ADDIS ABABA UNIVERSITY

ADDIS ABABA INSTITUTE OF TECHNOLOGY

SCHOOL OF CIVIL AND ENVIRONMENTAL ENGINEERING

Study on Saturation Flow Rate and its Influencing Factors at Signalized Intersections Under Hetrogenous Traffic Condition (The Case of Addis Ababa)

Getacher Negesse

A Thesis Submitted to the School of Civil and Environmental Engineering

in Partial Fulfillment of the Requirements for the Degree of

Master of Science

In

Civil Engineering (Road and Transport Engineering)

Main Advisor: Bikila Teklu (PhD)

Co-Advisor: Helen Zewudie (MSc)

October, 2020

Addis Ababa, Ethiopia

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UNDERTAKING

I, the undersigned, certify that this research work entitled "Study on Saturation Flow Rate and Its Influencing Factor at Signalized Intersections Under Heterogeneous Traffic Condition the Case of Addis Ababa" is my original work and has not been presented partially or in full for any award or degree in any other university or institute. To the best of my knowledge and belief, it does not contain any material previously published or written but all sources of materials used for this thesis have been referred and duly acknowledged. I retain the right to use this content in whole or part in future works such as articles.

Getacher Negesse Anawot
Addis Ababa, Ethiopia
October, 2020

Dedicated

To

My parents and friends who have been my constant source of inspiration to complete the thesis with enthusiast and determination.

Hibst Takele Belete (I don't know what to say)

Tedros Kiros Medhin ***(ETDDY)***

Filimon Kiros Medhin ***(Fila)***

&

To You!

Abstract

In Addis Ababa signalized intersections are the most important and common bottleneck locations because the functional traffic signals are inadequate to the job of handling current traffic levels and poor traffic management strategies. To mitigate capacity-related problems at signalized intersections appropriate allocation of traffic signal timing and providing effective management of signalized intersections have great importance.

The saturation flow is the most important design parameter for traffic signal timing and performance evaluation of signalized intersections. In different cities, various studies have been done to evaluate the saturation flow rate under homogeneous traffic conditions and estimate it only for through movements. However, until now no sufficient study has been conducted on the saturation flow rate at signalized intersections in the case of Addis Ababa for different lane groups under heterogeneous traffic conditions.

Therefore the major objective of this research was to determine prevailing Saturation Flow Rate for specific lane groups at signalized intersections during peak hours the case of Addis Ababa, Ethiopia. The lane groups considered were an exclusive left lane, shared left and through lanes, through only lane, and shared through plus right lanes. Using video recording technique data were collected from 24 approaches of six signalized intersections and HCM 2010 standard procedure was followed in the data collection, extraction, and analysis processes.

The results of the study indicate that both in the morning and afternoon peak hours the highest mean prevailing saturation flow rate was found for the through lane group, while the lowest was to be determined for the exclusive left lane. Generally, the overall mean prevailing saturation flow rate appropriate for Addis Ababa signalized intersections are 1462 vehicles per hour per lane for exclusive left lane, 1446 vehicles per hour per lane for shared left and through lane, 1542 vehicles per hour per lane for through lane movement and 1492 vehicles per hour per lane for through plus right lane. Those prevailing SFRs can be used as input for planning, design, operation, and analyses of signalized intersections in Addis Ababa.

It was determined from ANOVA analysis there was a significant statistical difference between four types of lanes in the morning and afternoon peak hour at 5% significance level. Independent sample t-test shows that there is a statistically significant difference between saturation flow rate values of the lane groups considered in this research.

Acknowledgments

I write this acknowledgment with great honor, pride, and pleasure to pay my respects to all who enabled me either directly or indirectly in completing my MSc thesis.

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List of Abbreviations and Acronyms

ANOVA	ANalysis Of VAriance
AACRA	Addis Ababa City Road Authority
CBD	Central Business District
CCG	Canadian Capacity Guide
ERA	Ethiopian Road Authority
HCM	Highway Capacity Manual
LBS	Leghar Bus Station
MUTCD	Manual on Uniform Traffic Control Devices
SFR	Saturation Flow Rate
SH	Saturation Headway
TMA	Traffic Management Agency
TPMO	Transport Programs Management Office
STATA	Statistical Software Package
Vphpln	Vehicle per Hour per Lane
$\boldsymbol{c}$	Capacity of lanes
$\boldsymbol{S}$	Saturation flow rate
$\boldsymbol{g}$	Effective green time
$\boldsymbol{C}$	Cycle length
$\boldsymbol{t_l}$	Total lost time
$\boldsymbol{t_{sl}}$	Start up lost time
$\boldsymbol{t_{cl}}$	Clearance lost time
$\boldsymbol{G}$	Displayed green time
$\boldsymbol{Y}$	Displayed yellow time
$\boldsymbol{ar}$	Displayed all-red time

CHAPTER ONE

INTRODUCTION

1.1 Research Background and Motivation

An intersection is a location where two or more roads cross each other and used in addressing traffic problems. The intersection may be signalized for several reasons and should be done after an engineering study. The engineering study must include different warrant analysis related to vehicular traffic, pedestrian volume, and crash experiences (MUTCD 2009).

Signalized intersections are key elements and most significant parts of urban transportation network and carry heavy traffic, which, in turn, generates many conflicts and affects the overall performance of the road network. The capacity of signalized intersections is estimated or determined based on two parameters; saturation flow rate (SFR) and allocated green time in traffic engineering practice. The allocation of appropriate green time is based on traffic demand, lane, and phase configurations. However, at local level, different traffic conditions and driving characteristics affect saturation flow rate (Shao et al., 2011).

Traffic signals are mainly used to control traffic movements and stop conflicts among them in urban and semi urban areas of the developing and developed countries. Study of saturation flow at signalized intersections is one of most credible and prompt measure to enhance the capacity of road intersections and reduce the congestion on the roads.

From year to year in Addis Ababa vehicle ownership undergoing rapid increase and creates serious problems such as congestion, the formation of long queues, and increase in the number of crashes. According to Addis Ababa City Transport Bureau latest report in the fiscal year of 2020, the total number of vehicles registered in Ethiopia including motor bicycles and the locally assembled is over 1,200,100. However over half of the totals registered in the country around 630,440 are operated in the capital city, Addis Ababa.

Traffic characteristics and operations particularly in Addis Ababa is very complex due to the heterogeneous traffic stream sharing the same carriageway and there is difficult lane changing behavior among drivers. Within the city the most important and common bottleneck locations are signalized intersections this is due to functional traffic signals prove to be inadequate to the job of handling the current traffic level.

To effectively control different traffic movements, traffic lights are considered if they alleviate more problems than they create. Traffic signals are traffic control devices used to manage the flow of traffic through intersections in a safe and efficient manner. Whether it is for designing new timing plans (to allocate green times) or operational analysis (to determine level of service) of existing ones, traffic engineers require an accurate estimate of the capacity of the signal (Hamad 2015). Therefore, it is important to estimate under prevailing local conditions.

Government institutions like traffic management agency and transport program offices do not typically collect saturation flow rate data as they do for traffic volume count and peak hour factor analysis. Because data collection and extraction are the most challenging aspects in studying saturation flow at signalized intersections. Using default values of saturation flow rate may lead to inappropriate guidance in real-time traffic information, not represent the current flow of traffic, may lead to wrong assessment of delays, leads to under or overestimate of the capacity of signalized intersections and have a strong impact on level of service predictions.

In view of such concerns, the Highway Capacity Manual (HCM) has urged state and local municipalities to conduct field validation of their default saturation flow rates in intersection traffic analyses. One of the emerging vital issues for traffic professionals is to properly select a saturation flow rate and update it in a timely manner to reflect the behavior of their local driving populations. Saturation flow rate is a key variable to calculate the capacity of an approach and used as the basis for the determination of traffic signal timings.

Highway Capacity Manual (HCM 2010), define saturation flow rate as the equivalent hourly flow rate at which previously queued vehicles can traverse an intersection approach under prevailing conditions, assuming that the green signal is available at all times and no lost times are experienced and expressed vehicles per hour of green per lane.

HCM provides general techniques and procedures for the measurement of prevailing saturation flow rates at signalized intersection approaches. It states that the discharge saturation flow rate typically reaches its maximum after about 10 to 14 s of green time, which corresponds to the front axle of the fourth to the sixth vehicle, and the saturation flow rate is the inverse of saturation headway. For measuring saturation headway HCM proposes to commence with the fifth vehicle headway in the queue and end when the front wheels of the last vehicle cross the stop line.

A number of factors influence the saturation flow rate of an intersection approach lane, including geometric, traffic, and environmental conditions can all affect the saturation flow rate HCM 2010. Unfortunately, most of the previous studies on saturation flow rate mainly focus on through lane only but recent studies investigate saturation flow rate for heterogeneous lane types including exclusive and shared lanes (Abuhijleh et al. 2020; Arhin et al. 2016; Shang et al., 2014; Siddiqui 2015). Many researchers pointed that the estimated saturation flow rate is higher than field measurements and the prevailing saturation flow rate was different for morning and afternoon peak hours (Bonneson et al. 2005; Dunlap 2005).

To the best of my knowledge, no study determines prevailing saturation flow rate for different lane groups under mixed traffic conditions especially in the case of Addis Ababa. Therefore the primary aim of this research focuses on studying traffic volume, composition, and overall distribution of discharge headway and saturation flow rate based on field data collected from 24 approaches of selected signalized intersections during morning and afternoon peak hours. To achieve the objectives of the study pertinent literature was reviewed and preliminary survey and site selection criteria were organized to select a suitable signalized intersection.

Based on HCM standard procedure using video recording technique data was collected at all approaches of selected intersections in the morning and evening peak periods. The measurement period starts at the beginning of the green interval and ends when the last vehicle crosses the stop line. Type of vehicles and their headway is recorded when their front axles cross the stop line and all the recorded video data is extracted manually using Avidemux (version 2.6) Software.

Using STATA accurate statistical analysis of prevailing saturation flow rates was done for exclusive and shred lane types at selected signalized intersections in the morning and afternoon peak hours. Finally to ascertain if there were any significant differences between mean saturation flow rate values of different lane groups, ANOVA and independent sample t tests were carried out at a 95% confidence interval.

The outcome of this study provide significant improvements to the capacity of signalized intersections and the recommended saturation flow rates values may be used as input parameters for Addis Ababa city traffic management agency traffic engineers and planners and for other researchers in the area of signalized intersections capacity and saturation flow rate.

1.2 Statement of the Problem

The poor performance of signalized intersections is one important cause of congestion. Some of the reasons for congestion of traffic are poor performance of intersections, variation of traffic volume from one location to another and from hour to hour. A further reason might be that the drivers do not make full use of the available green time because there is no lane disciplined movement at signalized intersections. Additionally, in almost all signalized intersections the phasing arrangement and allocated signal timings for different movements are the same for different peak and off-peak hours of the day.

Addis Ababa city's traffic management agency looking for new answers to deal with the perennial road traffic problems, such as traffic congestion, delay, and safety observed at signalized intersections. Currently, the agency takes different measurements to minimize the above problems including the relocation of the existing signals and normal installation. Studying traffic volume, composition, and saturation flow rate is crucial in determining capacity at signalized intersections which have great importance in planning and designing new intersections as well as modifying existing ones (Rahman et al., 2005).

Different studies recommended the value of saturation flow rate for different cities is based on the through lanes. And other lane types' saturation flow rates are calculated by certain formulas about the through lanes' base rates, which possibly lead to inconsistent results with real traffic (Shang, Zhang, and Fan 2014). Using inaccurate values of saturation flow rate for different lane group types may under or overestimate of the capacity of signalized intersections which leads to congestion, increased traffic delays, unnecessary fuel consumption, and fails to account for driver behavior as well as varying traffic performance (Bonneson et al. 2005; Perez-Cartagena 2004).
Therefore the primary aim of this research focuses on studying traffic volume, composition, saturation headway, and estimation of saturation flow rate at selected signalized intersections during morning and afternoon peak hours in the case of Addis Ababa. The results of this study can help traffic engineers or planners to better estimate and select a "reasonable" saturation flow rate which reflects the local driving population and capacity analysis of signalized intersections to improve the functionality of signals and reduce delays for the vehicles.

1.3 Research Questions

The research objectives are specified into five different research questions:

1) What is the traffic magnitude and share of different vehicles at selected signalized intersections in the case of Addis Ababa?
2) What is the overall queue discharge characteristic of vehicles during the effective green time and its effect on saturation flow rate at the selected signalized intersections?
3) What are the saturation flow rates of different lane types at different signalized intersections during peak periods in Addis Ababa?
4) Is there any probable significant difference between the average values of prevailing saturation flow rate for different lane group types?

1.4 Objectives of the Study

1.4.1. General Objective

To address some of the issues discussed earlier and based on the research questions, the main objective of the study was to study prevailing saturation flow rate and its influencing factors at signalized intersections under heterogeneous traffic conditions in the case of Addis Ababa.

1.4.2 Specific Objectives

The specific objectives of this study are the following:

1) To conduct field studies and discusses traffic volume and composition at all approaches of selected signalized intersections;
2) To investigate the distribution of discharge headway of vehicles based on data collected from the case study signalized intersections in Addis Ababa;
3) To measure saturation headway and determine saturation flow rate of selected signalized intersections as a function of different lane types;
4) To ascertain if there is significant difference between the mean prevailing saturation flow rate value of different lane group types in the morning and afternoon peak hours.

1.5 Scope and Limitation of the Study

Study of saturation flow is one of most credible and prompt measure to enhance the capacity of signalized intersections and to reduce traffic congestion at intersections. Therefore the present study is a step in the direction of realistic computation of prevailing saturation flow rate for different lane types with due emphasis on traffic volume, composition and distribution of discharge headway in the morning and afternoon peak hours.

Generally the scope of study is summarized as follows:

- To collect data based on HCM procedures at different signalized intersections in case of Addis Ababa using video recording technique during morning and afternoon peak hours.
- To compare the morning and afternoon traffic volume and composition at all approaches of selected signalized intersections.
- To study the headway characteristics of vehicles during queue discharge and to determine the saturation headway (hs) for each of case study intersections and lane groups.
- To show and analyze the variability of prevailing saturation flow rate with respect to different types of lanes in the morning and afternoon peak hours in case of Addis Ababa.
- Generally to accurately determine saturation flow rate of different lane groups because using poorly estimated values may lead to incorrect results and inappropriate signal timing plans, this can increase delay and traffic congestion.

The scope of this study is limited to studying saturation flow rate at isolated signalized intersections in case of Addis Ababa even if there are many geometric, traffic, operational and environmental factors affecting saturation flow rate at signalized intersections.

1.6 Research Contribution

The main contribution of this thesis is that it describes the traffic flow characteristics and study the variability of saturation flow with respect to different factors at signalized intersections during morning and afternoon peak hours in case of Addis Ababa. All in one the contributions of this study can be distinguished in two parts: scientific contributions and practical relevance.

1.6.1 Scientific Contributions

The research presented in this thesis is a kind of foundational work for the study of saturation flow rate at signalized intersections which have mixed traffic flow.

- It is expected that the knowledge provided in this dissertation will open up new concepts about saturation flow rate under mixed traffic condition and will provide valuable information to traffic engineers and policy makers.
- Transportation Planners or policy makers may develop new strategies and provide funds for installation normal and portable signalized intersections.
- Getting new insight about traffic volume and composition which is extremely crucial in attempting capacity of signalized intersections during different peak hours of day.
- Time of day analysis is important for the traffic engineer to acquire general knowledge.

1.6.2 Practical Relevance

Since precise and accurate measurement of saturation traffic flow is critical for supporting traffic operations, this study aims to offer an efficient input to analyze overall capacity as well as determining value of saturation flow rate for different traffic movements. The results attained from this study have important implications in practice and the following are some of them.

- Traffic engineers and transportation planners may find value in the results of this study to allocate new signal timings based on time of day for different traffic movements.
- Determination of prevailing saturation flow rate during different peak hours is important to choose mode of phase for exclusive and shared lanes (protected or permitted).
- The outcomes of this research have prime importance for setting traffic signal timings, developing saturation flow rate models and determining local base saturation flow rate.
- The results of this study used as basis to evaluate performance of signalized intersections and allocating the optimum signal timing.

1.7 Structure of the Study

The research work presented in this document structured in the manner from giving general background to the main work results, finally conclusions and recommendations. This thesis consists of five chapters and a brief outline of each chapter is given below.

Chapter one includes general background and motivation of the study, clear problem of statement, main research questions and objectives, scope and limitations, some relevant contribution and significance of the study. Finally chapter one presents the overall outline and brief summary of every chapter of the thesis.

Chapter two presents summary of the literature review on the topics of fundamental traffic flow at signalized intersections. This chapter further discusses various factors influencing saturation flow rate. Chapter two also covers exhaustive related work review of saturation flow study at signalized intersections under mixed traffic condition. Finally under this chapter there is summary of the overall literature review and identified knowledge gaps.

Chapter three develops and explains a comprehensive research methodology in order to achieve the aim and objectives of this study. This chapter delineates the overall data collection plan starting from conducting pilot survey up to general description of the selected signalized intersections. On the other hand under the chapter gives detail about data collection techniques and elaborate types of different lane groups and vehicle categories considered for further analysis. At the end chapter three presents detail data extraction and analysis methodology.

Chapter four presents the schemes considered for this research and discussions about the obtained results. Under this chapter both in the morning and afternoon peak hours traffic volume, composition and saturation flow rates are estimated and discussed at all selected signalized intersections and lane groups. Additionally chapter four includes the statistical tests to analyze the variation of saturation flow rate among different lane groups.

The final section of this thesis is covered by chapter five which provides significant conclusions and recommendations from the outcomes of the study. Also it gives the directions for future research directions on studying saturation flow rate under different traffic scenarios.

CHAPTER TWO

LITERATURE REVIEW

2.1 Fundamentals of Traffic Flow at Signalized Intersections

Fundamental of traffic flow at signalized intersections include vehicle and pedestrian flow characteristics and understanding the magnitude of traffic flow is important to express the flow properties, and to keep safety of traffic signals. All the following sections are discussed based on the general guidelines provided in (CCG 2008; HCM 2010) with special consideration on concepts and definition of terms most widely used at signalized intersections.

2.1. 1 Signalized Intersection

An intersection is an area or at-grade junction where two or more roads or streets meet or cross.

Guiding vehicles to their respective direction is the main function of intersection which may be signalized or unsignalized intersection. Traffic intersections should be able to serve their varying traffic demands, provide minimum delay in passage, and maximum safety to all types of users especially pedestrians. In most of urban areas intersections are signalized in order to address a number of issues including road safety (reducing a number of conflicts), operational efficiency and crossing opportunities for road users especially pedestrians and cyclists.

Signalization is the most common strategy used to control the flow of traffic at an intersection in order to improve the safety and efficiency of traffic flow. It solves the competition of different traffic movements by providing right of way in a cyclic manner to conflicting traffic at intersections. According to Manual on Uniform Traffic Control Devices (MUTCD 2009) the installation of a traffic signal control is justified based on the investigations of engineering study, signal warrant analysis and requests for traffic signal installations. An engineering study includes the overall traffic conditions, pedestrian activities and number, the physical or geometric characteristics of the intersection and the distance to other signalized intersections etc.

A signalized intersection is one where the shared space is used alternatively by a fixed number of approaches and operated with the assistance of a traffic signal. The basic function of signalized intersections is to sequence right-of-way between intersecting streams of users and allow all road users to access new streets and change in the direction of travel (Kyte and Tribelhorn 2014).

2.1.2 Types of Signal Control

Traffic signals are the most successful device in alleviating conflicts of movements at intersections by allocating time and space. Efficient regulation of traffic signals is called traffic signal control which is an important and challenging problem in area of traffic engineering. Signalized intersection control can generally be classified into two main types of signal control are Pretimed (or fixed) and actuated signal operation with many sub-categories as well.

A) Pretimed Signals

Under pre timed control the intersection is operated using predetermined, fixed cycle lengths, splits and offsets. In the case of fixed time traffic signals, the cycle time and each signal phase are fixed and serviced in programmed sequence. All GREEN, YELLOW, ALL-RED, and RED intervals are constant, repeating themselves in each cycle throughout the day or during different periods of the day. Fixed signal timing plans are often used as a foundation for developing traffic actuated types of intersection control.

B) Actuated Signals

Actuated traffic signal control or regulation differs from pre-timed because it does not rely on a fixed cycle length. Through the use of vehicle detectors and pedestrian push buttons this type of control assigns the right of way on the basis of current traffic conditions (demand).

Fully-Actuated Operation:

Fully-actuated control requires sensors in all legs of intersection phases with each phase timed according to preset parameters. Fully actuated control is primarily used at the intersection with approximately equal volumes with varying traffic distribution in all approaches.

Semi-Actuated Operation:

Semi-actuated signals are partially controlled signals and operate automatically by installing detectors only on the minor cross street. In these cases when the detector activated, the green light on the major road is interrupted to allow the minor road traffic to safely enter the intersection. Otherwise the signals remain green on the major road all the periods until a vehicle is detected or a pedestrian pushes the pushbutton to cross the main street. Generally semi-actuated signals are effective measures at intersections where the major street has a relatively uniform flow and the minor street has low volumes with random peaks.

2.1.3 Traffic Signal Indication

Traffic control signals are automated traffic control devices used to manage the flow of traffic in a safe and efficient manner by warning or directing target road users. As basic part of a traffic signal is its indication, it must be seen for the driver and pedestrian to react and make the required action. Indication of a signal means the information or meaning conveyed by the aspect of a signal which indicates how the traffic signal transmits information to the driver. The following are some of the traffic light indications:

- Green color represents the time for which a particular stream can utilize the intersection is referred to as the green time for that stream or movement.
- Red color indicates the time during which a particular movement cannot utilize the intersection is referred to as the red time for that movement.
- Amber or yellow light indicates that the red arrow is about to be displayed and the drivers must stop. But if the drivers entered the intersection during amber time they can go through the intersection in safely manner.

2.1.4 Traffic Signal Timers

The two types of traffic signal timers are countdown and without countdown signals. Countdown signals inform the road user (driver or pedestrian) about the remaining time to pass through intersections. Non-countdown signal control informs the drivers by flashing the yellow light indicating that green light to be displayed. Currently in Addis Ababa most of the intersections are converted in to without countdown timers with aim to reduce encroaching vehicles after the stop line. Within the city pedestrian countdown timers are now installed at newer signal intersections.

2.1.5 Signal Head Placement and Visibility

Traffic signals should be placed so the signal heads are visible at a distance upstream of the intersection and from all lanes on the approaches of intersections. Appropriate placing of traffic signals reduces rear end conflicts and collisions. In case of Addis Ababa most of the traffic signals are arranged vertically and the red light is above the green, with amber between. In the future the traffic management agency of the city plan to installs traffic signals arranged horizontally or sideways and the sequence is from left to right (red–amber–green).

2.2 Theoretical Framework

2.2.1 Capacity of Signalized Intersections

Before explaining the processes of determining saturation flow rate, which is the key parameter used in this research, this section aims to explain how saturation flow rate is used by traffic engineering researchers and practitioners.

According to HCM capacity is defined as the maximum sustainable hourly flow rate when persons or vehicles pass a point on a highway on a particular lane on particular direction in unit time under prevailing, geometric, traffic, environmental and other control conditions. The prevailing and operational characteristics present at the intersection affects the capacity of signalized intersections which is dependent of the capacity of approach or lane groups. For designing new timing plans (to allocate green times) for newly installed traffic signals or operational analysis of existing signalized intersections (to determine level of service), traffic engineers require an accurate estimate of the capacity of the signal (HCM, 2010).

Estimation of capacity at signalized intersections is one of the most important topics in traffic engineering and determine based on saturation flow rate, effective green time and the total cycle length of an approach. In other words capacity is an adjustment of the saturation flow rate by effective green time ratio that takes the real signal timing into account, since most signals are not allowed to permit the continuous movement or display of green time for full hour.

The proportion of the hour that is effectively available for a given movement is called the *effective green ratio*, or the ratio of the effective green time to the cycle length. The capacity of an approach or a lane is thus defined as the product of the saturation flow rate and the effective green ratio, as given below.

$$c = S({}^{g}/_{C})$$

Where

c = capacity of lanes serving movement i, vph or vphpl,

S = saturation flow rate for movement i, vphg or vphgpl,

${}^{g}/_{C}$ = effective green ratio (effective green time divided by cycle length),

g = Effective Green Time sec, and

C = Cycle Length, sec.

2.2.2 Saturation Flow Rate

Saturation flow rate is critical component in the analysis of signalized intersection capacity and can be defined as the flow in vehicles per hour of green that can be accommodated by different lane groups by assuming that in each movement green time is displayed 100 percent of total cycle time. 3As given in the equation below the total number of seconds in an hour (3600) should be divided by the saturation headway to calculate the saturation flow rate. The reason behind using the total seconds in the hour is that traffic signal at the intersection should be remains green throughout the full hour in order to achieve saturation flow at approaches of intersection. The headway between vehicles departing at the saturation flow rate is called the *saturation headway or average headway*.

Saturation flow rate as defined previously is simply the average headway converted to an hourly rate. It is calculated as follows:

$$Saturation\ Flow\ Rate = \frac{3600}{Average\ Headway}$$

The fifth edition of the Highway Capacity Manual (HCM 2010) proposes a base saturation flow rate of 1900 passenger cars per hour per lane, based on the average headway of vehicles queued after the fifth vehicle. But the manual provides adjustment factors to account for the effect of prevailing traffic and geometric conditions. The saturation flow rate for each lane group (HCM, 2010) is calculated by:

$$\boldsymbol{SF = S_o * N_{Lanes} * (f_{Geometry} * f_{Traffic} * f_{Parking} * f_{\dots})}$$

Where:

$\boldsymbol{SF}$: Maximum flow a section can handle under prevailing use;

$\boldsymbol{S_o}$ **:** Capacity of a given standard ideal roadway section;

$\boldsymbol{N_{Lanes}}$**:** Number of lanes;

$\boldsymbol{f_{Geometry}}$**:** Adjustment factor to account for geometric conditions;

$\boldsymbol{f_{Traffic}}$**:** Adjustment factor accounting for traffic conditions;

$\boldsymbol{f_{Parking}}$**:** Adjustment factors to account for parking conditions;

$\boldsymbol{f_{\dots}}$**:** Represents other adjustment factors to accounting for various nonideal conditions.

