ADDIS ABABA UNIVERSITY

ADDIS ABABA INSTITUTE OF TECHNOLOGY

SCHOOL OF CIVIL AND ENVIRONMENTAL ENGINEERING

SPEED-FLOW-DENSITY RELATIONSHIPS FOR TRAFFIC ON TWO-LANE TWO-WAY RURAL HIGHWAYS (THE CASE OF ETHIOPIA)

A Thesis in Road and Transport Engineering Stream

By Anuwar Mohammed

A Thesis submitted to the School of Graduate Studies of Addis Ababa University in Partial Fulfillment of the Requirement for the Degree of Master of Science in Civil and Environmental Engineering

(Road and Transport Engineering Stream)

Advisor: Dr. Bikila Teklu
Co-Advisor: Tamiru Tilahun

July, 2023

Addis Ababa, Ethiopia

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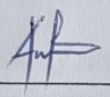
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DECLARATION

I, the undersigned, declare that this research work titled ***"Speed-Flow-Density Relationships for Traffic on Two Lane Two Way Rural Highways (The Case of Ethiopia)"*** is my original work performed under the supervision of my research advisor Dr. Bikila Teklu and has not been presented elsewhere for assessment and for a degree in any other university. All sources of materials used for this thesis have also been duly acknowledged.

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Date: 21/07/2023

Place: Addis Ababa, Ethiopia

ABSTRACT

Understanding the relationship between speed, flow, and density is essential for policymakers, designers, traffic engineers, and other professionals in determining operational capacities, reducing traffic congestion, improving traffic safety, developing effective traffic management strategies, designing highways, and improving overall traffic stream performance.

The Highway Capacity Manual, which were developed based on traffic and geometric conditions of the United States of America, were used in Ethiopia to study the Speed-Flow-Density relationship for Two-lane Two-Way Highways, which was necessary for capacity analysis and assessment of the overall operational performance. Moreover, no established travel time-flow and travel time-density relationships were studied, which is needed for transportation planning and traffic demand management purposes. To that end, it is crucial to examine those relationships by calibrating data obtained from those highways in order to obtain a capacity value that better reflects the actual traffic conditions and make conclusions regarding travel time relationships.

On three selected two-lane, two-way rural highways, traffic data was collected from both sides of the flow during the peak hour in the morning using video recording. Using an electric pole nearby the road stretch as a reference, travel time data and vehicle classes were recorded. Data processing was done using Adobe Premiere CS6. The average speed was calculated by dividing the measured distance between the reference points to the vehicle travel times averaged for every 1-minute and 15-minute time intervals. The average flow was computed by counting the vehicles passing, converting heavy trucks into equivalent passenger car equivalents, and using the steady state equation density was determined easily.

This study employed a regression approach for assessing different classical speed-density models, including Greenshields, Greenberg, Underwood, Drake, May and Schofer (North Western University Model), Drew, Multi-Regime Matrix, and Composite Models. At both 1-minute and 15-minute time intervals, the analysis revealed that the multi-regime matrix model better explained the data than the other models. With this model, the steady state equation was used to establish the corresponding speed-flow and flow-density relationships.

Finally, based on the developed speed-flow relationship, the capacity for both time interval analyses were less than the Highway Capacity Manual's recommended maximum capacity value, and the value of capacity obtained using the 15-minute time interval was less than the corresponding 1-minute time interval analysis. Furthermore, the travel time relationships matched the curves obtained with previous studies for similar highway types.

Keywords: Speed-Flow-Density Relationships; Capacity; Two-Lane Two-Way Highways; Travel time relationships

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LIST OF ABREVIATIONS AND ACRONYMS

ATS- Average Travel Speed

ERA- Ethiopian Roads Administration

FY- Fiscal Year

GoE- Government of Ethiopia

HCM- Highway Capacity Manual

ITA- International Trade Association

KM- Kilo Meter

LOS- Level of Service

Min- Minute

Pcphpl- Passenger car per hour per lane

PCU- Passenger Car Unit

PHF- Peak Hour Factor

ReCAP- Research for Community Access Partnership

RSDP- Road Sector Development Program

TRB- Transportation Research Board

USA- United States of America

WFP- World Food Program

CHAPTER ONE: INTRODUCTION

1.1. General

Traffic flow is a complex phenomenon that entails interactions between the road, the vehicle, and the driver and is constantly changing in both space and time. Traffic variables are used to characterize such time and space variations in traffic flow (Luttinen, 2001). The fundamental flow variables that traffic engineers measure are flow, speed, and density and are employed to characterize these variations in a traffic stream (Teodorovic & Janic, 2016).

Different approaches are utilized to understand the interaction between the road, the vehicle, and the driver in a traffic stream. The macroscopic approach that examines the flow in an aggregate manner and best represents the system's overall operating efficiency, the microscopic approach that takes into account each vehicle's response in a disaggregated way, and the human factor, which is closely associated with the microscopic approach, aims to describe the mechanism by which the driver (and his or her vehicle) locates itself in relation to other vehicles and the road network are among the major approaches (Khisty & Lall, 2016).

Flow, density, and speed are the three fundamental components of a traffic stream, and traffic flow theory involves the formulation of mathematical relationships between them. The traffic engineer can plan, design, and evaluate the effectiveness of putting traffic engineering strategies into effect on a highway system with the use of these relationships(Garber & Hoel, 2019).

Using the demand-supply analysis technique, which can only be accomplished after understanding the flow characteristics, planners evaluate the traffic and environmental effects of proposed changes to the transportation system. When deciding the number of lanes for a specific road section in the system, a designer, for example, must consider carefully the trade-off between levels of service and traffic flow (Hoogendoorn, 2010). In addition to forecasting the outcome, operators may need to pinpoint the exact locations and root causes of problems with the existing infrastructure and develop operational improvement plans (May, 1990).

In order to assess whether the available number of lanes would be sufficient to accommodate the traffic volume taking into consideration the volume of the vehicles, their composition, and other traffic-related parameters, capacity analysis is useful in determining the vehicular traffic carrying capacity of the roads and it helps in the planning of new roadways and performance analysis of the existing highway facilities (Tadesse & Sisay,2019).

In recent years, the GOE has steadily expanded the size of its highway system. Ethiopia had 144,024 kilometers (89,492 miles) of all-weather roads as of the end of FY 2019–20, covering about 41% of the necessary road network in the nation. The GOE spent $1.1 billion in FY 2018/19 on road building or 37.3 billion birrs. Through Ethiopia's Road Sector Development Programs, the GOE has been actively engaged in new road construction as well as the expansion of the existing road network for the last fifteen years (RSDP) (ITA, 2022).

The majority of states' and counties' transportation networks have two-lane highways as a critical component (TRB, 2016). The study conducted by (Demissie et al., 2020) showed that in 2019, around 15,886 Km length of the road are paved roads excluding highways in municipalities among this around 15,586 km length of road will be two-lane, two-way paved roads when the Addis-Adama expressway road are excluded from the data which accounts around 98% of paved roads in 2019.

Because of the unique relationship between traffic conditions in the two directions of travel, two-lane, two-way highway traffic operations are different from other facilities. On two-lane, two-way roads in particular, lane changing and passing movements are prohibited and are often carried out in the opposing lane of travel when visibility and, more significantly, gaps in the opposing traffic stream permit (Durbin, 2006).

Starting from the pioneering work of (Greenshields, 1935), various types of research have been conducted overseas to illustrate the relationships between traffic density, flow, and speed for both Interrupted and Uninterrupted flow facilities. Despite the fact that a huge amount of road network in Ethiopia is a two-lane, two-way highway type, research conducted in previous years focused on other highway facilities. To this end, evaluating those relationships on a two-lane, two-way highway of Ethiopia is very critical as they are the major inputs to important decisions during the planning stage, design stage, and operation of those facilities.

1.2. Statement of Problem

Two-lane, two-way highways make up the most of the Ethiopian Road network corridors. For the travel demand modeling used during the planning process and design stage, which is used in predicting the roadway capacity, determining the adequate level-of-service of traffic flow, and determining travel time for a specific roadway, an understanding of the relationships of the traffic flow parameters (speed, flow, and density) is extremely important. Therefore, a failure not to consider these relationships might lead to wrong decisions being made during the facility's planning, design, and operating phases.

The Highway Capacity Manual (TRB, 2016) of the USA is employed in numerous countries, including Ethiopia, for traffic operational analysis and LOS analysis of different highway facilities. The concepts, procedures, and methodologies utilized in this manual were derived from various empirical studies conducted in the USA beginning in 1950, which marks the beginning of the first HCM preparations.

However, the concepts, procedures, and methodologies developed in HCM are for traffic conditions of developed nations irrespective of the developing nations like Ethiopia, where traffic conditions in developed nations are homogenous in nature, presence of lane discipline emanates from the homogeneity of vehicle's size and maneuvering ability of vehicles, presence of skilled drivers compared to drivers in developing countries, a smaller number of accesses, absence or less number of pedestrians walking in the roadway and crossing the road. Due to those variations and the absence of inclusion of traffic conditions of developing countries like Ethiopia in HCM methodologies, there should be an investigation of these relationships that can consider the actual conditions of those two-lane, two-way highways and justification should be made by comparing the actual conditions with the relationships derived by the Highway Capacity Manual (TRB, 2016).

This study aims to identify an existing model that can sufficiently explain those relationships on two-lane, two-way rural highways of selected road segments in Ethiopia.

1.3. Research Questions

- Which of the existing well-known models are suitable to describe the actual traffic conditions for the selected rural two-lane two-way highways?
- What does travel time-density relationships looks like on those selected rural two-lane two-way highways?
- What does travel time-flow relationships looks like on those selected rural two-lane two-way highways?
- How to determine the capacity of those selected rural two-lane two-way highways?

1.4. Research Objectives

1.4.1 General Objective

The main objective of the study is to examine the speed-flow-density relationships for traffic on two-lane, two-way rural highways (the case of Ethiopia).

1.4.2 Specific Objective

Specifically, for road sections (i.e., Sendafa-Debrebirhan, Sebeta-Tullu Bolo, and Sululta-Chancho road corridors) located in Ethiopia, the research tries to address the following objectives:

- To evaluate which of the existing well-known models are suitable to describe the congested and uncongested part of the collected data for the selected rural two-lane two-way highways,
- To develop travel time-density relationships on selected rural two-lane two-way highways,
- To develop travel time-flow relationships on selected rural two-lane two-way highways, and
- Determine the capacity of the study sites.

1.5. Scope and Limitations of the Study

The study was carried out at selected rural highway corridors (Sendafa-Debrebirhan, Sebeta-Tullu Bolo, and Sululta- Chancho Road Corridors) in Ethiopia. An investigation of the speed-flow-density relationships in other rural road networks in Ethiopia is necessary in order to derive general conclusions which are applicable to all two-lane two-way federal rural highways throughout the country. The limitations and further research to be done emanating from this research will be indicated in the Conclusion and Recommendation chapter.

