ADDIS ABABA UNIVERSITY
SCHOOL OF GRADUATE STUDIES
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FACTORS AFFECTING SATURATION FLOW AT SIGNALIZED INTERSECTIONS IN ADDIS ABABA

By Worku Ambelu

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A THESIS SUBMITTED TO THE SCHOOL OF GRADUATE STUDIES OF ADDIS ABABA UNIVERSITY IN PARTIAL FULFILLMENT FOR THE REQUIREMENTS OF THE DEGREE OF MASTER OF SCIENCE IN STATISTICS

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Acronyms

ECA: Economic Commission for Africa

HG3: Heavy Goods Vehicle with three axels

HG4: Heavy Goods Vehicle with four axels

LB: Large Bus

LG: Light Goods Vehicle

MB : Medium Bus

MC: Motorcycle

MG: Medium Goods Vehicle

PC: Passenger Car

PCE: Passenger Car Equivalent

pcpgpl: passenger car equivalent per green time per lane

PCU: Passenger Car Unit

SB: Small Bus

Abstract

This study was conducted to identify factors affecting saturation flow at signalized intersections in Addis Ababa. Secondary data collected using headway method, synchronous method and asynchronous method were used for the analysis. The data consisted of headways, number and type of vehicles, number of lanes in an approach, approach grade, green time length of a signal, lane width, number of pedestrians crossing vehicle flows, and percentage of large buses that made vehicle flows in a lane (as derivative information).

Lane wise saturation flows were determined using headway ratio method, synchronous regression method and asynchronous regression method. Passenger car equivalents for each class of vehicles were also estimated.

The saturation flow estimated from the three methods was regressed on the independent variables. Based on the coefficient of determination, synchronous regression method was found to have better explanatory power. Slope of an approach and number of pedestrians crossing vehicle flows were found to be significant factors affecting saturation flow of vehicles at signalized intersections when the synchronous method was applied to estimate saturation flows. Therefore, attention should be paid to approach grade while designing new road intersections and modifying existing ones and pedestrians should be given sufficient awareness so that they do not disrupt traffic flow during green phase of traffic signal.

CHAPTER ONE

INTRODUCTION

1.1 BACKGROUND OF THE STUDY

Road safety problems are public health problems, economic problems, social problems and traffic problems. Traffic accident is one of the major causes of death and property damage in developing countries. As Jacobs and Sayer (1983) and Vasconcellos (2005) indicated, almost 10% of deaths in the age group of 5-44, considerable waste of scarce resources with accidents typically costing at least 1 percent - 2 percent of countries' GNP per annum, substantial pain, grief and suffering occur due to traffic accident in developing countries.

Compared with international risk figures, Ethiopia is one of the worst examples in terms of fatality rate per vehicle. In the year 1996/7, for example, police reported 1717 deaths, 2905 serious injuries and 4124 slight injuries. With the very low level of motorization in Ethiopia, this gives a very high fatality rate of 178 per ten thousand vehicles (Girma, 2000). But a case study from ECA (2009) indicated that it is one of the best countries when accidents are expressed in terms of number of fatalities per 100,000 population.

Different traffic rules and regulations are set in Ethiopia. However, people do not put them into practice properly for various reasons. For instance, zebra crossings are places where pedestrians get priority to cross roads while vehicles should stop. However, it is often the case that drivers fail to adhere to this rule. This is one of the causes for death and property damage. But it could be avoided by erecting pedestrian signals at zebra crossings.

As compared to the size of the population with other regions of Ethiopia, there is high traffic accident in Addis Ababa. For example, as data obtained from the Federal police of Ethiopia, Statistics division, Addis Ababa, and tabulated by Getu (Getu, 2008) for his research proposal indicates, there have been 364 deaths, 804 serious injuries and 1056 slight injuries in the year 2006/07 in the capital. The major reasons for these include inadequate road infrastructure, mixed vehicle types using the same road, behavior of drivers and pedestrian, improper road designs, parking conditions, increased population size, poor legislation and enforcement, and other road environment factors (Persson, 2008).

Road safety improvements broadly fall under what is widely well known as “the 3 E’s”: Education, Enforcement, and Engineering (Girma, 2003). In developed countries, various countermeasures under these categories have been identified and found to work well to improve road safety. However, these countermeasures cannot always be expected to produce similar positive effects in developing countries simply because there are differences in the components of the traffic system. This emphasizes the importance of designing appropriate safety remedial actions and evaluating the effectiveness of these measures initially as pilot schemes (Girma, 2003).

According to ECA report (2009), Ethiopia is one of the African countries with least vehicle-ownership. Available yearly inspected and registered national vehicle-fleet data indicates that motorization per ten thousand populations has increased from 15 to 22 in ten years (1994/5-2004/5), which is nearly 4% per year. The vehicle fleet has alarmingly increased at annual rate of 10% in the period 2001/2-2004/5 (ECA report, 2009).

The traffic management in Addis Ababa has been exerting its effort to maximize the capacity of the highway network, yet demand and congestion continues to increase. The traffic congestion varies between days and hours. Morning and evening are the peak hours for traffic congestion.

Junctions are bottle necks for traffic flow. The performance of the road net work is highly dependent on the performance of junctions. And the capacity of a junction in turn is dependent on the green time available on each arm and the maximum flows over the signal stop line (saturation flow).

Saturation flow is defined as the maximum rate of flow that can pass through a given road space (width), under prevailing roadway and traffic conditions, during the effective green time in a signal phase. Saturation flow is an important input parameter in the design of cycle time in a signal phase. When the light of a given signalized intersection turns green on an approach getting right of way, the flow across the stop line quickly rises to a steady state and will remain at this steady state value until all vehicles in the queue clear or the light turns to amber whichever comes first.

Saturation flow is used as a basic parameter in the determination of cycle times and to evaluate the performance of an intersection. Signalized intersections play an important role for the smooth operation of arterial and urban roads, where traffic movements from different direction meet together.

Under ideal geometric and operational conditions, the US Highway capacity manual (HCM 1998) estimates a lane's saturation flow rate (also known as "ideal" flow rate) to be 1,900 passenger Cars per hour of green time per lane (pcpgpl) which corresponds to saturation head way[1] of 1.9 seconds. This flow rate is said to be ideal for the reasons that it applies for an ideal lane whose width is 12 feet (or 3.66m), which consists only of passenger car, level gradient, no adjacent parking permitted, no bus blockages, and located in a non central business district (CBD) area. But it is hardly possible, at least in a short period, to fulfill these ideal conditions in Ethiopia due to mixed traffic composition and operating environment. Different lanes at the same signalized intersection or various signalized intersections can have different saturation flow.

1.2. STATEMENT OF THE PROBLEM

It is a customary situation to see a very long queue of vehicles at signalized intersections in Addis Ababa. Many people, passengers and drivers in particular, are bored of the situation as they are spending too much time to pass the intersections. While there are such problems, the number of vehicles in the city is increasing from time to time. Besides, Ethiopia is one of the world's leading countries in traffic accidents when comparison is made with respect to low level of motorization (Girma, 2000). However, there are no studies conducted on saturation flow rate at signalized intersections in Ethiopia, at least to the knowledge of this researcher, though study on traffic characteristics at signalized intersection is not a new topic in other countries.

[1] Headway is the time gap between two successive vehicles to pass the same point.

Many researches have been conducted on saturation flow rate to improve and increase efficiency on traffic condition at intersections or entire network in other countries.

Being cognizant to the problems, the government of Ethiopia is taking different measures including construction of new roads and improving existing ones. While taking these kinds of positive measures, the importance of related parameters and how those parameters are affected by different factors is worth studying.

1.2. OBJECTIVE OF THE STUDY

The general objective of this study is to identify the factors that affect saturation traffic flow among lanes within an intersection or different intersections in Addis Ababa. In determining the saturation flow, the passenger car equivalents for different vehicle types will be estimated using various techniques of estimating saturation flow and passenger car equivalent.

Specific objectives of the study include:

- Fitting statistical models to estimate passenger car equivalents and saturation flow,
- Fitting statistical models that will be used to identify factors that affect saturation flow

1.3. Significance of the research

Though there is no data collected on extent of traffic delay at signalized intersections in Addis Ababa, it is not questionable that many man-days are lost due to congestions at intersections which in turn indicate the cost incurred by different sectors due to failing to arrive on time and system disturbances (schooling, health services, etc.).

Traffic carrying capacity of signalized intersections is of fundamental importance in designing new intersections and modifying existing ones. In order to do this, identifying the most important factors that affect saturation flow is critically important.

The significance of this research can be summarized as:

- It helps road designers and concerned agencies to properly identify the factors that affect saturation flow that are vital in designing new road intersections and modifying existing ones.
- It serves as a basis for further research in the area.

CHAPTER TWO

LITRATURE REVIEW

2.1 Saturation flow and Passenger Car Equivalents

Traditionally capacity has been expressed in numbers of vehicles or passenger car units (PCUs). Vehicles vary in their performance and the amount of space they occupy. Passenger car equivalents (PCEs) also called passenger car units are used in highway capacity analysis to convert a mixed vehicle into an equivalent passenger car flow. In short passenger car unit can be said a metric which is used to convert vehicles into a similar unit.

The term passenger car equivalent was introduced in the 1965 Highway Capacity Manual. Since 1965, considerable effort has been directed toward the estimation of PCE value for various road types (Rahman et al, 2005).

The term saturation flow is defined as the maximum rate of flow that can pass through a given road space (width), under prevailing roadway and traffic conditions, during the effective green time in a signal phase. Saturation flow is an important input parameter in the design of cycle time in a signal phase.

The effects of different vehicles on saturation flow have been studied by different researchers. Kockelman and Shabih (1999) in Austin, a town in the USA, have found that a single large sport-utility vehicle in through traffic is equivalent to 1.41 passenger cars and a van is equivalent to 1.34. Such long headways reduce intersection capacity and increase urban congestion. The basic methodology used to analyze the collected data by Kockelman and Shabih (1999) was the measurement of the elapsed time from the moment the first vehicle in the queue started moving until the time the rear axle of the last vehicle crossed the stop bar reference line. The analysis was made using multiple linear regression models.

The passenger car equivalents of lower vehicles in size can sometimes possess higher PCE value as compared to higher size vehicles. For example, the studies of Turner and Harahap (1993) using multiple regression analysis revealed that the PCE of minibuses was 2.18 while the PCE of light trucks was 1.65. And according to them this could be as a result of their behavior in stopping at or near junctions.

The saturation flow and passenger car equivalents of motorcycles at two different cities of South East Asia, Hanoi and Bangkok, were calculated by Minch and Sano (2003). They have applied linear regression to see the effects of motor cycle to the saturation flow in the two cities. According to them, the PCEs of motor cycles at Hanoi was 0.24 and 0.18 in Bangkok while the saturation flow rates were 4092 PCE per effective green hour in Hanui, and 2253 PCE per effective green hour in Bangkok.

Mean headways of passenger cars differ from country to country. For example, Lee , et al (2005) cited that the 1.6998s headway value of cars in Malaysia (Lee , 2004) was less than the headway value of 1.895s adopted in the U.S. (HCM, 1994 and HCM, 2000) and 1.946s in Austria (Akcelik, 1981). This showed that elapsed time between two cars crossing the stop line of an approach at signalized intersection in Malaysia was faster than the cars in US and Austria.

Three methods of data collection and analysis to determine PCE and saturation flow are well documented in the literature. These methods are headway ratio method, synchronous regression method and asynchronous regression method.

In Headway ratio method, data on the headways of vehicles is collected and the mean headway of each vehicle type divided by the mean head way of passenger cars gives passenger car equivalents of the corresponding vehicle type. And the reciprocal of the mean headway of passenger car is the saturation flow per unit time.

On the other hand, the green time of an intersection is subdivided into counting phases; where in each counting phase fixed number of vehicles is counted. The time taken during each counting phase for that fixed number of vehicles to pass the stop line, and the number and type of vehicles passing the stop line are recorded. A regression of the time in each counting phase on the number of each vehicle type (or vehicle classes) in each counting phase is called synchronous regression. The estimate for the coefficient which is associated with the number of each vehicle type from the regression equation gives the mean headway of that vehicle type. The ratio of the mean headway of a vehicle class divided by the mean headway of the passenger cars gives the PCE of that vehicle type, and the reciprocal of the mean headway of the passenger cars is the saturation flow per unit time.

Asynchronous regression method is another alternative to the above methods. For this method, the green time of an intersection is subdivided into equal time intervals; within each time interval the number and type of each vehicle is recorded. The regression of the number of passenger cars on each number of the other types of vehicles is called asynchronous regression. The estimate of the constant term in the regression equation gives the saturation flow in PCE per unit time, and the estimate of the parameters associated with the number of each vehicle type in the regression equation gives the PCE of that vehicle type.