2.2.3 Lost Time

During green time traffic entering an approach of signalized intersection does not discharge at full rate since drivers do not react immediately to the change of signal indications vehicles need to accelerate and some portion time is lost. This means that a portion of the cycle cannot be completely utilized and the time is called *lost time or start up delay*.

Start-up lost time is defined as the additional time, in seconds, which is occurred at the beginning when the signal indication turns from red to green and vehicles are accelerating from a stopped position. It is consumed by the first few vehicles to react to the initiation of the green phase (due to the perception-reaction time) and need to accelerate to a desired speed. The total start-up lost time is the time interval between the initiation of green and the commencement of effective green time and computed using the following equation:

$$\boldsymbol{t_{sl} = \sum_{i=1}^{n} t_i}$$

Where

$\boldsymbol{t_{sl}}$ = Total start up lost time in seconds,

$\boldsymbol{t_i}$ = Lost time for ith vehicle in seconds,

$\boldsymbol{n}$ = Position of queued vehicle where lost time starts to occur uniformly.

A second lost time known as clearance lost time occurs at the end of the green light when the flow of vehicles stops. This lost time is measured as the time interval between the time the last vehicle entering the intersection and the termination of effective green on the next signal phase. Clearance lost time is the portion of clearance interval time (yellow or all red interval) which is used for stopping the movement of vehicles at the end of a green time because some traffic may continue flow, even during yellow.

Generally at signalized intersections lost time is occurred at the beginning and ending of the phases. Total lost time is the time when an intersection is not effectively not used by any critical movements even if the traffic signal displaying a green.

As per HCM, startup delay or startup lost time is the time lost at the beginning of the cycle for the traffic stream to start moving. It can be easily calculated by deducting the average headway from the time taken by the first four vehicles to enter the intersection. It is calculated as follows:

$$\text{Startup Delay} = T_4 - 4(Average\ Headway)$$

2.2.4 Effective Green Time and Effective Red Time

Effective green time is one of the key parameters used to calculate the capacity of signalized intersections and it is the time during which a given set of traffic movements are allowed to proceed at saturation flow rate. Effective red time is the *period* in the signal where drivers do not allowed to inter the intersection which indicates the intersection is not *effectively* used.

The total cycle length time minus the effective red time gives the time during which a traffic movement is effectively utilizing the intersection or effective green time. In other words, the effective green time can be determined using the following equation:

$$g = G + Y + ar - t_L$$

Where:

g = effective green time in seconds,

G = displayed green time in seconds,

Y = displayed yellow time in seconds,

ar = displayed all-red time for a movement in seconds, and

t_L= total lost time during a given cycle in seconds.

Likewise, the cycle that is not available to serve traffic or effective red time can be known by subtracting the effective red time from the cycle length. Optionally, the effective red time can be determined using the following equation:

$$r = R + t_L$$

Where

r = Effective red time in seconds,

R = Displayed red time in seconds, and

t_L = Total lost time for a cycle in seconds.

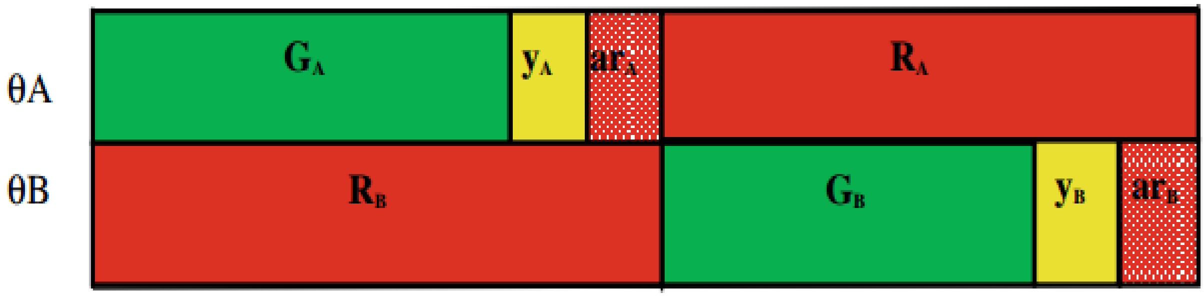


Figure 2.1 Relationships between Signal Intervals at Two Phase Signal

2.2.5 Optimum Cycle Length

The cycle length is the total time to complete one full cycle of iterations and determines how frequently each movement is served in an hour. Cycle lengths may be short or long which is dependent on a number of traffic conditions including intersections total lost time and critical lanes flow ratio. Shorter cycle lengths do not provide adequate green time for all phases but yield the best performance in terms of providing the lowest overall average delay during low peak periods. While longer cycle length leads to increased delays and queues for all users but it will accommodate more vehicles per hour when the intersection is heavily trafficked. Generally to effectively alleviate or prevent traffic congestion and to minimize the average travel delay a reasonable cycle length is required referred to as optimum cycle length.

2.2.6 Discharge of Vehicles at a Signalized Intersection

The type of traffic flow observed at signalized intersections is interrupted flow which is regulated by an external means, such as a traffic signal and affected by vehicle-vehicle and vehicle-roadway interactions. The most fundamental factor governing signalized intersections flow is the process by which vehicles depart from standing queue which was formed when traffic signal turns red. Platoons of vehicles are created and discharged at signalized intersection, because traffic is systematically stopped and restarted.

The major factor that influences the design of and analysis of traffic signals at signalized intersections is rate at which vehicles discharge from standing queue. The distribution of discharge headways is influenced by a number of geometric, traffic and signal timing factors.

Figure 2.2 shows a conceptual plot of discharge headways at signalized intersection. From the figure it can be observed that when the signal turns to green the queued vehicles during red time will start moving. The headway between vehicles can be observed as the vehicles cross the stop line of the signalized intersection. The first vehicle’s headway is measured as the time elapsed from the start of green to the time it crosses the stop line. The second headway is the time interval between the first and second vehicle crossing time. In general, the headway value corresponding to the i^{th} vehicle was determined by subtracting the crossing time of $(i-1)^{th}$ from its crossing time. Similarly, vehicles coming towards an intersection and forming a queue during red time and departing one by one by following its leading vehicle (HCM 2010).

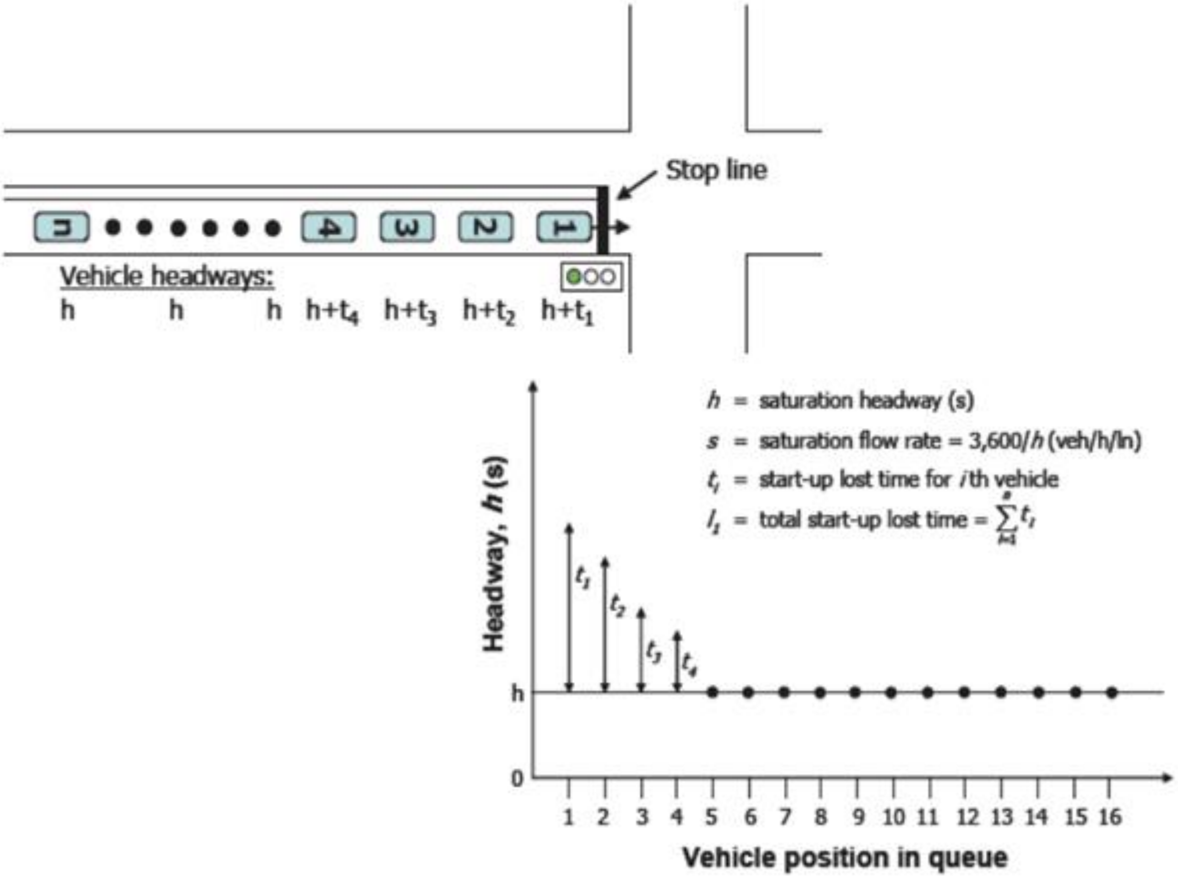


Figure 2. 2 Illustrations of Discharge Headways at a Signalized Intersection

As shown in the figure the first headway is generally the longer than other, because as the first driver must observe and react when the signal changes to green. Perception reaction sequence and time required to accelerate the vehicle from a standing stop position makes the first headway comparatively longer. The second headway is lower as compared to the first, as the second driver only requires time to accelerate because the perception reaction time was overlapped with the first driver. It indicates the second driver had an extra vehicle length in which to accelerate which makes the second vehicles headway lower than the first and higher than the third. This process repeated by all following vehicles where each vehicle's headway will be slightly lower than the preceding vehicle. Then subsequent vehicles departed at saturation flow by creating a more stable or constant headway called saturation headway (h) as shown in the above figure. The HCM finds out consecutive vehicles reach a constant headway after the 4th or 5th vehicle and the accepted value recommended is 1.9 seconds.

2.3 Types of Saturation Flow Rate

The Highway Capacity Manual, HCM (2010) defines saturation flow rate as the maximum hourly flow rate for a traffic lane measured at the stop line during the green phase of a signalized intersection approach, assuming that green signal is available all the time and no time loss are experienced by the vehicles and expressed in vehicles per hour per lane. Base, prevailing and adjusted saturation flow rates are the three different terms related to saturation flow rate at signalized intersections.

According to HCM 2010 the base saturation flow rate represents the saturation flow rate value under ideal conditions, including: lane width of 3.6 m, level terrain, no parked vehicles, no heavy vehicles and turning vehicles, no pedestrians, and even lane utilization. The manual proposes a base saturation flow rate value of 1900 pc/h/ln.

The other type of saturation flow rate is prevailing saturation flow rate which is measured in the field for a specific lane group at a specific intersection under certain prevailing conditions. It varies significantly from one lane group to another and from one intersection to another because it is affected by a number of prevailing, geometric, traffic and other control factors.

Adjustment of saturation flow rate is needed if it is not possible to measure it for prevailing geometric, traffic and environmental conditions. This saturation flow rate is called adjusted saturation flow rate and computed using formulas provided in the manuals. To estimate SFR without field measurement HCM 2010 adjust the base saturation flow rate with eleven different adjustment factors that are related to prevailing site traffic and geometric conditions.

$$\boldsymbol{S = S_0 N f_W f_{HV} f_g f_p f_{bb} f_a f_{LU} f_{RT} f_{LT} f_{Rpb} f_{Lpb}}$$

Where

$\boldsymbol{S}$ = adjusted saturation flow rate for the lane group in vehicles per hour per lane

$\boldsymbol{S_0}$= base saturation flow rate in passengers car per hour per lane

$\boldsymbol{N}$ = number of lanes in the approach or lane group

$\boldsymbol{f}$ = adjustment factor for prevailing condition (W for lane width; HV for heavy vehicles; g for approach grade; p for parking activity; bb for local bus blockage; a for area type; LU for lane utilization, LT for left turn, RT for right turn; Rpb = pedestrian/bicycle interference with right turns; and Lpb = pedestrian/bicycle interference with left turns)

2.4 Various Factors Influencing Saturation Flow Rate

Saturation flow rate is the most important factor in the performance measure, geometric design, control and operation of signalized intersections. Several researchers have underlined the importance of saturation flow rate and studied different factors influencing saturation flow rate. A number of factors influence saturation flow rate of an intersection approach lane, including geometric, traffic, operating conditions, environmental and other control factors. The following paragraphs summarize some of the details of the major factors.

Geometric elements that are important for saturation flow rate estimation include gradient and width of approach, width and number of lanes number of lanes, type of lanes, accommodation of turning movements and its radius, curbside parking maneuvers, and road surface conditions etc. A sufficient amount of studies on saturation flow rate at signalized intersections and the influences of geometric factors on saturation flow have been examined by many studies (M M Bruwer, C J Bester 2019; Savitha et al. 2017; Yadav and Marsani 2019) and their finding show that a number of roadway geometry factors have significant impact on the value of saturation flow rate.

An extensive literature review was conducted on the topics of traffic factors affecting saturation flow rate. Biswas et al., 2018; Kulakarni et al., 2020; Preethi & Ashalatha, 2017 examined the effect of traffic factors including heterogeneous traffic condition and concludes that saturation flow rate is significantly affected by different traffic situations. Generally traffic factors influencing saturation flow rate includes traffic composition, presence and type of turning movements, U-turn behavior of vehicles, presence of public transport facilities and pedestrian activities, traffic condition.

Different types of operating conditions at signalized intersections affect the maximum flow rate due to the reasons of signal timing and phasing arrangements, vehicle position in the queue, peaking characteristics, lane discipline characteristics, taxi blockages, and bus stop operations or presence of frequent bus stops. Some studies examined the influence of operating characteristics at signalized intersections on saturation flow rate. Hajbabaie et al., 2017; Hashemi, A.H.; Nakamura, H.; Goto, 2017; Ranasinghe & Bunker, 2018 study the effect of upstream intersections due to coordination affects and downstream bus stops and bicycle lanes on saturation flow rate respectively.

Under mixed traffic conditions the effect of encroaching vehicles on saturation flow at signalized intersections were studied by (Ramireddy, Sala, and Ravishankar 2020) and conclude that encroaching vehicles (vehicles standing beyond the stop line when red is given to that particular approach) has a significant effect on the value of saturation flow rate.

Several researchers have underlined the importance of investigating the influence of environmental and other controls on saturation flow rate at signalized intersections. Environmental and other control factors influencing saturation flow rate are; different types of weather conditions (sunny, cloudy, rainfalls, snowfalls etc), driver behavior, population of the intersection area, adjacent land uses, time of day, information points, speed limit, location and size of the city. Saturation flow at an intersection is influenced by the environment of individual approaches which inludes cenetral business and non centeral business areas, commercial deliveries and driveway turns etc.

Various studies have suggested that the saturation flow rate varies according to the environmental conditions and number of other factors that reflect the local area conditions.

Asamer & Van Zuylen, 2011; Chodur, Ostrowski, & Tracz, 2011; Sun et al., 2013 investigate effect of different weather conditions including sunny, cloudy, rainfalls, snowfalls etc on saturation flow rate at signalized intersections. The researchers conclude that bad weather conditions have large impact on the value of saturation flow rate and inconsistency in the value of saturation flow rate may be observed at different signalized intersections.

The influence of driver behaviour on saturation flow rate was investigated by (Al-Hamadani & Al-Arkawazi, 2019; Al-omari, 2015) based on actual field saturation flow rate measurement at signalized intersections. They conclude that driver behavior has a significant influence on the saturation flow rate and identify two types of driver behaviors; non aggressive (conservative) with high saturation headway and aggressive driver with reduced saturation headway.

Violations by users such as pedestrians and motorcyclists are the most problematic traffic behaviors at signalized intersections in developing cities which lead to reduction in saturation flow rate and increased delay. Analysis of the impact of users' violations on the saturation flow rate at signalized intersections was estimated by (Melerdi and Boroujerdian 2018; Rachchh et al. 2019) and recommends that traffic rules for pedestrian movement and other road users should be enforced and effectively managed to reduce the effect on flow of vehicles.

2.5 Related Work

Previous studies have emphasized the importance of evaluating and determining saturation flow rate under prevailing local conditions at signalized intersections. The following paragraphs summarize previous studies conducted on saturation flow rate.

A study which is focused on determining prevailing SFR value for specific lane groups was conducted by (Arhin et al. 2016) in an urban area of Canada. The major objective of the study was to determine and compare the prevailing saturation flow rate values of through, shared through and right, shared through and left, and exclusive left turn lane groups. Based on the procedures described in the HCM data on vehicle discharge headway for each type of lane groups were during the morning and evening peak hours.

According to the study in the morning peak hour the highest and lowest mean prevailing SFR was recorded at through and exclusive left lane groups with 1577 vphpl and 1451 vphpl respectively. Again in the evening (PM) peak hour the through lane group had the highest mean prevailing SFR value with an average value of 1542 vphpl, while the shared through and right lane had the lowest (1,426 vphpl). The study concludes that at 5% significance level mean prevailing SFR values of all lane group types are statistically similar.

Based on HCM 2000 procedures (Dunlap 2005) measure ideal saturation flow rate in the field in USA with main objective checking the appropriateness of 1,800 pc/h/ln because the engineers use this lower ideal saturation flow rate in Pennsylvania. The study has also additional objectives to compare ideal saturation flow rate by types of country, lane type, approach grade, lane width, percentage of heavy vehicles, and atmospheric conditions.

Data were collected in the four counties and the data collection was performed in accordance with the Highway Capacity Manual 2000. The three lane types considered in the study are exclusive left-turn lanes, exclusive through lanes, and shared through and right or left-turn lanes. According to the study the determined average ideal saturation flow rate was 1701 pc/h/ln, which is clearly below the value suggested by the HCM. It was hypothesized that if a significant difference emerged among the various lane types. Based on single factor ANOVA analysis result there was no statistical difference in the three categories at a 95% confidence level.

Shang et al., 2014 conducted study at 36 signalized intersections in Beijing to examine SFR of heterogeneous lanes which includes right, left, through, through right and through left lanes. Collection of data was done during peak hours of weekdays by using video cameras under good weather conditions, in order to reflect the effect of various factors on saturation flow rate. For each of different lane types considered in the study average saturation headway was calculated individually and the results show that the overall average saturation headway approximately follows the normal distributions.

At 95% confidence interval independent samples t-test was performed for different lanes' saturation flow rates. Results show that the saturation headways approximately follow the normal distributions and the study concludes the following base saturation flow rates are appropriate for Beijing intersections. The saturation flow rates are: 1520 passenger cars per hour per lane (pc/h/ln) of left-turn lane, 1411 pc/h/ln of the through-left lane, 1535 pc/h/ln of the through lane, 1457 pc/h/ln of the through-right lane, and 1380 pc/h/ln for right lane.

Saturation flow rates and start-up lost times were investigated by (Siddiqui 2015) for one through lane and double exclusive left lane at major signalized intersections in the city of Bozeman. From an appropriate vintage point near the selected intersection traffic data were recorded during the evening peak hours using stopwatch and standard worksheet. Based on general descriptive statics the study analyze the collected data using a series of t-tests to determine whether there was a significant difference in saturation flow rates and start-up lost time between the two exclusive left-turn lanes and the through lane.

The study reported that a mean saturation flow rate value for the inner left-turn, outer left-turn and through lane are 1815, 1768 and 1846 pcphpl respectively. The study also showed that the average saturation flow rates for exclusive left-turn lanes are 0.98 seconds and 0.95 seconds for through lane. The standard error associated with the mean, standard deviation and variance of saturation flow rates for the through lanes were lower compared to the two exclusive left-turn lanes which indicates vehicles on the through lanes are entering the intersection in a more uniform manner compared to the double exclusive left turn lanes. At 95% confidence interval the results of the study are showing statistically significant difference which may be due to lower sample sizes (only 12 cycles). The study recommends a more comprehensive study must be conducted based on a large number of signalized intersections and cycles.

Shao & Liu, 2012 estimate saturation flow rate at 11 selected signalized intersections in Beijing, China. Data were collected during morning and evening peak periods on weekdays by video cameras and the data were manually extracted from the videotapes. Generally a total of 1023 vehicle discharge headways were recorded. The basic methodology to extract the recorded video was removing the first 5 headways from each signal cycle to minimize the effect of start-up lost time and acceleration on the saturation flow rate. The results of the study confirms that average headway estimation method of saturation flow rate does not accurately reflect the true value of headway but the median value of headways may provide more accurate value of SFR.

Impact of geometry and traffic characteristics on saturation flow rates at signalized intersections was conducted by (Helmy, Hashim, and El-desoky 2018) in EGYPT. The data required for the study was collected at four selected signalized intersections and the data collection method includes both manual and video recording. The methodology used in the research was determining saturation headway and saturation flow rates of each observed vehicle queue at each intersection. Based on the saturation headway data taken from 18 cycles the minimum and maximum values of saturation flow rate are 1613 veh/h/ln and 1810 veh/h/ln respectively. The output of this study shows that the overall average base saturation flow rate for Egypt was to be determined 1788 pc/h/ln. But to conclude the results of the study and to apply this base value for other intersections in EGYPT a large sample size must be considered in the number of signalized intersections.

Bester & Meyers, 2007 studied the saturation flow rate for through-traffic at six signalized intersections in Stellenbosch, South Africa. Saturation flow rate is a critical value in the design and capacity analysis of signalized intersections and the determination of traffic signal phasing plans. Cycle by cycle determination of start-up lost times, saturation headways and saturation flow rates were computed for each selected signalized intersections. In this study the effects of speed limit, gradient and number of through lanes on the saturation flow rate were modeled and the value of saturation flow rates ranged from minimum value of 1711 pc/h/ln to 2370 pc/h/ln with mean value of 2076 pc/h/ln. The study concludes that the obtained values are much higher than other western countries, which could be an indication of the aggressiveness of local drivers.

Study carried out by (Md. Jobair Bin Alam, Khalid A. Osra 2010) at Makkah, Saudi Arabia, has shown that saturation flow rate and capacity adjustment factor for signalized intersections varied from HCM recommendations. The study is carried out at five signalized intersections which are composed of three and four legs. According to the study from a total of 156 cycles of saturation headway were analyzed. The overall saturation headway lies between 1.07 to 1.97 seconds with average of 1.44 seconds. The results of the study showed that the base saturation flow rate of through lanes during cycles containing only passenger cars for Makkah was determined to be 2,500 pc/h/ln which is much higher than the value suggested by the HCM (1900 pc/h/ln).

Estimation of Base Saturation Flow Rate for Selected Signalized Intersections in Khartoum State, Sudan was conducted by (Galal A Ali 2017). The study was done at three selected signalized intersections and traffic operation data were recorded in the Morning, Afternoon and Evening periods using video camera. According to the study the saturation headway ranges from 1.6 to 2.6 seconds with mean of 2.20 seconds of all intersections. The findings of the study indicates that the ideal saturation flow rate of Khartoum city is 1636 pcphpl which is much lower than the value recommended by HCM (1900pcphpl).

Saturation flow was estimated at multi lane intersections in Hyderabad India by (Harinder, D Pandu and Kumar 2017). This study is focused to determine the saturation flow rate at four selected multi lane intersections. The data was collected at four intersections which were selected based on consideration of a range of criteria. Saturation headway was computed using the discharge times of the fourth and eighth queue positions from 2901 signal cycles. The study reports the median values of flow rate for each intersections and lane group types due to reason that the median values are less influenced by outlier’s than average values.

According to the study around 7105 vehicles were observed in the through traffic lanes, and 3055 vehicles were observed in shared through plus right-turn lanes and foe exclusive left lanes only 92 cycles were analyzed. The value of SFR ranges between 1376 veh/h/ln and 2149 veh/h/ln. The overall median saturation flow rate for the through traffic lanes and for the shared through plus right-turn lanes are 1735 veh/h/ln and 1591 veh/h/ln respectively. The study concludes that right-turning vehicles turn at a lower saturation flow rate.

2.6 Summary of the Literature Review

The aim of this literature review was to fully appreciate the importance of studying saturation flow rate and its main influencing factors at signalized intersections. Generally the following points are grasped during reviewing related works in this chapter.

- Most studies conclude that saturation flow rate an important parameter in the planning, design and control of signalized intersections.
- Reviewed works revealed that saturation flow rate varies from one location to another and is affected by a number of factors at or in the vicinity of the intersection.
- Many researchers pointed that field measured saturation flow rate is different from estimated one using different models.
- Previous studies estimated saturation flow considering stop line as reference line as suggested by HCM to extract vehicle discharge headways.
- All of the existing methodologies presented in previous works calculate saturation flow rate based on average discharge headway method.

2.7 Knowledge Gaps in Literature

All in one the following are some knowledge gaps observed from reviewing related studies on saturation flow rate at signalized intersections.