1.6. Significance of the Study

This research attempts to contribute to the efforts of Transport Planners, Traffic Engineers, Highway Design Engineers, and academic endeavors in different ways.

First, as it has not been thoroughly studied in previous years, the development of the speed-flow-density relationship for Ethiopia's rural, two-lane, two-way rural highways will serve as a foundation for future research in a wider context.

Second, since the development of the speed-flow-density relationship assists transport planners in gaining knowledge about transport demand modeling, which can be applied during the planning stage of road investments, this research will serve as a basis for other, more comprehensive studies that take into account all rural, two-lane, two-way highways in Ethiopia which finally can be useful in classifying highways, identify traffic trends, study origin-destination patterns, and forecast revenue. Speed-flow-density relationships can be used to forecast road capacity, assess the degree of service provided by traffic flow, and calculate travel times on a particular road (Twagirimana, 2013).

Thirdly, by considering an appropriate design criterion to design an adequate number of lanes and lane width, horizontal and vertical alignment, curve widening, lateral clearance, speed, and sight distance, the development of the speed-flow-density relationship for rural two-lane two-way highways will serve as a foundation for further research on the speed-flow-density relationship in a broader context for the case of Ethiopia. The travel time study will also assist designers in emphasizing how grade, the type of road surface, alignment, roadway width, and

sight distance all influence travel time. To make sure that roads are planned to meet the anticipated traffic volume and flow, engineers must consider elements including design speed, access control, and traffic composition ((Naser, 2021) & (Twagirimana, 2013)).

Last but not least, this study will serve as a foundation for additional, more comprehensive research on the development of the speed-flow-density relationship for rural, two-lane, two-way highways in Ethiopia so that traffic engineers can examine traffic operations, evaluate the effectiveness of putting traffic engineering measures into practice on a highway system, assess traffic accidents, determine what kinds of improvements are required, and predict the impact of changes in traffic flow on factors like crashes, travel time, air pollution, and gasoline consumption. By calculating the maximum flow, defining functional relationships, developing time-space diagrams, forecasting highway capacity, enhancing traffic signal timing, and modelling traffic flow, traffic engineers may employ speed-flow-density relationships to improve traffic flow((Naser, 2021) & (Twagirimana, 2013)).

1.7. Thesis Organization

There are five chapters in this thesis. Chapter-1 is an introduction of the thesis, which comprised of the general background, statement of the problem, thesis objectives, scope and limitations of the study and the thesis organization. Chapter-2 is the literature review part which discusses the theoretical background of topics related to the thesis. Chapter-3 indicates the different materials used and methodologies adopted in the research. Chapter-4 presents the collected data from the study areas. Chapter-5 presents the analysis of collected traffic data from the site using the existing traffic models. Chapter-6 put forward the conclusions and recommendations.

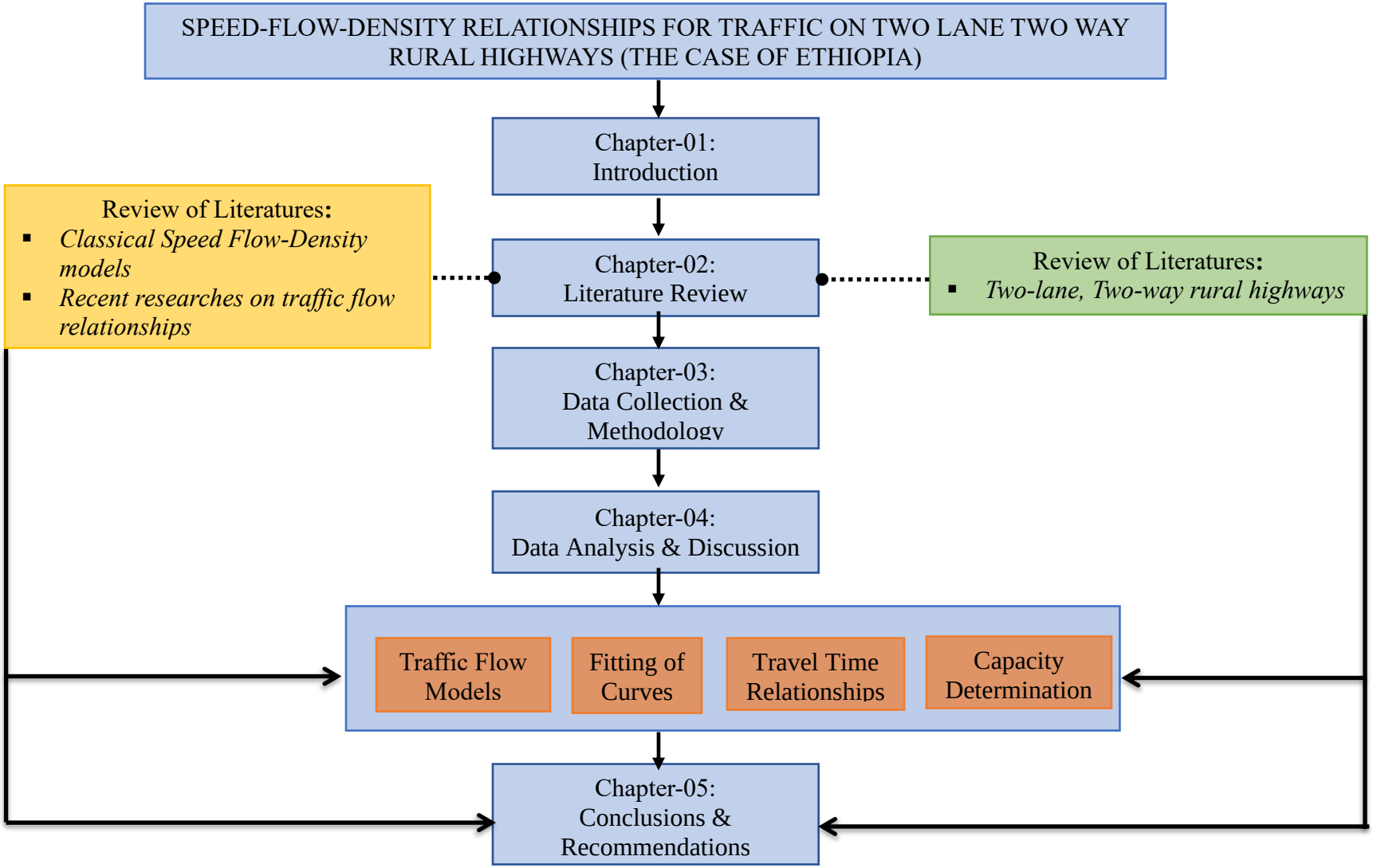


Figure 1. 1 Thesis Organization

CHAPTER TWO: LITERATURE REVIEW

2.1. Chapter Introduction

As the research is mainly focused on examining speed-flow-density relationships for traffic on Ethiopian two-lane, two-way rural highways, the structure of the research is shown as below:

i. Traffic flow study (Section 2.2)
ii. Interrupted and uninterrupted flow states (Section 2.3)
iii. Parameters related to traffic theory (Section 2.4)
iv. Fundamental relationships between traffic flow parameters (Section 2.5)
v. Review of classical speed-flow-density models (Section 2.6)
vi. Review of recent researches on traffic flow relationships (Section 2.7)
vii. Theoretical review on two-lane two-way rural highways (Section 2.8)
viii. Summary and gaps in literature review (Section 2.9)

2.2. Traffic Flow Study

2.2.1. Historical Background

Bruce D. Greenshields' pioneering work at the Yale Bureau of Highway Traffic in the 1930s on the analysis of models relating to volume and speed and the investigation of the performance of traffic at intersections marked the commencement of the scientific study of traffic flow. Probability theory was implemented for the characterization of traffic during that time. There was a huge growth in the study of traffic characteristics and the formulation of traffic-flow theories following World War II, which coincided with the enormous rise in the usage of automobiles and the advancement of the road network (Dhingra & Gull, 2011).

A variety of theories were developed in the 1950s, including queuing theory, traffic wave theory (hydrodynamic analogy), and car-following theory.(Gartner et al., 2002) These days, traffic flow theory studies and applications are ongoing, and the scientific field has greatly expanded to incorporate a wide variety of topics (Maerivoet & De Moor, 2005).

2.2.2. Types of Traffic Flow Studies

The application of quantitative analysis and modeling differentiates the field of traffic engineering. Two aspects, notably the microscopic and macroscopic approaches, can be utilized to examine traffic flow. The microscopic approach takes traffic as a mix of distinct or distinct vehicles. It is possible to pinpoint three fundamental characteristics of the microscopic approach: microscopic speed, time headways, and distance headways. Traffic is represented as a stream or fluid continuum in the macroscopic approach (hydrodynamic analogy). There are three fundamental characteristics that may be distinguished: macroscopic speed, flow, and density (Van As & Joubert, 1989).

According to (Garber & Hoel, 2019), the primary objective of traffic flow theory is to establish quantitative relationships between the three main components of a traffic stream: flow, density, and speed so that the traffic engineer can easily plan, design, and assess the effectiveness of implementing traffic engineering solutions into practice on a highway system with the help of these relationships. Supply-demand modeling, capacity and level of service analysis, traffic stream modeling, shockwave analysis, queuing analysis, and simulation modeling are some of the traffic flow analytical methodologies (May, 1990).

2.3. Interrupted Vs. Uninterrupted Traffic Flow States

2.3.1. Uninterrupted Traffic Flow States

A facility with an uninterrupted flow is one where there are no predictable delays or disruptions in vehicular movement. Facilities included under uninterrupted traffic flow states are multilane highways, two-lane highways, basic freeway sections, freeway weaving sections, and freeway merge and diverge sections (Kuhn, 2019).

2.3.2. Interrupted Traffic Flow States

Facilities with interrupted flows experience recurring delays or interruptions brought on by a permanent element in the highway facility. Urban streets and urban street sections, signalized junctions, all-way stop-controlled intersections, roundabouts, interchange ramp terminals, and

off-street bicycle and pedestrian facilities are examples of facilities with interrupted flow (Kuhn, 2019).

2.4. Parameters related to Traffic flow theory

Traffic flow theories seek to describe the relationships between the facilities (the fixed element) and the vehicles and their drivers in a rigorous mathematical manner while making these relationships easier to understand (Gartner et al., 2002).

(TRB, 2016) asserts that there are three fundamental traffic flow parameters: volume, speed, and density that may be used to describe various traffic flow scenarios on various types of roads. In characterizing the traffic flow characteristics of two-lane highways, understanding and establishing the relationships between the traffic flow parameters is a particularly important steady-state flow fundamental relationship, as indicated in the equation below, which relates the three traffic flow parameters:

$$Q = U_S * K \qquad (2.1)$$

Where: Q= rate of flow, Veh/h

U_s= Space mean speed (Macroscopic speed), Km/h

K= Density, Veh/Km

There are definitions provided for a number of terminologies used in traffic flow analysis. Definitions of the terminology are provided below, divided into two sections based on their use in macroscopic and microscopic approaches.

