EVALUATION OF WORK ZONE MANAGEMENT STRATEGIES: THE FSM BRIDGE CASE STUDY

by

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ABSTRACT

EVALUATION OF WORK ZONE MANAGEMENT STRATEGIES: THE FSM BRIDGE CASE STUDY

Rising traffic congestion is an inevitable condition in large and growing metropolitan areas across the world. Traffic congestion has become one of the most famous term in the biggest problems of modern and civilized societies. Main reasons of traffic congestion are work zones, bottlenecks and incidents. Especially, work zones cause decrease in capacity of the roads which already serve at capacity. Work zones create 10% of the traffic congestion in the U.S. (FHWA, 2005) and 11% of the traffic congestion in Istanbul (Ergün and Şahin, 2006). Additionally, work zones cause bottlenecks and more incidents (GDH, 2012). Traffic analysis and knowledge gained from past experiences are necessary to effectively deal with congestion. Hence, the main goals of this study are (i) conducting comprehensive research on work zone management studies, traffic surveillance systems and data archiving in the world, the authorities responsible for the traffic management and ITS implementations in Istanbul, (ii) evaluating work zone management strategies used in the FSM Bridge case study, (iii) comparing the effectiveness of the implemented strategies before and after work zone management and (iv) providing future recommendations based on the evaluation results. To achieve these goals; change in traffic flow parameters, peak-hours, queues, vehicle types, alternative routes, the number of incidents, and the effects of toll policies, bottlenecks and the number of toll booths before and after work zone management are analyzed. With this thesis, it is aimed to provide the authorities responsible for the traffic management of Istanbul with the recommendations for developing solutions to the existing and similar future problems.

ÖZET

ÇALIŞMA ALANI TRAFİK YÖNETİM STRATEJİLERİNİN DEĞERLENDİRİLMESİ: FSM KÖPRÜSÜ DURUM ANALİZİ

Büyüyen trafik sorunu Dünya'da büyüyen ve gelişen metropoliten alanların getirdiği kaçınılmaz bir sonuçtur. Trafik sıkışıklığı, büyük şehirlerin ve çağdaş toplumların çözülmeyi bekleyen en büyük sorunlarından biri haline gelmiştir. Trafik sıkışıklığının ana nedenleri çalışma alanları (yol-bakım çalışmaları), darboğazlar ve kaza, araçların yolda kalması gibi olaylardır. Özellikle, yaşlanan yolların bakım çalışmaları, zaten tam kapasite hizmet veren yolların kapasitesinde daha da düşüşe neden olmaktadır. ABD'deki trafik sıkışıklığının %10'una (FHWA, 2005) ve İstanbul'daki trafik sıkışıklığının %11'ine yol bakım çalışmaları neden olmaktadır (Ergün ve Şahin, 2006). Buna ek olarak, yol bakım çalışmaları, darboğazlara ve daha fazla trafik olaylarına neden olmaktadır (GDH, 2012). Trafik sıkışıklığı ile başa çıkmak için trafik analizi ve geçmiş tecrübelerden yararlanmak gereklidir. Bu çalışmanın ana hedefleri (i) çalışma alanı trafik yönetimi çalışmaları, Dünya'da trafik izleme sistemleri ve veri arşivleme, İstanbul'da trafik yönetimi ve Akıllı Ulaşım Teknolojileri uygulamalarını kapsamlı bir şekilde incelemek, (ii) FSM Köprüsü 2012 bakım çalışmaları sırasında izlenen trafik yönetim stratejilerini değerlendirmek, (iii) uygulanan stratejilerinin etkisini ölçmek için bu kararlardan öncesi ve sonrası trafik durumunu karşılaştırmak ve (iv) trafik analizi sonuçlarına dayanarak gelecekte uygulanacak çalışma alanı trafik yönetim stratejileri için öneriler sunmaktır. Bu hedeflere ulaşmak için trafik akış parametreleri, zirve saatler, oluşan araç kuyrukları, araç sınıfları, alternatif güzergahlar, trafik olayları, gişe ücretleri, darboğaz ve gişelerin varlığının trafiğe etkisi analiz edilmiştir. Bu önerilerin, İstanbul trafiğinden sorumlu yetkililere mevcut ve gelecek benzer sorunlara çözüm geliştirmede yardımcı olması hedeflenmiştir.

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LIST OF SYMBOLS

c_k	Constant
d	Length of the Detector
k	Density
L	Length of Vehicle
m	Number of Passing Vehicles from a Point Over a Period of Time.
n	Number of Vehicles on Road Segment at an Instant Time.
v_i	Speed of the *i*th Vehicle
v_s	Average Space Mean Speed
v_t	Average Time Mean Speed

LIST OF ACRONYMS/ABBREVIATIONS

CCTV	Closed Circuit Television
DLM	Dynamic Lane Merge
DMS	Dynamic Message Signs
EDS	Electronic Detection System
ETC	Electronic Toll Collection
HAR	Highway Advisory Radio
HELP	Highway Emergency Lender Program
ITS	Intelligent Transportation Systems
FHWA	Federal Highway Administration
FSM	Fatih Sultan Mehmet
GDH	General Directorate of Highways
GDP	Gross Domestic Product
IMM	Istanbul Metropolitan Municipality
ISBAK Inc.	Istanbul Transportation Communication and Security Tech. Co.
LED	Light-Emitted Diode
NMSHTD	New Mexico State Highway and Transportation Department
RTMS	Remote Traffic Microwave Sensors
SMS	Space Mean Speed
TCC	Traffic Control Center
TMC	Traffic Management Center
TMP	Traffic Management Plan
TMS	Time Mean Speed
TSI	Turkey Statistical Institute
TTI	Texas Transportation Institute
US	United States of America
VMS	Variable Message Signs

1. INTRODUCTION

1.1. General

Rising traffic congestion is an inevitable condition in large and growing metropolitan areas across the world. Istanbul is an example of these metropolitan cities where traffic jam is holding the first place among all city problems for almost decades. Therefore, every second is valuable to find effective solutions to this problem. As the cities becoming larger the problem becomes more serious. For example, between 1980 and 1999 while the roads increased 1.5%, vehicle miles traveled increased by 76% in the USA (Federal Highway Administration, 2012).

Traffic congestion has become one of the biggest problems of modern and civilized societies. The congestion has grown substantially in all over the world. The congestion growth in the U.S. Cities between 1982 and 2002 is shown in Figure 1.1.

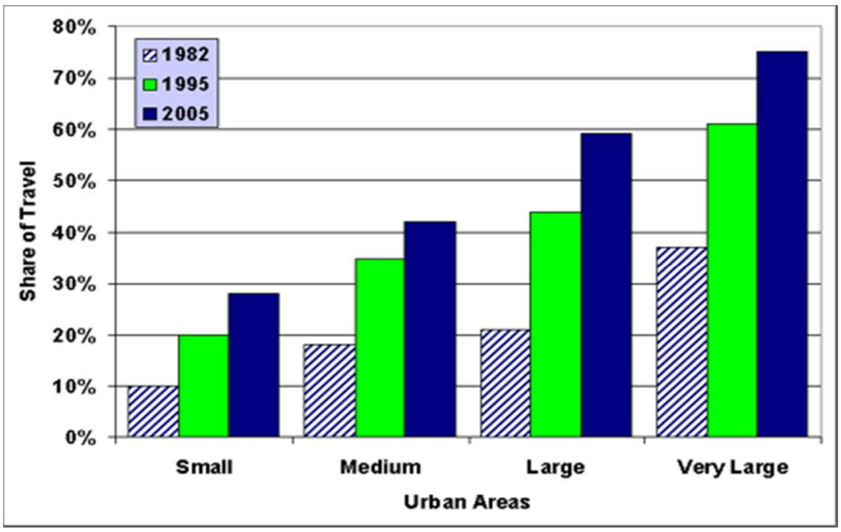

Figure 1.1. Congestion growth in the US cities between 1982-2002 (TTI, 2005).

Texas Transportation Institute (2005) showed that the traffic congestion in cities of all sizes from small to very large is increasing dramatically. The large cities are the most congested ones compared to small cities but nonetheless congestion is a growing problem in every size of cities.

Traffic congestion is widely known as an excess of vehicles on a section of roadway at a particular time that causes average speed to get slower than normal or “free flow” speed. Congestion is also characterized as longer travel times and increased vehicular queues. Congestion often known as stop-and-go traffic or completely stopped traffic. Federal Highway Administration (FHWA) defines congestion as

> *“Congestion results when traffic demand approaches or exceeds the available capacity of the system. While this is a simple concept, it is not constant. Traffic demands vary significantly depending on the season of the year, the day of the week, and even the time of day. Also, the capacity, often mistaken as constant, can change because of weather, work zones, traffic incidents, or other non-recurring events” (FHWA, 2012).*

Traffic Congestion is caused from many reasons. The research has been made by FHWA (2005) showed the possible causes of congestion in the U.S. (Figure 1.2). According to this research incidents and bottlenecks are the leading factor which causes congestion. Bad weather conditions and work zones also affect the traffic significantly. The other reasons of congestion are special events and poor signal timing.

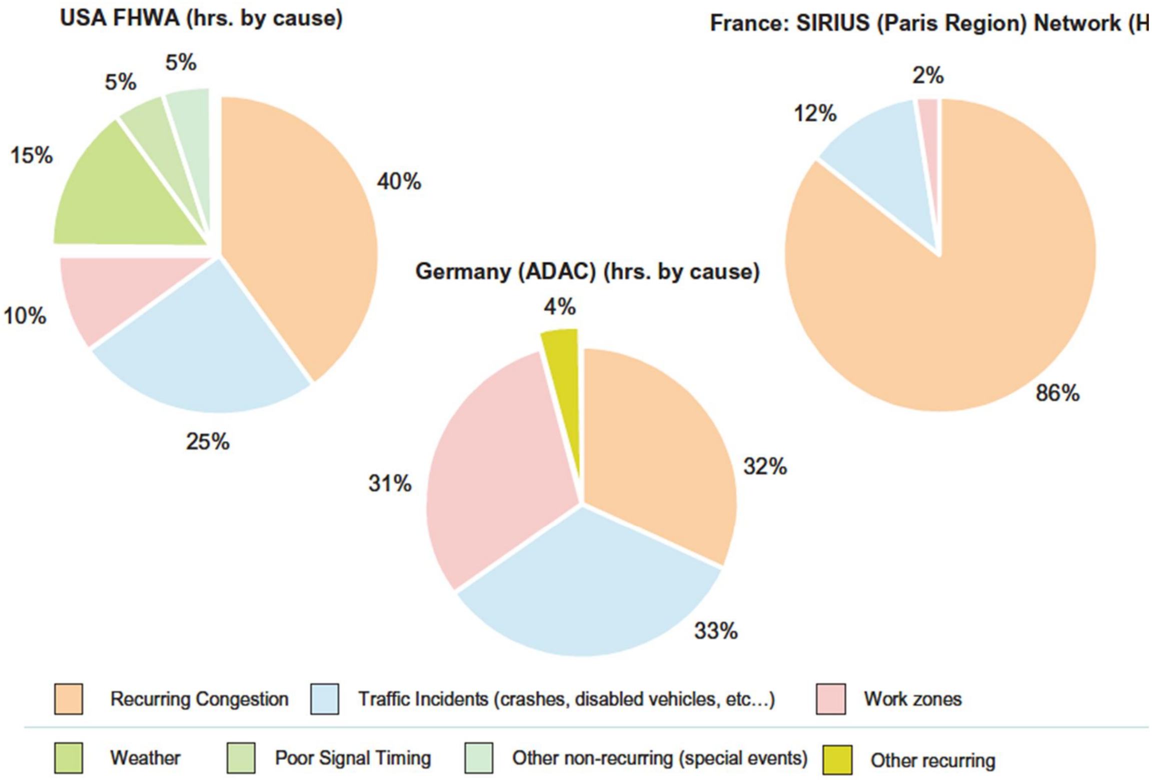

Figure 1.2.The sources of congestions (FHWA, 2005, ACEA, 2004, SIRIUS, 2004).

Traffic congestion results in consumption of national resources, loss of time, excess consumption, decrease in productivity and psychological exhaustion of citizens. According to the Urban Mobility Report of Texas Transportation Institute, in the year 2010, traffic congestion cost was 4.8 billion vehicle-hours of delay, 1.9 billion gallons of wasted fuel and approximately $101 billion decrease in productivity in 439 metropolitan cities (TTI, 2011). Japan's international co-operation agency claimed that because of congestion Bangkok loses one-third of its potential output (The Economist, 1998). Ergün and Şahin (2006) estimated that the cost of congestion in Istanbul is $3.12 billion per year by considering fuel and time consumption only. This means congestion cost of Istanbul is nearly 1% of the GDP of Turkey (Turkey Statistical Institute, 2012).

While traffic jams in usual is an important problem already, roads need reconstruction and repair which creates work zones. On the roads, which already carry traffic near capacity, work zones bring more traffic and make additional traffic jam. Unlike congestion in regular periods, non-recurrent events like work zones cause unexpected travel delays. Federal Highway Administration (2012) claimed that work zones in the U.S. cause more than 480 million vehicle hours delay. As a result, during road construction periods, traffic inevitably becomes more complex and harder to maintain *mobility* and *safety*.

Before starting a road construction project, a work zone traffic management plan is required more than usual. Work Zone Traffic Management Plan is use of program of operations at multi-faceted and multi- jurisdictional roads by communication and demand management in order to maintain acceptable level of traffic flow during the times of reconstruction and repair. After starting of a construction, work zone management strategies should be updated by analyzing real-time data. Intelligent Transportation Systems are used in road construction periods for collecting real-time data and observing the change in traffic conditions.

The term Intelligent Transportation Systems (ITS) is described as a method of combining information technology and other advanced methods of transportation engineering in order to solve transportation problems by involving technology, human perception, cognition and behavior, social economic and political systems (Leung *et al.*, 2011). Intelligent Transportation Systems (ITS) are widely used in work zones to cope with traffic congestion and safety of the work zone areas. ITS involve the use of electronics, computers and communication equipment to collect information, process it and take appropriate actions. ITS technologies can be applied in work zones for (FHWA, 2008b):

- Traffic monitoring and management
- Providing traveler information
- Incident management
- Enhancing safety of both the road user and worker

- Increasing capacity
- Enforcement
- Tracking and evaluation of contract incentives/disincentives (performance-based contracting)
- Work zone planning.

Many ITS applications in work zones serve a combination of the above purposes.

ITS technologies are used to monitor traffic conditions and to send this information to the drivers and agency personnel. *Benefits of ITS* is mainly collecting data, improving mobility, increasing safety and reducing costs.

ITS devices allow the agencies to collect speeds of the vehicles, occupancy, traffic flow, and types of vehicle data. These data are used to analyze the traffic and to archive for future traffic management plans.

ITS applications at work zones increase the mobility by providing traffic information to the drivers so that they can readjust their route and decrease the density at the roads where there is traffic congestion occurs. In this way travel times of the vehicles decreases. ITS also gives information to the agency personnel so they can control traffic by applying some measurements and send backups where needed.

ITS technologies also help to increase safety at work zones. ITS applications provide information to the key agency personnel so they can give the drivers advance notice of the existing work zones and associated traffic conditions such as slowed or stopped traffic ahead. Safety is measured in terms of the number and severity of vehicle crashes at the work zones.

In order to deal with traffic congestion, one needs to understand the reasons and use every necessary applicable tool to relieve traffic jams. In old metropolitan cities like Istanbul, one of the main reasons of traffic congestion may be the work zone and other related non-recurrent incidents. To be able to deal with maintenance and related traffic congestion, a well-thought-out work zone traffic management plan should be developed before construction using historical data from recent work zones. The management plan should be closely monitored and revised during the construction. ITS is a useful tool to collect data for traffic analysis, to inform and to guide the travelers about the upcoming work zone, incidents and traffic conditions. Data collection is crucially important for the future work zone management plans. In order to collect reliable and useful data; (a) traffic surveillance systems should be selected to satisfy the needs under local circumstances, (b) traffic surveillance devices should be placed based on a planned system, (c) traffic management authorities should be qualified enough to make traffic analysis so they can collect and archive all the needed data. After that, a professional traffic analysis team should be gathered to develop successful work zone management plans using the recorded historical data. In summary, in order to make a successful work zone management plan, the followings are needed:

- Professional traffic engineers; who have expanded literature knowledge of work zone management, ITS and traffic conditions of the city

- Effective traffic surveillance systems; selected by considering local circumstances and placed in a predefined system

- Well-collected reliable data acquired from past work zones; fulfilling all requirements for successful traffic analysis

- Past work zone management strategies

1.2. Goals and Objectives

The FSM Bridge case study is chosen for the analysis. A three-month maintenance project was started in 2012. Various work zone management strategies were implemented in this case study. Therefore, this case created an opportunity to observe the effects of various work zone management strategies.

Istanbul is a transcontinental city and it is divided by a strait. Only two bridges connect the roads of Istanbul over the strait. Therefore, these bridges carry huge traffic every day. The FSM Bridge carries approximately 240.000 vehicles per day (GDH, 2012). As a result, almost all city traffic is affected by an incident on these bridges.

The main goals of the study are (i) evaluating work zone management strategies used in Istanbul using the FSM Bridge case study, (ii) comparing the effectiveness of the implemented strategies before and after work zone management and (iii) providing future recommendations for work zone management implementations based on the evaluation results.

To achieve these goals the following objectives are set:

- Literature review on studies for work zone management,
- Conduct a research on traffic surveillance systems used on the highways of variable countries,
- Survey on the authorities responsible for traffic management in Istanbul and their responsibilities,
- Analyzing the work zone case study of FSM Bridge based on traffic flow theory,
- Collecting traffic flow data and project schedule for analyzing the case study,
- Evaluating the effects of work zone management strategies applied in the FSM Bridge case study,
- Discussing the results of the analysis,
- Present recommendations for traffic engineers responsible for traffic management of Istanbul and all over the world.

2. LITERATURE REVIEW

2.1.Traffic Flow Characteristics

Traffic flow is formed by individual drivers and their interaction with each other along with the physical conditions of the roadway. Traffic flow is a complex phenomenon because there is a big impact of human factor; hence traffic doesn't behave in the same manner (Roess *et al.*, 2004). However, some basic mathematical model structures are needed in order to supply demand, to design new roads, to maintain optimum traffic flow during recurrent and non-recurrent events, to analyze collected data from surveillance systems and to be used for so many other reasons (Papageorgiou *et al.*, 2006). Over the years a number of traffic stream models have been proposed (May, 1990). In this thesis, one of the most basic, fundamental and accepted traffic stream model, namely Greenshield's model is used to analyze the data.

Greenshield offered the first single-regime model in 1934, based on observing speed-density relationship which he concluded as linear (Naylor *et al.*, 1968). There are three macroscopic flow characteristics, namely flow (veh/hour), speed (km/hour) and density (veh/km). However, occupancy is used instead of density because density measurements cannot be obtained directly through traffic detectors. The fundamental graphs based on Greenshields´ model are given in Figures 2.1, 2.2, 2.3 and 2.4. These diagrams are used to determine the critical values –maximum flow rate, jam density, maximum density and free-flow speed. Flow vs. density relationship is shown in Figure 2.1.

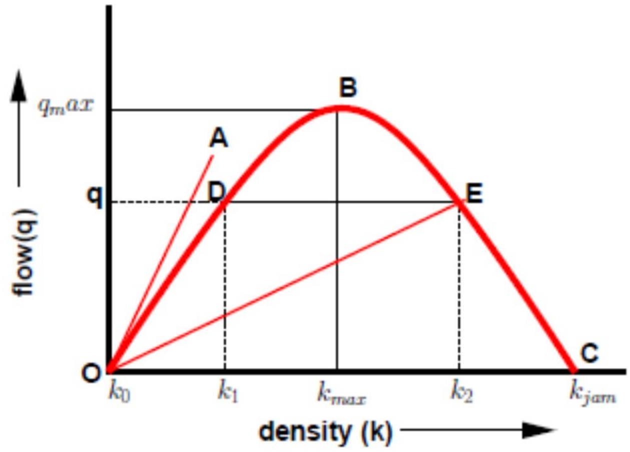

Figure 2.1. Flow vs. density curve (Mathew and Rao, 2006).

Using this diagram, maximum flow rate qmax, jam density kjam and maximum density kmax can be found. If one of the density values is known, then the corresponding flow rate can be measured using this diagram. The relationship between density and speed is presented in Figure 2.2.

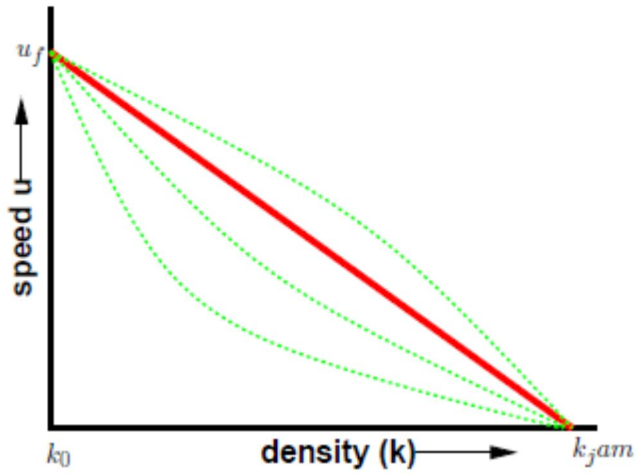

Figure 2.2. Speed vs. density diagram (Mathew and Rao, 2006).

There is a linear relationship between these parameters. The intersection points refer to jam density kjam and free-flow speed, uf. Flow rate vs. speed relationship is shown in Figure 2.3.

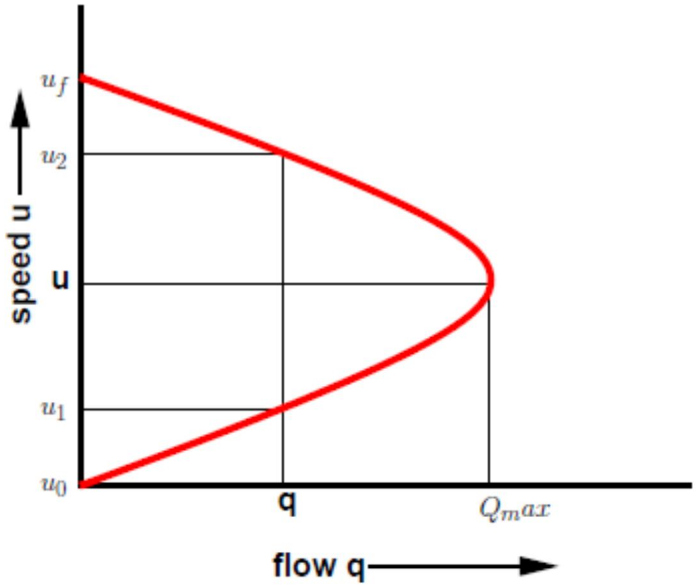

Figure 2.3. Speed vs. flow diagram (Mathew and Rao, 2006).

Maximum flow rate and free-flow speed can be found by using this graph. Maximum flow occurs when the average speed is half of the free-flow speed. Three fundamental graphs in Greenshield's model are presented in Figure 2.4.

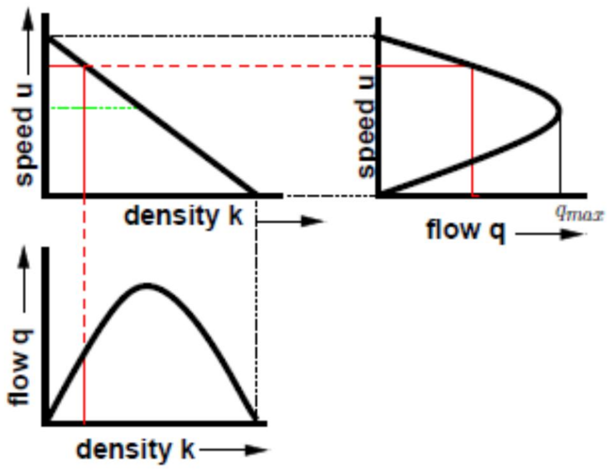

Figure 2.4. Fundamental diagram of traffic flow (Mathew and Rao, 2006).

These graphs are put together to illustrate the relation between the flow rate, density and speed.

2.1.1. Speed

Speed is defined as distance covered per unit time. Its unit is kilometer per hour (*km/h*) or miles per hour (*mi/h*). In design phase average speed is taken into account. There are two methods for finding average speed namely time mean speed (TMS) and space mean speed (SMS) (Mathew and Rao, 2006).

Time mean speed is calculated at a reference point over a fixed period of time. In practice, the speeds of vehicles passing from inductive loops or toll booths are recorded. The average of these speeds gives TMS, shown in Equation 2.1.

$$v_t = \left(\frac{1}{m}\right)\sum_{i=1}^{m} v_i \,, \tag{2.1}$$

where m is number of passing vehicles from a point over a period of time, v_i is individual speed of ith vehicle and v_t is time mean speed.

Space mean speed is measured at a segment of roadway at an instant time. SMS is calculated using two aerial photos or video images of the road segment. The SMS equation is shown in equation (2.2).

$$v_s = n / \sum_{i=1}^{n} (1/v_i) \,, \tag{2.2}$$

where n is number of vehicles on road segment at an instant time, v_i is individual speed of ith vehicle and v_s is space mean speed.

Time mean speed is always greater than space mean speed.

2.1.2. Density

Density is defined as number of cars passing a roadway segment at an instant in time. Density is expressed as vehicles per kilometer (*veh/km*) or vehicles per miles (*veh/mi)*. In practice, density is measured from one aerial photo. Taking aerial photo is not an easy option to determine density, so it is found using empirical relationship between occupancy and density.

2.1.3. Flow Rate

Flow rate is defined as number of cars passing a reference point in a fixed period of time. Flow rate is generally expressed as vehicles per hour (*veh/h*). In practice, flow rate can be measured using various kinds of detectors such as remote traffic microwave sensors (RTMS), radars, inductive loops. Flow rate is one of the parameters included in the fundamental relationship. The fundamental relationship of traffic flow theory is presented in equation (2.3).

$$q = k \times v \,, \tag{2.3}$$

where q is flow rate (veh/h), k is density (veh/km) and v is space mean speed (km/h).

2.1.4. Occupancy

Occupancy is defined as the percent of time a detector is occupied by passing vehicles over total time period. Athol (1965) proposed that there is linear relationship between density and occupancy. This relationship is important because detectors cannot provide density measurements. Because of the direct relationship between density and occupancy, one can find approximate maximum flow rate using occupancy vs. flow diagram instead of density vs. flow diagram. Athol (1965) described the relationship between density and occupancy as:

(2.4)

occupancy = average lengths of vehicles x density ,

where unit of occupancy is a ratio, unit of average lengths of vehicles is kilometer and unit of density is kilometer per hour.

2.2. Traffic Surveillance

Data collection and reliability of these data may be the most important part of traffic analysis. Advanced traffic management applications are supported by real time traffic flow information. The data is also archived for future traffic management and transportation planning purposes. Real-time traffic flow, occupancy, speed and non-recurrent events can be observed by the municipality agencies or departments of transportation. These agencies provide the drivers with real-time traffic information, inform the emergency agencies about encountered incidents and collect data for future planning.

2.2.1. Traffic Surveillance Systems in the World

While the traffic volume is growing all around the world, traffic surveillance has become an inevitable part of the traffic management. In order to handle traffic congestion, real-time traffic and traffic management plans should be observed carefully. To achieve these goals, most of the governments ready to make large expense on traffic surveillance systems. While considering the gains that these systems provide, the expenses of establishing these systems are considerably small. Therefore, common traffic surveillance systems are used in almost every metropolitan city from all around the world.