Passenger car equivalents depend on the method of derivation. According to a study conducted by Kimber et al (1985), asynchronous regression gives lower estimates for medium and heavy goods vehicles and buses/coaches than the headway and synchronous methods. They also stated that estimates were obtained from direct measurement of headways or by synchronous regression.

Like the method of derivation, passenger car equivalents can also vary in accordance with the direction of turn for the same vehicle class. Kockelman and Raheel (1999) applying multiple regression obtained that light duty trucks have significantly higher headways than passenger cars when in through traffic but not so much when in right and left turning traffic.

Generally, there are a number of reasons for the passenger car equivalents of a given vehicle type to differ from country to country or within a given country at different intersections or lanes. This could be due to behavior of drivers, vehicle mix, direction of turn, method of derivation, etc. Therefore it is necessary to determine an ideal saturation flow rate based on local conditions in order to reflect the prevailing traffic situation more accurately.

Similarly, saturation flow rates differ from country to country. The range between the minimum saturation rate and the maximum saturation rate for developed countries is lower than the range between developing countries. Turner and Harahap (1993) stated that the western studies have a range of saturation flow values somewhere between 1700 and 2080 PCE/hr green time. This is for straight ahead traffic in a 3.5 meter wide lane, at level gradient, and without opposed flow. Studies derived in developing countries have a value between 1200 and 2000 for the same conditions (Turner and Harahap, 1993).

2.2. Factors that influence saturation flow rate

Saturation flow occurs when there is a discharge of vehicles from a standing queue, as happens at the start of a green period in a traffic signal cycle, and it is regarded as the maximum possible instantaneous flow rate for a traffic element such as a traffic lane.

Saturation flow describes the number of passenger car equivalents in a dense flow of traffic for a specific intersection lane group or single lane.

Saturation flow rate at signalized intersection can be affected by different factors. Taylor et al. (2000) classified the primary factors of saturation flow into environment class of intersection, lane type, lane width, gradient, and traffic composition.

A study conducted on saturation flow rates in South Africa by Bester and Meyers (2007) have shown that

- an increase in the speed limit leads to an increase in saturation flow;
- an increase in gradient leads to a decrease of saturation flow
- an increase (from 1 to 2) in the number of through lanes leads to an increase in the saturation flow;
- the saturation flow rate on exclusive single right turn lanes with their own phase can even be greater than that of a single through lane.

Many independent variables were considered by Turner and Harahap (1993) which include: number of junctions from micro accident analysis package (MAAP) network, arm of junctions being surveyed, survey method used (time slice method, 10 second method, 3 car method), surveyed lane counted from 1 on the near side, survey type (either surveyed lane by lane or across the full approach), observed saturation flow, length of signal green time for an approach being surveyed, percentage of total flow made up by motor cycles, width of junction exit for left turning traffic, width of junction exit for right turning traffic, width of junction exit for traffic travelling straight on, percentage of total flow made up by minibuses, percentage of total flow made up of buses and percentage of total flow made up by trucks.

Their result showed that lane width, percentage of total flow made up of trucks, percentage of total flow made up of motor cycles, percentage of total flow made of buses and width of junction exit for traffic travelling straight on were the most significant factors in the case of individual lane analysis.

On the other hand, in the case of full width (full approach) analysis length of signal green time for approach being surveyed, lane width and width of junction exit for traffic travelling straight on was found most significant. In both of the cases (individual lane and full approach) lane width, width of junction exit for traffic travelling straight on have a positive relationship with the dependent variable, saturation flow. Moreover, percentage of total flow made of buses in the case of individual lane and length of signal green time for approach being surveyed in the case of full approach are positively related with saturation flow. But percentage of total flow made up by trucks and percentage of total flow made up by motorcycles are negatively related to saturation flow.

CHAPTER THREE

METHODOLOGY

In this chapter, three methods of estimating passenger car equivalents, namely, headway ratio method, asynchronous regression method and synchronous regression method are presented with detail development for the latter two methods. Moreover, a model that will be used to identify factors affecting saturation flow is discussed.

3.1 Description of the study area

The study was based on secondary data collected from seven signalized intersections located at different sites of Addis Ababa with different approaches; these intersections are the major places of the city where traffic congestion is so high. The intersection places (with approaches in parenthesis) are:

- Dembel city center (Bole to Meskel square and Meskel square to Bole)
- Harambe (Ambasdor to Meskel square and Meskel square to Ambassador)
- Cathedral (Piassa to Tewodros)
- Urael (Megenagna to Bambis, and Bambis to Megenagna)
- Atlas (Atlas to Urael and Urael to Atlas)
- St. Mary (Arat kilo to Amist Kilo, and Amist kilo to Arat kilo)
- Business and Construction Bank (Biherawi to Mexico and Mexico to Biherawi)

3.2. Variables of the Study

3.2.1 The dependent variable

In this study, the outcome/dependent variable, saturation flow, is estimated using three methods (later discussed in detail), and the estimate from these three methods are utilized to determine the best fit. Two of the methods fall in the same category of "regression methods" and the other one is the head way ratio method. The dependent variable for the case of asynchronous regression is the number of passenger cars per unit of time and for synchronous is the time that is required for three vehicles to pass the stop line when the flow is at its saturation stage. Saturation flow from headway method is obtained as the reciprocal of the mean head way of passenger cars.

3.2.2 Explanatory Variables

Independent variables that can affect saturation flow were selected based on related literature. The explanatory variables that are selected based on related literature include lane width, approach grade (slope of an approach), green time length, percentage of large buses, number of lanes in an approach, pedestrian crossing (interference). Each of the explanatory variables is described below.

- **Lane width**: the demarcated road width accommodating one vehicle at a time, excluding shoulders, (shoulders are continuation of the travelled for accommodation of stopped vehicles, emergency use, lateral support of pavement layers and recovery area for errant vehicles).

  The capacity of a traffic lane is, proportional to its width provided that the width is within certain limits. Clearly, there is a lower limit to the width of a lane below which it is operationally impractical to run vehicles. i.e. below a lane width of about 2.0m, capacity deteriorates rapidly. As lane width approaches the point where two narrow lanes can be marked or vehicles tend to form up in two lanes there is a rapid increase in capacity. In urban areas and road junctions traffic will tend to form up in two lanes when the lane width exceeds 5.0m (Slinn, et al,2005)

- **Approach grade:** is the slope of an approach. A steep uphill gradient can significantly affect the acceleration rate of all vehicles when pulling away from stationary position at road junctions. Heavy vehicles speed also deteriorates on a combination of gradient and length of gradient (Slinn, et al,2005)

- **Green time length**: the time allotted for green signal in the red, yellow, green alteration of a cycle for which vehicles are allowed to pass the stop line and flow keeping their proper direction.

  If the green time is longer the number of vehicles passing on a lane or group of lanes is high in quantity. But if the green time length is short the number of vehicles passing the stop line on a given lane will be low.

- **Number of lanes in an approach**: these are the number of lanes that entertain one vehicle in each of its demarcated width in the same approach.

- **Percentage of Large buses**: these are the percentage of large buses in each lane from the total vehicle. The presence of large buses can affect the performance of other vehicles negatively and may have negative effect on saturation flow.
- **Pedestrian crossing**: number of people crossing the road while the light turns to green while people are not allowed to pass across. The presence of pedestrian crossing while the light is green negatively affects the saturation flow.

Table 3.1: Independent variables included in the study

Independent variable	Description
Lane width	Lane width
Slope	Approach grade/Slope
Green time	Length of green time for a lane being surveyed
Number of lane	Number of lanes in the group
Pedestrian crossing	Number of pedestrian crossing vehicle flows
% of large bus	Percentage of total flow made by large buses

3.4 Method of Data collection

The data for this research were secondary data collected by the Addis Ababa University, Civil Engineering Department, Transportation engineering group. The group has collected the data in the year 2007 using three methods of data collection to study saturation flow. These methods are headway method, fixed number of vehicles within a counting phase (synchronous counting method) and fixed time method (asynchronous counting method). Data were collected during peak hours of vehicle flows (morning, mid-day and in the evening) on different days.

3.4.1 Headway Method:

This method requires the measurement of headways between successive vehicles in a traffic stream under saturation conditions. The measurement of time headways is made continuously between the passages of the rear wheels of a vehicle over the stop line until the passage of the rear wheels of the succeeding vehicle over the stop line with precision of 0.1 second or better. The types of vehicle are designated as shown on table 3.2.

Table 3.2 Vehicle classifications

Designation	Type of vehicle/Vehicle c lass	Description
MC	Motor cycle	Motor cycles with or without sidecars eg. Motor cycles
PC	Passenger car	Cars, pickups, land cruisers, land rovers, etc with <= 9 seats
SB	Small bus	Passenger vehicles with 10-25 seats
MB	Medium bus	Passenger vehicles with from 26 to 40 seats
LB	Large buses	Large passenger vehicles with >40 seats
LG	Light goods	Two axels light goods vehicles with 4 tyres
MG	Medium Goods	Two axle with twin tyres on rear axles
HG3	Heavy Goods	Large trucks with three axles
HG4	Heavy goods	Large trucks with four axles

As one observer starts his stop watch and identifies the last vehicle in the queue as the green light starts and shoots to indicate the time and the type of vehicle passing the stop line, the other observer records the head ways and the type of vehicles. The head way of the first vehicle that passes the stop line as the green light is shown is the time between the instant the green light shown up to the passage of the rear wheels of this vehicle. Headways of vehicles going ahead (A), turning to left (L) and turning to right (R) were recorded by noting direction of movement and the type of vehicles until the flow of vehicles on the lane(s) stops.

The site should be selected in such a way that the observers can clearly view the traffic signals, the lane(s) being measured, a visible stop line; the vehicle at the back of the standing queue; and possible interferences (for example, pedestrian, road side activity, bus, etc) to the traffic to determine if the queue is impeded. Observations must be in positions where they cannot obstruct the pedestrian of traffic flow nor should they be in conspicuous positions that may cause drivers to modify their behavior. In addition observers should be completely familiar with the signal phasing arrangements and lengths before starting to record data.

3.4.2 Data collected based on fixed time (asynchronous counting method) and fixed vehicle (synchronous counting method)

These methods are alternative methods which require less intensive data collection and apply multiple linear regression modeling. Based on the counting methods used during data collection and the model that are used to estimate the passenger car equivalents, researchers in the area prefer to call this methods as synchronous and asynchronous. The counting period is chosen to exclude the start and end effects (lost time effects). The methods are applied only during the saturation flow.

a) Fixed number of vehicles per phase (synchronous counting method): in this method, n_i vehicle departures of class i vehicles are recorded over a time period Δt, where Δt starts at the instant the first vehicle departs in the first counting phase and finishes with the departure of the first vehicle in the second counting phase (three vehicles are counted in each phase). In order to exclude the start time lag, the start of the counting period begins after the departure of the fourth vehicle in the queue and continues until the start of yellow or amber light. It should be noted that counting for the first phase is started after the first four vehicles have already departed from the queue and the fifth vehicle starts moving. The value of Δt is equal to the time for three vehicles to depart (i.e starts at the instant the rear wheel of the fourth vehicle passes the stop line until the rear wheel of the 7^{th} vehicle passes the stop line and continues in this way).

b) Fixed time per phase (asynchronous counting method): in this method, the number of departing vehicles is recorded over periods of equal duration T, which begin and end at arbitrary instants so long as the signal is at its green phase. The lost time is excluded by starting the counting after the departure of the fourth vehicle and continues until the start of yellow or amber light.

The start lag effects occur as the first driver in the queue needs to observe and react to the signal change at the start of green time. After the observation, the driver accelerates through the intersection from standstill which results in a relatively long first headway. The second driver follows the same process except that the second driver could react and start accelerating while the first vehicle began moving. This results in a relatively shorter headway than the first. This continues until a certain number of vehicles have crossed the intersection and start up and acceleration no longer have an effect on the headways. From this point, headways will remain relatively constant until all vehicles in the queue have crossed the intersection or green time has ended. This constant headway is known as the saturation headway and can start to occur anywhere between the third and sixth vehicle in the queue (Bester and Mayers, 2007).

The end loss effects occur when vehicles in the queue do not completely cross the intersection due to the length of the queue formed during the red time and continues to cross in the yellow time. But after the green time finishes, the rate of vehicle flow decreases and the headways will be longer (Bester and Mayers, 2007).

For this study the frequency of cycles (one cycle being the alteration of green, yellow and red signals) by method of data collection, lane number as designated by the group who collected the data, direction of vehicle flow (approach), and intersection sites is depicted in table A1 of the annex. Using the headway method data was collected in 485 cycles at 7 intersections and on 22 lanes. Similarly, data in 545 and 411 cycles was collected using the asynchronous and synchronous methods respectively. The data for the asynchronous method was collected on 25 lanes and for the synchronous on 20 lanes.

3.5 Methods of Analysis

Employing different methods of analysis provides more useful information about the consistency and reliability of findings. To assess the general feature of the data descriptive statistics, such as percentage, mean, and variance were calculated on each variable. As mentioned earlier, since there are no observed saturated flow data, there is a need to estimate the saturation flow using the three methods based on the data collected.