- It is evident that studies related to saturation flow rate at signalized intersections especially in case of Addis Ababa are not yet studied.
- Most studies have been conducted to study saturation flow rate under homogenous traffic conditions were cars are dominant modes of transport.
- Some studies does not determine the prevailing saturation flow rate of other lane types other than through lane and does not consider time of day variation.
- One of the major problems obtained in reviewing related works on saturation flow is that many authors do not report the details of their survey techniques to collect video data.
- Having identified these gaps, this study pays particular attention to study saturation flow rate at selected signalized intersections in Addis Ababa.

CHAPTER THREE

RESEARCH METHODOLOGY

3.1 Overview

Since the capacity of a signalized intersection depends predominantly on the saturation flow rate, realistic estimation of saturation flow rate at prevailing conditions is crucial for performance evaluation of existing intersections and signal timing allocation for newly installed signalized. In this study after pertinent literature was reviewed, all data required to achieve the objectives of the study were collected and analyzed at selected signalized intersections for different types of lane groups. However, the data collection and extraction process in this study turned out to be much more difficult and time consuming than anticipated.

The intent of this chapter is to describe the methodology followed in the execution of this research. The chapter has different sections which describe a separate issues regarding saturation flow rate study methodology. Section 3.1 presents general over view and outlines of each section of the research methodology. Section 3.2 describes field saturation flow rate study methodology with flow chart showing over all process, procedures and methods used to execute this research.

Section 3.3 describes the purposes pilot survey, study site selection criteria's and explains detailed description of the selected signalized intersections. Section 3.4 presents the overall process of data collection methods. Namely, this section describe data to be collected, required number of sample size, identification of study periods, data collection equipment set up and general data collection techniques and procedures followed in this study.

Types of different lane groups and vehicle categories considered for further analysis are presented in section 3.5 and section 3.6 of this chapter respectively. Section 3.7 describes the data extraction methodologies including how to process the recorded video data. Section 3.8 includes different stages of data analysis which are used to answer the research questions and achieve the objectives of this study. The last part of this chapter summarizes the collected data and concludes that the overall data collection plan was coordinated with the literature review and the analysis of framework was described earlier.

3.2 Saturation Flow Rate Study Methodology

The main attempt of this study is to measure saturation flow rate in the field by actually measuring the flow at the stop line during saturated green phase and to analyze its variability with respect to various influencing parameters. A systematic flow chart showing methodology of this research work is depicted in Figure 3.1.

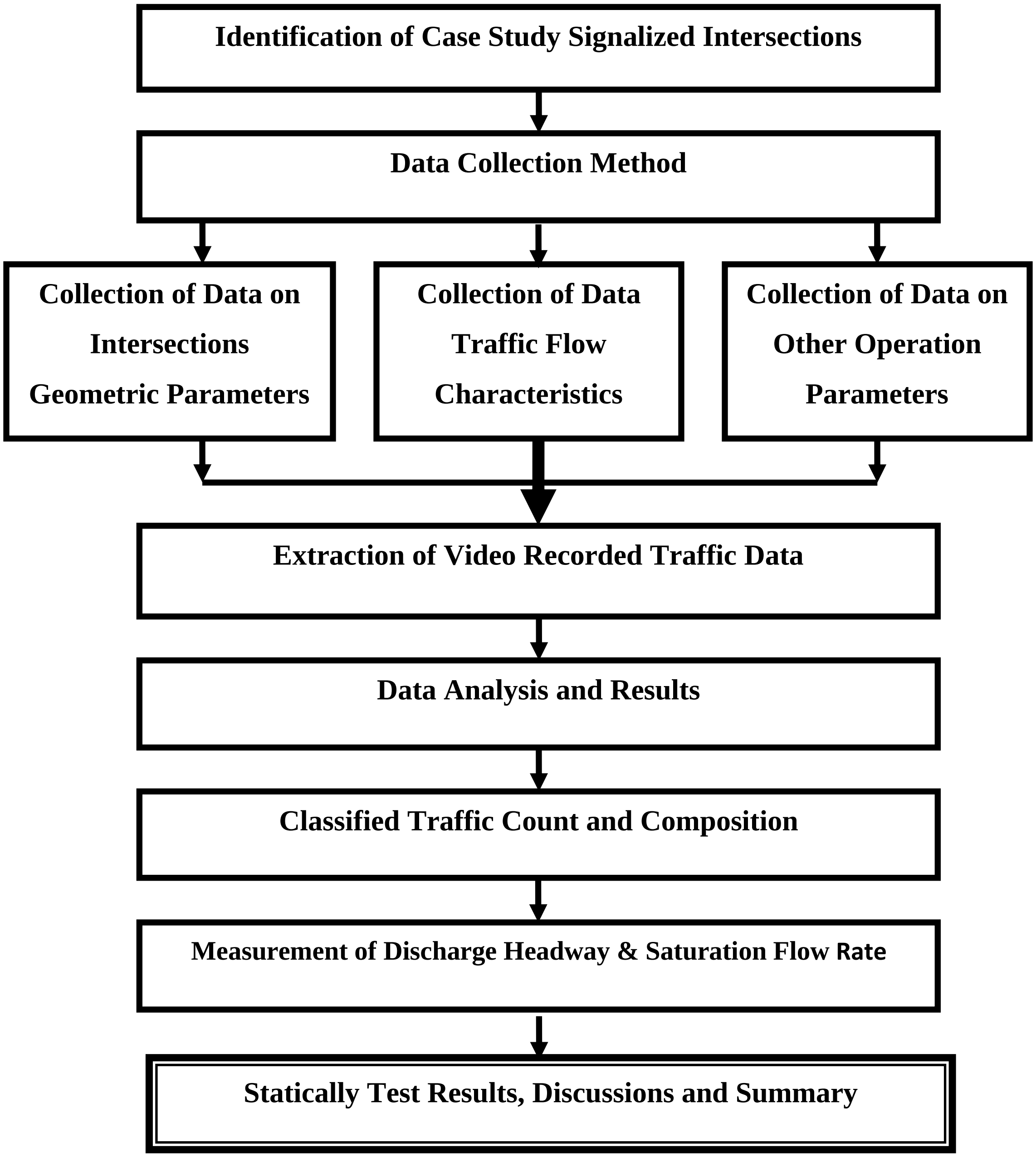


Figure 3.1 Schematic Diagram of Research Methodology

3.3 Pilot Survey and Selection of Study Sites

3.3.1 Purpose of Pilot Survey

For the purposes of this study it was important to identify and observe intersections to select a suitable signalized intersection which possesses the specific site conditions required by the study. Prior to the actual data collection, several signalized intersections in Addis Ababa were visited with main intention to identify a suitable site for data collection.

The following are the purposes of the preliminary survey of this research.

- To develop a detail data collection plan based on the parameters identified in the literature review and the inputs needed for achieving the key objectives of the study.
- To make sure that how all the data needed would be collected and all the requirements for collecting the field data would be satisfied.
- To set out brief guidelines for the selection of case study signalized intersections.
- To observe when saturated vehicle queues are formed at signalized intersections which are helpful to identify the real peak hours for detail data collection purpose.
- To indentify types of lane groups and characteristics of different approaches of signalized intersections within the city.
- To select a convenient permanent location at the intersections to observe all the events clearly including the stooping points of vehicles, the flow of vehicles and end of queue.
- To collect sample data at the study sites this helps to gain proficiency in using different data collection procedures in the field.
- To fix the number of selected signalized intersections, labors and devices necessary for the detail data collection and finally the types and quantities of the data needed.

3.3.2 Study Site Selection Criteria

Selection of suitable site is the foremost criterion for estimating prevailing saturation flow rate value. Saturation flow rate is different for different signalized intersections. The selection of suitable study sites was based on consideration of a range of criteria and also with a view to minimize other extraneous factors that may influence saturation flow rate. Site selection criteria of this study were developed based on findings from the literature review, observations refined during the pilot survey and consultations from traffic management agency engineers.

To achieve the research objective the following criteria were used to select the candidate signalized intersections for this research:

- The selected signalized intersection location allows the data collection process safely which includes having good access, wide view and safety for video camera set up.
- Should be able to record safely, to record the signals changing and see vehicles as they cross stop line or the reference line set instead of stop line.
- There should be relatively long queues at all approaches of intersections capable of causing saturation conditions to facilitate the observation of saturation flow rate.
- The selected intersections should be isolated intersections to be free from bunching effect (coordination influence) of other signalized intersections.
- Moreover the selected sites have different geometric characteristics (different lane group types) and variable signal timing conditions to consider the importance of these intersections in the overall road network within the city of Addis Ababa.
- To find out the scope of permission from the Addis Ababa Traffic Management Agency it was, therefore, essential to select sites based on the above requirements.
- The researcher tries to assess all signalized intersection of the city through field survey and come up with a concrete selection based on the above listed factors.

3.3.3 Selected Case Study Signalized Intersections

After conducting pilot survey and analyzing its findings in relation to case study intersection selection screening criteria's, six signalized intersections with different operational characteristics under heterogeneous traffic condition were identified for this study. The following are the six carefully selected signalized intersections were their geometric design and traffic control feathers represent the most common situations of intersections in Addis Ababa city.

1) Leghar Signalized Intersection
2) Harambi Signalized Intersection
3) Mesqel Square Signalized Intersection
4) Shola Signalized Intersection
5) Imperial Signalized Intersection
6) Bole Michael Signalized Intersection

3.3.4 General Description of the Selected Signalized Intersections

All the six selected signalized intersections are four-legged intersections with well-defined stop line markings and each approach of the intersections has different traffic movements. All these six intersections lie on a major corridor of the city and they form part of the CBD of Addis Ababa. By collecting the actual operational data the detail study of these intersections was therefore expected to give the prevailing saturation flow rate values of different lane group types that exit at different signalized intersections in case of Addis Ababa.

The average cycle length of all six selected intersections is 95 seconds while the average green interval in major approaches of the different intersections is 35 seconds. The maximum green interval is 95 seconds observed at major approaches of Leghar signalized intersection and the minimum found at Bole Michael intersection for Bole Bulbula approach which is 20 seconds. The maximum cycle length is 213 seconds at Imperial signalized intersection. At All intersections all the phases have an amber period of 3 seconds at the end of green.

The details of all the selected intersections including geometrical, traffic control and operation characteristics were discussed in the following sections.

3.3.5 Specific Site Conditions at Leghar Signalized Intersection

This is a four - legged signalized intersection located in CBD area of the city. It has four approaches which are North Bound (Mexico Approach), East Bound (Beherawi Approach), South Bound (Stadium Approach) and West Bound (Leghar Bus Station Approach). The major traffic movement takes place from Stadium and Mexico Approach towards this intersection.

During the data collection period of this study this intersection is controlled by a permitted signal having a cycle time of 203 seconds with four phases. Right-turn vehicles were not controlled by signal light in all approaches of the intersection. Left-turning vehicles were separated from through vehicles in North and South Bound direction. The green time for exclusive left-turning phase for both approaches was 45 second.

There is an elevated railway line constructed across North to South Bound direction. Since there is railway station many passengers are creating traffic congestion near the intersection while alighting and boarding into elevated train. Generally the surface condition and road markings were good during data collection of this study. The geometrical details and signal plan at this intersection is presented in Figure 3.2.

Figure 3. 2 Aerial Photo of Leghar Signalized Intersection

3.3.6 Specific Site Conditions at Harambi Signalized Intersection

Harambi signalized intersection is four - legged four phase intersection and located near Harambi Hotel. The four approaches are Beherawi approach (north bound direction), EBC approach (east bound direction), FilWuha or Kasanchis approach (south bound direction) and Stadium approach (west bound direction). All four approaches are three lane separated. There is **TOTAL** fuel station towards FilWuha approach approximately at 100m from the intersection. There are two hotels near this intersection one is called Ethiopia Hotel located on the north bound direction and the other is Harambi hotel located at the corner of east bound direction of the intersection.

Figure 3. 3 Aerial Photo of Harambi Signalized Intersection

3.3.7 Specific Site Conditions at Mesqel Square Signalized Intersection

Mesqel Square Intersection officially called Estifanos Intersection is at grade four arm signalized intersection located at the heart of the city. This study intersection is one of the critical intersections for smooth traffic movement having large volume of traffic and used as the hub of traffic movement of Addis Ababa City. There is Saint Estifanos Church, over pass railway station and a lot of cross country bus station ticket offices near this intersection so there is higher proportion of pedestrian traffic and buses at the intersection. There is also one international hotel named HAYAT REGENCY near the intersection from West Bound (Dembel Approach).

The north bound direction or stadium approach of the intersection has 5 lanes with one exclusive left-turn lanes with green time of 30 seconds, one shared through and left lane, two exclusive through lanes and one shared right-turn and through lane. On other hand the Dembel or so called Bole approach has one shared through and left lane, two through lanes and one shared through and right-turn lane. But Arat Kilo and Hayahulet approaches of the intersection both have one shared through and left lane, one through lane and one shared right and through lane.

Figure 3. 4 Aerial photo of Mesqel Square Signalized Intersection

3.3.8 Specific Site Conditions at Shola Signalized Intersection

Figure 3-5 shows the layout of the Shola signalized intersection which is typical of those in the study. The four approaches are indicted as Denberewa approach (north bound), Shola Gebeya approach (east bound), Megenagna approach (south bound) and Lem Hotel approach (west bound). Like the Harambi signalized intersection all four approaches of this intersection are three lanes separated. The major approaches of Shola intersection are Denberewa and Megenagna while the minor approaches are Lem Hotel and Shola Gebeya. Near this intersection there is well known all day open market known as Shola Gebeya and there are a lots of pedestrian movement and on street markets which are sometimes disturb the discharge flow of vehicles during the onset of green time than other selected intersections in this study.

Figure 3. 5 Aerial photo of Shola Signalized Intersection

3.3.9 Specific Site Conditions at Imperial Signalized Intersection

This is four-legged four phase intersection. The surface condition of the road is moderate with proper road markings during data collection for this study. The major traffic movement takes place from Megenagna approach (east bound direction) and Bole approach (west bound direction). On both of these major approaches of the intersection there is a channelized island used for exclusive right turning vehicles and allows them to Right Turn on Red (RTOR).

The minor approaches of imperial signalized intersection are Gerji approach (south bound) and Atlas approach (north bound). Both of these minor approaches have one shared through and left lane, one through lane and one shared right and through lane with green time of 42 seconds. In addition to the types of lanes exist on the minor approaches of this intersection there are two exclusive left lanes one on the Megenagna and the other on Bole approach with green time of 30 and 25 second respectively. Figure 3-6 provides an aerial photograph of this intersection.

Figure 3. 6 Aerial photo of Imperial Signalized Intersection

3.3.10 Specific Site Conditions at Bole Michael Signalized Intersection

Bole Michael signalized intersection is one of the important intersections of Addis Ababa city road network. The intersection is four- legged intersection controlled by a pretimed four phase signal with a cycle time of 186 seconds. This intersection is located in the southern part of Addis Ababa along one of the most congested routes within the city. A lot of traffic and pedestrian movement were observed at this intersection all throughout the day.

The major approaches of the intersection are Saris Abo (West bound) and Bole International Airport (East bound) approaches were observed to have high traffic volume in the morning and evening peak hours. These minor approaches are Bole Bulbula (south bound) and Bole Rwanda (north bound) directions and have only shared through left and through right lanes the same too Gerji and Atlas approaches of Imperial signalized intersection.

Figure 3. 7 Aerial View of Bole Michael Signalized Intersection

Table 3. 1 Details of Geometric and Signal Timing at Selected Intersection Approaches

Intersections	Traffic Approach From	No. of Lanes	Red Time (Sec)	Amber Time (Sec)	Green Time (Sec)	Cycle Length (Sec)
Leghar	**Mexico (NB)**	3	105	3	95	**203**
	Beherawi (EB)	3	175	3	25	
	Stadium (SB)	4	105	3	95	
	Leghar (WB)	3	175	3	25	
Harambi Hotel	**Beherawi (NB)**	3	123	3	46	**172**
	EBC (EB)	3	144	3	25	
	FilWuha (SB)	3	128	3	41	
	Stadium (WB)	3	133	3	36	
Mesqel Square	**Stadium (NB)**	6	125	3	60	**188**
	Arat Kilo (EB)	3	150	3	35	
	Hayahulet (SB)	3	124	3	61	
	Dembel (WB)	4	135	3	50	
Shola	**Denberewa (NB)**	3	144	3	41	**188**
	Shola Gebeya (EB)	3	160	3	25	
	Megenagna (SB)	3	155	3	30	
	Lem Hotel (WB)	3	150	3	35	
Imperial	**Atlas (NB)**	3	168	3	42	**213**
	Megenagna (EB)	3	132	3	78	
	Gerji (SB)	3	168	3	42	
	Bole (WB)	3	175	3	35	
Bole Michael	**Rwanda (NB)**	3	148	3	35	**186**
	Bole (EB)	3	95	3	88	
	Bole Bulbula (SB)	3	163	3	20	
	Saris Abo (WB)	3	100	3	83	

**** NB = North Bound, EB = EAST Bound, SB = South Bound, WB West Bound***

3.4 Data Collection Methods

3.4.1 Introduction

Data collection is one of the most important tasks of the study. Once the pilot survey was conducted based on detailed field study and the selection of suitable signalized intersections was completed it was needed to develop data collection plan. To test the data collection plan, pilot data were collected at the selected signalized intersections. At the beginning of this research permission for conducting data collection activity was acquired from Addis Ababa city traffic management agency. The agency is the hub of traffic management system of the city and it provides information about the signalized intersections and the facilities which are used to control the flow of traffic within the city.

In this study different methods of data collection were used to collect the required data for achieving the objectives of the research including obtaining information from TMA, field visiting, and recording traffic video. The field measurement of the saturation flow rate shall be in accordance with methodology described in Chapter 31 of the 2010 Highway Capacity Manual and submitted on the HCM Field Saturation Flow Rate Field Study Worksheet(s).

3.4.2 Data Requirement

The planning, design and operation of signalized intersections all require estimation of saturation flow rate under prevailing geometric, traffic and signal control conditions. A study of the saturation flow rate at signalized intersections under heterogeneous traffic would require a large data from the field. As the goal of this study was to collect enough data in the field and accurately analyze saturation flow rates using the following:

- Traffic data include the type and number of vehicles crossing the stop line during saturated green time, compositional share of each category of vehicle, time headway for each vehicle traversing the intersection.
- Geometric data include number and types of lanes on all approaches of the selected intersections. Signal control data are cycle length, effective green time, red time.
- Generally in order to acquire the required data for the study data collection was conducted during 2 hours separately in the morning and afternoon peak hour.

3.4.3 Sample Size Determination

A field saturation flow study at an intersection provide the most accurate measure of experienced flow rates on its approaches. To obtain a statistically significant value HCM 2010 recommend a minimum of 15 cycles with eight or more vehicles in the initial queue is typically required for each approach of selected signalized intersections.

The standard deviation of the average saturation headway for the subject approach can be computed using the following equation (Bonneson et al. 2005).

$$S_{\bar{h}} = \frac{S_h}{\sqrt{4}} = \frac{0.5}{2} = 0.25$$

Where:

$S_{\bar{h}}$= Standard deviation of $\bar{h}$, sec/veh; and

S_h= standard deviation of saturation headway (= 0.5 s/veh).

The tolerance error for saturation flow rate study at signalized intersections was determined by many researchers. According to (Dehghani-Zadeh and Fallah Tafti 2018; Tarko and Tracz 2000; Wang et al. 2020), for SFR estimation at approaches of intersections, an error rate of 8 to 10% would still be acceptable. In this research, the acceptable error rate is considered to be 9% which is the average value recommended by previous studies.

To determine the minimum sample size required to have a 95 percent confidence level equation (14) was used to compute the minimum number of signal cycles needed for collecting the data for each approaches of all the selected intersections.

$$N = \left(\frac{Z * S_{\bar{h}}}{e}\right)^2$$

$$= \left(\frac{1.96 * 0.25}{0.09}\right)^2$$

$$= 29.642 \approx 30$$

Where:

N = Minimum number of signal cycles for which a value of for each approach;

Z = Standard deviation of the data (= 1.96 for 95 percent confidence interval);

$S_{\bar{h}}$= Standard deviation for subject approach (0.25 sec/veh); and

e = Acceptable (allowable) error rate (= 0.09 sec/veh).

3.4.4 Data Collection Techniques and Procedures

The data collection technique used in this research was identical in principle to the procedures described in the HCM. The technique for measuring saturation flow rate for the selected signalized intersections is described below. The technique requires at least two people working together to gather the necessary data on each approach of the selected intersections. One person's task was to control the camera and the second person used a stopwatch to identify the beginning of the green signal phase on the study approach.

In the present study, the actual vehicular traffic flow during saturated green time has been recorded at all approaches of the selected signalized intersections during the morning and afternoon peak hours. The duration of green time over which observations are recorded is termed here as saturated green time because it is the green time over which a continuous stable flow of vehicles is observed from the approach under consideration.

A video based photographic technique was used for data collection. Video recording using smart phone (infinix Hot 6 Pro) is adopted in this study to carry out the field data collection. Continuous records of the traffic flow were recorded with the video camera for peak morning and evening period. For cross authentication of the videography data, concurrently manual counts were also conducted for obtaining phase time, cycle time with the help of prepared standard worksheet.

Data collection technique using video recording has the following advantages:

- The technique has the advantage of lesser requirement of manpower.
- It has the advantage of repeating the traffic flow phenomena during data extraction.
- Video recording was used to provide accurate records of traffic flow and permanent record of data to be collected.
- It provides the chance to review the impact of special conditions through playback at the data extraction stage to reduce the risk of error.
- Because it makes the data collection more reliable and efficient; the researcher decided to use the video-based measuring technique for this study; however data extraction will be bit tedious.

3.4.5 Study Periods

The time of the study period is important to record the traffic and the signal well enough such that it is able to observe clearly as vehicles move. Identifying peak hours was based on the data provided by the Traffic Management Agency of the city, personal interviews with traffic policemen's and results of preliminary survey analysis.

Accordingly based on the recommendations from TMA and initial data filtration of collected pilot data, it was observed that the queues at the selected intersections were denser and had longer lengths in the morning from 1.30am - 3.30 am and in the afternoon from 9.30am - 11.30am. All observations were done in under clear weather conditions, normal traffic, no incidents, and no construction activities. The purpose of collecting data during morning and afternoon peak periods was used to check if there is probably significant difference between the two peaks hours prevailing saturation flow rate value for different lane groups.

3.4.6 Video Camera Placement

Field data collection for the present study was more challenging for the heterogeneous traffic condition with less lane disciplined flow. During the green signal, vehicles move through the intersection together and randomly depending upon the gap available between them. Therefore in order to get an accurate headway value, it is required to collect data from a vantage point so that the movement of every vehicle can be traced correctly.

Firstly during detail field observations, suitable positions of video-camera have been decided and identified at the candidate intersections and obtained the required permissions from different buildings owners and other concerned bodies including Addis Ababa traffic police.

Within the scope of this study, data were collected by means of video cameras which were placed on high buildings for some intersections or may be hand held methods for other intersections. Since it is not possible to see the flow of vehicles discharged from the stop line of all approaches of a given signalized intersection, a separate camera was needed for each approach. The cameras were positioned in a way that the signal display, queue lengths, and stop lines were clearly visible for all selected approaches and video recording was done without interfering with the traffic flow.

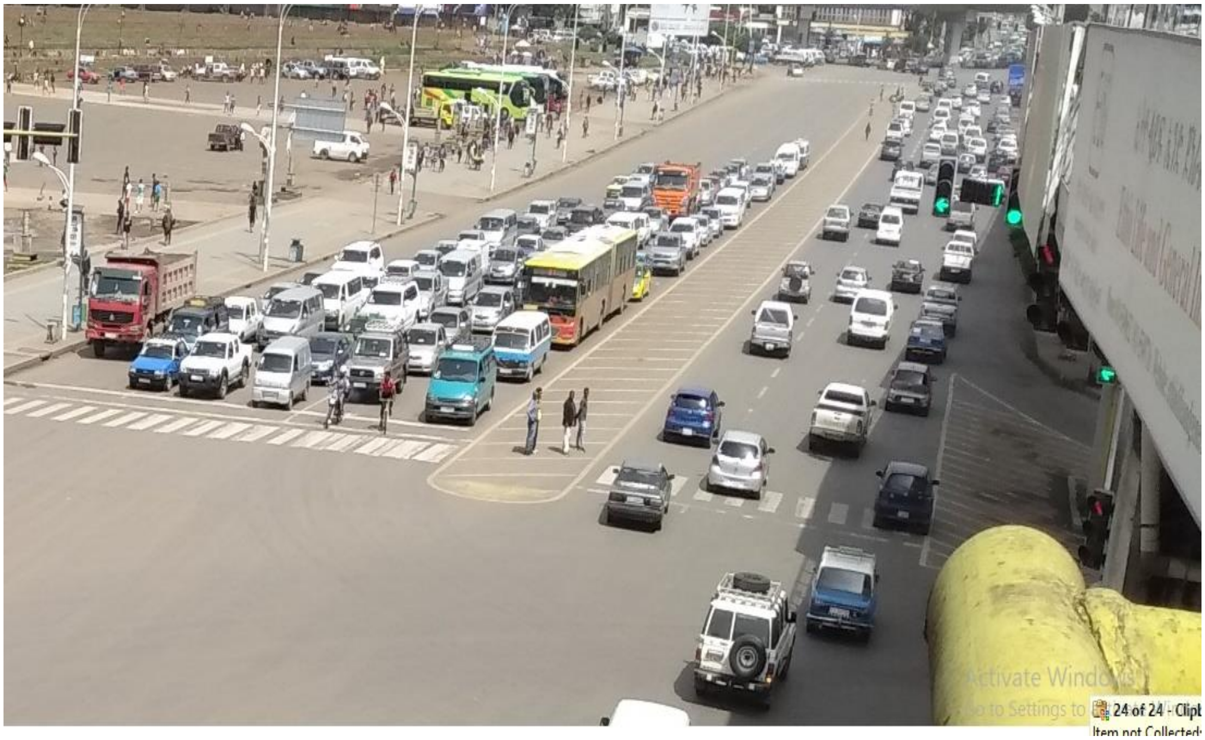


Figure 3. 8 Video Camera View at Mesqel Square Signalized Intersection

- ***General procedure of data collection***

As mentioned earlier, it is important to set up the camera in such a way that both the traffic signals well as the stop line on the direction of intersection are clearly visible. Therefore, the equipment (video camera) was set up at least 15 minutes before the start of each study period. From the video, it is easy to extract the exact time when the signal turns green, as well as exact times when vehicles cross the stop line.