Establishing traffic surveillance system to a city is not just about money. If an authority wants to establish traffic surveillance system to a city, at first the authority should define why they need the traffic surveillance system. After setting the goals, the second step is to determine a suitable traffic surveillance system type which fulfills the goals in their budget range. One of the key points of establishing traffic surveillance system is to determine the most suitable places for surveillance devices. Even with the most expensive and high technology devices, poor choice of placement may lead to failure of goals of traffic surveillance system.

Since 1990s, traffic surveillance systems such as inductive loops, RTMSs, radars etc. have been used all around the world. All devices have their advantages along with disadvantages. Authorities usually select combination of these devices to eliminate loss of data caused by the disadvantages of one device. A summary of the traffic surveillance devices used in the highways of the world is shown in Table 2.1.

Along with real-time traffic surveillance purposes, traffic surveillance devices are also used to collect traffic flow data. These data are archived for better understanding the nature of traffic and preparing more effective traffic management plans in the future. Especially, in work zones, traffic flow is affected by many factors that make nearly impossible to estimate traffic conditions with analytical methods. Hence, for preparing work zone traffic management plan, archiving the essential traffic flow data is crucially important. Professional traffic engineers should be responsible for archiving data. Poor choice of archived data type can create difficulties while creating traffic management plans in the future. Therefore, traffic engineers, who are responsible for archiving traffic data, should know which data is useful for traffic analysis applications. Usually, traffic management centers, traffic control centers and transportation departments are responsible for archiving traffic flow data. A summary of archived data types of the agencies around the world is presented in Table 2.2.

Table 2.1. Traffic surveillance systems used in the World.

Location	Country	Surveillance Devices	Advantages	Disadvantages	Collected Data
Istanbul	Turkey	Cameras	Real-time traffic surveillance, Good incident verification, Provides wide area detection, Electronic detection of violation of rules, Easy to install and relatively cheap	Limitation in bad weather and presence of bad air quality, Missing of data due to poor placement of cameras	Speed Occupancy Volume Travel Time Measuring
		Loop Detectors	Well-known mechanics, Large variety of application, Relatively more reliable data, Useful for vehicle classification, Good for data collection	Installation needs pavement cut, Maintenance and installation needs lane closures, Pavement degrading, Non-movable, Usually need of multiple detectors	Speed Occupancy Volume Vehicle Classification
		Microwave Radar Sensors	Generally insensitive to inclement weather, Direct measurement of speed, Multiple lane operation available	Some models cannot detect stopped vehicles, Antenna beam width and transmitted waveform must be suitable to the operation	Speed Occupancy Volume Vehicle Classification Queue Detection
		ESS (Environmental Sensor Stations)	Easy to install	Spot should be selected carefully	Temperature Humidity, Wind Rain - Snow
		Subsurface Detectors	Early detection of road conditions	Pavement cut for installation	Frozen road
Hokkaido	Japan	Cameras	Real-time traffic surveillance, Good incident verification, Provides wide area detection, Electronic detection of violation of rules, Easy to install and relatively cheap	Limitation in bad weather and presence of bad air quality, Missing of data due to poor placement of cameras	Speed Occupancy Volume Travel Time Measuring
		Microwave Radar Sensors	Generally insensitive to inclement weather, Direct measurement of speed, Multiple lane operation available	Some models cannot detect stopped vehicles, Antenna beam width and transmitted waveform must be suitable to the operation	Speed Occupancy Volume Vehicle Classification Queue Detection
		Ultrasonic Vehicle Detectors	Non-invasive Multiple lane operation available	Affected by weather conditions Large pulse repetition may degrade occupancy at high speeds	Speed Occupancy Volume
		Infrared Vehicle Detectors	Non-invasive Multiple lane operation available	Affected by weather conditions	Speed Occupancy Volume Classification Queue Length
		ESS (Environmental Sensor Stations)	Easy to install	Spot should be selected carefully	Temperature Humidity Wind-Rain - Snow
		Subsurface Detectors	Early detection of road conditions	Pavement cut for installation	Frozen road

Table 2.1. Traffic surveillance systems used in the World (cont.).

Location	Country	Surveillance Devices	Advantages	Disadvantages	Collected Data
States*	USA	Cameras	Real-time traffic surveillance, Good incident verification, Provides wide area detection, Electronic detection of violation of rules, Easy to install and relatively cheap	Limitation in bad weather and presence of bad air quality, Missing of data due to poor placement of cameras	Speed Occupancy Volume Travel Time Measuring
		Loop Detectors	Well-known mechanics, Large variety of application, Relatively more reliable data, Useful for vehicle classification, Good for data collection	Installation needs pavement cut, Maintenance and installation needs lane closures, Pavement degrading, Non-movable, Usually need of multiple detectors	Speed Occupancy Volume Vehicle Classification
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		Subsurface Detectors	Early detection of road conditions	Pavement cut for installation	Frozen road
Athens	Greece	Cameras	Real-time traffic surveillance, Good incident verification, Provides wide area detection, Electronic detection of violation of rules, Easy to install and relatively cheap	Limitation in bad weather and presence of bad air quality, Missing of data due to poor placement of cameras	Speed Occupancy Volume Travel Time Measuring
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Table 2.1. Traffic surveillance systems used in the World (cont.).

Location	Country	Surveillance Devices	Advantages	Disadvantages	Collected Data
Frankfurt	Germany	Cameras	Real-time traffic surveillance, Good incident verification, Provides wide area detection, Electronic detection of violation of rules, Easy to install and relatively cheap	Limitation in bad weather and presence of bad air quality, Missing of data due to poor placement of cameras	Speed Occupancy Volume Travel Time Measuring
		Loop Detectors	Well-known mechanics, Large variety of application, Relatively more reliable data, Useful for vehicle classification, Good for data collection	Installation needs pavement cut, Maintenance and installation needs lane closures, Pavement degrading, Non-movable, Usually need of multiple detectors	Speed Occupancy Volume Vehicle Classification
		Microwave Radar Sensors	Generally insensitive to inclement weather, Direct measurement of speed, Multiple lane operation available	Some models cannot detect stopped vehicles, Antenna beam width and transmitted waveform must be suitable to the operation	Speed Occupancy Volume Vehicle Classification Queue Detection
	Netherlands	Cameras	Real-time traffic surveillance, Good incident verification, Provides wide area detection, Electronic detection of violation of rules, Easy to install and relatively cheap	Limitation in bad weather and presence of bad air quality, Missing of data due to poor placement of cameras	Speed Occupancy Volume Travel Time Measuring
		Loop Detectors	Well-known mechanics, Large variety of application, Relatively more reliable data, Useful for vehicle classification, Good for data collection	Installation needs pavement cut, Maintenance and installation needs lane closures, Pavement degrading, Non-movable, Usually need of multiple detectors	Speed Occupancy Volume Vehicle Classification
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Table 2.1.Traffic surveillance systems used in the World (cont.).

Location	**Country**	**Surveillance Devices**	**Advantages**	**Disadvantages**	**Collected Data**
	U.K.	Cameras	Real-time traffic surveillance, Good incident verification, Provides wide area detection, Electronic detection of violation of rules, Easy to install and relatively cheap	Limitation in bad weather and presence of bad air quality, Missing of data due to poor placement of cameras	Speed Occupancy Volume Travel Time Measuring
		Loop Detectors	Well-known mechanics, Large variety of application, Relatively more reliable data, Useful for vehicle classification, Good for data collection	Installation needs pavement cut, Maintenance and installation needs lane closures, Pavement degrading, Non-movable, Usually need of multiple detectors	Speed Occupancy Volume Vehicle Classification
		Microwave Radar Sensors	Generally insensitive to inclement weather, Direct measurement of speed, Multiple lane operation available	Some models cannot detect stopped vehicles, Antenna beam width and transmitted waveform must be suitable to the operation	Speed Occupancy Volume Vehicle Classification Queue Detection
Copenhagen	Denmark	Cameras	Real-time traffic surveillance, Good incident verification, Provides wide area detection, Electronic detection of violation of rules, Easy to install and relatively cheap	Limitation in bad weather and presence of bad air quality, Missing of data due to poor placement of cameras	Speed Occupancy Volume Travel Time Measuring
		Loop Detectors	Well-known mechanics, Large variety of application, Relatively more reliable data, Useful for vehicle classification, Good for data collection	Installation needs pavement cut, Maintenance and installation needs lane closures, Pavement degrading, Non-movable, Usually need of multiple detectors	Speed Occupancy Volume Vehicle Classification
		Microwave Radar Sensors	Generally insensitive to inclement weather, Direct measurement of speed, Multiple lane operation available	Some models cannot detect stopped vehicles, Antenna beam width and transmitted waveform must be suitable to the operation	Speed Occupancy Volume Vehicle Classification Queue Detection
		ESS (Environmental Sensor Stations)	Easy to install	Spot should be selected carefully	Temperature Humidity, Wind Rain - Snow
	India	Manual Counting**			
		Cameras	Detection of violation	Personal are needed to watch	

*The U.S. States Deployment Statistics is given in Table 2.2

**No surveillance system is built so far because lane order cannot be achieved yet. (Sen and Raman, 2012)

Table 2.2. Archived data types in the World.

Agency Name	Location	Country	Volume	Speed	Occupancy	Classification	Travel Time	Weather	Video Surv.
Traffic Control Center	Istanbul	Turkey	YES	YES	YES	YES	NO	YES	NO
Traffic Management Center	Istanbul	Turkey	YES	YES	YES	YES	NO	YES	NO
Traffic Control Center	Hokkaido	Japan	YES	YES	YES	YES	YES	YES	N/A
Traffic Control Center	Athens	Greece	YES	YES	YES	YES	N/A	N/A	N/A
Traffic Control Center	Frankfurt	Germany	YES	YES	YES	YES	YES	N/A	N/A
Traffic Control Center		Netherland	YES	YES	YES	YES	N/A	N/A	N/A
Traffic Control Center		U.K.	YES	YES	YES	YES	N/A	N/A	N/A
Traffic Control Center	Copenhagen	Denmark	YES	YES	YES	YES	YES	YES	N/A
Center for Development of Advanced Computing		India	YES	NO	NO	NO	NO	NO	NO
Ohio Department of Transportation District 4	Akron, OH	USA	NO	NO	NO	NO	NO	NO	NO
Ohio Turnpike Commission	Akron, OH	USA	YES	NO	NO	YES	NO	YES	NO
New York State Department of Transportation	Albany-Schenectady-Troy, NY	USA	YES	YES	YES	NO	YES	NO	NO
New York State Thruway Authority	Albany-Schenectady-Troy, NY	USA	YES	YES	YES	NO	YES	NO	NO
New Mexico DOT	Albuquerque, NM	USA	YES	YES	YES	YES	NO	NO	NO
Pennsylvania Department of Transportation-Allentown	Allentown-Bethlehem-Easton, PA-NJ	USA	NO	NO	NO	NO	NO	NO	NO
Pennsylvania Turnpike Commission	Allentown-Bethlehem-Easton, PA-NJ	USA	YES	YES	YES	YES	NO	NO	NO
North Carolina DOT	Asheville, NC	USA	NO	NO	NO	NO	NO	NO	NO
Georgia Department of Transportation	Atlanta-Sandy Springs-Marietta, GA	USA	YES	YES	YES	YES	YES	NO	NO
Texas Department of Transportation Austin District	Austin-Round Rock, TX	USA	YES	YES	YES	YES	NO	YES	NO
Caltrans District 6	Bakersfield, CA	USA	YES	YES	NO	YES	NO	NO	NO
Maryland State Highway Administration	Baltimore-Towson, MD	USA	NO	NO	NO	NO	NO	NO	NO
Louisiana Department of Transportation	Baton Rouge, LA	USA	YES	YES	YES	YES	YES	NO	NO
Texas Department of Transportation	Beaumont-Port Arthur, TX	USA	NO	NO	NO	NO	NO	NO	NO
Washington State Department of Transportation	Bellingham, WA	USA	YES	YES	YES	YES	YES	YES	NO
Alabama Department of Transportation	Birmingham-Hoover, AL	USA	YES	YES	YES	YES	YES	NO	NO
Ada County Highway District	Boise City-Nampa, ID	USA	YES	YES	YES	YES	NO	NO	NO
Massachusetts Highway Department	Boston-Cambridge-Quincy, MA-NH	USA	YES	YES	NO	YES	NO	NO	NO
Sarasota/Manatee Metro Planning Organization	Bradenton-Sarasota-Venice, FL	USA	NO	NO	NO	NO	NO	NO	NO
Connecticut Department of Transportation(CT)	Bridgeport-Stamford-Norwalk, CT	USA	NO	NO	NO	NO	NO	NO	NO
New York State Department of Transportation	Buffalo-Niagara Falls, NY	USA	YES	YES	NO	NO	YES	YES	NO
New York State Thruway Authority	Buffalo-Niagara Falls, NY	USA	YES	YES	YES	NO	YES	NO	NO
Florida DOT	Cape Coral-Fort Myers, FL	USA	YES	YES	NO	NO	NO	NO	NO
Tennessee DOT	Chattanooga, TN-GA	USA	YES	YES	NO	NO	NO	NO	NO

Table 2.2. Archived data types in the World (cont.).

Agency Name	Location	Country	Volume	Speed	Occupancy	Classification	Travel Time	Weather	Video Surv.
Illinois Department of Transportation	Chicago-Naperville-Joliet, IL-IN-WI	USA	YES	YES	YES	YES	YES	NO	NO
Indiana Department of Transportation	Chicago-Naperville-Joliet, IL-IN-WI	USA	YES	YES	YES	YES	NO	NO	NO
ISTHA	Chicago-Naperville-Joliet, IL-IN-WI	USA	YES	YES	YES	YES	YES	NO	NO
Ohio Department of Transportation District 12	Cleveland-Elyria-Mentor, OH	USA	YES	YES	YES	YES	NO	YES	NO
Ohio Department of Transportation	Columbus, OH	USA	YES	YES	NO	NO	YES	YES	YES
Texas Department of Transportation Dallas District	Dallas-Fort Worth-Arlington, TX	USA	YES	YES	YES	YES	NO	NO	NO
Ohio Department of Transportation District 7	Dayton, OH	USA	NO	YES	NO	NO	YES	YES	YES
Florida DOT	Deltona-Daytona Beach-Ormond Beach, FL	USA	YES	YES	YES	YES	YES	NO	NO
Iowa DOT	Des Moines-West Des Moines, IA	USA	YES	YES	YES	YES	NO	NO	NO
Michigan Department of Transportation	Detroit-Warren-Livonia, MI	USA	YES	YES	YES	NO	NO	NO	NO
Texas Department of Transportation-El Paso District	El Paso, TX	USA	YES	YES	NO	YES	NO	NO	NO
Indiana DOT	Fort Wayne, IN	USA	NO	NO	NO	NO	NO	NO	NO
Caltrans District 6	Fresno, CA	USA	YES	YES	NO	YES	NO	NO	NO
Michigan Department of Transportation	Grand Rapids-Wyoming, MI	USA	YES	YES	YES	YES	NO	NO	NO
North Carolina Department of Transportation-Greensboro	Greensboro-High Point, NC	USA	NO	NO	NO	NO	NO	NO	NO
North Carolina DOT	Greenville, NC	USA	NO	NO	NO	NO	NO	NO	NO
Pennsylvania Department of Transportation	Harrisburg-Carlisle, PA	USA	YES	YES	NO	NO	NO	NO	NO
Pennsylvania Turnpike Commission	Harrisburg-Carlisle, PA	USA	YES	YES	YES	YES	NO	NO	NO
Connecticut Department of Transportation	Hartford-West Hartford-East Hartford, CT	USA	YES	YES	YES	NO	NO	NO	NO
Alabama DOT	Huntsville, AL	USA	NO	NO	NO	NO	NO	NO	NO
Florida Department of Transportation	Jacksonville, FL	USA	YES	YES	YES	NO	YES	YES	NO
Wisconsin Department of Transportation District 1	Janesville, WI	USA	NO	NO	NO	NO	NO	NO	NO
Tennessee Department of Transportation	Knoxville, TN	USA	YES	YES	NO	NO	NO	NO	NO
Pennsylvania DOT	Lancaster, PA	USA	YES	YES	NO	NO	NO	NO	NO
Nevada Department of Transportation	Las Vegas-Paradise, NV	USA	YES	YES	YES	YES	YES	NO	NO
Arkansas State Highway and Transportation Department	Little Rock-North Little Rock-Conway, AR	USA	NO	NO	NO	NO	NO	NO	NO
Caltrans District 12	Los Angeles-Long Beach-Santa Ana, CA	USA	NO	NO	NO	NO	NO	NO	NO
Los Angeles County	Los Angeles-Long Beach-Santa Ana, CA	USA	NO	NO	NO	NO	NO	NO	NO
Kentucky Transportation Cabinet, District 5	Louisville/Jefferson County, KY-IN	USA	YES	YES	YES	NO	NO	NO	NO

Table 2.2.Archived data types in the World (cont.).

Agency Name	Location	Country	Volume	Speed	Occupancy	Classification	Travel Time	Weather	Video Surv.
Texas DOT	McAllen-Edinburg-Mission, TX	USA	NO	NO	NO	NO	NO	NO	NO
Tennessee Department of Transportation	Memphis, TN-MS-AR	USA	YES	YES	NO	NO	NO	NO	NO
Florida DOT-District 6 - SunGuide Transportation Management Center	Miami-Fort Lauderdale-Pompano Beach, FL	USA	YES	YES	YES	NO	YES	NO	NO
Wisconsin Department of Transportation	Milwaukee-Waukesha-West Allis, WI	USA	YES	YES	YES	NO	NO	NO	NO
Minnesota Department of Transportation	Minneapolis-St. Paul-Bloomington, MN-WI	USA	YES	NO	YES	NO	NO	NO	NO
Caltrans	Modesto, CA	USA	YES	YES	YES	YES	NO	YES	NO
Alabama Department of Transportation Sixth Division	Montgomery, AL	USA	YES	YES	YES	YES	NO	NO	NO
Tennessee Department of Transportation	Nashville-Davidson--Murfreesboro, TN	USA	YES	YES	NO	NO	NO	NO	NO
Connecticut Department of Transportation	New Haven-Milford, CT	USA	NO	NO	NO	NO	NO	NO	NO
Greater New Orleans Expressway Commission	New Orleans-Metairie-Kenner, LA	USA	NO	NO	NO	NO	NO	NO	YES
Louisiana Department of Transportation - Crescent City Connection Division	New Orleans-Metairie-Kenner, LA	USA	YES	NO	YES	YES	NO	NO	NO
New Jersey Department of Transportation(NJ) Traffic Operations North	New York-Northern New Jersey-Long Island, NY-NJ-PA	USA	YES	YES	NO	NO	YES	NO	YES
New Jersey Turnpike Authority (Parkway)	New York-Northern New Jersey-Long Island, NY-NJ-PA	USA	YES	YES	YES	YES	NO	NO	NO
New Jersey Turnpike Authority(NJ) (Traffic Operations Center)	New York-Northern New Jersey-Long Island, NY-NJ-PA	USA	YES	NO	NO	NO	NO	YES	NO
New York State DOT-Long Island Region 10	New York-Northern New Jersey-Long Island, NY-NJ-PA	USA	YES	YES	YES	NO	YES	NO	NO
New York State DOT-Region 11	New York-Northern New Jersey-Long Island, NY-NJ-PA	USA	YES	YES	NO	YES	YES	YES	YES
New York State Thruway Authority	New York-Northern New Jersey-Long Island, NY-NJ-PA	USA	YES	YES	YES	NO	YES	NO	NO
Palisades Interstate Park Commission	New York-Northern New Jersey-Long Island, NY-NJ-PA	USA	NO	NO	NO	NO	NO	NO	NO
Port Authority of New York and New Jersey	New York-Northern New Jersey-Long Island, NY-NJ-PA	USA	YES	YES	YES	YES	YES	YES	NO
Transcom	New York-Northern New Jersey-Long Island, NY-NJ-PA	USA	NO	YES	NO	NO	YES	NO	NO

Table 2.2.Archived data types in the World (cont.).

Agency Name	Location	Country	Volume	Speed	Occupancy	Classification	Travel Time	Weather	Video Surv.
Connecticut DOT	Norwich-New London, CT	USA	NO	NO	NO	NO	NO	NO	NO
Oklahoma Department of Transportation	Oklahoma City, OK	USA	YES	YES	NO	NO	NO	NO	NO
Nebraska Department of Roads - District 2	Omaha-Council Bluffs, NE-IA	USA	NO	YES	NO	NO	NO	YES	NO
Florida Department of Transportation	Orlando-Kissimmee, FL	USA	YES	YES	YES	YES	YES	NO	NO
New Jersey DOT- Traffic Operations Center South	Philadelphia-Camden-Wilmington, PA-NJ-DE-MD	USA	NO	NO	NO	NO	NO	NO	NO
New Jersey Turnpike -Traffic Operations Center	Philadelphia-Camden-Wilmington, PA-NJ-DE-MD	USA	YES	NO	NO	NO	NO	YES	NO
Pennsylvania Department of Transportation District 6-0	Philadelphia-Camden-Wilmington, PA-NJ-DE-MD	USA	YES	YES	NO	NO	YES	NO	NO
Pennsylvania Turnpike Commission	Philadelphia-Camden-Wilmington, PA-NJ-DE-MD	USA	YES	YES	YES	YES	NO	NO	NO
South Jersey Transportation Authority/Atlantic City Expressway	Philadelphia-Camden-Wilmington, PA-NJ-DE-MD	USA	YES	NO	NO	YES	NO	NO	NO
Arizona DOT Statewide TOC	Phoenix-Mesa-Scottsdale, AZ	USA	YES	YES	YES	NO	YES	NO	NO
Pennsylvania DOT- Dist. 11 - Western Regional Traffic Management Center (Pittsburgh)	Pittsburgh, PA	USA	NO	NO	NO	NO	NO	NO	NO
Pennsylvania Turnpike Commission	Pittsburgh, PA	USA	YES	YES	YES	YES	NO	NO	NO
Oregon Department of Transportation	Portland-Vancouver-Beaverton, OR-WA	USA	YES	YES	YES	NO	NO	YES	NO
Rhode Island Department of Transportation	Providence-New Bedford-Fall River, RI-MA	USA	YES	YES	YES	YES	YES	NO	NO
Utah Department of Transportation Region 3	Provo-Orem, UT	USA	YES	YES	YES	YES	NO	NO	NO
North Carolina Department of Transportation	Raleigh-Cary, NC	USA	NO	NO	NO	NO	NO	NO	NO
Virginia DOT - Richmond Transportation Operations Center	Richmond, VA	USA	YES	YES	YES	YES	NO	NO	NO
Caltrans District 8	Riverside-San Bernardino-Ontario, CA	USA	YES	YES	YES	YES	YES	NO	NO
Virginia DOT	Roanoke, VA	USA	YES	YES	YES	YES	NO	YES	NO
New York State Department of Transportation	Rochester, NY	USA	YES	YES	YES	YES	YES	NO	NO
Caltrans District 3	Sacramento--Arden-Arcade--Roseville, CA	USA	YES	YES	YES	YES	YES	YES	NO
Utah Department of Transportation-Region 1	Salt Lake City, UT	USA	YES	YES	YES	YES	NO	NO	NO
Utah Department of Transportation-Region 2	Salt Lake City, UT	USA	YES	YES	YES	YES	NO	NO	NO

Table 2.2.Archived data types in the World (continued).

Agency Name	Location	Country	Volume	Speed	Occupancy	Classification	Travel Time	Weather	Video Surv.
Texas Department of Transportation - TransGuide Operations Center	San Antonio, TX	USA	YES	YES	YES	NO	NO	NO	NO
Caltrans District 11 Transportation Management Center	San Diego-Carlsbad-San Marcos, CA	USA	YES	YES	NO	NO	YES	NO	NO
Caltrans District 4	San Francisco-Oakland-Fremont, CA	USA	YES	YES	YES	YES	YES	NO	NO
Pennsylvania Department of Transportation	Scranton--Wilkes-Barre, PA	USA	NO	NO	NO	NO	NO	NO	NO
Pennsylvania Turnpike Commission	Scranton--Wilkes-Barre, PA	USA	YES	YES	YES	YES	NO	NO	NO
Washington State Department of Transportation Northwest Region	Seattle-Tacoma-Bellevue, WA	USA	YES	YES	YES	YES	YES	YES	NO
Washington State DOT - Olympic Region Traffic Management Center	Seattle-Tacoma-Bellevue, WA	USA	YES	YES	NO	YES	NO	NO	NO
Washington State Department of Transportation Eastern Region	Spokane, WA	USA	YES	YES	YES	YES	YES	NO	NO
Massachusetts Highway	Springfield, MA	USA	NO	NO	NO	NO	NO	NO	NO
Missouri DOT	Springfield, MO	USA	NO	NO	NO	NO	NO	NO	NO
Illinois Department of Transportation	St. Louis, MO-IL	USA	NO	NO	NO	NO	NO	NO	NO
Missouri Department of Transportation	St. Louis, MO-IL	USA	YES	YES	YES	YES	YES	NO	NO
Caltrans - Stockton	Stockton, CA	USA	YES	YES	YES	YES	NO	YES	NO
New York State Department of Transportation	Syracuse, NY	USA	YES	YES	YES	YES	NO	NO	NO
New York State Thruway Authority	Syracuse, NY	USA	YES	YES	YES	NO	YES	NO	NO
Florida Department of Transportation	Tampa-St. Petersburg-Clearwater, FL	USA	YES	YES	YES	NO	YES	NO	NO
Ohio Department of Transportation District 2	Toledo, OH	USA	NO	NO	NO	NO	NO	NO	NO
Arizona DOT	Tucson, AZ	USA	NO	NO	NO	NO	NO	NO	NO
Oklahoma Department of Transportation	Tulsa, OK	USA	YES	YES	NO	NO	NO	NO	NO
Virginia Department of Transportation	Virginia Beach-Norfolk-Newport News, VA-NC	USA	YES	YES	YES	YES	NO	YES	NO
District of Columbia Transportation Management Center	Washington-Arlington-Alexandria, DC-VA-MD-WV	USA	NO	NO	YES	YES	NO	NO	NO
Maryland State Highway Administration	Washington-Arlington-Alexandria, DC-VA-MD-WV	USA	NO	NO	NO	NO	NO	NO	NO
Virginia DOT - NRO Traffic Management Center	Washington-Arlington-Alexandria, DC-VA-MD-WV	USA	YES	YES	YES	NO	NO	NO	NO
Kansas Department of Transportation	Wichita, KS	USA	NO	NO	NO	NO	NO	NO	NO
North Carolina Department of Transportation-Winston-Salem	Winston-Salem, NC	USA	NO	NO	NO	NO	NO	NO	NO
Ohio Department of Transportation-District 4	Youngstown-Warren-Boardman, OH-PA	USA	YES	YES	NO	YES	NO	NO	NO

2.2.2. Traffic Surveillance Systems in Istanbul

Various types of surveillance systems are used in Istanbul highways. These surveillance systems are namely RTMSs, doppler radars, cameras and loop detectors. General Directorate of Highways (GDH) and Traffic Control Center (TCC) are responsible for these systems. The types and numbers of the surveillance systems controlled by TCC are given in Table 2.3.

Table 2.3. The types and numbers of traffic surveillance systems contolled by TCC.

	Total	**Outside the Tunnels**	**In the Tunnels**
Surveillance Camera	670	430	240
RTMS	508	508	
TERRA	247	7	240
EDS (Total)	191		
EDS (Traffic Lights)	123		
EDS (Shoulders)	18		
EDS (Railways)	15		
EDS (Corridor Speed)	11		
EDS (Reverse Direction)	1		

*These values are valid as of January 2013

In highways, heavy traffic conditions make installation of the loop detectors very difficult, because lane closure is required for the installation and maintenance of loop detectors. On the other hand, there are loops at toll booths at the exits of each bridge in Istanbul. These loops are installed for determining amount of toll fee based on vehicle classification. These loops are also useful to collect flow rate data of the bridges for traffic flow analysis. GDH is responsible for operating and maintaining the bridges. The data acquired from toll booths are collected by Traffic Management Center (TMC). TMC is directed by GDH. This loop detector data also includes average vehicle speeds and occupancy measurements.