3.5.1 Headway Ratio Method

For the headway ratio method, mean head way of each vehicle type will be calculated and this mean headway of each vehicle class divided by the mean headway of passenger car gives the passenger car equivalent of the class; while the saturation flow is determined by taking the reciprocal of the mean headway of passenger cars.

Let $\bar{h}_i$ be the mean headway of the ith vehicle type, and let Π_i be the actual PCE value of the vehicle class i. An estimate of Π_i can be obtained as:

$$P_i = \frac{\overline{h_i}}{\overline{h_1}} \quad \text{.......(1)}$$

where $\bar{h}_1$ denotes the mean headway of the class of passenger cars. The mean headway of vehicle type i is obtained by summing the total head way for that vehicle type and then dividing by the total number of vehicle departures of the class. The saturation flow, Σ, is estimated by s which is given by:

$$s = \frac{1}{\bar{h}_1} \text{ PCE per unit time} \quad \text{.......(2)}$$

3.5.2. Multiple Regression Model

3.5.2.1. Multiple regression models to estimate passenger car equivalents and saturation flow

For data that is collected using fixed number of vehicles to pass (synchronous method) and fixed time interval (asynchronous method) multiple regression models have been used. Kimber et al (1985) have cited that these regression methods had been used by Holoroyd (1963), Branston and van Zuylen (1978), Branston and Gips (1981) and Kimber et al, (1982).In what follows, the two regression methods are described in detail. Much of the development has been adopted from Kimber et al, (1985).

a. Synchronous regression

For the synchronous regression method, a multiple regression will be used to determine the passenger car equivalents of each vehicle type and the saturation flow as well, in such a way that the time T that was required for fixed number of vehicles (vehicles of different or the same type depending on their position in the queue) to pass the stop line is regressed on the number of vehicles of each vehicle type/class.

The number and type of vehicles departing from the queue of vehicles are recorded over a total time period T which is required for the fixed number of vehicles to pass a stop line (it should be noted that the number of each vehicle type in period T should add up to the fixed number of vehicles). The recording of time T is as discussed in section 3.4.2-a. T is regressed on n_i (where n_i is the number of departing vehicles of type i) to obtain estimates $\hat{\mu}_i$ of the coefficients μ_i in the linear model:

$$T = n\mu + \varepsilon\,,\ \varepsilon_i \sim Niid(0, n\sigma^2), \quad \text{.......(3)}$$

where n is an nxk deterministic data matrix, $\mu=(\mu_1, \mu_{2,\dots,} \mu_k)'$ is a kx1 vector of parameters, ε is an nx1 vector of the error terms and T is an nX1 vector of the dependent variable.

The parameters μ_i represent the population mean headway of vehicles of type i (i =1, …,k).

- Let i=1 denote passenger cars, then passenger car equivalent of vehicle type i ($i \neq 1$) would be estimated by $\frac{\hat{\mu}_i}{\hat{\mu}_1}$ (Kimber et al, 1985).
- Saturation flow rate per unit time would be estimated by $\frac{1}{\hat{\mu}_1}$
- The regression plane is constrained to include the origin since the counting period is chosen to exclude start and end lag effects –lost time effects. (Kimber et al, 1985). The start lags usually occur because vehicles may not start departing at the same time the traffic signal turns into green. Similarly vehicles may tend to slow their speed before the signal turns into yellow. But the saturation flow should be computed when the green time is effectively utilized.

The derivation of this model can be elaborated as follows.

Suppose first there is one type of vehicle and headways H_i (i=1,…,n) are normally, identically and independently distributed with mean μ and variance σ^2:

$$H_i \sim Niid(\mu, \sigma^{*2}) \quad \text{.......(4)}$$

Suppose also n vehicles (therefore n head ways) take time T_j, j = 1,2,…,N to pass. So

$$T_j = H_1 + \dots + H_n \quad \text{.......(5)}$$

$E(T_j) = E(H_1) + \ldots + E(H_n) = n\mu$ by assumption (4)……………………………………………(6)

$Var(T_j) = Var(H_1 + \ldots + H_n) = var(H_1) + \ldots + Var(H_n) = n\sigma^{*2}$ by assumption (4)…………(7)

Therefore: $T_j \sim N(n\mu, n\sigma^{*2})$ ……………………………………………………………………(8)

If a sample of N pairs (n,T) values $\{(n_1,T_1), \ldots, (n_j,T_j), \ldots, (n_N,T_N)\}$ is collected and T_j regressed on n_j through the origin, then an estimate $\hat{\mu}$ of the parameter μ can be obtained from an equation of the form:

$$T_j = \mu n_j + \varepsilon_j^*, \qquad \varepsilon_j^* \sim (0, n\sigma^{*2}), \text{ where } j = 1,..,N \qquad \ldots(9)$$

For efficient estimation the regression should therefore be weighted by $1/\sqrt{n}$. In practice the effects of weighting are slight, and even if it is not done, the parameter estimate $\hat{\mu}$ is very nearly correct (Kimber et al, 1985).

We can apply the Ordinary Least Square (OLS) method to estimate μ by $\hat{\mu}$ after weighting the regression by $1/\sqrt{n}$. After weighting we have:

$$\varepsilon_j' = T_j/\sqrt{n_j} - \mu\sqrt{n_j} \qquad \ldots(10)$$

$$S = \sum_{j=1}^{N} \varepsilon_j'^2 = \sum_{j=1}^{N} (T_j/\sqrt{n_j} - \mu\sqrt{n_j})^2 \qquad \ldots(11)$$

Taking the partial derivative with respect to μ and equating to zero at $\mu = \hat{\mu}$, we get

$$\hat{\mu} = \frac{\sum_{j=1}^{N} T_j}{\sum_{j=1}^{N} n_j} = \frac{\bar{T}}{\bar{n}} \qquad \ldots(12)$$

where $T_j = \sum_{k=1}^{n_j} h_k$, and h_k is the k^{th} vehicle headway, n_j is the number of vehicles that pass the stop line in the j^{th} phase (counting period in a given green time).

Due to the assumption that $\varepsilon_j' \sim Niid(0, \sigma^{*2})$, $\hat{\mu}$ is an unbiased estimator of μ.

Now suppose that there are two types of vehicles (two vehicle class), vehicle type 1 and 2, and the corresponding headways are drawn from normal distributions:

$$h_1 \sim N(\mu_1, \sigma_1^2);\ h_2 \sim (\mu_2, \sigma_2^2) \quad \text{.........(13)}$$

Suppose also the two types of vehicle arrive in a random order. Since it is known that vehicles arrive at the stop line in saturation flow, the sum of the probability of vehicle type 1 and type 2 arrival should add up to 1. Let also the probability of arrival for type 1 vehicles is 1-ξ and of type 2 is ξ. Then if n_{1j} of the first type and n_{2j} of the second type depart in the j^{th} phase, the time will be:

$$T_j = \sum_{k=1}^{n_{1j}} h_{1jk} + \sum_{k=1}^{n_{2j}} h_{2jk} \quad \text{.........(14)}$$

where h_{1jk} = the k^{th} headway in the j^{th} phase (counting period within a given green time length) for vehicle type 1 and h_{2jk} = the k^{th} headway in the j^{th} phase for vehicle type 2.

If the two components of T_j in equation (14) could be identified separately then equation (9) could be used as a model for bivariate regression for each class, with the obvious result that the estimates of μ would be equal to $\bar{h}_1$ and $\bar{h}_2$. However these components are not known separately. Since the time T_j (j^{th} counting phase) is spent to pass the two vehicle types of quantity n_{1j} and n_{2j}, a regression model for the total sample green periods is of the form:

$$T = \mu_1 n_1 + \mu_2 n_2 + \varepsilon \quad \text{.........(15)}$$

Suppose the number of vehicles to be counted is chosen and fixed prior to each phase (there are practical difficulties, of course, becau se phases-and saturation flows-do not last indefinitely and freedom of choice is limited). Say it is r.

$$n_{1j} + n_{2j} = r \quad \text{......... (16)}$$

Now the choice of r imposes correlation of some kind on n_1 and n_2. Two characteristics can be identified. If from a set of r values a subset of given r is selected, then within that subset there is perfect negative correlation between n_1 and n_2 (whose variations correspond to fluctuations in the proportion f_j, a sample value of ξ, of one class from phase to phase at constant r). In contrast if a subset of phases is selected in which f_j is the same for all j but r is allowed to vary, then $n_{1j} = (1- f_j)r$ and $n_{2j} = f_j\, r$, and n_1 and n_2 are positively correlated.

In general the net effect of fluctuations (from positive to negative or vice versa) of the correlation between n_1 and n_2 in the different phases of the counting process depends on the relative values of the parameters f and r. If the effect of r is large, correlations will be positive; if it is small, they will be negative.

If R, the correlation coefficient, is zero, the coefficients μ_1 and μ_2 of equation (15) can be estimated by partial regression with models of the type

$$T = a_0 + \mu'_1 n_1 + \varepsilon, \text{ and } T = b_0 + \mu'_2 n_2 + \varepsilon'' \qquad (17)$$

where μ'_1 and μ'_2 are population mean headways of vehicle type 1 and 2, respectively. Constant terms are included in equation (17) since the time T is recorded for both vehicle classes; where as each of the partial regression considers one type of vehicle as explanatory variable. If for example the number of type 1 vehicles departing the stop line is zero while there are type 2 vehicles passing the stop line in the first partial regression equation, then the constant term should be the time spent for type 2 vehicles.

However, R is generally not zero, and the estimation of the parameters is best treated by multiple regression. In fact Kimber et al, (1985) stated that for a typical public road site, the correlation coefficient falls between -0.3 and 0.3, which indicates that there is no severe multicollinearity to halt the use of multiple regression.

The estimates of μ_1 and μ_2 are free of any significant bias. Over all it seems reasonable to conclude that synchronous regression provides to a very good approximation sound estimates of the mean headways. And the parameters μ_1 and μ_2 can be estimated from the regression equation: $T = \mu_1 n_1 + \mu_2 n_2 + \varepsilon$ (Kimber et al, 1985).

b) Asynchronous regression:

In asynchronous method of counting, the number of departing vehicles is recorded over periods T, which begin and end at arbitrary instants. Then the number of passenger cars n_1 is regressed on T and on the number of vehicles n_i ($i \neq 1$) of class (type) i to obtain estimates $\hat{\beta}_0, \hat{\beta}_i$ (i =2, ..., k) in the model:

$$n_1 = \beta_0 T - \sum_{i \neq 1}^{k} \beta_i n_i + \varepsilon \quad \text{......(18)}$$

where β_0 represents saturation flow in PCE per unit time and β_i represent the PCE value of vehicle class i, i = 2,3, …,k

In this model we see that the relationship between the number of the other vehicle types departing from the queue and the number of departing passenger cars is inverse; that is in a given time period T, as the number of other vehicle types crossing a stop line increases then the number of passenger cars crossing the same stop line within that same period decreases.

In asynchronous regression, the number of passenger cars departing in time T is regressed on a constant term and the remaining vehicle class, where the constant term divided by the constant time T is the saturation flow and the coefficients of the other vehicle class are the passenger car equivalents of the class.

Kimber, et al (1985) has cited Branston and Gips (1981) for they have investigated the effects of non constant variance in the counts with respect to time. They have demonstrated that constant variance can be achieved in the error term by weighting by $1/\sqrt{T}$ if T is made to vary from counting phase to counting phase (which is not a case in this study). In this case the following regression model can be used:

$$\frac{n1}{\sqrt{T}} = \beta_0 \sqrt{T} - \sum_{i \neq 1}^{k} \beta_i n_i / \sqrt{T} + \varepsilon' \quad \text{......(19)}$$

If the data collection process avoids the start and end lag effects and constant period T= t seconds is used (which is the case for this study), the model that will be utilized in finding the regression coefficients can be expressed as

$$\mathbf{n_1 = \beta_0 - \sum_{i \neq 1}^{k} \beta_i n_i + \varepsilon} \quad \text{......(20)}$$

The derivation of this model is described below.

Suppose head ways are normally, independently and identically distributed random variables:

$$h \sim Niid(\mu, \sigma^2) \qquad (21)$$

If the number of departures n_j within mutually exclusive time windows (time allotted for each counting period in a given green time at signalized intersections) are recorded where the beginning of each window are random, Kimber et al (1985) have shown using simulation that:

$$Var(n) \cong cT \qquad (22)$$

where c is constant of proportionality.

So a regression of n on T is : $n = \beta T + \varepsilon$, where $\varepsilon \sim N(0, cT)$ ....(23)

The expected number of departures is $E(n) = \beta T$. i.e. the saturation flow per unit time is β. Similar to the synchronous regression discussed in section (a) above, OLS method can be employed to get the estimate $\hat{\beta}$ of β after weighting (23) by $1/\sqrt{T}$.

