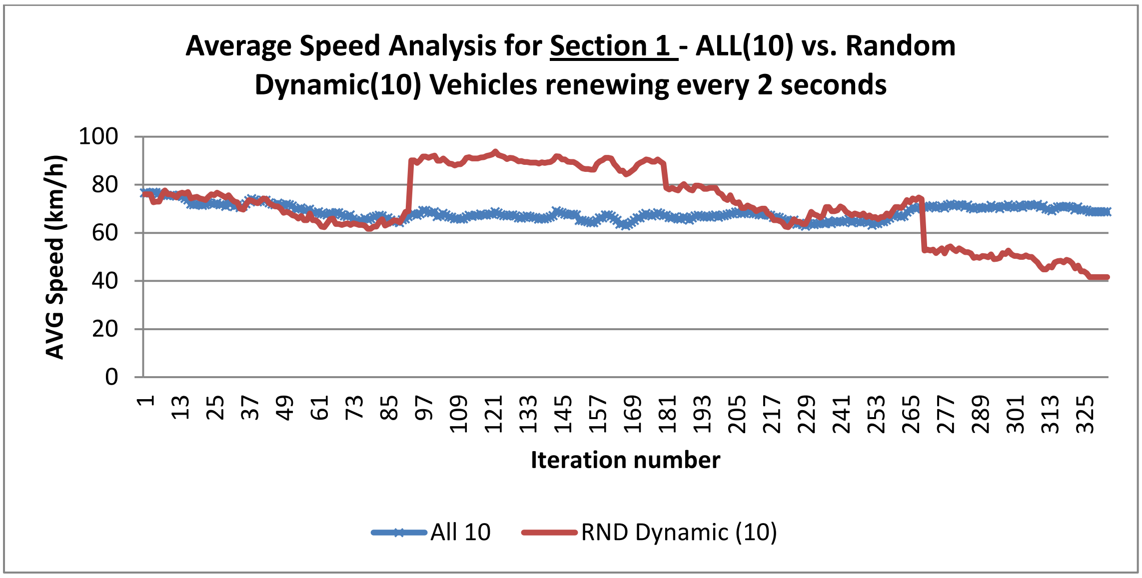


Source: Türk Telekom Technical Report, 2012; Extraction of Congestion Information and Dynamic Route Planning, May 2012.

4.8.5.2.2 *10 vs. random dynamic(10) vehicles*

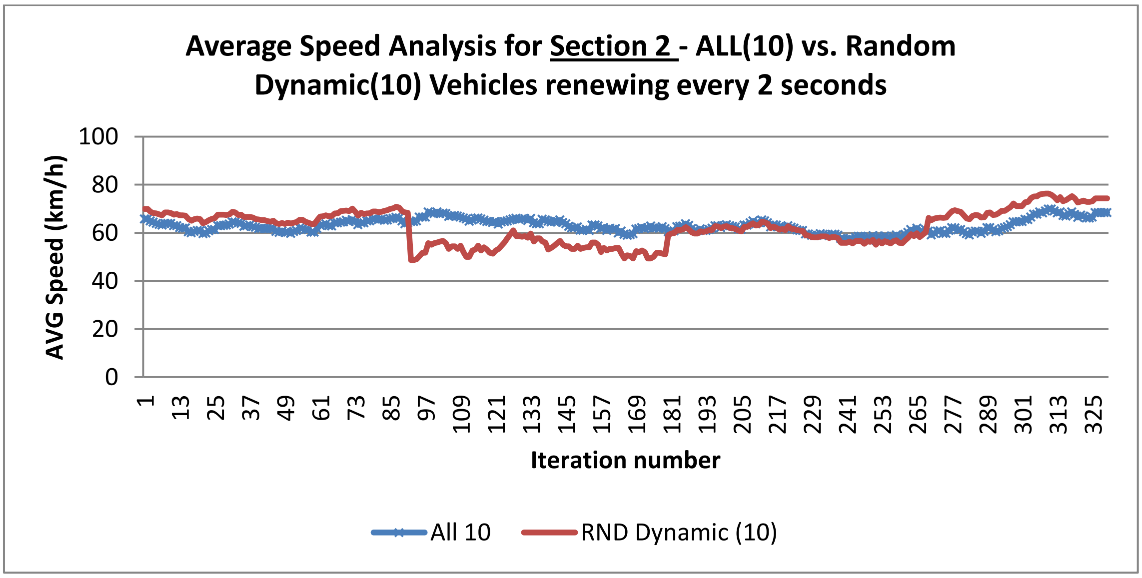
This analyses aims at observing the big differences between the real average speed and the random vehicles average speed. Before the analyses it is anticipated that the gap between the two lines representing the two average speeds shall not be low. The reason behind the scenes is that the number of vehicles is lowered to 1/10 times of the previous analysis (containing 100 vehicles). The speed assigned to each vehicle in such a configuration becomes quite diverse with a high probability and hence the average speeds generated via the random vehicles list diverge markedly for most of the sections.

Figure 4.40: Average speed analysis for 10 vehicles vs. dynamic random 10 vehicles with the renewal time of 2 seconds in Section 1



Source: Türk Telekom Technical Report, 2012; Extraction of Congestion Information and Dynamic Route Planning, May 2012.

Figure 4.41: Average speed analysis for 10 vehicles vs. dynamic random 10 vehicles with the renewal time of 2 seconds in Section 2



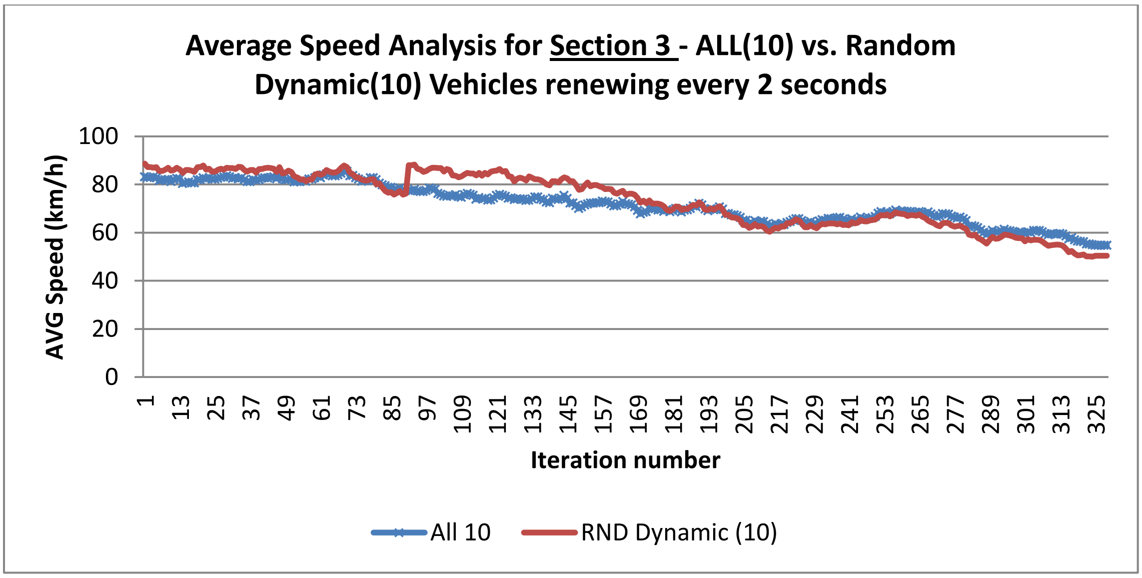
Source: Türk Telekom Technical Report, 2012; Extraction of Congestion Information and Dynamic Route Planning, May 2012.

Figure 4.40 is one of the instances that depict the aforementioned situation for the first section. The randomized vehicle list changes two times in this figure at the iterations of about 90 and 270, and it is possible to see that at several time instants it yields up to 27 km/h difference from the original values.

The same analysis is plotted in Figure 4.41, Figure 4.42 and Furthermore the difference values in section 3 plotted by Figure 4.42 changes between 0 to 11 km/h, where as in Figure 4.43 that plots the last section the difference interval becomes larger to such an extent that the higher boundary becomes 26 km/h.

Figure 4.43 for section 2, section 3 and section 4, respectively. In section 2 the difference of the average speeds vary from very low values to some decent ones, where at some point it becomes 0.1 km/h and at another it becomes 16 km/h.

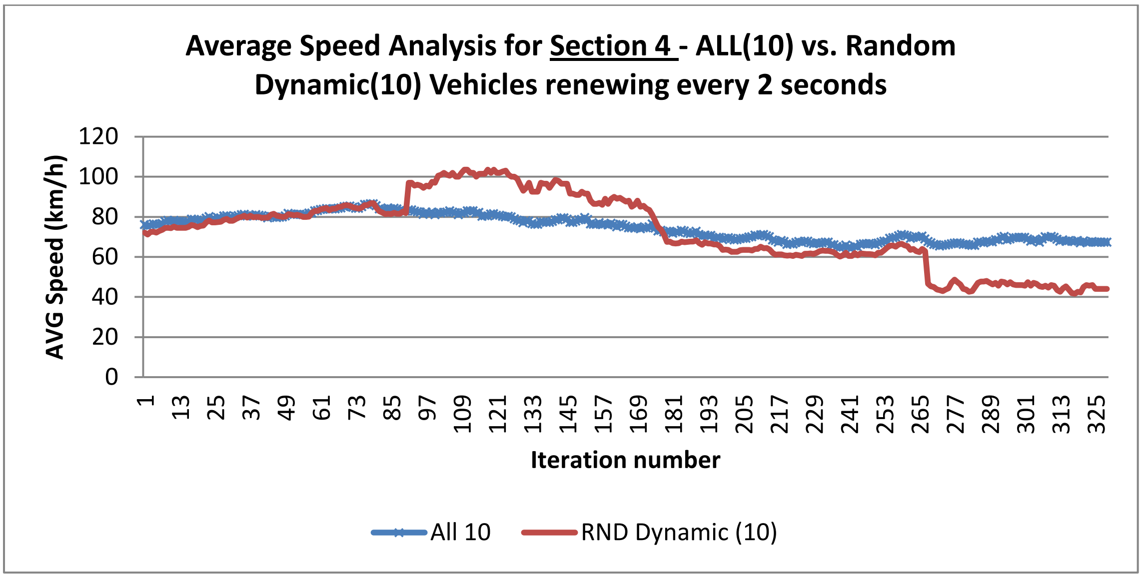
Figure 4.42: Average speed analysis for 10 vehicles vs. dynamic random 10 vehicles with the renewal time of 2 seconds in Section 3



Source: Türk Telekom Technical Report, 2012; Extraction of Congestion Information and Dynamic Route Planning, May 2012.

Furthermore the difference values in section 3 plotted by Figure 4.42 changes between 0 to 11 km/h, where as in Figure 4.43 that plots the last section the difference interval becomes larger to such an extent that the higher boundary becomes 26 km/h.

Figure 4.43: Average speed analysis for 10 vehicles vs. dynamic random 10 vehicles with the renewal time of 2 seconds in Section 4



Source: Türk Telekom Technical Report, 2012; Extraction of Congestion Information and Dynamic Route Planning, May 2012.

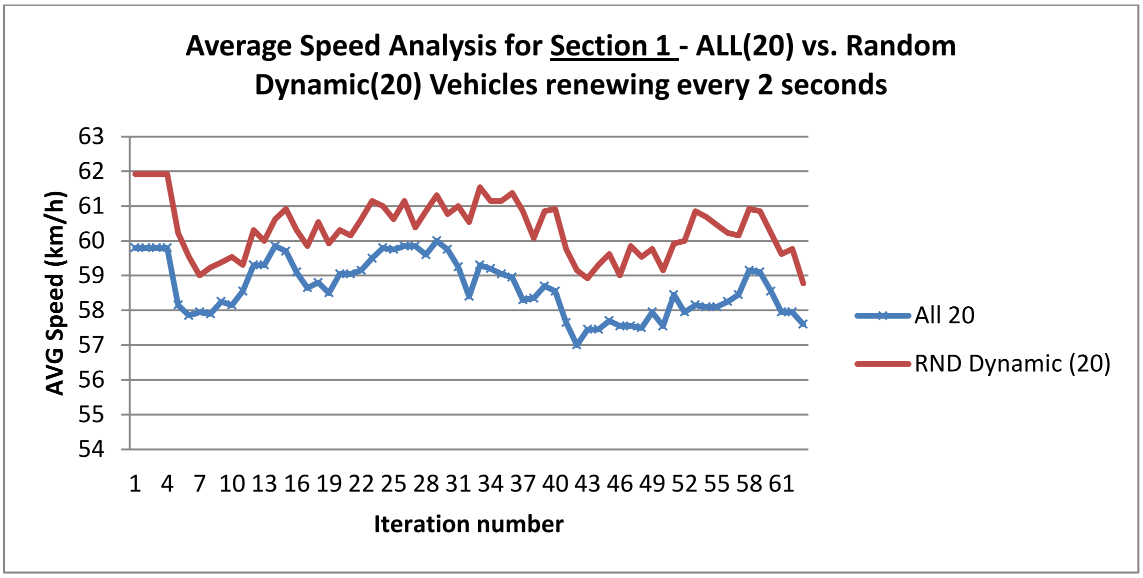
4.8.5.2.3 *20 vs. random dynamic(20) vehicles*

This analysis is basically the same as the previous one but just the number of vehicles starting in each section is doubled, i.e. defined as 20. The plot which is depicted in Figure 4.44 showed that if it is a lucky random selection, the gap between the lines may be so lower that it is under even 3 km/h.

For section 2, the same lucky condition is also valid, in other words the difference is under 3 km/h. But the random selections done in Figure 4.46 and Figure 4.47 are not as lucky as it was in previous sections.

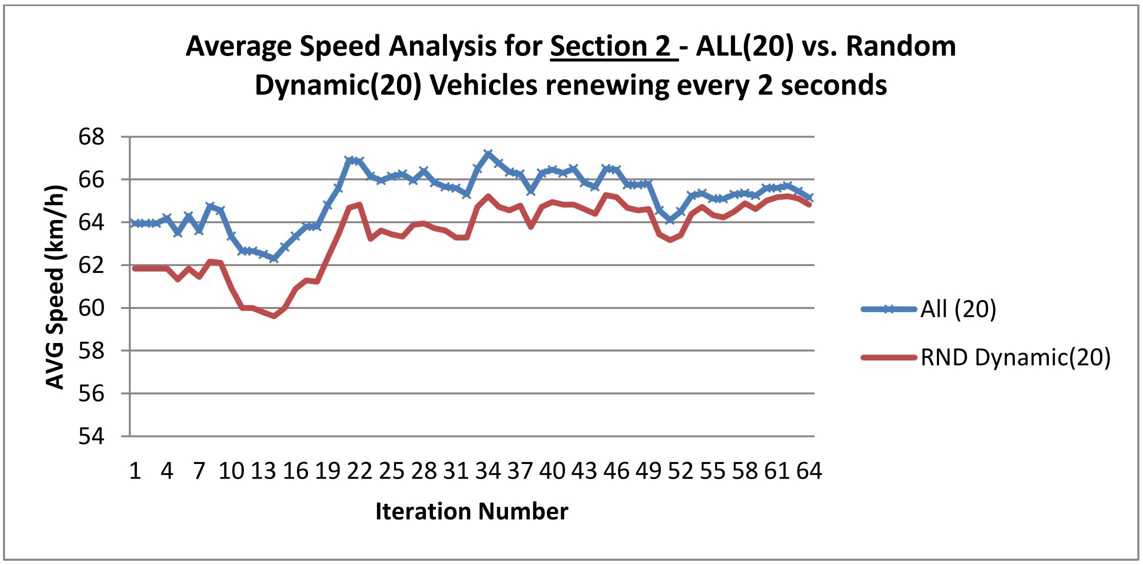
The observation on Figure 4.46 and Figure 4.47 shows that the average speed variations are somewhat higher this time. Specifically in Figure 4.46 it is more than 8 km/h and it gets larger in the following iterations whereas in Figure 4.47 it is above 24 km/h which constitutes a big difference compared to the first two sections.