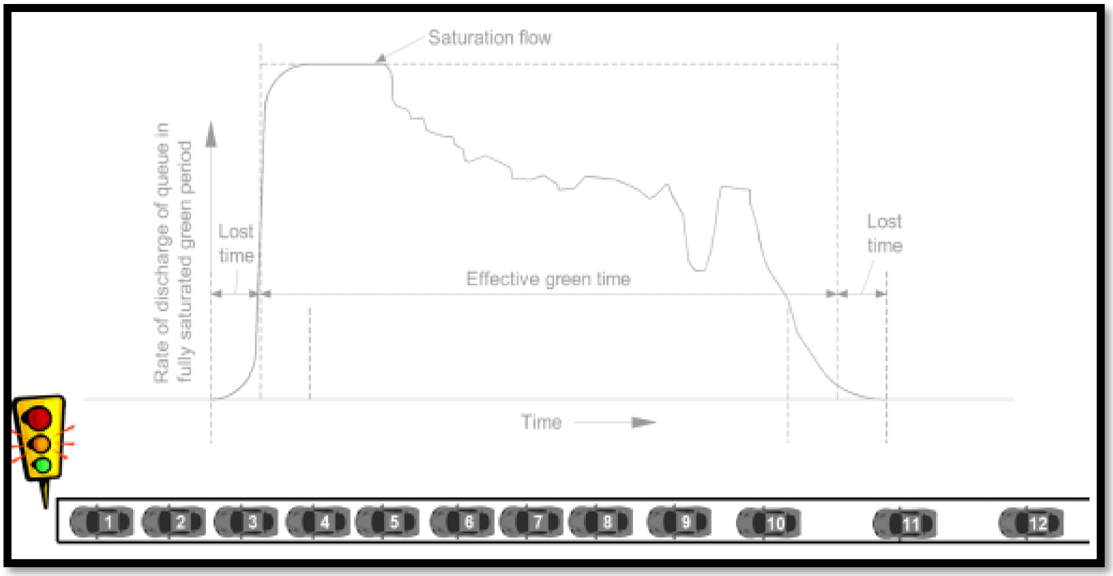
- Make sure that the recording angle is good by taking pictures and making sure the signal and the stop line are clearly visible.
- In order to properly record headways, the video camera has to capture the signal head (in order to see beginning of green) as well as the stop line.
- At the start of green, start the TIMESTAMP video recorder.
- Prepare to record over multiple cycles separately both in the AM and PM peak hours.
- Record the time and number of vehicles discharging during the saturated period.
- Cycles should have at least eight queued vehicles at start of green phase (HCM, 2010).
- Prepare to note the number of queued vehicles for each recorded cycle.

Table 3. 2 Saturation Flow Rate Measurement Requirements

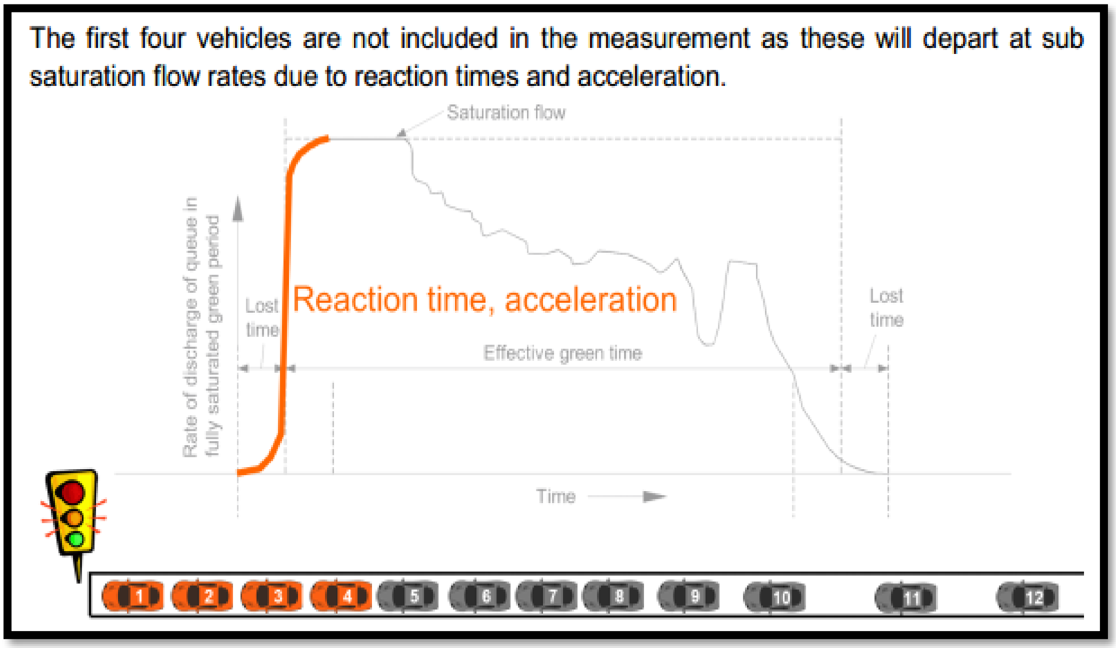
Measurement Requirements	Remark
Collecting sample video recording data at selected signalized intersections based on the selected study periods and camera placement locations.	Before real data was collected it is necessary to collect data using inventory survey to gain proficiency in using this methodology for accurate data collection.
Measure the saturation flows for each individual lane, not a group of lanes.	Because the traffic behaviour, discharge rate, queuing, for each lane is different.
A minimum of 15 signal cycles samples are to be collected for each lane, across all periods. In each of signal cycles eight or more queued vehicles are needed for each approach during data collection at start of green.	To ensure a steady queue discharge and a valid saturation flow measurement. More samples may be required if the results are found to be significantly inconsistent to eliminate outliers and minimize errors.
Take measurements throughout each of the study periods both morning (1:30 AM – 3:30 AM) and afternoon (9:30 AM – 11:30 AM) peak hours.	To ensure that the average saturation flow represents the site conditions for the period being studied as saturation flow can change due to peak specific site conditions.
Not undertaking measurements when there is exit blocking and other activities disturbing the traffic flow.	Saturation flow rates can only occur during free flow conditions. Sufficient traffic flow is needed to obtain the SFR at the stop line.
Measure the time as the front axle of each vehicle passes the stop line or other reference line which is marked as reference like stop line for headway analysis.	Regardless of the chosen vehicle reference point, the measurement should be consistent. Recommended by HCM and for consistency purposes front wheel is selected.

3.4.7 Saturation Flow Rate Measurement Diagrams

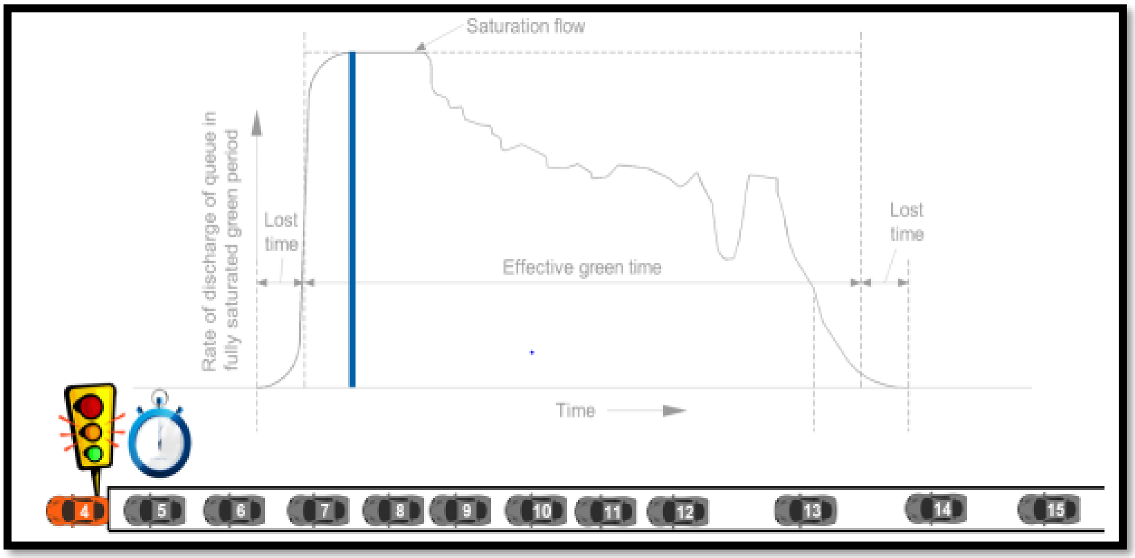
1. At the start of green, for the lane to be measured, note the length of the queue



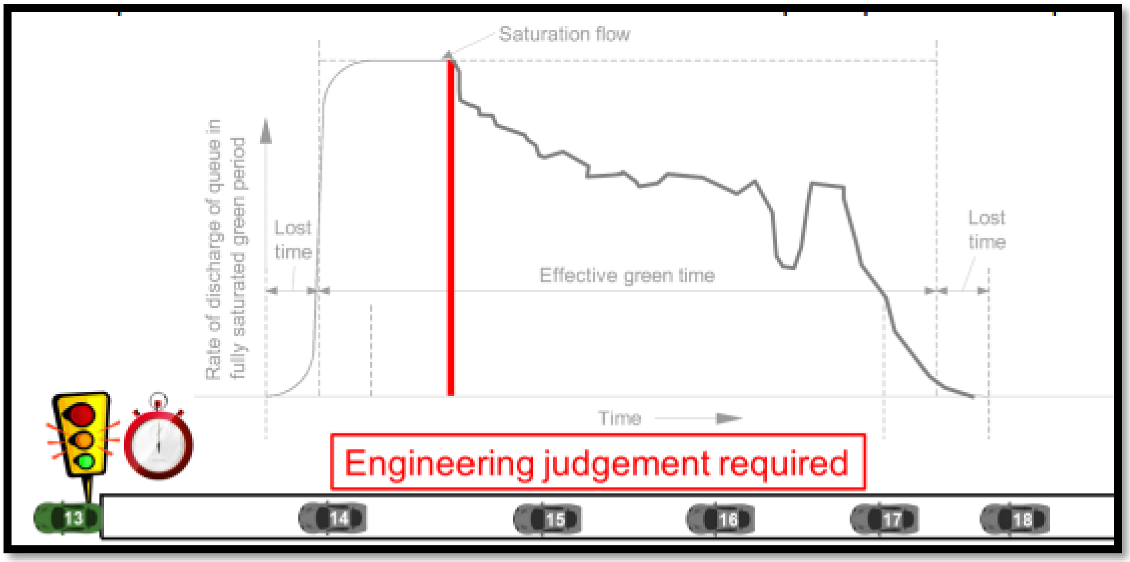
2. Start timing at the start of green time or when the front axle of the fourth vehicle passes the stop line.


The first four vehicles are not included in the measurement as these will depart at sub saturation flow rates due to reaction times and acceleration.

3. Stop the count when the front axle of the last vehicle in the queue passes the stop line.



4. If more vehicles may join the back of the queue, engineering judgment which making the last vehicle time the end of green is required to record their saturation headway.



3.5 Types of Lane Groups Considered

Lane group is a set of lanes which may be exclusive or shared and established at an intersection approach. It is used as input for separate capacity and level-of-service analysis.

During data collection it is observed that there are different types of movement's occurred at approaches of selected signalized intersections in Addis Ababa. Based on the lane and traffic movement distribution at the selected signalized intersections approach the following are different types of lane groups considered in this study. However, U - turning vehicles are considered in exclusive left and shared lanes.

1) Exclusive Left-turn Lane Group (L)
2) Shared Left and Through Lane Group (LT)
3) Through lane movement (TH)
4) Shared Through and Right Lane Group (RT)

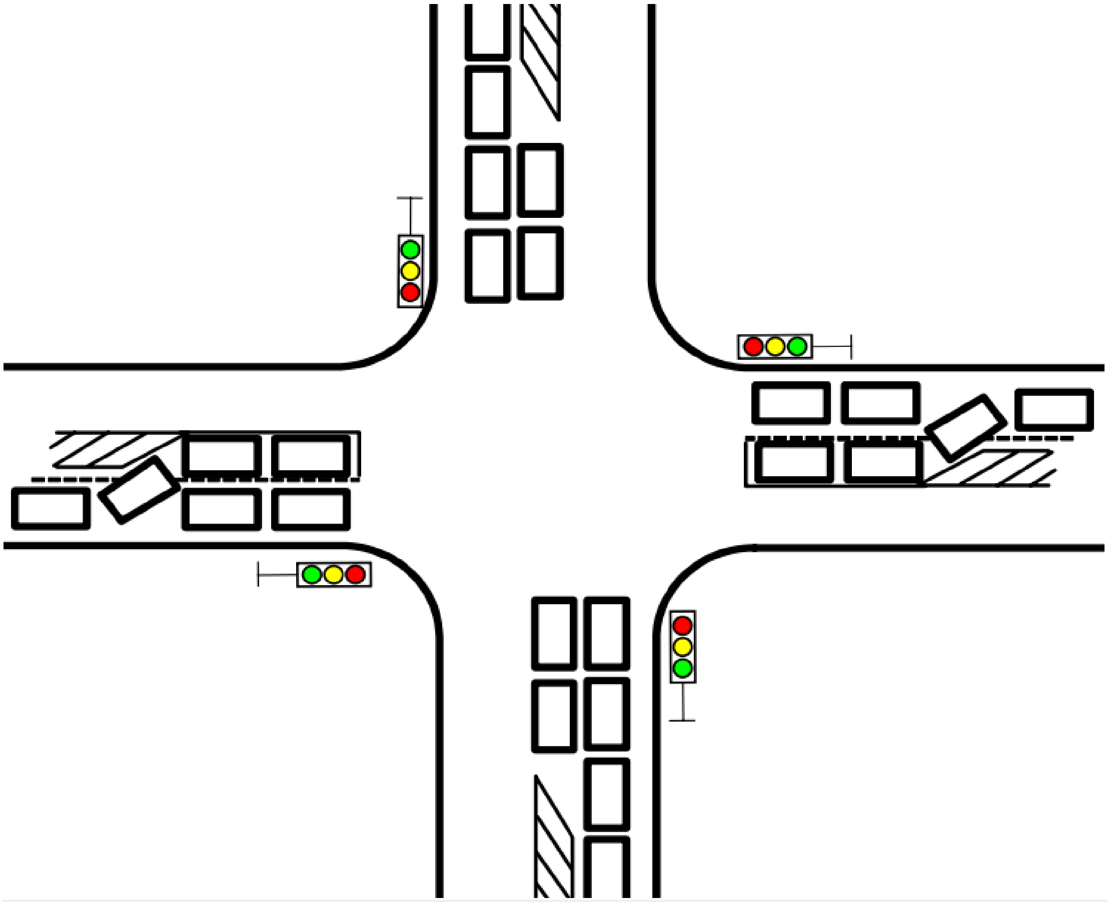


Figure 3. 9 Approaches at signalized intersections with exclusive and shared lanes

3.6 Vehicle Classification

Road traffic in developing countries such as Ethiopia is highly heterogeneous in nature. Heterogeneous or mixed traffic systems operate very differently compared to homogeneous traffic systems, due to the reason that it is composed of fast and slow moving vehicles. Generally mixed traffic condition includes different vehicle types which are different each other in operation and performance characteristics.

Based on Ethiopian Road Authority (ERA) pavement design manual and observations made during pilot data collection period five categories of vehicles were identified. Generally common modes of transport in the city are Cars so called passenger cars, Minibuses which is mostly include Taxies, Buses, Small Trucks and Large Trucks. This classification is also based on preliminary analysis of data taken from traffic management agency of the city and in line with Addis Ababa City Road Authority (AACRA) design vehicle grouping traffic manual.

Table 3. 3 Addis Ababa City Road Authority Design Vehicle Grouping Traffic Manual

Class	Types of Vehicles	Axles	Description
1	Cars	2	Passenger Cars, Taxies, Pick Ups, Land Rovers etc.
3	Small Bus	2	≤ 27 Seats
4	Large Bus	2	> 27 Seats
5	Small Truck	2	≤ 3.5 tonnes
7	Large Truck	2	3.5 < 7.5 tonnes
8	Truck Trailer	2	> 7.5 tonnes
*	Other Vehicle Types	*	*

Generally the different types of vehicles considered in this study needs to be representative of typical traffic stream composition of Addis Ababa city traffic behaviour and distinct classes of vehicles suitable for grouping for analysis. The compositional share of each vehicle class and their discharge headway was extracted from the collected video data.

3.7 Data Extraction Methodology

Saturation flow is the most important parameter used in designing and analyzing signalized intersections. It is the flow of vehicles, which start to move across the stop-line when the light turns green. According HCM discharge headway of vehicle is measured when its front axle passes the reference line known as stop line or intersection line.

In this study the recorded data is extracted by recording the time from the start of green time to the time each vehicle's front wheels crossed the stop line and this was done until the queue ended. Therefore, it is necessary to perform the following tasks in order to be able to estimate the saturation flow rate from the collected field data while extracting data:

1) Initially, in order for a cycle to be used, it needs to have a minimum of 8 vehicles in the stopped queue at the start of green.
2) Secondly, the observed cycles that contain some kinds of disturbance was eliminated; including interference of pedestrian, lane changing disturbance, and also signal cycles with events such as presence of emergency vehicles should be discarded.
3) Thirdly, where timing errors were found in post-processing of video data caused by the camera positions, observation angle and reaction time these cycles were removed.
4) Fourthly, in order to eliminate the effect of star-up lost time, the first four time headways in each signal cycle are not considered in the determination of saturation headway.
5) Finally, since only saturated cycles were selected for analysis, all discharged vehicles were either from a standing queue stopped by the red light or joining the standing queue after the green light turns on is considered for extraction.

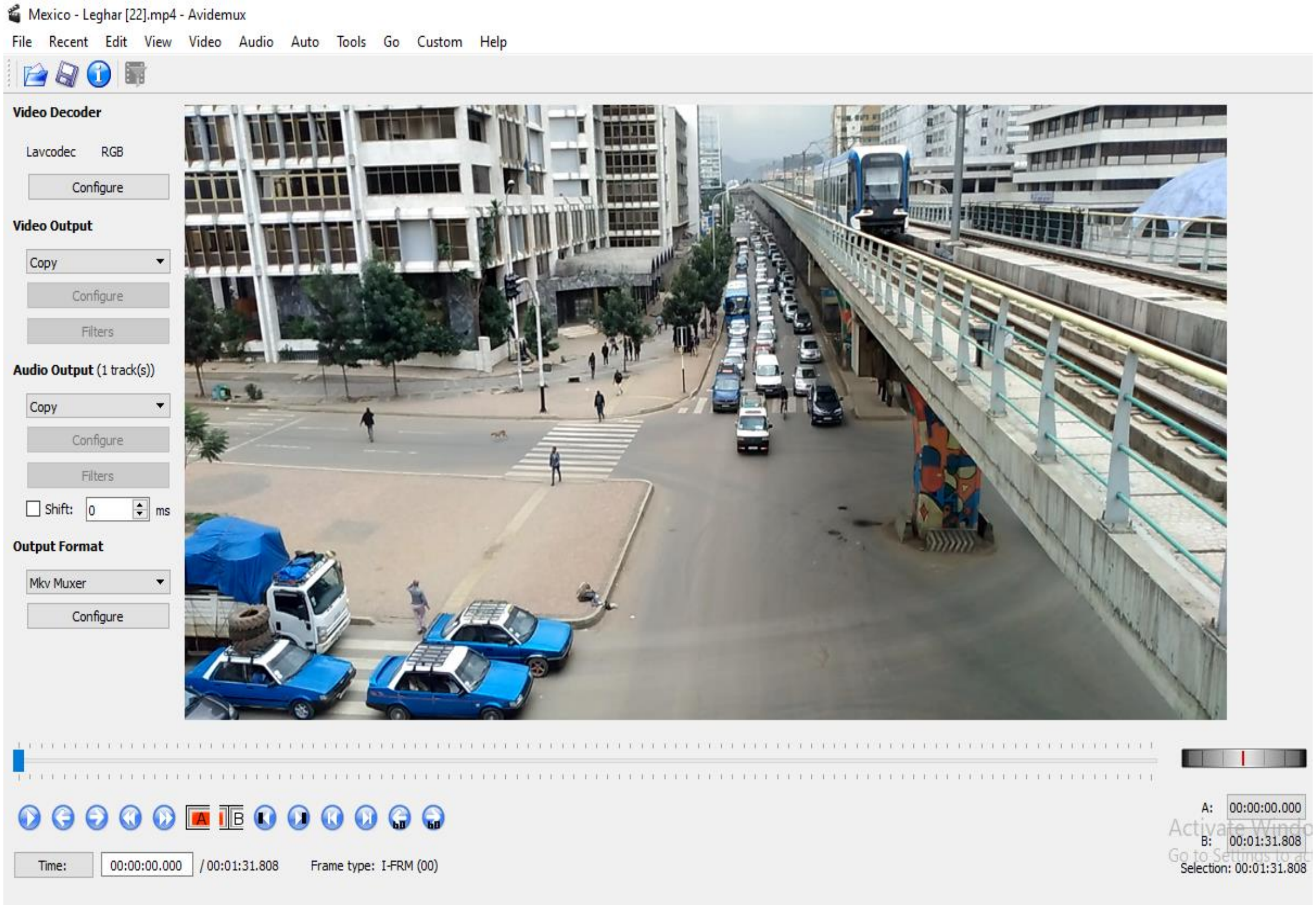
Time measurements begin when the signal turns to GREEN. Then:

- The first headway is the time between the initiation of the GREEN signal and the time the front axle of the first vehicle cross the intersection line.
- The second headway is the time between the front wheels of the first vehicle crossing the stop line and the front wheels of the second vehicle doing so.
- Subsequent headways are similarly measured.
- Generally manually record the time when each vehicle's front axle passes the stop line from and also note down the type of vehicle the recorded video.

3.7.3 Processing the Video

All the recorded video data were processed to extract the type of vehicles and their time headway value during the onset of saturated green interval time separately for each types of lane groups at all approaches of the selected signalized intersections. In this study the individual headway and type of vehicle were extracted manually using Avidemux software which is an open source free software tool used for extracting the recorded video. Fig. 3-9 shows the extraction of vehicle count and headway time with the help of Avidemux software at Leghar intersection. Additionally an Excel based software and spreadsheet forms were used to record the extracted data.

HCM recommends measurement of prevailing saturation flow rate for every cycle of each lane by recording the headways values as vehicles pass over the stop line of the intersection approach. Since all the selected signalized intersections in this study have marked STOP line, it is used as a reference point for extraction purpose.



Video Decoder: Lavcodec RGB

Video Output: Copy

Audio Output (1 track(s)): Copy

☐ Shift: 0 ms

Output Format: Mkv Muxer

Time: 00:00:00.000 / 00:01:31.808 Frame type: I-FRM (00)

A: 00:00:00.000

B: 00:01:31.808

Selection: 00:01:31.808

Figure 3. 10 Screen of the Avidemux Software showing Data Extraction Methodology

3.8 Data Analysis

The basic methodology used to analyze the extracted traffic data was the measurement of the elapsed time from the moment the fourth vehicle in the queue started until the time the front axle of the last vehicle in the queue crossed the stop-bar reference line. Saturated green period and direction wise traffic volume count are pre requisite to calculate saturation flow for a particular lane group at signalized intersections.

3.8.1 Traffic volume and Composition Analysis

Traffic volume is the number of vehicles crossing a section of road per unit time while traffic comosition is the percentage share of vehicles which shows their distribution along different traffic streams. and classification of vehiclesat any selected period. Both terms are key traffic paramerts and used in planning, of traffic facilities such as intersections and are essential characteristics of traffic flow.

Time of day analysis is important to acquire general knowledge about traffic flow characteristics. During data collection periode it is observed that afternoon peaks traffic flow is different from morning peak traffic flow. In the former traffic flow characteristics tend to be longer and flatter than the latter because most morning trips are work-related while afternoon trips are more diverse. This indicates the arrival flow in the afternoon is higher than the morning time because in the morning peak hour, vehicles were navigating very slowly through the intersections.

Therefore in this study classified traffic volume count was conducted for all types of vehicle catagories in the morning and afternoon peak hours at all approaches of selected signalized intersections. These results may be important for the traffic engineer in attempting any planning in the future and to identify relative importance of intersections based on time of day.

3.8.2 Computing the Saturation Headway

Saturation headway is also known a stable constant headway which is defined as the headway of vehicles when departing at the saturation flow rate during green signal and measured in units of seconds/vehicle. It is the primary input parameter to estimate saturation flow rate at signalized intersection and can be achieved by a saturated, stable moving queue of vehicles passing through the signal. According to HCM 2010 saturation headway is obtained by averaging headways from the fifth headway up to last vehicle headway.

In the present study headways were recorded manually for each lane and for each cycle separately at all approaches of the selected intersections. Then, the average saturation headway for each lane during each cycle was calculated as follows:

$$h_i = \frac{T_{ni} - T_{4i}}{N_i - 4}$$

Where

h_i= Saturation headway for the ith cycle measured in seconds,

T_{ni} = Observed discharge time of the nth queued vehicle during cycle i (sec);

T_{4i} = Observed discharge time of the fourth queued vehicle during cycle i (sec) and

N_i = Number of queued vehicles observed during cycle i.