2.4.1 Macroscopic Analysis Terms

Macroscopic analysis of flow characteristics consists of flow, density, and speed. They are terms used to describe the traffic flow analysis when traffic is studied at a macroscopic level. As per the Highway Capacity Manual (TRB, 2016):

a) Volume and Flow rate

- Volume: is the total number of vehicles that pass over a given point or section of a lane or a roadway during a given time interval and can be expressed in terms of annual, daily, hourly, or sub-hourly periods.
- Flow rate: is the equivalent hourly rate at which vehicles pass over a given point or section of a lane or roadway during a time interval of less than 1-hr, usually 15-min. and can be expressed as, veh/hr.
- Peak hour factor (PHF): is the hourly volume during the maximum-volume hour of the day divided by the peak 15-minute flow rate within the peak hour:

$$\text{PHF}=\frac{\text{Hour volume}}{\text{Peak flow rate (within the hour)}}$$

If 15 min. periods are used, the PHF may be computed as follows:

$$\text{PHF}=\frac{\text{V}}{4*V_{15}} \qquad (2.2)$$

Where:

PHF= Peak hour factor
V = Hourly volume (veh/hr)
V_{15} = Volume during the peak 15 min of the peak hour

- Capacity: is the maximum hourly rate at which persons or vehicles reasonably can be expected to traverse a point or a uniform section of a lane or roadway during a given time period under prevailing roadway, traffic, and control conditions.

b) Speed:

- Speed**:** the rate of motion of a vehicle or a group of vehicles along a given road segment which can be expressed in distance per unit of time. Generally expressed as kilometers per hour (Km/hr).

Each vehicle travels at a varying speed on a certain stretch of road with regard to time and a specific segment of the road or space. (Mathew & Rao, 2007) defined and discussed various categories of speeds to describe this variation, as shown below:

- Running speed: is the average speed maintained over a particular course while the vehicle is moving and is found by dividing the length of the course by the time duration the vehicle was in motion.
- Journey speed: is the effective speed of the vehicle on a journey between two points and is the distance between the two points divided by the total time taken for the vehicle to complete the journey including any stopped time.
- Space mean speed: Space mean speed is defined as the average speed of all the vehicles occupying a given section of a highway over some specified time period and it is the harmonic average of spot speeds. Macroscopic speed and space mean speed are terms that are interchangeable for analyzing traffic flow occurrences. The equation for space mean speed looks as follows:

$$U_s = \frac{1}{\frac{1}{n}\sum_i^n \frac{1}{U_i}} \qquad (2.3)$$

c) Density:

Density is the number of vehicles that may be stated in terms of vehicles per mile or vehicles per kilometer that are present on a specific stretch of road or lane. The case of low densities signifies that vehicles are quite far apart whereas high densities indicate that individual vehicles are quite near to one another (Kutz, 2004).

(Van As & Joubert, 1989) has given the definitions of the following density parameters which have paramount importance in defining relationships for a given traffic stream characteristics.

- Optimum density: the density at which the flow is maximum. When densities are higher or lower, flow is lessened.
- Jam density: the maximum density that can be found on any street, which is the density of stopped vehicles.

2.4.2 Microscopic Analysis Terms

The three main components of the microscopic analysis of flow characteristics are the microscopic speed, time headway, distance headway, and time mean speed.

- Microscopic Speed (Spot Speed): is a vehicle's instantaneous speed at a certain point that can be employed to design the geometry of the highway, the position and size of signs, the design of signals, determining the safe speed and speed zones, accident analysis, road maintenance, and congestion, among other thing (Mathew & Rao, 2007).

- Headway and Spacing: Headway is the time interval, determined from the same position on each vehicle, between two vehicles as they pass a point on a lane or on a roadway and the spacing between vehicles in a traffic stream is the distance that is measured from the same location on each vehicle (e.g., front bumper, front axle) (TRB, 2016).

- Time mean speed: is the mean of the microscopic/spot speeds and is represented as:

$$U_t = \frac{1}{n}\sum_i^n U_i \qquad (2.4)$$

Where:

U_t = Time mean speed (Km/hr)
U_i = Speed of the i^{th} vehicle (Km/hr)
n = Volume during the peak 15-min of the peak hour

With the exception of the unlikely situation where all vehicles are traveling at the same speed, both Time mean speed and Space mean speed will always differ from each other. Space mean speed is a measurement related to the length of a lane or highway, whereas time mean speed is a point measurement (Mathew & Rao, 2007).

The overall relationship between time mean speed and space mean speed has been shown by (Wardrop, 1952) using data gathered from Western Avenue, Greenford (Middlesex), in London, England as follows:

$$U_t = U_s + \frac{{\sigma_s}^2}{U_s} \qquad (2.5)$$

Where:

U_t = Time mean speed (Km/hr)
U_s = Space mean speed (Km/hr)
$\sigma_s{}^2$= The variance of Space mean speed

The variance of the Space mean speed (i.e., macroscopic speed) can be determined:

$$\Sigma_s{}^2 = \sum_{i=1}^{n} k_i \frac{(U_i - U_s)^2}{K} \qquad (2.6)$$

Where:

k_i = Density (concentration) at any instant i
K = Total density (Concentration)

2.5. Fundamental relationships between traffic flow parameters

The fundamental relationship of traffic flow parameters is the inter-relationship of speed, flow, and density which is fundamental/basic in the determination of capacity and level of service of any transportations system, such as freeway and two-lane two-way highways in which they are related by the equation named as the steady state equation formulated by (Wardrop, 1952). These relationships support the traffic engineer's efforts to plan, design, and assess the effectiveness of having put traffic engineering provisions into practice on a road network (Garber & Hoel, 2019).

Figure no. illustrates the fundamental relationships between uninterrupted flow facilities' flow, density, and speed.

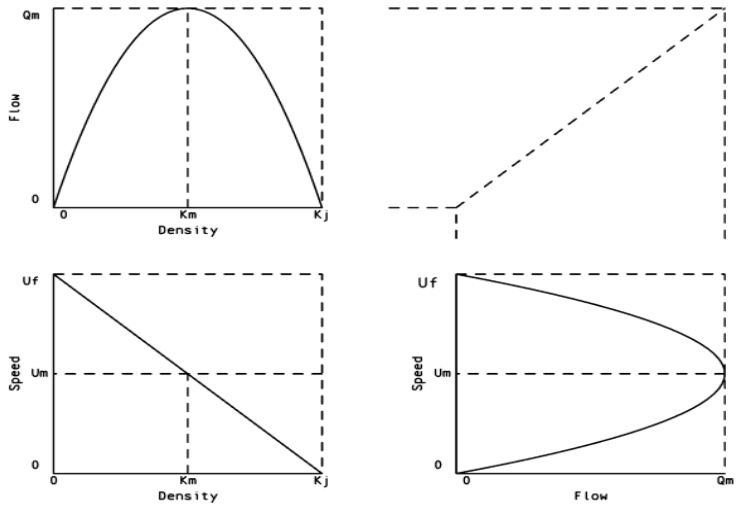


Figure 2. 1 Flow-concentration, speed-flow, and speed-concentration curves (assuming single-regime linear speed-concentration model) (Source: (Gerlough & Huber, 1975)).

The speed-density relationship is steadily decreasing. Speed reduces as density increases. The figure demonstrates that flow is zero in two distinct conditions (Kutz, 2004):

i. When density is zero, flow rate is also zero because there are no vehicles on the roadway.
ii. when the speed limit is zero Vehicles are at a dead stop due to traffic congestion.

To accurately understand the nature of the relationships between traffic flow parameters, it is crucial to study the several significant points on the fundamental diagram curves shown in Figure.

For the first scenario, the theoretical speed referred is the maximum speed U_f possible on a particular highway. The speed that vehicles travel on a highway without being hindered by the presence of other vehicles is known as the "free-flow speed" (Twagirimana, 2013).

In the second scenario, when traffic congestion causes all vehicles to come to a complete halt and the speed is zero, density becomes so high and the flow rate is zero since there is no movement and no possibility for vehicles to pass a particular location on the road. The jam density, represented by k_j in the diagram, is the density at which all movement comes to a complete stop (Chiguma, 2007).

The flow also rises gradually from zero to a maximum value as density rises starting at zero. When the flow reaches that point, any additional increases in density will cause it to decline until it eventually zeros out at the jam density. The capacity of a specific roadway corresponds to that maximum flow under the prevailing circumstances (Twagirimana, 2013).

In addition, the non-congested regime refers to the flow conditions associated with low density and fast speed, and congested regimes are those where the flow is low-speed and the density is higher. The slope of any line drawn from the origin of the speed-flow curve to any point on the curve indicates density, and in a similar manner, the slope of any line drawn from the origin of the flow-density curve indicates speed (Roux, 2001).

The speed, flow, and density relationship illustrated in Figure 2.1 considers a single linear relationship between speed and density. However, in actual it is difficult to get this single linear relationship. Different researchers have developed complex models to describe the actual speed, flow, and density relationships starting from single and three regimes linear to exponential and logarithmic functions (Roux, 2001).

The discussions of some of those complex models was made on the coming section.

2.6. Review of Classical Speed-Flow-Density Models

Starting from 1935's first single regime model of Greenshields (Greenshields, 1935) by which he put forward a linear relationship between speed and density, various researchers have proposed different models which aimed in providing the fundamental relationships of both macroscopic and microscopic traffic stream characteristics of two lane and freeways facilities.

Those models were developed for both Macroscopic and Microscopic traffic stream characteristics of uninterrupted flow facilities. Where, the Macroscopic models deal with a group of vehicles on a given road segment where the fundamental relationships of Speed, Density, and Flow of a traffic stream is derived and the equations of the relationships of those models are derived based on actual traffic data conducted on uninterrupted flow facilities. This was achieved by considering Single-Regime traffic flow conditions, multi-Regime traffic flow conditions or a combination/composite of models which can clearly shows the actual traffic condition of a given road section.

The Microscopic model which is the Car following theory deal with individual vehicle spacing and speed between each other and the interaction of vehicles by which how one vehicle follows the other vehicle on a given road section. Below, some of both traffic flow models (i.e., macroscopic and microscopic models will be discussed.

2.6.1. Macroscopic Traffic Flow Models

The first Macroscopic Single-Regime traffic flow model which was implemented to measure the fundamental traffic flow parameters (i.e., Flow, Density and Speed) in the history of traffic flow theory was developed by (Greenshields, 1935), by conducting an observation made using areal photographic method utilizing 16-mm simplex movie camera.

On the study conducted to investigate the traffic capacity of two-lane roadway, (Greenshields, 1935) proposed that "as the density of a two-lane roadway increases, the average speed of all vehicles decreases." The linear model proposed by (Greenshields, 1935) shown as below:

$$U = U_f \left(1 - \frac{K}{K_j}\right) \qquad (2.7)$$

Where:

U = Speed in (km/h)
U_f = Free flow speed in (km/h)
K = Density in (Veh/km)
K_j = Jam density in (Veh/km)

The study conducted by (Greenshields, 1935) depicts that the decrease in speed due to an increase in density of two-lane roadways is because of the measure of the congestion which is greater than the free carrying capacity of the roadways caused by slow-moving vehicles on the roadways.