Figure 4.44: Average speed gaps between 20 vehicles and dynamically selected random vehicles amongst 20 in section 1



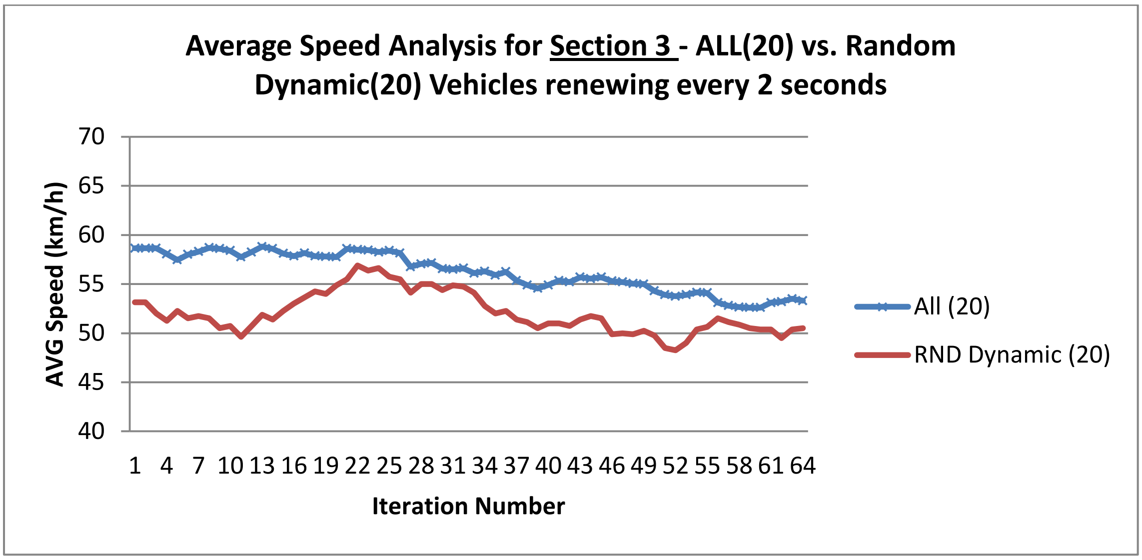
Source: Türk Telekom Technical Report, 2012; Extraction of Congestion Information and Dynamic Route Planning, May 2012.

Figure 4.45: Average speed gaps between 20 vehicles and dynamically selected random vehicles amongst 20 in section 2



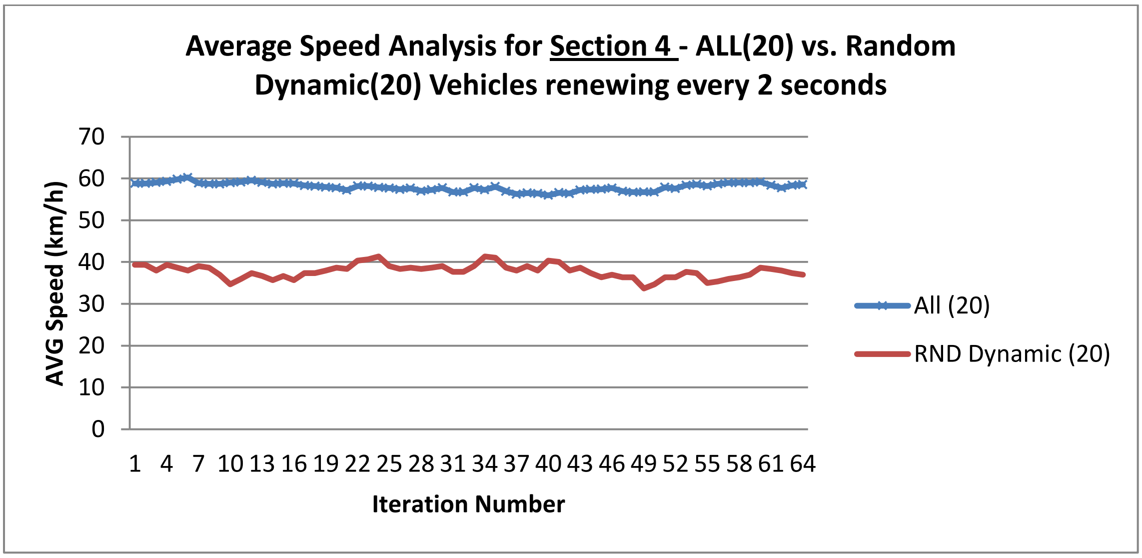
Source: Türk Telekom Technical Report, 2012; Extraction of Congestion Information and Dynamic Route Planning, May 2012.

Figure 4.46: Average speed gaps between 20 vehicles and dynamically selected random vehicles amongst 20 in section 3



Source: Türk Telekom Technical Report, 2012; Extraction of Congestion Information and Dynamic Route Planning, May 2012.

Figure 4.47: Average speed gaps between 20 vehicles and dynamically selected random vehicles amongst 20 in section 4

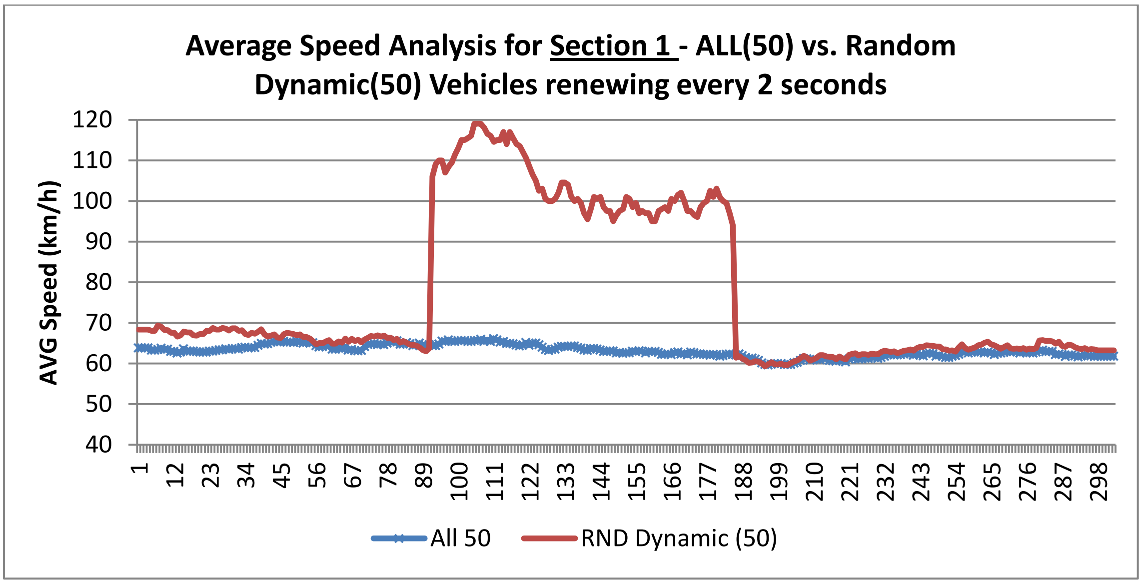


Source: Türk Telekom Technical Report, 2012; Extraction of Congestion Information and Dynamic Route Planning, May 2012.

4.8.5.2.4 *50 vs. random dynamic(50) vehicles*

The analyses done with fifty vehicles in each section provides relatively closer values in each iteration except in one part of the section 1. Overall, the plots show that an increase in vehicle numbers leads to the approximations that are closer to real values. The abrupt leap in the middle part of Figure 4.48 is only because of the large range of assigned vehicle speeds. In the further analyses the speed range of the vehicles will be narrowed down greatly to prevent such anomalies.

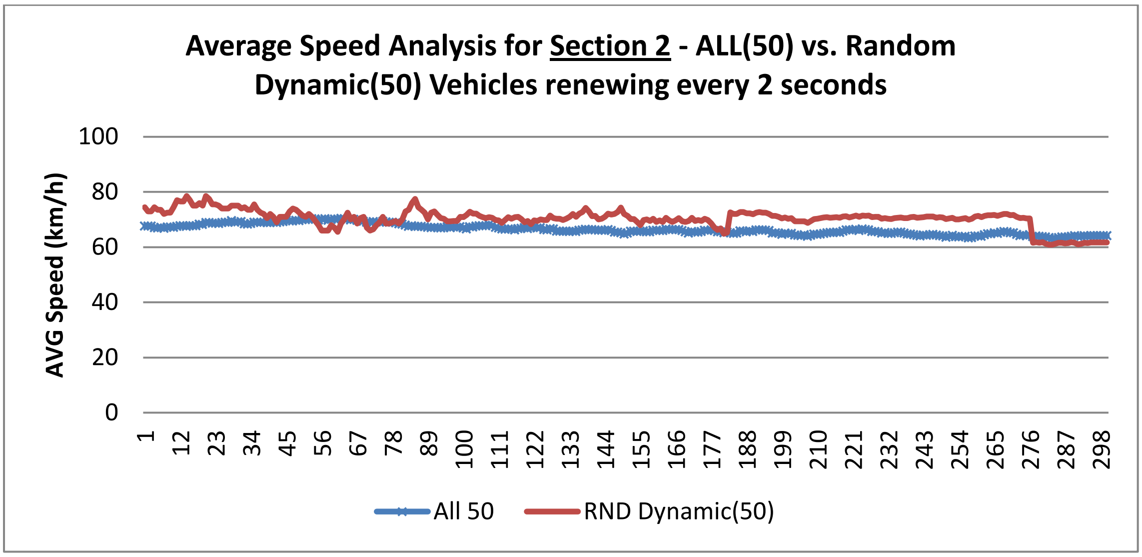
Figure 4.48: The comparison of 50 vehicles vs. random dynamic 50 vehicles renewing every 2 seconds in section 1



Source: Türk Telekom Technical Report, 2012; Extraction of Congestion Information and Dynamic Route Planning, May 2012.

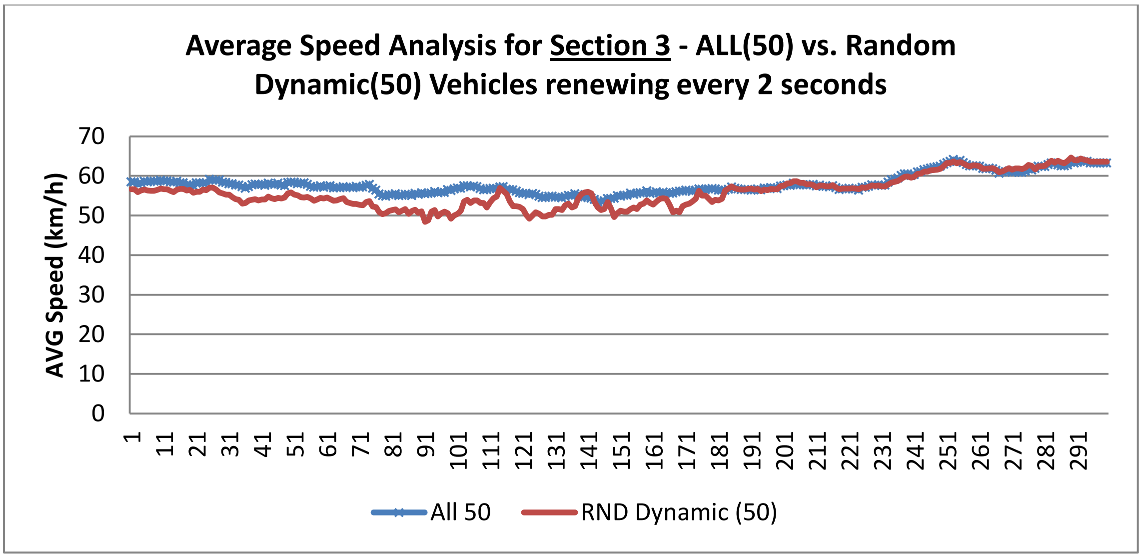
The average random vehicles speeds except from the abrupt leap in section 1 converge in the analyses illustrated by Figure 4.49, Figure 4.50 and Figure 4.51. If the speed intervals are narrowed down more to accommodate the real-life scenarios, the simulation results will have no such anomalies.

Figure 4.49: The comparison of 50 vehicles vs. random dynamic 50 vehicles renewing every 2 seconds in section 2



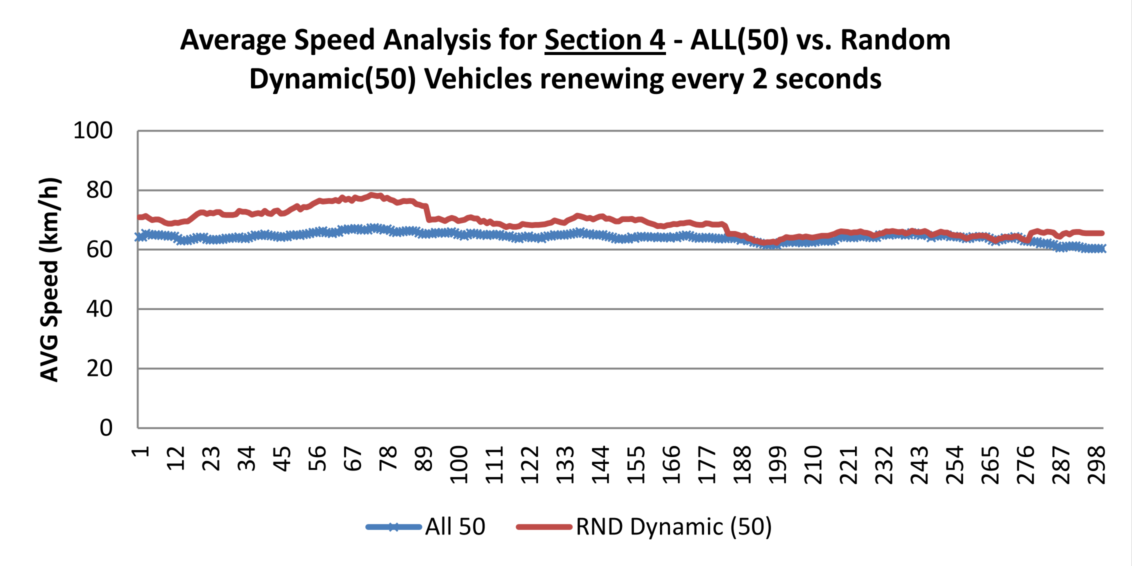
Source: Türk Telekom Technical Report, 2012; Extraction of Congestion Information and Dynamic Route Planning, May 2012.