After weighting we have: $\varepsilon_j' = n_j/\sqrt{T_j} - \beta\sqrt{T_j}$ ....(24)

Taking the partial derivative of the sum of squares of errors with respect to β and equating to zero at $\beta = \hat{\beta}$, we get:

$$\hat{\beta} = \frac{\sum_{j=1}^{N} T_j}{\sum_{j=1}^{N} n_j} = \frac{\bar{n}}{\bar{T}} \qquad (25)$$

$$\bar{h} = \frac{\sum_{j=1}^{N} \sum_{k=1}^{n_j} h_{jk}}{\sum_{j=1}^{N} n_j} = \frac{\sum_{j=1}^{N} \sum_{k=1}^{n_j} h_{jk}}{N\bar{n}} \qquad (26)$$

where $\bar{h}$ is the sample mean headway (the mean of all headways of vehicles counted within the intervals T_j).

When N is large, $\frac{1}{N}\sum_{j=1}^{N}\sum_{k=1}^{n_j} h_{jk} \cong \bar{T} = \frac{1}{N}\sum_{j=1}^{N} T_j$. ....(27)

so for large samples, $\hat{\beta} = \frac{\bar{n}}{\bar{T}} \approx \frac{1}{\bar{h}}$ ....(28)

Now suppose that there are two type (class) of vehicles, 1 and 2 with head ways drawn from normal distributions as: $h_1 \sim N(\mu_1, \sigma_1^2)$; $h_2 \sim (\mu_2, \sigma_2^2)$ and assume that vehicles arrive in a random order.

Let 1-ξ be the probability of an arrival of type-1 vehicle and let ξ be the probability of an arrival of type-2 vehicles.

Consider four cases,

i) Suppose that $\sigma_1 = \sigma_2 = 0$ and $\mu_1 = \mu_2 = \mu$, i.e. the distinction between types of vehicles has nothing to do with traffic behavior. For example, the type or class could be based on the colour of vehicles. If all vehicles were green or red cars then type 1 can be red and type- 2 green cars. Then var (n_1) = var (n_2) = 0

Kimber et al (1985) have also geometrically shown that

$$n_1 + n_2 = \frac{T_k}{\mu} \quad k=1,2,\ldots \qquad \text{and } T_k = T, \text{ for all } k= 1, 2,\ldots \text{(i.e equal time interval)}$$

$$\text{or} \quad n_1 = \frac{T_k}{\mu} - n_2 \qquad \ldots\ldots\ldots(29)$$

where $T_k = T$ is the k^{th} counting time interval. This means that the number of departures of class 1 vehicles per interval time is a function of the number of departures of class 2 vehicles in that interval. We also note that (28) is a deterministic model. If we add an error term with all values equal to zero for the purpose of construction, and rewrite equation (28) as regression equation of the form below there will no be loss of generality. So the regression equation of n_1 on T and n_2 can be given by:

$$n_1 = \beta_0 T + \beta_2 n_2 + \varepsilon \ldots\ldots\ldots(30)$$

$\hat{\beta}_0 = \beta_0 = 1/\mu$ and $\hat{\beta}_2 = \beta_2 = -1$ (i.e there is no distinction between population and sample mean values). Here the estimates are equal with the corresponding population parameters, because the difference between the population equation (29) and the constructed regression equation (30) is with the number of counting intervals (note that all ε is equal to zero, $\mu_1 = \mu_2 = \mu$). Obviously, the number of counting intervals with time T which is k, in the case of the population equation (29) is higher than the number of counting intervals of time T when considering the regression equation (30). This is because n_1 and n_2 are sample vehicles in (30) but are population vehicles in (29). In short we need case (i) to discuss the subsequent cases; otherwise we could simply calculate the value of μ from equation (29).

ii. Suppose $\sigma_1=0=\sigma_2$, but $\mu_2 \neq \mu_1$

Consider the regression equation constructed from (29) $n_1 = \beta_0 T + \beta_2 n_2 + \varepsilon$, but now ε are not all equal to zero. Note also that β_0 corresponds to $\frac{1}{\mu}$ and β_2 corresponds to (-1) of equation (28).This is so because in the case of asynchronous regression we are concerned with the PCE of vehicle types other than n_1 (passenger cars) and the saturation flow. Now, applying OLS on this regression equation we have:

$$\hat{\beta}_0 = \frac{\overline{n_1}}{T} - \hat{\beta}_2 \frac{\overline{n_2}}{T} \quad \text{.......(31)}$$

$$\hat{\beta}_2 = \frac{\sum_{j=1}^{N}(n_{1j}-\bar{n}_1)(n_2-\bar{n}_2)}{\sum_{j=1}^{N}(n_{2j}-\bar{n}_2)2} \quad \text{.......(32)}$$

From an ordinary regression we know that the expected value of $\hat{\beta}_2$ is β_2. But for this particular case of asynchronous regression, for the expected value of $\hat{\beta}_2$ to be equal to one in absolute value, we need the expected value of the numerator and the denominator of (32) to be the same in absolute value . But this is not always the case. Kimber et al (1985) in fact have shown geometrically that $\hat{\beta}_2$ fluctuate below and above 1 in absolute value. Similarly for the expected value of $\hat{\beta}_0$ to be equal to $\frac{1}{\mu}$, the expected value of $\hat{\beta}_2$ should be equal to -1. For further clarity, suppose E $\left(\bar{\beta}_2\right)$ = -1, then from (31) we have E $\left(\hat{\beta}_0\right)$ = 1/T E($\bar{n}_1$) –(-1)1/T E($\bar{n}_2$). The expected value of ($\bar{n}_1$) is the population mean of the number of departing vehicles of type1 (say V_1) and E($\bar{n}_2$)

is the population mean of the number of departing vehicles of type 2 (say V_2), then, $E\left(\hat{\beta}_0\right) = V_1/T + V_2/T = 1/\mu$.

iii. Suppose $\sigma_1>0$ or $\sigma_2>0$ but $\mu_2 = \mu_1$

Considering again the regression stated in equation (29) but with not all the error terms are zero, Kimber et al (1985) have geometrically shown that in this case $\hat{\beta}_0$ is less than $1/\mu$ and $\left|\hat{\beta}_2\right| <1$.

Case iv. Suppose in general $\sigma_1>0$, $\sigma_2>0$ and $\mu_2 \neq \mu_1$

Consider the fixed time T for N counting phases of a green time (i.e. green time divided in equal time of counting period- this is the usual case in asynchronous regression).

Let the sum of all headways for vehicles within N counting periods be T^N

$$\sum_{j=1}^{N}\left(\sum_{l=1}^{n_{1j}} h_{1jl} + \sum_{l=1}^{n_{2j}} h_{2jl}\right) = T^N \qquad (33)$$

Now, $$\overline{n_1} = \frac{1}{N}\sum_{j=1}^{N} n_{1j},\quad \overline{n_2} = \frac{1}{N}\sum_{j=1}^{N} n_{2j} \qquad (34)$$

$$\bar{h}_1 = \frac{\sum_{j=1}^{N}\sum_{j=1}^{n_{1j}} h_{1jl}}{N\overline{n_1}},\quad \bar{h}_2 = \frac{\sum_{j=1}^{N}\sum_{j=1}^{n_{2j}} h_{2jl}}{N\overline{n_2}} \qquad (35)$$

As $N \to \infty$, (34) and (35) become the population mean values v_1 and v_2, and μ_1 (Population mean headway for type 1 vehicles) , μ_2 (population mean headway for type 2 vehicles) respectively, and $(T^N/N) \to T$, so,

$$\mu_1 V_1 + \mu_2 V_2 = T$$

$$, V_1 + \frac{\mu_2}{\mu_1} V_2 = \frac{T}{\mu_1} \qquad (36)$$

Equation (36) is an equation in V_1, V_2 and T with μ_1 and μ_2 as parameters of interest. And the population equation (36) tells us that the regression equation that could be used to estimate the PCE of type 2 vehicle, $\frac{\mu_2}{\mu_1}$, and the saturation flow rate, $\frac{1}{\mu_1}$ (given that vehicle type 1 is passenger cars) is of the form:

$$n_1 = \beta_0^* T + \beta_2^* n_2 + \varepsilon \quad \text{.....(37)}$$

where β_0^* corresponds to $\frac{1}{\mu 1}$ and β_2^* corresponds to $\frac{\mu 2}{\mu 1}$ but the expected value of the estimators would not give their respective population parameters and Kimber et al (1985) stated that the estimates are less than their respective population parameters.

i.e $\quad \hat{\beta}_0^* < \frac{1}{\mu 1}$ and $\left| \hat{\beta}_2^* \right| < \frac{\mu_2}{\mu_1}$ .....(38)

Therefore, it is only in case (ii) that the estimated saturation flow per unit time, $\hat{\beta}_0$, may be greater or less than $\frac{1}{\mu}$, and the estimated PCE value, $\hat{\beta}_2$, may be greater or less than the actual value $\frac{\mu_2}{\mu_1}$. In the rest of the cases, the estimates are less than or equal to the population values; equality holds due to the assumption that the two classes of vehicles do not vary in traffic behaviors. So we are saying that the saturation flow estimator in time T, $\hat{\beta}_0$, and the PCE estimator, $\hat{\beta}_2$ are biased estimators.

Another alternative to find estimates of $1/\Sigma$ (where Σ is the population mean saturation flow per unit time of the two vehicle types) and ξ (the proportion of type 2 vehicle) from the primary relations of population values is discussed below.

Since ξ is the true independent variable, n_1 and n_2 are subject to the underlying constraint that:

$$\lim_{N\to\infty}\left(\frac{\overline{n_2}}{\overline{n_1}+\overline{n_2}}\right) = \frac{V_2}{V_1+V_2} = \xi \quad \text{.....(39)}$$

Let the population mean number of vehicle departures be V, where $V = V_1 + V_2$. Then the primary relation with the mean headways μ_1 & μ_2 and the constant time interval T is given by:

$$V = \frac{T/\mu_1}{1+(\frac{\mu_2}{\mu_1}-1)\xi} \quad \text{...(40)}$$

and $1/\Sigma = T/V = \mu_1 [1+(\frac{\mu_2}{\mu_1} - 1)\,\xi] = \mu_1 + (\mu_2 - \mu_1)\,\xi$ ....(41)

Now suppose $n_i = n_{1i}+n_{2i}$ (i= 1,2,…,N) be the i^{th} green phase number of vehicle departures of the two vehicle class and $m_i = n_{2i}/(n_{1i}+n_{2i})$, represents green phase specific value of f (an estimate of ξ) and. Then from the deterministic model (41), we have the regression equation stated below (which is just an extension of the deterministic equation in to a regression equation by adding the random disturbance term to allow measurement or other errors):

$$\frac{T}{n} = \Upsilon_0 + \Upsilon_1 m + \varepsilon \quad \text{.. (42)}$$

where Υ_0 corresponds to μ_1 and Υ_1 corresponds to $(\mu_2 - \mu_1)$ of equation (41). The regression equation can give us estimates of $\frac{T}{n}$ from given values of m_i and from this what we can get is the mean value $\overline{T/n}$ (which is not an interest) and the parameter estimates $\hat{\Upsilon}_0$ and $\hat{\Upsilon}_1$. But this parameter estimates obtained using the regression equation (41) are inherently biased for the reason that $E(T/n) \neq 1/\Sigma = T/V$ and $E(m) \neq \xi$. The bias of $\frac{T}{n}$ and m is shown below.

Mood et al, (1974, P 181) have indicated as: $E\left(\frac{x}{y}\right) \cong \frac{\mu_x}{\mu_y} - \frac{1}{\mu_y^2}Cov(x,y) + \frac{\mu_x}{\mu_y^3} var(y)$.

With"T" fixed then we get:

$$E\left(\frac{T}{n}\right) = TE\left(\frac{1}{n}\right) \cong T\left[\left(\frac{1}{V}\right)+\frac{var[n]}{V^3}\right] = T\,\frac{1}{V}\,(1+\Delta) \quad \text{.....................................(43)}$$

where $\Delta = \frac{var[n]}{V^2}$, and the bias is $\frac{T\Delta}{V}$

$$E(m) = E\left(\frac{n_2}{n}\right) \cong \frac{V_2}{V} - \frac{1}{V^2}cov(n_2,n) + \frac{V_2}{V^3}var(n) = \xi(1+\delta) \quad \text{.....................................(44)}$$

where δ= {[var (n]- (1/ξ) covar(n_2,n)}/V^2 and equation (43) implies that the estimator of ξ (the probability of an arrival of type 2 vehicles) is biased.

Kimber et al (1985) have suggested that the results from regression (41) provides better estimates of saturation flow per unit time than the regression of n_1 on n_2 though the equation is complicated.