The crossing time of the fourth vehicle is used as the start point of saturation flow rate estimation to eliminate the impact of start-up lost time, and the time that the last vehicle crosses the stop line is used as the upper bound to end the estimation of saturation flow rate for a given cycle.

3.8.3 Saturation Flow Rate Computation

Saturation flow rate is defined as the number of vehicles that would pass through an intersection in an hour if the signal were continuously green and expressed in vehicles per hour of green time, per lane. For a lane or lane group HCM recommends discharge headway method for calculating saturation flow rate from saturation headway. The manual suggest that the calculation of saturation flow rate begins after the 5th vehicle since it is assumed the headways of successive vehicles become constant after the departure of the first four vehicles in the queue.

Finally, the average saturation flow rate for each cycle and the overall average saturation flow rate was computed using the following equations.

$$SFR_i = \frac{3600}{h_i}$$

$$\text{SFR}= \frac{1}{M}\sum_i^M SFR_i$$

SFR_i = average saturation flow rate for ith cycle (sec/veh);

SFR= overall average saturation flow rate (veh/h/ln);

M = Number of signal cycles in t hours of observation = 3600t/C;

3600 = number of seconds per hour;

C = Signal cycle length (sec).

CHAPTER FOUR

RESULTS AND DISCUSSIONS

4.1 Traffic Volume and Composition at Selected Signalized Intersections

Traffic volume, composition and characteristics have been found to be significant variables in determining saturation flow at signalized intersections, which made it necessary to collect traffic data and discusses its composition as well. It indicates that saturation flows rates can be gained through counting the vehicles crossing the stop line during the GREEN period. The stable moving queue has been crossing the stop line and movement wise classified traffic volumes are used for determination of prevailing saturation flow rate for different lane groups.

4.1.1 Traffic Volume and Composition at Leghar Signalized Intersection

Table 4.1 presents the vehicular volume and composition at all approaches of Leghar Signalized intersection during the morning and afternoon peak hours. From the table it can be shown that from all vehicle types considered the share of passenger car is the highest one. In the morning peak hour the number of cars is 1978 which accounts for 77 percent at Mexico approach and 87.16 percent from Leghar Bus Station approach in the afternoon peak hour.

Table 4. 1Traffic Volume and Composition at Approaches of Leghar Intersection

Time	Approach Name	Number of Vehicles (Percentage Composition, %)					
		Cars	Mini Buses	Buses	Small Trucks	Large Trucks	Total
Morning Peak Hour	Mexico	1978(76.99)	404 (15.73)	76 (2.96)	106 (4.13)	5 (0.19)	2569 (37.50)
	Beherawi	654 (77.21)	175 (20.66)	6 (0.71)	12 (1.42)	0 (0)	847 (12.36)
	Stadium	1603 (66.38)	663 (27.45)	89 (3.69)	57 (2.36)	3 (0.12)	2415 (35.25)
	Leghar B.S	889 (87.16)	88 (8.63)	4 (0.39)	39 (3.82)	0 (0)	1020 (14.89)
Afternoon Peak Hour	Mexico	2295 (76.96)	490 (16.32)	132 (4.43)	65 (2.18)	0 (0)	2982 (39.99)
	Beherawi	689 (78.92)	162 (18.56)	8 (0.92)	14 (1.600	0 (0)	873 (11.71)
	Stadium	1847 (69.80)	614 (23.20)	81 (3.06)	97 (3.67)	7 (0.26)	2646 (35.48)
	Leghar B.S	846 (88.49)	75 (7.85)	15 (1.57)	20 (2.09)	0 (0)	956 (12.82)

Note: B.S stands for Bus Station

4.1.2 Traffic Volume and Composition at Harambi Signalized Intersection

From the table it can be seen that cars are the dominant vehicle type at all approaches of Harambi signalized intersection during the study period of this research. The maximum percentage composition of passenger cars was found at Beherawi approach (78.22 %) in the morning and 82.91 percent in the afternoon. The maximum and minimum percentage composition of mini buses was observed in the afternoon peak hour which ranges from 13.94 percent from Beherawi approach to 29.88 percent from Stadium approach.

The share of buses is highest at Beherawi approach (2.68%) in the morning and lowest at south bound direction or FilWuha approach which is close to 1 percent. The table also indicates that the proportion of Small Trucks on the approaches ranged from 0.82 to 1.62 percent. The percentage of Large Trucks is less than zero at all approaches but few Trucks are cross this intersection during green time.

During the data collection period of this study it is observed that the major share of vehicles at Harambi Intersection comes from Beherawi approach with traffic volume 1717 which accounts for 31.08 percent in the morning and 1750 vehicles or 33.04 percent of total traffic flow in the afternoon peak hour. The next dominating approach is FillWuha approach which covers 26.96 percent of total traffic flow in the morning and 25.81 percent in the evening peak hours.

Table 4. 2 Traffic Volume and Composition at Approaches of Harambi Intersection

Time	Approach Name	Number of Vehicles (Percentage Composition, %)					
		Cars	Mini Buses	Buses	Small Trucks	Large Trucks	Total
Morning Peak Hour	**Beherawi**	1343 (78.22)	314 (18.29)	46 (2.68)	14 (0.82)	0 (0)	1717 (31.08)
	EBC	703 (73.46)	227 (23.72)	12 (1.25)	15 (1.57)	0 (0)	957 (17.32)
	FilWuha	1115 (74.88)	338 (22.70)	18 (1.21)	17 (1.14)	1 (0.07)	1489 (26.96)
	Stadium	985 (72.37)	336 (24.69)	17 (1.25)	22 (1.62)	1 (0.07)	1361 (24.64)
Afternoon Peak Hour	**Beherawi**	1451 (82.91)	244 (13.94)	35 (2.00)	17 (0.97)	3 (0.17)	1750 (33.04)
	EBC	776 (82.20)	139 (14.72)	18 (1.91)	10 (1.06)	1 (0.11)	944 (17.82)
	FilWuha	1089 (79.66)	239 (17.48)	14 (1.02)	21 (1.54)	4 (0.29)	1367 (25.81)
	Stadium	825 (66.80)	369 (29.88)	22 (1.78)	17 (1.38)	2 (0.16)	1235 (23.32)

4.1.3 Traffic Volume and Composition at Mesqel Square Signalized Intersection

Table 4.3 shows traffic composition at different approaches of Mesqel Square Signalized Intersections and from the table it is observed that percentage of car is more than the other category of vehicles. The highest share of cars observed at Stadium approach accounts for 87.02 percent in the morning and 86.50 percent from Dembel approach in the afternoon.

The maximum volume and percentage share of Mini Buses was observed at Arat Kilo approach which covers about 17.86 percent of total traffic volume in the morning peak hour. But the minimum share of mini busses is observed from HayaHulet approach both in the morning and afternoon peak hour traffic flow. The percentage of mini bus is then followed by buses and small trucks and their share at all approaches is found out and given in table 4.3. The share of large trucks is low as compared to other vehicle categories and their composition is almost zero percent due to restriction periods or rules of their operation within the city intersections.

At Mesqel Square intersection Dembel approach ranked as first approach in terms its traffic volume (2602) which covers about 28.48 percent of total traffic volume in the morning peak hour. But in the afternoon the dominant approach is stadium approach which covers about 34.25 percent of the total traffic volume of all approaches.

Table 4. 3 Traffic Volume and Composition at Approaches of Mesqel Square Intersection

Time	Approach Name	Number of Vehicles (Percentage Composition, %)					
		Cars	Mini Buses	Buses	Small Trucks	Large Trucks	Total
Morning Peak Hour	Stadium	2574 (87.02)	271 (9.16)	54 (1.83)	58 (1.96)	1 (0.03)	2958 (32.38)
	Arat Kilo	1079 (79.63)	242 (17.86)	17 (1.25)	17 (1.25)	0 (0)	1355 (14.83)
	HayaHulet	1914 (86.22)	186 (8.38)	51 (2.30)	57 (2.57)	12 (0.54)	2220 (24.30)
	Dembel	2223 (85.43)	336 (12.91)	14 (0.54)	28 (1.08)	1 (0.04)	2602 (28.48)
Afternoon Peak Hour	Stadium	2402 (75.92)	588 (18.58)	120 (3.79)	53 (1.68)	1 (0.03)	3164 (34.25)
	Arat Kilo	1110 (84.73)	178 (13.59)	11 (0.84)	11 (0.84)	0 (0)	1310 (14.18)
	HayaHulet	1770 (86.26)	154 (7.50)	46 (2.24)	76 (3.70)	6 (0.29)	2052 (22.21)
	Dembel	2346 (86.50)	310 (11.43)	12 (0.44)	42 (1.55)	2 (0.07)	2712 (29.36)

4.1.4 Traffic Volume and Composition at Shola Signalized Intersection

Table 4.4 shows the vehicular volume and composition of approaches of Shola signalized intersection. Share of cars varies from 65.35 percent (Denberewa approach) to 85.36 percent (Lem Hotel approach) in the morning peak hour and from 12.80 percent (Lem Hotel) to 29 percent Megenagna approach in the afternoon peak hours. The percentage composition of cars shows their significant presence in the traffic pattern. Next highest percentage composition at this signalized intersection is that of mini buses which lie between 11.70 percent from Lem Hotel approach to 30.13 percent at Denberewa approach in the morning peak hour.

The maximum and minimum percentage of buses is observed at east bound direction or Shola Gebeya approach and Megenagna approach respectively. During both peak periods the composition of Small Trucks at each approach of Shola intersection is less than five percent. For example the table shows in the afternoon peak hour the share of Small Trucks ranges from 0.75 to 4.28 percent at Megenagna and Shola Gebeya approach respectively. The percentage composition of large trucks is negligible in all approaches of this candidate intersection.

More close analysis shows that at this intersection the most dominating approach is Denberewa approach 28.19 percent in the morning and 31.15 percent in the afternoon peak hour. From table 4.4, it is concluded that majority of traffic is of cars; mini buses and buses both in the morning and afternoon peaks hour during the study period of this study.

Table 4. 4 Traffic Volume and Composition at Approaches of Shola Signalized Intersection

Time	Approach Name	Number of Vehicles (Percentage Composition, %)					
		Cars	Mini Buses	Buses	Small Trucks	Large Trucks	Total
Morning Peak Hour	**Denberewa**	809 (65.35)	373 (30.13)	25 (2.02)	25 (2.02)	6 (0.48)	1238 (28.19)
	Shola	636 (71.22)	191 (21.39)	31 (3.47)	30 (3.36)	5 (0.56)	893 (20.34)
	Megenagna	783 (68.68)	340 (29.82)	8 (0.70)	6 (0.53)	3 (0.26)	1140 (25.96)
	Lem Hotel	956 (85.36)	131 (11.70)	9 (0.80)	24 (2.14)	0 (0)	1120 (25.51)
Afternoon Peak Hour	**Denberewa**	1040 (75.20)	290 (20.97)	15 (2.46)	34 (2.46)	4 (0.29)	1383 (31.15)
	Shola	735 (74.92)	181 (18.45)	20 (2.04)	42 (4.28)	3 (0.31)	981 (22.09)
	Megenagna	645 (69.50)	269 (28.99)	5 (0.54)	7 (0.75)	2 (0.22)	928 (20.90)
	Lem Hotel	953 (83.01)	147 (12.80)	7 (0.61)	40 (3.48)	1 (0.09)	1148 (25.86)

4.1.5 Traffic Volume and Composition at Imperial Signalized Intersection

At Imperial selected signalized intersection the maneuverability of cars is more than other category of vehicles. From the table of total traffic volume and composition of different approaches of Imperial signalized intersection it can be clearly seen that the major share of traffic is of cars, mini buses, buses, and trucks.

During morning peak hour cars account for 83.06 percent of traffic flow from Atlas approach, 76.28 percent from Megenagna approach, 81.83 percent from Gerji and 69.11percent from the west bound direction or Bole approach. In the afternoon share of cars is maximum at Atlas approach and minimum at Bole approach (69.18%). During both peak hours the maximum number of Mini Buses was found at Bole approach with approximately 22 percent of total traffic volume. The shares of all remaining vehicle types considered in this study contribute almost less than 5 percent at all approaches of Imperial signalized intersections.

The table also shows that Megenagna and Bole approach are the most dominating approaches of Imperial Signalized intersection in terms of vehicular movement which indicates that above half percent of the total traffic volume comes from both approaches. The least vehicles are comes from Atlas approach and it is only around 13 percent in the afternoon peak hour.

Table 4. 5 Traffic Volume and Composition at Approaches of Imperial Intersection

Time	Approach Name	Number of Vehicles (Percentage Composition, %)					
		Cars	Mini Buses	Buses	Small Trucks	Large Trucks	Total
Morning Peak Hour	**Atlas**	902 (83.06)	132 (12.15)	19 (1.75)	32 (2.95)	1 (0.09)	1086 (15.74)
	Megenagna	1894 (76.28)	468 (18.85)	71 (2.86)	48 (1.93)	2 (0.08)	2483 (35.98)
	Gerji	1031 (81.83)	205 (16.27)	5 (0.40)	17 (1.35)	2 (0.16)	1260 (18.26)
	Bole	1432 (69.11)	456 (22.01)	84 (4.05)	95 (4.58)	5 (0.24)	2072 (30.02)
Afternoon Peak Hour	**Atlas**	930 (87.08)	96 (8.99)	28 (2.62)	12 (1.12)	2 (0.19)	1068 (15.03)
	Megenagna	1708 (72.25)	499 (21.11)	102 (4.31)	51 (2.16)	4 (0.17)	2364 (33.26)
	Gerji	835 (79.52)	184 (17.52)	15 (1.43)	16 (1.52)	0 (0)	1050 (14.77)
	Bole	1816 (69.18)	586 (22.32)	109 (4.15)	111 (4.23)	3 (0.11)	2625 (36.94)

4.1.6 Traffic Volume and Composition at Bole Michael Signalized Intersection

Table 4.6 shows the traffic volume and composition of different vehicle types considered in this study at Bole Michael signalized intersection. Again in this case study intersection the total number and percentage composition of cars is higher than other vehicle types which show their significant presence at all approaches of this intersection.

Next highest percentage composition at this signalized intersection is that of mini buses and the maximum number of this vehicle category was observed at Rwanda approach in the morning peak hour with 21.04 percentage composition. The minimum and maximum number of buses is observed at north bound direction or Rwanda approach and Saris or Kadisco approach in the morning peak hour. The volume of small and large trucks was concentrated on the west to east corridor of Bole Michael signalized intersections (Saris Abo approach).

From table 4.6 it is presented that during morning and afternoon peak hours the maximum and minimum total number of vehicles was observed at Saris Abo and Bole Bulbula approaches. Generally Bole and Saris Abo approaches are the most important and dominant approaches Bole Michael intersection because of there is high volume of vehicles especially trucks and truck trailers come to this intersection from these approaches.

Table 4. 6 Traffic Volume and Composition at Approaches of Bole Michael Intersection

Time	Approach Name	Number of Vehicles (Percentage Composition, %)					
		Cars	Mini Buses	Buses	Small Trucks	Large Trucks	Total
Morning Peak Hour	**Rwanda**	632 (67.23)	231 (24.57)	4 (0.43)	71 (7.55)	1 (0.21)	940 (14.75)
	Bole	1652 (67.87)	512 (21.04)	69 (2.83)	185 (7.60)	16 (0.66)	2434 (38.20)
	B. Bulbula	406 (72.50)	134 (23.93)	2 (0.36)	18 (3.21)	0 (0)	560 (8.79)
	Saris Abo	1453 (59.62)	510 (20.93)	126 (5.17)	291 (11.94)	57 (2.34)	2437 (38.25)
Afternoon Peak Hour	**Rwanda**	800 (76.19)	187 (17.81)	5 (0.48)	57 (5.43)	1 (0.10)	1050 (16.51)
	Bole	1454 (66.73)	467 (21.43)	79 (3.63)	148 (6.79)	31 (1.42)	2179 (34.26)
	B. Bulbula	358 (70.61)	133 (26.33)	4 (0.79)	12 (2.37)	0 (0)	507 (7.97)
	Saris Abo	1695 (64.57)	473 (18.02)	111 (4.23)	286 (10.90)	60 (2.29)	2625 (41.27)

4.2.7 Morning and Afternoon Traffic Volume at Selected Signalized Intersections

It is observed from Figure 4.1 the highest hourly traffic volume observed in the morning peak hour is at Mesqel Square signalized intersection, with a total of 9106 vehicles and least amount is at Shola intersection with a total of 4386 vehicles spotted during the morning peak hour. On the other hand in the afternoon peak hour the highest and lowest traffic volume is occurred at both the aforementioned intersections with total traffic volume 9253 and 4440 respectively.

As can be clearly seen from the figure shown below at all the selected intersections the afternoon peaks tend to be longer and flatter than morning peaks because most morning trips are work-related while afternoon trips are more diverse. This indicates the arrival flow in the afternoon peak hour is higher than the morning time in almost all of the candidate intersections. The possible reason is that in the morning peak hour, vehicles were navigating very slowly through the intersections during green time.

Collectively, a total of 79072 vehicles were involved in the analysis, 39173 vehicles during the morning peak hour and 39899 vehicles during afternoon peak hour. Knowing traffic volume and composition during different time of day is important to design road properly and to improve its capacity in order to accommodate the traffic based on the tidal phenomenon of traffic flow.

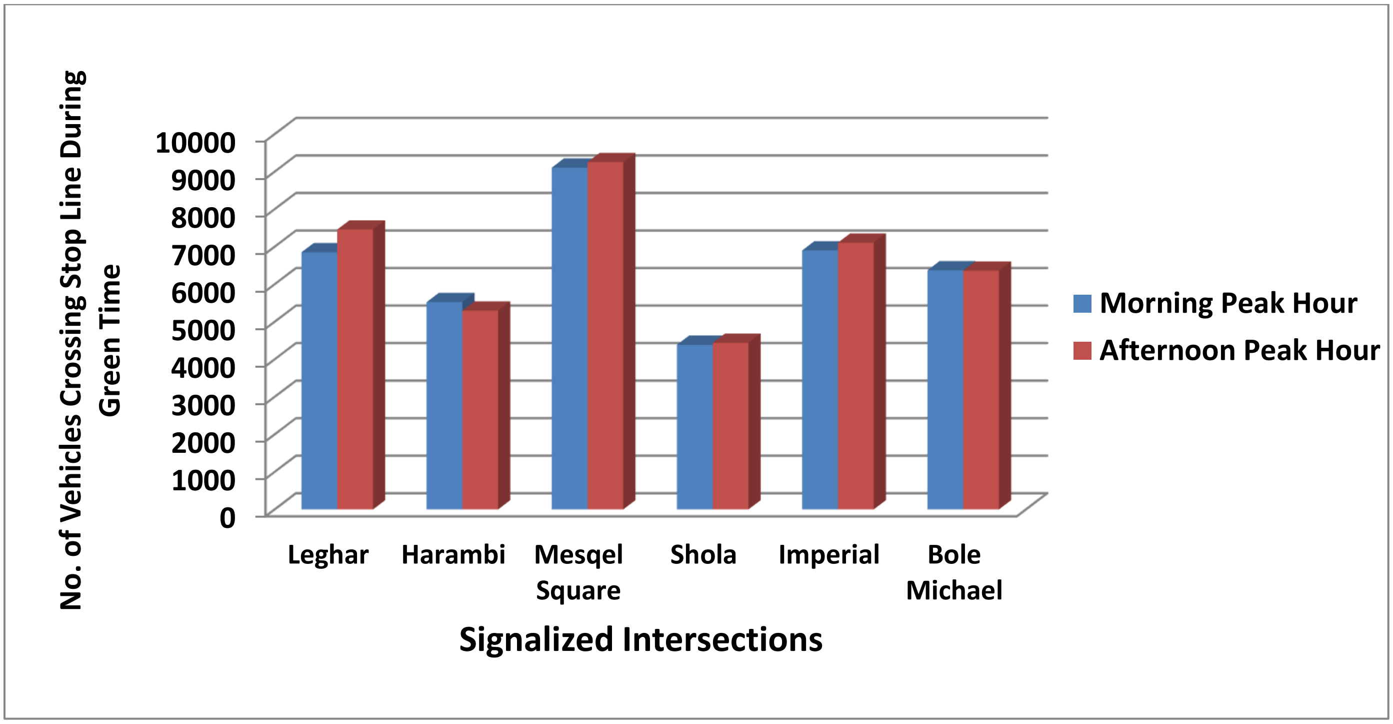


Figure 4.1 Mornings and Afternoon Peak Hour Traffic Volume

4.2.8 Traffic Composition Analysis at the Selected Signalized Intersections

Vehicles passed the intersection through green time are category wise counted and their composition is found out. The percentage composition of each category of vehicles at the selected signalized intersections is determined and the results are presented through pie charts in Figures 4.2 to 4.4.

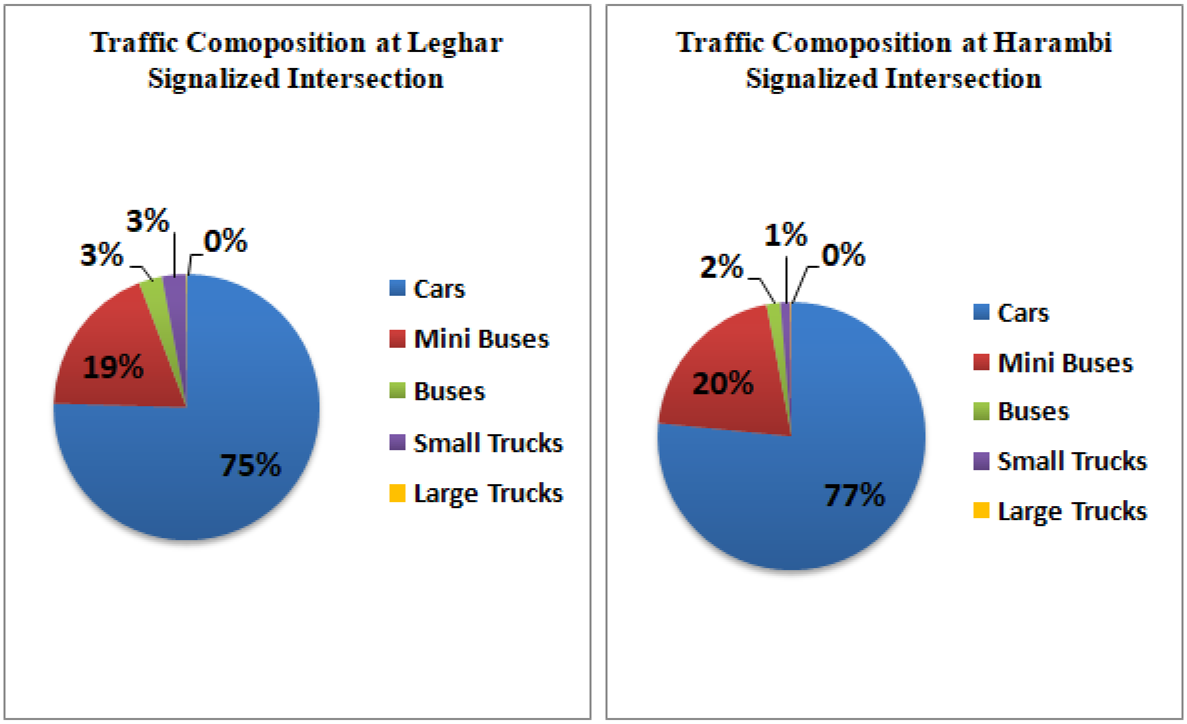


Figure 4. 2 Vehicular Composition at Leghar and Harambi Signalized Intersections

It is observed from Figure 4.2 that major share of vehicles are of Cars and Mini Buses in the proportion of 75 and 19 percent respectively at Leghar Signalized Intersection. The figure also indicates that percentage of Buses in the traffic stream at this intersection is equal to that of Trucks. At Harambi signalized intersection from the comparison graphical form, it shows that the most dominating vehicle is car and they account for 77 percent of total traffic volume. Then cars are followed by Mini Buses with compositional share of 20 percent.

Considering both intersections, it is found that, the share of large trucks is negligible in the traffic stream and percentage of other vehicle categories shows slightly variation in volume of traffic. It is observed from these Figures Cars traffic is predominant at both intersections.

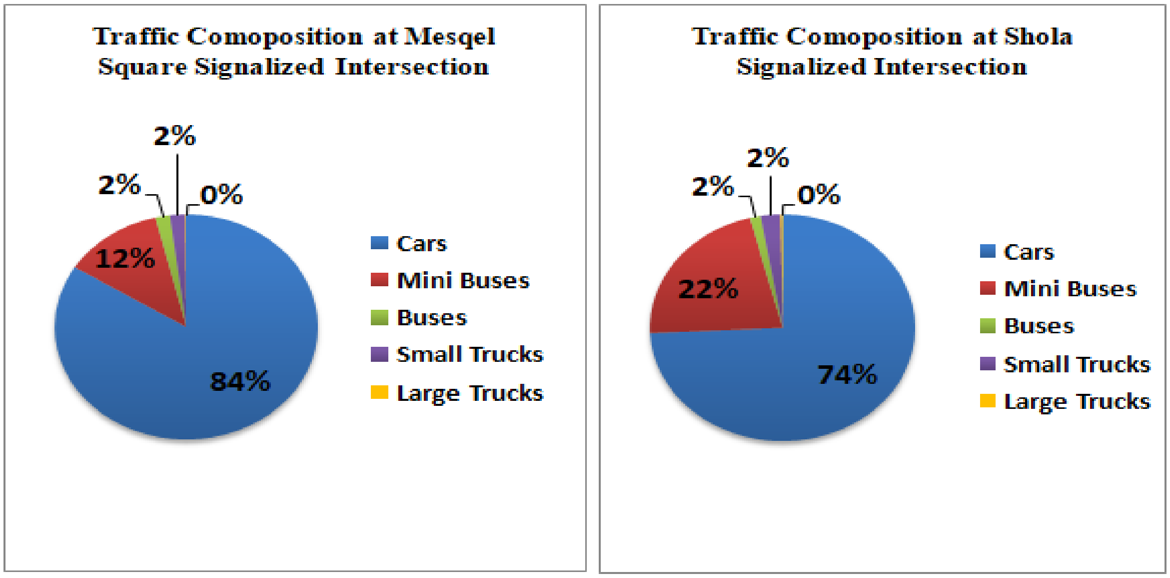


Figure 4. 3 Vehicular Composition at Mesqel Square and Shola Signalized Intersections

Figure 4.3 shows that the most dominating vehicle is Cars and constitutes about 84 percent of the total traffic at Mesqel Square intersection. Next highest percentage composition is that of Mini Buses (12%) followed by buses and small trucks. The higher composition of cars indicates that cars will have significant impact on the discharging vehicles. On the other hand at Shola signalized intersection this study revealed that Passenger Cars constitute about 74 %, Mini Buses constitute 22%, Buses and trucks constitute less than 5 percent.