Figure 4.50: The comparison of 50 vehicles vs. random dynamic 50 vehicles renewing every 2 seconds in section 3



Source: Türk Telekom Technical Report, 2012; Extraction of Congestion Information and Dynamic Route Planning, May 2012.

Figure 4.51: The comparison of 50 vehicles vs. random dynamic 50 vehicles renewing every 2 seconds in section 4



Source: Türk Telekom Technical Report, 2012; Extraction of Congestion Information and Dynamic Route Planning, May 2012.

4.8.5.3 Random Dynamic with Multiple Random Lists

This part of the simulator is started in the constructor of the Board class. After the sections are created, and the vehicles are generated for the section, an instance of the RandomVehiclesThread class is also created. This class extends the Thread class and is responsible for the task that fills the randomVehiclesArray, as well as the averageSpeedAnalysesArray.

While the randomVehiclesArray keeps track of the random number of vehicles selected among the whole list of vehicles (e.g. 73 vehicles out of 100), the averageSpeedAnalysesArray keeps track of the 4 other random vehicles lists. These are namely the lists with i) 1/5 random dynamic vehicles of the whole vehicles in the section (e.g. 20 vehicles out of 100), ii) 2/5 random dynamic vehicles of the whole vehicles in the section (e.g. 40 vehicles out of 100), iii) 3/5 random dynamic vehicles of the whole vehicles in the section (e.g. 60 vehicles out of 100), 4/5 random dynamic vehicles of the whole vehicles in the section (e.g. 80 vehicles out of 100).

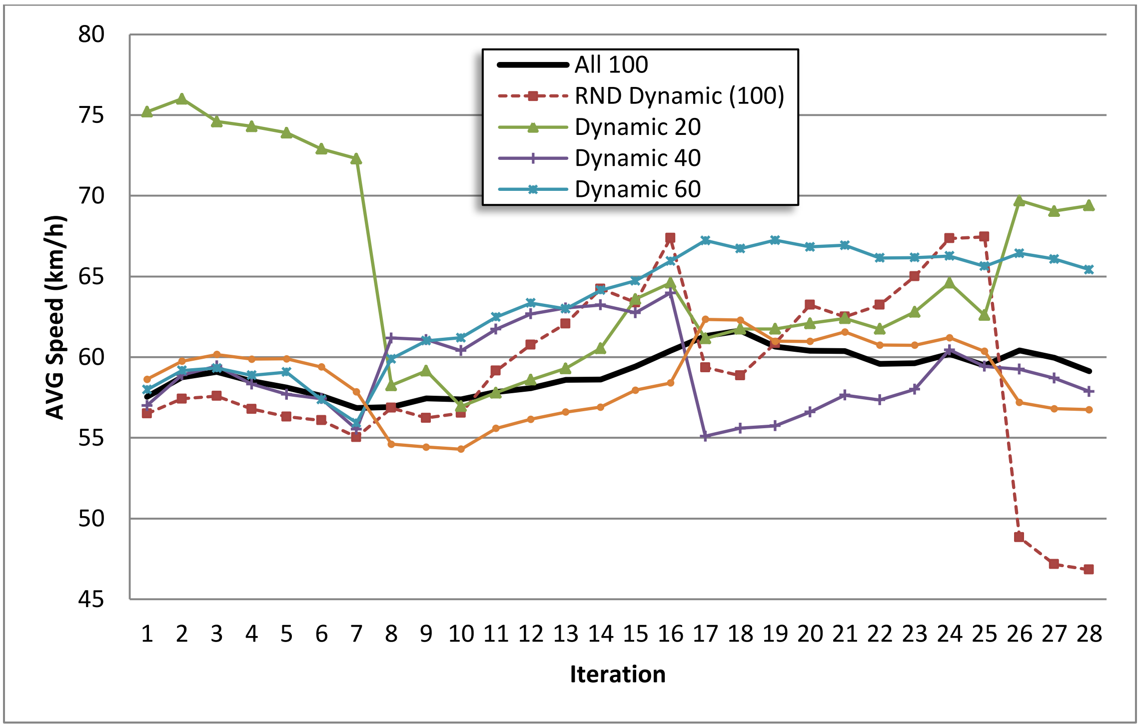
The analyses after this point aims at comparing the outputs generated by 6 different arrays one of which is the complete vehicle list itself. Other arrays that are plotted in the following figures are made of by a randomized dynamic array that has random number of vehicles out of the specified number of total vehicles that are present at the start of the simulation; for instance, 33 vehicles out of 100 vehicles in a section. The random number of vehicles to be picked are determined differently in each section. Nevertheless, every vehicle determined to be picked are different in each section. This situation reflects the totally random and arbitrary nature of the real-life scenarios.

Furthermore, other randomized dynamic arrays are made of 20, 40, 60 and 80 vehicles out of 100 vehicles. All of these vehicle lists (i.e. arrays) are illustrated in the same plot to see the all exact variations in one.

4.8.5.3.1 *100 vs. random dynamic (100) and 20, 40, 60, 80 vehicles*

Figure 4.52 to Figure 4.55 depicts the all six different outputs at once for each section respectively. As expected, the most abrupt leaps occur in the lists of both random dynamic (100) and the dynamic randomly selected 20 vehicles.

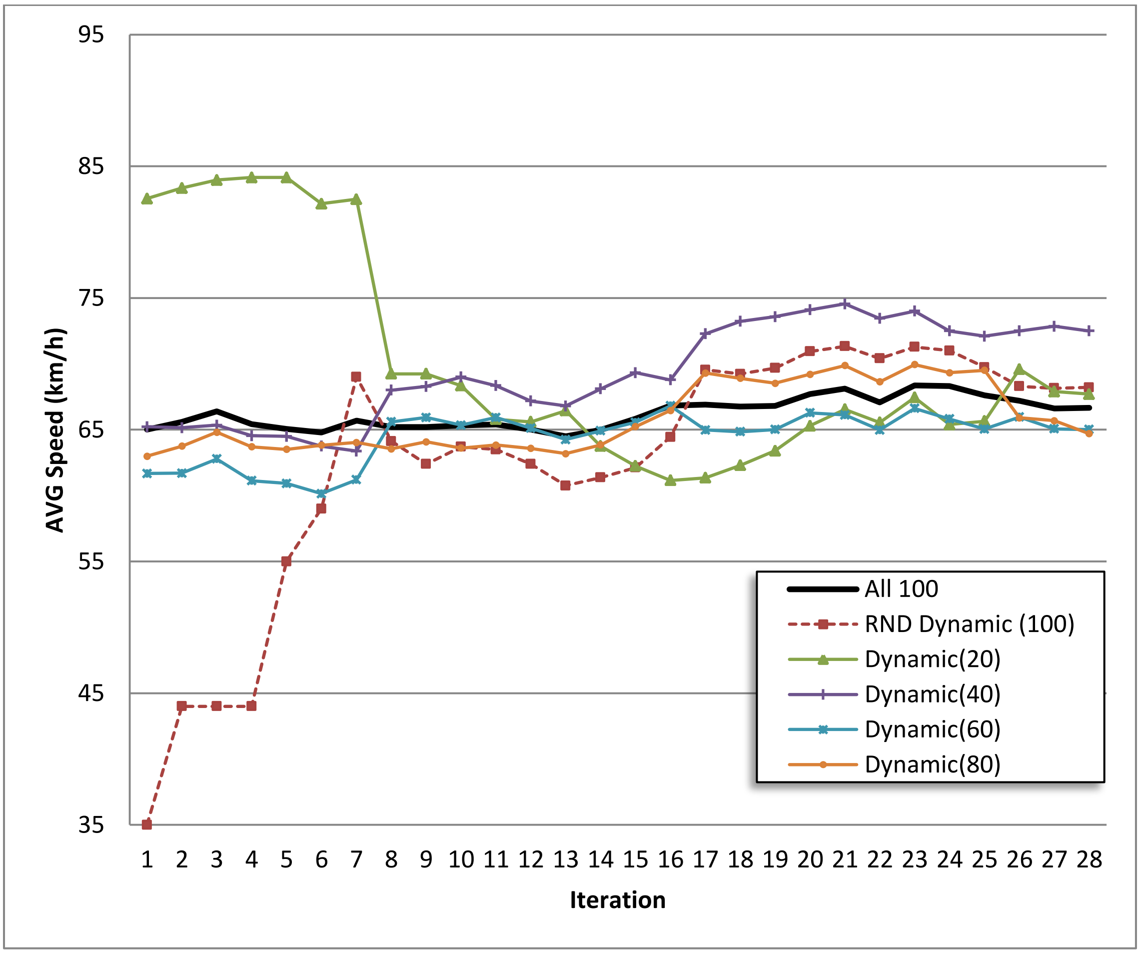
Figure 4.52: Average speed analysis for section 1 - all(100) vs. random dynamic(100), dynamic(20, 40, 60, 80) vehicles renewing every 2 seconds



Source: Türk Telekom Technical Report, 2012; Extraction of Congestion Information and Dynamic Route Planning, May 2012.

The abnormal leaps observed for the random dynamic (100) is due to the fact that the number of vehicles to be selected for average speed calculation varies too much. For example in one selection phase it may be 13, in another it may be 95, and in one last it may be 55. The picked vehicles are also different in each selection phase. In one selection only the fastest 10 vehicles may be chosen which results in a high average speed calculation, whereas in another selection phase the 20 slowest vehicles might be chosen which results in an opposite condition. Hence the calculations are a highly unstable for random dynamic (100) list.

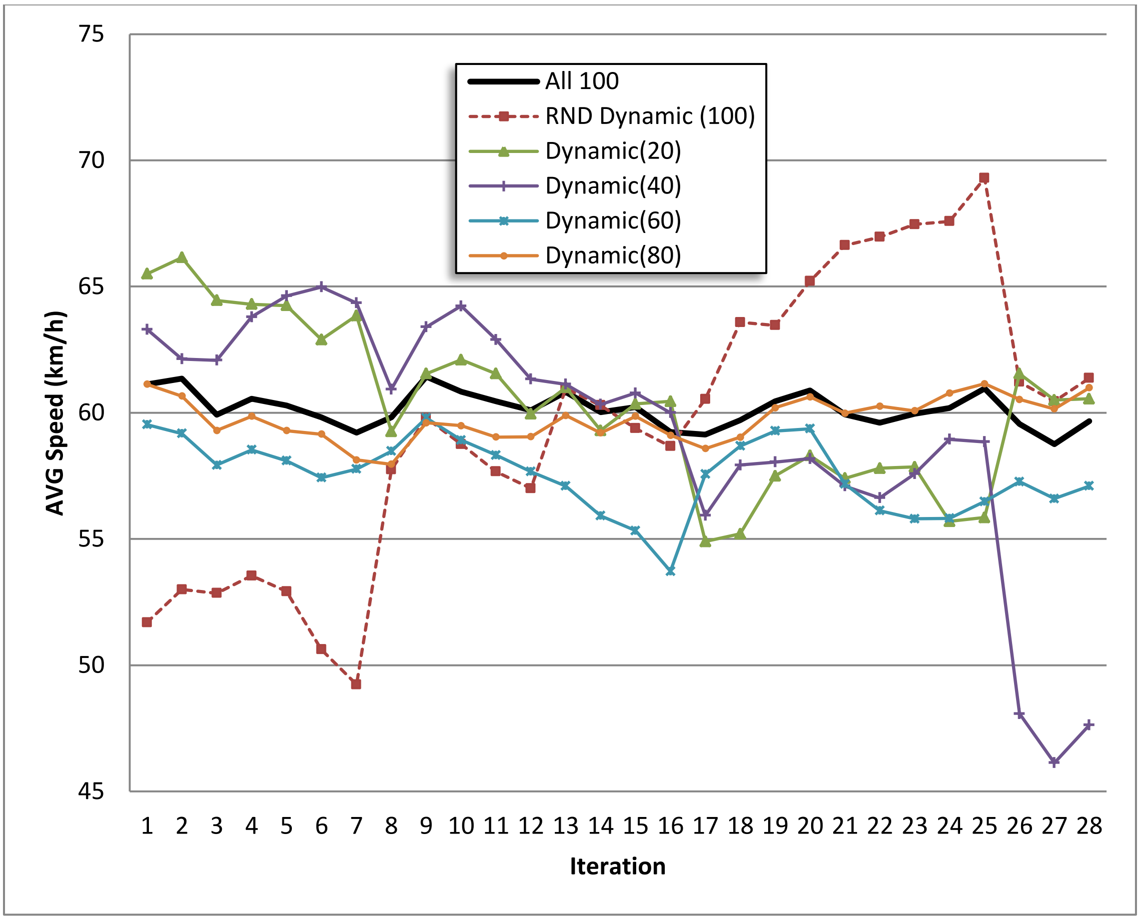
Figure 4.53: Average speed analysis for section 2 - all(100) vs. random dynamic(100), dynamic(20, 40, 60, 80) vehicles renewing every 2 seconds



Source: Türk Telekom Technical Report, 2012; Extraction of Congestion Information and Dynamic Route Planning, May 2012.

On the other hand, the unstable nature of random dynamic 20 is because of the fact that the ratio is statistically too low. The 20 vehicles chosen randomly might have completely different speed values, i.e. they might have totally far values from each other. Thus the average speed calculated using such a list will indicate values far from acceptable deviation levels. Both of these unsteady conditions are given by all of the plots in this sub-section.