Therefore, from the discussions above we have no way of finding unbiased estimates of saturation flow and PCE values from data that is collected using the asynchronous counting method. But we see basic relationships between n_1 and n_2 from equation (35), (40) and (41). According to Kimber et al, (1985), an essential difference between the three methods (headway ratio, synchronous and asynchronous regression) exists when there are only two classes of vehicles. This means that if we have more than two classes of vehicles and we extend the regression of number of type 1 departing vehicles on more than one type of departing vehicles there is no essential difference with the headway ratio and synchronous regression methods.

3.5.2.2 Identifying factors that affect saturation flow

Once the appropriate saturation flows are selected from the three methods the next step will be to identify the factors that affect the saturation flow. To identify the factors that affect saturation flow significantly, multiple regression model can be applied.

Let S be the dependent variable, saturation flow, and X_i's (i=1, 2,..,k) be the explanatory variables. The linear regression can then be given by

$$S = \beta_0 + \beta_1 X_1 + \beta_2 X_2 + \ldots + \beta_k X_k + u$$

where u= (u_1, u_2, …,u_n) is a vecter of error terms, β_i,for i = 0, 1,2,…,k are unknown fixed regression coefficients that need to be estimated and each β_i , i=1,2,…,k measures the expected change in the response variable S per unit change in the j^{th} explanatory variable X_j when all X_i ($j \neq i$) are kept constant.

The basic assumptions for the model are:

i. $E(u_i) = 0$ $i = 1, 2, ..., n$
ii. $Var(u_i) = \sigma^2$ $i = 1, 2, ..., n$
iii. $Cov(u_i, u_j) = 0$ for $i \neq j$ (the error terms are uncorrelated).

Under this assumption the usual method that is used to estimate the unknown parameters is the method of least squares. In order to make inference an additional assumption is that $u_i \sim N(0, \sigma^2)$. It should be noted that these assumptions are also applicable in the synchronous and asynchronous regression discussed above to determine the passenger car equivalents of each vehicle class and the saturation flows.

3.5.2.2.1 Testing the significance of the model

After fitting a linear regression model, its overall significance is tested using F test by calculating the test statistics F as, $F = \frac{MSR}{MSE} = \frac{SSR/k}{SSE/(n-k-1)}$

where $SSR = \hat{\beta}' \mathbf{X}' S$ and $SSE = S' S - \hat{\beta}' \mathbf{X}' S$. Once the model is found to be significant, the statistical significance of each of the coefficients can be tested using t- test. And if a coefficient is found to be significant it means that the corresponding independent variable is statistically significant in explaining the dependent variable.

Both F and t test are valid if the assumptions for the model are fulfilled. Therefore, we need to check multicollinearity between the independent variables, and hetroscedasticity and normality of the random error.

3.5.2.2.2 Model selection

It is likely that we will have data on more independent variables than we can reasonably expect to include in the model. So we must decide on a method to select a subset of explanatory variables. However, there is no unique statistical procedure or method for selecting the best regression equation. One can use one of the methods of model selection which are listed below as described by Draper and Smith (1966).

- All possible regressions
- Backward elimination procedure
- Forward selection procedure
- Stepwise regression procedure
- Stage wise regression procedure

For many problems these procedures give the same result but they do not always necessarily lead to the same solution (Draper and Smith, 1966). And which selection procedure to use depends on personal judgment. In this study all possible regression procedure is used.

CHAPTER FOUR

DATA ANALYSIS AND RESULTS

4.1. Passenger Car Equivalents and Saturation Flow

4.1.1. Descriptive Statistics

As discussed in the methodology part, the data used in this study were secondary data, collected using the three counting methods; headway ratio, asynchronous and synchronous methods. In this subsection the percentage distribution of vehicle types that passed the stop lines in each of the counting techniques is briefly described.

In the headway ratio method, the data was collected in 485 green phases of signals during peak traffic hours. In these green times, 4938 mixed vehicle types passed the stop lines. The majority of the vehicles (69.8%) were passenger cars followed by minibuses (24.5%). Large buses made 2.4% of vehicle flows at the stop lines. The percentage distribution of goods vehicles is low as compared to public transport vehicles: they represent only 1.5% of vehicle flows in the sample (detail percentage results by lane and type of vehicles are presented in table A2 of the annex).

The data collected from the asynchronous counting method, with 10 seconds time interval, reveals that about 5586 vehicles in 545 green phase passed stop lines from different intersections. Similar to the headway ratio method, more than 70% of the total vehicle flows were made of passenger cars, and minibuses made more than 24%. Large buses, which take more space in the queue of vehicles to pass the stop lines made 1.7% of the vehicle flows counted by the method. Public transport vehicles including passenger cars made more than 98% of vehicle flows passing stop lines, while the remaining was made by goods vehicles (Table A3 of the annex gives detailed results).

The percentage distribution of vehicles in the synchronous counting method was found to be similar to the distributions in the headway ratio and asynchronous methods. More than 62 % of vehicle flow in this counting method was made by passenger cars. The second most abundant vehicle type that made about 32% of the flows is minibus. Large buses comprise 1.7% of the flows. These results were computed from data collected by the method in 411 green phases with a total vehicle flow of 3392 different vehicles (figures are presented on table A4 of the annex).

4.1.2. **Passenger car equivalents and Saturation flows from headway, asynchronous and synchronous regression methods**

For data collected using fixed time and fixed number of vehicles method, regression was performed for each of the lanes to calculate saturation flow from each of the methods and also lane wise passenger car equivalents (lane wise passenger car equivalent might not have a significant importance parametrically rather it gives some clue on how the PCE values change from lane to lane). Some of the vehicles observed in some classes were not found significant, that is to say that the presence of some classes of vehicles does not affect the dependent variables (in the case of synchronous the time T, and in asynchronous the number of departing passenger cars, n_1). Hence their passenger car equivalent is not shown. But they appeared in the headway ratio method. On the other hand, goods vehicles were not allowed to pass into most of the intersections during peak hours of traffic flow and hence most of the lanes did not have passenger car equivalent values for the different classes of goods vehicles in this study. The absence of heavy goods vehicles in the vehicle flows due to traffic regulation is to improve the saturation flow in each of the lanes. The lane wise saturation flow is very important quantity as the main concern of this study is to identify factors affecting saturation flow.

4.1.2a. PCE and saturation flow Estimates from headway ratio method

The basic mathematical formulas used to find the passenger car equivalent in this method is:

$P_i = \frac{\bar{h}_i}{h_1}$ where P_i is the estimated PCE value of vehicle class i , $\bar{h}_i$ is the mean headway of vehicle type i which is obtained as the total headway for that vehicle type divided by the total number of departing vehicles of this type and $\bar{h}_1$ is the mean headway of passenger cars.

An estimate of the saturation flow is given by:

$S = \frac{1}{\bar{h}_1}$ PCE per unit time.

In the headway ratio method the passenger car equivalent value of motorcycles(MC) was between 0.463 to 2.726, small buses (SB) between 0.888 and 1.204, medium buses (MB) between 0.67 and 1.603, large buses (LB) between 0.947 and 4.163 (only on one lane the PCE value 4.163 and the rest less than or equal to 2.844), light goods vehicles (LG) between 0.929 and 2.32, medium goods (MG) between 0.554 and 1.649, and heavy goods vehicles with three axles (HG_3) between 0.86 and 1.958. On some of the lanes the passenger car equivalents of some vehicles are different from our expectation. For instance, the PCE value for motorcycles 2.726 is high, and this can be either the motor cycles were not performing well so that they took longer times to pass stop lines, or the riders were not riding fast. On the contrary the reason for the PCE values which are lower than our expectation might be that the vehicles were performing well or drivers were driving faster than the normal or the standard. The saturation flow computed using this method is between 1259 and 1697 passenger car equivalent per green hour per lane (pcpgpl). The PCE value for each vehicle type and the saturation flow for each of the lanes from headway method are presented in Table 4.1

Table: 4.1 Passenger car equivalents and saturation flow from headway ratio method by lane

Intersection	Approach	Lane no.	MC	SB	MB	LB	LG	MG	HG3	Saturation flow per green hour
Cathedral	Piazza to Tewodros	1	0.865	1.010	-	2.844	0.929	1.649	-	1622
		2	0.984	1.154	0.952	4.163	2.320	0.927	-	1625
Business and construction bank	Mexico to Biherawi	1	-	1.038	1.036	1.938	-	0.828	-	1498
		2		0.951	0.670	-	-	-	-	1656
		3	2.726	1.008	0.757					1562
	Biherawi to Mexico	1	0.833	1.018	1.190	1.945	1.615		1.958	1432
		2	-	1.204	0.728	2.772	1.205	-	-	1541
		3		0.888	0.953	0.947	1.842	1.140	0.860	1259
Dembel city center	Bole to Meskel square	2	0.562	1.081	1.266	1.367	0.970	-	1.345	1658
		3	0.530	1.033	1.246	1.339	0.915	-	1.269	1564
	Meskel square to Bole	1	-	0.919	1.088	1.226	1.146	-	-	1612
		2		0.945	1.603	1.374	-	1.211	-	1527
Urael	Bambis to Megenagna	3		1.094	1.050	2.088	0.886	-	-	1444
	Megenagna to Bambis	2		1.031	1.595	2.311	0.885	0.964	-	1518
Atlas hotel	Atlas to Urael	3		0.919	-	-	-	0.554	-	1426
	Urael to Atlas	3		1.017	0.804	1.763	1.534	0.976		1562
Harambe	Meskel to Ambassador	3	2.726	1.008	0.757	-				1573
	Ambassador to Meskel	1	1.269	1.131	-	-	1.338	1.082		1575
	Ambassador to Meskel	2		1.058	0.830	1.161	-	1.224		1697
Kidst Mariam	Sidist kilo to Arat kilo	1	1.208	1.076	1.111	1.726	0.910	1.296		1370
	Arat kilo to Sidist kilo	1	0.463	1.150	0.765	2.286	-	1.221	-	1424
	Arat kilo to Sidist kilo	2	-	0.945	1.603	1.374	-	1.211	-	1545

4.1.2b. PCE and saturation flow estimates from asynchronous regression method

The regression equation applied to find estimates of PCE and saturation flow was: $\mathbf{n_1} = \boldsymbol{\beta_0} - \sum_{i=2}^{k} \beta_i n_i + \boldsymbol{\varepsilon}$, where $\hat{\beta}_0$ divided by 10 seconds gives the saturation flow estimate per second, and $\hat{\beta}_i$ gives estimated PCE value of vehicle type i, i= 2,..,k. Here division by 10 seconds is for the reason that $\hat{\beta}_0$ gives an estimated saturation flow per 10 seconds. This is so because the data collection was done in such a way that the number and type of vehicles crossing the stop lines in each 10 seconds was recorded.

From this method, PCE value of MC was 0.979 and 1.089 on two different lanes, SB between 0.387 and 1.089, MB between 0.817 and 2.017, LB between 1.044 and 2.663, LG between 0.86 and 1.542, MG between 0.642 and 2.463, and HG3 on two lanes with PCE values of 0.979 and 2.070. And the saturation flow is between 916 and 1762 pcpgpl.

Similar to the headway method, some of the PCE values obtained from the asynchronous method are lower or higher than our trivial expectation; for instance PCE value of 0.642 for MG is low. The only different suggestion for this method as discussed in the methodology part is that, the estimates obtained using this method might be lower and biased especially when there is one vehicle type that significantly explain the number of departing passenger cars. The calculated PCE value for each vehicle type and the saturation flow for each of the lanes from asynchronous regression are presented in Table 4.2.

Table 4.2 Passenger car equivalents and saturation flow by lane as computed from asynchronous method

Intersection	approach	lane	MC	SB	MB	LB	LG	MG	HG3	Saturation flow/ghr
Cathedral	Piassa to Tewodros	1		0.572						1543
	Piassa to Tewodros	2		0.913	1.919	2.166		2.463		1740
Business and construction	Mexico to Biherawi	1		0.553		1.744	-			957
	Mexico to Biherawi	2		0.761	0.862	1.262	1.063	1.783		1413
	Mexico to Biherawi	3		0.924		1.575	1.499	1.190		1620
	Biherawi to Mexico	1		0.416	1.062	1.116				916
	Biherawi to Mexico	2		0.618	1.715	1.366				1246
	Biherawi to Mexico	3		0.921	2.070		0.86		2.070	1465
Dembel city center	Bole to Meskel	2		0.749		1.511	1.510			1533
	Bole to Meskel	3	1.089	1.089	0.817	2.089				1472
	Meskel to Bole	1		0.589		2.003				1209
	Meskel to Bole	2		1.000	1.895			1.395		1762
Urael	Bambis to Megenagna	3		0.941	1.779	1.653				1361
	Megenagna to Bambis	2		0.654	1.070	1.342		1.025		1474
Atlas hotel	Atlas to Urael	1								
	Atlas to Urael	2	0.979	0.675	1.061	1.088		0.642	0.979	1433
	Urael to Atlas	3		0.917						1590
Harambe hotel	Meskel to Ambassador	2		0.467	0.871	2.663				1127
	Ambassador to Meskel	1		0.784				1.380		1266
	Ambassador to Meskel	2		0.619						1238
Kidst Mariam	Sidist kilo to Arat kilo	1		0.579	1.239	1.044				1015
	Sidist kilo to Aratkilo	2		0.773		1.776	1.542			1112
	Arat Kilo to Amst Kilo	1		0.387		1.190				941

4.1.2c. PCE and saturation flow estimates from synchronous regression method

The regression equation applied here was: $T = \sum_{i=1}^{k} \mu_i n_i + \varepsilon$, where $\frac{1}{\hat{\mu}_1}$ gives an estimate of saturation flow and $\frac{\hat{\mu}_i}{\hat{\mu}_1}$ gives PCE estimate of vehicle class i.