RTMS is the most widely used traffic detectors in Istanbul highways. RTMS is a true RADAR (Radio Detection and Ranging) device, specially designed for traffic surveillance applications. There are more than 500 RTMSs deployed in Istanbul. Most of these detectors are controlled by TCC. RTMSs are used to collect traffic flow data. Average speeds, occupancies, flow rates and types of the vehicles data are collected per lane every 2 minutes. RTMSs can collect data from 8 lanes in two directions at the same time. These data are archived in 2, 10, 30 and 60 minutes periods. They are not shared systematically; yet, they are provided for some of the research projects and Transportation Department of IMM if demanded.

These RTMSs are capable of measuring queue lengths; however, in order to measure queue lengths, RTMSs should be installed parallel to the road (Figure 2.5).

Figure 2.5. Queue Control Application with RTMS (EIS, 2003).

In Istanbul highways, RTMSs are placed vertical to the roads. TCC determines the locations of RTMSs. TCC also considers the availability of the possible deployment places. The criteria used for RTMS deployment is that the place should have at least 5 meter clearance from the road and there must be lane discipline at the road section.

12 million traffic data are collected in one month. However, reliability of flow rates and classifications data is significantly low. Some of the reasons for low reliability of flow rate data are change in the number of lanes, additional lane policy at the Bridges and lack of lane discipline.

TCC uses two models of RTMSs. The first model is bought between 2004 and 2006. This type of RTMSs is still being used; because they are of good quality and they need so little maintenance. The second model of RTMSs has a relatively new technology and they have been in use for the last few years. Despite the fact that the second model has a new technology, it does not provide reliable and continuous data. They are not resistant to Istanbul's weather conditions; therefore, they need calibration frequently and they stop providing data more than usual. They are also affected by bad air quality of Istanbul. For those reasons, TCC started to use image processing technology.

TCC deployed new image processing devices, namely TERRA, for traffic surveillance where the RTMSs cannot work efficiently. There are more than 240 TERRAs in Istanbul. These detectors are mostly located in the tunnels and other closed areas. RTMSs work with emitting microwaves. RTMSs cannot work in closed area because of reflection of microwaves. Therefore, TERRA devices are deployed at such places. These devices are very useful for collecting reliable traffic flow data. They can also detect presence of smoke, pedestrians and stopped vehicles. These detectors can even detect if a vehicle stops and throw a trash from the vehicle. TERRA detectors have dual-processors in them. They collect images from their cameras, process the image in the area and send the traffic flow data to TCC. In open areas, these detectors are affected by change in daylight and weather conditions; yet, they give more accurate data than RTMSs even in open areas. Another disadvantage of TERRA devices is their range. One TERRA detector can only read one lane; so for eight lanes, eight TERRAs are needed. They should be located over the road. Therefore, overhead gantries should be built. For that reasons TERRAs are much more expensive than RTMSs.

Traffic cameras are widely used in Istanbul highways. TCC and TMC are both observing real-time traffic using this technology. The real-time traffic information is used to inform drivers via VMSs, call centers, web sites and smart phone applications. TCC has 670 surveillance cameras located in Istanbul. TMC is controlling additional 20 cameras. These data are shared with the Disaster Coordination Center (AKOM) when there is a case of emergency. The names and locations of RTMSs in Istanbul are shown in Figure 2.6.

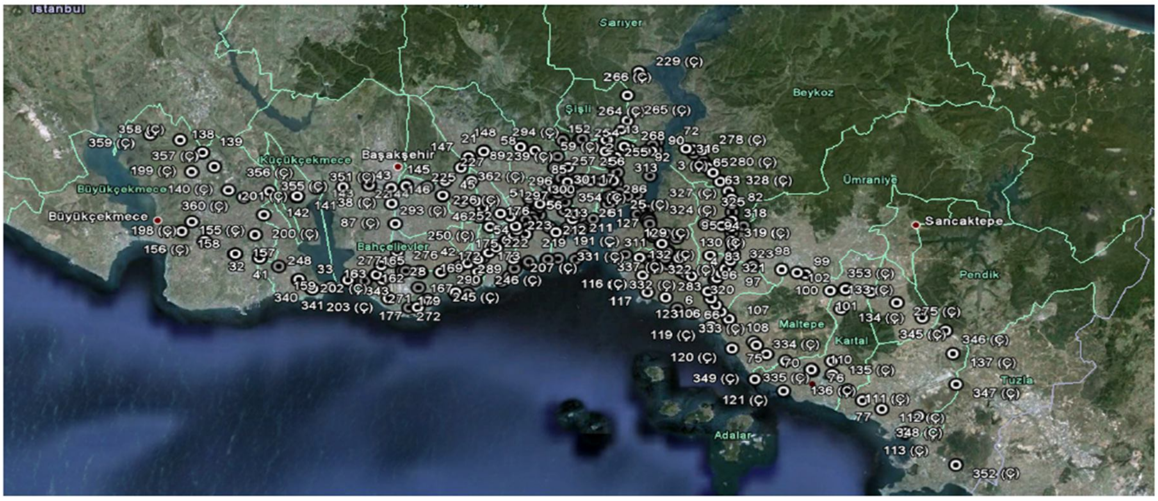

Figure 2.6. Locations of RTMSs in Istanbul (Google Earth, 2012).

More than 500 RTMSs are located in Istanbul in order to collect traffic flow data.

Doppler radar is another type of surveillance device used in Istanbul highways. These detectors measure speeds of the vehicles. However, they cannot detect stopped vehicles. Hence, these detectors are not useful for observing traffic flow conditions under congested traffic. The location of the traffic cameras are shown in Figure 2.7.

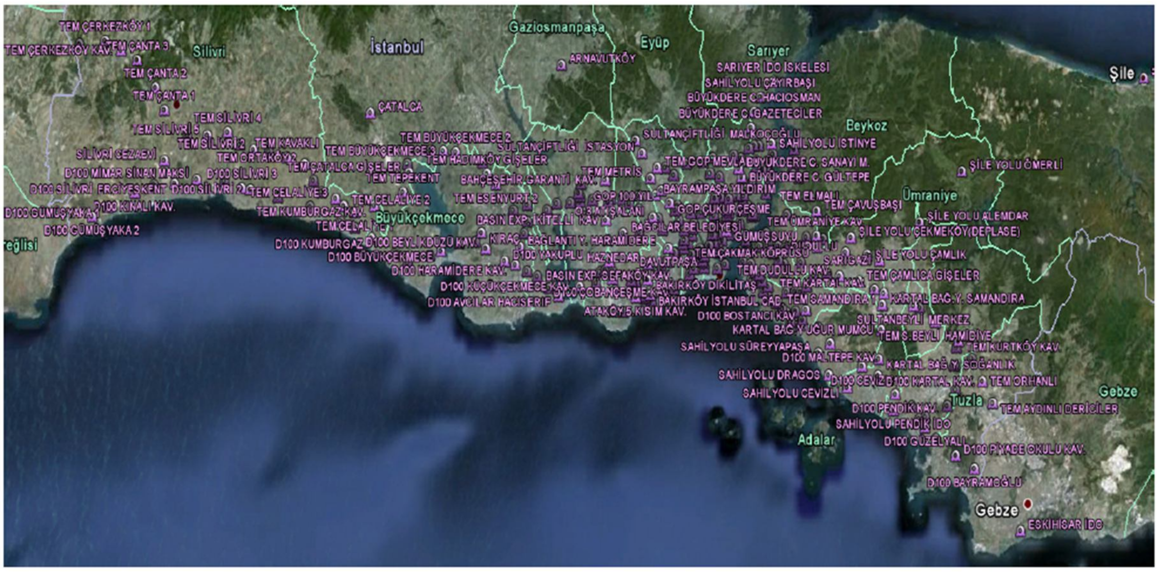

Figure 2.7. Location of the traffic cameras in Istanbul (Google Earth, 2012).

There are more than 200 traffic cameras in Istanbul.

Weather conditions and road surface conditions are observed by both TCC and TMC. There are 35 Environmental Sensor Stations (ESSs) in Istanbul. 10 of them provides only weather information, whereas 25 of them provides both road surface and weather information. These data are collected by TMC and TCC. TCC and TMC distribute these data to drivers. Early detection of frozen roads technology is used for timely preparation of disasters.

TCC tries to follow new technology solutions for Istanbul traffic. After TERRA devices, they are planning to start using Bluetooth technology devices in 2013. Before implementing new technologies; these devices are tested for a year and then, another year is spent with purchasing processes. TMC is supported by ASELSAN. ASELSAN established a traffic management server for TMC and responsible for technological developments of TMC.

2.2.3. Traffic Management Authorities in Istanbul

Istanbul is a metropolitan city experiencing traffic congestion for decades. Istanbul Metropolitan Municipality (IMM) founded an establishment, namely ISBAK Inc., in 1986 in order to develop traffic solution technologies. ISBAK Inc.'s objective is to develop solutions for traffic problem of Istanbul as well as other cities as. ISBAK Inc. aims to develop new technologies regarding Intelligent Transportation Systems, LED Applications and City Lighting Automation system. The main mission of ISBAK Inc. is claimed as follows:

> *" Supplying traffic signalization systems supervised by the control center, conducting traffic surveys and planning works, manufacturing equipment of signalization superstructure, "Junction Control Devices", supplying traffic signalization training and consultancy services, undertaking project analysis and feasibility works, and supplying traffic and system engineering services"* (ISBAK Inc., 2012).

In Istanbul, ITS technologies are implemented by Traffic Control Center (TCC) and Traffic Management Center (TMC). TCC (Figure 2.8) is an organization of Istanbul Metropolitan Municipality (IMM) and is responsible for roads in Istanbul, whereas TMC is directed by General Directorate of Highways (GDH) and is responsible only for state highway roadways (TCC, 2012, GDH, 2012).

Figure 2.8. Traffic control center in Istanbul (TCC, 2012).

The responsibilities of TCC and TMC are quite similar to each other. Their common responsibilities can be summarized as:

- Observing the city traffic,
- Analyzing and commenting on traffic flow data,
- Informing and guiding drivers, travelers and pedestrians.

In addition to these responsibilities, TCC is also responsible for;

- Determining the signal times to maintain uninterrupted traffic flow,
- Maintaining road signs and road lines.

TMC (Figure 2.9) is mainly focused on detecting traffic incidents. TMC personnel watch the traffic cameras 24/7. TMC is responsible for sending warning to the emergency response vehicles when an incident is detected on state highways. Additionally, TMC deployed underground heat detectors to provide the drivers with early notices of frozen roads via VMSs and mass media communication tools.

Figure 2.9. Traffic Management Center (TMC) located at the entrance of FSM Bridge (GDH, 2012).

ITS technologies applied by TCC are; traffic cameras, RTMSs, traffic density map, variable message signs (VMS), electronic detection systems (EDS), providing expected travel times, TCC web site (tkm.ibb.gov.tr) and smart phone applications, traffic systems and traffic software (TCC, 2012).

TMC of GDH is implementing ITS technologies similar to TCC. Traffic Management Software of the TCC is created by ASELSAN Inc. TMC has its own traffic cameras, VMSs, sub-road heat detectors, electronic toll collection systems and loop detectors at the entrance of both of the bridges of Istanbul (GDH, 2012).

Approximately 700 traffic cameras are directed by TCC and TMC. They are located in roadways of Istanbul to observe real-time traffic. Travelers are informed and guided using ITS technologies like VMSs. They are also informed via call centers about the alternate routes by TMC or TCC. Moreover, TCC adjust the timing of traffic lights based on these camera images with the help of signalization programs. These data are also used for traffic density maps, TCC web site, image processing and smart phone application, namely "*İBBCepTrafik*". Traffic Control Call Center and the Broadcast Room are guiding drivers based on these data. The images are also used for the emergency situations (TCC, 2012, GDH, 2012).

RTMSs are used by TCC in order to acquire traffic flow data. These sensors provide speed, number and type of vehicles, occupancy and queue length. These data are used in smart intersection systems for optimizing signal times automatically and detecting incidents via computer software (TCC, 2012).

Traffic density map is software developed for using the current road efficiently by serving real-time traffic information to drivers (Figure 2.10). Traffic density map can be accessed through the web-site of TCC. It doesn't require any software or plug-in to run. Traffic density map provides real-time density data, live camera views, incidents, warnings, traffic statistics of last one hour and weather conditions (TCC, 2012).

VMSs are implemented in Istanbul to inform drivers of incidents, density, weather and road conditions and to direct them to alternate routes (Figure 2.11). VMSs are controlled by both TCC and TMC with radio frequency (RF) communication technology.

Figure 2.10. A view of traffic density map (TCC, 2012).

Figure 2.11. A view of VMS in Istanbul (TCC, 2012).

Electronic Detection System (EDS) is managed by police department personal assigned at TCC. The main purpose of implementing EDS is to detect violation of red lights at the intersections and unnecessary use of shoulders. In this way, authorities have achieved decreasing the number of incidents, enhancing safety and diminishing the traffic congestion. The Police Department Traffic Inspection Branch Office is responsible for the violation penalties (TCC, 2012).

TCC and TMC both operate call centers for informing drivers. They direct the drivers to the roads where traffic condition is better and safer. They also inform the drivers about upcoming work zone and any other traffic incidents.

2.3.Work Zone Management

Most of the motor roadways are at a stage where repair is needed. Work zone traffic management is required to minimize traffic delays, to maintain safety, to complete construction in time and to provide un-interrupted traffic flow. In order to evaluate work zone management strategies, work zone capacity should be evaluated. Once the capacity is estimated, then work zone management strategies can be evaluated by revising case studies and engineering judgments. The studies of work zone management are summarized in this section.

2.3.1. Work Zone Management

Work zone traffic management strategies should consider project constraints, project schedule and stages, type of work zone and anticipated work zone impacts (FHWA, 2013). Road constructions bring economic burden to the cities along with traffic congestion. For dealing with traffic congestion caused by construction, some mathematical equations were evaluated; however the reliability of these equations was very low due to large number of factors affecting work zone traffic flow. Some computer models were also developed and this allows engineers to put more inputs to the models. In some of the work zone management studies, case base reasoning structures were proposed for work zone traffic management purposes. Case base reasoning models are based on traffic analysis data acquired from past work zone experiences. For success of the all models, traffic analysis of recent work zones is crucially important. When a work zone traffic management plan is evaluated, progress of the plan should be observed in real-time. ITS technologies are an effective and inalienable tool for work zone traffic management.

Beside from the construction costs, there are some additional negative impacts of poor work zone management strategies by considering economic perspective of view. Vidya *et al*. (2012) states that many work zones are not adequately designed resulting in delay and drastic speed reduction which increases vehicle operating costs and delay costs.

Carr (2000) proposed a system called the Construction Congestion Cost System (CO^3). CO^3 is an integrated set of tools in order to estimate the impact of traffic maintenance contract provisions on congestion, road user cost and construction cost. CO^3 is used to provide an acceptable balance between construction cost and congestion. CO^3 provides ability to model the common characteristics of work zones. Some of these characteristics are as follows; road capacity can vary from hour to hour as lanes close or open and work conditions changes. In addition to these variations traffic demands change accordingly such that drivers change their route to alternate roads. CO^3 allows designers to estimate traffic delay due to congestion as a function of demand and capacity. In addition, it also allows designers to estimate traffic cancellations and diversions as a function of traffic delay. By using these estimates; traffic delay, user cost impact, construction cost impact, integrated user cost and construction cost impact, period costs for contract provisions and traffic related contract payments can be calculated. The CO^3 is implemented in an Excel spreadsheet. The system was tested in several Michigan Department of Transportation projects. The output of the CO^3 system provides a detailed view of construction impact for each period and each day. By integrating traffic impacts and user costs with construction costs of alternative plans, the acceptable methods can be selected.

Building a work zone management strategy is very difficult because of the constant change in traffic conditions during constructions. Although there are some existing computer models used to estimate queue delay upstream of the work zone; these models do not provide accurate estimate of work zone capacity which has a significant factor to determine the congestion level and queue delays.

Martinelli and Xu (1996), Jiang (1999), Schonfeld and Chien (1999) and Chitturi *et al*. (2008) used deterministic queuing diagram due to reduced congestion for analytical analysis of traffic congestion impacts. These studies were based on reduction in work capacity and the impacts were calculated as a function of reduction in capacity. Hence, estimating work zone capacity reduction is crucially important in order to evaluate the models. However, there are too many factors affecting work zones which make hard to estimate an accurate work zone capacity.

Adeli and Jiang (2003) claimed that work zone capacity cannot be estimated by any mathematical function due to presence of large number of interacting variables. For that reason they suggest “a novel neuro-fuzzy freeway work zone capacity estimation model”. Seventeen different factors can be entered as inputs to the model. The model is put into test for six different states in the US and city of Toronto. The model gives relatively more accurate result than empirical equation because of considering large number of factors than equations, yet still its reliability should be checked in many different work zones.

Jiang and Adeli (2004) proposed an object oriented (OO) model in order to estimate work zone capacity and queue delay and length. The model provides three different types of output such that network training curve, hourly queue length curve and report output. Another research was done aiming to help engineers for creating work zone management plan by Karim and Adeli (2003). They proposed a case-based reasoning (CBR) model in order to evaluate traffic management strategies for work zones. A hierarchical object-oriented case model is developed to support CBR system. This model provides an intelligent decision-support tool to help traffic agencies with dealing work zone traffic management. CBR is a methodology of storing and retrieving knowledge of decision acquired from previous case experience and adapting this knowledge to the new problem in order to evaluate effective solutions (Leake, 1996, Maher and Pu, 1997).

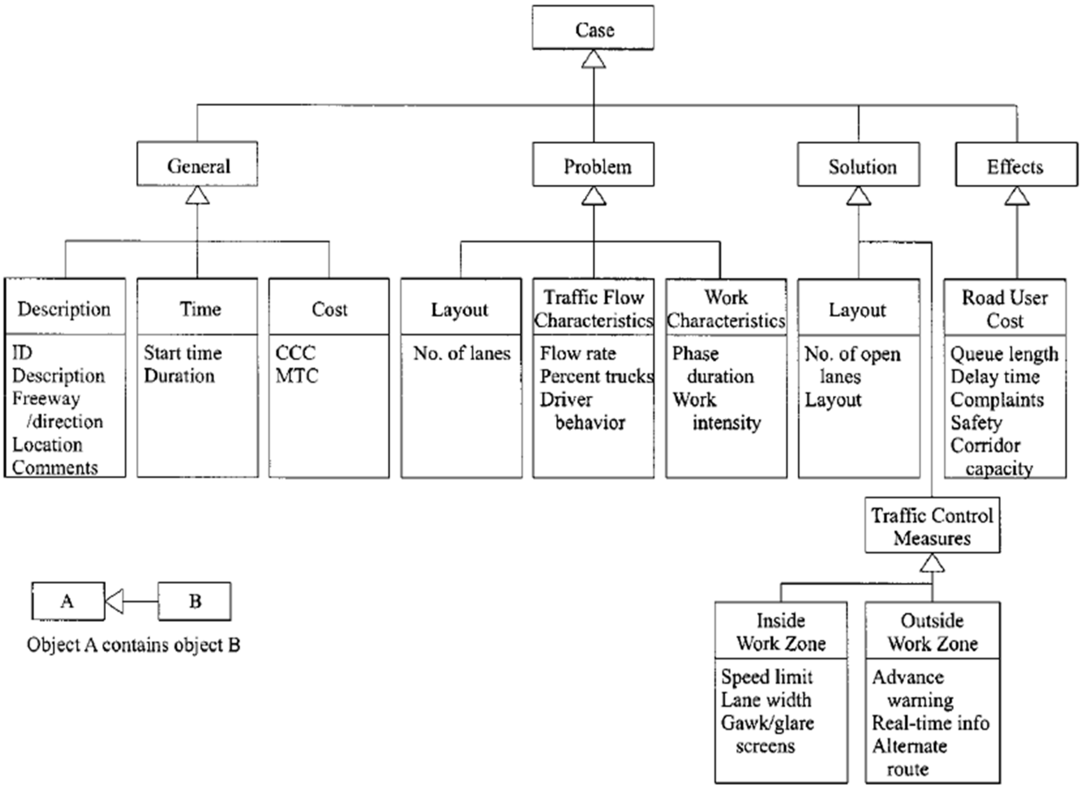

Figure 2.12. Object-oriented case model for CBR system (Karim and Adeli, 2003).

In order to evaluate an efficient work zone strategy, traffic analysis of recent work zones is crucial because (i) no accurate mathematical models for work zone traffic flow is available, (ii) there are finite number of cases to be considered and (iii) traffic agencies can use previously solved cases to find solutions to new problems (Karim and Adeli, 2003). Traffic analysis is needed for evaluating recent work zone management strategies and archiving the outcomes for future work zone traffic management plans. Edara and Cottrell (2006) states that at the design phase of work zone traffic management plan; a traffic analysis, which provides information in order to estimate queue lengths, travel times and delays, is required for determining lane closure times. Some of the performance measures for monitoring work zone traffic flow are volume, average speed of vehicles, travel times, queue lengths, delay, number of incidents, incident response and clearance times, community complaints, user costs and cumulative impacts from adjacent construction activities (FHWA, 2013).

Real-time traffic monitoring is important for work zone traffic management. Work zones create constantly changing conditions. Therefore, real-time traffic information is required for keeping travelers informed of upcoming traffic condition (Jackson, 2010). ITS technologies are used for real-time work zone traffic management by means of informing travelers and directing them to alternate routes. Using of ITS also helps with detecting an incident and ensuring an acceptable incident response time.

2.3.2. ITS Implementations in Work Zone Management: Case Studies from the U.S.

Analyzing the past work zone traffic flow data is useful for future work zone traffic management plans. For that reason, case studies of work zone traffic management plans play a key role in building successful traffic management plans for future work zones. ITS is used to collect traffic data and ITS helps traffic engineers with managing real-time work zone traffic. Federal Highway Administration of the US publishes studies on integrated work zone systems to demonstrate the results of some real-world experience of using ITS in work zones in the US (FHWA, 2002).

The goal of intelligent transportation systems (ITS) is to improve the effectiveness, efficiency, and safety of the transportation system (Bertini, 2005). Most of the roads, which need repair/maintenance, carry a lot of traffic during regular times. Eventually, road construction works continues almost all days of the week until end of the projects in order to finish the project faster. Construction works create uncertain traffic conditions and lane closure times may vary from time to time. Hence, traffic patterns can be changed regularly. Travelers should be provided with high quality real-time information on traffic route availability. Additionally, there would be incidents in the roadway such as crashes, cars running out of gas or flat tires. The incidents cause additional decrease in capacity, so demand for faster response increases. ITS technologies are useful in such situations in order to maintain road safety and mobility.

To better understanding of the role of ITS implementation in work zones, findings from 4 case studies from the US states between 2004 and 2007 will be summarized in this thesis. In these case studies the real-time information, delay monitoring system, delay merge system, dynamic merge system and work zone information system were implemented. Results of these implementations are presented in this section. Summary of these implementation and findings is given in Table 2.1.

The first case study is DC-295 in Washington, D.C. in 2006. District of Columbia Department of Transportation deployed an ITS on the Highway 295. Aim of the ITS system was to diminish congestion by providing real-time information to the drivers in the field and via a website. DMSs are used to inform the drivers with real-time delay and speed information based on predefined speed limits. Alternate routes were also recommended via DMSs. A study team is gathered for work zone traffic analysis. They calculated queues using detector spacing for time periods where speeds dropped below 30 miles per hour. Over 9 time periods were analyzed and the results compared with similar days of the week. 3% to 90% (average of 52%) reduction in mainline volume is observed. Thus, it is concluded that drivers listened to the recommendations which were transmitted via DMSs and the website (FHWA, 2008a).

The second case study is I-35 in Waco, Texas. The Texas Department of Transportation deployed an ITS in the work zone in 2006. The main purpose of the system was to give drivers real-time delay information in order to decrease the demand and direct the drivers to the alternate routes. The system includes six microwave sensors, six message boards, a central processing and communication unit and three CCTV cameras. Study team found that mainline traffic volume is decreased by 1%to 28% (average of 10%) during congested periods. However, the study team couldn't determine impacts of the diversion on mainline travel times; because the system had only two speed collecting sensors which are not enough for such analysis (FHWA, 2008a).

The third case study is US-131 in Kalamazoo, Michigan. The Michigan Department of Transportation deployed Dynamic Lane Merge (DLM) System in the work zone in 2004. The purpose of the DLM System was to merge the traffic early, to smooth traffic flow by reducing aggressive driving at the merge point. They place RTMSs and lighted signs that say “Left Lane Do Not Pass When Flashing”. They establish a closed loop system which is operated based on occupancy. For example, when sensor #1 detected the threshold occupancy, sensor #1 sent a message to sensor #2 alerting it to activate the flashing lights. The study team compared the time periods of flashing and not flashing. They observed that three times the number of dangerous merges and seven times the number of forced merges during periods where the flashers were off compared to the periods where flashes were on. In this way, it can be concluded that the use of ITS enhanced the safety performance of the highway during construction. On the other hand, travel times increased from 4 minutes to 7 minutes when the flashes were on (FHWA, 2008a).

The fourth case study is I-30 Little Rock to Benton, Arkansas. Arkansas Highway and Transportation Department started a construction project for widening the roads in 2004. Prior to beginning, there was an average of approximately 40 percent truck traffic during day-time and increasing to 75 percent at night. The large truck volumes may create large impacts on traffic in work zones. A smart work zone system with 47 vehicle detector sensors, 4 radio transmitters, 15 DMSs and 8 stationary video cameras mounted on trailers in and around the work zone. There was also flashing beacons on the HAR and the alert signs “Urgent when flashing, tune to 1490 AM”. Survey with 286 commercial vehicle drivers and 306 private vehicle drivers is done to evaluate the ITS system (FHWA, 2008a). The results of the survey are presented in Table 2.4.

Table 2.4. Key measures of the work zone case studies in the U.S.

Location	Type of System Used	System Objectives	Types of ITS Devices Used	Key Performance Measures	Benefits Based on Relative Change in Measures
District of Columbia System	Real Time Information	Provide delay and travel speed information, and reduce congestion by actively diverting traffic.	DMSs Network Cameras Traffic Sensors	Traffic Diversion, Queue Lengths	3% to 90% lower observed mainline volumes (with an average of 52%) over 9 observation periods by warning motorists prior to entering the mainline, compared with similar days of the week.
Texas	Delay Monitoring System	Provide delay information, and reduce demand and congestion by actively diverting traffic.	Microwave sensors DMSs CCTV Cameras	Traffic Diversion	1% to 28% reduction in mainline traffic volume (with an average of 10% reduction) over 20 observation periods where the system actively diverted traffic during congested periods, lessening the demand for restricted mainline capacity.
Michigan	Dynamic Merge System	Reduce aggressive driving and smooth traffic flow and reduce delay at merge point.	DLM System RTMS Cameras	Aggressive Maneuvers	Significant reduction in forced and dangerous merges when flashers were on (by a factor of 7 for forced merges, and a factor of 3 for dangerous merges), potentially reducing the risk of rear-end and side-swipe collisions near the merge taper.
		Reduce delay from aggressive passing at the merge area.		Travel Times	Increase in travel times (from an average of 4 minutes to 7 minutes) when lights were flashing due to slightly longer queues prior to merge.
Arkansas	Work Zone Information System	To improve traveler safety by providing real-time information to motorists.	Vehicle Detector Sensors Radio Transmitters DMSs Video Cameras	Survey Response to Safety-Related Questions	82% of surveyed drivers felt that the ITS system improved their ability to react to stopped or slow traffic. 49% of surveyed drivers agreed that they felt safer traveling through the work zone because of the electronic messages. 17% were neutral, 32% disagreed, and 2% did not answer.