Even though (Greenshields, 1935) postulated a simple single regime model by asserting a linear relationship between density(concentration) and average speed of vehicles, several investigators have proposed different complex models with the nonlinear relationship between speed and density starting from single regime model to three regime models by applying either different statistical approaches or hydro dynamic analogy to the traffic flow conditions (Twagirimana, 2013).

A study conducted by (Lighthill & Whitham, 1955)) to assess the relationship of traffic flows on long crowded stretch of an arterial roads by applying the kinematic waves method of fluid dynamics principles. On this study they have postulated a fundamental hypothesis of the study as *"at any point of the road the road the flow q is a function of the concentration k"*. In relation to this hypothesis, they have indicated that as there is a slight variation in the traffic, the flow increases back through the traffic stream as a kinematic wave and indicated that the slope of the flow versus concentration(density) graph is the velocity of the traffic stream on a given roads.

Based on the theoretical background of (Lighthill & Whitham, 1955) which had considered vehicles in a traffic stream act as continuous fluid, (Greenberg, 1959) proposed the second single regime model by utilizing the two hydro-dynamic equations namely the equation of motion in one-dimensional flow and equation of continuity from the traffic data collected from Lincoln Tunnel and derived a logarithmic relationship between speed and Concentration (Density) as follow:

$$u = c \ln\left(\frac{k_j}{k}\right) \qquad (2.8)$$

Where:

u = Traffic velocity, miles per hour
c = u_o (Speed at a maximum flow, miles per hour)
k= Density in (Vehicles/mile)
k_j = Jam density in (Vehicles/mile)

The (Greenberg, 1959) model has established a base for the later finding that the macroscopic model of traffic streams and the microscopic car following models related mathematically (May, 1990). Even though the (Greenberg, 1959) model better describes the collected traffic data for the high density (congested flow states), the model did not accurately describe the filed data for low density (un-congested flow states).

(Underwood, 1960) proposed the third single regime model based on the traffic data obtained from two sites of Merritt Parkway and derived an exponential relationship between traffic speed and density over the range of data collected as follow:

$$u = u_f \exp\left[-\frac{k}{k_o}\right] \qquad (2.9)$$

Where:

u = Speed, Kilometers per hour
u_f = Free Flow Kilometers, per hour
k = Density, Vehicles/Km
k_o = Optimum density, Vehicles/Km

(Underwood, 1960) established a generalized speed-volume relationship comprised of three different zones which are described probabilistically. The separate zones are indicated as a zone of normal flow, a zone of unstable flow and a zone of forced flow.

In his study, (Underwood, 1960) also inspected the different curves developed by Greenshields, Normann, and Greenberg whether those curves represent or not represent the overall range of data collected from both sites of Merritt Parkway under the study and arrived to a conclusion that the on the Greenshields's model speed-volume relationship the flow is unstable near the probable capacity, in the Normann's curve he showed up that the existence of some inconsistency between the normal flow zone and Normann's curve near the probable capacity and the Greenberg's relationship indicates unrealistic results in relation to the actual data since as the volume approaches to zero, the density (concentration) approaches to infinity.

(Drake et al., 1965), have a proposed a bell shaped (S-shaped) speed -density relationship model which is also called as the Northwestern model during their study on the Eisenhower Expressway located in Chicago, USA and proposed the equation that shows the speed -density relationship as:

$$u = u_f \exp\left[-\frac{1}{2}\left(\frac{k}{k_0}\right)^2\right] \qquad (2.10)$$

The Parameters in the equation are the same as discussed previously.

This study was conducted based on the study of Underwood's model and concluded that as the density increases to jam density, the speed does not go to zero (May, 1990).

(Drew, 1968) conducted a study on Gulf Freeway in Houston, Texas which is basically done to set some of the basic parameters that are useful to come up with a better understanding of different traffic operations of freeway facilities. Based on his study (Drew, 1968) proposed a Generalized equations of state for the speed-density relationship by entertaining a new

parameter n which describes different family of traffic models as the n valued differs and developed the model as:

$$u = u_f \left[1 - \left(\frac{k}{k_j}\right)^{\frac{n+1}{2}}\right] \quad (2.11)$$

Where: n is a parameter with -1,0 and +1 having the Greenshields linear model, Exponential model and parabolic model respectively.

The Parameters in the equation are the same as discussed previously.

(Pipes, 1966) in his study conducted to evaluate the different car-following models with their associated fundamental diagrams, he has developed a model that shows the speed-density relationships as follows:

$$u = u_f \left[1 - \left(\frac{k}{k_j}\right)^{n}\right] \quad (2.12)$$

(Edie, 1961) was the first researcher who proposed the concept of multi-regime models (i.e., two-regime models) in the determination of the flow -concentration relationships. In this study, after (Edie, 1961) thorough investigation of different traffic data and the flow density(concentration) relationship diagrams, he observed the occurrence of discontinuities on different empirical curves shown over a sharp drop in flow at a critical density and bottlenecks and put forwarded there should be discontinuity curves that are developed to show the relationship. Finally, based on (Edie, 1961) observation made by fitting the free flow model by the collected traffic data to detect whether Greenberg's model better describes the free flow case or not, he has proposed to implement the Greenberg's model for the congested flow conditions as it does not describe the free flow conditions better and the underwood's model for the uncongested(free-flow) regime (May, 1990).

(Drake et al., 1965) during their observation of sets of data fitted to seven (7) speed-density models proposed that a multi-regime model has good performance in describing the speed-density relationship and indicated that there is a limitation in defining the exact location where the break-points of the curves occurs.

2.6.2. Car Following Models/ Microscopic Traffic Flow Models

The development of the study of the car following model for traffic flow dated back to the 1950s (May, 1990). The study of the Car following theory describes the movement of one vehicle in relation to the movement of vehicle leading it. Different Car following models was developed based on the linear relationship equation of the Stimulus-Response which demonstrated the reaction of a driver to a certain stimulus as shown below (Gerlough & Huber, 1975):

$$\text{Response} = \text{Sensitivity} * \text{Stimulus} \tag{2.13}$$

Based on Equation- the Response is the reaction of a following driver in relation to the reaction of leading driver which is either acceleration or deceleration, the Stimulus is expressed as the difference in velocity between the lead vehicle and the following vehicle, the difference in spacing between the two vehicles, and the absolute velocity level between them and the Sensitivity term is a term that evaluate the sensitivity of the following driver's reaction (Nam, 1995).

(Pipes, 1953) postulated that the California Motor Vehicle Code which states *" A good rule for following another vehicle at a safe distance is to allow yourself at least the length of a car between your vehicle and the vehicle ahead for every ten miles per hour of speed at which you are traveling"* is the guiding principle for a driver to follow.

The distance headway d can be described based on the Figure 2.2 that illustrates the Car following notation as below:

$$d_{min} = [x_n(t) - x_{n+1}(t)]_{min} = L_n \left[\frac{\dot{x}_{n+1}(t)}{(10)(1.47)}\right] + L_n \tag{2.14}$$

Where:

n = lead vehicle
$n + 1$ = following vehicle
L_n = length of lead vehicle (ft)
x_n = position of lead vehicle (ft)
x_{n+1} = position of following vehicle (ft)
$\dot{x}_{n+1}$ =speed of following vehicle (ft/sec)
t =at time t

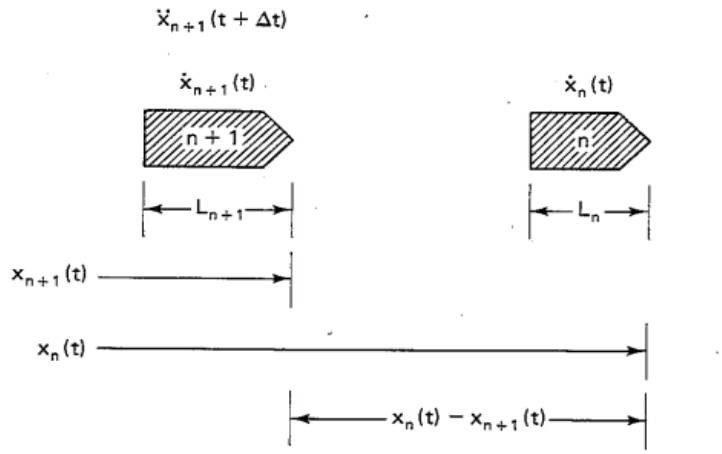


Figure 2. 2 Notation of the Car following theory. (Source: (May, 1990))

(Forbes et al., 1958) included the concept of ascertaining the inclusion of safe distance between vehicles by taking in to account the perception-reaction time which did not considered in the (Pipes, 1953) car following theory and indicated the minimum time headway required between vehicles as:

$$h_{min} = \Delta t + \frac{L_n}{\dot{x}_n(t)} \qquad (2.15)$$

Where:

Δt = reaction time (minimum time gap)
L_n = length of lead vehicle (ft)
$\dot{x}_n$ =speed of lead vehicle (ft/sec)

General Motors have developed the most well-known car following model which was a basis for the development of different researches through an in-depth study conducted by involving various researchers in the area. The harmonization of the collected field data with the model and the relationship of the model with the macroscopic model makes the General Motors model different from the other car following models developed in the past (Mathew, 2009).

The researchers involved in the formulation of the General Motors model considered that the driver's reaction is not only due to an external stimulus but also the driver's sensitivity matters the driver's reaction. Based on this fact, the researchers have developed a response-stimulus relations as indicated in the following equation (Alizadeh).

$$\text{Response} = \text{Function}[\text{Sensitivity}, \text{Stimulus}] \quad (2.16)$$

During the formulation of the above relationship, the researchers of General Motors model expressed the Response term as either the acceleration or the deceleration of the following vehicle which is based on the change in velocity of the leading vehicle, the Stimulus as the change in velocity between the lead vehicle and the following vehicle and the Sensitivity term as the term used to differentiates one group of generation from other group of generation (May, 1990).

The General Motor's team of researchers have indicated five different family/of models based on the concept of Stimulus and Sensitivity.

The first-generation model of the General Motor's model considered the sensitivity term as a constant and the model is expressed using the next equation.

$$\ddot{x}_{n+1}(t + \Delta t) = \alpha[\dot{x}_n(t) - \dot{x}_{n+1}(t)] \quad (2.17)$$

Where:

$\ddot{x}_{n+1}$ = acceleration rate (or deceleration rate) of the following vehicle ($\frac{\text{ft}}{sec^2}$)
Δt = reaction time (sec)
α =sensitivity (sec^{-1})
Other terms are as discussed in the previous sections.