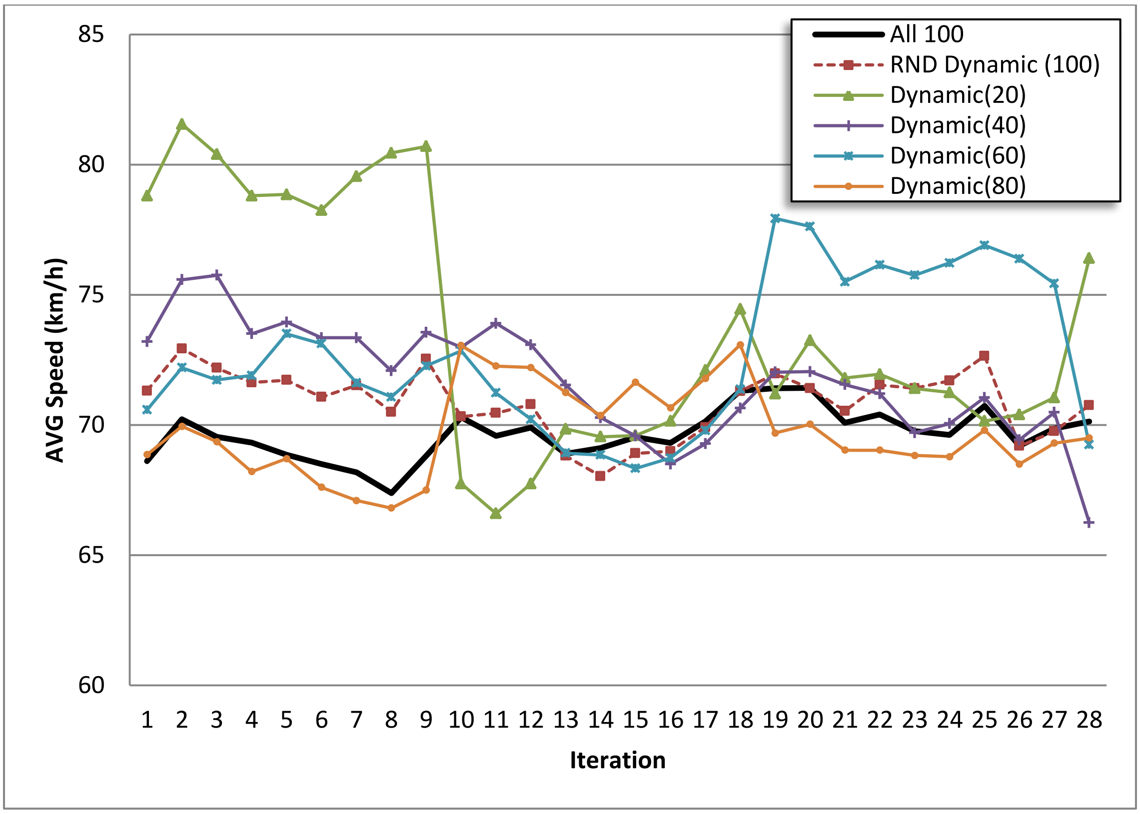
Figure 4.54: Average speed analysis for <u>section 3 </u>- all(100) vs. random dynamic(100), dynamic(20, 40, 60, 80) vehicles renewing every 2 seconds



Source: Türk Telekom Technical Report, 2012; Extraction of Congestion Information and Dynamic Route Planning, May 2012.

Moreover another expected result which is based on the idea that the more vehicles present in a section, the more accurate the average speed calculation results are, is justified by the Figure 4.52, Figure 4.53, Figure 4.54 and Figure 4.55.

Figure 4.55: Average speed analysis for <u>section 4</u> - all(100) vs. random dynamic(100), dynamic(20, 40, 60, 80) vehicles renewing every 2 seconds



Source: Türk Telekom Technical Report, 2012; Extraction of Congestion Information and Dynamic Route Planning, May 2012.

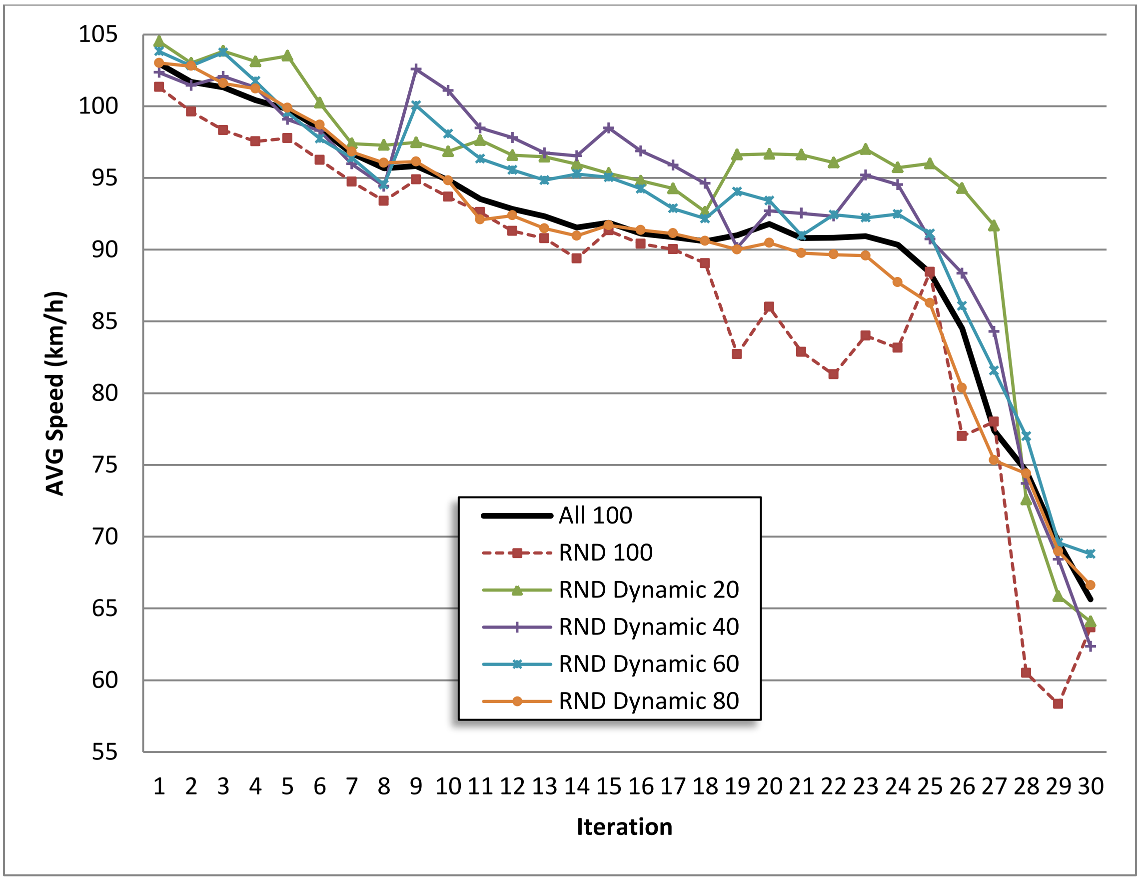
Overall, the closest values to the real average speed are calculated using the random dynamic 80 vehicles. Second closest values are calculated most of the time by the list with random dynamic 60 vehicles, later on random dynamic 40, and so on.

4.8.5.3.2 *100 vs. random dynamic (100) and 20, 40, 60, 80 vehicles with different speed intervals constraint in sections*

The last analyses carried out during the research are presented in this sub-section. The purpose in these analyses is to observe the results of the average speed calculation when speed variation of the vehicles in a section is narrowed down to simulate the real-life scenarios properly. Because in real-life scenarios there are no such big speed differences of above 60 km/h or even above 100 km/h.

In order to provide the speed intervals at the start of the simulations, each section is created with the minimum and maximum speed boundaries. Thus the speed of the vehicles created within a section can only have the values determined between the minimum and the maximum speed boundaries, at the start of the simulation.

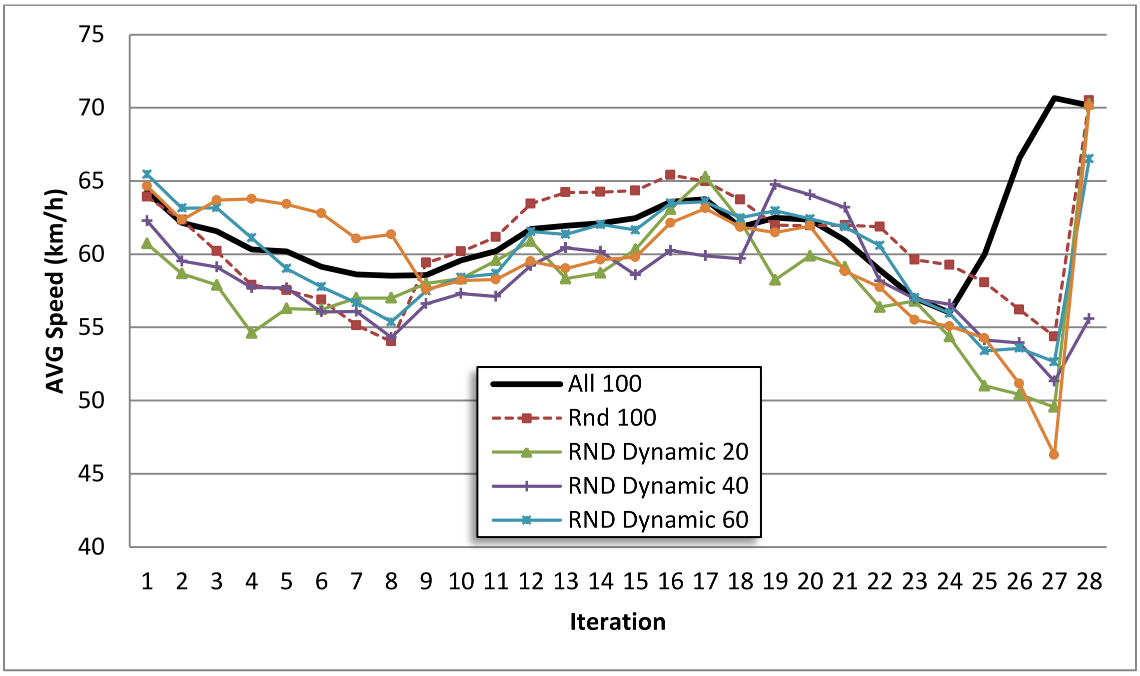
Figure 4.56: Average speed analysis for section 1 implementing the speed intervals - all(100) vs. random dynamic(100), dynamic(20, 40, 60, 80)



Source: Türk Telekom Technical Report, 2012; Extraction of Congestion Information and Dynamic Route Planning, May 2012.

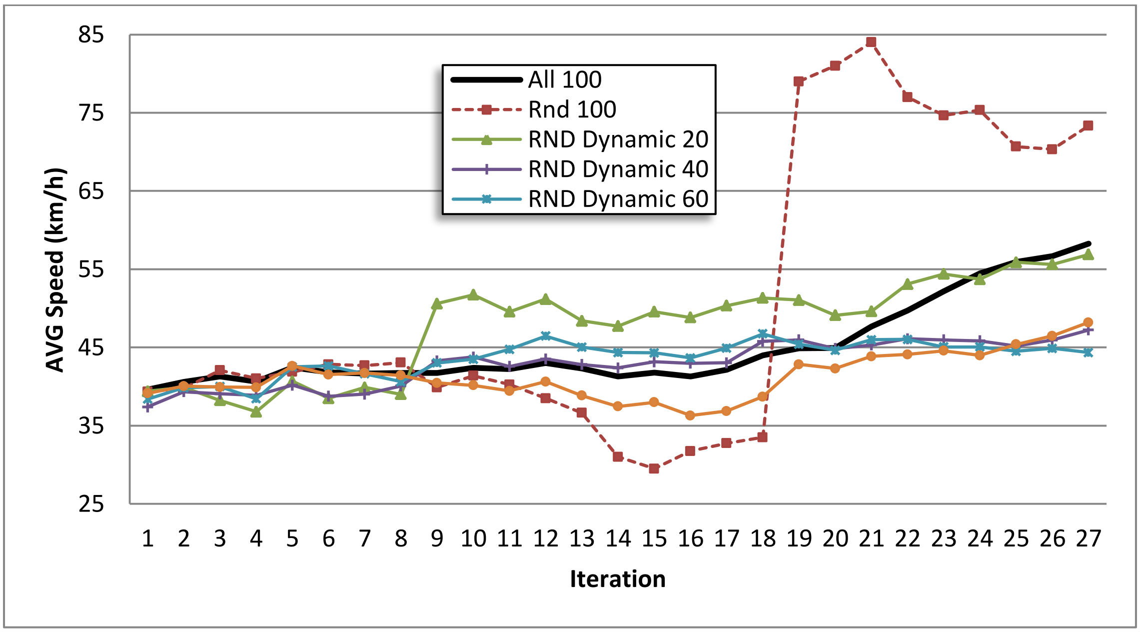
The simulation outputs presented from Figure 4.56 to Figure 4.59 integrates the section speed interval constraints. Implementing such a mechanism makes the simulator to be able to generate closer values to the real average speeds compared to the previous analyses, even for the random dynamic 20 vehicles list.

Figure 4.57: Average speed analysis for section 2 implementing the speed intervals - all(100) vs. random dynamic(100), dynamic(20, 40, 60, 80)



Source: Türk Telekom Technical Report, 2012; Extraction of Congestion Information and Dynamic Route Planning, May 2012.

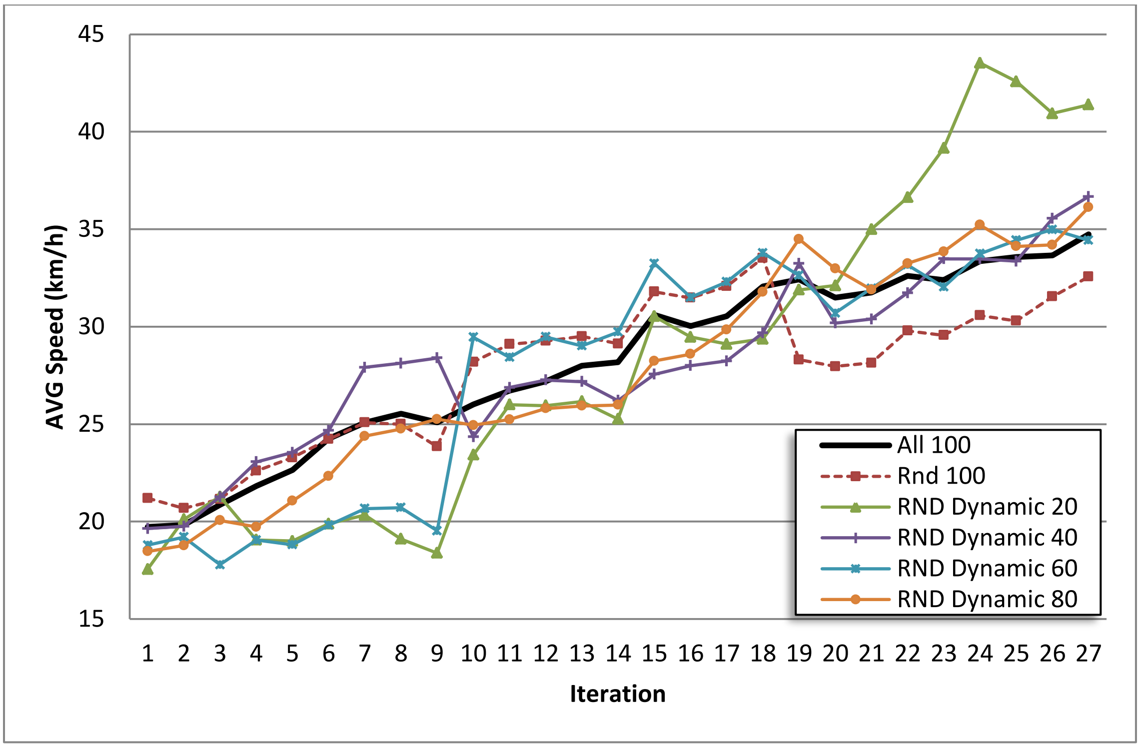
Figure 4.58: Average speed analysis for section 3 implementing the speed intervals - all(100) vs. random dynamic(100), dynamic(20, 40, 60, 80)



Source: Türk Telekom Technical Report, 2012; Extraction of Congestion Information and Dynamic Route Planning, May 2012.