The PCEs and saturation flows computed using synchronous regression method are presented in table 4.3. The PCE value of MC is 0.774 and 0.821 for two different lanes, SB between 0.818 and 1.356, MB between 0.628 and 2.758, LB between 1.285 and 3.8, LG between 0.885 and 2.32, MG between 1.01 and 2.747, HG3 between 0.86 and 1.958. The saturation flow estimated in this method is between 1165 and 1842.

Table: 4.3 Passenger car equivalents and saturation flow by lane as computed by the synchronous regression method

Intersection	Approach	Lane No	MC	SB	MB	LB	LG	MG	Saturation flow per green hour
Cathedral	Piassa to Tewodros	1		0.846			3.422		1622
	Piassa to Tewodros	2		1.356			2.657		1793
Business and Construction Bank	Mexico to Biherawi	1		1.060	1.412	1.796			1543
	Mexico to Biherawi	2		0.833	1.075	1.812	1.622		1500
	Mexico to Biherawi	3		1.205	2.758	1.915	1.457	2.747	1773
	Biherawi to Mexico	1	0.821	1.153	1.854	2.561	1.541		1566
	Biherawi to Mexico	2		1.294	1.086	2.131			1688
	Biherawi to Mexico	3		1.108	1.490	3.024	1.923		1605
Dembel city center	Bole To Abiot	2		1.102	1.561	3.80	1.183		1701
	Bole To Abiot	3		1.189	0.922	1.480		1.202	1470
	Meskel square to Bole	1		0.818	1.274	1.285		1.010	1396
	Meskel square to Bole	2		1.004		2.047	1.676	1.216	1624
Urael	Bambis to Megenagna	3		0.957	1.231	1.596	2.170		1434
	Megenagna to Bambis	2		1.005	2.278				1571
Atlas hotel	Atlas to Urael	2		1.189		1.318	1.216		1636
Harambe hotel	Meskel square to Ambassador	2		0.932		1.938	1.533	1.666	1691
	Ambassador to Meskel Meskel square	1	0.774	1.071				1.772	1842
	Ambassador to Meskel square	2		0.953		2.366		1.556	1639
Kidst Mariam	Sidst Kilo to Arat Kilo	1		1.079	1.180	2.133			1165
	Arat Kilo to Amst kilo	1		1.010	0.628	2.142			1421

4.2 Factors affecting saturation flow

4.2.1 Descriptive Measures

In order to have some general information on the dependent and independent variables, some descriptive statistics were computed and presented in this subsection.

Independent variables:

Table 4.4 shows the maximum, minimum and mean values of some independent variables, namely lane width as measured in meter, slope, green time in seconds, and number of lanes. While lane width, green time and number of lanes can positively contribute to saturation flow, a negative increase in slope (upward sloping) decreases saturation flow.

Table 4.4 Minimum, maximum and mean values of independent variables

Variable	Minimum	maximum	Mean
Lane width	2.40	4.30	3.07
Slope	-8.85	4.13	-0.13
Green time	22.06	35.87	29.18
Number of lanes	2	4	3

The dependent variable

As it was mentioned in the previous sections, the dependent variable, saturation flow, is not directly obtained from observations; it is obtained by applying estimation methods. Three different methods were employed to estimate the saturation flow. Table 4.5 presents the mean, standard deviation and coefficient of variation of the saturation flow from the three methods.

Table 4.5 Mean, standard deviation and coefficient of variation of saturation flow computed from the three methods

Method	Mean	Standard deviation	Coefficient of variation
Headway	1531.3636	104.8843	0.0685
Asynchronous	1337.7171	253.7798	0.1897
Synchronous	1571.0552	163.8670	0.1043

In order to see the existence of significant difference between the mean saturation flows of the methods t-test was applied. The test has confirmed that there is a significant difference between the mean saturation flows from the headway and asynchronous methods as well as asynchronous and synchronous methods. On the other hand there was no significant difference between the mean saturation flows from the headway and synchronous methods.

4.2.2. Bivariate correlation coefficients

In order to have some idea about the relationship between the independent and dependent variables, and also within the independent variables themselves, correlation coefficients are helpful.

The bivariate correlation coefficient between each of the independent variable and also the dependent variable are given in tables 4.6a to 4.6c

Table 4.6a Baivariate correlation coefficient from headway method

Variable	Slope	Green time	Number of lane	Pedestrian crossing	% of large bus	Saturation flow
Lane width	-0.226	0.064	-0.731**	0.312	0.409	-0.424*
Slope		0.439*	-0.173	-0.104	0.085	0.280
Green time			-0.175	0.308	0.439*	-0.411
Number of lane				-0.043	-0.333	0.374
Pedestrian crossing					0.320	-0.527*
% of large bus						-0.341

Table 4.6b Bivariate correlation coefficients from asynchronous/fixed time method

Variable	Slope	Green time	Number of lane	Pedestrian crossing	% of large bus	Saturation flow
Lane width	-0.113	0.107	-0.579**	0.696**	0.126	-0.453*
Slope		0.468*	-0.253	-0.040	0.165	-0.179
Green time			-0.274	0.223	0.485*	-0.130
Number of lanes				-0.611**	-0.319	0.610**
Pedestrian crossing					0.196	-0.430
% of large bus						-0.514*

Table 4.6c Bivariate correlation coefficients from synchronous/fixed vehicle method

Variable	Slope	Green time	Number of lane	Pedestrian crossing	% of large bus	Saturation flow
Lane width	-0.083	0.186	-0.768**	-0.704**	0.289	-0.473*
slope		0.448*	-0.223	-0.103	0.090	-0.312
Green time			-0.231	0.233	0.473*	-0.371
Number of lane				-0.604**	-0.323	0.412
Pedestrian crossing					0.212	-0.704**
% of large bus						-0.283

* significant at the 0.05 level and** significant at the 0.01 level (2-tailed).

Both Table 4.6a and Table 4.6c (i.e. data from headway method and synchronous method) suggest that there is a significant negative relationship between number of pedestrian crossing vehicle flows and the dependent variable, saturation flow. On the other hand the numbers of lanes in an approach and saturation flow are found to be positively related in the case of asynchronous method but not in the other two methods. A dubious result observed in the bivariate correlation analysis is the negative relationship of lane width with saturation flow in all of the three methods. Many reaserches have revealed that the relationship between saturation flow and lane width is positive within certain limits of lane width; for example Slinn, *et al* (2005).

The bivariate correlation has also shown that there is a significant correlation between some of the independent variables. Lane width and number of lanes are negatively correlated and this could be for the reason that a given road is divided into lanes. So an increase in the number of lanes decreases the width that each lane should have. As expected, the number of pedestrians and number of lanes are negatively related in the case of asynchronous and synchronous methods. Lane width is related to number of pedestrian negatively in the case of synchronous method and this result is in agreement with what we observe in our daily life (when width increases people get afraid to cross vehicle flows). Unexpected positive relationship between lane width and number of pedestrian crossing lanes is observed in the asynchronous method (Table 9.4b). This result might have come from the fact that even though the lanes at Urael (Megenagna to Bambis and Bambis to Megenagna) and also at Kidst Mariam (Sidst kilo to Arat kilo and Arat kilo to Sidist kilo) are wider compared to many of the lanes in other intersections, a large number of people (pedestrians) cross the lanes to follow church ceremonies.

4.2.3. Variable Selection

The study considers six explanatory variables: lane width, slope of an approach, green time length, number of lanes in an approach, number of pedestrians crossing vehicle flows and percentage of large buses that made vehicle flows. And the response variable is saturation flow. The objective here is to select the most important variables among these six explanatory variables and the corresponding "best" regression model to describe the relationship between saturation flow and the explanatory variables.

Regression analysis (with stepwise variable selection method) was performed to select the most important factors affecting the saturation flow of vehicles (converted into the same unit of measurement called passenger car equivalent). Since lane width and number of lanes were found highly correlated, one of them, lane width, has been excluded.

There are a number of methods that suggest whether multicollinearity exists or not in a given data set of explanatory variables. Among these methods the method of variance inflation factor (VIF) is usually used to check the existence of multicollinearity. A Large variance inflation factor is an indicator of the existence of multicollinearity. Montgomery and Pecks (1992) suggested that VIF greater than 10 implies serious problem due to the presence of multicollinearity. After excluding lane width which is highly correlated with number of lanes, the maximum variance inflation factor observed in this study is 1.98 for the explanatory variable number of lanes in an approach in the synchronous method. Therefore, we can assume that there is no serious multicollinearity problem.

Table 4.7 Variance inflation factors of the explanatory variables

Variable	VIF		
	Headway method	Asynchronous method	Synchronous method
Slope	1.380	1.386	1.592
Green time	1.698	1.690	1.809
Number of lane	1.156	1.824	1.980
Pedestrian crossing	1.245	1.665	1.449
% of large bus	1.447	1.400	1.418

4.2.4. Model fitting and residual analysis

1. Synchronous method

In the synchronous method, saturation flow obtained from synchronous counting method is regressed on the number of pedestrian crossing vehicle flows, approach grade (slope), number of lanes, percentage of total flow made by large buses (% of large buses) and length of green time for a lane (Green time). Diagnostic check of the residuals indicated that two of the residuals have a large Cook's distance, and hence, two observations corresponding to these residuals are removed. The regression result has then shown that slope of an approach and pedestrians crossing vehicle flows at stop lines were found to be significant factors affecting saturation flow. with F= 7.086 (p-value =0.003); whereas green time length, number of lanes and percentage of large buses were found insignificant in affecting the saturation flow. The coefficients of the variables with the corresponding t-test are presented in table 4.8 below.

Table 4.8 Variables in the final model from synchronous method

Variable	Coefficients ($\hat{\beta}$)	SE of coefficients SE ($\hat{\beta}$)	t-value	p-value
Constant	1952.653	229.154	8.521	0.000
Pedestrian crossing	-15.455	3.112	-4.967	0.000
Slope	-22.475	8.272	-2.717	0.019
Number of lane	-74.515	54.067	-1.378	0.193
% of large bus	-10.302	8.109	-1.270	0.228
Green time	-0.980	6.441	-0.152	0.882

R^2 = 75%, F= 7.086 (p-value=0.003)

In order to fit an appropriate model, it is necessary to check whether the stated assumptions are fulfilled so that the model can be used for estimation or prediction. In other words, model adequacy checking has to be done before using it to the intended purpose of estimation or prediction. Checking model adequacy is equivalent to checking whether the variance is constant, the error terms are normal and independent, and also checking multicollinearity between the explanatory variables.

The normal probability plot (P-P) of residual can be used to examine whether the error terms are approximately normal. Fig 4.1 presents the normal probability plot of residuals for the case of data from synchronous method. We can observe from this figure that there is no clear departure from normality assumption for the plot approximates a straight line that passes through the origin. Therefore, we have the rationale to assume that the error terms are approximately normal.