The second-generation model of the General Motor's model considered the effect of spacing that brings to select different sensitivity coefficients α which ranges from 0.17 to 0.74 and the model is expressed using the following equation.

$$\ddot{x}_{n+1}(t + \Delta t) = \binom{\alpha_1}{\alpha_2}[\dot{x}_n(t) - \dot{x}_{n+1}(t)] \quad (2.18)$$

The third-generation model of the General Motor's model recommended the spacing should be definitely specified in the model as the second-generation was failed to fully describe the effect of spacing since it is necessary to repeatedly calibrate the sensitivity coefficient based on the car-following distances and this brings to the development of the third-generation model as shown here under.

$$\ddot{x}_{n+1}(t + \Delta t) = \frac{\alpha_0}{x_n(t) - x_{n+1}(t)}[\dot{x}_n(t) - \dot{x}_{n+1}(t)] \quad (2.19)$$

Where:

α_0 = sensitivity parameter the slope of the line for sensitivity and spacing relationship ($\sec^{-1}$)
$x_n(t)$ = the position of the lead vehicle

$x_{n+1}(t)$ = the position of the following vehicle

The fourth-generation model of the General Motor's model recommended that to definitely take into account the speed as stimulus as the third-generation model failed to differentiate the car following cases either as high speed or low speed and this brings to the development of the fourth-generation model as shown here under.

$$\ddot{x}_{n+1}(t+\Delta t) = \frac{\alpha'[\dot{x}_{n+1}(t+\Delta t)]}{x_n(t)-x_{n+1}(t)}[\dot{x}_n(t) - \dot{x}_{n+1}(t)] \quad (2.20)$$

Where:

α' = constant (dimensionless)

Other terms are as discussed in the previous sections.

The fifth/final-generation model of the General Motor's model summarized the concepts discussed on the above models by incorporating their shortcomings and developed a model that tries to find the interrelationship between the macroscopic and microscopic traffic models as indicated below.

$$\ddot{x}_{n+1}(t+\Delta t) = \frac{\alpha_{l,m}[\dot{x}_{n+1}(t+\Delta t)]^m}{[x_n(t)-x_{n+1}(t)]^l}[\dot{x}_n(t) - \dot{x}_{n+1}(t)] \quad (2.21)$$

Where:

l = distance headway exponent
m = speed exponent

Other terms are as discussed in the previous sections

2.6.3. A "Bridge" between the Car Following / Microscopic and the Macroscopic Models

The study conducted by General Motors Corporation's researchers namely (Gazis et al., 1961) and (May & Keller, 1967) showed that the inter-relationships of car-following models with macroscopic models given that an appropriate integer are selected for the speed sensitivity (m) and spacing sensitivity (l) functionals.

(Gazis et al., 1961) have obtained an equation after an integration of the general expression the car-following models proposed by the team of researchers of the General Motors indicated in Equation and the new expression becomes:

$$f_m(u) = c' + cf_l(s) \qquad (2.22)$$

Where:

$u =$ steady-state speed of a traffic stream,
$s =$ constant average spacing, and
c and c' = constants consistent with physical restriction.

Based on the general expression stipulated by (Gazis et al., 1961) and (May & Keller, 1967) proposed a matrix of steady-flow equations for different *m* and *l* values so that the macroscopic traffic models could be related into the car-following family of models by implementing the *m* and *l* matrix and suggested that in addition to the macroscopic and car-following models, other likely models in the future may be located based on different *m* and *l* combinations. (Gazis et al., 1961) described the already developed macroscopic models described in the previous sections based on the *m* and *l* combinations as for instance, the (Greenshields, 1935) model attained when *m*=0 and *l*=2, similarly the (Greenberg, 1959) model when *m*=0 and *l*=1, (Drew, 1968) model when *m*=0 and *l*=3/2, the (Underwood, 1960) model when *m*=1 and *l*=2 and the North Western University model by (Drake et al., 1965) is attained when *m*=1 and *l*=2. Table 2.1 and Table 2.2 are adopted from (May & Keller, 1967) which shows matrix of steady-state flow equations for different *m* and l combinations and matrix of existing traffic-flow models.

Table 2. 1 Matrix of steady-state flow equations for different m,l values (source:(May & Keller, 1967)

m / *l*	*m*<1	*m*=1	*m*>1
***l* <1**	$u^{1-m} = ck_j{}^{l-1} + ck^{l-1}$	Boundary conditions not satisfied	$u^{1-m} = {u_f}^{1-m} + ck^{l-1}$
***l* =1**	$u^{1-m} = c\ln(\frac{1}{k_j}) + c\ln(\frac{1}{k})$	$\ln u = c\ln(\frac{1}{k_j}) + c\ln(\frac{1}{k})$	$u^{1-m} = c\ln(\frac{1}{k_j}) + c\ln(\frac{1}{k})$
***l* >1**	$u^{1-m} = ck_j{}^{l-1} + ck^{l-1}$	$\ln u = c\ln u_f + ck^{l-1})$	$u^{1-m} = {u_f}^{1-m} + ck^{l-1}$

Table 2. 2 Matrix of existing traffic flow models (source:(May & Keller, 1967))

m / *l*	*m*=0	*m*=1
***l* =0**	$u = \frac{1}{s}\left(\frac{1}{k} - \frac{1}{k_j}\right)$ With s=constant	-
***l* =1**	$u = u_0.\ln\left(\frac{k_j}{k}\right)$	-
***l* =1.5**	$u = u_f\left(1 - \left(\frac{k}{k_j}\right)^{1/2}\right)$	-
***l* =2**	$u = u_f\left(1 - \frac{k}{k_j}\right)$	$u = u_f e^{-k/k_0}$
***l* =3**	-	$u = u_f e^{-\frac{1}{2}\left(\frac{k}{k_0}\right)^2}$

The study conducted by (May & Keller, 1967) indicated that not only the integer combinations of *m* and *l* are implemented to successfully describe the actual speed-density but also non-integer combinations of *m* and *l* can be implemented to obtain the best representation of the models with actual data by making either *m* or *l* constant and changing the other parameter (May & Keller, 1967).

A simple demonstration has been done to describe the utilization of both integer and non-integer combination of models, by making the *m* value constant which is 1 and the value of *l* to vary starting from 2 to 3 in increment of 0.2 and inserted those values to into the generalized car-following model and finally transforming it to the macroscopic models, the resulting speed-density models shown in Figure depicts that the spectrum of the relationships changed

from the Underwood model (Exponential model) to the Northwestern model(Bell shaped model) (May, 1990).

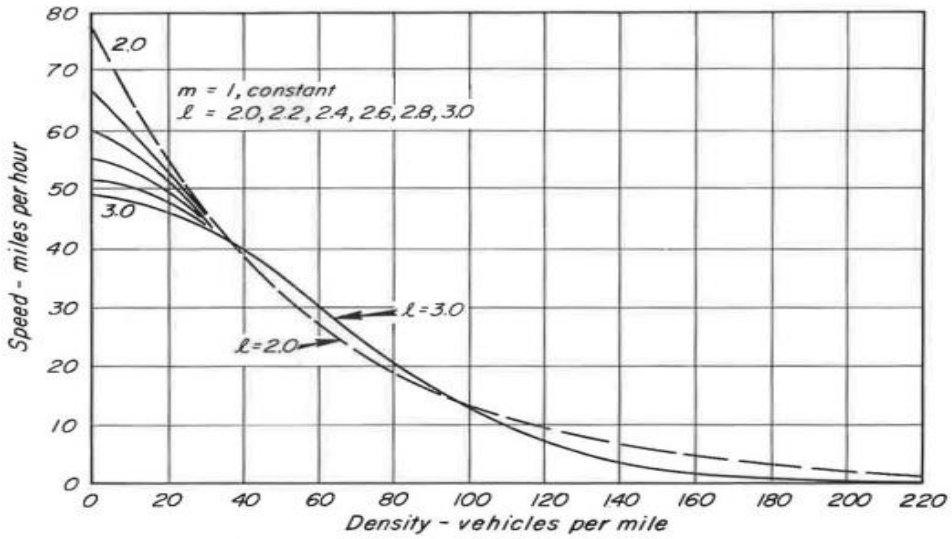


Figure 2. 3 Influence of the use of non-integer exponents on the speed-density relation (Source:(May & Keller, 1967))

2.7. Review of recent researches on traffic flow relationships

While examining the speed-flow relationships on the Caldecott Tunnel, USA through which California State Highway 24 crosses; (Chin & May, 1991) considered the data taken from two lanes which come out of the Caldecott Tunnel and plotted the speed-flow data for the average of both lanes by aggregating the data in 2-min, 15 min, and 1-hr intervals, they then have indicated that the existence of a distinct speed- flow relationship which can be expressed in the form of bilinear function. The research also confirmed the findings of previous reports on the absence of sharp drop in speed as the flow tends to its capacity, assured that the amount of capacity in excess of 2,200 pcphpl can be achieved even though the speed-flow relationship of the study location does not be affected by the existence of an up-stream queue and finally they have indicated that the HCM speed-flow curves did not expressed perfectly the speed-flow relationship of the study location.

Speed- Flow relationships were investigated in a study carried out in Indonesia, on rural roads using empirical data and simulation. In this study the speed-flow data obtained from 150 locations are aggregated in 5-min interval and utilized for the purpose of testing the relevance of the existing speed-flow and speed-density models which includes the linear speed-flow

model, Single-regime, Underwood, and May models. The result obtained from the regression analysis of the speed-flow and speed- density models using the site field data showed that the linear speed-flow model selected with R^2>0.6 among other models (Bang & Carlsson, 1995).

(Roux, 2001), examined the relevance of different existing traffic flow models developed earlier as whether those models depict or not the actual traffic condition of South African freeways. Regression analysis have been done models like Greenshields model, Greenberg model, Underwood model, Drake, May and Schofer model, multi-regime matrix model and the Composite model have been examined by utilizing the data obtained from three separate freeway sections. From regression analysis result, they have indicated that the congested flow conditions are better expressed by the Greenberg model and the un-congested flow conditions are better described by the multi-regime model.

While examining the speed-flow relationships for rural two-lane two-way highways in the Western Cape, South Africa; (Twagirimana, 2013) considered field data collected from two distinct locations located on two lane highways of South Africa. In this study each direction was examined separately and analysis was done by aggregating the collected traffic data in 1-min and 5-min interval of time in order to test the relevant existing traffic flow models developed earlier in order to arrive on a model which best describes the actual traffic condition of two-lane highways of South Africa. Models like Greenshields model, Greenberg model, Underwood model, Drake, May and Schofer model, Drew model, Multi-regime matrix model and the Composite model have been utilized and the result of the analysis showed that, for the data aggregated in 1-min interval, due to the occurrence of discontinuity between low density data and high density data a Composite model have been decided as the Drake model better represent the uncongested/free flow regime and the Greenberg model better represent the congested regime. For 5-min case, the curve fitting was made using one single model for the whole range of data as multi-regime matrix model was recommended to represent section-1 of the study area and the Drake, May and Schofer model to represent section-1 of the study area. Finally, the research concluded that as there exists a change in one model to another due to change in time interval since there was occurrence of less points that relates with congested traffic condition.