Federal Highway Administration (FHWA, 2002) deduced some key strategies from the case studies as follows:

- It is too important to address communications issues early in the process. This is a trivial issue at the outset of a project that may evolve into intractable problem when deploying and operating the system.

- It is also important to allow start-up time when deploying a system. Operation sensors, communications (wireless), applying licenses, calibration or software take time to address.

- Using a proactive approach for building public awareness of the project. The information acquired from ITS systems in the work zones is also important. Municipality or departments should hold press conferences regularly and keep the local media up-to-date while project developments.

- Delivering accurate information to the public all the time has vital importance. Inaccurate information causes decrease in reliability of agencies which cannot be regained easily.

- It is important to create ITS management system of work zones which must include all the stakeholder agencies such as responsible for incident management.

- How to set up an automated information delivery system and to share with other agencies should be carefully considered. It is important to deliver too much information to the agencies and to process the system effectively.

ITS system functions in work zones can be summarized as (FHWA, 2002):

- Provides data on traffic conditions via traffic cameras
- Ability to operate the work zone continuously (7/24)
- Display messages to the travelers about detour routes and incidents.

- Allows to develop pre-set scenarios of DMS motorist information messages
- Provides current traffic condition information via internet using camera images and staff reports
- Enables direct communication between ITS staff and police station
- Provides traffic and construction reports to businesses, emergency service personnel and media via automated fax and e-mail system

As a result it can be said that ITS technologies in work zones in the US give satisfactory results. Application of ITS technologies such as mobile traffic monitoring, management, traveler information and incident management systems has showed that ITS is very useful in work zone management. These technologies provided beneficial information to the agencies and travelers. The real-time information helps with improving mobility and safety conditions while decreasing the costs. Many informed travelers use alternate routes so they decrease their travel times and help to reduce the congestion at the work zones.

The agencies collect and archive traffic flow data acquired from ITS devices. These data are essential for preparing work zone traffic management plans in the future. More data allow the agencies to find better solutions for work zone traffic management. Most of the ITS systems are kept after the end of construction period in order to maintain better traffic operations in regular times (FHWA, 2002).

3. CASE STUDY: THE FSM BRIDGE MAINTENANCE PROJECT

3.1. Overview of the Work Zone

Istanbul which is divided by a strait is a trans-continental city spread over Europe and Asia and. There are two bridges, namely Fatih Sultan Mehmet (FSM) Bridge and Boğaziçi Bridge, connecting the roads of both sides. A major periodic maintenance work FSM Bridge was undertaken during the summer of 2012. The project details for this maintenance work have been presented in the following section. Approximately two lanes were closed throughout the project. Some ITS technologies were implemented during the course of this project.

FSM Bridge is a part of Trans-European Motorway (TEM). There are 4 lanes in each direction. The bridge carries average of 120.000 vehicles per day in one direction (GDH, 2012). There were 21 toll booths at the European entrance of the bridge until 12th July 2012 (Figure 3.1). A maximum speed limit of 120 km/h and a minimum speed limit of 40 km/h are implemented. TEM is classified as a 'state highway'. Therefore, General Directorate of Highways (GDH) is responsible for TEM including roads on FSM Bridge.

Figure 3.1. FSM Bridge and the toll booths at the entrance of FSM Bridge (Milliyet, 2012).

FSM Bridge connects the continents Europe and Asia. Highway widens at the toll booths and then it merges in four lanes.

FSM Bridge needs maintenance every 10 years (GDH, 2012). One of these maintenance projects was started on 18th June 2012. The maintenance was completed on 22th August 2012. Traffic flow of TEM is observed via RTMSs.

3.2. Overview of FSM Bridge Maintenance Project

General Directorate of Highways (2012) states that FSM Bridge needs maintenance every 10 years. One of these maintenance projects was conducted in the summer of 2012.

This project included:

- Removing of existing asphalt layer,
- Isolating steel bridge deck against corrosion,
- Pavement of bridge floor with mastic asphalt.

Air conditions should be appropriate for galvanizing and pavement of asphalt processes. For galvanization, hot and humid-free environment is required. Pavement of mastic asphalt should be completed in day-time. In addition, all processes of the maintenance project require continuity. As a result, there were no actions at some parts of the construction; yet, lane closures were applied during the whole project.

3.3. Implemented Work Zone Management Strategies

After the beginning of the construction project, traffic congestion had become intolerable for the drivers. Therefore, IMM, governorship of Istanbul, Police Department and GDH were gathered in a crisis table at 11th July. They came up with several solution ideas. These decisions were implemented starting from 12th July. The decisions related to work zone traffic management were as follows;

(i) Number of toll booths were decreased from 21 to 11 in order to eliminate the effects of bottleneck;
(ii) Buses were allowed to pass Boğaziçi Bridge between the hours 12:00 AM-5:00 AM, which are normally not allowed to use;
(iii) Trucks were not allowed to pass FSM Bridge except 12:00 AM-5:00 AM,
(iv) A new ferry line was put into service between Küçüksu-İstinye to divert some drivers to this alternative.

Additionally, in order to eliminate the effect of bottleneck at the toll booths, government set the tolls free on 17th July. Using FSM Bridge was free until the end of the construction.

3.4. Input Data

FSM Bridge is a part of TEM highway. European side of TEM was analyzed for this study. Study area included the highway road section between Seyrantepe and FSM Bridge. RTMSs were used to collect traffic flow data in TEM. Loop detectors were also placed in toll booths to collect traffic flow data.

There are 7 RTMSs located between Seyrantepe and FSM Bridge observing Europe-Asia direction (Figure 3.2).

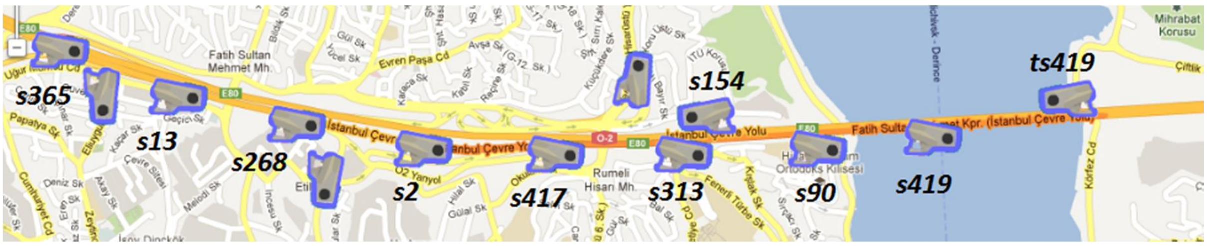

Figure 3.2. Locations of the RTMSs in TEM on map (TCC, 2012).

As can be seen in Figure 3.2, s313 sensor is located near toll booths. s90 is located after the toll booths; whereas, s417, s2 are located before toll booths. The locations of RTMSs and traffic flow directions of concerning RTMSs are given in Table 3.1.

Table 3.1. Locations and traffic flow directions of the RTMSs (TCC, 2012).

		Traffic Flow		
RTMS	**Location**	**From**	**To**	**Lane Count**
s90	FSM European Entrance	Karanfilköy	FSM Bridge	1
s313	FSM Toll Booths	FSM	Kavacık	1
s417	FSM Before Toll Booths	Levent Tem	FSM Toll Booths	2
s2	TEM Karanfilköy	Hasdal	FSM Bridge	4
s268	Levent TEM	Hasdal	FSM	3
s13	TEM Seyrantepe	Hasdal	FSM Bridge	1
s365	Seyrantepe	Hasdal	FSM	1

Locations of seven RTMSs used for analyses are presented in Table 3.1. All of these seven RTMSs are observing traffic flow from Europe to Asia. RTMSs in Istanbul are capable of measuring 8 lanes at the same time; however, these RTMSs do not measure all existing lanes probably due to change in number of lanes at the road section. The approximate distances among these RTMSs are summarized in Table 3.2.

Table 3.2. Distances between RTMSs located between Seyrantepe and FSM Bridge.

Distances (m)	**s90**	**s313**	**s417**	**s2**	**s13**	**s268**	**s365**
s90	-	700	1230	1870	2670	3470	5000
s313	700	-	530	1170	1970	2770	4300
s417	1230	530	-	640	1440	2240	3770
s2	1870	1170	640	-	800	1600	3130
s268	2670	1970	1440	800	-	800	1600
s13	3470	2770	2240	1600	800	-	1530
s365	5000	4300	3770	3130	1600	1530	-

From Table 3.2, it can be seen that RTMSs are, somewhat, randomly located. This is because of the availability of the appropriate places to deploy RTMSs. In order to deploy an RTMS, there should be at least 5 meter clearance at the side of the road (TCC, 2012). Further information about RTMSs is given in “Traffic Surveillance Systems in Istanbul” section (Section 2.2.2).

In this thesis, the RTMSs have been referred with their distance from s90, the last RTMS before FSM, such that s90 (0m), s313 (700m), s417 (1230m) and so on. For example, s2 (1870m) indicates that s2 is the RTMS located 1870 meters away from s90.

Traffic flow data acquired from RTMSs and loops at the toll booths. Toll booths provide flow rates and vehicle classifications. RTMSs provide average speeds, occupancies and flow rates data; however, reliability of the flow rate data taken from RTMSs are lower than that of loop detectors. Therefore, hourly flow rates from loop detectors; hourly average speeds and occupancies from RTMSs are used in this study. For s2 (1870m), s417 (1230m), s313 (700m), s90 (0m) sensors, flow rates and vehicle classifications are assumed to be the same as the data taken from toll booths; because, there are only one rarely used entrance and one rarely used exit. Samples of data taken from RTMSs and loop detectors are shown in Table 3.3, 3.4 and 3.5.

Table 3.3. A sample of RTMS data sheet (TCC, 2012).

month	day	hour	sensor	mSpeed	mOcc
6	1	0	303	82	5
6	1	1	303	89	2
6	1	2	303	97	1
6	1	3	303	99	0
6	1	4	303	102	0
6	1	5	303	96	1
6	1	6	303	85	4
6	1	7	303	16	49

In Table 3.3, month, day, hour, RTMS numbers, hourly average speeds and occupancy data are listed, respectively. Average speeds are given in kilometer per hour and occupancy is given in percent ratio. Hourly numbers of vehicles passing from the toll booths are shown in Table 3.4. Columns show days and rows show hours.

Daily number of vehicles and their classifications are taken from loop detector data sheet shown in Table 3.5. GDH measures 6 types of vehicles according to their axle number and axle space. "Type 0" in Table 3.5 refers to unidentified vehicles. These vehicles are not taken into account for this study.

Table 3.4. A sample of loop data sheet showing number of passing vehicles (GDH, 2012).

hour	**1.6**	**2.6**	**3.6**	**4.6**	**5.6**	**6.6**	**7.6**	**8.6**	**9.6**	**10.6**	**11.6**	**12.6**	**13.6**	**14.6**
00-01	2925	4337	5272	3955	2616	2854	3021	4265	4834	6007	4541	2839	3174	3543
01-02	1450	2208	2877	1725	1351	1512	1528	4254	2696	3854	2194	1715	1653	1777
02-03	855	1251	1486	829	758	886	887	1042	1456	1670	917	925	937	1029
03-04	610	915	940	541	560	581	642	675	995	1082	630	669	682	756
04-05	684	832	883	646	659	710	701	758	989	978	704	779	838	827
05-06	1274	1300	1057	1196	1332	1362	1275	1408	1583	1388	1407	1483	1463	1567
06-07	2637	2047	1763	2754	2711	2661	2630	2718	2373	1970	2957	2728	2655	2769
07-08	6847	3562	2537	6938	6718	6558	6833	6835	3735	2763	6049	6801	6795	6680
08-09	6400	4665	3206	6413	6288	4618	6109	6164	4805	3560	6389	6154	6207	6056
09-10	6605	5831	4427	5867	6565	7139	6100	6547	6323	4595	6086	6320	5852	6305

Table 3.5. A sample of loop data sheet showing classification of vehicles (GDH, 2012).

DATE	**TOTAL**							
	CLASS							**TOTAL**
	0	**1**	**2**	**3**	**4**	**5**	**6**	
01.06.2012	**2.581**	**98.507**	**20.485**	**4.469**	**5.670**	**91**	**388**	**132.191**
02.06.2012	**3.022**	**102.824**	**16.251**	**3.687**	**4.258**	**60**	**321**	**130.423**
03.06.2012	**2.641**	**98.146**	**10.597**	**1.503**	**1.869**	**50**	**318**	**115.124**
04.06.2012	**2.576**	**96.705**	**18.836**	**3.898**	**5.187**	**79**	**378**	**127.659**
05.06.2012	**2.683**	**97.903**	**19.674**	**4.456**	**5.651**	**75**	**423**	**130.865**
06.06.2012	**2.614**	**97.143**	**19.899**	**4.588**	**5.883**	**102**	**335**	**130.564**
07.06.2012	**2.745**	**97.239**	**19.696**	**4.355**	**5.628**	**75**	**361**	**130.099**
08.06.2012	**3.740**	**104.390**	**20.386**	**4.714**	**6.193**	**120**	**442**	**139.985**

After data collection, hourly flow rates, average speeds and occupancy data are used to fit these data into traffic flow models. Speed versus occupancy, flow rates versus occupancy and flow rates versus speed graphs of s90 are shown in Figure 3.3, 3.4 and 3.5, respectively. The speed versus occupancy and flow rates versus occupancy graphs of s2 (1870m), s417 (1230m) and s313 (700m) are provided in the Appendix A.

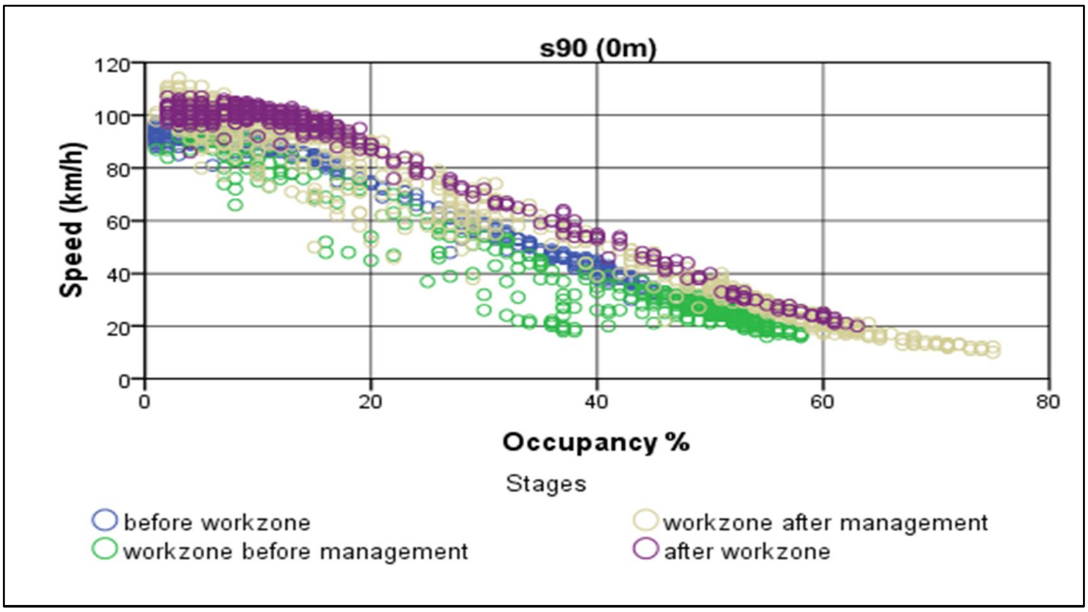

Figure 3.3. Speed versus occupancy graph of s90 (0m).

From Figure 3.3, a nearly linear relationship between speed and occupancy is observed. Free-flow speed and maximum occupancy can be determined using the intersections of the axes and fitting lines show, respectively.

There seems to be a quadratic relationship between flow rates and occupancy data, as shown Figure 3.4. Maximum flow rate can be determined by taking derivative of quadratic fitting lines. Intersection of the fitting lines and occupancy axes give jam occupancy values.

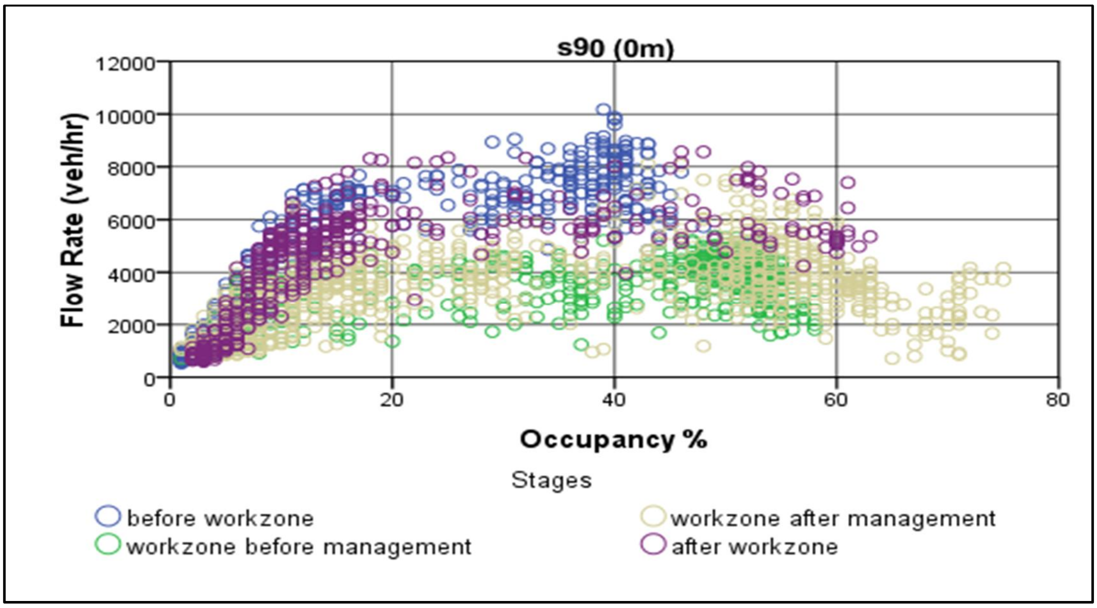

Figure 3.4. Flow rate versus occupancy graph of s90 (0m).

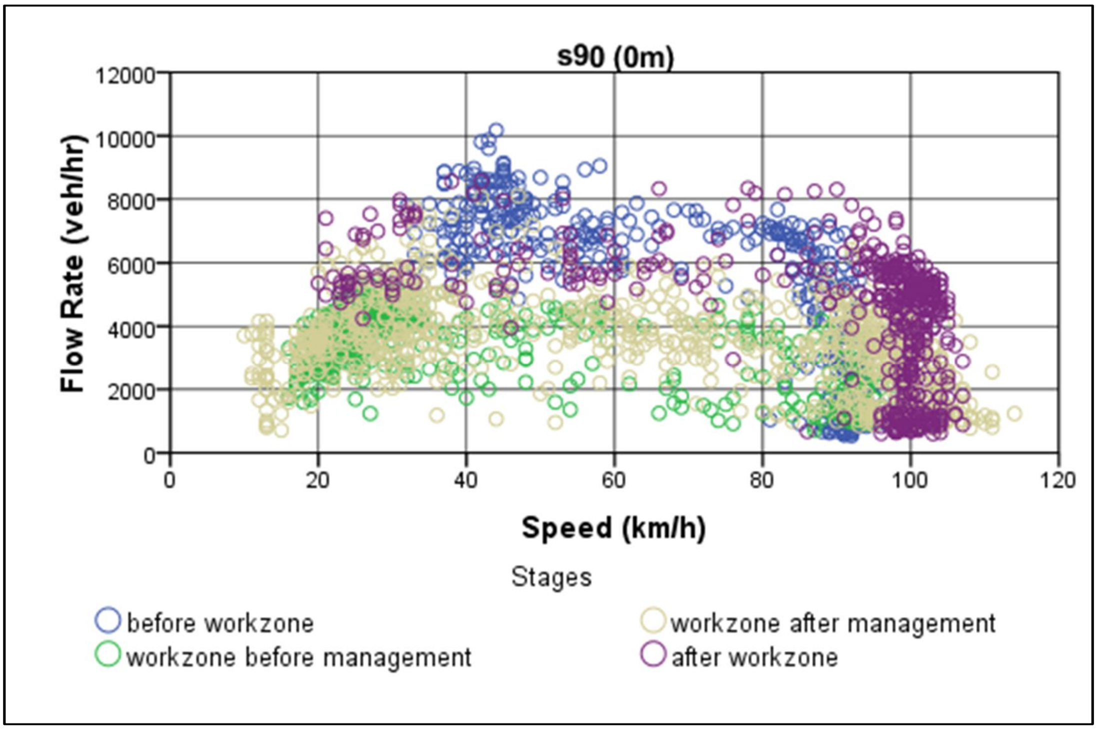

Figure 3.5. Flow rate versus speed graph of s90 (0m).

3.5. Methodology

Methodology of work zone traffic analyses is described in this section. Work zone traffic analysis was conducted by comparing the implemented strategies in different time periods of the work zone management. Statistical tests were applied to check if differences in means are statistically significant. Types of statistical tests used in this study and interpretation of sample outputs of these tests are included in this section.

In this thesis, FSM Bridge work zone traffic analysis included the following steps; determination of critical traffic flow parameters, analysis of mean traffic flow parameters, peak-hour analysis, queue length analysis, toll payment policy analysis, analysis of classification of vehicles, alternate route analysis and accident analysis.

The analyses for FSM Bridge maintenance project case study was mainly divided into four main stages called as; (i) before maintenance work started at the work zone, (ii) The time interval before management strategies were applied at the work zone, (iii) Time during which various traffic management strategies were applied at the work zone and (iv) after the maintenance work was completed at the work zone. These stages are implemented in the following time periods, respectively;

(i) from June-1 to June-17 (beginning of the construction),

(ii) from June-18 to July-11 (implementation of new work zone management strategies),

(iii) from July-12 to August-19 (end of construction project – excluding 3 days of holiday),

(iv) from August-22 (the end of construction period) to September-10 (the beginning of the school season).

Statistical analyses of measurements of traffic flow parameters were performed in order to evaluate if changes in the data are significantly important. SPSS is used for statistical analysis. SPSS is a software package developed by IBM for statistical analysis. While choosing type of statistical analysis, assumptions of the tests should be considered. For example, one-way ANOVA tests assume homogeneity of variances and t-tests assume the data are normally distributed. In case of violation of these assumptions, different tests are chosen (Walpole *et al*., 2002). The procedures for choosing statistical analyses used in this study are as follows:

(i) Regression analysis is used for fitting lines, testing goodness of fit and curves, and finding critical parameters (capacity, free flow speed and critical occupancy)from the fitted lines,

(ii) If two means are compared, tests for normality was conducted;

- If data are normally distributed, t-tests and Levene Tests are conducted,
- Otherwise, Mann-Whitney U Tests are conducted,

(iii) If more than two means are compared ANOVA was used and for this first, homogeneity of variances are tested with Levene's Test,

- If variances are equal, one-way ANOVA was used to test the equality of all the means and Tukey Tests were conducted, for testing bivariate means test,
- Otherwise, ANOVA was used to test the equality of all the means the Welch and Games-Howell Tests are used for testing bivariate means test.

Based on the statistical results, statistical difference in means is checked. To illustrate the method of commenting the results from the outputs of SPSS, sample outputs are given in Table 3.6 through 3.15.

Table 3.6. A sample R^2 test output for fitting lines.

Model Summary[a]

R	R Square	Adjusted R Square	Std. Error of the Estimate
.968	.936	.936	1510.303

The independent variable is Speed (km/h).

a. The equation was estimated without the constant term.

R^2 is a goodness-of-fit measure of the created model (Table 3.6). It is also called as the coefficient of determination. It ranges in value from 0 to 1. There is no critical value for R^2; yet, large values indicate that the model fit the data well.

Analysis of variances for the fitted line gives various statistics about the fitted line (Table 3.7). F value states for the ratio of two mean squares. When the F value is large and significance is lower than 0.05 or 0.01 (95% or 99% confidence level); then null hypothesis all the coefficients of the regression model is equal to zero can be rejected.

Table 3.7. A sample ANOVA test output.

ANOVA[a]

	Sum of Squares	Df Degrees of freedom	Mean Square	F	Sig.
Regression	1.356E10	2	6.780E9	2972.495	.000
Residual	9.238E8	405	2281016.386		
Total	1.448E10	407			

The independent variable is Speed (km/h).

a. The equation was estimated without the constant term.

Table 3.8 gives an example output for the regression coefficients and the associated test statistics. The t-statistic provides a test for testing the null hypothesis of equality of the individual coefficients being equal to zero. Hence in this example this null hypothesis can be rejected for n-both “speed” and “speed**2” coefficients.

Table 3.8. A sample regression output regression coefficients.

Coefficients

	Unstandardized Coefficients		Standardized Coefficients	t	Sig.
	B	Std. Error	Beta		
Speed (km/h)	300.062	5.099	3.647	58.842	.000
Speed (km/h) ** 2	-2.915	.061	-2.946	-47.533	.000

Both in one-way ANOVA, which test the equality of means for more than two groups, and t-tests, equality of variances, are assumed. In order to check equality of variances, Levene Test is conducted before ANOVA and t-tests. If significance in the Levene test result is greater than 0.05, then that the equality of the variances can be rejected. For the sample in Table 3.9, significance is lower than 0.05; therefore variances are not equal in this case.

Table 3.9. A sample Levene test output for homogeneity of variances.

Test of Homogeneity of Variances

Flow Rate (veh/hr)

Levene Statistic	df1	df2	Sig.
573.390	4	9788	.000

If assumption of homogeneity of variances is violated, welch test can be performed instead of one-way ANOVA test (Table 3.10). Welch test is used to determine if there is any difference in means. Significance lower than 0.05 means there is statistical difference in means.

Table 3.10. A sample Welch test output.

Robust Tests of Equality of Means

Flow Rate (veh/hr)

	Statistic[a]	df1	df2	Sig.
Welch	309.380	4	1791.837	.000

a. Asymptotically F distributed.

After one-way ANOVA and Welch tests, post-hoc tests are done to determine in which groups statistical differences exist. Tukey test is chosen as a post-hoc test after the one-way ANOVA test. A sample Tukey test output is shown in Table 3.11. Significance lower than 0.05 means, there is a statistical difference between means two groups of data. Additionally, mean differences, lowest and highest values in 95% confidence level are given in the output table.

Table 3.11. A sample Tukey test output.

Tukey HSD

Dependent Variable	(I) stages	(J) stages	Mean Difference (I-J)	Std. Error	Sig.	95% Lower Bound	95% Upper Bound
q	before work zone	work zone before management	1939.762*	112.658	.000	1632.23	2247.30
		work zone after management	2012.897*	103.285	.000	1730.95	2294.85
		after work zone	1042.442*	118.645	.000	718.56	1366.32

Table 3.12. A sample Games-Howell test output.

Multiple Comparisons

Games-Howell

(I) Stages	(J) Stages	Mean Difference (I-J)	Std. Error	Sig.	95% Confidence Interval Lower Bound	95% Confidence Interval Upper Bound
before work zone	work zone before management	1939.762*	68.015	.000	1754.07	2125.46
	work zone after management	2012.897*	68.160	.000	1826.81	2198.98
	after work zone	1042.442*	80.299	.000	823.28	1261.61
	holiday	2491.134*	98.635	.000	2221.45	2760.82

After conducting a Welch test, Games-Howell tests are preferred as post-hoc tests. The output table of Games-Howell test (Table 3.12) is the same as Tukey test. Significance lower than 0.05 means, there is a statistical difference between means two groups of data.

Table 3.13. A sample output of t-test.