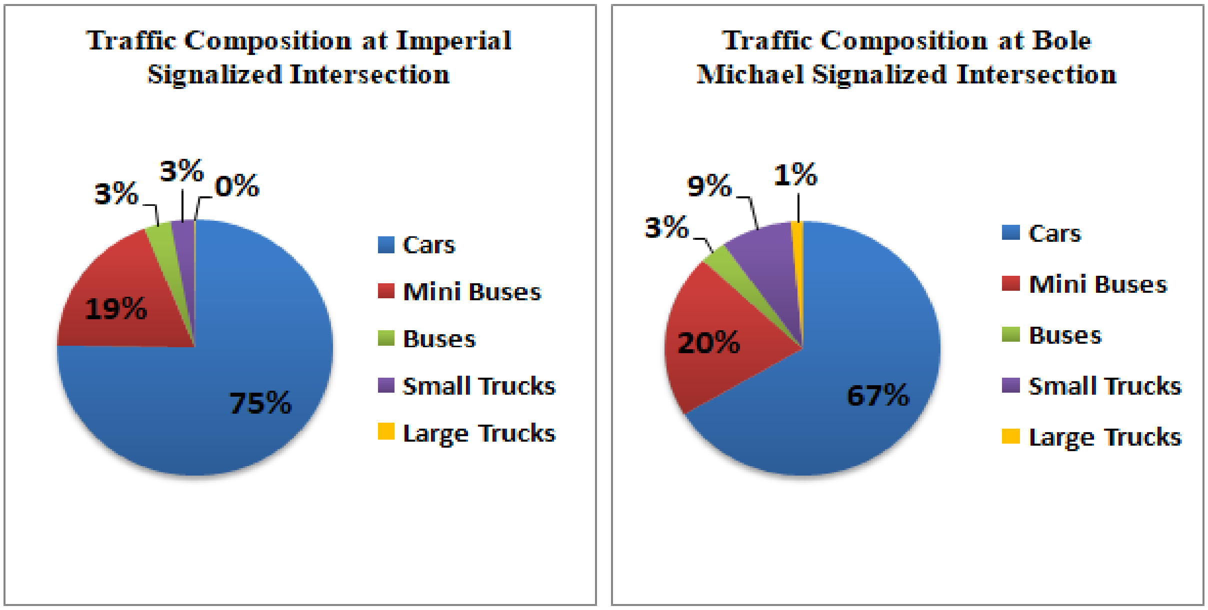


Figure 4. 4 Vehicular Composition at Imperial and Bole Michael Signalized Intersections

In Figure 4.4, a pie chart is shown, which is expressing the vehicular composition of Imperial and Bole Michael signalized intersections.

From the above pie chart the dominancy of Cars was observed, which was 75 percent of total vehicular flow of traffic at Imperial signalized intersection and among the vehicular flow, Mini Buses were the next mostly governed vehicle type in this intersection, which was 19 percent of total traffic volume. But Buses and Trucks constitute the same percentage which is 3 percent of the total vehicles at Imperial signalized intersection during data collection period of this study. Figure 6, also shows that at Bole Michael signalized intersection the composition of vehicular traffic is dominated by Cars, Mini Buses and Small Trucks and it is inferred that their composition is 67%, 20% and 9% respectively.

All of the above charts show that cars are the mostly governed vehicle type in all selected signalized intersections. It also shows that during both peak periods truck trailer movement is very less almost 0% of total traffic at all selected intersections. This is due to the reason that the Traffic Management Agency of Addis Ababa City has banned trucks and truck trailers from operating within the city during peak hours of the day in an attempt to reduce large vehicles clogging roads during peak hours which ensures smooth and efficient flow of traffic.

Generally in this study a total of 79072 vehicles were analyzed, out of this around 60000 cars have been observed which accounts to 76 percent of the total traffic. Next to cars, the traffic mainly consists of Mini Buses with a volume of 14337 making 18 percent of traffic composition. Other catagories of vehicles considered in this study are Buses, Small Trucks and Large Trucks witth total amount of 1871, 2543 and 260 respectively all with less than 5% composition.

The term saturation flow rate accounts for the variability or the peaking that may occur of vehicles passing a point along a roadway or signalized intersection approach during periods of less than one hour. Therefore understanding traffic volume and composition is significant for traffic engineers to take in to consideration the tidal phenomenon when designing traffic signal control strategies and also when computing passenger car equivalents for different vehicle types.

4.3 Overall Distribution of Discharge Headway

At signalized intersections understanding discharge headway and its distribution is essential in estimation of saturation headway and saturation flow rate. From Table 4.7 it can be concluded that the first vehicle in the queue had a relatively long headway and the differences between headway values of vehicles are almost immutable after the fifth vehicle queue position.

Table 4. 7 Descriptive statics of overall observed departure headway (seconds)

Queue Position	Average	Std. Err.	Std. Dev.	Median	Skewness	Range	85 Percentile	95% Conf. Interval
1	3.030	0.038	0.417	3.138	-0.206	1.937	3.441	2.955 - 3.106
2	2.906	0.037	0.400	2.977	-0.153	2.000	3.204	2.833 - 2.978
3	2.778	0.037	0.407	2.871	-0.068	1.864	3.215	2.705 - 2.852
4	2.752	0.038	0.421	2.830	-0.265	2.021	3.061	2.676 - 2.828
5	2.697	0.033	0.367	2.754	-0.221	1.762	3.092	2.631 - 2.764
6	2.633	0.033	0.363	2.583	0.049	1.826	3.100	2.568 - 2.699
7	2.540	0.030	0.323	2.542	0.090	1.714	2.857	2.482 - 2.599
8	2.497	0.026	0.290	2.447	0.454	1.641	2.857	2.445 - 2.549
9	2.486	0.028	0.309	2.441	0.689	1.924	2.870	2.431 - 2.542
10	2.433	0.029	0.315	2.409	0.432	1.760	2.659	2.376 - 2.490
11	2.431	0.030	0.324	2.443	0.290	1.763	2.659	2.372 - 2.489
12	2.431	0.026	0.290	2.362	0.313	1.740	2.767	2.379 - 2.483
13	2.424	0.027	0.300	2.398	-0.075	1.810	2.694	2.370 - 2.479
14	2.388	0.027	0.301	2.368	0.079	1.791	2.749	2.334 - 2.442
15	2.373	0.025	0.271	2.366	0.246	1.758	2.651	2.324 - 2.422
16	2.370	0.027	0.301	2.399	0.259	1.753	2.565	2.315 - 2.424
17	2.368	0.025	0.279	2.403	0.449	1.701	2.593	2.318 - 2.418
18	2.336	0.028	0.306	2.260	0.536	1.634	2.613	2.280 - 2.391
19	2.331	0.026	0.286	2.326	0.147	1.651	2.628	2.279 - 2.382
20	2.310	0.023	0.255	2.325	0.063	1.644	2.582	2.264 - 2.356
21	2.326	0.024	0.264	2.326	0.173	1.569	2.613	2.278 - 2.373
22	2.343	0.027	0.294	2.354	0.337	1.609	2.615	2.289 - 2.396
23	2.332	0.027	0.296	2.325	-0.112	1.613	2.628	2.279 - 2.386
24	2.354	0.027	0.297	2.362	-0.211	1.697	2.659	2.301 - 2.408
25	2.348	0.027	0.291	2.342	-0.185	1.766	2.626	2.295 - 2.401
26	2.320	0.024	0.262	2.325	0.242	1.816	2.553	2.272 - 2.368
27	2.315	0.022	0.238	2.266	0.097	1.700	2.575	2.272 - 2.359
28	2.303	0.021	0.230	2.237	0.277	1.690	2.532	2.261 - 2.345
29	2.309	0.024	0.266	2.321	-0.115	1.516	2.544	2.261 - 2.357
30	2.280	0.020	0.217	2.264	-0.159	1.465	2.527	2.241 - 2.320

Figure 4.5 presents the overall headway distribution across vehicle positions in this study which include the maximum, minimum and average values of the discharge headway. From the figure the value headways show a significant decreasing tendency with the increase of vehicle position in a queue, though with some minor fluctuations at the beginning and at the end of the green time. The first vehicle in the queue had a relatively long headway from the time that the traffic signal turned green until the front wheel of that vehicle passed the stop line. The headways between subsequent vehicles then reduced systematically, as anticipated.

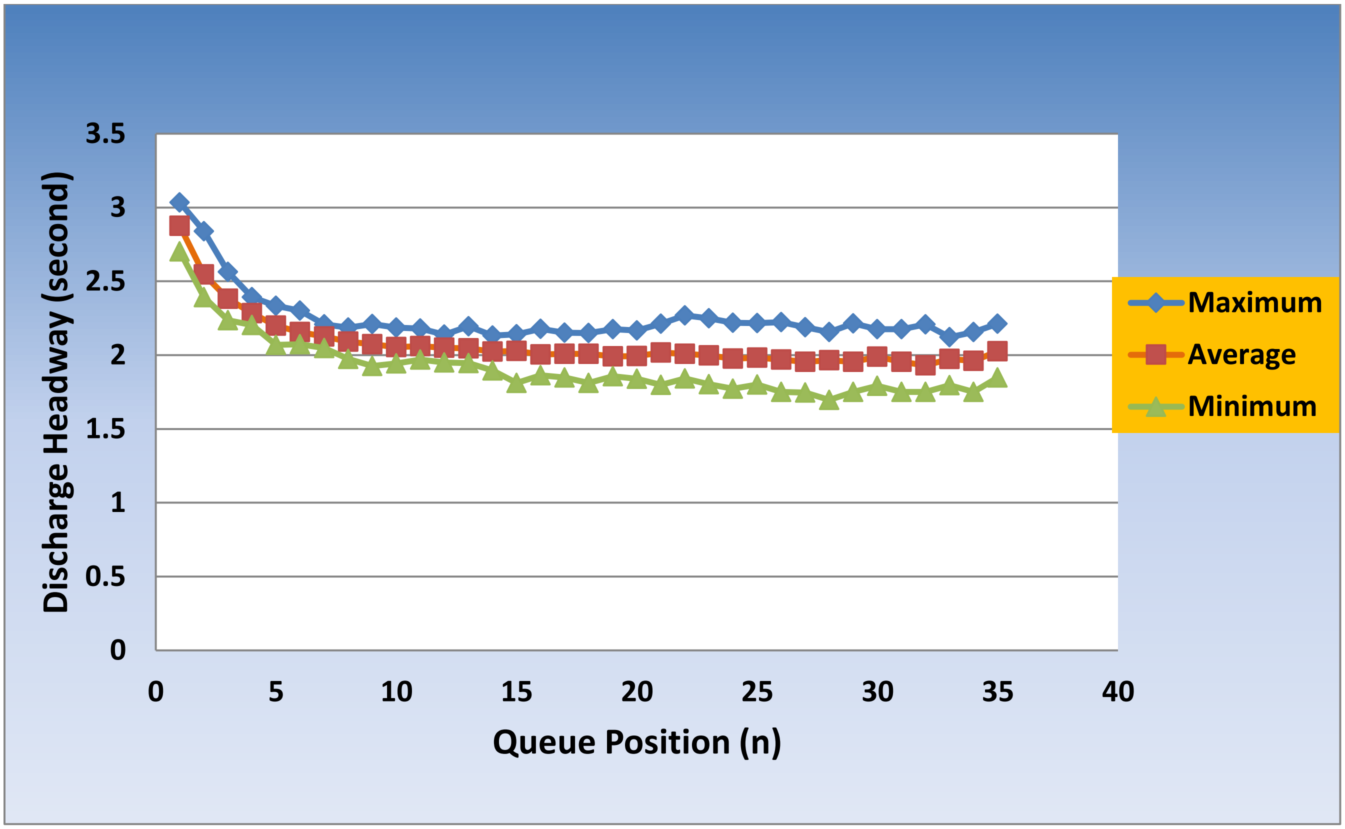


Figure 4. 5 Observed Discharge Headway as a Function of Queue Position

The time headway of vehicles is of fundamental importance in traffic engineering applications like capacity, level of-service and safety studies. Further, the performance of traffic simulation depends on inputs into the simulation process and ‘accurate vehicle generation is critical in this context. Thus, it is important to define headway distribution pattern for the purpose of analyzing traffic and subsequently, taking infrastructure related decisions. Additionally distribution of the discharge headways of vehicles is used to understand traffic flow process and driving behavior of mixed traffic streams.

4.4 Analysis of Field data Saturation Headway

The discharge headway showed a decreasing trend until it reached a stabilized interval. The headway of consecutive vehicles progressively decreased until it reached a constant (saturation headway) till the initial queue dissipated. Saturation flow is the maximum discharge rate during the saturated green time. As per the HCM, saturation flow is reciprocal of the saturation headway. Basic statistical results of saturation headway for each type of lane groups are shown in Table 4.8. Figure 4.6 presents a plot of the average queue discharge rate at different queue positions for lane types considered in this study.

Table 4. 8 Summary of Computed Saturation Headway

Lane Group	Mean	Std. Dev.	Median	Min	Max	Skewness	95% C.I
Exclusive Left Lane	2.465	0.067	2.460	2.321	2.571	-0.360	2.44 -2.490
Shared Left and Through	2.494	0.048	2.499	2.397	2.588	-0.430	2.479 - 2.510
Through Lane	2.340	0.040	2.336	2.268	2.436	0.347	2.325 - 2.355
Shared Through and Right	2.415	0.042	2.414	2.349	2.492	0.260	2.400 - 2.431

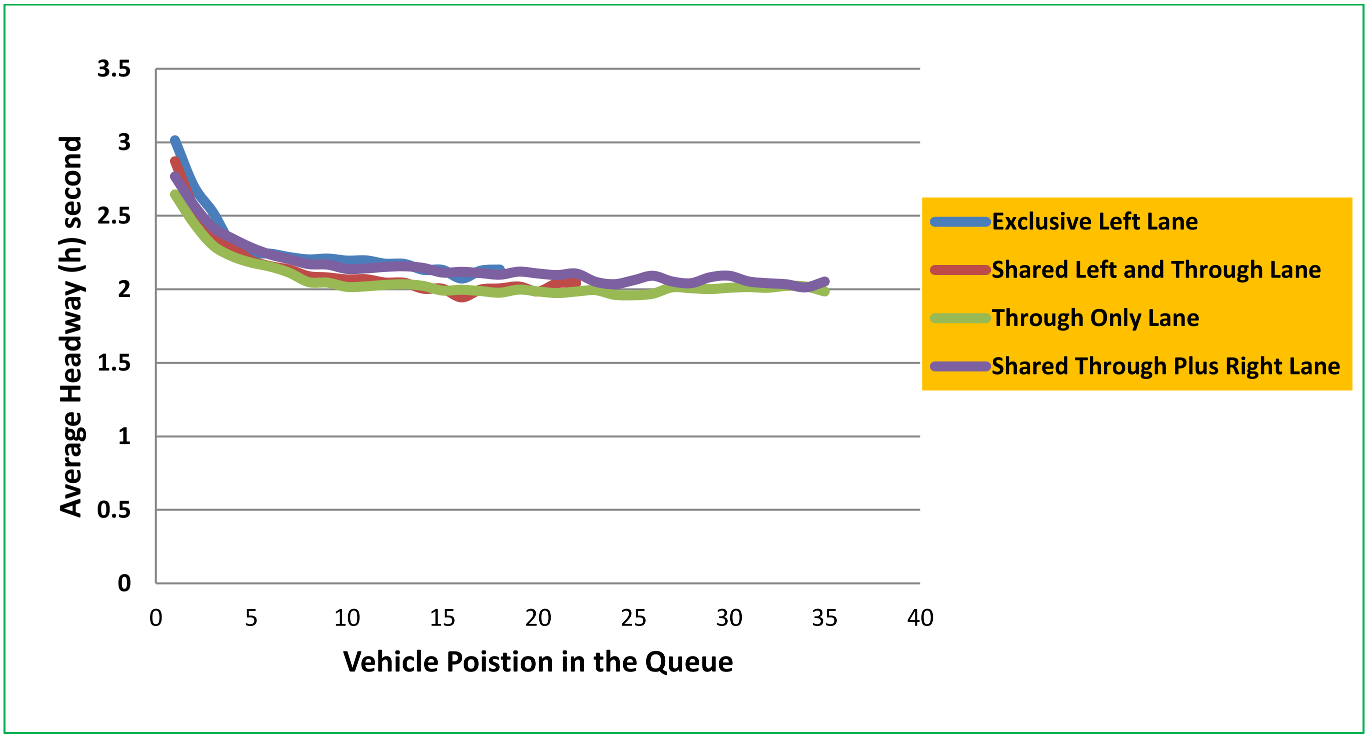


Figure 4. 6 Average Queue Discharge Rate by Queue Position for Different Lane Groups

4.5 Prevailing Saturation Flow Rate at Selected Intersections

The results of the saturation headway and saturation flow rate analysis of six signalized intersections in Addis Ababa are presented in Table 4.9 Saturation flow rate is indicated in terms of vehicles per hour per lane and the flow rate is prevailing saturation flow rate which was measured in the field under mixed traffic condition.

Table 4. 9 Summary of Saturation Headway and Flow Rate at Selected Intersections

Intersections	Total No. of Vehicles	SH (sec)			SFR (vphpln)		
	N	Mean	Std. Dev.	Median	Mean	Std. Dev.	Median
Leghar	14308	2.397	0.076	2.398	1503.62	47.616	1501.18
Harambi	10820	2.475	0.060	2.470	1455.34	35.962	1457.65
Mesqel Square	18373	2.304	0.049	2.295	1562.85	32.729	1568.43
Shola	8826	2.565	0.078	2.556	1405.01	42.972	1408.66
Imperial	14008	2.423	0.042	2.420	1486.11	25.668	1487.76
Bole Michael	12732	2.367	0.064	2.364	1522.06	41.156	1522.64

According to Table 4.9, Shola signalized intersection has the maximum saturation headway and minimum saturation flow rate due to the fact that this intersection can be located in the central business district, the public park (especially taxies) at the outlet of all approaches which causes traffic jams at the beginning of the green time. Whereas Mesqel Square has the minimum saturation headway which yields maximum saturation flow rate than other intersections considered in this study due to the wide width of the desired outlet and the greater freedom of movement for drivers in all lane directions both in the morning and afternoon peak hours.

Leghar signalized intersections has the highest standard deviation of both saturation headway and flow rate than other intersections. On the other hand; the lowest saturation headway and prevailing saturation flow rate standard deviation is observed at Imperial signalized intersection and at Bole Michael intersections both the mean and median value of SFR is the same.

At Harambi signalized intersection the overall saturation headway ranged from 2.30 sec to a 2.58 sec with a mean value of 2.48 seconds. The saturation flow rates varied from a maximum of 1568 veh/hour to a minimum of 1394 veh/hr, with a mean of 1455 vehicles per hour.

4.5.1 Prevailing Saturation Flow Rate at Approaches of Selected Intersections

After determining the saturation headway, the saturation flow rate of every approach of the selected intersections was calculated and the result is presented in Table 4.10 below.

Table 4. 10 Prevailing Saturation Flow Rate at Approaches of Selected Intersections

Intersections	Traffic Approach From	No. of Cycles	Prevailing Saturation Flow Rate (veh/hr/lane)					
		N	Mean	Std. Dev.	Median	Min	Max	95% Conf. Interval
Leghar	**Mexico**	**60**	1533	43.76	1541	1444	1604	1517 - 1549
	Beherawi	**60**	1513	74.80	1530	1304	1624	1485 - 1541
	Stadium	**60**	1470	145.20	1431	1297	1730	1416 - 1524
	Leghar B.S	**60**	1499	88.41	1483	1347	1678	1466 - 1532
Harambi Hotel	**Beherawi**	**60**	1456	56.19	1462	1347	1616	1436 - 1477
	EBC	**60**	1462	64.70	1459	1339	1625	1438 - 1487
	FilWuha	**60**	1409	62.76	1405	1312	1589	1386 - 1433
	Stadium	**60**	1493	72.57	1499	1329	1640	1466 - 1520
Mesqel Square	**Stadium**	**60**	1570	45.34	1572	1482	1659	1553 - 1587
	Arat Kilo	**60**	1521	51.81	1527	1418	1640	1502 - 1541
	HayaHulet	**60**	1585	57.98	1584	1486	1775	1563 - 1606
	Dembel	**60**	1575	60.29	1572	1461	1685	1552 - 1598
Shola	**Denberewa**	**60**	1401	60.34	1402	1287	1513	1378 - 1424
	Shola Gebeya	**60**	1422	55.06	1415	1305	1535	1402 - 1443
	Megenagna	**60**	1395	56.69	1402	1285	1525	1374 - 1416
	Lem Hotel	**60**	1402	57.38	1406	1312	1515	1380 - 1423
Imperial	**Atlas**	**60**	1418	42.47	1420	1320	1506	1403 - 1434
	Megenagna	**60**	1549	46.71	1546	1466	1705	1531 - 1566
	Gerji	**60**	1472	59.15	1478	1346	1563	1450 - 1494
	Bole	**60**	1505	36.29	1505	1429	1603	1492 - 1519
Bole Michael	**Rwanda**	**60**	1477	56.04	1474	1373	1587	1456 - 1498
	Bole	**60**	1531	76.59	1513	1401	1725	1502 - 1559
	Bole Bulbula	**60**	1520	94.09	1540	1309	1705	1484 - 1555
	Saris Abo	**60**	1561	49.38	1557	1455	1674	1543 - 1580

4.6 Prevailing Saturation Flow Rate for Different Lane Groups

4.6.1 Prevailing Saturation Flow Rate for Exclusive Left Lane Group

This type of lane is not exit at all the selected signalized and the summary of the descriptive statistics of prevailing SFR for each of the selected signalized intersections for this type of lane both in the morning and afternoon peak hours is presented in table 4.11.

Table 4. 11 Summary of Saturation Flow Rate for Exclusive Left Lane Group

Signalized Intersections	Prevailing Saturation Flow Rate (vphpln)							
	Morning Peak Hour				Afternoon Peak Hour			
	Mean	Std. Dev.	Min	Max	Mean	Std. Dev.	Min	Max
Leghar	1341	77.60	1105	1471	1536	91.76	1311	1966
Mesqel Square	1506	74.26	1397	1650	1531	83.75	1392	1720
Imperial	1425	83.13	1233	1674	1474	65.80	1347	1700
Bole Michael	1424	97.70	1246	1627	1455	68.58	1287	1569

4.6.2 Prevailing SFR for Shared Left and Through Lane Group

According to table 4.12 for both morning and afternoon peak hours the highest mean prevailing SFR for shared left and through lane group type was found at Leghar and the lowest was observed at Bole Michael signalized intersection.

Table 4. 12 Summary of SFR for Shared Left and Through Lane Group

Signalized Intersections	Prevailing Saturation Flow Rate (vphpln)							
	Morning Peak Hour				Afternoon Peak Hour			
	Mean	Std. Dev.	Min	Max	Mean	Std. Dev.	Min	Max
Leghar	1462	98.98	1191	1636	1682	128.93	1473	1927
Harambi	1389	48.01	1293	1499	1421	47.42	1344	1532
Mesqel Square	1570	85.82	1445	1717	1497	70.43	1363	1613
Shola	1365	54.12	1274	1499	1367	47.57	1267	1476
Imperial	1457	50.34	1354	1539	1405	61.66	1286	1519
Bole Michael	1438	111.88	1228	1661	1531	110.85	1198	1693

4.6.3 Prevailing Saturation Flow Rate for Through Lane Group

Table 4.13 shows the summary of the descriptive statistics of prevailing saturation flow rate of through lane of different intersections. From all the six signalized intersections, the maximum mean value of prevailing SFR is observed at Imperial during morning peak hour.

Table 4. 13 Summary of Saturation Flow Rate for Through Lane Group

Signalized Intersections	Prevailing Saturation Flow Rate (vphpln)							
	Morning Peak Hour				Afternoon Peak Hour			
	Mean	Std. Dev.	Min	Max	Mean	Std. Dev.	Min	Max
Leghar	1587	115.63	1368	1821	1548	99.95	1313	1761
Harambi	1512	51.97	1431	1642	1519	61.32	1428	1704
Mesqel Square	1599	30.83	1549	1667	1574	41.50	1483	1709
Shola	1436	53.34	1306	1573	1444	59.25	1312	1556
Imperial	1573	42.86	1470	1688	1577	44.93	1467	1653
Bole Michael	1614	81.44	1513	1874	1620	87.16	1457	1801

4.6.4 Prevailing SFR for Shared Through and Right Lane Group

For shared through and right lane during the minimum prevailing SFR was found at Shola intersection in the morning and the maximum was at Harambi intersection in the afternoon peak hour as shown in table 4.14.