(Xu et al., 2014) examined the relevance of 10 existing speed-density models developed earlier as whether those models represent or not the actual traffic condition of Beijing expressway data aggregated on an interval of 20-sec, 30-sec, 1-min, 2-min, 3-min and 5-min through curve fitting and calibration of parameters. The result of the study showed that the errors aroused during curve fitting of the speed-density models does not impacted by the different types of data used while on the contrary free-flow speed and jam-density altered based on the type of field data used. Finally, the research concluded that the Newell and Logistic models showed good stability than the other models.

(Saha et al., 2017) evaluated the speed-flow characteristics of two-lane highways with mixed traffic in north eastern India. Field studies were carried out on eight sections where the observations are made for 10-hr during typical weekday and weekend and an investigation of speed-low relationship were conducted. Different models had been utilized to analyze whether those models satisfactorily represent the actual traffic condition of the study site. Based on their finding they have found that Exponential model better describe the free-flow/uncongested flow condition and the linear model better describes the congested flow condition.

(Tadesse & Dr. Sisay, 2019), evaluated the traffic flow characteristics of mixed traffic on Addis Ababa ring road, Ethiopia. The field data collection was carried out from three locations using a video technique and speed-density models were examined by using data aggregated in 1-min interval where regression analysis was made to analyze the relationship. Based on the investigation, (Tadesse & Dr. Sisay, 2019) found Greenshields model better represent the relationship than other classical models.

2.8. Theoretical review on two-lane two-way rural highways

Two-lane two-way highways are defined as two-lane highways that are not separated by any means, where one lane to be utilized for traffic in each direction, and which overtaking process happens in the lane of oncoming traffic, when the sight distance and the opposing traffic circumstances allow whereby due to this reason, the traffic performance of one direction is affected by the other direction traffic (Roess, 2011).

Two-lane, two-way highways are a critical element of the transportation infrastructure system in the majority of nations. They serve a variety of transportation related functions, are found everywhere, and perform a number of transportation-related tasks (TRB, 2016).

In Ethiopia the majority of the highway infrastructure composed of two-lane two-way highways where those highways majorly traverse in rural areas. The study conducted by (Demissie et al., 2020) on ReCAP (Research for Community Access Partnership) Impact case study on Ethiopia showed that in 2019, around 15,586 Km length of road are two-lane two-way highways excluding highways in municipalities.



Figure 2. 4 Typical two-lane, two-way highway in Ethiopia (Source:(Davey, 2012))

Due to the occurrence of distinct relationship among the two direction's traffic conditions, the traffic phenomenon that occurs on two-lane, two-way highways differ from other highway facilities (Durbin, 2006). In this regard, an investigation is required to understand the behavior of two-lane, two-way highways traffic phenomenon, in order to increase the traffic mobility and operational performance of two-lane, two-way highways of Ethiopia.

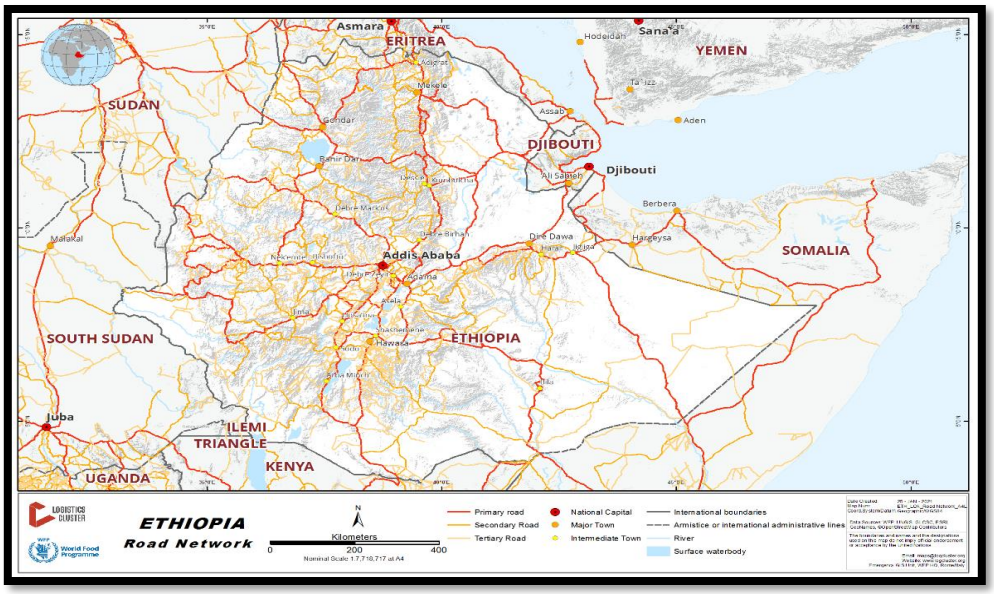


Figure 2. 5 Ethiopian road network (Source: (WFP, 2021))

2.8.1. Classification of two-lane highways

The highway capacity manual distinguishes two-lane highways into three major groups, the first two of which are only found in rural settings and the third of which is found in urban settings (TRB, 2016).

The three types of two-lane roads are defined in the following sections. (TRB, 2016):

- Class-I two-lane highways: are highways where drivers anticipate travelling at quite high speeds. Class I roads are two-lane highways that are key intercity routes, principal connections of major traffic generators, daily commuter routes, or major linkages in state or national highway networks. These kinds of facilities primarily serve long-distance travel or interconnect facilities that support long-distance journeys.
- Class-II two-lane highways: are roadways where drivers should not expect to go at high speeds. Class-II highways are two-lane highways that serve as access routes to Class-I facilities, as scenic or leisure routes (rather than as major arterials), or that traverse through harsh terrain (where high-speed operation would be impractical). These facilities are typically used for relatively short journeys, the beginning or finish of longer trips, or trips where sightseeing is important.
- Class-III two-lane highways: service modestly developed regions. They might be segments of Class I or Class II roads that run through small towns or established

recreational areas. On these segments, local traffic frequently mixes with through traffic, and the frequency of unsignalized driveways and cross streets is notably larger than in a totally rural region. Class III highways may have longer route portions that travel through more spread-out recreational areas, as well as higher roadside concentrations. These parts are frequently accompanied by decreased speed restrictions to reflect the increased activity extent.

2.8.2. Methodology for operational analysis of two-lane, two-way highways

The Highway Capacity manual is a manual which act as a basic guide for measuring the capacity of a highway, concepts, performance measures, and analysis methods for assessing the multimodal operation of streets, highways, freeways, and off-street routes (TRB, 2016). The techniques outlined in the Highway Capacity Manual are being used to undertake operational analysis of two-lane highways in various countries including Ethiopia even though the manual is developed based on traffic condition of USA.

The methodologies stated in the HCM may not be applicable or sufficient for the other local conditions, according to various research conducted outside of the United States (Ghosh et al., 2013). Earlier versions of Highway Capacity Manuals have indicated different methodologies on the operational analysis of two-lane highways. However, the latest version of the HCM which is HCM, 2016 had retained an operational analysis methodology similar with the HCM, 2010's methodology that deals with analyzing directional two-lane highway segments in general terrain (level or rolling) and directional segments on specific grades.

2.8.2.1 Capacity studies of two-lane, two-way highways

Techniques for evaluating highway capacity are relied on both theoretical and empirical study (Luttinen, 2001). Unfortunately, capacity conditions are only sometimes noticed and then only for short stretches. The majority of two-lane highways are rebuilt before demand approaches capacity because service quality begins to diminish at relatively low demand flow rates (TRB, 2016).

The first edition of Highway Capacity Manual (TRB, 1950) identified the basic capacity is equivalent to 2,000 passenger cars per hour without consideration to the directional

distribution and the practical capacity of two-lane highway under ideal circumstances was 900 passenger cars per hour (Luttinen, 2001).

The second edition of Highway Capacity Manual (TRB, 1965) indicated the capacity under an ideal condition, which was identical to the basic capacity concept stated in the 1950 HCM, was 2000 passenger cars per hour in total in both directions without consideration to the directional distribution (Luttinen, 2001).

The third edition of Highway Capacity Manual (TRB, 1985) established the value of a two-lane highway capacity as 2800 passenger cars per hour, with a critical density of 19.4veh/km and speed of 72kph (TRB, 1985).

The fourth edition of Highway Capacity Manual (TRB, 2000) showed that the two-lane highway's capacity, which is nearly independent of the highway's directional distribution, is 1,700 passenger cars per hour in each direction. and 3200 pc/h combined for both directions of travel (TRB, 2000). Based on this condition, (Luttinen, 2001), expressed the capacity of two-lane highways mathematically as follows:

$$C = min\left\{\frac{1700}{P_d}; 3200\right\} \qquad (2.23)$$

Where:

$C =$ Capacity of two-lane highways, and

$P_d =$ the proportion of traffic in the major direction.

Both the fifth edition of HCM (TRB, 2010) and sixth edition of (TRB, 2016) suggested that the capacity is given as 1700 passenger cars per hour in each direction under ideal conditions, as already stated previously in the fourth edition of the HCM, with a maximum of 3200 passenger cars per hour for all directions combined (TRB, 2010, 2016).

2.9. Summary and gaps in literature review

Different researchers worldwide had conducted studies on traffic flow relationship starting from the Bruce D. Greenshields' pioneering work in the 1930s and several researches was made for different highway facilities and researches are continuing as the nature of traffic flow changes through time. However, most of those studied based on the developed nations and little works was done on developing countries.

In Ethiopia, Despite the fact that most of the road stretches in Ethiopia was comprised of Two-Lane Two-Way rural highways, a little number of literatures was available on the development of Speed-Flow-Density relationship, travel time analysis and capacity determinations, as major works was necessary given the importance of studying those concepts thoroughly.

In this chapter the methodologies implemented along with their results of different classical traffic flow models and recent researches on traffic flow relationships was briefly discussed. The literature review started by reviewing the history of traffic flow study, describing the different traffic flow states, the different parameters related to traffic flow theory along with their fundamental relationships. In addition to this, theoretical review on two-lane two-way highways was done.

Reviewing researches on traffic flow relationships, various researchers considered the data taken from different areas of their study where the number of study sections utilized varies from researcher to researcher given that there are no standard or accepted criteria for selection of number of study sites and also the time taken for the observations was also varies from researcher to researcher. Besides, the data aggregation employed for the examination of those relationship varies from researcher to researcher as researches reviewed had employed a data aggregated starting from 20-Sec to 1-hour. Study conducted by (Roux, 2001) on developing countries like, South African freeways, analysis was done by aggregating the data in 1-min with a data collected for 3 hours and also the study conducted by (Twagirimana, 2013) for South African Two lane Two Way highways, analysis was done by aggregating the data in 1-min and 5-min interval with a data collected for 2 hours. In Ethiopia, the study conducted by (Tadesse & Dr. Sisay, 2019) on Addis Ababa ring road were examined by using data aggregated in to 1-min interval with a data collected for 2-hours. In addition, the different

models utilized to analyze whether those models satisfactorily represent the actual traffic condition of the study sites varies from researcher to researcher.