		Levene's Test for Equality of Variances		t-test for Equality of Means						
									95% Confidence Interval of the Difference	
		F	Sig.	t	df	Sig. (2-tailed)	Mean Difference	Std. Error Difference	Lower	Upper
Speed (km/h)	Equal variances assumed	3.300	.069	-17.058	6028	.000	-12.926	.758	-14.412	-11.441
	Equal variances not assumed			-17.100	4905.954	.000	-12.926	.756	-14.408	-11.444

T-test is one of the mostly used statistical tests to compare the means of two groups. There are two assumptions in t-test; (a) data are normally distributed and (b) there is homogeneity of variances. A t-test output table (Table 3.13) includes Levene test. If significance of Levene test is greater than 0.05, then variances are assumed to be equal. In the output table, results for both equal variances and unequal variances are calculated. Levene test helps to choose one of them. If significance of t-test (Sig. 2-tailed) is lower than 0.05, then it can be concluded that there is significant difference between the means of the two groups of data.

Table 3.14. A sample output of Mann-Whitney Test.

	Speed (km/h)
Mann-Whitney U	3261378.000
Wilcoxon W	5907528.000
Z	-15.661
Asymp. Sig. (2-tailed)	.000

a. Grouping Variable: Stages

While comparing means of two groups; if data are not normally distributed, then Mann-Whitney test can be used instead of T-test. An output table of Mann-Whitney test is demonstrated in Table 3.14. In this table, significance lower than 0.05 means there is a statistical difference between the means of two groups.

Table 3.15. A sample output of the tests of normality.

Tests of Normality

		Kolmogorov-Smirnov[a]			Shapiro-Wilk		
	Stages	Statistic	df	Sig.	Statistic	df	Sig.
Speed (km/h)	before work zone	.180	1623	.000	.894	1623	.000
	work zone before management	.183	2300	.000	.877	2300	.000
	work zone after management	.133	3730	.000	.917	3730	.000
	after work zone	.108	1821	.000	.930	1821	.000
	holiday	.158	284	.000	.911	284	.000

a. Lilliefors Significance Correction

While comparing the difference in means of two groups; firstly, normality of the data should be checked. If data are normally distributed t-test can be used, otherwise a non-parametric test such as Mann-Whitney test should be used (Table 3.15). In this study Kolmogorov-Smirnov test is used in this study for testing the normality. In Table 3.15, significance of Kolmogorov-Smirnov test is lower than 0.05 means that the data are not normally distributed.

3.6. Work Zone Traffic Analysis

3.6.1. Determination of Critical Traffic Flow Parameters

In this section, capacity flow, free-flow speeds and jam density values at the RTMS, namely s2 (1870m), are determined for each time periods of the work zone. Regression analyses are performed to determine the relationship between the parameters and R^2 values. . Firstly, capacity and free-flow speeds are determined using flow rate versus average speed graphs of each RTMS. Then, jam densities are calculated using fundamental relationship of traffic flow (Equation 2.3).

In Figure 3.6, flow rate versus average speed graphs of the RTMS s2 (1870m) are shown. After the graph, a table is presented showing capacity, free-flow speed, jam density and regression test results (Table 3.16). The fitting equations acquired with regression analyses are shown in equation 3.1.

$$q = Av^2 + Bv \, , \tag{3.1}$$

where q is flow rate (veh/h), v is speed (km/h), A and B are coefficients.

Critical traffic flow parameters for all the detectors are summarized in Table 3.17.

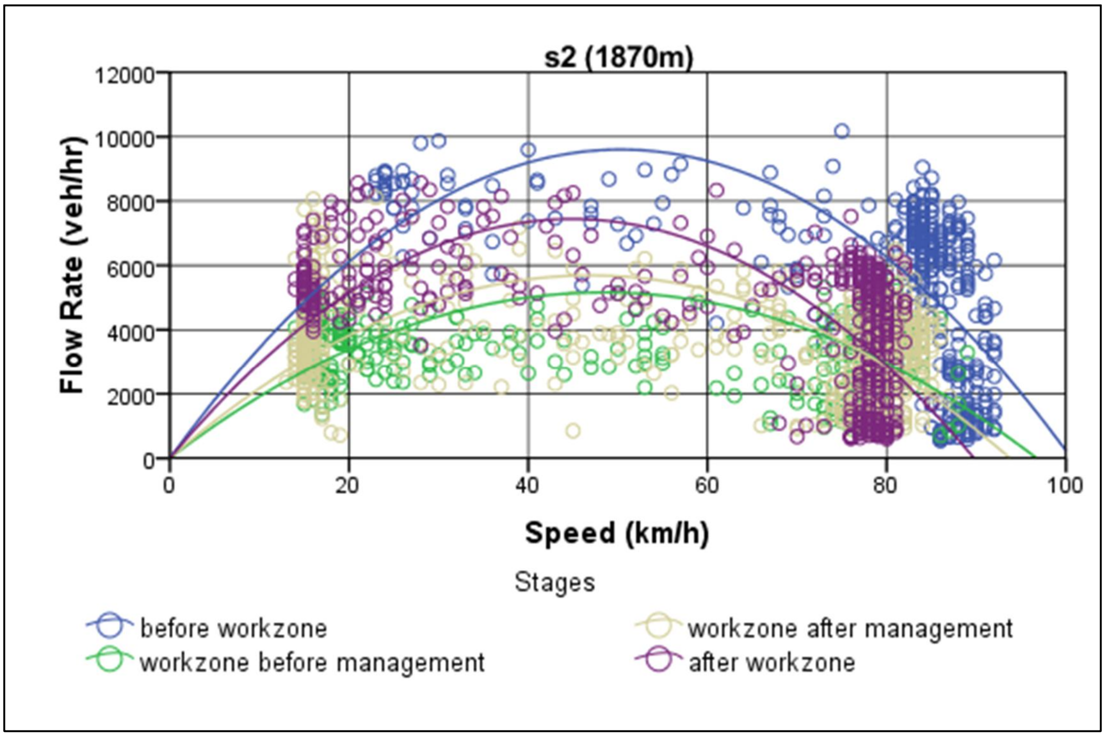

Figure 3.6. Flow rate versus average speed graph of s2 (1870m).

Based on Figure 3.6, it can be said that maximum flow rates are low during the construction. The capacity was almost halved during the construction as expected before the management strategies were applied. After the management strategies were applied there was a 10% increase, from 5161 to 5692 in the capacity. After the end of the construction, capacity increased; however, capacity of the road before the beginning of the construction is 22.5% more than that of after the construction. This difference may be caused by the decreased bottleneck effect due to decreased number of toll booths. As discussed in Bottleneck Analysis Section in this thesis (Section 3.6.5), decreased bottleneck effect causes smoothening of the traffic flow. Eventually, mean speeds at the toll booths increases; whereas mean speeds before the toll booths decreases so that vehicles travel at almost constant speeds. Difference in free-flow speeds are less than difference observed with other detectors. Regression results of this graph are given in Table 3.16.

In Table 3.16, the regression equations between the flow (q) and speed (v) are presented. As can be seen from this table all the coefficients are significantly different from zero with at least 99.999 confidence (t significances of 0.000). There is decrease in capacity during the construction. Free-flow speeds decreased in every stage.

Table 3.16. Flow rate vs. speed equations and results of s2 (1870m).

Stages	**Equation**	**Capacity**	**kjam**	**vf**	**R2**	**t sign.**	**F sign.**
Before Work Zone	$q= -3.794v^2+381.737v$	9602	382	100.62	0.877	0.000	0.000
Work Zone Before Management	$q=-2.207v^2+213.442v$	5161	213	96.71	0.858	0.000	0.000
Work Zone After Management	$q=-2.589v^2+242.79v$	5692	243	93.78	0.828	0.000	0.000
After the End of Work Zone	$q=-3.696v^2+331.7v$	7442	332	89.75	0.854	0.000	0.000

Table 3.17. Critical traffic flow parameters by stages.

		s90 (0m)	s313 (700m)	s417 (1230m)	s2 (1870m)	Average
Free-flow speed (km/h)	Before Work Zone	102.94	77.21	115.61	100.62	99.09
	Work Zone Before Management	100.93	73.98	99.28	96.71	92.72
	Work Zone After Management	114.34	80.22	94.83	93.78	95.79
	After Work Zone	117.93	89.31	96.94	89.75	98.48
Capacity (veh/h)	Before Work Zone	7722	10027	8942	9602	9073.17
	Work Zone Before Management	4791	5498	4588	5161	5009.35
	Work Zone After Management	5017	4260	4739	5692	4927.18
	After Work Zone	7086	4993	6823	7442	6586.01
Jam Density (veh/km)	Before Work Zone	300	519	309	382	377.65
	Work Zone Before Management	190	297	185	213	221.36
	Work Zone After Management	176	212	200	243	207.66
	After Work Zone	240	224	282	332	269.30

Critical traffic flow parameters grouped by periods of the work zone are summarized in Table 3.17. Due to the distance from the turbulent areas near the toll booths the most reliable values are those obtained from the must distant RTMS of s2. From this table, it can be concluded that free-flow speeds in the road section are between 90 km/h and 100 km/h. Average speeds decreased 6% with the beginning of the construction; after the end of the construction, they increased to the level observed before construction. Capacity of the road section is decreased by 44.79% after the beginning of the construction. The new work zone management implementations, i.e. decreased number of toll booths, restrictions on busses and trucks, did not affect the capacity of the road. After the end of the construction, capacity increased by 33.67%. Jam density behave similar to the capacity values; i.e. construction causes a significant decrease in jam density.

May (1990) states that congestion starts at occupancy levels between 42% and 67%. Percentage distribution of the scatter points whose occupancy values are greater than 42 and lower than 42 is presented in Table 3.18.

Table 3.18. Percent distribution of data according to their occupancy values.

		Before Work Zone	Work Zone Before Management	Work Zone After Management	After Work Zone
s2 (1870m)	Occupancy >42%	10.0	37.5	26.5	23.0
	Occupancy <42%	90.0	62.5	73.5	77.0
s417 (1230m)	Occupancy >42%	1.7	35.7	27.9	31.8
	Occupancy <42%	98.3	64.3	72.1	68.2
s313 (700m)	Occupancy >42%	23.3	21.8	21.6	12.7
	Occupancy <42%	76.7	78.2	78.4	87.3
s90 (0m)	Occupancy >42%	8.6	62.0	39.3	13.6
	Occupancy <42%	91.4	38.0	60.7	86.4

From Table 3.18, it can be concluded that there are significant differences in occupancy distribution between time periods. When the construction was started, occupancies increased dramatically. After implementation of new work zone strategies, occupancy levels decreased considerably. Then, occupancies further decreased after finishing of the construction.

3.6.2. Analysis of Mean Traffic Flow Parameters

Changes in flow rates, average speeds and occupancies are analyzed in this section. Average values of flow rates, average speeds and occupancies are compared by stages. A descriptive table for traffic flow parameters by stages is given in Table 3.19. Levene test is conducted for choosing the test type for comparison (Table 3.20).

Table 3.19. Descriptives of traffic flow parameters of TEM.

		N	Mean	Std. Deviation	Std. Error	95% Confidence Interval for Mean		Minimum	Maximum
						Lower Bound	Upper Bound		
Speed (km/h)	before work zone	1623	70.99	26.331	.654	69.71	72.27	6	109
	work zone before management	2300	42.33	28.399	.592	41.17	43.49	3	98
	work zone after management	3730	55.26	28.694	.470	54.34	56.18	5	114
	after work zone	1821	65.12	27.030	.633	63.88	66.37	11	107
	Total	9474	56.71	29.639	.305	56.11	57.31	3	114
Occupancy %	before work zone	1623	16.33	17.666	.439	15.47	17.19	0	81
	work zone before management	2300	27.87	22.538	.470	26.95	28.79	0	68
	work zone after management	3730	23.27	22.626	.370	22.55	24.00	0	75
	after work zone	1821	18.54	18.149	.425	17.71	19.37	0	63
	Total	9474	22.29	21.407	.220	21.86	22.72	0	81
Flow Rate (veh/hr)	before work zone	1632	5368.04	2586.800	64.033	5242.44	5493.63	541	10174
	work zone before management	2304	3428.27	1100.640	22.930	3383.31	3473.24	703	5371
	work zone after management	3744	3355.14	1429.157	23.357	3309.35	3400.93	714	8107
	after work zone	1824	4325.59	2069.385	48.454	4230.56	4420.63	599	8568
	Total	9504	3904.77	1908.875	19.581	3866.39	3943.15	541	10174

From Table 3.19, it is determined that average speeds decreased dramatically after the beginning of the construction. The new work zone management implementations, i.e. decreased number of toll booths, restrictions on busses and trucks, were effective in increasing average speed values. Occupancy values were relatively high during the construction. The new work zone management implementations were effective in decreasing occupancy level. On the other hand, flow rates decreased with construction and they were not affected by the new implementations.

Table 3.20. Levene Test results for traffic flow parameters.

Test of Homogeneity of Variances

	Levene Statistic	df1	df2	Sig.
Speed (km/h)	61.430	3	9470	.000
Occupancy %	300.768	3	9470	.000
Flow Rate (veh/hr)	740.213	3	9500	.000

Significances of Levene results of traffic flow parameters are significantly important (Table 3.20). In other words, assumptions of homogeneity of variances are violated. Therefore, Welch tests are used to compare means of the traffic flow parameters.

Table 3.21. Welch test results for traffic flow parameters.

Robust Tests of Equality of Means

		Statistic[a]	df1	df2	Sig.
Speed (km/h)	Welch	416.248	3	4493.585	.000
Occupancy %	Welch	131.268	3	4636.071	.000
Flow Rate (veh/hr)	Welch	383.990	3	4078.434	.000

a. Asymptotically F distributed.

From Table 3.21, it can be concluded that differences in mean traffic flow parameters are significantly important. Hence, Games-Howell tests are conducted to understand in which stages the differences are statistically important (Table 3.22, 3.23 and 3.24).

Table 3.22. Games-Howell Test for speed by stages.

Speed (km/h)
Games-Howell

(I) Stages	(J) Stages	Mean Difference (I-J)	Std. Error	Sig.	95% Confidence Interval	
					Lower Bound	Upper Bound
before work zone	work zone before management	28.658*	.882	.000	26.39	30.92
	work zone after management	15.732*	.805	.000	13.66	17.80
	after work zone	5.866*	.910	.000	3.53	8.21
work zone before management	before work zone	-28.658*	.882	.000	-30.92	-26.39
	work zone after management	-12.926*	.756	.000	-14.87	-10.98
	after work zone	-22.792*	.867	.000	-25.02	-20.56
work zone after management	before work zone	-15.732*	.805	.000	-17.80	-13.66
	work zone before management	12.926*	.756	.000	10.98	14.87
	after work zone	-9.866*	.789	.000	-11.89	-7.84
after work zone	before work zone	-5.866*	.910	.000	-8.21	-3.53
	work zone before management	22.792*	.867	.000	20.56	25.02
	work zone after management	9.866*	.789	.000	7.84	11.89

*. The mean difference is significant at the 0.05 level.

Differences in mean speeds between all the stages are statistically significant with 95% confidence level (Table 3.22). It can be concluded that mean speeds are affected by work zone and implementation of the new work zone management strategies were beneficial for increasing speeds.

Table 3.23. Games-Howell Test for occupancy by stages.

Occupancy %
Games-Howell

(I) Stages	(J) Stages	Mean Difference (I-J)	Std. Error	Sig.	95% Confidence Interval	
					Lower Bound	Upper Bound
before work zone	work zone before management	-11.539*	.643	.000	-13.19	-9.89
	work zone after management	-6.945*	.574	.000	-8.42	-5.47
	after work zone	-2.211*	.611	.002	-3.78	-.64
work zone before management	before work zone	11.539*	.643	.000	9.89	13.19
	work zone after management	4.595*	.598	.000	3.06	6.13
	after work zone	9.328*	.634	.000	7.70	10.96
work zone after management	before work zone	6.945*	.574	.000	5.47	8.42
	work zone before management	-4.595*	.598	.000	-6.13	-3.06
	after work zone	4.733*	.564	.000	3.28	6.18
after work zone	before work zone	2.211*	.611	.002	.64	3.78
	work zone before management	-9.328*	.634	.000	-10.96	-7.70
	work zone after management	-4.733*	.564	.000	-6.18	-3.28

*. The mean difference is significant at the 0.05 level.

From Table 3.23, it can be said that there are statistical differences in occupancy values in all the stages. Consequently, mean occupancy increased with the construction and the new work zone management implementations were effective in decreasing occupancies.

Table 3.24. Games-Howell Test for flow rate by stages.

Flow Rate (veh/hr)
Games-Howell

(I) Stages	(J) Stages	Mean Difference (I-J)	Std. Error	Sig.	95% Confidence Interval	
					Lower Bound	Upper Bound
before work zone	work zone before management	1939.762*	68.015	.000	1764.89	2114.64
	work zone after management	2012.897*	68.160	.000	1837.65	2188.14
	after work zone	1042.442*	80.299	.000	836.04	1248.85
work zone before management	before work zone	-1939.762*	68.015	.000	-2114.64	-1764.89
	work zone after management	73.134	32.731	.114	-10.98	157.25
	after work zone	-897.320*	53.606	.000	-1035.12	-759.52
work zone after management	before work zone	-2012.897*	68.160	.000	-2188.14	-1837.65
	work zone before management	-73.134	32.731	.114	-157.25	10.98
	after work zone	-970.454*	53.790	.000	-1108.73	-832.18
after work zone	before work zone	-1042.442*	80.299	.000	-1248.85	-836.04
	work zone before management	897.320*	53.606	.000	759.52	1035.12
	work zone after management	970.454*	53.790	.000	832.18	1108.73

*. The mean difference is significant at the 0.05 level.

Decrease in mean flow rates after the beginning of the construction is statistically important (Table 3.24). However, implementation of the new work zone management strategies did not change flow rates significantly.

The test results show that change in flow rates due to construction is significant. On the other hand, change in flow rate values due to the implementation of new work zone management strategy is statistically not significant. As a result, test outcomes of flow rates show that

(i) Change in flow rates due to lane closures is significantly important and,
(ii) The new work zone management strategies such as decreased number of toll booths, trucks and buses, which come into effect on 12th July, did not affect flow rates significantly.

The results of the tests for average speed and occupancy indicate that change in average speeds and occupancies are statistically significant in every stage. Therefore, it can be concluded that

(i) Average speeds decreased and occupancies increased due to lane closures and,
(ii) The implementation of new work zone management strategies was efficient in increasing the average speeds and decreasing occupancies.

Distribution of the average traffic flow parameters in days are shown in Figure 3.7, 3.8 and 3.9. The data acquired from s417 (1230m) detector are used in these figures. s417 (1230m) is located before the toll booths; therefore, these data may demonstrate traffic flow conditions before the toll booths.

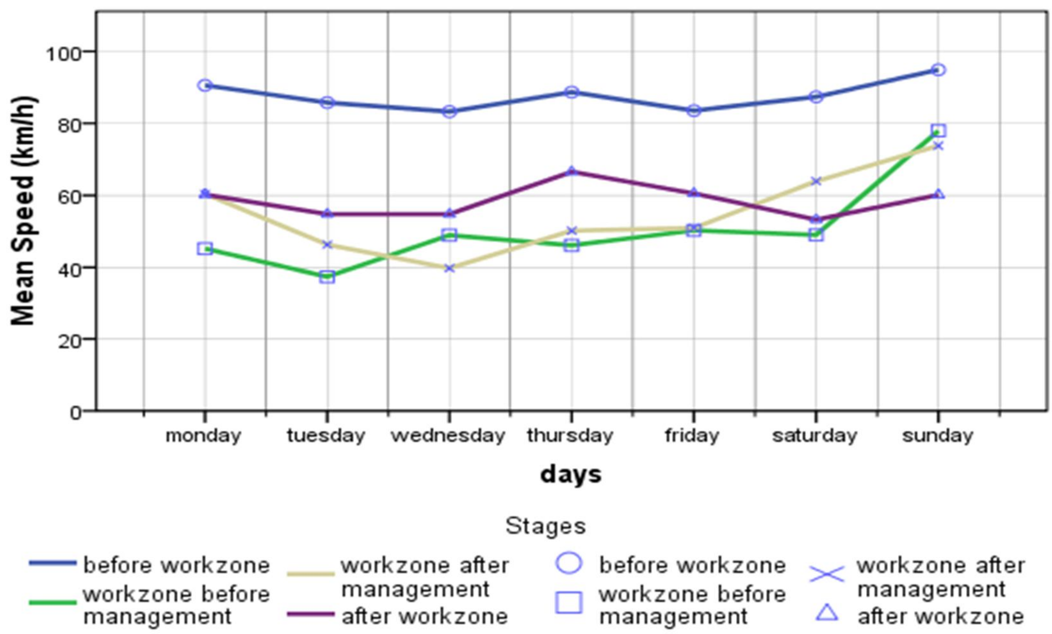

Figure 3.7. Mean speeds by weekday acquired from s417 (1230m) detector.

In Figure 3.7, it can be said that mean speeds did not fluctuate between weekdays Mean speeds before work zone were higher than the others.

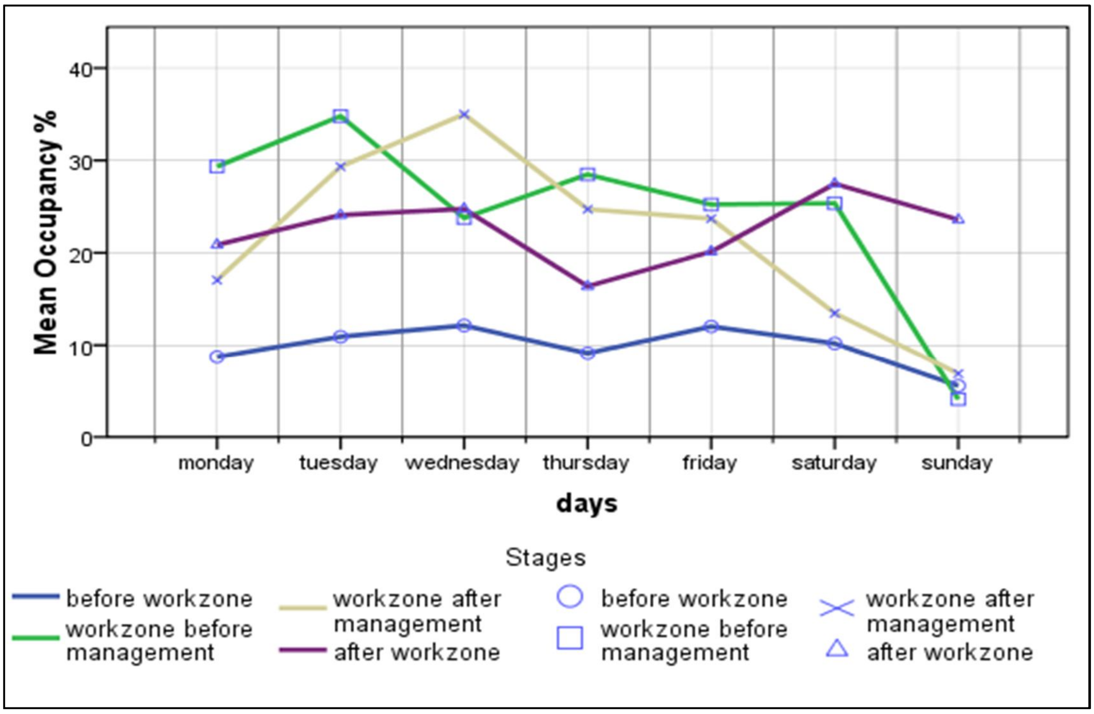

Figure 3.8. Mean Occupancies by weekdays acquired from s417 (1230m) detector.

Mean occupancies did not fluctuate before work zone. On weekends occupancies decreased significantly.

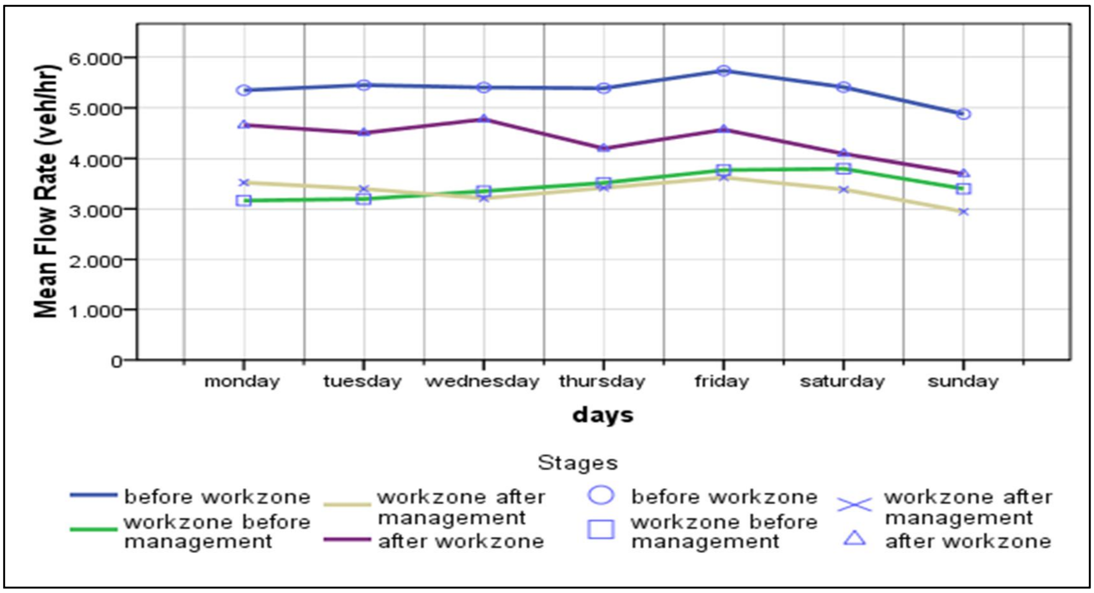

Figure 3.9. Mean flow rates by weekdays acquired from s417 (1230m) detector.

As seen in Figure 3.9, mean flow rates decreased due to lane closures; however, the implementation of new work zone management strategies did not affect mean flow rates. There is no significant fluctuation in flow rates between weekdays.

3.6.3. Peak-hour Analysis

Traffic flow conditions changed significantly during construction period. Almost all the city road network was affected by the traffic congestion in the work zone. Peak-hour factors cannot be determined due to the lack of data. However, changes in mean speeds, occupancies and flow rates in day in each stage are analyzed in this section. Thursday´s traffic flow values are similar to the average traffic flow values of weekdays; hence Thursdays, from the beginning till the end of the analysis period, are chosen for evaluation. In Figure 3.10, 3.11 and 3.12 hourly mean traffic flow values of Thursdays are used.

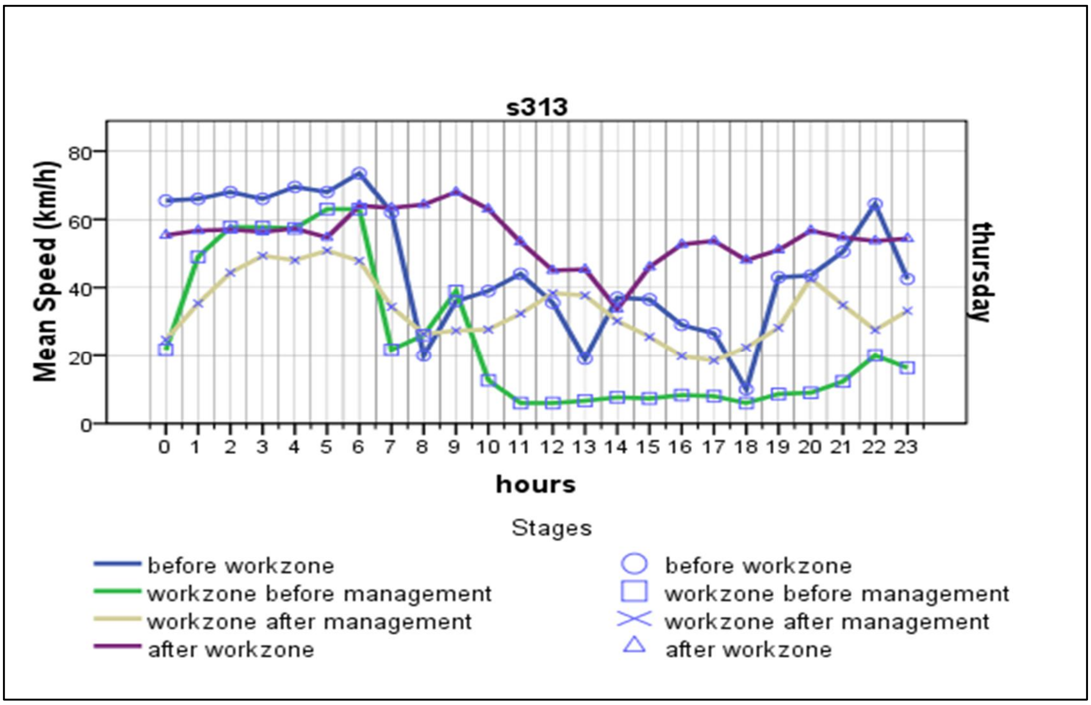

Figure 3.10. Hourly mean speeds of Thursdays at toll booths.