Figure 4.56 illustrates the case for section 1 and has the speed interval starting from 90 km/h to 120 km/h. Figure 4.57 represents the case where the lower speed boundary is 50 km/h and the upper speed boundary is 80 km/h for the second section. Figure 4.58 depicts the third section and has the speed interval between 30 km/h and 50 km/h. Lastly, Figure 4.59 illustrates the last section and is bounded by the limits of 10 km/h to 30 km/h.

Figure 4.59: Average speed analysis for section 4 implementing the speed intervals - all(100) vs. random dynamic(100), dynamic(20, 40, 60, 80)



Source: Türk Telekom Technical Report, 2012; Extraction of Congestion Information and Dynamic Route Planning, May 2012.

4.8.6 Traffic Scenarios

Three traffic scenarios are presented in this section using the BAU Traffic Simulator. In the first scenario the purpose is to simulate an ordinary traffic case. The second scenario is based on the free flow traffic whereas the third scenario illustrates a traffic accident with lane closures. All the three scenarios are depicted with various snapshots taken from the simulator.

4.8.6.1 Case 1: Normal Traffic

The scenario shown in Figure 4.60 depicts the traffic simulation setup which has 10 vehicles for each vehicle at the start. The vehicles have the initial speeds specified for the section in which they are created and located. Moreover, there are 4 sections with the varying lengths and initial speed intervals. The first section starts from the right hand side and continues to the left. The vehicles move on the same direction as the sections, i.e. from right hand side to the left hand side.

In this setup, there are 5 vehicles starting in each section. Section one (the right most section) has 96 km/h average speed, and the random vehicles average speed that are transmitting data to the server is 98.67 km/h. The average speed in the first section is high since its interval is between 90 km/h and 120 km/h. First section's congestion color is green and congestion level is 5 which informs that the section is in free flow condition.

Figure 4.60: Depiction of the first scenario: normal traffic

Source: Türk Telekom Technical Report, 2012; Extraction of Congestion Information and Dynamic Route Planning, May 2012.

In the second section, there are no randomly transmitting vehicles at all. Hence, the average speed for transmitting vehicles is zero although the real average speed is 88 km/h in this section. The second section's speed interval is between 50 km/h and 80 km/h. The section's congestion color is green and congestion level is 5 which means that it is in free flow state.

On the other hand, the third section has an average speed of 25.4 km/h whereas its average speed for the vehicles that are transmitting GPS data to the central server is 32.67 km/h. The third section's initial speed interval is 30 km/h for the lower limit and 50 km/h for the upper limit. The section's congestion color is red and congestion level is 2 which represents its status as congested.

Furthermore, the last section has an initial speed interval between 10 km/h and 30 km/h. The average speed of all vehicles in the section is 12.4 km/h while the average speed of the transmitting vehicles is 16.5 km/h. The section's congestion color is magenta and congestion level is 1 which notifies that it is heavily/highly congested.

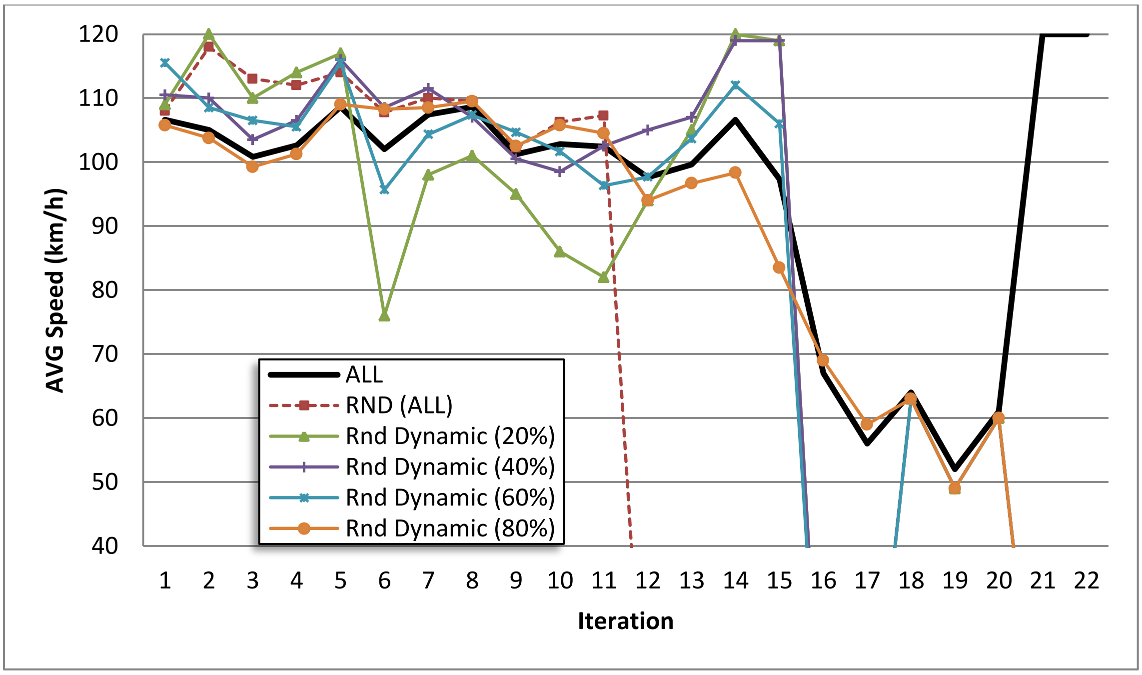
Figure 4.61: Depiction of the same normal traffic scenario showing the randomization

Source: Türk Telekom Technical Report, 2012; Extraction of Congestion Information and Dynamic Route Planning, May 2012.

The same setup is run again to show the randomization process. This time the congestion status of each section is as shown in Figure 4.61. In this simulation run, the first section is highly free (congestion level 6) with 106 km/h average speed and 0 km/h transmitting vehicles average speed, the second section is in smooth flow (congestion level 4) with 79.4 km/h average speed and 63 km/h transmitting vehicles average speed, the third section is in dense flow (congestion level 3) with 41.4 km/h average speed and 0 km/h transmitting vehicles average speed, and the last section is in congested state (congestion level 2) with 25.2 km/h average speed and 6.5 km/h transmitting vehicles average speed. So the congestion colors are blue, yellow, orange, and red for section 1, section 2, section 3 and section 4, respectively.

The normal traffic case presented in Figure 4.61 is analyzed in Figure 4.62, Figure 4.63, Figure 4.64, and Figure 4.65 for section 1, section 2, section 3, and section 4, respectively. The first section is highly free, around 100-110 km/h as it can be seen in Figure 4.62 until 15th iteration (see Appendix A-1: Table 1 for the raw traffic data of section 1). After that point the fast vehicles get in to the next section and thus the average speed in section 1 drops considerably, even down to 50 km/h.

Figure 4.62: Average speed analysis for case 1 (normal traffic scenario) in section 1

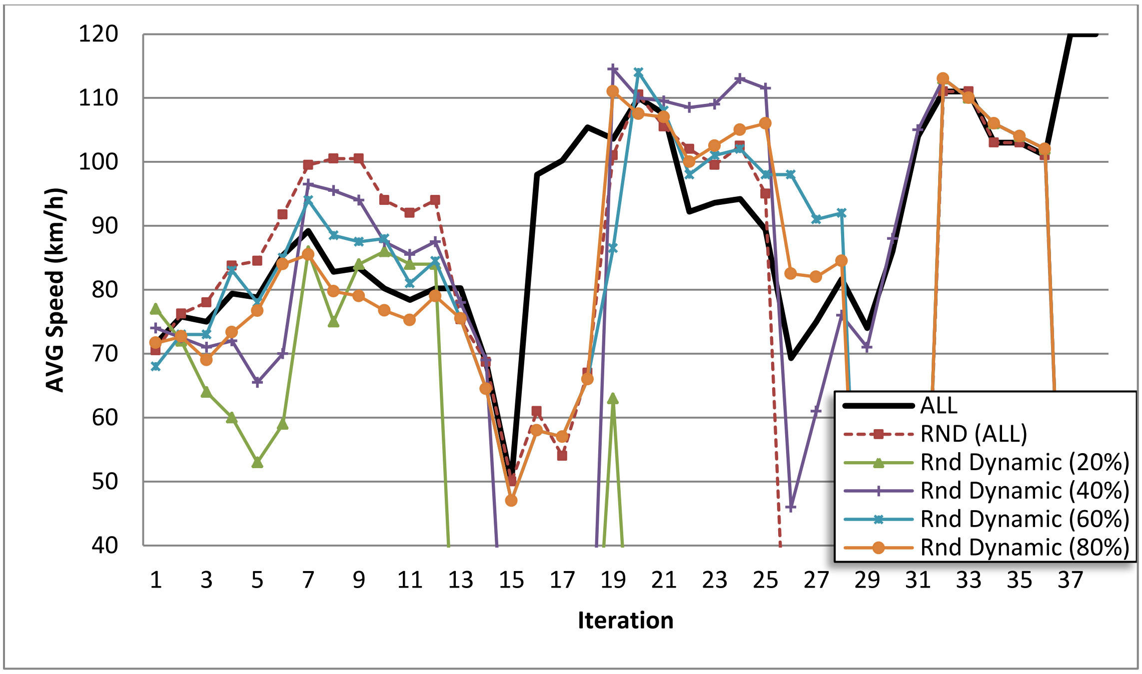


Source: Türk Telekom Technical Report, 2012; Extraction of Congestion Information and Dynamic Route Planning, May 2012.

The second section has an average speed at around 80 km/h which shows that congestion status is in smooth flow with an average speed weight of 4 until 13th iteration, as shown in Figure 4.63. After this point the average speed drops down to 50 km/h. This is due to the vehicles that have high speed values leave the section and continue on the next section. Then at 16th iteration the average speed bursts up to 100 km/h due to entry of many high speed vehicles into the second section.

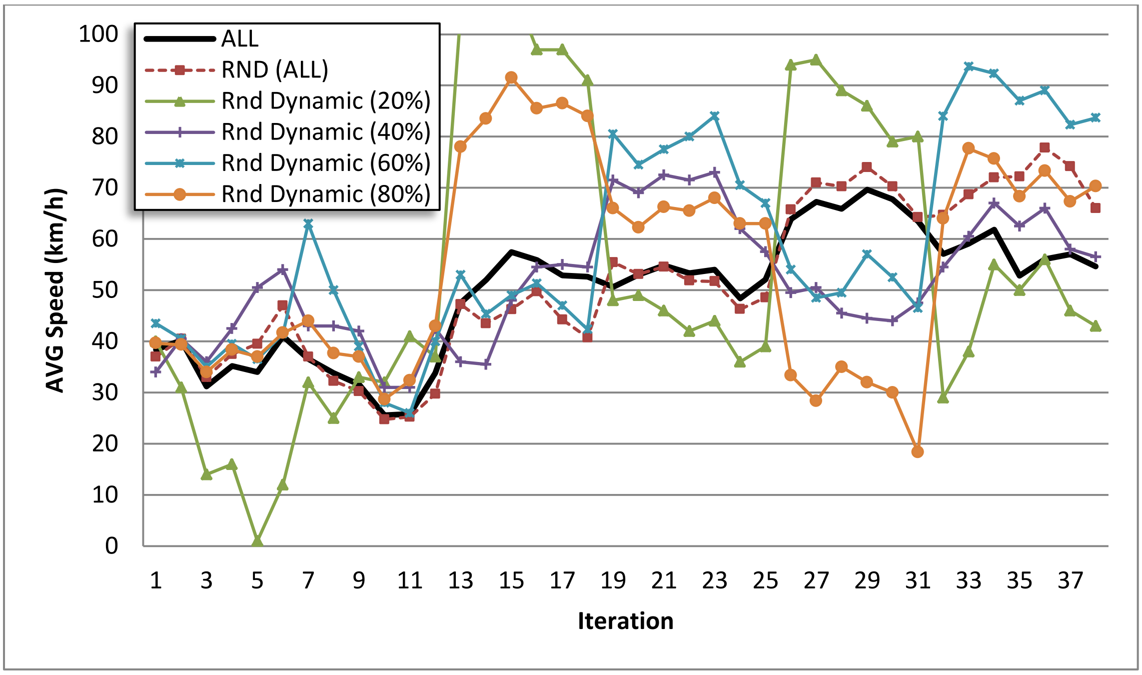
The third section's average speed fluctuates between 30 km/h and 40 km/h in the beginning, which stands for a traffic status of level 3, dense flow. As seen in Figure 4.64, after a while at 13th iteration, it starts rising due to the high speed vehicles moving into the section. As more high speed vehicles that come from section 1 and section 2 get involved in the third section, the average speed increases further. The increase stops after a while and the average speed gets stabilized between the values of 50 km/h and 70 km/h.

Figure 4.63: Average speed analysis for case 1 (normal traffic scenario) in section 2



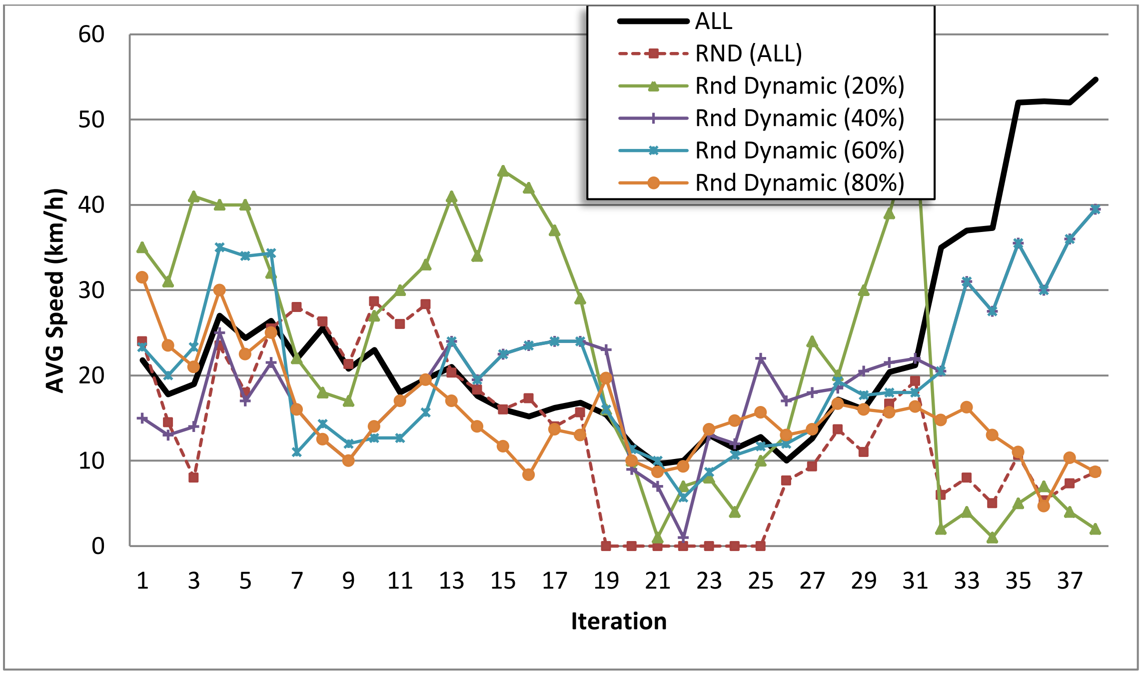
Source: Türk Telekom Technical Report, 2012; Extraction of Congestion Information and Dynamic Route Planning, May 2012.