Table 4. 14 Summary of SFR for Shared Through Plus Right Lane Group

Signalized Intersections	Prevailing Saturation Flow Rate (vphpln)							
	Morning Peak Hour				Afternoon Peak Hour			
	Mean	Std. Dev.	Min	Max	Mean	Std. Dev.	Min	Max
Leghar	1412	59.73	1307	1552	1514	59.88	1390	1650
Harambi	1435	61.46	1314	1557	1457	71.53	1330	1599
Mesqel Square	1582	53.03	1481	1684	1570	41.89	1486	1670
Shola	1414	53.28	1314	1536	1404	60.37	1268	1533
Imperial	1517	36.69	1440	1593	1506	35.86	1437	1629
Bole Michael	1561	53.36	1454	1673	1531	68.14	1415	1705

4.6.5 Overall Average SFR of Signalized Intersections by Lane Type

Figure 4.7 compares the overall average values of prevailing saturation flow rate of the different lane groups considered in this study for each of the selected signalized intersections.

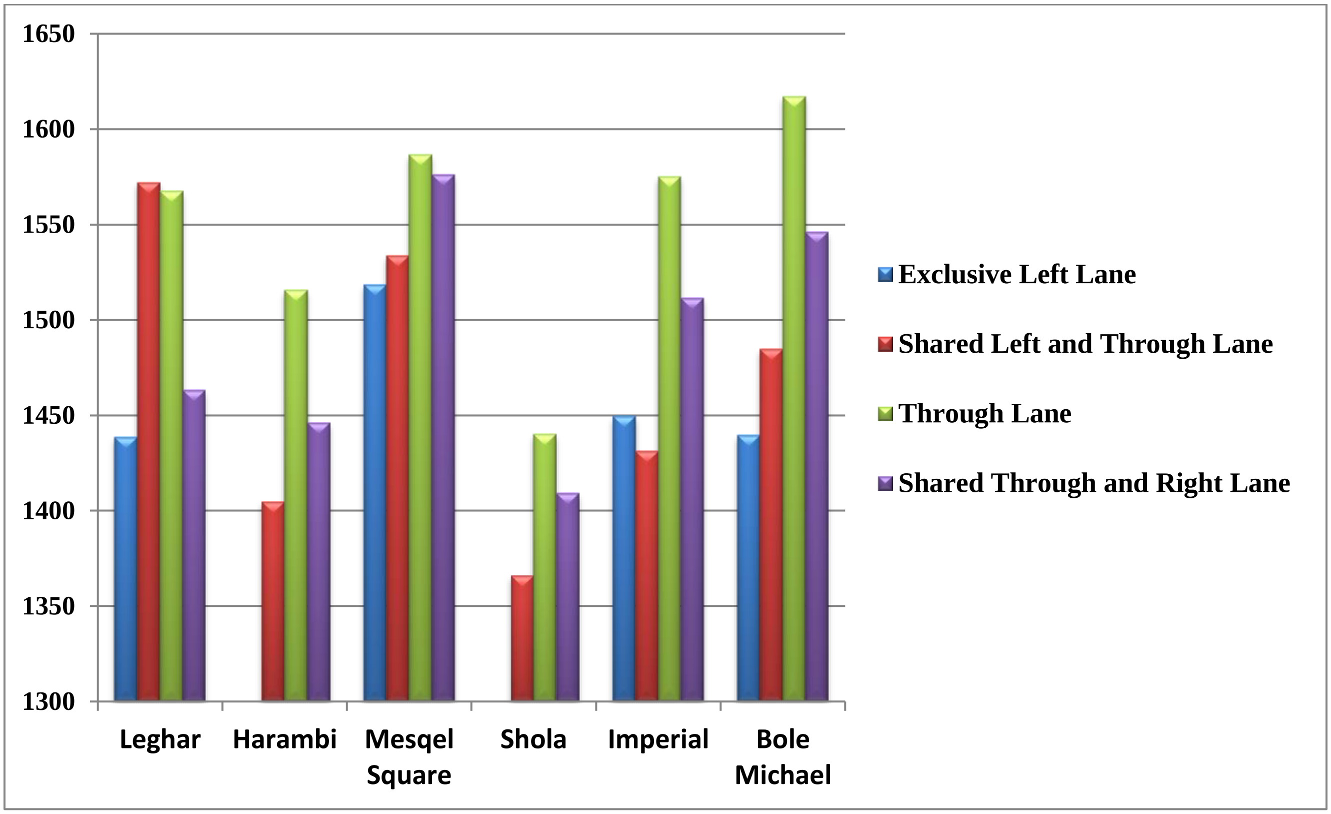


Figure 4. 7 Overall Average SFR of Signalized Intersections by Lane Type

From the graph it is indicated that the mean prevailing saturation flow rate of left lane group is lower than other types of lane groups at all intersections except Bole Michael signalized intersection. The primary reason for this exceptionally low flow rate is the influence of gap acceptance and presence of U turn vehicles and other operational factors.

From the figure it can be concluded that the overall average prevailing saturation flow rate in through lane movement is greater than the values of other lane group types considered in this study. It is easy to understand because through vehicles in general have higher travelling speeds and more compact headways than other types of lane groups.

4.7 Morning and Afternoon Peak Hour Prevailing Saturation Flow Rate

The time of day peak hour comparison was brought about by findings in the initial data collection. A comparison of prevailing saturation flow rate in the morning and afternoon peak hours for each of lane group types was done and the results are presented in table 4.15. It was hypothesized that the ideal saturation flow rate may vary by the time of day. These findings would be useful for more technologically advanced signal controllers offering the ability to vary signal timings over the course of the day. The number shown in the table represents the number of each type of lanes considered in this study from all selected intersections.

Table 4. 15 Summary of Average Prevailing SFRs per Lane Group

Time	Lane Groups	Prevailing Saturation Flow Rate (vphpln)				
		Number	Mean	Std. Err.	Std. Dev.	Median
Morning Peak Hour	**Exclusive Left Lane**	8	1424	7.96	43.57	1426
	Shared Left and Through Lane	16	1429	5.26	28.81	1426
	Through Lane	24	1545	5.47	29.98	1546
	Shared Through & Right Lane	24	1487	4.97	27.25	1492
Afternoon Peak Hour	**Exclusive Left Lane**	8	1499	8.70	47.64	1489
	Shared Left and Through Lane	16	1462	5.85	32.04	1459
	Through Lane	24	1537	5.93	32.47	1537
	Shared Through & Right Lane	24	1497	5.24	28.71	1496

During morning peak hour the through lane had the highest mean prevailing SFR value with 1545 vphpl, while the exclusive Left-turn lane had the lowest (1424 vphpl). In the afternoon peak hour through lane had the highest average SFR of 1537 vphpl, followed by the shared through lane (1767 vphpl). Again, shared left and through lane had the lowest mean prevailing SFR of 1462 vphpl followed by shared through & right lane group with 1497 vphpl.

At 95% confidence interval, the prevailing SFR value for shared through and right lane falls between 1432 and 1541 vphpl during morning and between 1436 to 1547 vphpl in the afternoon peak hour. Generally shared lanes at signalized intersections are designed for use by vehicles of different movement directions.

Figure 4.8 and Figure 4.9 presents the mean prevailing SFR values by lane group in the morning and afternoon peak hours respectively.

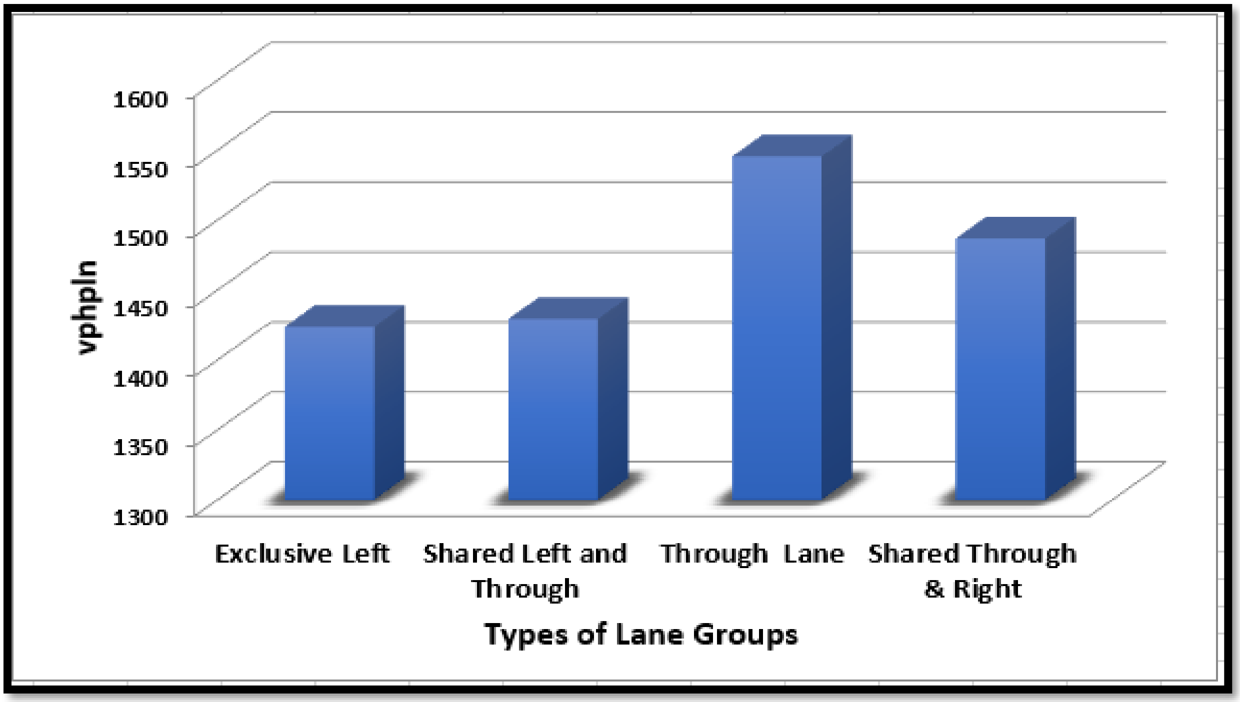


Figure 4. 8 Mean Prevailing SFR by Lane Groups during the Morning Peak Hour

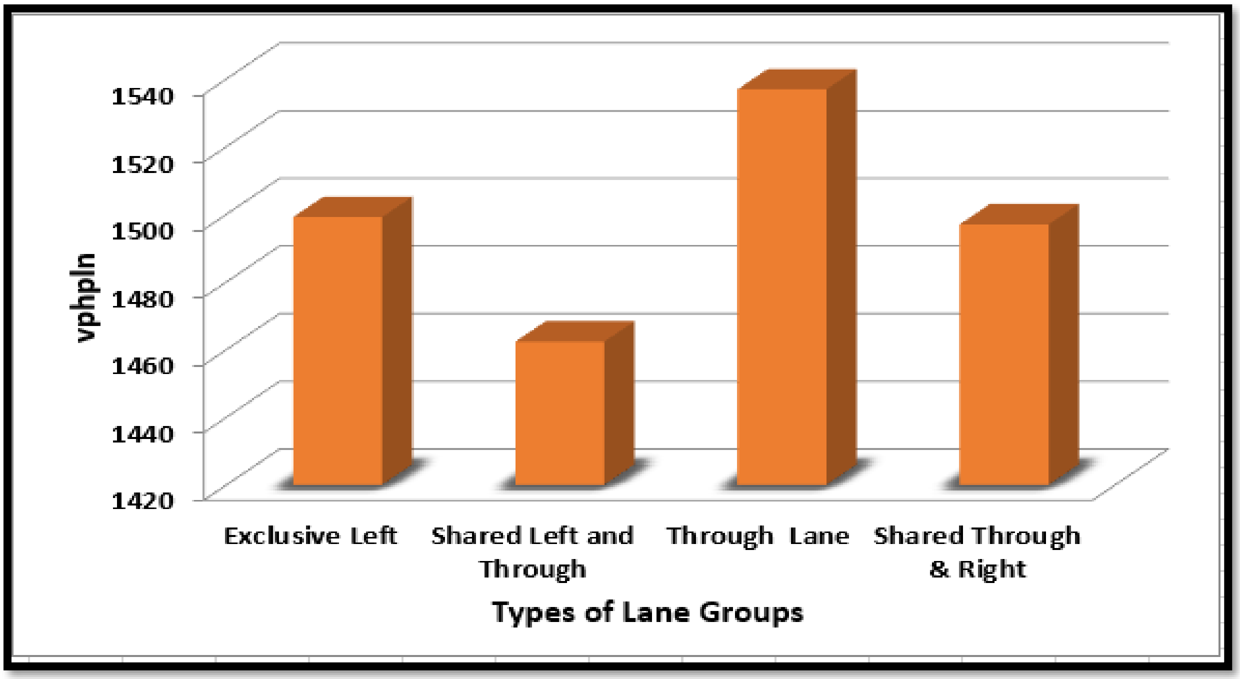


Figure 4. 9 Mean Prevailing SFR by Lane Groups during the Afternoon Peak Hour

4.8 Test of Hypothesis

One way analysis of variance (ANOVA) tests were conducted in this study to determine the significance of the differences among the saturation flow rate for different lane groups. The proposed hypothesis is that there is at least a significant difference between the average prevailing saturation flow rate for the lane groups considered in this study. A one-way ANOVA was used to test the hypotheses and is expressed mathematically as:

$$\boldsymbol{H_o}: \mu_{\boldsymbol{L}} = \mu_{\boldsymbol{LT}} = \mu_{\boldsymbol{TH}} = \mu_{\boldsymbol{RT}}$$

$$\boldsymbol{H_a}: \mu_{\boldsymbol{L}} \neq \mu_{\boldsymbol{LT}} \neq \mu_{\boldsymbol{TH}} \neq \mu_{\boldsymbol{RT}}$$

Where $\mu_{\boldsymbol{L}}, \mu_{\boldsymbol{LT}}, \mu_{\boldsymbol{TH}}, \mu_{\boldsymbol{RT}}$ and are the average prevailing SFRs for exclusive left, shared left and through, through only, and shared through plus right lane groups respectively. A 95% confidence interval was used to test the hypothesis with the assumption that the sample is normally distributed. If the associated p-value is determined less than ($\alpha = 0.05$) (p-value < α), we fail to accept the null hypothesis. However, if the p-value is greater than (p-value > α), we fail to reject the null hypothesis. This test was conducted due to the fact that the magnitude of prevailing saturation flow rate cannot be assumed equal for all lane groups used in this study.

The principal of an ANOVA table is to compare the F-value and the Fcritical value at a given confidence level. If F > Fcritical the null hypothesis will be rejected. Since the purpose of the test was to evaluate whether the lane group had a significant impact on the saturation flow rate at signalized intersections, in the morning and afternoon peak hours.

The principle of ANOVA is to analyze the variability of the data into two sources of variation, namely: variation within groups (within) and between groups (between). If the variation of within and between group is the same, it means that there is no difference in the effect of the intervention, or in other words there is no difference between both means compared. Conversely, if the variation between groups is greater than the variation within the group, it means the intervention has an effect.

4.8.1 One way ANOVA Single Factor Test for Morning Peak Hour

A 95% confidence interval was used to test the hypothesis with the assumption that the sample is normally distributed. Table 4.16 presents the summary statistics and single factor ANOVA for the morning and afternoon peak hours. The results show that a significant difference exists between at least one pair of lane groups prevailing SFR values.

According to the result of one-way analysis of variance for the four lane group categories, lane type had a statistically significant effect on average saturation flow rate. Therefore, lane group must be considered when conducting the study on saturation flow rate in Addis Ababa intersections in the morning peak hour.

Thus null hypothesis Ho was rejected and we can conclude that lane configuration had a significant impact on the saturation headways, so much attention is required in case of capacity analysis of signalized intersections for different lane type and time of day.

Table 4. 16 Single Factor ANOVA Test Results of Morning Peak Hour

Summary Statics: Morning Peak Hour						
Groups	***Count***	***Sum***	***Average***	***Variance***		
Exclusive Left Lane	30	44974.68	1499.16	2269.89		
Shared Left and Through	30	43869.93	1462.33	1026.28		
Through Lane	30	46107.28	1536.91	1054.04		
Shared Through and Right	30	44909.60	1496.99	824.47		
Single Factor ANOVA: Morning Peak Hour						
Source of Variation	***SS***	***df***	***MS***	***F***	***P-value***	***F critical***
Between Groups	83571.5	3	27857.17	21.53339	3.71E-11	2.682809
Within Groups	150066.1	116	1293.67			
Total	233637.6	119				

4.8.2 One way ANOVA Single Factor Test for Afternoon Peak Hour

As expected, in the afternoon peak hour lane group had the most significant effect on value of saturation flow rate. Table 4.17 shows that F value is greater than F critical value and P value is more than 0.05. Fobserved > Fcritical is showing the probability of acceptance of independent variables with the dependent. It is observed from the validation that observed saturation flow is affected by the variables like lane group type, traffic composition and time of day.

Based on the ANOVA analysis, it was found that the saturation flow rate is significantly affected by lane groups at 95 % confidence level (F-value = 25.852, $p < 0.05$). As a consequence, we reject the null hypothesis at 5% level of significance.

Table 4. 17 Single Factor ANOVA Test Results of Afternoon Peak Hour

Summary Statics: **Afternoon Peak Hour**						
Groups	***Count***	***Sum***	***Average***	***Variance***		
Exclusive Left Lane	30	42712.00	1423.73	1898.53		
Shared Left and Through	30	42880.42	1429.35	830.29		
Through Lane	30	46363.89	1545.46	898.76		
Shared Through and Right	30	44606.62	1486.89	742.43		
Single Factor ANOVA: **Afternoon Peak Hour**						
Source of Variation	***SS***	***df***	***MS***	***F***	***P-value***	***F critical***
Between Groups	292970.97	3	97656.99	89.38832	4.98E-30	2.682809
Within Groups	126730.33	116	1092.50			
Total	419701.30	119				

4.9 Box Plot of Saturation flow Rate over Different Lane Groups

Figure 4.10 illustrates the dispersions of prevailing saturation flow rates for each of lane types. The box plot indicates the minimum and the maximum saturation flow rate, and the low and high standard deviations for each of lane groups considered in this study.

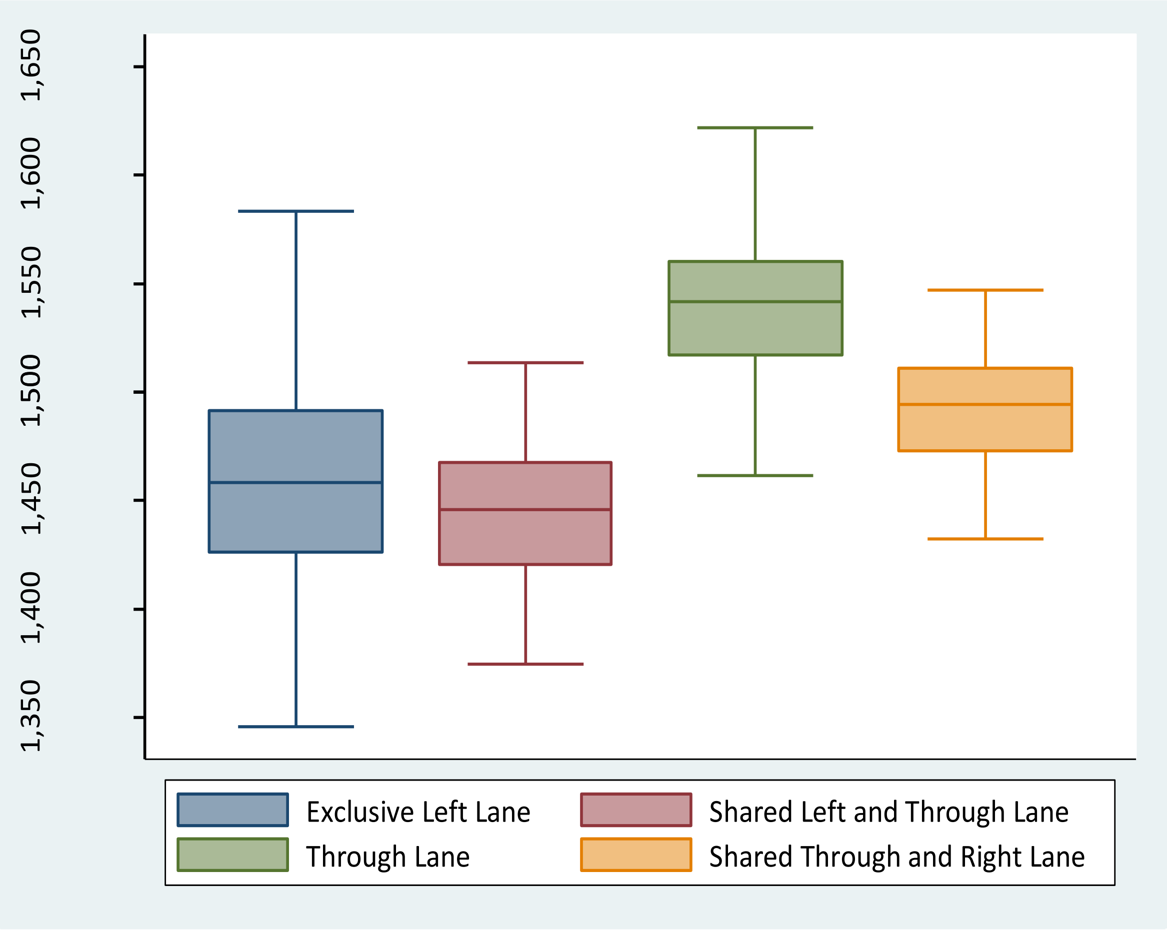


Figure 4. 10 Box Plot of Saturation Flow Rate over Different Lane Groups

As seen in Figure 4.10, the general trend shows that the mean and standard deviation of the saturation saturation flow rate vary among. However, there is noticeable overlapping between some of the lane group types, such as between exclusive left and shared left plus through lane, and between the two shared lane group types.

4.10 Independent Sample t-test

The collected data were further analyzed to determine whether there was a significant difference in prevailing saturation flow rates between the four lane types. As the samples collected were from different signalized intersections, the saturation flow rate is expected to be different and hence the observations can be considered independent of each other. Independent sample t test was used to determine whether the difference is statistically significant or not. All analyses were performed at the 95 percent confidence level. To start the process, some general descriptive statistics about the data were reported for each lane. `

Table 4. 18 General Descriptive Statistics for Prevailing Saturation Flow Rates

	Exclusive Left Lane	Shared Left and Through Lane	Through Lane	Shared Through and Right Lane
Number of Cycles	60	60	60	60
Average	1461.45	1445.84	1541.19	1491.94
Standard Deviation	59.12	34.48	31.28	28.22
Variance	3495.14	1189.15	978.45	796.11
Minimum	1345.76	1374.46	1461.39	1432.31
Maximum	1626.73	1541.23	1621.72	1546.92

As it can be seen from Table 4.18 the standard deviation and variances are higher for the exclusive left lane than other lane group types. This is may be due to drivers of the vehicle at outer lane (exclusive left lane) which is influenced by the roadside activities and left-turning vehicles must find appropriate gaps to complete their maneuvers. This may be resulted bigger headway value and variable saturation flow rate compared to that of through and right-turn movements. But the standard deviation and variance of through lane are lower than other lane types which indicate that the traffic clears the intersection more uniformly for the through lane.

A series of t-tests were conducted to determine if there were any statistically significant difference in the average prevailing saturation flow rates between different lane groups considered in this research. To see if there is any difference between the different lane types they were compared with each other. The statistical software program STATA was used in the analysis and the results are reported in Table 4.19.

Table 4. 19 Statistical significance test for difference between prevailing SFR

Scenario	*df*	*T-Statistics*	*P-Value*	95% CI. of the Difference	
				Lower	Upper
Exclusive Left Lane vs. Shared Left and Through Lane	51	1.8228	0.074	-2.4651	33.6763
Exclusive Left Lane vs. Through Lane	58	9.0708	0.000	-97.3729	-62.1099
Exclusive Left Lane vs. Shared Through and Right Lane	49	3.6341	0.001	-47.35411	-13.63038
Shared Left and Through Lane vs. Through Lane	58	13.4947	0.000	-109.492	-81.20193
Shared Left and Through Lane vs. Shared Through and Right Lane	58	7.0265	0.000	-59.2314	-32.9642
Through Lane vs. Shared Through and Right Lane	57	7.1819	0.000	35.51639	62.98186

When reporting the result of an independent t-test, it is necessary to include the *t*-statistic value, the degrees of freedom (df) and the significance value of the test (*p*-value). The format of the test result is: *t*(df) = *t*-statistic, *p* = significance value. For example the result of an independent t-test for the first scenario is expressed as *t* (50) = 1.8228, *p* = .074.

The degrees of freedom represent how many values involved in the calculation and have the freedom to vary. The reported t value is the absolute value except for the difference of mean between through and shared through plus right lane. Since the value of *t statistics* is negative for other scenarios it shows the direction of the mean difference is to the left of the mean.

The null hypothesis in all the tests was to check any probable difference between the saturation flow rates of different lane types. From table 4.19 it can be seen that there is significant differences between all lane group combinations. Anaylsis of independent sample t test indicates that the prevailing saturation flow rate values of all scenarious shows significant differences at 0.05-level since the p value computed was very small ($p<0.05$). This is important to suspect the type of lane studied since it had an influence on the outcome of prevailing saturation flow rate value.

4.11 Summary

According to the 2010 HCM, to determine a local base saturation flow rate the first step is determining prevailing saturation flow rate. HCM also advices that the local traffic conditions/driver behavior, affects the estimation of the capacity of a signalized intersection and therefore it should be measured at the local level. The main aim of this study is to determine prevailing SFR for different lane groups at signalized intersections in Addis Ababa.