From Figure 3.10, it can be observed that speeds are below 20 km/h before the implementation of work zone management strategies. The new work zone management strategies increased the observed speed values. An important result derived from Figure 3.10 is that after the end of construction, mean speed values became smoother than the period before construction. The reason for this situation could be the reduced number of toll booths; because, decreasing the number of the toll booths was the only permanent action which continued after the end of construction. Number of toll booths was decreased from 21 to 11 as work zone management strategy and it was not increased after the end of construction. This implementation caused a decrease in the size of the bottleneck at the toll booths. Therefore, it can be concluded that bottleneck caused fluctuations in mean speed values in the study area.

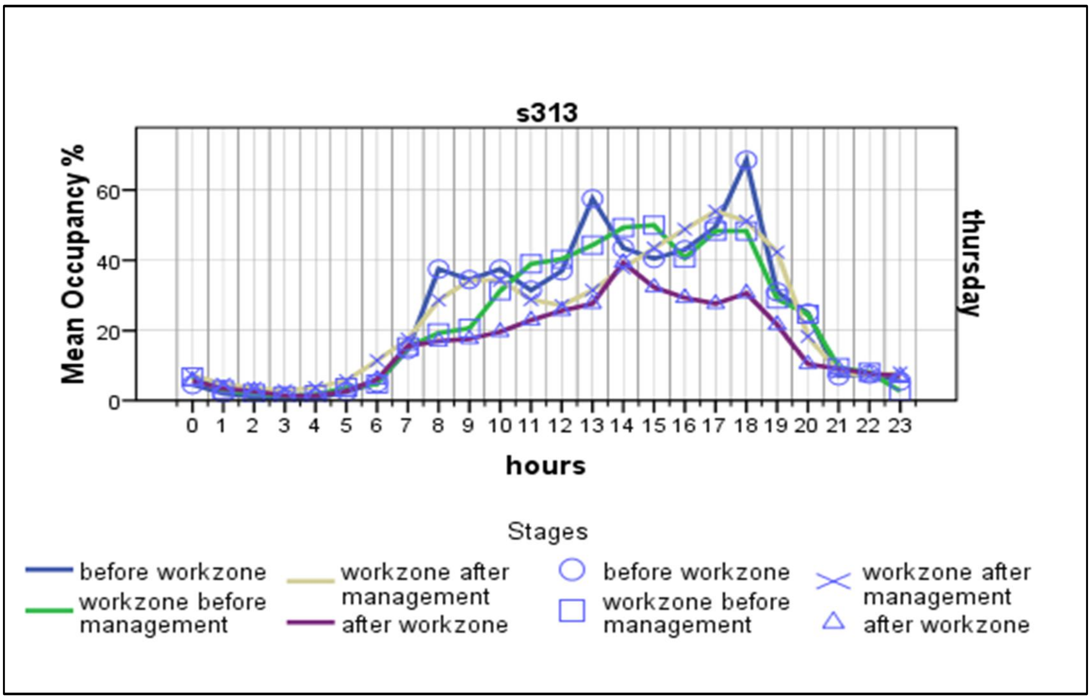

Figure 3.11. Hourly mean occupancy values of Thursdays at toll booths.

As seen in Figure 3.11, mean occupancies are considerably high during day time. After the end of the construction, mean occupancies decreased significantly.

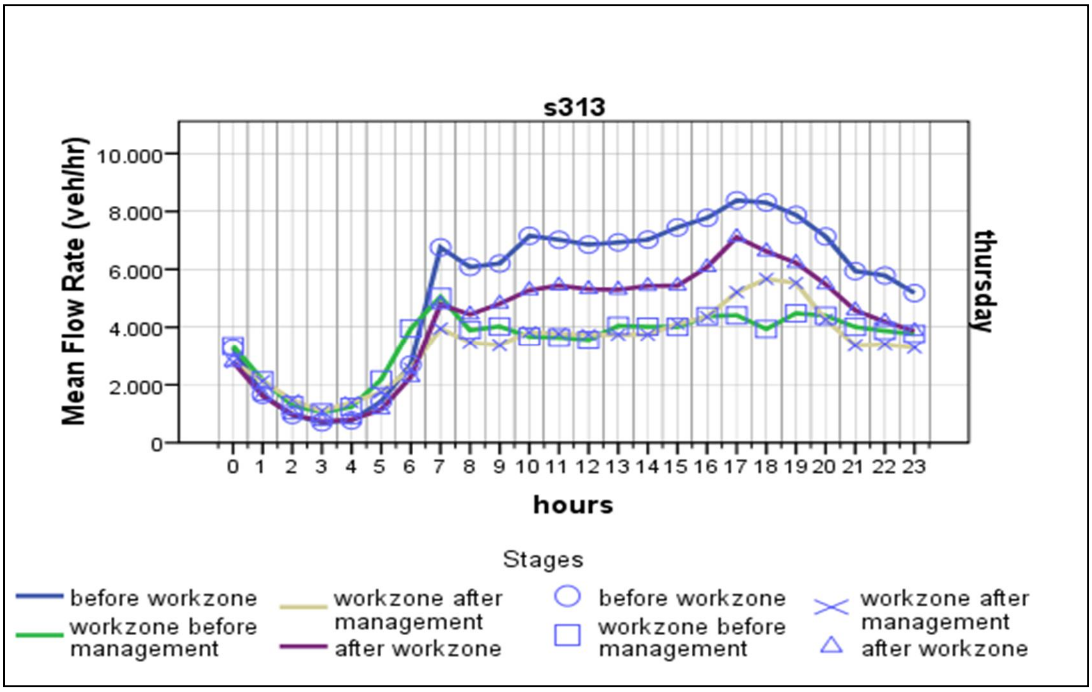

Figure 3.12. Mean flow rates of Thursdays by hours.

In Figure 3.12, observed mean flow rates before construction are higher than the other stages. Flow rates decreased after the beginning of the construction and increased after the end of the construction. In day-times, mean flow rates during construction were less than the period before and after the end of construction; whereas, mean flow rates at nights during construction are higher than other periods. On the other hand, daily mean flow rates did not change significantly, between stages.

After the beginning of the construction, speeds were below 20 km/h for 14 hours a day. This number decreased to 2 hours a day with the implementation of the new work zone management strategies. Congested hours are summarized in Table 3.25.

Table 3.25. Congested hours for each stage.

	Hours Speeds below 20km/h	# of Hours	Hours Speeds below 40km/h	# of Hours
Before Work Zone	8:00, 13:00, 18:00	3	08:00-10:00, 12:00-18:00	10
Work Zone Before Management	10:00-23:00	14	07:00-0:00	18
Work Zone After Management	16:00-17:00	2	07:00-19:00, 21:00-1:00	18
After Work Zone	-	-	14:00	1

The hours when the mean speeds are below 20 km/h and the hours below 40 km/h are presented in Table 3.25. The counts of these hours are also given in the table. From this table, it can be concluded that after the beginning of the construction speeds were below 20 km/h for 14 hours a day and speeds were between 20 km/h and 40 km/h for 4 hours a day. After implementation of the new work zone management strategies, means speeds were below 20 km/h for 2 hours a day and speeds are between 20 km/h and 40 km/h for 16 hours a day. Consequently, the new work zone management strategies increased means speeds from the level below 20 km/h to the level between 20 km/h and 40 km/h.

3.6.4. Queue Analysis

Queue length is an important parameter for analyzing work zone traffic condition. Unfortunately, there are no data regarding queue lengths and travel times. Therefore, queue lengths are estimated using average speed data from RTMSs on TEM. Average speed data are drawn in the same graphs (Figure 3.13, 3.14, 3.15 and 3.16). By comparing these sensor data, the road section where the speed drop occurs can be determined. This method might be useful to find out where the traffic congestions started. FHWA (2008b) states that 30 mph (48.2 km/h) is a threshold common for a rolling queue. 50 km/h is used as threshold for rolling queue.

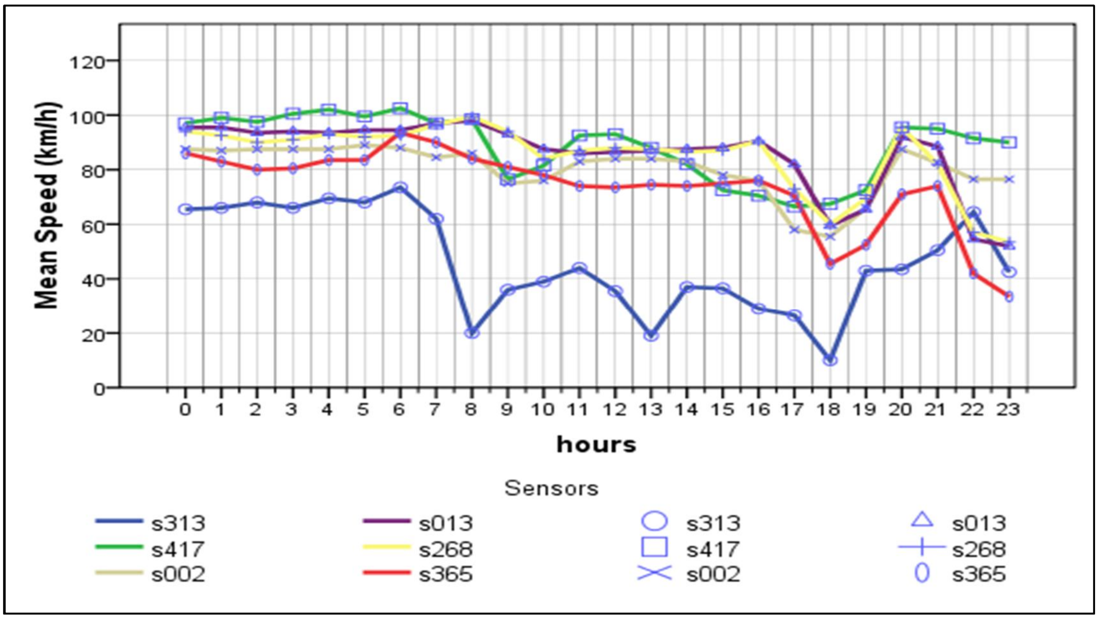

Figure 3.13. Mean speeds of Thursdays at the RTMSs before work zone.

Before the beginning of the construction, mean speed measured by s313 (700m) sensors are lower than the speeds measured by other sensors between 7:00-21:00 (Figure 3.13). This means vehicles were traveling at uncongested traffic conditions until toll booths area; then traffic became congested at the toll booths area. This situation might occur because of three possible reasons;

(i) Accumulation of the vehicles at the bottleneck, caused by large number of toll booths,

(ii) Due to the presence of two types of payment, most of the vehicles needed to change lanes and,

(iii) Vehicles were slowing down for passing through toll booths.

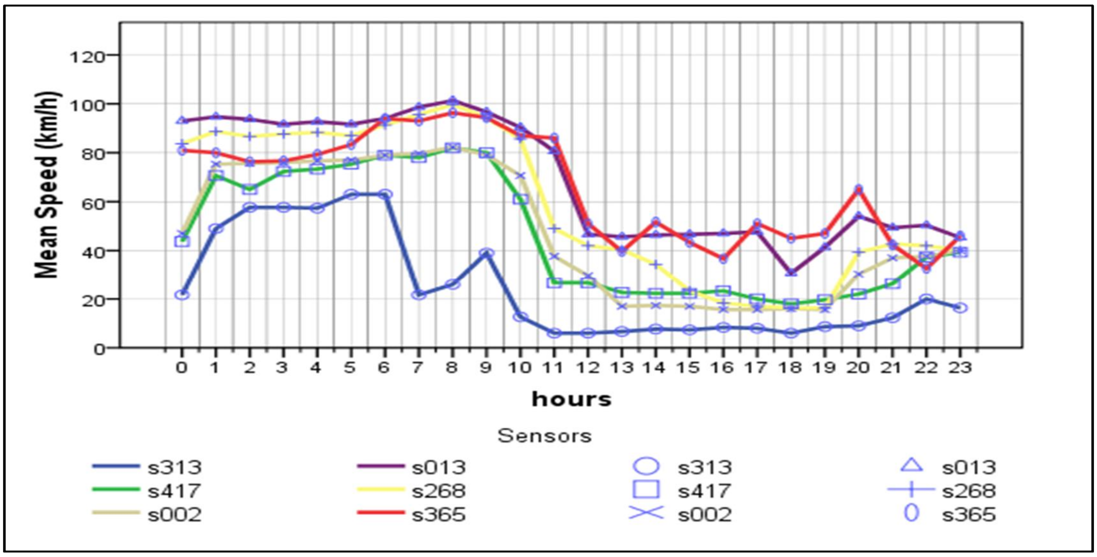

Figure 3.14. Mean speeds of Thursdays at the RTMSs between 18th June – 11th July 2012.

After the beginning of the construction (Figure 3.14), congestion at toll booths started at 7:00 and lasted until midnight. At 11:00 queue reached the area of sensor s2 (1870m) (Levent-TEM Participation) and this continued until midnight. From 12:00 to 23:00, traffic flow speeds were below 50km/h from the toll booths to sensor 365 (TEM-Seyrantepe). In other words, congestion started approximately 5 km away from FSM Bridge.

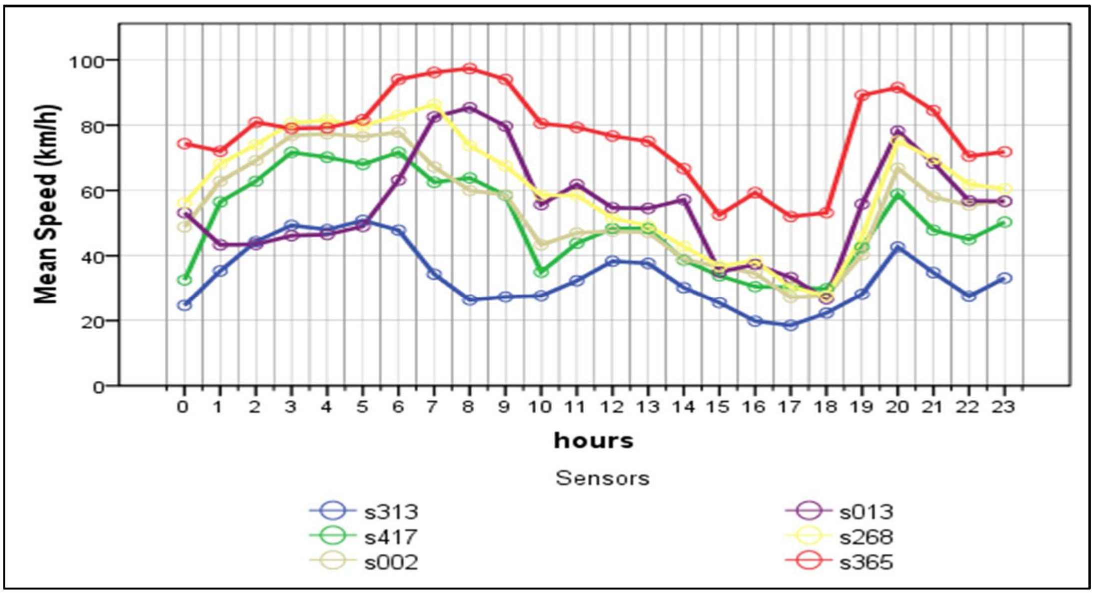

Figure 3.15. Mean speeds of Thursdays at the RTMSs between 12th July – 19th August 2012.

After implementation of the new work zone management strategies (Figure 3.15), average speed at the toll booths are increased over 20 km/h. By looking at speeds from different sensors, it can be said that there is smoothening of traffic flow. In other words, instead of traveling at high speeds and being stuck at the toll booths; vehicles traveled at lower speed and pass through toll booths without waiting for a long time.

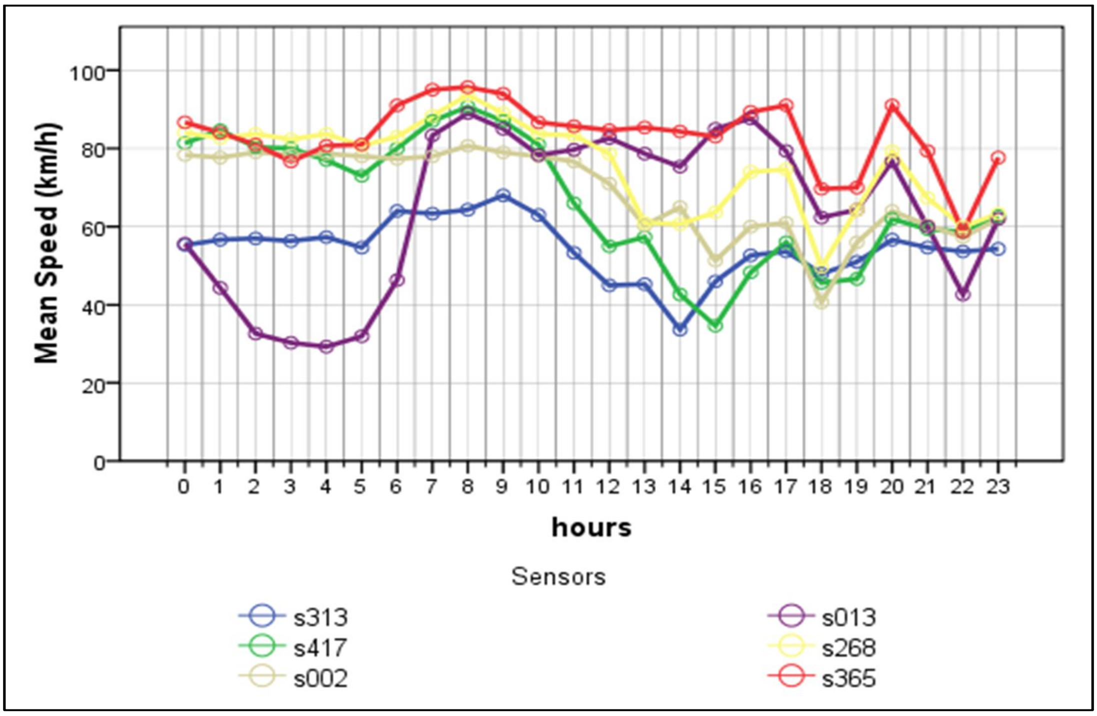

Figure 3.16. Mean speeds of Thursdays at the RTMSs between 22nd August – 10th September.

After the end of construction (Figure 3.16), traffic flow seems still smooth. The only difference between the periods before and after the end of construction is the number of toll booths. For this reason, it can be concluded that decreased number of toll booths, that is, reducing bottleneck caused smooth traffic flow.

3.6.5. Bottleneck Analysis

40% of traffic congestion in the U.S. is caused by bottlenecks (Figure 1.2). Additionally, bottlenecks cause more traffic crashes (GDH, 2012). Apart from safety issues, such incidents also create more congestion. Therefore, traffic engineers should always consider preventing bottlenecks while designing roads. In the FSM Bridge case study, a large bottleneck occurs due to large number of toll booths. In order to observe effects of bottleneck on the traffic flow, mean speeds acquired from sensors before and after toll booths are compared in this section. Speeds observed before and after the toll booths during the construction period before and after management are shown in Figure 3.17 and 3.18, respectively.

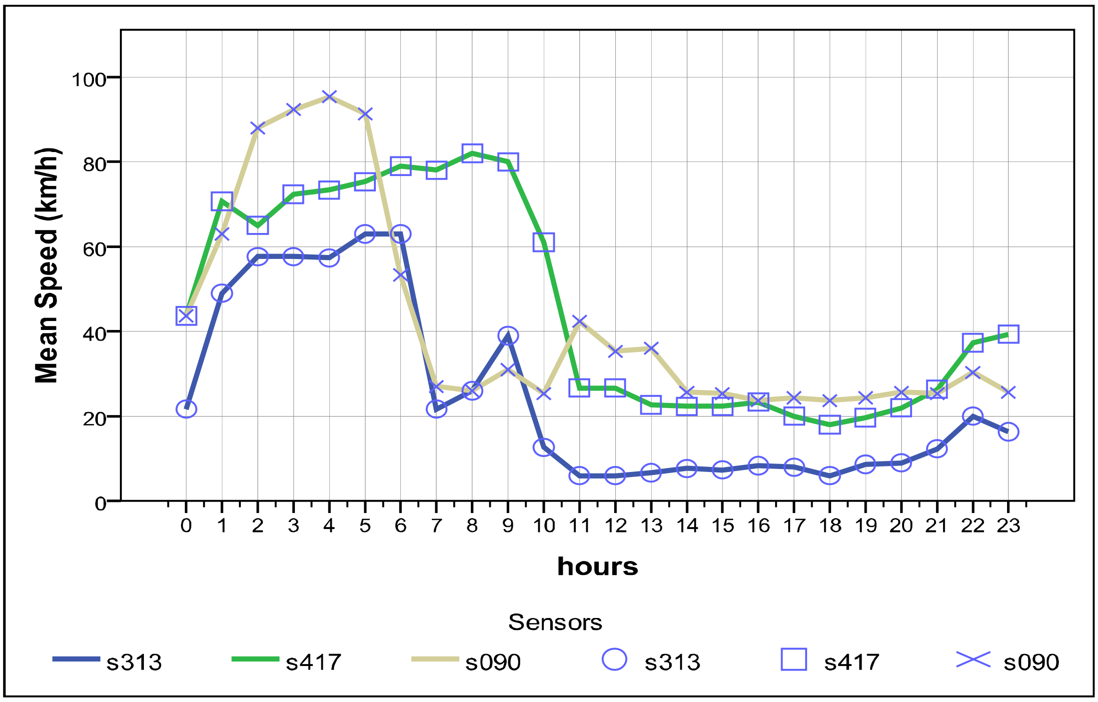

Figure 3.17. Mean speeds from the sensors located two sides of the toll booths between 18th June – 11th July.

After the beginning of the construction (Figure 3.17), vehicles were traveling between 20km/h – 40km/h until they reached bottleneck during day-time. Then, speeds decreased to below 20km/h at the bottleneck. After passing the bottleneck speeds increased. Statistical tests are conducted to compare the mean speeds from s313 (700m) and s90 (0m) on 5th July measurements. Firstly, normality test is conducted to determine the test type for comparison (Table 3.26).

Table 3.26. Normality test for speed at s90 (0m) and s313 (700m) on the 5th of July.

Tests of Normality

		Kolmogorov-Smirnov[a]			Shapiro-Wilk		
	sns m d	Statistic	df	Sig.	Statistic	df	Sig.
Speed (km/h)	313 7 5	.252	24	.000	.776	24	.000
	90 7 5	.260	24	.000	.805	24	.000

a. Lilliefors Significance Correction

Based on normality tests results, it can be said that the speed data are not normally distributed. Therefore, Mann-Whitney U test is used instead of t-test (Table 3.28). Group statistics are also given in Table 3.27.

Table 3.27. Group statistics of average speeds of s90 (0m) and s313 (700m) on 5th July 2012.

	sns m d	N	Mean	Std. Deviation	Std. Error Mean
Speed (km/h)	313 7 5	24	24.79	21.315	4.351
	90 7 5	24	52.88	26.668	5.443

From Table 3.27, it can be said that on the 5th of July, mean speed values of s313 (700m) are considerably higher than mean speed values of s90 (0m).

Table 3.28. Mann-Whitney test result for mean speeds of s313 (700m) and s90 (0m) on 5th July.

Test Statistics[a]

	Speed (km/h)
Mann-Whitney U	124.500
Wilcoxon W	424.500
Z	-3.376
Asymp. Sig. (2-tailed)	.001

a. Grouping Variable: V186

Based on Mann-Whitney U test result (Table 3.28), it can be said that mean speeds of s90 (0m) and s313 (700m) are significantly different with 95% confidence level. In other words, speeds of the vehicles increase after passing the toll booths during the construction period before implementation of the new work zone management strategies. Mean speeds after implementation of the new work zone management strategies are shown in Figure 3.18.

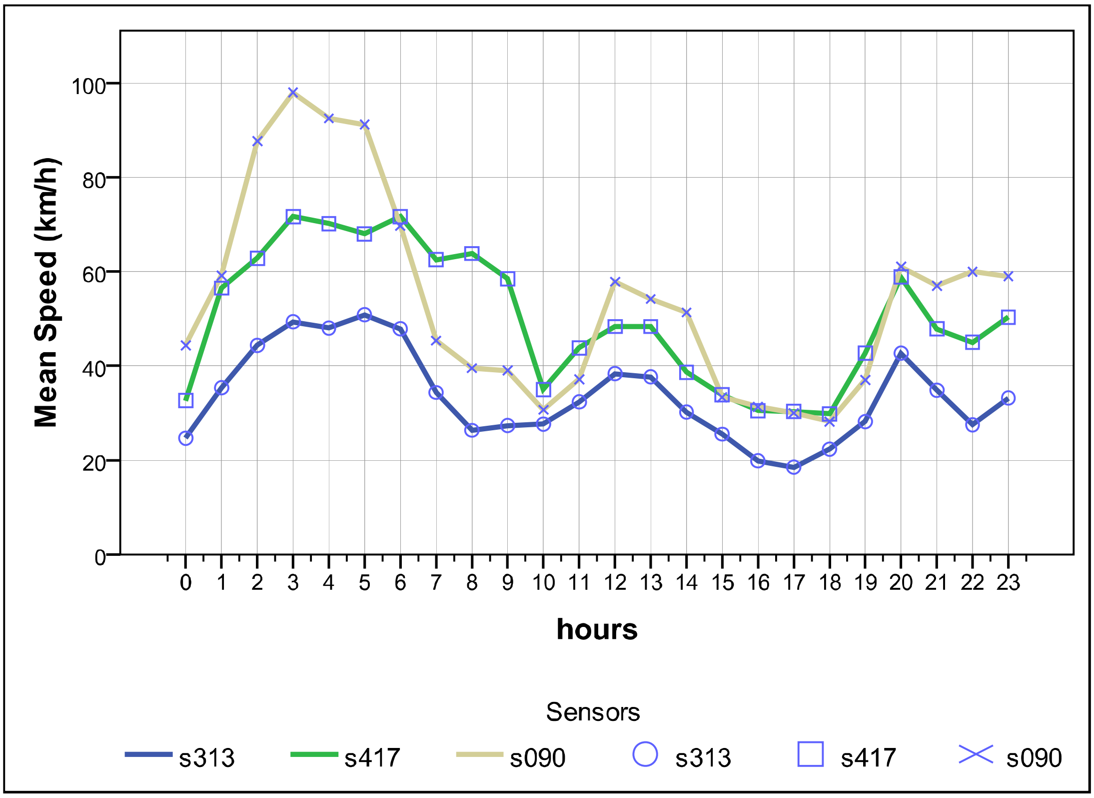

Figure 3.18.Mean speeds from the sensors located two sides of the toll booths between 12th July–19th August.