Figure 4.64: Average speed analysis for case 1 (normal traffic scenario) in section 3



Source: Türk Telekom Technical Report, 2012; Extraction of Congestion Information and Dynamic Route Planning, May 2012.

Figure 4.65: Average speed analysis for case 1 (normal traffic scenario) in section 4



Source: Türk Telekom Technical Report, 2012; Extraction of Congestion Information and Dynamic Route Planning, May 2012.

Similar decrease and increase patterns are seen for the average speed in section 4, as it can be observed in Figure 4.65. The initial average speed is between 20 km/h and 10 km/h, and the congestion level is 2 (congested). When the speedy vehicles in other sections start entering the 4th section, the average speed constantly increases up to 60 km/h, in other words to a traffic state that represents the smooth flow.

4.8.6.2 Case 2: Free Flow Traffic

The second traffic scenario presents a case where the average speed is quite high. The setup that is configured for this case, i.e. the free flow traffic case, consists of only 1 section. The section contains 10 vehicles and has the length of 0.6 km.

The vehicles have initial speeds of randomly assigned from the interval of 80 km/h and 120 km/h. That is the reason such high average speeds is observed within the roadway during the simulation in each iteration. The vehicles are moving close to each other and at high speeds. The setup, in this regard, is able to simulate the real life scenarios of free flow traffic that mostly occurs in highways.

Figure 4.66: Free flow traffic case with single section of 600 m length containing 10 high speed vehicles

Source: Türk Telekom Technical Report, 2012; Extraction of Congestion Information and Dynamic Route Planning, May 2012.

The snapshot depicted in Figure 4.66 provides the average speed information of the all vehicles in the section as 86.5 km/h which is also given as “(5) FREE FLOW” in terms of congestion weight. On the other hand, at the time instant the snapshot is taken, there appears 5 selected vehicles that are transmitting GPS data to the central system. The average speed of these transmitting vehicles is 88.4 km/h. The transmitting vehicles, in this sense, represent close average speed values.

Another free flow traffic case using different parameters is presented in the snapshot given in Figure 4.67. This setup contains a single section, as well. However, the length of the single section is 1.6 km. The number of vehicles that appear in the section is 20. The average speed of the vehicles in the roadway is 87.96 km/h. This average speed corresponds to the congestion weight “(5) FREE FLOW”, and the congestion color of green.

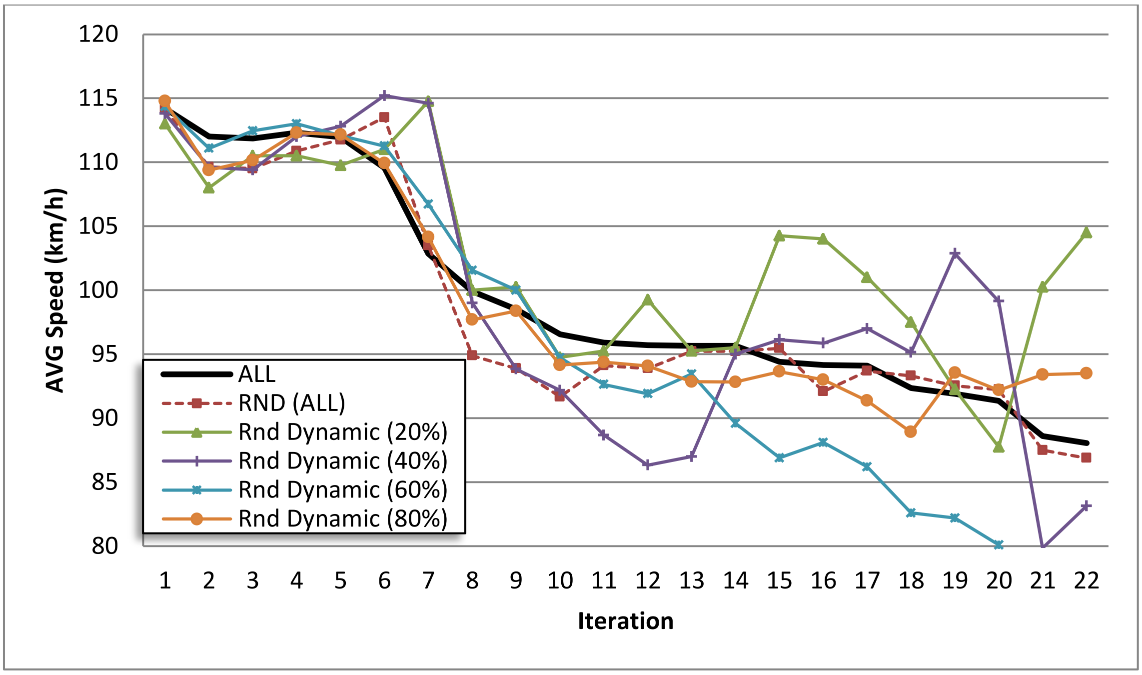
Figure 4.67: Free flow traffic with the setup of 20 vehicles in one section of 1600m length

Source: Türk Telekom Technical Report, 2012; Extraction of Congestion Information and Dynamic Route Planning, May 2012.

On the other hand, the selected vehicles that are transmitting data to the central system is 10 in the time instant the snapshot is taken. It still keeps varying over time. In such conditions, the average speed of the transmitting vehicles is 94.42 km/h. The error in this case is higher compared to the previous setup. The approximate error value is ≈7.34 percent. This is due to the increased number of vehicles with varying speeds.

Figure 4.68 depicts the average speed analysis carried out for the setup in Figure 4.67 (see Appendix A-2: Table 1 for the raw traffic data used to represent the free flow case). The average speed tends to decrease in time due to deceleration of some vehicles even at times the road traffic is in free flow.

Figure 4.68: Average speed analysis for case 2 (free flow traffic scenario) which contains 20 vehicles and in a single section



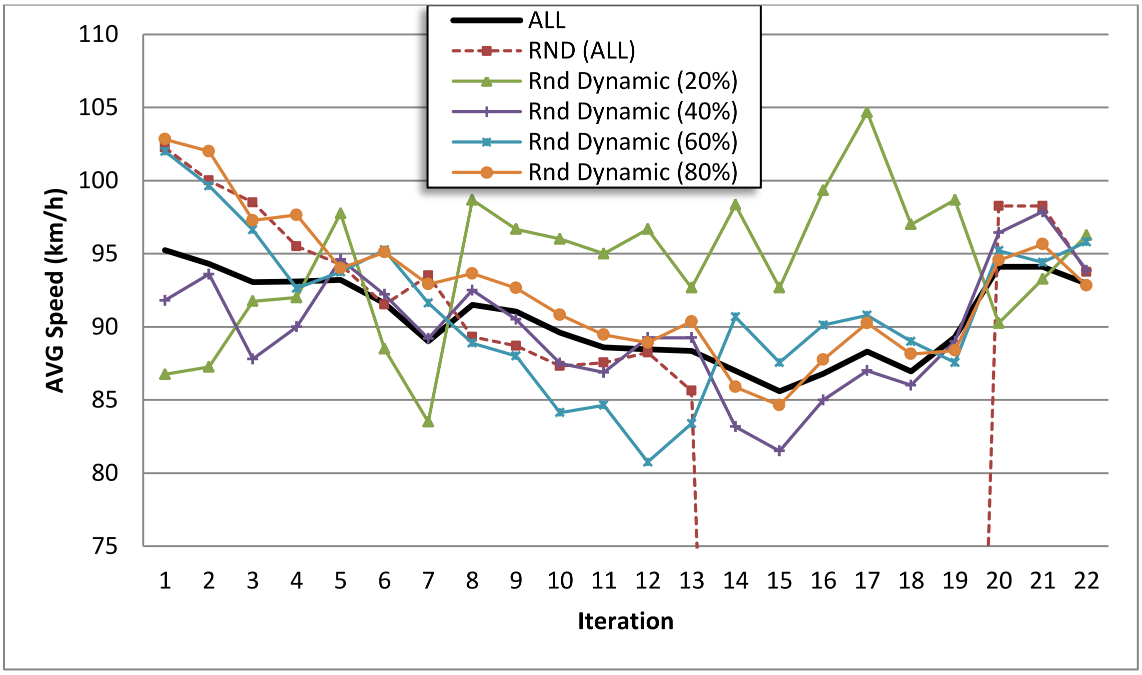
Source: Türk Telekom Technical Report, 2012; Extraction of Congestion Information and Dynamic Route Planning, May 2012.

On the other hand, one other free flow traffic case presented in Figure 4.69 does not have constantly dropping average speed values for the section as shown in the analysis given by Figure 4.70, since the vehicles keep traveling at the same speed interval such as [80,120] km/h. This is a lot more realistic free flow traffic scenario compared to the previous setup.

Figure 4.69: Traffic status in a single section for case 2 (free flow traffic scenario) which contains 20 vehicles with [70,120] km/h speed interval

Source: Türk Telekom Technical Report, 2012; Extraction of Congestion Information and Dynamic Route Planning, May 2012.

Figure 4.70: Average speed analysis for case 2 (free flow traffic scenario) which contains 20 vehicles and in a single section with [70,120] km/h speed interval



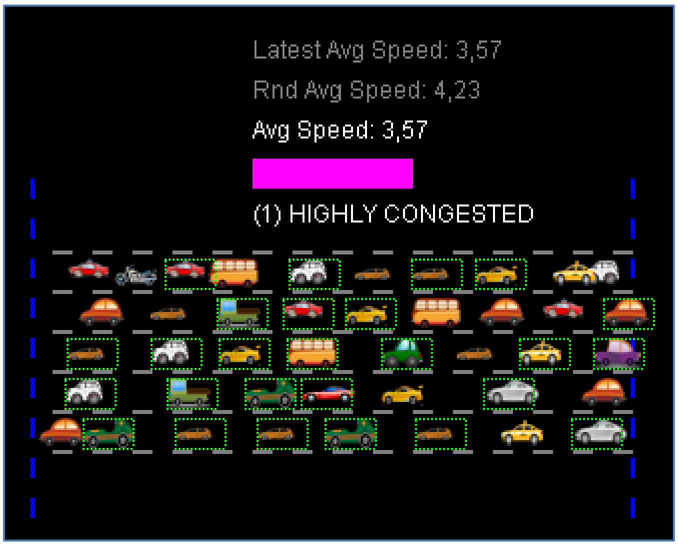
Source: Türk Telekom Technical Report, 2012; Extraction of Congestion Information and Dynamic Route Planning, May 2012.

4.8.6.3 Case 3: Traffic Accident (Multiple Lanes Closed)

The third case simulates the traffic accident scenarios. There are two setups with different parameters that are simulated in Figure 4.71 and Figure 4.72. Both of the setups have continuously generated vehicles in them.

The setup depicted in Figure 4.71 is made up of continuously generated vehicles from the starting section, i.e. the first section at the right hand side. The traffic in the first, second, and third lanes (in the vertical direction starting from up and going down, respectively) are highly congested due to the traffic accidents happened in them. The other lanes, namely the fourth and the fifth, are moving. The movement occurs quite slowly, though.

Figure 4.71: Traffic accident setup with 42 vehicles in a single section of length 600 meter and 3 closed sections



Source: Türk Telekom Technical Report, 2012; Extraction of Congestion Information and Dynamic Route Planning, May 2012.

There are 27 vehicles which completely stopped in the upper three lanes. Moreover, there are 15 vehicles which are slowly moving in the lower two lanes. Thus, the system has 5 lanes and is comprised of 42 vehicles. The length of the section is 600 meters. The system has an average speed of 3.57 km/h at the time instant the snapshot is taken. The congestion weight is (1) which stands for “HEAVYLY CONGESTED” and the congestion color is magenta.

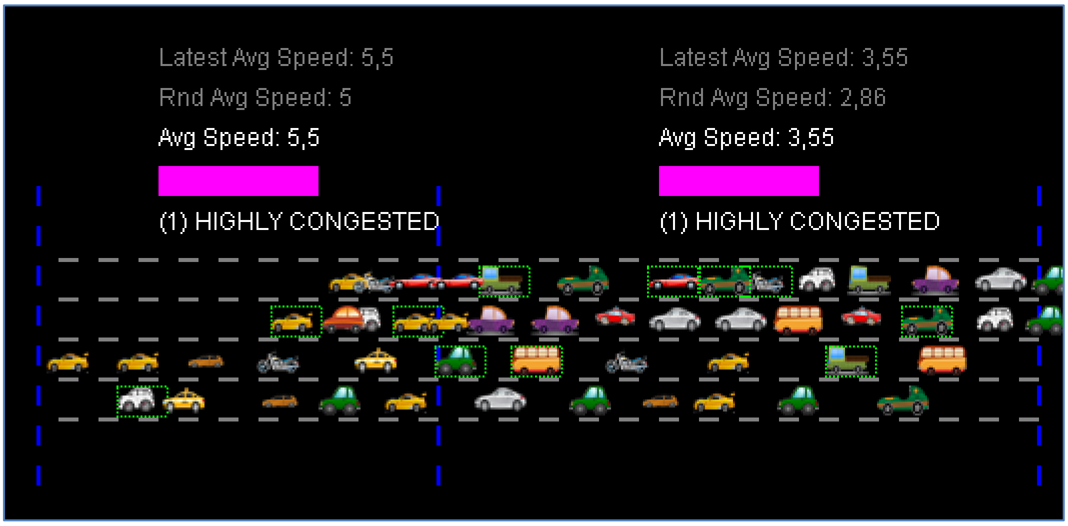
At the same time, there are 15 vehicles transmitting their vehicle data amongst the stopping vehicles in the first three lanes. Hence 15 vehicles out of 26 transmitting vehicles will report their speed as zero kilometers per hour and their location as constant coordinates. The average speed of transmitting vehicles, on the other hand, is 4.23 km/h which is quite close to the real value.

Furthermore, there are 11 vehicles amongst the moving ones in the lower two lanes that are transmitting their vehicle data to the central server. Hence, only 11 vehicles out of 26 transmitting vehicles will report their speed as non-zero values. The average speed values calculated for the roadway is low due to the 15 vehicles reporting their speed as zero.

One other setup is also simulated for the traffic accident case which is depicted in Figure 4.72. This time the setup contains many more vehicles and two different sections. The first section at the right hand side has 4 lanes in total. The total number of vehicles in the section has 32 vehicles. The upper two lanes are heavily congested due to the traffic accident occurred in the second section (the one at the left hand side).

There are 21 vehicles in the congested lanes and 5 of them are transmitting vehicle data to the server. These vehicles report their speed as zero km/h and their location as constant coordinates since they are stopping. On the other hand, the lower two lanes have 11 vehicles that are moving slowly with approximately 10 km/h speed and only two of them are reporting their vehicle data to the central structure. The average speed in in the section to the right hand side (first section) is 3.55 km/h whereas the average speed reported by the transmitting vehicles is 2.86 km/h. Hence, the reported data has relatively low error rates. Besides, the congestion weight is again (1) that means “HEAVYLY/HIGHLY CONGESTED” and the corresponding congestion color is painted as magenta.