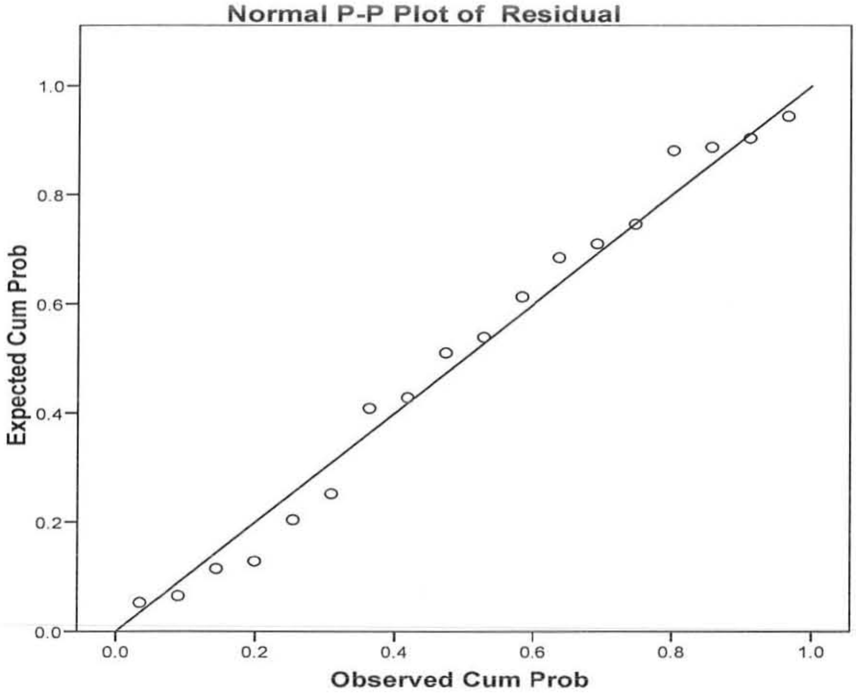

Figure 4.1 *Normal probability plot of residual*

To formally check whether the error terms from the synchronous method follow a normal distribution, the Liliefors test, a non-parametric test for normality, was applied. The rule for Liliefors test is rejecting the null hypothesis that the observations are from normal distribution if D_{max} = $|F(x) - S(x)|$ is greater than the tabulated value for Leliefors test with sample size n and α-level of significance; where F(x) is the cumulative distribution function: [(x-μ)/ σ)] and S(x) is the proportion of values of x that are less than or equal to the observed value. Applying this procedure it was found that D_{max} = 0.248 and is less than the critical value in Liliefors table with sample size =18 and α= 0.05 which is 0.31. Therefore, there is no evidence to conclude that the error terms do not follow a normal distribution.

In order to determine whether the variance is constant or not, figural representation of residuals can be employed. If there is a pattern on the graph, then we suspect hetroscedasticity. From figure 4.2 there is no increasing or decreasing pattern of residuals and hence there is no reason to suspect hetroscedsticity from the graph. We can also confirm this using formal statistical test.

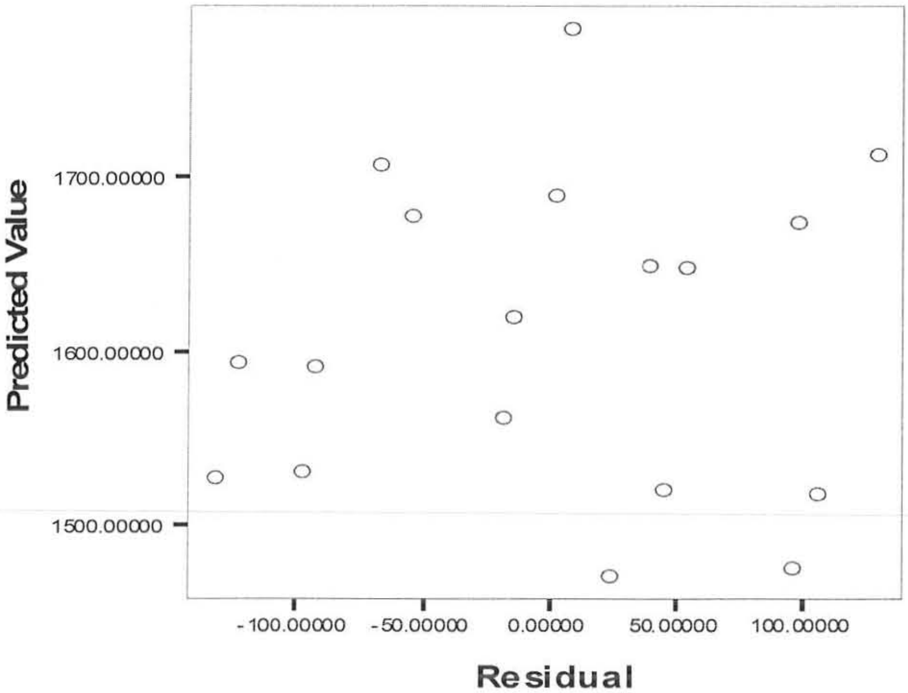

Figure 4.2 *Plot of residual against predicted value*

The Breusch pagan test was employed to test the existence of hetroscedasticity. For this the null hypothesis is the variance is homoscedastic where as the alternative hypothesis is the variance is hetroscedastic. This Breusch pagan test involves application of ordinary least square methods to:

$$\frac{\hat{\varepsilon}_i^2}{\hat{\sigma}^2} = \gamma_0 + \gamma_1 (\text{ped}) + \gamma_2(\text{slope}) + u$$

where $\hat{\sigma}^2 = \frac{1}{n-k} \sum_{i=1}^{k} \hat{\varepsilon}_i^2$. Once we have the regression sum of square from the ANOVA, the Breusch pagan test statistic is: $\chi^2_{cal(BP)} = \frac{RSS_B}{2}$, and we reject the null hypothesis if the calculated value is larger than the tabulated value of chi-square at α – level of significance and k degree of freedom, where k is the number of independent variables in the model.

For our case, the ANOVA (Table A5 of the annex) has resulted in a Regression Sum of Square (RSS) equal to 2.737. Upon dividing this RSS by 2 we found the calculated value of the χ^2 (chi-square) to be 1.369.

This calculated value of chi-square is less than the tabulated value of chi-square at 0.05 level of significance with 2 degrees of freedom ($1.369 < \chi^2_{0.05}(2) = 5.991$). Thus, there is no apparent reason to reject the null hypothesis and we conclude from both the Breusch Pagan test and the graph that the variance is constant.

2. Headway ratio Method

In the headway ratio method, only one explanatory variable, number of pedestrians crossing vehicle flows, was found to be significant to explain the dependent variable. The coefficient of the explanatory variables with their test of significance is given in table 4.9

Table 4.9 Variables in the final model from headway method

Variable	Coefficients ($\hat{\beta}$)	SE of coefficients SE($\hat{\beta}$)	t-value	p-value
Constant	1485.113	186.361	7.969	0.000
Pedestrian crossing	-11.068	4.393	-2.519	0.023
Number of lanes	49.229	33.147	1.485	0.157
Slope	-7.606	6.627	-1.148	0.268
Green time	-2.142	5.647	-0.379	0.709
% of large bus	-1.018	8.770	-0.116	0.909

R^2 = 49%, F= 3.015 (p-value = 0.042)

Lieliefors test has confirmed that the normality assumption of the error terms is valid with $D_{max} = 0.095 < D_{crt} = 0.28$. And the Breusch Pagan test has shown that the variance is constant ($\chi^2_{cal} = 0.189 < \chi^2_{0.05(1)} = 3.841$)

3. Asynchronous method

The regression result obtained from asynchronous method, after removing one case with too extreme value of residual and predicted value, indicated that the significant factor affecting saturation flow is the percentage of large buses that pass stop lines on each lane. If we relax the level of significance to 0.1, number of lanes in an approach also affects the saturation flow rate (Table 4.10). It should be pointed out that the exclusion of the data point with extreme predicted value and residual didn't change the significance of variables except very minor change on the coefficient of determination and the coefficient of the explanatory variables.

Table: 4.10 Variables in the final model from asynchronous method

Variable	Coefficients $\hat{\beta}$	SE of coefficients SE ($\hat{\beta}$)	t-value	p-value
Constant	398.451	452.061	0.881	0.392
% of large bus	-60.207	22.470	-2.679	0.017
Number of lane	166.529	93.188	1.787	0.094
Green time	19.571	12.325	1.588	0.133
Pedestrian crossing	-4.481	3.745	-1.196	0.250
Slope	-12.052	14.841	-0.812	0.429

R^2 = 55%, F= 3.683 (p-value = 0.023)

The Liliefors test for normality has suggested that there is no reason to reject the hypothesis that the error terms are normally distributed (D_{max}= 0.085<D_{crt} = 0.28) . Besides, the Breusch Pagan test has indicated that the error terms have constant variance ($\chi^2_{cal(BP)} = 0.099 < \chi^2_{0.05(1)} = 3.841$)

In order to select the best regression equation among the three models, the coefficient of determination for each of the cases was compared. For saturation flow that was estimated using the headway ratio method the coefficient of determination, R^2, was found to be 49%; for saturation flow estimated using asynchronous regression R^2 = 55%, and for synchronous, R^2 = 75%.

The significant explanatory variable in the headway method (that is pedestrian crossing) is contained in the model that is obtained using the data from the synchronous method. Moreover, the explanatory power of the model from the synchronous method is by far better than the model in the headway method. Hence, there is no need to prefer the model from headway method to the model from synchronous method. On the other hand, the significant explanatory variable (i.e percentage of large buses) in the model obtained from asynchronous method was not found to be significant in the model that is obtained from the synchronous method. But the explanatory power of the model from asynchronous method as measured by R^2 is very low compared to model from the synchronous method. Therefore, the model from the synchronous method is superior and is preferred. But the model from asynchronous method gives an indication that percentage of large buses among all vehicles that passes stop lines in an approach has a significant negative effect on saturation flow.

CHAPTER FIVE

Discussion, Conclusion and Recommendation

As the main objectives of this research is to determine factors affecting saturation flow after estimating the Passenger Car Equivalent (PCE) values of different vehicle types at signalized intersections, six potential explanatory variables were investigated. The PCE values were computed for each lane of a given intersection and approach. Similarly, in the analysis the saturation flows for each of the lanes was estimated using three estimation methods namely, headway, synchronous and asynchronous. Further analysis was made to identify factors that affect saturation flow at signalized intersection.

In most of the lanes, the PCE results obtained are in line with expectation and previous studies elsewhere in the world. Those vehicles which are larger than the passenger cars have PCE values greater than one. But in some of the lanes PCE values obtained differ from our expectation (since our trivial expectation is that larger vehicles will have higher headways as compared to smaller ones and hence larger passenger car equivalent). But as discussed in the literature review, previous studies also indicate that smaller vehicles can have higher PCE values.

The PCE and saturation flow values obtained from each of the methods were also found to be different. For instance, PCEs computed from the combined dataset for small buses were 1.011, 0.830 and 1.045 in the synchronous, asynchronous and headway methods, respectively.

Similarly, the saturation flow estimated from each of the methods was found to be different. For example, the saturation flow obtained on lane 2 of Mexico to Biherawi approach was 1500 pcpgpl for the synchronous method, 1656 pcpgpl for the headway method, and 1413 pcpgpl for the asynchronous method.

The variations of PCE and saturation flow from the three methods can be attributed to different factors. Some of the potential causes for the variation can be the methods of calculation themselves; different vehicle mixes from one data collection method to the other data collection method, sample size, etc

The saturation flow per green hour per lane from three of the methods was found to be less than the ideal saturation flow stated in the US highway capacity manual. In the US highway capacity manual, the ideal saturation flow is 1,900 passenger Cars per hour of green time per lane (pcpgpl) while the maximum saturation flows obtained using the three methods in this study were 1697 pcpgpl, 1762 pcpgpl and 1842 pcpgpl for headway ratio, asynchronous regression, and synchronous regression methods, respectively.

The other important issue in this study is identifying the factors that significantly affect saturation flow at signalized intersection. Though there might be other factors, six potential factors that may affect saturation flow were analyzed. These are lane width, approach grade (slope of an approach), green time length, number of lanes in an approach, number of pedestrian crossing vehicle flows, and percentage of large buses.

After excluding lane width which was significantly correlated with number of lanes, regression analysis applied for the three method of data collection (and hence three method of determining saturation of flow) revealed that number of pedestrians crossing vehicle flows and slope of an approach are significant factors affecting saturation flow when the dependent variable estimated using synchronous regression was used. Number of pedestrians crossing vehicle flows was also found to be a significant factor when the saturation flow was estimated using headway ratio method. The other variables (number of lanes, green time length, and percentage of large buses) were not found significant in the synchronous method. This result is in agreement with the lane-wise regression analysis that was conducted by Turner and Harahap (1993) in which the number of lanes and green time length were found to be insignificant. The reason for this could be that the number of lanes and green time length for a given approach are the same where as the saturation flow is different from lane to lane on the same approach.

In order to determine the most preferable model, the coefficient of determination was computed and the model that used the saturation flow obtained from synchronous regression as a dependent variable was found to have the highest coefficient of determination (R^2 = 0.75) . Besides, the factor that was found to be statistically significant in the headway method was also found as one of the two significant factors in the synchronous method. The saturation flow obtained from the asynchronous method may be unreliable since the parameter estimates from OLS regression are known to be biased. Therefore, the model whose saturation flows were estimated from the synchronous regression method, and whose significant explanatory variables include slope of an approach as well as number of pedestrians crossing vehicle flows, is preferred for prediction or estimation.

According to the result from all possible regression, approach grade significantly affects saturation flow at signalized intersection. An increase in approach grade decreases saturation flow per green hour (high negative slope of an approach decreases saturation flow). This result is consistent with the findings of the study conducted on saturation flow rates in South Africa by Bester and Meyers (2007).

The other important factor that affects saturation flow was number of pedestrians crossing vehicle flows while the traffic signal is at its green phase allowing vehicles which were stopped to clear from the stop line. An increase in pedestrians crossing decrease the number of passenger car equivalents that would pass during the green time.