In this study, three representative section was selected for analysis of the speed-density-flow relationships, for a data taken for 5 hours for each section and representative models were selected for the examining, utilizing both single regime models and multi-regime models.

CHAPTER THREE: DATA COLLECTION AND METHODOLOGY

3.1. Chapter Introduction

In this chapter, the traffic data information gathered from the traffic flow of selected Two-Lane Two-Way rural highways during morning peak hour time along with their site description of the study sections was presented. The collected data was used as an input in the following chapter in order to analyze the collected data so that speed-flow-density relationships for the above-mentioned rural roads was deduced that specifically focus majorly on the selected rural road sections of Ethiopia.

Despite the fact that there are other road sections that meet the criteria for two-lane two-way rural highways, three typical sections were chosen to meet the research's objective. The selected road stretches are trunk road sections radiating from Addis Ababa, Ethiopia's capital, due to the economic importance of those highways as the highways serve better traffic movement than other highways of the same type. From those highways three typical sections was selected among those five highways of the same type radiating from Addis Ababa that can represent the prevailing traffic condition of the highways by excluding the old Addis-Adama section because of the opening of Expressway and the Addis-Ambo by considering that it has similar feature with the Sululta-Chancho road. Based on this assumptions Sebeta-Tullubollo section was selected from the Addis-Jimma Road, Sululta-Chanco section was selected from the Addis-Bahirdar Road and Sendafa-Debrebirhan section was selected from the Addis-Dessie Road.

After the study roads are selected, the study sections from the selected roads are selected by considering road stretches that can approximately describe the prevailing traffic conditions that comprise variety of traffic conditions (i.e., free flow, moderate flow, congested flow). In addition to this as the rural roads are uninterrupted flow facilities which are free from any interruptions on the movement traffic, the study section is selected where there are no any traffic signals, intersections etc. as per the Highway Capacity Manual, uninterrupted traffic

conditions on a specific stretch of roadway happen when it is situated 2 to 3 miles from the closest signalized intersection. Moreover, different factors had been considered that majorly influence the driver behaviors on the given rural highways. During study section selection, a section with straight alignment, flat terrain, rural adjacent land use, no parking area, a smaller number of pedestrians, and good weather condition is considered in order to get better representation of the actual traffic condition so that to minimize physical and environmental interruptions on the traffic stream as various researches asserted that those factors are among the major cause that affects driver's behavior.

In order to collect the required data for the research, a video technique of recording the actual traffic conditions of both sides of the highway standing some distance away from the movement of the traffic in order to get better resolution for the camera and avoid any disruption on the driver's behavior due to the recording process. A fixed point which is electric pole is considered as a reference during recording, which was used as a reference point marked on the Adobe Premiere CS6 interface during the filming of the recorded video which will be used as a distance beacon during measurements.

For every vehicle under consideration, travel time data and vehicle classification using the ERA 2012 vehicle classification guideline is incorporated for further data processing. From the video recording, the average speed was determined for both sides of the highway by dividing the measured distance between the reference point to the calculated average vehicle travel times computed by registering the entrance and exit time of every vehicle using the Adobe Premiere CS6.

Further, as there are various types of vehicles traverse the study section an adjustment factor had been applied so that to minimize the effects of those heavy vehicles on the traffic stream. Based on this it is simple to calculate the traffic flow for a given time interval. Hence, the density for a given time can be measured easily by implementing the steady state fundamental relationship equation.

In this research, the speed, density, and flow data gathered from the field data collection using the video techniques were processed for every 1-minute, and 15-minute time intervals.

3.2. Description of Study Road Sites

To ascertain the objective of this research, as previously discussed, the data for speed, flow, and density was collected form three representative two-lane two-way rural highways of Ethiopia. The figure shown below depicts the map for the study road sites as the comprehensive information of road site presented in the following section.

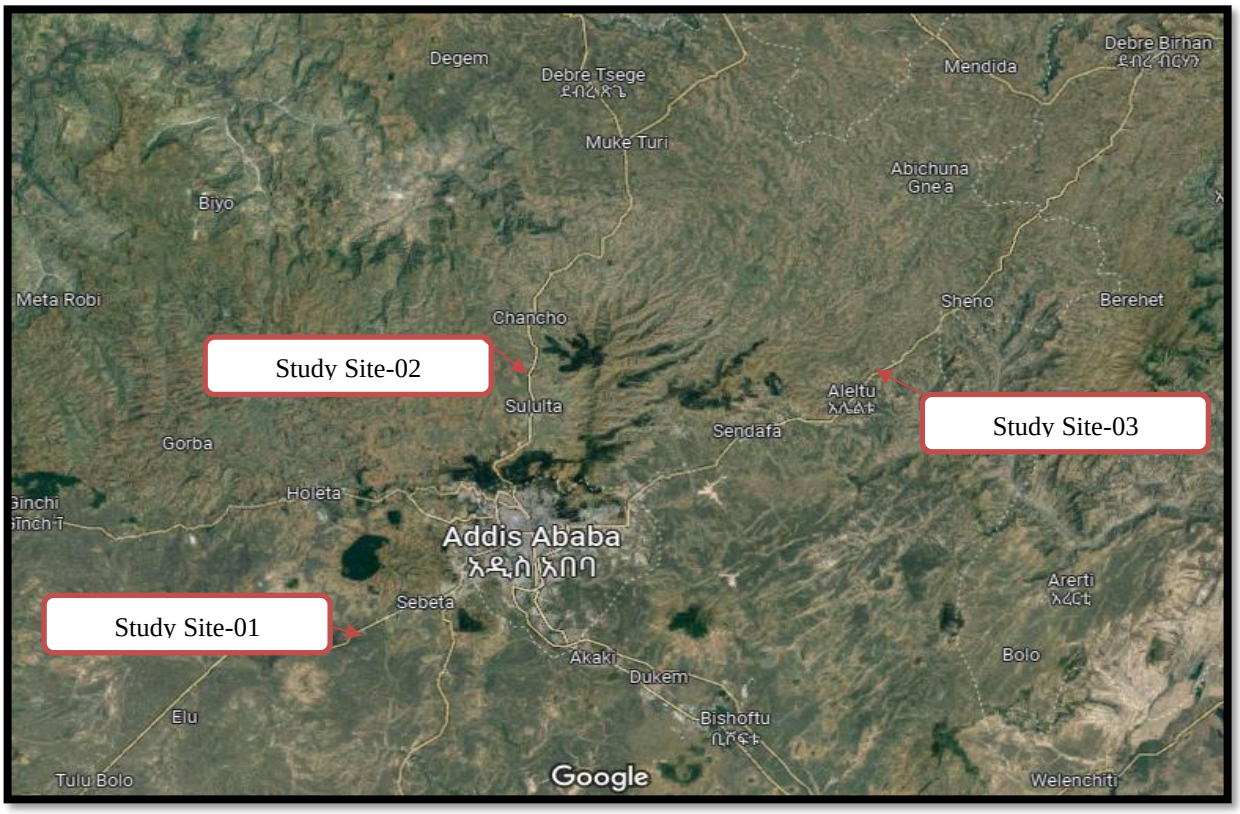


Figure 3. 1 Map depicting the locations of the study sections (Google map)

Study Site -01: Sebeta -Tullu bolo:

The road from Sebeta-Tullubolo is part of the Addis Ababa-Jimma-Mettu Road where it is numbered as A-5-1 according to the Ethiopian Road Numbering System. The sebeta-tullubolo road stretch have around 57 Km length and the total length of the study section is located 10 Km from sebeta town towards tullubollo side on a level terrain which is <3%.

As it is witnessed from the field verification, the lane width and shoulder width of this section is 3.5m and 1.5m respectively. On this section, passing is not controlled, and through traffic

is not hampered by traffic signals or turning vehicles. For this section the data collection was done during morning peak hour period of about 5 hours (7:24-12:29).

Study Site -02: Sululta -Chancho:

The road from Sululta -Chancho is part of the Addis Ababa-Bahirdar-Gonder Road where it is numbered as A-3-1 according to the Ethiopian Road Numbering System. The Sululta -Chancho road stretch have around 15 Km length and the study section is located 4.7 Km from Sululta town towards Chancho side on a level terrain which is <3%.

As it is witnessed from the field verification, the lane width and shoulder width of this section is 3.5m and 1.5m respectively. On this section, passing is not controlled, and through traffic is not hampered by traffic signals or turning vehicles. For this section the data collection was done during morning peak hour period of about 5 hours (7:38-12:29).

Study Site -03: Sendafa -Debre Birhan:

The road from Sendafa -Debre Birhan is part of the Addis Ababa-Axum Road where it is numbered as A-2-1 according to the Ethiopian Road Numbering System. The Sendafa -Debre Birhan Road stretch have around 91.5 Km length and the study section is located 9.3 Km from Sendafa town towards Debre Birhan side on a level terrain which is <3%.

As it is witnessed from the field verification, the lane width and shoulder width of this section is 3.5m and 1.5m respectively. On this section, passing is not controlled, and through traffic is not hampered by traffic signals or turning vehicles. For this section the data collection was done during morning peak hour period of about 5 hours (7:58-12:59).

3.3. Methodology for Data Processing

Following site visits to the selected study sites, the researcher determined that the morning peak hour is more important for the study than the afternoon peak hour because more traffic traverses the road stretches during the morning period, and conducting a video recording is easier during the morning period for a better resolution and clarity of the recording as the video recording technique had been adopted for the data collection. Following the recording of the video, the data was turned to an excel spreadsheet for the upcoming analysis of the collected data using the following methodologies shown in the figure below.

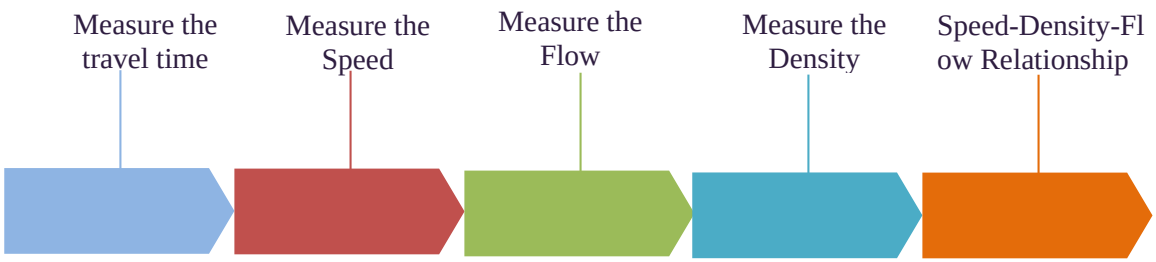


Figure 3. 2 Methodologies utilized for the data processing

The detail description for the methodologies utilized for the data processing is indicated as hereunder:

3.3.1. Measuring travel time for a specific time interval

In order to determine the travel time for each vehicle under consideration with the aid of the video recording technique, by calculating the difference in time when a particular vehicle enters the study section and leaves the study section which is the difference in time when the front bumper of the corresponding vehicle reaches the entrance point of the study section and when the front bumper of the same vehicle reaches the entrance point of the study section. Finally, the calculated travel time was averaged for the number of vehicles observed for a given time interval.