Figure 4.72: Traffic accident setup with two sections where two lanes are closed in each

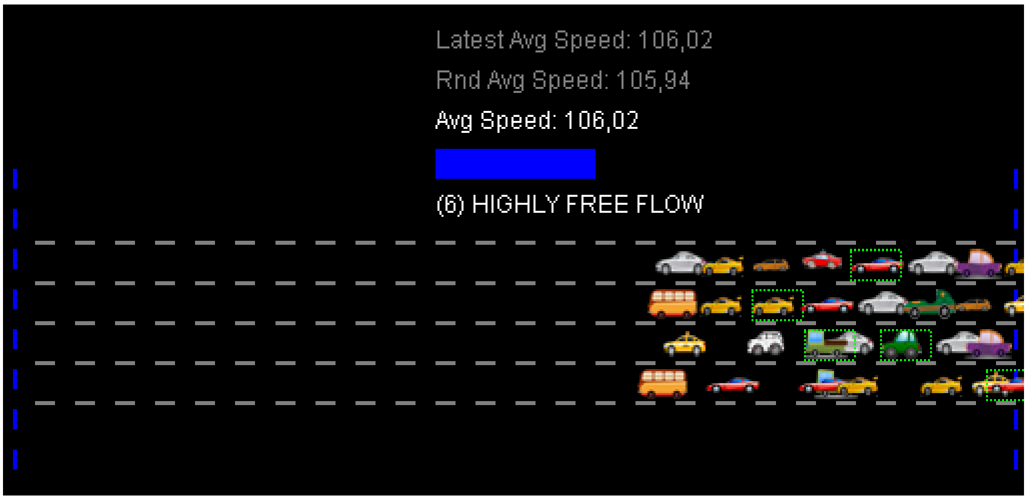


Source: Türk Telekom Technical Report, 2012; Extraction of Congestion Information and Dynamic Route Planning, May 2012.

The second section (the one on left hand side) is relatively freer in terms of traffic flow. This is mainly due to the accelerating vehicles in the second section. The traffic accident occurred before the half distance of the section length, hence there are fewer vehicles that are stopped compared to the first section. There are 19 vehicles that appear in the second section where 8 of them are stopped due to the traffic accident in the upper two lanes. Two of the vehicles among the stopped ones report their data to the central server. These are reporting zero km/h speed values and are stationary again as the other crashed vehicles that are mentioned before. On the other hand, only two of the moving vehicles report their vehicle data.

The average speed of all the vehicles in the section is 5.5 km/h and is marked with the congestion weight of (1) that stands for "HEAVYLY/HIGHLY CONGESTED" traffic. On the other hand, the average speed calculated for the vehicles that are reporting data to the server is 5 km/h. The average speed reported from the transmitting vehicles and calculated for the all vehicles in the section have a difference of 0.5 km/h which stands for an error rate of 10 percent.

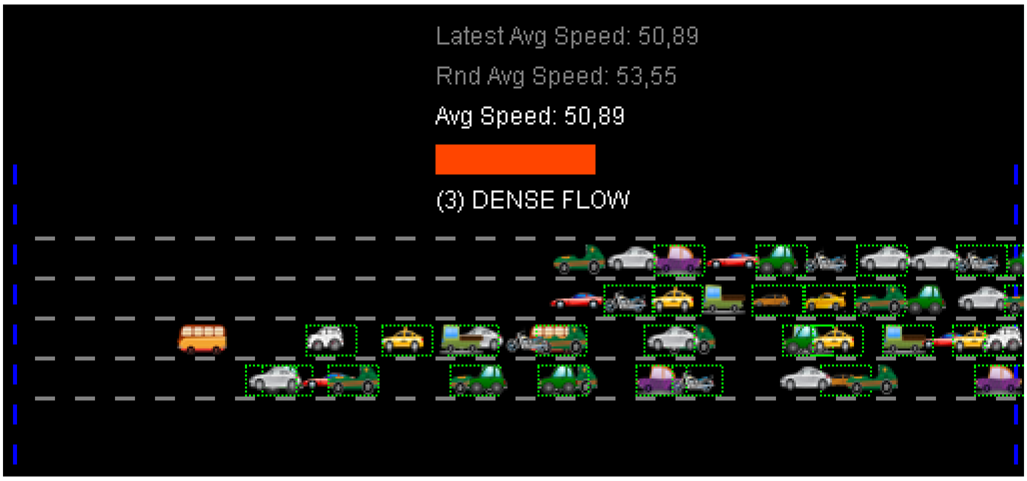
Figure 4.73: The situation before the traffic accident



Source: Türk Telekom Technical Report, 2012; Extraction of Congestion Information and Dynamic Route Planning, May 2012.

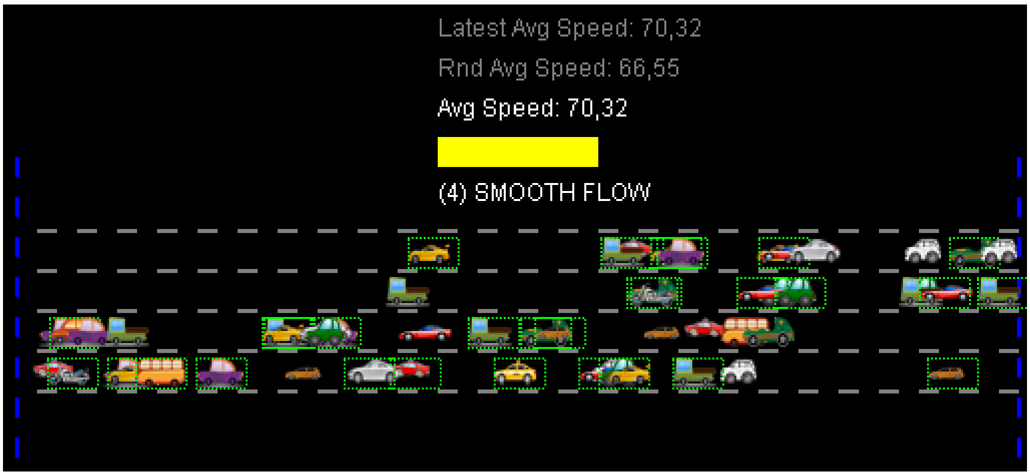
Lastly, we represent a traffic accident scenario (case 3) which is comprised of one section with 4 lanes. The case is visualized by Figure 4.73, Figure 4.74, Figure 4.75 that show the situation prior to the traffic accident, the situation at the moment the traffic crash occurs, and the situation when the section starts recovering from crash, respectively.

Figure 4.74: The situation right after the traffic accident occurs



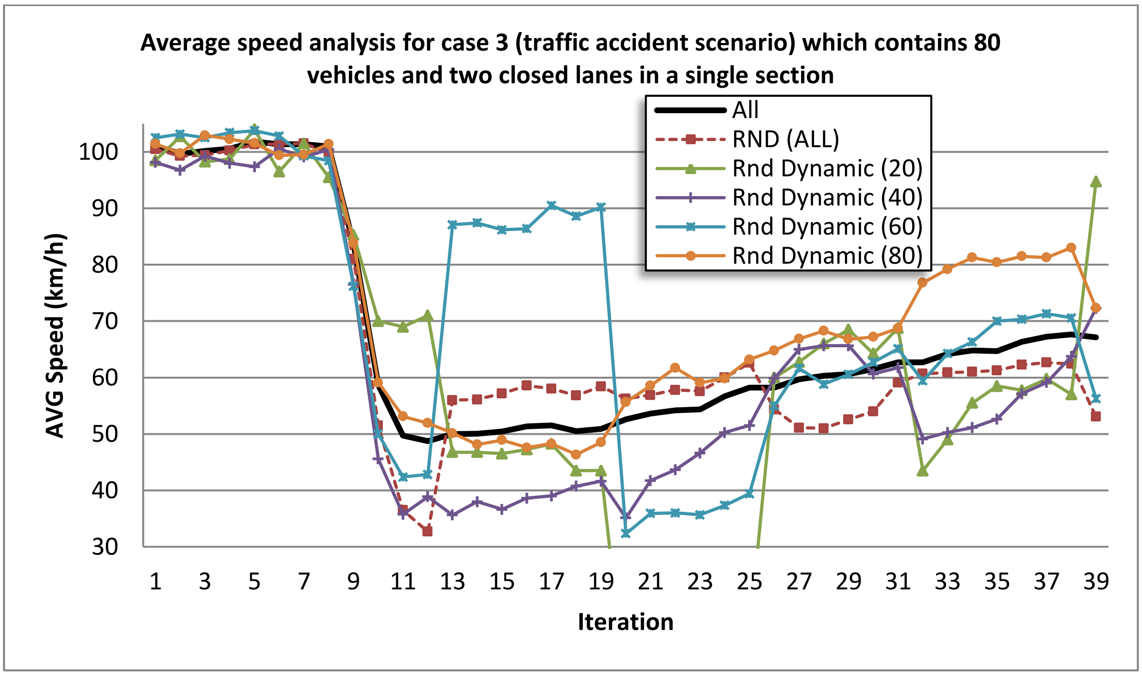
Source: Türk Telekom Technical Report, 2012; Extraction of Congestion Information and Dynamic Route Planning, May 2012.

Figure 4.75: After the crash is cleaned and the lanes are opened to traffic once again



Source: Türk Telekom Technical Report, 2012; Extraction of Congestion Information and Dynamic Route Planning, May 2012.

Figure 4.76: Average speed analysis for case 3 (traffic accident scenario) which contains 80 vehicles and two closed lanes in a single section



Source: Türk Telekom Technical Report, 2012; Extraction of Congestion Information and Dynamic Route Planning, May 2012.

Moreover, the case is analyzed in terms of average speed values in Figure 4.76. There are 80 vehicles in total in the scenario. The first two lanes (the upper lanes) are closed due to the crash occurred in the 8th iteration, as shown in the analyses depicted by Figure 4.76 (see Appendix A-3: Table 1 for the raw traffic data used to represent the traffic accident case). The crash causes almost half of the vehicles to stop in a few seconds. This time corresponds to three iterations as depicted in the analyses. From the 11th iteration to the 19th iteration, the upper two of the lanes are unusable because of the traffic accident. After a while the lanes are opened again, and hence the average speed of the section starts rising towards 70 km/h. However, it takes a while to fully recover from the traffic congestion caused by the crash on the upper lanes.

5. CONCLUSIONS

In intelligent / smart transportation systems (ITS) applications, it is crucial to provide and manage the flow of real time information. Corporations which serve their communication infrastructure for this purpose should consider the dynamic environment of traffic and also the spatio-temporal features of roads as well as the basic requirements of the wireless communication such as low latency, reliable transmission and security. Therefore, powerful communication infrastructure is required to assure optimum performance for all applications in the ITS field. Processing the large amounts of data from various types of sources without causing any delay or performance loss is a crucial task that should be handled by the network provider. However, existing communication infrastructures should be upgraded for reliable transmission of information by preventing any kinds of cyber-attacks that may be encountered.

Security of the data should be confirmed by telecom operators especially for the applications where the timing is critical and the fault tolerance is low such as in signaling systems in junctions. On the other hand, except the basic features of the communication network, different properties such as greater processing power and extensive data storage may be required in specific applications.

Although many projects have been carried out in the different fields of Smart Transportation; most of them are related with the traffic management. In early ITS applications; mobility has not been considered as a feature, hence, many applications that require costly hardware have been developed. On the other hand, in today's world, companies give much more attention to the mobility of their products so that different solutions such as mobile applications and publicly available web sites have been generated. The major disadvantage of using web-based services for traffic management is their low accuracy due to the long update time intervals.

For many years, transportation systems relied on infrastructure based equipment such as loop detectors and cameras. Although the accuracy rate of such systems is high, they cannot be deployed to the every segment on roads due to their high costs. Hence the trends in the smart transportation industry have been changed from infrastructure based systems to mobile systems and applications for increasing the reliability while reducing the cost.

Many applications have been launched to supply real time traffic information to the drivers but almost all of them have not taken into account of short-term predictions. Hence, traffic management applications should be developed by considering short-term predictions about the traffic congestion status on the roads to provide more reliable route planning features to their customers. The mobility of ITS solutions is considered as a crucial task in the development of such systems, hence many corporations and telecom operators have launched their own products based on the user's mobility.

5.1 PREDICTION SYSTEM CONCLUSIONS

Specifically, in this thesis we first of all surveyed the state of the art in smart transportation systems in chapter 2. We covered the numerous existing systems in the literature in great detail which are used in real-life scenarios. We noticed that several of these systems offered in the literature in order to provide real-time traffic status solutions and/or an advanced traveler information systems. We classified these systems in terms of the organization type that offers the solution. In light of this classification there are 5 different organizational categories. The first category consists of the solutions offered by top telecom companies such as china mobile, vodafone, verizon, etc. We provided a comparative table for this category. The second category is named as the solutions by municipalities. The third category is the solutions by corporations such as MSN Direct, Pioneer Information Systems, Sigalert, etc. Fourth category includes the solutions developed by universities. The most prominent university project was carried out by UC Berkeley called Mobile Millennium. The third and the fourth categories are given in a table for a brief comparison. Last category introduces the EU projects such as COOPERS, NOW and HAVEit which aims at providing comprehensive smart transportation solutions. We saw that although several of these solutions offer beneficial applications none of them provide a way to predict the short-term future traffic. Moreover, the research challenges vs. opportunities are reviewed as well as the communication technologies are discussed. Our studies showed that these technologies vary in terms of the technology used from conventional approaches to more specified vehicular communication approaches. We also reviewed literally a large number of simulation tools which were developed to be used in various aspects of Smart Transportation Systems.

Then we investigated the traffic theory background in detail throughout the chapter 3. We introduced meaning and the importance of several parameters which are common in all traffic applications such as density, flow, speed, gap, etc. The basic relationship between flow, density and velocity is given and its importance is stated. We also explored the mathematical traffic flow models that are widely mentioned in the traffic engineering discipline and are listed in two categories, namely Macroscopic and Microscopic traffic flow models. We described how the traffic flow models are classified in terms of level of detail, continuity, physical implementation and processes. We represented both models and their application domain in detail. The fundamental diagram which is a significant concept that is used in both macroscopic and microscopic levels of traffic flow is studied, as well. Its parameters and carrying out its calibration process are presented in great detail. We chose the macroscopic traffic flow models in our project because of their ability to cope with complex traffic phenomenon with the use of aggregate traffic variables such as average density, average speed and average flow. We investigated 4 types of macroscopic models, namely LWR, Payne, Papageorgiou and CTM. In the end, CTM (Cell Transmission Model) has turned out to be the most promising and suitable model to proceed with in our project due to its analytical simplicity, its good style in representing the roadway segments, and ability to reproduce congestion wave propagation dynamics.