Therefore, we can conclude that the findings of this study suggest that approach grade and number of pedestrians crossing vehicle flows during green signal phase at intersections significantly affect saturation flow. And both of these variables contribute negatively to saturation flow at intersections.

Finally, the findings of this study lead us to the following recommendations:

- Attention should be paid to approach grades, i.e, slope of an approach, while designing new road intersections and modifying existing ones.
- Sufficient awareness should be created for pedestrians so that they should not cross while a signal is at its green phase. This can help not only to increase the saturation flow of vehicles per green time but also reduces loss of life and property damage.
- Due attention should be given to introduce traffic light signals for pedestrians crossing vehicle flows.

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Annexes

Table A1 Number of cycles by lane and method of data collection

Intersection	Approach	Lane number	Headway method	Asynchronous /fixed time	Synchronous/fixed vehicle
Cathedral	Piazza to Tewodros	1	26	21	20
		2	34	22	21
Business and Construction Bank	Mexico to Biherawi	1	20	17	19
		2	20	20	20
		3	22	24	19
	Biherawi to Mexico	1	20	20	20
		2	20	19	19
		3	20	20	20
Dembel city center	Bole to Meskel square	2	20	20	20
		3	20	20	20
	Meskel square to Bole	1	20	21	20
		2	20	21	20
	Bambis to Megenagna	1		20	
Urael	Bambis to Megenagna	3	20		20
	Megenagna to Bambis	2	20	20	20
	Atlas to Urael	1			20
	Atlas to Urael	2		20	
	Atlas to Urael	3	20	20	
Atlas	Urael to Atlas	2		40	
	Urael to Atlas	3	20	13	
Harambe	Meskel to Ambassador	2		37	29
	Meskel to Ambassador	3	20	22	
	Ambassador to Meskel	1	28	28	22
	Ambassador to Meskel	2	22	20	21
Saint Marry	Sidist kilo to Arat kilo	1	33	21	20
	Sidist kilo to Arat kilo	2		18	
	Arat kilo to Sidist kilo	1	20	21	21
	Arat kilo to Sidist kilo	2	20		

Table A2 Percentage Distribution of vehicles by lane during saturation flow-Headway Method

Intersection	Approach	Lane No	No. of cycles	Total vehicle	MC	PC	SB	MB	LB	LG	MG	HG3	HG4
Cathedral	Piassa to Tewodros	1	26	171	0.585	76.608	19.298	0.00	0.585	1.70	1.750	0.000	0.000
	Piassa to Tewodros	2	34	266	0.442	73.451	22.566	1.327	0.885	0.442	0.885	0.000	0.000
Construction and Business Bank	Mexico to Biherawi	1	20	152	0.000	38.816	53.289	0.658	6.579	0	0.658	0.000	0.000
	Mexico to Biherawi	2	20	209	0.000	80.383	13.397	1.435	2.870	0	1.914	0.000	0.000
	Mexico to Biherawi	3	22	245	0.408	82.449	10.204	1.224	0.816	0.816	4.082	0.000	0.000
	Biherawi to Mexico	1	20	160	0.625	38.125	48.750	5.000	6.250	0.625	0.000	0.6250	0.000
	Biherawi to Mexico	2	20	170	0.000	74.118	21.765	0.588	2.353	1.176	0.000	0.000	0.000
	Biherawi to Mexico	3	20	154	0.649	85.065	9.091	0.649	1.299	2.597	0.000	0.649	0.000
Dembel city center	Bole to Abiot	2	20	254	0.394	52.362	42.520	0.787	2.362	1.181	0.000	0.394	0.000
	Bole to Abiot	3	20	283	0.000	90.813	8.481	0.353	0.353	0.000	0.000	0.000	0.000
	Abiot to Bole	1	20	232	0.000	44.397	53.017	0.431	1.724	0.431	0.000	0.000	0.000
	Abiot to Bole	2	20	244	0.000	78.689	19.672	0.410	0.410	0.000	0.820	0.000	0.000
Urael	Bambis to Megenagna	3	20	274	0.000	80.292	11.679	1.460	5.109	1.460	0.000	0.000	0.000
	Megenagna to Bambis	2	20	310	0.000	41.290	52.903	0.323	4.516	0.323	0.645	0.000	0.000
Atlas hotel	Atlas to Urael	3	20	217	0.000	97.235	2.304	0.000	0.000	0.000	0.461	0.000	0.000
	Urael to Atlas	3	20	225	0.000	92.889	3.556	1.333	0.444	0.000	1.778	0.000	0.000
Harambe hotel	Meskel to Ambassador	3	20	193	0.518	86.528	11.399	1.554	0.000	0.000	0.000	0.000	0.000
	Ambassador to Meskel	1	28	239	0.418	87.029	10.460	0.000	0.000	0.418	1.674	0.000	0.000
	Ambassador to Meskel	2	22	214	0.000	71.495	23.832	0.467	2.804	0.000	1.402	0.000	0.000
Kidst Mariam	Sidist kilo to Aratkilo	1	33	344	0.872	55.233	37.500	1.163	4.360	0.291	0.581	0.000	0.000
	Arat Kilo to Amst Kilo	1	20	181	0.552	39.227	48.066	1.105	9.392	0.000	1.657	0.000	0.000
		2	20	201	0.498	79.602	18.408	0.498	0.498	0.000	0.498	0.000	0.000
Total			**485**	**4938**	**0.3**	**69.8**	**24.5**	**0.9**	**2.4**	**0.5**	**0.9**	**0.1**	**0.0**

Table A3 Percentage Distribution of vehicles by lane and approach during saturation flow-Asynchronous method

Intersection	Approach	Lane No	No. of cycles	Total vehicle	MC	PC	SB	MB	LB	LG	MG	HG3	HG4
Cathedral	Piassa to Tewodros	1	21	195	1.026	82.564	13.846	1.026	0.000	0.000	1.538	0.000	0.000
	Piassa to Tewodros	2	22	199	0	77.387	19.095	0.502	1.508	0.502	1.005	0.000	0.000
Construction and Business Bank	Mexico to Biherawi	1	17	126	0	30.952	65.079	0.794	3.175	0.000	0.000	0.000	0.000
	Mexico to Biherawi	2	20	214	0.467	56.075	30.841	6.075	4.673	0.934	0.934	0.000	0.000
	Mexico to Biherawi	3	24	226	0	75.664	20.796	0.442	0.885	2.212	0.000	0.000	0.000
	Biherawi to Mexico	1	20	126	1.587	38.889	45.238	5.556	8.730	0.000	0.000	0.000	0.000
	Biherawi to Mexico	2	19	112	0.893	64.286	26.786	2.678	4.464	0.893	0.000	0.000	0.000
	Biherawi to Mexico	3	20	138	0.000	84.783	10.870	0.725	0.000	2.898	0.000	0.725	0.000
Dembel city center	Bole to Abiot	2	20	258	0.388	57.364	39.922	0.388	1.550	0.388	0.000	0.000	0.000
	Bole to Abiot	3	20	292	0.342	90.412	7.534	1.370	0.342	0.00	0.00	0.000	0.000
	Abiot to Bole	1	21	244	2.049	49.590	44.672	0.410	1.230	1.230	0.820	0.000	0.000
	Abiot to Bole	2	21	262	0.382	75.572	22.519	0.763	0.000	0.000	0.763	0.000	0.000
Urael	Bambis to Megenagna	3	20	210	0.952	74.762	16.667	0.476	3.333	3.810	0.000	0.000	0.000
	Megenagna to Bambis	2	20	331	0.000	53.172	41.390	1.813	2.115	0.000	1.510	0.000	0.000
Atlass hotel	Atlas to Urael	1	20	228	0.438	87.719	7.895	1.754	1.316	0.877	0.000	0.438	0.000
	Atlas to Urael	2	20	258	0.000	90.698	7.752	1.163	0.000	0.388	0.000	0.000	0.000
	Urael to Atlas	2	40	634	0.158	91.956	4.574	0.473	0.789	1.262	0.789	0.000	0.000
	Urael to Atlas	3	13	186	0.000	96.774	3.226	0.000	0.000	0.000	0.000	0.000	0.000
Harambe hotel	Meskel to Ambassador	2	37	245	0.408	73.061	20.816	0.408	0.408	2.857	0.000	1.633	0.408
	Meskel to Ambassador	3	22	139	0.719	94.964	3.597	0.000	0.000	0.719	0.000	0.000	0.000
	Ambassador to Meskel	1	28	210	0.952	69.524	26.190	0.000	0.000	1.428	1.905	0.000	0.000
	Ambassador to Meskel	2	20	161	0.000	58.385	40.373	0.000	0.621	0.000	0.621	0.000	0.000
Kidst Mariam	Sidist kilo to	1	21	207	0.000	65.217	24.154	1.449	7.246	0.483	1.449	0.000	0.000
	Aratkilo	2	18	200	0.000	25.000	70.500	0.500	3.500	0.500	0.000	0.000	0.000
	Arat Kilo to Amst Kilo	1	21	185	0.540	44.865	49.189	2.162	0.000	0.000	0.000	0.000	0.000
Total			**545**	**5586**	**0.4**	**70.7**	**24.6**	**1.1**	**1.7**	**0.9**	**0.1**	**<0.1**	**<0.1**

TableA4 Percentage Distribution of vehicles by lane and approach during saturation flow-synchronous method

Intersection	Approach	Lane No	No. of cycles	Total vehicle	MC	PC	SB	MB	LB	LG	MG	HG3	HG4
Cathedral	Piassa to Tewodros	1	20	141	0.709	87.234	11.348	0.000	0.000	0.709	0.000	0.000	0.000
	Piassa to Tewodros	2	21	144	0.000	81.944	17.361	0.000	0.000	0.694	0.000	0.000	0.000
Business and Construction	Mexico to Biherawi	1	19	144	1.389	40.972	53.72	1.389	2.778	0	0	0	0
	Mexico to Biherawi	2	20	168	0	38.690	45.238	2.381	11.905	1.786	0	0	0
	Mexico to Biherawi	3	19	168	0	73.810	20.833	1.190	2.381	0.595	1.190	0	0
	Biherawi to Mexico	1	20	108	3.704	49.074	31.481	4.630	10.185	0.926	0	0	0
	Biherawi to Mexico	2	19	141	0.000	62.411	31.915	2.837	0.709	2.218	0	0	0
	Biherawi to Mexico	3	20	165	0.000	86.061	12.121	0.606	0.606	0.606	0.000	0.000	0.000
Dembel city center	Bole To Abiot	2	20	165	0.000	55.756	38.182	1.212	1.212	3.030	0.000	0.606	0.000
	Bole To Abiot	3	20	219	0.000	90.868	6.849	1.370	0.457	0.000	0.457	0.000	0.000
	Abiot to Bole	1	20	203	0.000	37.438	60.098	2.463	0.493	0.000	0.493	0.000	0.000
	Abiot to Bole	2	20	204	0.000	36.274	61.765	0.490	1.470	0.490	0.490	0.000	0.000
Urael	Bambis to Megenagna	3	20	138 Bank	2.898	42.754	50.000	2.174	0.725	0.725	0.000	0.000	0.000
	Megenagna to Bambis	2	20	208	1.923	47.115	45.673	0.962	3.846	0.000	0.481	0.000	0.000
Atlas hotel	Atlas to Urael	1	20	207	0.483	85.507	10.145	0.483	1.449	0.000	0.000	0.000	0.000
Harambe hotel	Meskel to Ambassador	2	29	202	0.495	74.752	21.287	0.000	2.475	0.990	0.000	0.000	0.000
	Ambassador to Meskel	1	22	162	2.469	77.778	17.901	0.000	0.000	0.000	1.852	0.000	0.000
	Ambassador to Meskel	2	21	164	0.610	50.610	48.171	0.000	0.610	0.000	0.000	0.000	0.000
Kidst Mariam	Sidst Kilo to Arat Kilo	1	20	191	0.000	71.204	17.801	2.094	6.806	0.524	1.571	0.000	0.000
	Arat Kilo to Amst kilo	1	21	150	0.000	51.333	42.667	2.667	3.333	0.000	0.000	0.000	0.000
Total			**411**	**3392**	**0.6**	**62.9**	**31.8**	**1.3**	**2.6**	**0.6**	**0.5**	**<0.1**	**0.00**

Table A5 Analysis of Variance for the Breusch Pagan test statistics from the synchronous method

Model		Sum of Squares	df	Mean Square	F	Sig.
1	Regression	2.737	2	1.368	2.482	.117(a)
	Residual	8.270	15	.551		
	Total	11.007	17			

a Predictors: (Constant), slope, Pedestrian

b dependent variable $\frac{\hat{\varepsilon}_i^2}{\hat{\sigma}^2}$

Declaration

I, the undersigned, declare that the thesis is my original work, has not been presented for a degree in any other university and that all sources of material used for the thesis have been duly acknowledged.

Declared by

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