The vehicular volumes considered in this study were based on the present data collected on field and the analysis used to accurately forecast the future traffic volumes and composition at different signalized intersections. On the other hand detail analysis and understanding characteristics discharge headway of vehicles at signalized intersections is essential in estimation of saturation headway and saturation flow rate.

About 1440 traffic signal cycles were involved in the analysis, with equal number of cycles both during the morning and afternoon peak periods. From the selected signalized intersections the maximum prevailing saturation flow rate is observed at Mesqel Square signalized intersection (1563 vphpln) and the minimum was found at Leghar signalized intersection which is about 1405 vphpln. On the other hand the prevailing saturation flow rate for the lane groups considered in this is as low as for shared left and through lane (1446 vphpln) and as high as for through lane movement which is determined to be 1542 vehicle per hour per lane.

Saturation flow rate value of left turning vehicles more fluctuate and may be reduced than through lane movements because they must find appropriate gaps to complete their maneuvers. Therefore it is recommended to design protected signal phase when left-turn volumes become quite perceptible and receive the same number of vehicles as the through lane(s) right-turn movements at a signalized intersection. A shared lane can cause severe reduction in saturation flow rate because during straight-through green phase a right-turn vehicle may block straight-through vehicle and vice versa. Therefore to overcome the above problem, different researchers suggest to use protected right-turn signal control when traffic volume is high.

CHAPTER FIVE

CONCLUSIONS AND RECOMMENDATIONS

5.1 Conclusions

The present study focuses on a comprehensive analysis of traffic volume and composition, discharge headway and prevailing saturation flow rate at signalized intersections under mixed traffic conditions in case of Addis Ababa. In this study, about 24 approaches from six different signalized intersections were selected to be taken as case study. Based on the estimation procedure described in the HCM 2010 data were collected during the morning and afternoon peak hours on weekdays using video recording technique.

In the morning peak hours the highest mean prevailing saturation flow rate was found for the through lane group (1545vphpl), while the lowest was 1424vphpl for exclusive left lane. Again in the afternoon peak hour the highest and lowest values of the mean prevailing saturation flow rate were recorded for through and shared left and through only lanes and were determined to be 1542 and 1492vphpl respectively. It was determined from ANOVA analysis there was significant statistical difference between four types of lanes in the morning and afternoon peak hour at 5% significance level.

To recapitulate, this study provides recommended saturation flow rate values for different lanes types which are appropriate for Addis Ababa signalized intersections. The corresponding saturation flow rate for exclusive left lane, shared left and through lane, through lane, and shared through plus right lane are 1462 vehicles per hour, 1445 vehicles per hour, 1542 vehicles per hour, and 1492* vehicles per hour respectively. Independent sample t test was used to determine whether the mean difference between four types of lanes is statistically significant or not.

This is very important finding, because using the same saturation flow rate for different types of lanes will be clearly incorrect and resulting in the reduction for the efficiency of signalized intersections. The obtained saturation flow rates can be used to accurately determine the existing level of service and control delay of different intersections in case of Addis Ababa.

5.2 Recommendations and Future Research Works

Depending on the final results of this study the researcher recommends the following points so that it adds its own positive impact on the improvement of studying saturation flow rate and its main influencing factors at signalized intersections under different traffic scenarios.

- It is recommended that further research should be conducted in other intersections in Addis Ababa to generalize the findings of this study and be capable of estimating the saturation flow rate at any signalized intersection.
- Traffic awareness and traffic enforcement must be applied in order to reduce the impact of pedestrian and driver behaviors on saturation flow rate.
- Establishing guidelines and pavement markings at all approaches of signalized intersections can improve the saturation flow rate value for different traffic movements.
- Providing advance street names and signs are important for non local drivers and visitors to identify the next upcoming intersections and to use the correct lane.
- At signalized intersections visual attention of the driver is attracted by different information points and pedestrian activities. The information points may be music concerts near the intersections, high raised buildings, shopping's, churches, fuel stations etc. A study must be attempted to identify how information point factors affect saturation flow rate and their relationship at signalized intersections.
- It is observed that at all signalized intersections in Addis Ababa, most vehicles are staying beyond the stop line during red period which may affect the saturation flow rate. Therefore it is important to study the effect of encroaching vehicles on SFR.
- As Addis Ababa gets rapid urbanization and improvements examining the effect of intersection location area types such as recreational, business, residential, and shopping on saturation flow rate is effective for traffic management.

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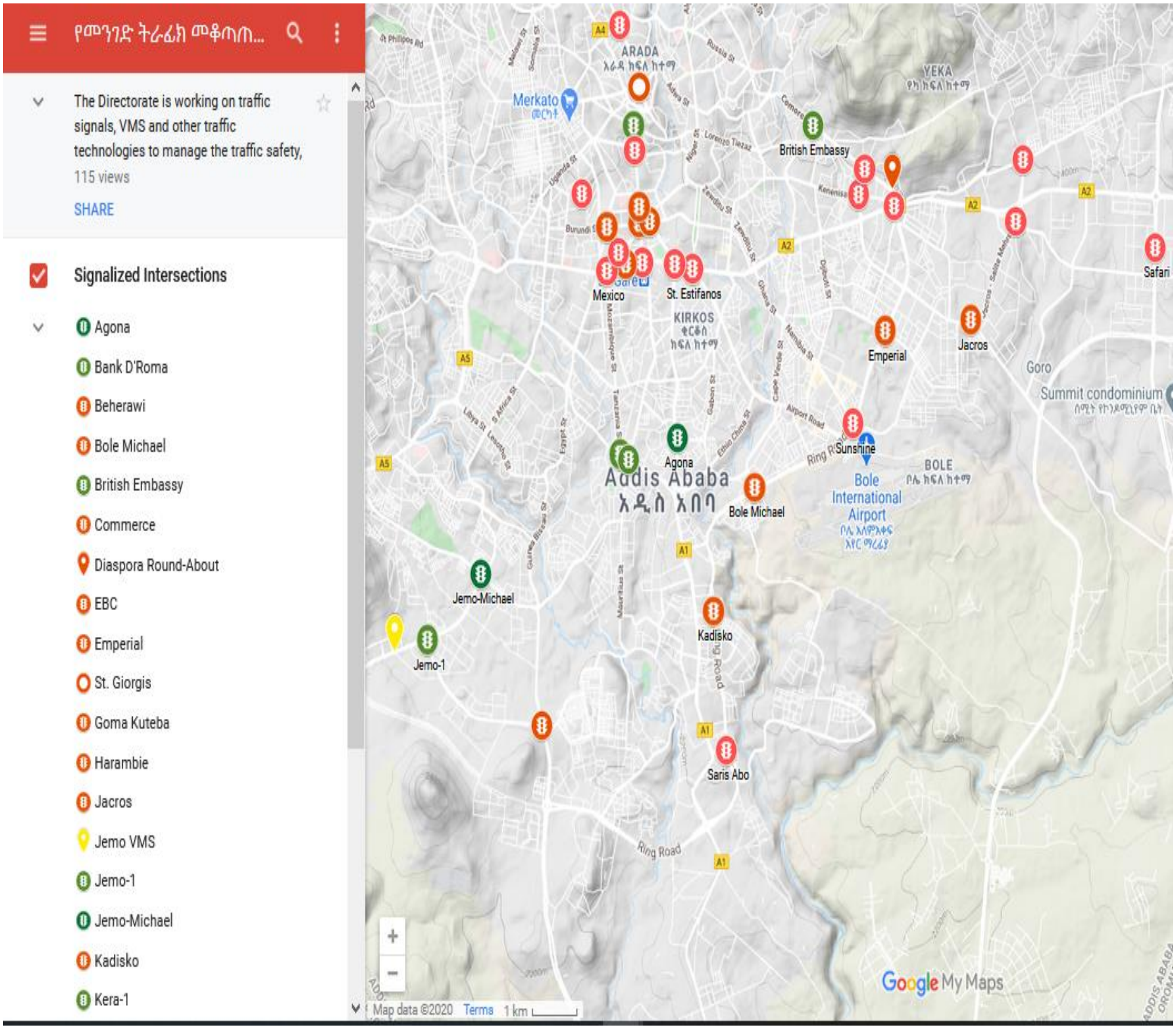
Appendices

Appendix A: Distribution of Signalized Intersections in Addis Ababa



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The Directorate is working on traffic signals, VMS and other traffic technologies to manage the traffic safety,

115 views

SHARE

☑ Signalized Intersections

- Agona
- Bank D'Roma
- Beherawi
- Bole Michael
- British Embassy
- Commerce
- Diaspora Round-About
- EBC
- Emperial
- St. Giorgis
- Goma Kuteba
- Harambie
- Jacros
- Jemo VMS
- Jemo-1
- Jemo-Michael
- Kadisko
- Kera-1

Appendix B: Morning Peak Hour Prevailing Saturation Flow Rate

Table B-1: Saturation Flow Rate and Startup Delay Calculations for Exclusive Left Lane

Cycle	Time of 4th Vehicle (T_4)	Number of Vehicles (N)	Time of Last Vehicle (T_n)	Average Headway	Saturation Flow Rate	Startup Delay
1	11.716	14	36.549	2.483	1449.68	1.783
2	12.381	16	41.490	2.426	1484.08	2.678
3	11.716	15	39.622	2.537	1419.05	1.568
4	11.696	16	41.125	2.452	1467.94	1.886
5	11.071	15	37.629	2.414	1491.08	1.414
6	11.150	16	40.939	2.482	1450.20	1.220
7	11.764	14	37.212	2.545	1414.65	1.585
8	11.878	14	38.365	2.649	1359.16	1.283
9	11.878	16	41.474	2.466	1459.66	2.013
10	12.475	14	37.322	2.485	1448.87	2.536
11	11.878	15	39.114	2.476	1453.96	1.974
12	12.468	16	43.378	2.576	1397.61	2.165
13	11.878	15	39.864	2.544	1414.99	1.701
14	12.699	14	36.598	2.390	1506.34	3.139
15	9.872	16	41.956	2.674	1346.47	-0.823
16	13.662	15	40.150	2.408	1495.02	4.030
17	10.463	16	40.988	2.544	1415.23	0.288
18	13.065	16	43.346	2.523	1426.64	2.971
19	10.690	15	38.310	2.511	1433.74	0.646
20	12.468	16	42.298	2.486	1448.21	2.525
21	10.093	14	35.437	2.534	1420.45	-0.045
22	11.871	15	40.210	2.576	1397.37	1.566
23	11.275	16	42.009	2.561	1405.61	1.030
24	11.287	14	36.137	2.485	1448.69	1.347
25	10.099	16	41.157	2.588	1390.95	-0.254
26	10.696	14	37.447	2.675	1345.74	-0.004
27	10.105	16	41.888	2.649	1359.22	-0.489
28	10.099	14	36.264	2.617	1375.88	-0.367
29	11.119	14	34.929	2.381	1511.97	1.595
30	10.522	16	40.529	2.501	1439.66	0.520
Average				**2.521**	**1429.27**	**1.383**

Table B-2: SFR and Startup Delay Calculations for Shared Left and Through Lane

Cycle	Time of 4th Vehicle (T_4)	Number of Vehicles (N)	Time of Last Vehicle (T_n)	Average Headway	Saturation Flow Rate	Startup Delay
1	10.832	19	47.461	2.442	1474.24	1.064
2	12.909	17	46.056	2.550	1411.89	2.710
3	12.274	17	45.707	2.572	1399.81	1.987
4	11.220	19	48.547	2.488	1446.67	1.266
5	10.281	16	41.218	2.578	1396.39	-0.031
6	11.321	16	41.531	2.518	1429.99	1.251
7	11.709	19	49.067	2.491	1445.47	1.747
8	10.967	17	43.389	2.494	1443.46	0.991
9	11.386	18	46.206	2.487	1447.44	1.437
10	11.931	15	40.742	2.619	1374.48	1.454
11	11.927	18	47.067	2.510	1434.26	1.887
12	10.654	16	41.194	2.545	1414.54	0.474
13	11.255	16	42.304	2.587	1391.35	0.905
14	12.168	17	44.351	2.476	1454.18	2.266
15	11.956	15	40.187	2.566	1402.71	1.690
16	11.062	16	41.928	2.572	1399.60	0.773
17	12.472	18	47.920	2.532	1421.80	2.344
18	11.182	18	46.855	2.548	1412.83	0.990
19	9.317	19	47.082	2.518	1429.90	-0.754
20	10.794	19	48.770	2.532	1421.95	0.667
21	9.787	19	47.293	2.500	1439.77	-0.215
22	11.686	18	46.770	2.506	1436.55	1.662
23	12.528	17	45.744	2.555	1408.96	2.308
24	10.819	18	46.404	2.542	1416.33	0.652
25	12.131	19	48.523	2.426	1483.84	2.426
26	13.126	18	48.676	2.539	1417.72	2.969
27	11.501	17	44.862	2.566	1402.84	1.236
28	11.543	19	47.612	2.405	1497.13	1.925
29	11.914	18	46.157	2.446	1471.83	2.130
30	12.313	17	44.556	2.480	1451.48	2.392
Average				**2.520**	**1429.31**	**1.420**

Table B-3: Saturation Flow Rate and Startup Delay Calculations for Through Lane

Cycle	Time of 4th Vehicle (T_4)	Number of Vehicles (N)	Time of Last Vehicle (T_n)	Average Headway	Saturation Flow Rate	Startup Delay
1	9.364	37	83.876	2.258	1594.37	0.332
2	9.992	39	93.030	2.373	1517.38	0.502
3	11.550	39	92.164	2.303	1563.00	2.337
4	9.441	38	88.846	2.335	1541.46	0.099
5	11.304	39	93.156	2.339	1539.36	1.949
6	10.620	38	89.988	2.334	1542.18	1.283
7	10.543	34	82.810	2.409	1494.46	0.907
8	10.543	37	88.812	2.372	1517.84	1.056
9	9.915	37	89.870	2.423	1485.84	0.223
10	11.290	35	85.073	2.380	1512.54	1.770
11	11.753	37	90.766	2.394	1503.55	2.176
12	9.915	38	91.368	2.396	1502.71	0.332
13	10.714	38	89.966	2.331	1544.44	1.390
14	12.884	36	84.962	2.252	1598.27	3.874
15	10.527	38	89.587	2.325	1548.19	1.226
16	11.705	38	90.359	2.313	1556.18	2.452
17	11.534	36	84.732	2.287	1573.81	2.384
18	11.078	39	91.825	2.307	1560.43	1.850
19	12.936	37	88.873	2.301	1564.45	3.732
20	10.543	39	89.957	2.269	1586.62	1.467
21	9.364	38	86.403	2.266	1588.81	0.301
22	11.248	39	93.107	2.339	1539.23	1.893
23	10.543	39	93.732	2.377	1514.62	1.036
24	11.155	37	88.765	2.352	1530.73	1.748
25	10.084	38	88.555	2.308	1559.81	0.852
26	11.155	39	93.354	2.349	1532.87	1.761
27	11.705	39	92.407	2.306	1561.30	2.482
28	11.705	39	91.968	2.293	1569.84	2.532
29	12.868	36	87.075	2.319	1552.41	3.592
30	11.155	39	91.267	2.289	1572.80	1.999
Average				**2.330**	**1545.65**	**1.651**

Table B-4: SFR and Startup Delay Calculations for Shared Through Plus Right Lane

Cycle	Time of 4th Vehicle (T_4)	Number of Vehicles (N)	Time of Last Vehicle (T_n)	Average Headway	Saturation Flow Rate	Startup Delay
1	10.983	37	90.412	2.407	1495.68	1.355
2	10.974	36	88.070	2.409	1494.24	1.337
3	12.136	36	88.932	2.400	1500.08	2.537
4	12.273	35	86.426	2.392	1505.00	2.705
5	12.136	36	87.902	2.368	1520.47	2.665
6	11.601	35	86.034	2.401	1499.33	1.997
7	10.387	34	83.321	2.431	1480.79	0.662
8	11.643	34	85.234	2.453	1467.57	1.831
9	10.416	34	82.018	2.387	1508.34	0.869
10	11.783	33	83.652	2.478	1452.64	1.870
11	12.136	33	83.094	2.447	1471.29	2.349
12	9.520	35	86.782	2.492	1444.44	-0.449
13	11.144	36	90.450	2.478	1452.60	1.231
14	12.764	33	81.797	2.380	1512.32	3.242
15	11.509	35	87.980	2.467	1459.38	1.642
16	12.773	36	92.576	2.494	1443.55	2.798
17	11.509	33	82.163	2.436	1477.62	1.764
18	11.509	36	89.821	2.447	1471.04	1.720
19	12.764	36	88.741	2.374	1516.25	3.267
20	10.974	36	86.555	2.362	1524.19	1.526
21	10.346	35	82.761	2.336	1541.12	1.002
22	10.148	36	88.094	2.436	1477.95	0.405
23	10.194	36	89.739	2.486	1448.24	0.251
24	12.136	36	89.508	2.418	1488.91	2.465
25	11.703	35	86.855	2.424	1484.99	2.006
26	13.410	36	93.841	2.513	1432.28	3.356
27	12.136	36	88.888	2.399	1500.94	2.542
28	12.136	35	86.561	2.401	1499.50	2.533
29	12.662	34	84.943	2.409	1494.17	3.025
30	13.982	37	91.815	2.359	1526.34	4.548
Average				**2.423**	**1486.38**	**1.968**

Appendix C: Afternoon Peak Hour Prevailing Saturation Flow Rate

Table C-1: Saturation Flow Rate and Startup Delay Calculations for Exclusive Left Lane

Cycle	Time of 4th Vehicle (T_4)	Number of Vehicles (N)	Time of Last Vehicle (T_n)	Average Headway	Saturation Flow Rate	Startup Delay
1	13.516	15	40.344	2.439	1476.07	3.760
2	14.584	13	35.850	2.363	1523.56	5.132
3	10.842	15	37.659	2.438	1476.68	1.090
4	15.089	13	36.701	2.401	1499.17	5.484
5	12.459	14	36.528	2.407	1495.70	2.831
6	10.851	15	37.402	2.414	1491.47	1.196
7	10.078	13	32.154	2.453	1467.66	0.266
8	9.607	14	33.808	2.420	1487.54	-0.073
9	11.499	13	33.226	2.414	1491.23	1.843
10	10.575	15	38.128	2.505	1437.23	0.556
11	10.524	15	37.332	2.437	1477.17	0.776
12	9.795	14	34.852	2.506	1436.72	-0.228
13	9.714	15	36.898	2.471	1456.74	-0.171
14	9.514	14	32.251	2.274	1583.32	0.419
15	9.475	13	31.135	2.407	1495.84	-0.152
16	9.007	14	31.138	2.213	1626.68	0.155
17	9.212	14	32.538	2.333	1543.34	-0.118
18	10.365	15	35.915	2.323	1549.90	1.074
19	11.078	15	36.348	2.297	1567.08	1.889
20	11.021	15	36.314	2.299	1565.65	1.824
21	10.814	13	32.264	2.383	1510.49	1.281
22	11.988	15	37.879	2.354	1529.49	2.573
23	11.089	13	32.904	2.424	1485.22	1.393
24	12.286	14	35.511	2.323	1550.05	2.996
25	12.041	14	36.501	2.446	1471.79	2.257
26	11.113	13	32.977	2.429	1481.89	1.396
27	13.611	15	41.078	2.497	1441.73	3.623
28	14.609	14	39.708	2.510	1434.32	4.569
29	13.94	15	40.734	2.436	1477.94	4.197
30	15.392	15	45.331	2.722	1322.69	4.505
Average				**2.411**	**1495.15**	**1.878**

Table C-2: SFR and Startup Delay Calculations for Shared Left and Through Lane

Cycle	Time of 4th Vehicle (T_4)	Number of Vehicles (N)	Time of Last Vehicle (T_n)	Average Headway	Saturation Flow Rate	Startup Delay
1	9.829	19	44.867	2.336	1541.18	0.486
2	13.117	18	44.375	2.233	1612.39	4.186
3	13.649	19	50.092	2.430	1481.77	3.931
4	10.890	18	45.934	2.503	1438.19	0.877
5	9.782	16	38.966	2.432	1480.26	0.054
6	10.021	16	39.592	2.464	1460.89	0.164
7	10.903	19	48.718	2.521	1428.00	0.819
8	10.922	18	46.342	2.530	1422.92	0.802
9	12.010	18	46.735	2.480	1451.40	2.089
10	12.043	14	36.933	2.489	1446.36	2.087
11	12.010	18	46.487	2.463	1461.84	2.159
12	10.357	14	34.954	2.460	1463.59	0.518
13	11.464	16	42.525	2.588	1390.81	1.110
14	11.991	18	45.289	2.378	1513.60	2.477
15	11.430	14	36.199	2.477	1453.44	1.523
16	13.644	16	43.523	2.490	1445.83	3.684
17	13.098	18	48.027	2.495	1442.93	3.118
18	13.696	18	48.660	2.497	1441.48	3.706
19	10.082	18	44.840	2.483	1450.03	0.151
20	11.977	17	44.050	2.467	1459.17	2.108
21	8.722	19	45.955	2.482	1450.33	-1.207
22	11.972	16	41.258	2.441	1475.11	2.210
23	12.570	17	44.631	2.466	1459.72	2.705
24	9.829	16	40.282	2.538	1418.58	-0.322
25	9.815	19	45.685	2.391	1505.44	0.250
26	13.117	16	43.371	2.521	1427.91	3.032
27	10.323	19	46.739	2.428	1482.86	0.612
28	11.991	19	47.845	2.390	1506.11	2.430
29	12.010	19	48.534	2.435	1478.48	2.270
30	12.010	17	43.168	2.397	1502.02	2.423
Average				**2.457**	**1466.42**	**1.682**

Table C-3: Saturation Flow Rate and Startup Delay Calculations for Through Lane

Cycle	Time of 4th Vehicle (T_4)	Number of Vehicles (N)	Time of Last Vehicle (T_n)	Average Headway	Saturation Flow Rate	Startup Delay
1	11.102	30	68.818	2.220	1621.73	2.223
2	11.429	33	80.467	2.381	1512.21	1.907
3	11.537	29	71.317	2.391	1505.52	1.972
4	11.621	34	81.318	2.323	1549.56	2.328
5	13.632	33	80.823	2.317	1553.78	4.364
6	14.010	35	85.851	2.317	1553.43	4.740
7	14.394	31	80.906	2.463	1461.39	4.540
8	11.920	31	75.554	2.357	1527.49	2.493
9	11.959	33	80.318	2.357	1527.23	2.530
10	11.340	32	77.591	2.366	1521.49	1.876
11	12.444	33	81.312	2.375	1515.94	2.945
12	11.810	33	81.194	2.393	1504.67	2.240
13	10.465	35	83.054	2.342	1537.42	1.099
14	11.369	34	81.663	2.343	1536.40	1.996
15	12.500	32	79.454	2.391	1505.51	2.935
16	10.500	33	78.093	2.331	1544.54	1.177
17	11.517	32	74.509	2.250	1600.20	2.518
18	11.227	34	82.618	2.380	1512.80	1.708
19	10.845	35	82.670	2.317	1553.78	1.577
20	11.069	35	83.637	2.341	1537.87	1.705
21	11.382	33	78.708	2.322	1550.66	2.096
22	11.957	35	84.859	2.352	1530.82	2.550
23	12.064	34	84.367	2.410	1493.71	2.424
24	13.463	34	85.312	2.395	1503.15	3.883
25	11.106	34	80.605	2.317	1553.98	1.839
26	12.071	31	75.931	2.365	1522.08	2.610
27	12.928	33	79.073	2.281	1578.35	3.805
28	11.672	35	82.974	2.300	1565.17	2.472
29	13.002	34	82.290	2.310	1558.71	3.764
30	11.944	33	78.753	2.304	1562.66	2.729
Average				**2.344**	**1536.74**	**2.568**

Table C-4: SFR and Startup Delay Calculations for Shared Through and Right Lane

Cycle	Time of 4th Vehicle (T_4)	Number of Vehicles (N)	Time of Last Vehicle (T_n)	Average Headway	Saturation Flow Rate	Startup Delay
1	12.267	37	89.064	2.327	1546.94	2.958
2	11.962	37	91.346	2.406	1496.52	2.340
3	13.189	35	85.575	2.335	1541.73	3.849
4	11.866	35	85.719	2.382	1511.11	2.337
5	11.872	38	93.029	2.387	1508.19	2.324
6	12.788	38	98.037	2.507	1435.79	2.759
7	11.527	37	91.696	2.429	1481.87	1.810
8	11.617	38	94.032	2.424	1485.17	1.921
9	9.480	36	87.640	2.443	1473.90	-0.290
10	11.732	36	88.953	2.413	1491.82	2.079
11	12.990	37	90.832	2.359	1526.17	3.555
12	11.222	36	89.394	2.443	1473.67	1.451
13	12.250	35	89.322	2.486	1448.00	2.305
14	13.502	36	89.181	2.365	1522.22	4.042
15	11.232	34	85.008	2.459	1463.89	1.395
16	10.710	33	82.951	2.491	1445.16	0.746
17	12.478	37	91.994	2.410	1494.04	2.840
18	11.866	35	86.188	2.397	1501.57	2.276
19	13.006	34	84.480	2.382	1511.04	3.476
20	13.172	37	92.089	2.391	1505.38	3.606
21	12.362	37	90.322	2.362	1523.86	2.912
22	12.827	35	88.119	2.429	1482.23	3.112
23	11.840	35	86.485	2.408	1495.08	2.208
24	11.850	36	88.932	2.409	1494.51	2.215
25	13.787	36	91.446	2.427	1483.41	4.080
26	11.132	35	87.048	2.449	1470.05	1.336
27	11.928	36	90.908	2.468	1458.60	2.056
28	13.488	36	90.495	2.406	1495.97	3.862
29	10.645	34	83.198	2.418	1488.57	0.971
30	10.604	35	86.835	2.459	1463.97	0.768
Average				**2.416**	**1490.68**	**2.377**