Mean speeds are increased with the beginning of the new work zone management policies (Figure 3.18). It can also be concluded that the gaps between the speeds are lower than before. This means that smoothening of the traffic flow also efficient in increasing the speeds after passing the toll booths. On the other hand, mean speeds before the construction decreased and vehicles travel at almost same speeds before and after the toll booths. The decreased speeds caused decrease in capacity as discussed in the Section 3.6.1 in this thesis. Statistical tests are conducted to compare the mean speed of s313 (700m) and s90 (0m) during this time period. Test of normality is done in order to check normality assumption (Table 3.29).

Table 3.29. Normality test for speed at s90 (0m) and s313 (700m) on 26th July.

Tests of Normality

		Kolmogorov-Smirnov[a]			Shapiro-Wilk		
	sns m d	Statistic	df	Sig.	Statistic	df	Sig.
Speed (km/h)	313 7 26	.241	24	.001	.830	24	.001
	90 7 26	.365	24	.000	.662	24	.000

a. Lilliefors Significance Correction

From Table 3.29, it can be concluded that mean speed data are not normally distributed. Therefore, Mann-Whitney U test is conducted to compare the means (Table 3.31). Group statistics are given also in Table 3.30.

Table 3.30. Group statistics of average speeds recorded by s90 (0m) and s313 (700m) at 26th July 2012.

	sns m d	N	Mean	Std. Deviation	Std. Error Mean
Speed (km/h)	313 7 26	24	23.50	13.250	2.705
	90 7 26	24	29.33	28.168	5.750

In Table 3.30, it can be said that mean speeds of s313 (700m) and s90 (0m) are close to each other on the 5th of July.

Table 3.31. Mann-Whitney test result for mean speeds of s313 (700m) and s90 (0m) on 26th July.

Test Statistics[a]

	v
Mann-Whitney U	268.500
Wilcoxon W	568.500
Z	-.404
Asymp. Sig. (2-tailed)	.687

a. Grouping Variable: V9

Based on Mann-Whitney U test result (Table 3.31), it can be said that difference in mean speeds of s90 (0m) and s313 (700m) are not significantly different.

3.6.6. Toll Fee Policy Traffic Analysis

As discussed in the previous sections, TEM is a toll highway. There are toll booths located at the entrance of FSM Bridge. Tolls are collected in two ways, namely (1) OGS and (2) KGS. Tolls are collected with electronic detection system without stopping the vehicles via OGS. On the other hand, KGS is a system with an electronic passage card. Most of the vehicles needed to change lane in order to go to their toll booths.

On the 19th of July, toll for the bridges was set free until the end of the maintenance project. Downs (2004) states that increasing the tolls can be an efficient way to reduce traffic congestion. On the other hand, authorities of Istanbul did the opposite of this statement in order to reduce the congestion caused by lane changes due to different payment methods.

The new work zone management strategies, i.e., decreased number of toll booths, restriction on busses and trucks, are implemented on the 12th of July. After 5 days, tolls were set free. Therefore, it is difficult to analyze the actual effects of the free toll policy; but, toll fee analysis is conducted by comparing the 5 days between these policies with the 5 days in the following weeks. Mean speed distribution by these 5 days periods are shown in Figure 3.19.

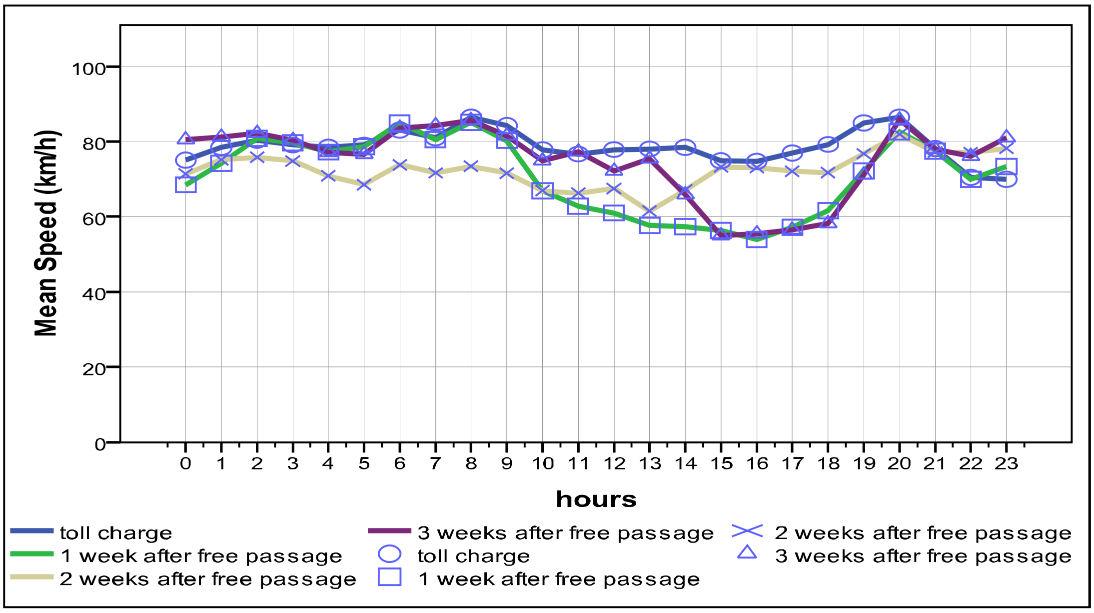

Figure 3.19. Mean speed distribution before and after the new toll policy.

Tolls were set free 5 days after the new work zone management implementations. For this reason, these 5 days are compared with the same weekdays of the following weeks. A graph is conducted to show change in mean speeds in period with toll charge and 3 following weeks (Figure 3.19). Based on Figure 3.19, it can be concluded that there is a visible reduction in mean speeds with the free toll policy. 2 and 3 weeks after the beginning of the policy, mean speeds increased to the levels achieved before this policy.

Statistical tests are conducted to compare the traffic flow parameters of these 4 weeks with 95% confidence level in order to understand the effects of the new toll policy. Homogeneity of variances test is done to determine appropriate test type for comparison (Table 3.32).

Table 3.32. Levene test of homogeneity of variances between toll policy periods.

Test of Homogeneity of Variances

	Levene Statistic	df1	df2	Sig.
Flow Rate (veh/hr)	16.705	3	1916	.000
Speed (km/h)	29.281	3	1913	.000
Occupancy %	75.529	3	1913	.000

Levene test demonstrates that there is no homogeneity of variances. Therefore, Welch test is conducted to understand the statistical difference in traffic flow parameters between stages (Table 3.33).

Table 3.33. Welch test for traffic flow parameters during toll policy periods.

Robust Tests of Equality of Means

		Statistic[a]	df1	df2	Sig.
Flow Rate (veh/hr)	Welch	12.608	3	1058.011	.000
Speed (km/h)	Welch	17.320	3	1059.955	.000
Occupancy %	Welch	32.181	3	1048.757	.000

a. Asymptotically F distributed.

From Table 3.33, it can be said that there is statistical difference in mean traffic flow parameters during toll policy periods. Games-Howell test is used to determine in which periods these differences occurred (Table 3.34, 3.35 and 3.36).

Table 3.34. Games-Howell test for flow rate comparison between toll policy periods.

Flow Rate (veh/hr)

Games-Howell

(I) toll	(J) toll	Mean Difference (I-J)	Std. Error	Sig.	95% Confidence Interval	
					Lower Bound	Upper Bound
toll payment	toll-free 1	157.775	77.920	.180	-42.77	358.32
	toll-free 2	209.308*	79.614	.043	4.40	414.21
	toll-free 3	-305.783*	84.170	.002	-522.43	-89.13
toll-free 1	toll payment	-157.775	77.920	.180	-358.32	42.77
	toll-free 2	51.533	86.112	.933	-170.08	273.15
	toll-free 3	-463.558*	90.341	.000	-696.06	-231.05
toll-free 2	toll payment	-209.308*	79.614	.043	-414.21	-4.40
	toll-free 1	-51.533	86.112	.933	-273.15	170.08
	toll-free 3	-515.092*	91.806	.000	-751.36	-278.82
toll-free 3	toll payment	305.783*	84.170	.002	89.13	522.43
	toll-free 1	463.558*	90.341	.000	231.05	696.06
	toll-free 2	515.092*	91.806	.000	278.82	751.36

*. The mean difference is significant at the 0.05 level.

Change in flow rates between the week before the toll policy and 1st week after the beginning of the toll policy is statistically not significant (Table 3.34). However, in the following weeks the change became significant with 95% confidence level.

Table 3.35. Games-Howell test for mean speed comparison between toll policy periods.

Speed (km/h)
Games-Howell

(I) toll	(J) toll	Mean Difference (I-J)	Std. Error	Sig.	95% Confidence Interval	
					Lower Bound	Upper Bound
toll payment	toll-free 1	10.467*	1.718	.000	6.05	14.89
	toll-free 2	7.642*	1.725	.000	3.20	12.08
	toll-free 3	.711	1.639	.973	-3.51	4.93
toll-free 1	toll payment	-10.467*	1.718	.000	-14.89	-6.05
	toll-free 2	-2.825	1.874	.433	-7.65	2.00
	toll-free 3	-9.756*	1.795	.000	-14.38	-5.14
toll-free 2	toll payment	-7.642*	1.725	.000	-12.08	-3.20
	toll-free 1	2.825	1.874	.433	-2.00	7.65
	toll-free 3	-6.931*	1.802	.001	-11.57	-2.29
toll-free 3	toll payment	-.711	1.639	.973	-4.93	3.51
	toll-free 1	9.756*	1.795	.000	5.14	14.38
	toll-free 2	6.931*	1.802	.001	2.29	11.57

*. The mean difference is significant at the 0.05 level.

From Table 3.35, it can be concluded that speeds change significantly after the implementation of the toll policy. However, change in the week before the policy and 3rd week after the policy is statistically not significant.

Table 3.36. Games-Howell test for occupancy comparison between toll policy periods.

Occupancy %
Games-Howell

(I) toll	(J) toll	Mean Difference (I-J)	Std. Error	Sig.	95% Confidence Interval Lower Bound	95% Confidence Interval Upper Bound
toll payment	toll-free 1	-11.372*	1.293	.000	-14.70	-8.04
	toll-free 2	-7.487*	1.211	.000	-10.60	-4.37
	toll-free 3	-7.152*	1.162	.000	-10.14	-4.16
toll-free 1	toll payment	11.372*	1.293	.000	8.04	14.70
	toll-free 2	3.885*	1.464	.040	.12	7.65
	toll-free 3	4.220*	1.424	.016	.56	7.89
toll-free 2	toll payment	7.487*	1.211	.000	4.37	10.60
	toll-free 1	-3.885*	1.464	.040	-7.65	-.12
	toll-free 3	.335	1.350	.995	-3.14	3.81
toll-free 3	toll payment	7.152*	1.162	.000	4.16	10.14
	toll-free 1	-4.220*	1.424	.016	-7.89	-.56
	toll-free 2	-.335	1.350	.995	-3.81	3.14

*. The mean difference is significant at the 0.05 level.

Difference in occupancy level between the week before the toll policy and the weeks after the toll policy is statistically significant with 95% confidence level (Table 3.36). Difference in occupancy between the 2nd week and 3rd week is the only difference which is statistically not important. The statistics of traffic flow parameters in these time periods are given in Table 3.37.

Table 3.37. Descriptives of traffic flow parameters by before and after toll policy periods.

		N	Mean	Std. Deviation	Std. Error	95% Confidence Interval for Mean Lower Bound	95% Confidence Interval for Mean Upper Bound	Minimum	Maximum
Flow Rate	toll payment	120	3224.47	1098.303	100.261	3025.94	3422.99	1033	6020
	toll-free 1	120	3066.69	1313.944	119.946	2829.19	3304.20	808	6467
	toll-free 2	120	3015.16	1362.104	124.343	2768.95	3261.37	714	6510
	toll-free 3	120	3530.25	1488.555	135.886	3261.18	3799.32	895	6929
	Total	480	3209.14	1334.314	60.903	3089.47	3328.81	714	6929
Speed	toll payment	120	68.18	21.860	1.996	64.23	72.13	12	101
	toll-free 1	120	58.03	33.774	3.083	51.92	64.13	17	111
	toll-free 2	120	71.47	37.141	3.391	64.75	78.18	10	110
	toll-free 3	120	76.79	29.673	2.709	71.43	82.16	21	106
	Total	480	68.62	31.788	1.451	65.77	71.47	10	111
Occupancy	toll payment	120	20.64	15.873	1.449	17.77	23.51	1	74
	toll-free 1	120	34.75	22.920	2.092	30.61	38.89	3	66
	toll-free 2	120	27.29	25.759	2.351	22.64	31.95	3	75
	toll-free 3	120	23.88	19.511	1.781	20.35	27.40	2	62
	Total	480	26.64	21.910	1.000	24.67	28.60	1	75

The mean flow parameters during the toll policy time periods are shown in Table 3.37. The overall results show that *compared to the week before the implementation of the toll policy*;

(i) Mean flow rates;

- decreased by 6.49% in the 2nd free week,
- did not change significantly in other weeks,

(ii) Mean speeds;

- decreased by 16.92% in the 1st free week,
- decreased by 12.31% in the 2nd free week,
- did not change significantly in the 3rd free week,

(iii)Mean occupancy;

- increased by 91.67% in the first free week,
- increased by 66.67% in the 2nd free week,
- increased by 58.33% in the 3rd week.

The results indicate that;

(i) At first, congestion level increased due to probable increase in demand for the road.

(ii) Then, congestion level decreased back to the level before the implementation of the toll policy. This is because of probable decrease in demand for the road due to the increased congestion after the toll policy.

3.6.7. Vehicle Classification Analysis

As mentioned in the previous sections, there are only two bridges in Istanbul that connects the continents. All types of vehicles are allowed to use FSM Bridge; on the other hand, only automobiles and bikes are allowed to use Boğaziçi Bridge. In other words, FSM Bridge is the only choice for trucks, busses and long vehicles to cross the strait. Additionally, European side coach station of Istanbul is located near TEM; so buses want to use FSM Bridge even if there is no restriction. The authorities of Istanbul implemented a new regulation, which was valid during construction period, as one of the work zone management strategy. According to this new regulation, buses were allowed to use Boğaziçi Bridge between 0:00-5:00 and trucks are allowed to use FSM Bridge between 0:00-5:00. The change in the vehicle class distribution is analyzed in this section.

Distribution of vehicle types using FSM Bridge between 1st June and 10th September 2012 is shown in Figure 3.20.

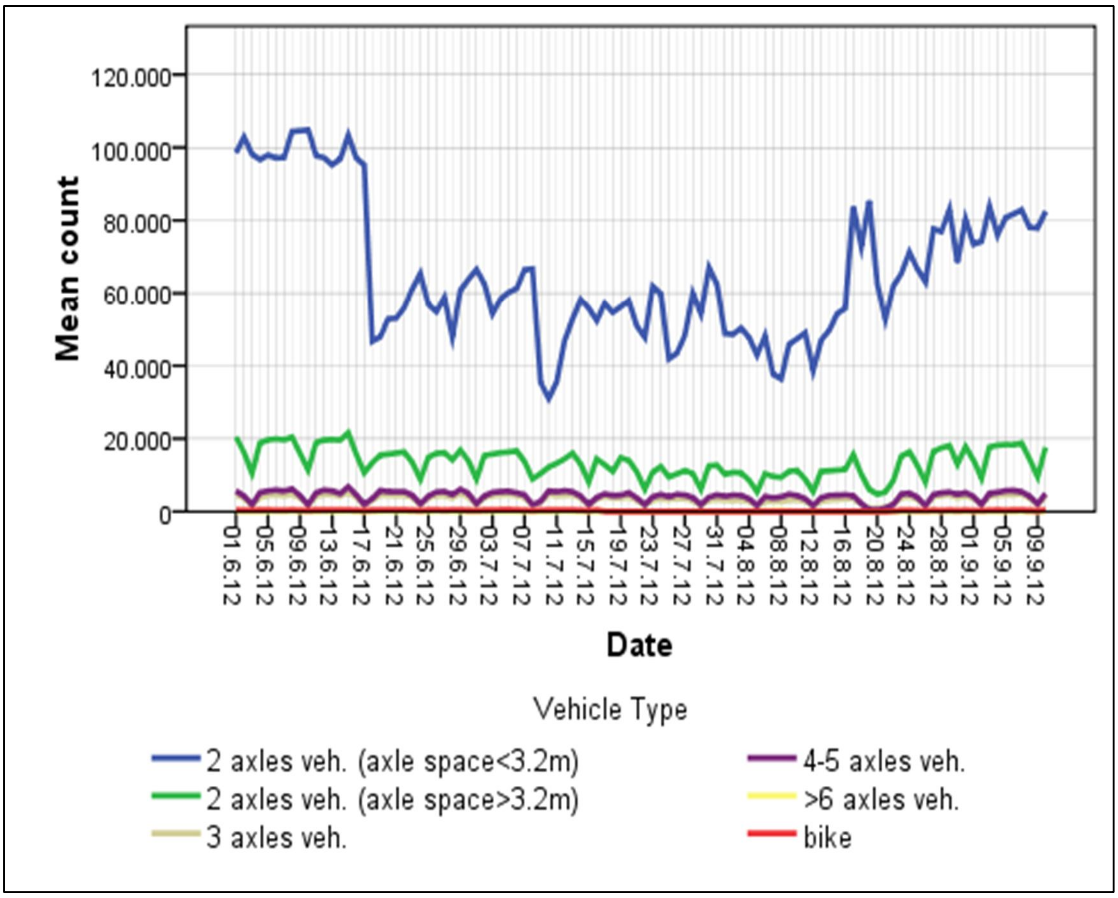

Figure 3.20. Daily vehicle distribution by classes between 1st June – 10th September at toll booths.

As seen in Figure 3.20, proportion of vehicles with 3 axles and long 2 axles are small. However, their attribution to traffic congestion cannot be ignored. Authorities claim that long vehicles are responsible for most of the accidents (TMC, 2012). Besides that they also occupied large amount of space and they create congestion while changing lanes. Distribution of vehicles of 3 axles and 2 axles with axle space higher than 3.2m is given in Figure 3.21.

Implementation of new policy results in a reduction in the number of buses using FSM Bridge (Figure 3.21). A statistical test is conducted to determine if this reduction is significant. Firstly, a test of normality is done to choose appropriate test type (Table 3.38).

Table 3.38. Tests of normality for the vehicle classifications.

Tests of Normality

	Vehicle Type	Kolmogorov-Smirnov[a]			Shapiro-Wilk		
		Statistic	df	Sig.	Statistic	df	Sig.
count	2-axle veh. (axle space<3.2m)	.125	102	.000	.936	102	.000
	2-axle veh. (axle space>3.2m)	.080	102	.106	.978	102	.091
	3-axle veh.	.109	102	.005	.918	102	.000
	4-5-axle veh.	.144	102	.000	.902	102	.000
	>6-axle veh.	.162	102	.000	.778	102	.000
	Bike	.254	102	.000	.788	102	.000

a. Lilliefors Significance Correction

From Table 3.38, it is observed that the assumption of normal distribution of the data is violated for the vehicles with 3 axles. Therefore, Mann-Whitney U test is used to compare the number of vehicles with 3 axles (Table 3.39) and t-test is used to compare the number of vehicles with 2 axles (axle space longer than 3.2m) (Table 3.40). A descriptive table is also presented in Table 3.41.

Table 3.39. Mann-Whitney U test for vehicles with 3 axles.

Test Statistics[a,b]

	count
Mann-Whitney U	179.000
Wilcoxon W	882.000
Z	-4.068
Asymp. Sig. (2-tailed)	.000

a. Vehicle Type = 3 axles veh.

b. Grouping Variable: Stages

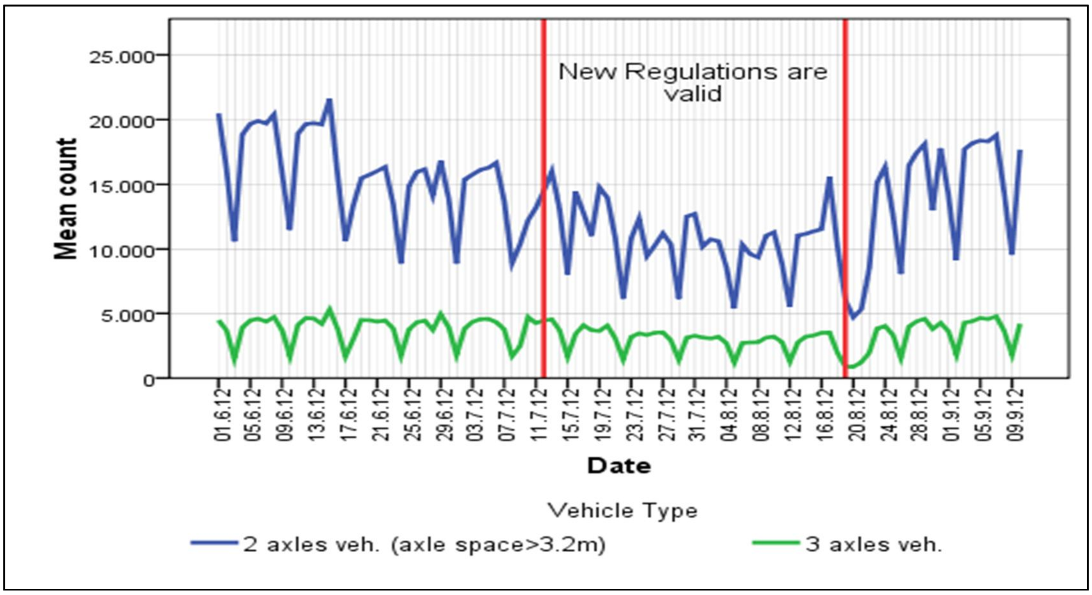

Figure 3.21. Daily distribution of 3 axles and long 2 axles vehicles between 1st June – 10th September at toll booths.

From Table 3.39, it can be concluded that the difference in the number of vehicles with 3 axles between the construction periods before and after the new work zone management strategy implementation is statistically important with 95% confidence level.

Table 3.40. T-test for 2-axle vehicles with axle space longer than 3.2m.

		Levene's Test for Equality of Variances		t-test for Equality of Means						
									95% Confidence Interval of the Difference	
		F	Sig.	t	df	Sig. (2-tailed)	Mean Difference	Std. Error Difference	Lower	Upper
count	Equal variances assumed	.083	.774	5.111	60	.000	3335.012	652.497	2029.823	4640.201
	Equal variances not assumed			5.129	52.281	.000	3335.012	650.231	2030.394	4639.629

a. Vehicle Type = 2 axles veh. (axle space>3.2m)

In Table 3.40, it is observed that there is homogeneity of variances and the difference in the number of 2-axle vehicles with axle space longer than 3.2m between the construction periods before and after the new work zone management strategy implementation is statistically important with 95% confidence level.

Table 3.41. Statistics of vehicles by work zone management stages.

	Stages	N	Mean	Std. Deviation	Std. Error Mean
2-axle veh. (axle space>3.2m)	work zone before management	25	14133.12	2493.526	498.705
	work zone after management	37	10798.11	2538.006	417.246
3-axle veh.	work zone before management	25	3849.16	955.947	191.189
	work zone after management	37	3004.03	788.675	129.657

From Table 3.41, it can be concluded that due to the new regulation about buses and trucks;

(i) The mean number of 2-axle vehicles with axle space longer than 3.2m decreased by 23.60%,

(ii) The mean number of vehicles with 3 axles decreased by 21.96%.

Unfortunately, it cannot be determined that if this policy significantly affected work zone traffic condition; because, execution of this policy started with the other work zone management strategy implementations.

3.6.8. Traffic Flow Analysis of the Alternate Routes

Directing vehicles to alternate routes is an important work zone traffic management strategy. Unfortunately, there are many exits on TEM which have not covered with surveillance systems. On the other hand, the only alternative road to cross the strait is Boğaziçi Bridge. There was an adjacent construction work on the Golden Horn Bridge which is a part of D100 Highway as Boğaziçi Bridge. Hence, there was another traffic congestion caused by work zone near the Boğaziçi Bridge. In order to determine if vehicles are directed to the alternate routes effectively, a capacity analysis is conducted in this section. Daily capacity distribution of Boğaziçi Bridge between 1st June and 10th September 2012 is shown in Figure 3.22.

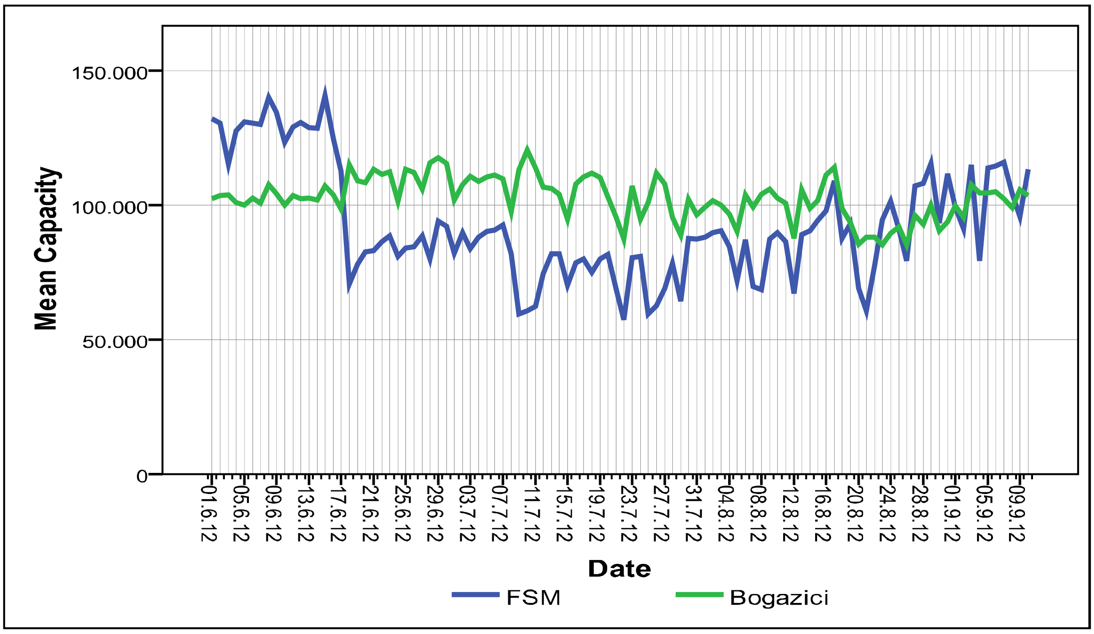

Figure 3.22. Daily capacities of the two bridges between 1st June – 10th September.

Figure 3.22 presents daily capacities of the two bridges in the summer period of 2012. There is a dramatic decrease in capacity of FSM Bridge. At the same time, capacity of Boğaziçi Bridge starts to fluctuate and slightly increased. Mean daily capacities of Boğaziçi Bridge are given in Table 3.42.

Table 3.42. Mean capacities of Boğaziçi Bridge by work zone management stages.

	Mean Capacity	**Standard Deviation**
Before Work Zone	102660	2403.13
Work Zone Before Management	110697	5231.52
Work Zone After Management	101520	6958.17
After Work Zone	91672	4794.48

Mean daily capacity of Boğaziçi Bridge is increased by 8.000 after the beginning of the construction in FSM Bridge. After the implementation of the new work zone management strategies, mean capacity decreased to the level before the construction. In order to determine if these changes are random or statistically significant, statistical tests are conducted. Firstly, homogeneity of variances is checked for choosing statistical test for comparison of means (Table 3.43).

Table 3.43. Test of homogeneity of variances for the capacity of Boğaziçi Bridge.