We also described our efforts to construct and introduce a short-term prediction system in this thesis. We presented a simple yet effective simulation tool called CTMsim and modeled a portion of TEM freeway ranging from Kavacık to Maslak with it. Meanwhile, we discussed the rules which need to be considered during the segmentation process of the roadway. We also described how the colorization process of the segments is carried out. We mentioned about the several changes done on the tool and how it allowed us to introduce a mechanism to predict the short-term future traffic states. We showed our main difference from Berkeley method by introducing the development of new equations for the travel time calculation. We represented the fact that the ratio between densities of the successive sections has such an impact that cannot be underestimated on the travel time calculation, as well. Moreover, every component in the tool's user interface and their functionalities were introduced elaborately in chapter 3 as well as in the video disk provided by the thesis. In addition, we demonstrated two scenarios modeled in the simulation environment. We depicted a traffic accident scenario in roadway section number 10 and displayed its effects both visually and statistically in the area of influence. In addition to the accident scenario, we interpreted and portrayed the prediction of the traffic state fifteen minute ahead of time in the second scenario which resulted in a slight difference from the real-time calculation.

All of the tools and their source codes that took place in the development phase as well as the other resources such as intro video, workshop poster and the presentation documents are supplied together with this thesis.

5.2 REAL-TIME TRAFFIC SIMULATOR CONCLUSIONS

Traffic management has become a challenging task over years due to the increased number of vehicles on roads. Many studies have been carried out under the caption of Intelligent Transportation Systems (ITS), to come up with reliable, efficient and accurate solutions for traffic congestion that lead to the balanced distribution of vehicles along the roads according to the road capacities. These studies can be categorized as infrastructure based and mobile applications according to their data gathering methodologies. In early ITS systems, infrastructure based, dedicated equipment have been utilized for data gathering. However, deployment of such systems as data sources lead to high costs and requires consistent maintenance of equipment to avoid errors and malfunctions which occur frequently in radars, loop detectors and cameras.

With the recent advances in wireless communications and emergence of sensor-equipped smartphones, the trends in the smart transportation industry changed from infrastructure based systems to mobile data gathering devices in order to adapt to the dynamic environment of traffic and also the spatio-temporal features of roads while reducing the cost. In chapter 4, new ways of data gathering have been reviewed. Utilization of these data sources to overcome the limitations of infrastructure based systems has been introduced. These data sources have been classified as on-board and mobile where former one refers to an embedded hardware deployed on vehicles and the latter one is based on the utilization of smartphones for data gathering.

Under the caption of on-board data sources, Radio Frequency Identification (RFID) transponders, License Plate Recognition (LPR) systems, GPS devices have been investigated and compared according to their benefits and drawbacks. High accuracy rates that enable the possibility of using on board systems as traffic information probes to obtain traffic data, have been indicated as the advantage of the utilization of such systems. On the other hand, common limitations of such systems have been stated as their high deployment costs and low penetration rates on roads. In order to come up with a solution for these issues, new approaches based on the utilization of smartphones in vehicles for data gathering have been introduced. These smartphone based approaches have been classified as cellular positioning, GPS positioning and hybrid systems where the former one stands for gathering of location data from triangulation of cellular network signals, the middle one refers to usage of GPS sensors deployed on smartphones as a data source and finally the latter one refers to the combination of these technologies to provide more accurate positioning data while avoiding the battery drainage arised from GPS based positioning. Based on the comparisons, it has been concluded that mobile data gathering devices got an edge over others wih their high accuracy and low cost features, hence state-of-the-art in mobile traffic monitoring systems has been reviewed.

Extracting the congestion information from the raw data is the essential part of traffic management systems. However, data extraction phase has solid challenges such as the determination process of locations that are contained by successive segments. In chapter 4, wireless sensor network based analogy have been proposed to represent the dynamic nature of traffic and three methods based on dividing road segments into micro-grids have been proposed to overcome the challenging issues of data extraction. Formulations and performance results of methods have been presented. Furthermore, improvements on wireless sensor network analogy have been introduced to overcome issues that mostly occur when data cannot be obtained from some of the sensors.

In addition, the BAU Real Time Traffic Simulator has been introduced in chapter 4 for analyzing and testing the raw data obtained from our mobile application and demonstrating the analyses of each method under various real life scenarios. The classes of BAU Real Time Traffic Simulator and their distinct responsibilities together with their interaction have been presented throughout chapter 4, as well. Analyses of the simulation have been categorized into three categories as static, dynamic and multiple random dynamic analyses where former one requires fixed number of vehicles and continuous data transmission while latter ones randomize vehicle selection for data transmission dynamically throughout the simulation. Furthermore, simulation of three real life scenarios have been conducted to demonstrate our data extraction method results under normal traffic, free flow and traffic accident with lane closure cases respectively. The analyses of the simulations of these cases have been presented by snapshots and average velocity graphics.

The research also covered the investigation of data gathering and extraction methodologies to develop an accurate and effective dynamic route guidance system based on alternative route suggestion which plays an essential role on the prevention of traffic congestion. Dynamic route guidance applications balance the loads on roads by distributing vehicles based on the road capacities. Alternative routes have been suggested to the users of such systems for alleviating the congestion on roads. Hence, development of such systems for providing alternative route suggestions and modeling traffic conditions and incidents in real time play essential part in traffic management.

Concisely, in this thesis, new technologies for accurate and low cost data gathering have been investigated. State-of-the-art in smartphone based data acquisition has been reviewed. New methodologies have been proposed for extracting traffic congestion. Besides, system architecture and implementation of BAU Real Time Traffic Simulator have been introduced. Results and analyses of proposed methods have been illustrated in the simulator, and the use cases of TTraffic have been presented. The simulator results showed that the traffic status can monitored even when only a small portion of vehicles report their GPS data over the 3G network in anyway road section.

5.3 FUTURE WORK

The future work of the project may include several steps to be carried out. The first step may examine the validation of the developed prediction method in comparison to the Berkeley method and the real traffic data provided by *IBB Traffic Control Center*. It is expected to attain similar levels of performance for the prediction mechanism using the real data. Another step may be dedicated to extending the current roadway configuration, thus it will involve the major arterial roads of the city within the design. The last step is to carry out a case study of an important intersection in order to apply adaptive signaling methods using the traffic status results taken from the prediction mechanism, and hence increase the efficiency of the roads affected by the intersection.

In addition to the possible future work to be done for the prediction mechanism part, BAU Real-time Traffic simulator can be extended, modified, and improved to provide more user friendly interface, and ease of access to the configuration parameters. Specifically a file menu can be added and a comprehensive configuration screen can be implemented for generating new network setups. The mobile application TTraffic and the BAU Real-time Traffic Simulator can be fully integrated and the whole system can be totally automated. Lastly, new methods for the average speed calculations can be studied using the simulator.

The prediction mechanism gives promising results according to the evaluation of the system within itself. In other words, our prediction mechanism generates an output according to the time the user want to predict ahead into the future, and this is compared with the real traffic status output corresponding to the exact same time of the day the prediction is given for. Thus the comparison is carried out within the system itself. However we also need to evaluate the system using the real data that can be provided by *IBB Traffic Control Center*. The studies we have done so far will be compared right after the real data is acquired, and this will undoubtedly generate more satisfactory results for the verification and calibration phases of our methods.

The prediction system currently models only a tiny portion of the whole traffic system in the city, namely between *Kavacık* and *Maslak*. The system requires the modeling of remaining arterial roads, namely E5 and TEM, to make it a complete design. Our major goal for this step is to append the remaining arterial roads including the traffic for both directions. Specifically, we consider of improving the road network in such a way that it will encompass all the major arterials including both bridges represented just like in the map supplied by *IBB Traffic Control Center*. We will need the real data gathered by the traffic sensors in order to determine the parameters that are used during the segmentation of the road network and the configuration of each segment within the network. It is obvious that extending the roadway including the both directions is not a trivial task. This step will require a decent configuration period, an immense processing power and optimization processes for proper integration within the design.

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APPENDICES

Appendix A-1: Table 1. Simulator data for case 1 (normal traffic)

All 20 Vehicles	RND(20) Vehicles	Rnd Dynamic 20% of All	Rnd Dynamic 40% of All	Rnd Dynamic 60% of All	Rnd Dynamic 80% of All
21.8	24	35	15	23.33	31.5
17.8	14.5	31	13	20	23.5
19	8	41	14	23.33	21
27	23.5	40	25	35	30
24.4	18	40	17	34	22.5
26.4	25.5	32	21.5	34.33	25
22	28	22	16	11	16
25.6	26.33	18	12.5	14.33	12.5
20.8	21.33	17	10	12	10
23	28.67	27	14	12.67	14
18	26	30	17	12.67	17
19.6	28.33	33	19.5	15.67	19.5
21	20.33	41	24	24	17
17.6	18.33	34	19.5	19.5	14
16	16	44	22.5	22.5	11.67
15.2	17.33	42	23.5	23.5	8.33
16.2	14	37	24	24	13.67
16.8	15.67	29	24	24	13
15.4	0	16	23	16	19.67
11.8	0	10	9	11.33	10
9.6	0	1	7	10	8.67
10	0	7	1	5.67	9.33
13	0	8	13	8.67	13.67
11.4	0	4	12	10.67	14.67
12.8	0	10	22	11.67	15.67
10	7.67	13	17	12	13
12.6	9.33	24	18	13.67	13.67
17.2	13.67	20	18.5	19.33	16.67
16	11	30	20.5	17.67	16
20.4	16.67	39	21.5	18	15.67
21.2	19.33	50	22	18	16.33
35	6	2	20.5	20.5	14.75
37	8	4	31	31	16.25
37.29	5	1	27.5	27.5	13
52	10.67	5	35.5	35.5	11
52.14	5.33	7	30	30	4.67
52	7.33	4	36	36	10.33
54.71	8.67	2	39.5	39.5	8.67

Appendix A-2: Table 1. Simulator data for case 2 (free flow traffic)

All 20 Vehicles	RND(20) Vehicles	Rnd Dynamic 20% of All	Rnd Dynamic 40% of All	Rnd Dynamic 60% of All	Rnd Dynamic 80% of All
95.25	102.25	86.75	91.8	102	102.82
94.3	100	87.25	93.6	99.63	102
93.05	98.5	91.75	87.8	96.63	97.27
93.1	95.5	92	90	92.63	97.64
93.2	94.25	97.75	94.6	93.75	94
91.6	91.5	88.5	92.2	95.25	95.09
89	93.5	83.5	89.2	91.63	92.91
91.5	89.31	98.67	92.5	88.88	93.64
91.05	88.69	96.67	90.5	88	92.64
89.6	87.31	96	87.5	84.13	90.82
88.6	87.54	95	86.88	84.63	89.45
88.45	88.23	96.67	89.25	80.75	88.91
88.35	85.62	92.67	89.25	83.38	90.36
87	0	98.33	83.17	90.67	85.88
85.6	0	92.67	81.5	87.56	84.63
86.8	0	99.33	85	90.11	87.75
88.3	0	104.67	87	90.78	90.25
86.95	0	97	86	89	88.13
89.3	0	98.67	89	87.56	88.38
94.1	98.25	90.25	96.43	95.2	94.55
94.1	98.25	93.25	97.86	94.4	95.64
92.95	93.75	96.25	93.86	95.8	92.82
92.35	93.75	101.25	92.43	96.2	89.09
92.85	93.25	96.75	91.86	94.4	91.18
92	93.75	99	93.57	93.8	88.82
91.3	90	92.5	85.86	91.1	87.55
90.8	92.25	94.75	90.25	89.1	88.67
94.15	96.5	97.25	93.63	91.6	90.11
94.5	95.5	102	95.75	92.8	91.44
94.45	94.08	104.75	95.38	96.5	91
95.2	93.75	104.75	97.5	94.9	92.33
97.65	97.83	111.25	99.5	98.6	93.33
97.3	97.42	112.5	97.5	98.7	94.11
96.35	89.11	102.5	95.83	105.44	102
98.1	94.67	100.5	97.17	104.22	101.18
98.55	99.33	103.5	100.67	105.44	102.73
100.45	100.67	111.75	99.5	106.33	105.73
101.05	101.78	110.25	99.5	110.56	105.27

100.8	100	111.75	102.67	111.56	105.55
101.85	103.9	100.25	104.57	105	99.77
104.25	107	107	108.57	107.5	102.85
102	105.3	105.5	103	107.25	101.15
102.05	104.2	107.75	102.14	108	99.85
102.4	104.5	108.25	102.43	105.88	101.31
101.9	105.1	107	101.86	102.63	100.62
100.4	103.2	101.5	99.29	98.13	98.54
98.05	98.91	90.75	87.83	97.88	95.62
94.25	95	86.5	82.5	90.5	89.31
93.75	92.45	93	85.5	90	89.38
95.2	93.36	90	89.5	88.63	91.77
93.5	93.09	87.75	88.5	88.38	89.54
96.7	95.45	92.75	92.83	90.38	91
97.5	98.64	91	84.71	96.64	95.4
97.05	98.07	88.5	86.14	99.82	97.1
96.4	97.14	94	87.14	96.27	97.7
96.85	97.14	94.75	90.86	98.55	96.3

Appendix A-3: Table 1. Simulator data for case 3 (traffic accident)

All 80 Vehicles	RND(80) Vehicles	Rnd Dynamic 20% of All	Rnd Dynamic 40% of All	Rnd Dynamic 60% of All	Rnd Dynamic 80% of All
101.06	100.47	98.5	98.13	102.5	101.44
99.65	99.27	102.75	96.75	103.17	99.75
100.18	99.43	98.25	99.25	102.5	102.94
100.58	100.23	98.75	98	103.42	102.25
101.83	101.33	104	97.38	103.75	101.56
101.39	101.4	96.5	100.5	102.83	99.38
101.34	101.5	101.5	99.13	99.27	99.53
100.94	99.83	95.5	100.38	98.45	101.4
83.61	81	85.25	76.5	76.18	83.87
58.69	51.5	70	45.56	50	59.1
49.7	36.5	69	35.75	42.36	53.13
48.76	32.67	71	38.88	42.82	51.93
50.01	55.98	46.75	35.63	87.1	50.13
50.06	56.1	46.75	38	87.4	48.13
50.43	57.17	46.5	36.63	86.2	48.93
51.35	58.57	47.25	38.63	86.4	47.6
51.54	58.02	48.25	39	90.5	48.27
50.51	56.81	43.5	40.75	88.6	46.33
50.91	58.43	43.5	41.63	90.2	48.53
52.58	56.24	4	35.13	32.33	55.64
53.61	56.91	12.25	41.75	35.92	58.57
54.16	57.8	13	43.63	36	61.71
54.34	57.59	14.5	46.63	35.67	59.07
56.69	59.98	10.5	50.25	37.33	59.86
58.24	62.59	14.75	51.5	39.42	63.21
58.2	54.33	60	59.88	55	64.8
59.69	51.11	62.75	65	61.64	66.87
60.29	51	66	65.63	58.82	68.27
60.6	52.56	68.5	65.63	60.55	66.8
61.51	54	64.25	60.63	62.73	67.2
62.71	59.11	68.75	61.75	65.09	68.73
62.7	60.67	43.5	49.13	59.42	76.79
64.16	60.91	49	50.25	64.25	79.21
64.79	61	55.5	51.13	66.33	81.29
64.71	61.28	58.5	52.63	70	80.43
66.33	62.26	57.75	57.13	70.33	81.5
67.23	62.65	59.75	59.13	71.33	81.29
67.63	62.43	57	63.75	70.58	83