Test of Homogeneity of Variances[a]

Capacity

Levene Statistic	df1	df2	Sig.
5.908	3	94	.001

a. Bridge = Boğaziçi

From Table 3.43, it can be concluded that assumption of homogeneity of variances is violated. Hence, Welch test is used to determine the difference in capacities is statistically important (Table 3.44).

Table 3.44. Welch test for capacity of Boğaziçi Bridge.

Robust Tests of Equality of Means[b]

Capacity

	Statistic[a]	df1	df2	Sig.
Welch	18.849	3	47.796	.000

a. Asymptotically F distributed.

b. Bridge = Boğaziçi

Based on the result of Welch test (Table 3.44), it can be said that the difference in capacities are statistically significant. Games-Howell test is conducted to determine which differences are important.

Table 3.45. Games-Howell test for capacities of Boğaziçi Bridge.

Multiple Comparisons[a]

Capacity
Games-Howell

(I) Stages	(J) Stages	Mean Difference (I-J)	Std. Error	Sig.	95% Confidence Interval	
					Lower Bound	Upper Bound
before work zone	work zone before management	-7288.290*	1263.169	.000	-10701.07	-3875.51
	work zone after management	1112.101	1277.871	.820	-2287.78	4511.98
	after work zone	6661.600*	1710.864	.004	1932.06	11391.14
work zone before management	before work zone	7288.290*	1263.169	.000	3875.51	10701.07
	work zone after management	8400.391*	1616.371	.000	4124.74	12676.05
	after work zone	13949.890*	1976.552	.000	8622.89	19276.89
work zone after management	before work zone	-1112.101	1277.871	.820	-4511.98	2287.78
	work zone before management	-8400.391*	1616.371	.000	-12676.05	-4124.74
	after work zone	5549.499*	1985.980	.039	213.96	10885.04
after work zone	before work zone	-6661.600*	1710.864	.004	-11391.14	-1932.06
	work zone before management	-13949.890*	1976.552	.000	-19276.89	-8622.89
	work zone after management	-5549.499*	1985.980	.039	-10885.04	-213.96

*. The mean difference is significant at the 0.05 level.

a. Bridge = Boğaziçi

Mean capacities increased significantly after the beginning of the construction. Capacity decreased significantly with the implementation of the new work zone management strategies. Then, capacity did not change after the end of the construction. In summary, mean capacity of Boğaziçi Bridge;

- Increased by 7.83% after the beginning of the construction,
- Decreased by 8.29% after the implementation of the new work zone management strategies,
- Did not change significantly after the end of the construction.

3.6.9. Accident Analysis

One of the main reasons of traffic congestion is incidents in work zones. Accidents at the toll booths and on FSM Bridge are analyzed in this section. The number of accidents occurred in FSM Bridge and in toll booths area during the summer of 2012 is given in Figure 3.23.

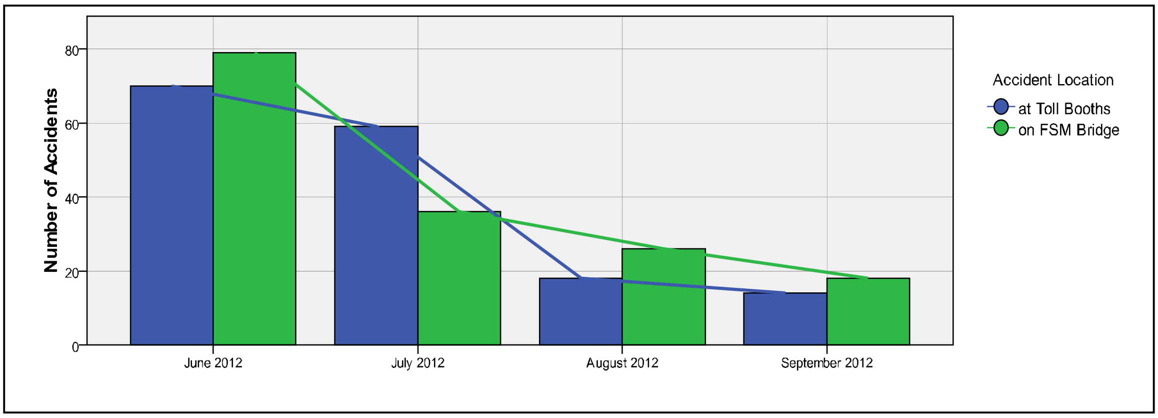

Figure 3.23. Number of accidents at the toll booths and on FSM Bridge.

Number of accidents by months is given in Figure 3.23. As seen, there is a significant reduction in number of accidents. The construction project started in June, the new work zone management strategies were implemented in July and the construction was finished at the end of August. The reason of decrease from June to July can be explained by the decline in mean speed due to construction. On the 12th of July, the number of toll booths was reduced from 21 to 11; i.e., the size of the bottleneck became smaller. At that time, number of accidents at the toll booths decreased nearly 70%. Hence, it can be concluded that relieving the bottleneck is the main reason of reduction in the number of accidents.

4. CONCLUSIONS AND RECOMMENDATIONS

The main conclusions of this thesis are summarized below. Specific recommendations for future improvements are also provided and italicized for emphasis.

(i) A comprehensive research on traffic surveillance system is conducted. Highway traffic surveillance systems used in different countries all over the world is presented. Variety of surveillance systems are used in Istanbul. However, these systems are not sufficient for providing continuous and reliable data. *There is a need for research on traffic surveillance systems to be used in Istanbul. Considering special conditions of Istanbul, e.g. low air quality, appropriate devices should be placed in the highways of Istanbul.*

(ii) A survey on data archiving strategies in the U.S. and Istanbul is done. Istanbul data needs improvement for data archiving. TMC and TCC are responsible for collecting data in Istanbul. TMC archives hourly traffic data. Researchers need more detailed and reliable data for their studies. These data are collected in these two different centers and sometimes they are unwilling to share the data with each other. In addition, GDH is usually reluctant to share data with researchers. These management centers are mainly focused on informing and guiding the drivers with real-time traffic information. On the other hand, Transportation Planning Department of IMM is responsible for traffic analysis and transportation planning; yet, this department does not analyze the traffic conditions regularly. The Transportation Planning Department analyzes traffic, only if there is a project the department assigned with. *A traffic management institute for Istanbul is crucially needed; that deals with (1) gathering traffic flow data from all agencies, (2) properly archiving the collected data, (3) sharing these data with the researchers, (4) archiving academic studies regarding Istanbul traffic and (5) preparing future traffic management plans. This institute should be managed by professional traffic engineers.*

(iii) Evaluation of work zone traffic management strategies was investigated. There are several methods evaluated for estimating capacity of work zones before beginning of the construction. After estimating an approximate capacity, work zone traffic management strategies were evaluated considering past work zone experiences in the world. On the other hand, in FSM Bridge case study the implemented new work zone management strategies are evolved one month after the beginning of the construction with a trial-and-error method. *Work zone management strategies should be evaluated using the analysis of past work zone traffic conditions. These types of experiences should be archived to be used timely in the future.*

(iv) Analyses of work zone traffic management case studies from the U.S. are inspected. *For preparing work zone traffic management strategies, research on case studies all over the world should be reviewed to gain experience.*

(v) A case study of FSM Bridge work zone management strategies was evaluated. Traffic flow parameters were investigated hourly, daily and weekly. This case study was analyzed using four time periods; traffic conditions (stage 1) before construction, (stage 2) from beginning of the construction to the beginning of the new work zone management strategies implementations; i.e. decreased number of lanes, buses and trucks, (stage 3) construction period with new work zone management strategy and (stage 4) after the end of the construction. The results show that in the road section of TEM between Levent entrance and FSM Bridge;

- Mean flow rates
  - (i) decreased by 36.14 % after stage 1,
  - (ii) did not change significantly after stage 2,
  - (iii) increased by 28.92 % after stage 3, (After the end of the construction, capacity increased; however, capacity of the road before the beginning of the construction is 22.5% more than that of after the construction. This difference may be caused by the decreased bottleneck effect due to decreased number of toll booths. Decreased bottleneck effect causes smoothening of the traffic flow. Eventually, mean speeds at the toll booths increases;

whereas mean speeds before the toll booths decreases so that vehicles travel at almost constant speeds).

- Mean speeds
  - (i) decreased by 40.37% after stage 1,
  - (ii) increased by 30.55% after stage 2,
  - (iii) increased by 17.84% after stage 3,

- Mean occupancy
  - (i) increased by 70.67% after stage 1,
  - (ii) decreased by 16.51% after stage 2,
  - (iii) decreased by 20.33% after stage 3.

Additionally, Greenshields´ Model is used to determine critical traffic flow parameters. However, the changes in critical traffic flow parameters are not analyzed statistically. The results of the analyses show that

- Maximum flow rate
  - (i) decreased by 44.79% after stage 1,
  - (ii) did not change significantly after stage 2,
  - (iii) increased by 33.67% after stage 3,

- Free-flow speed
  - (i) decreased by 6.43% after stage 1,
  - (ii) increased by 3.31% after stage 2,
  - (iii) increased by 2.81% after stage 3,

- Jam Density
  - (i) Decreased by 41.38% after stage 1,
  - (ii) Decreased by 6.19% after stage 2,
  - (iii) Increased by 29.68% after stage 3.

(vi) Peak-hours are investigated by the stages of the work zone schedule. After the beginning of the construction, vehicles traveled (a) 18 hours a day at speeds below 40 km/h and (b) 14 hours a day at speeds below 20 km/h. After the implementation of new work zone management strategies, vehicles traveled below 20 km/h for 2 hours a day. This shows that the new implemented work zone traffic management strategies; i.e. decreased number of toll booths and new schedule for the passage time of buses and trucks through the Bridges, were very effective in decreasing number of peak-hours on Thursdays near toll booths.

(vii) A queue length determination analysis was carried out. No data was available regarding queue length or delay time data of Istanbul. Queue length is estimated by observing the average speeds collected from different sensors placed on TEM. In this way, it is possible to see where the speeds dropped below 50 km/h. Based on this method; it was observed that the queue length reached to Seyrantepe that is nearly 5 km away from FSM Bridge during the construction period. Therefore, q*ueue lengths and travel times should be collected and archived for further research. Travel times can be acquired using GPS devices installed on public transportation vehicles.*

(viii) Effect of bottlenecks at the toll booths is analyzed. It is observed that vehicles are traveling at high speeds until they reach the toll booths; then, after passing the toll booths they start to speed up. In other words, vehicles are stuck at the toll booths because of congestion caused by bottleneck. *It is vitally important to decrease the number of toll booths for avoiding bottlenecks. TEM has a 4 lane in one direction and there are 11 working toll booths at the entrance of FSM Bridge. Eventually, bottleneck occurs at the entrance of FSM Bridge. A comprehensive study is needed to determine the most suitable number of toll booths.*

(ix) Congestion at toll booths is investigated. Besides the congestion due to recurrent bottlenecks, different toll payment methods are another important cause of congestion at toll booths. Drivers attempt to change lanes to pass through the toll booth where the payment type is suitable for them. Therefore, congestion occurs due to the vehicles trying to change lanes. This situation is also one of the main reasons of extraordinary number of accidents near toll booths. Long vehicles and trucks do not see automobiles changing lanes and; hence, incidents occur (GDH, 2012). Number of accidents at toll booths and on FSM Bridge is decreased by 78.5% in 4 months with the decreased number of toll booths. *In order to eliminate the bottleneck and the accidents, only single payment model should be implemented at toll booths. It is observed that even using ETC systems, accidents won't diminish without preventing lane changes.*

(x) Toll fee policy during construction period is analyzed. It is concluded that setting the tolls free leads to increase in demand; hence, after this policy average speeds and flow rates decreased significantly. After few weeks, speeds increased to speed levels before construction; because demand decreased due to congested traffic condition. The overall results show that *compared to the week before the implementation of the toll policy*;

- flow rates;
  - (i) decreased by 6.49% in the 2nd free week,
  - (ii) did not change significantly in other weeks,
- speeds;
  - (i) decreased by 16.92% in the 1st free week,
  - (ii) decreased by 12.31% in the 2nd free week,
  - (iii) did not change significantly in the 3rd free week,
- occupancy;
  - (i) increased by 91.67% in the first free week,
  - (ii) increased by 66.67% in the 2nd free week,
  - (iii) increased by 58.33% in the 3rd week.

Free-toll policy had negative impacts on traffic flow. On the contrary, *toll fees should be increased during the construction periods for decreasing the demand. Increasing tolls may also cause the people to prefer public transportation.*

(xi) New policy about buses and trucks for using FSM Bridge is investigated. Based on the statistical results, it is determined that reduction in the number of buses using FSM Bridge is significantly achieved with 95% confidence level. Due to new regulation about busses and trucks;

- The mean number 2-axle vehicles with axle space longer than 3.2m decreased by 23.60%,
- The mean number of vehicles with 3 axles decreased by 21.96%.

Because of the location of the coach station of Istanbul, buses are using FSM Bridge. *This coach station should be moved to the Asian Side. In this way, most of the buses would not use FSM and Boğaziçi Bridges. This would cause reduction in traffic congestion and air quality in Istanbul.*

APPENDIX A: FUNDAMENTAL TRAFFIC FLOW DIAGRAMS OF THE ROAD SECTION BEFORE FSM BRIDGE

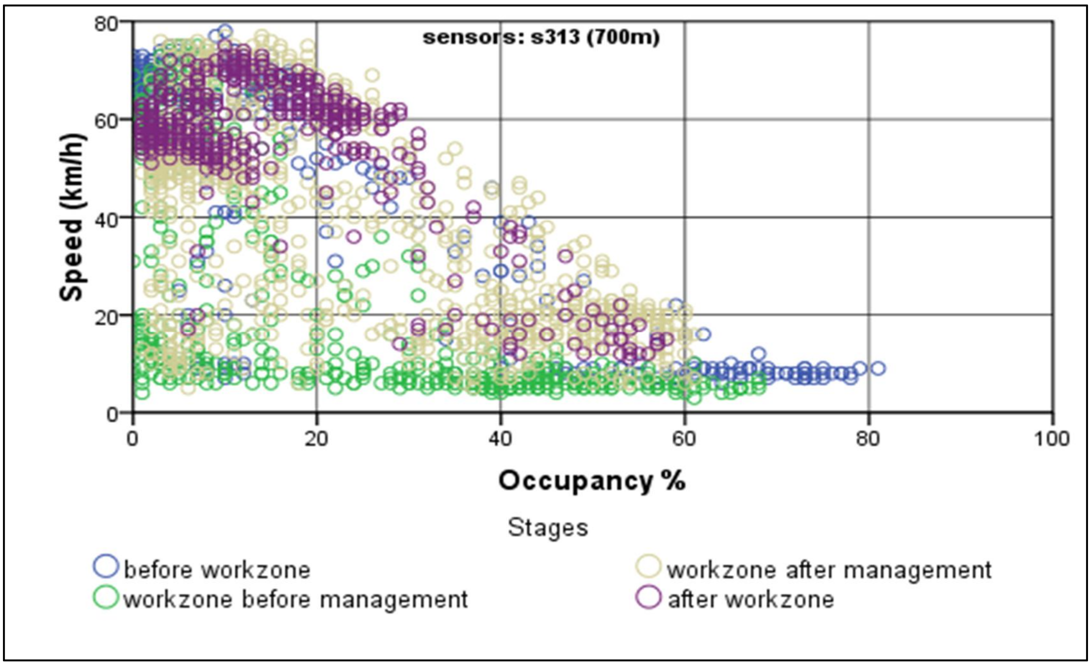

Figure A.1. Speed versus occupancy graph of s313 (700m).

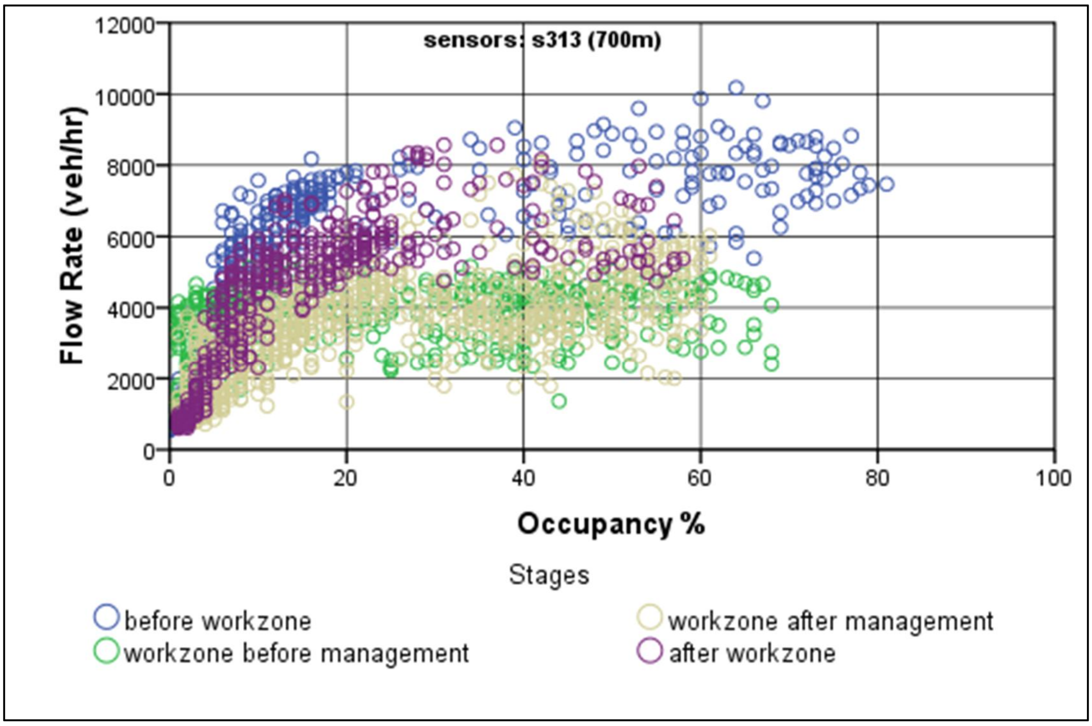

Figure A. 2. Flow rate versus occupancy graph of s313 (700m).

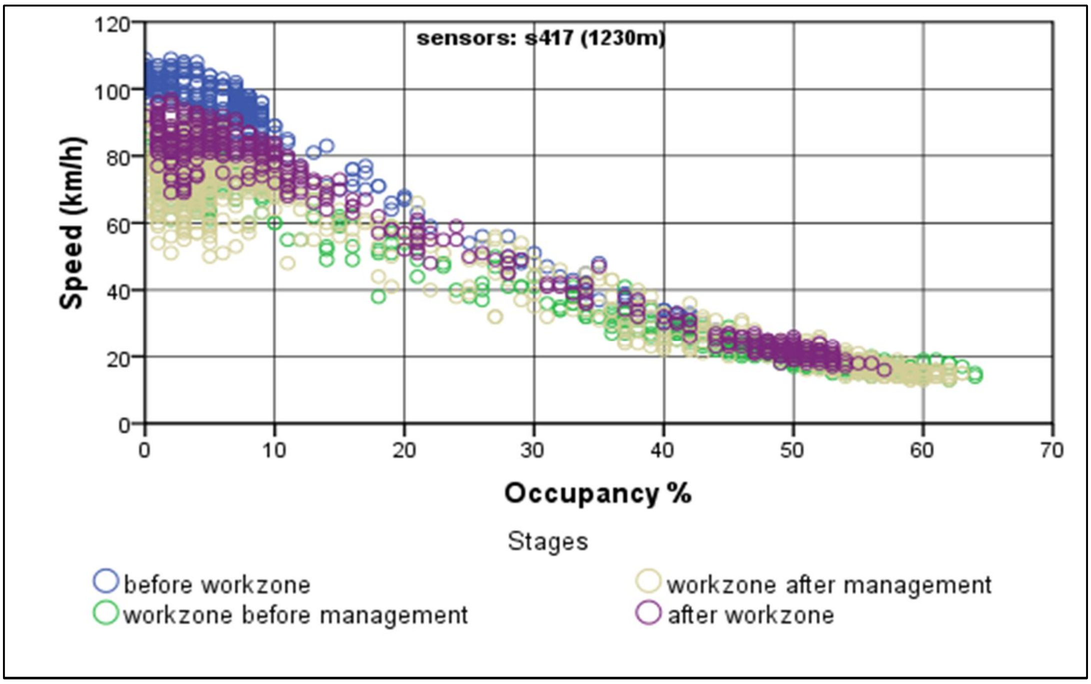

Figure A. 3. Speed versus occupancy graph of s417 (1230m).

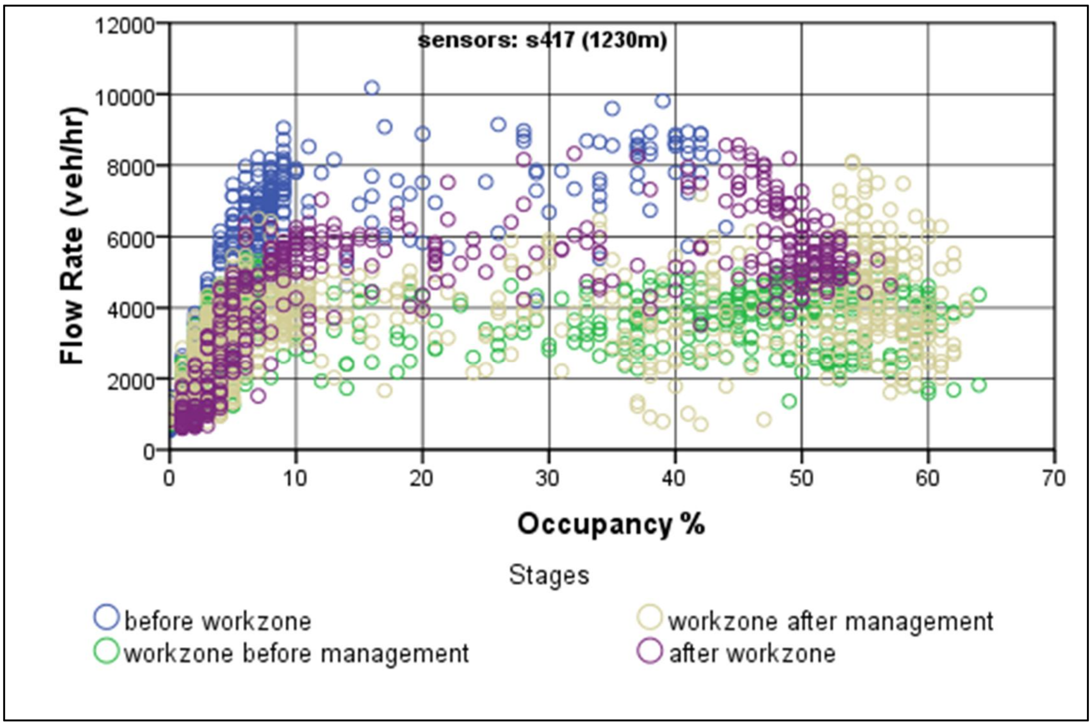

Figure A. 4. Flow rate versus occupancy graph of s417 (1230m).

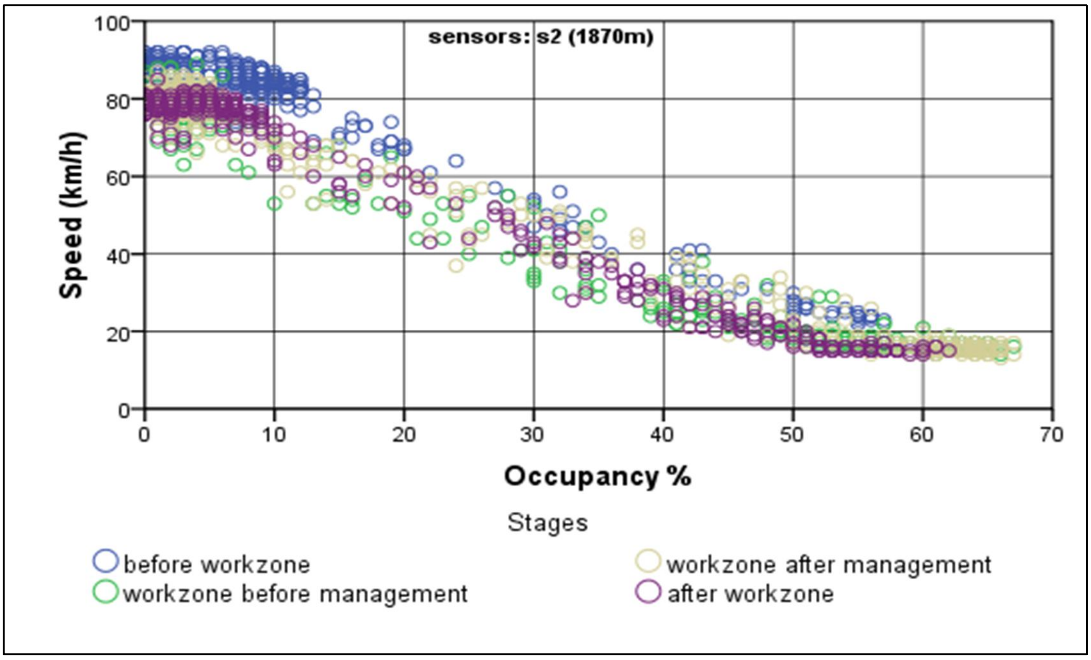

Figure A. 5. Speed rate versus occupancy graph of s2 (1870m).

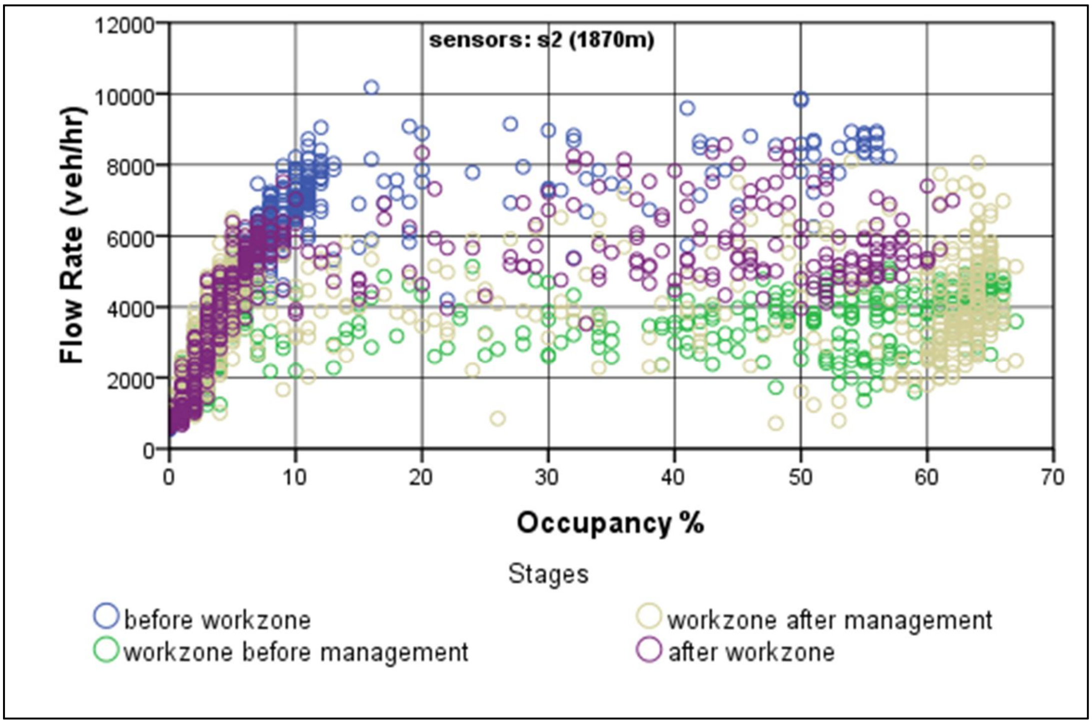

Figure A. 6. Flow rate versus occupancy graph of s2 (1870m).

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