3.3.2. Measuring Speed

(Minnesota Department of Transportation, 2007), indicated a general rule that shows at least 100 speed data should be gathered for a vehicular speed analysis. By implementing the Cochran's formula that helps in determining the number of sample size where in the population is not known precisely and assuming 95% confidence level, sampling error of e=0.05, p=0.5(standard deviation) and q=1-p=0.5, and taking Z valued as 1.96 from the normal distribution graph for a 95% confidence level, the number of sample size was determined using the equation and it can be deduced the sample size used in the research is greater than 385 value obtained using the Cochran's formula and the Space Mean Speed of the research was calculated using the formula:

$$U_S = \frac{L}{T} \qquad (3.1)$$

Where:

U_S =Space Mean Speed

L=Section Length

T=Average travel time of the vehicles traced in the study section

3.3.3. Measuring Flow

The traffic flow that was used for the analysis was measured by recording the number of vehicles along with their classification that enters and leaves the study section boundary points during a given time interval. Classification of vehicle types was done to consider the effect of heavy vehicles on the traffic stream.

The hourly traffic flow of the study section was determined using the following equation:

$$q = N_i * 60 \qquad (3.2)$$

Where:

q=Hourly traffic flow, N_i=The number of vehicles with type i that crosses the study section boundary for 1 min interval

3.3.4. Measuring Density

After the corresponding Speed and the Flow was determined, the Density of the traffic stream was determined based on the steady state equation for a given interval of time.

The Density was determined using the equation:

$$k = \frac{q}{u_s} \qquad (3.3)$$

Where:

q=Hourly traffic flow, u_s=The Space Mean Speed

3.3.5. Determining the Speed-Flow- Density Relationships

After the collected data using the video technique were transferred into an excel spread sheet and the corresponding, speed, flow, and density data was attained using the above methodology the Speed-Flow- Density Relationships that best describes the existing traffic

condition of the rural roads was determined based on the already developed traffic models by using the regression analysis technique.

The unknown parameters of the equations of the models under study should be obtained in order to find the equation of a model that best represents the actual traffic state. The regression analysis approach was used to acquire those unknown parameters by assessing the coefficient of determination (R^2) that demonstrated how good was the fit of the relationship. Minitab Software and an Excel Solver add-in were used for the regression analysis. The following steps were taken throughout the curve fitting procedure:

- Plot the scatter plot data for Speed and Density,
- Apply the curve for each of the selected models using their equation,
- Determine the unknown parameters of the equation,
- Evaluate the coefficient of determination (R^2) to examine the goodness of fit of the selected models.

3.4. Collected Data

In this section the traffic composition of the vehicles that traverse the study sections, the considerations taken in to account for the data collection, and the data collected which was used as an input for the next course of action was presented for both direction of the study section. The whole data set is incorporated in Appendix-A for a further information.



Figure 3. 3 Sample video footage using adobe premiere software

3.4.1. Traffic composition of the study sites

As it is impossible to have two-lane roads composed of totally 100% passenger cars, (TRB, 2016) recommends to apply heavy vehicle adjustment factor for heavy trucks and recreational vehicles as their presence affects the ATS of the traffic stream. In relation to this, it is very crucial to assess the traffic composition of the traffic stream so that the effects of the heavy trucks and recreational vehicles on the traffic stream could be mitigated. Based on the actual traffic condition of Ethiopia, (ERA, 2013) categorized vehicles classes in to 13 groups, by which the detailed description of the classes shown in the Table 3.1 below:

Table 3. 1 Vehicle classification (source: (ERA, 2013)**)**

ERA VEHICLE CLASSIFICATION					
Class	Type	Axles	Description		
1	Car	2	Passenger cars and taxis		Passenger Cars
2	Pick-up/4-wheel drive	2	Pick-up, Minibus, Land-Rovers, Land-Cruisers		
3	Small Bus	2	≤ 27 seats		Trucks and Buses
4	Bus/coach	2	> 27 seats		
5	Small truck	2	≤ 3.5 tonnes		
6	Medium truck	2 or 3	3.5 - 7.5 tonnes		
7	Large 2-axled truck	2	> 7.5 tonnes		
8	3-axled truck	3	*		

9	4-axled truck	4	*		
10	5-axled truck	5	*		
11	6-axled truck	6	*		
12	2-axled trailer	2	*		
13	3-axled trailer	3	*		

According to the (ERA, 2013) vehicle classification guideline, the vehicles that crossed the study section's boundaries were categorized. The following figures display the traffic composition of the study.

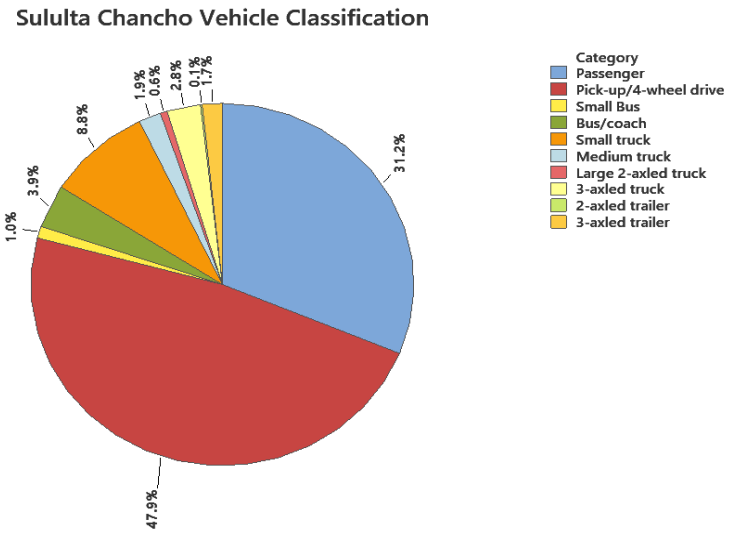


Figure 3. 4 Percentage of vehicle composition on Sululta-Chancho section

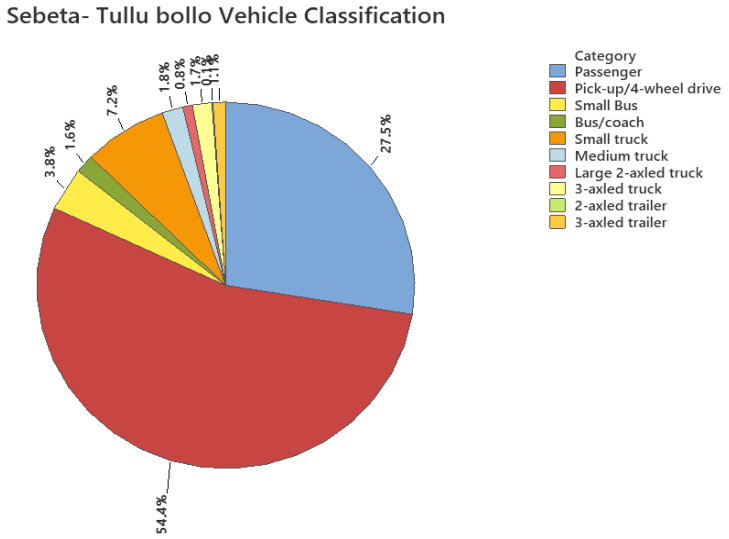


Figure 3. 5 Percentage of vehicle composition on Sebeta-Tullu bolo section

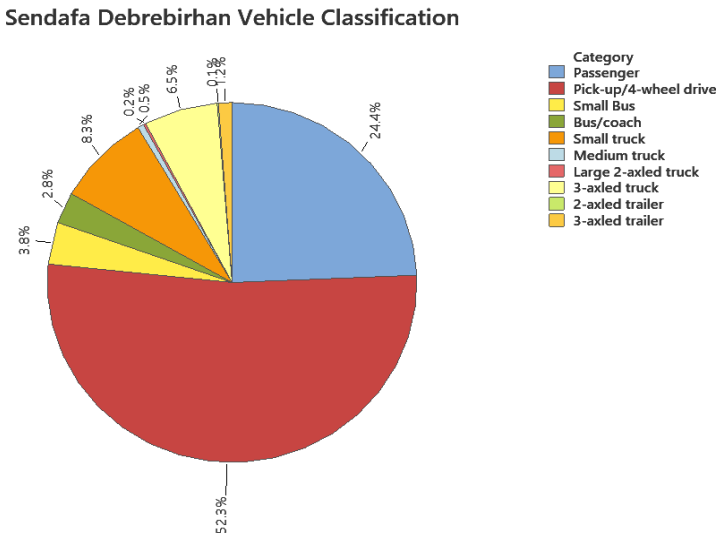


Figure 3. 6 Percentage of vehicle composition on Sendafa-Debre birhan section

The traffic composition of the study section depicts that, Pick-up/4-wheel drive type of vehicles contributes the major part of the vehicle composition accounting around 54.4%, for Sebeta-Tullubolo section, 47.9% for Sululta-Chancho section, and 52.3% for Sendafa Debre birhan section. Next to Pick-up/4-wheel drive type of vehicles, Passenger Cars have the second contribution for the traffic composition on all study sections. Majorly the traffic composition of all study sections was composed of Pick-up/4-wheel drive and Passenger Cars accounting around 81.9% for Sebeta-Tullubolo section, 79.1 for Sululta-Chancho section, and

76.7% or Sendafa Debre birhan section. Next to Pick-up/4-wheel drive and Passenger Cars, small trucks and 3-axled truck contribute a share for traffic composition of the study sections. From the resuts it can be deduced that the contribution of 2-axled trailer is less than 4% for all sections and the contribution of 3-axled trailer is less than 2%.

3.4.2. Speed Data

As it was discussed previously on Methodology for data processing section, the speed was calculated after the travel time that takes for each vehicle to pass the study section boundary was registered and average for each time interval and later the length of the study section divided by the averaged time gives the speed data.

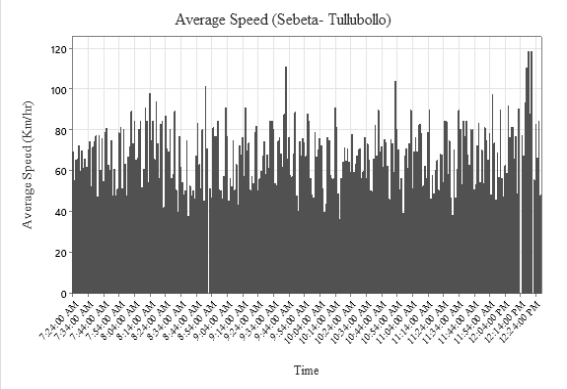
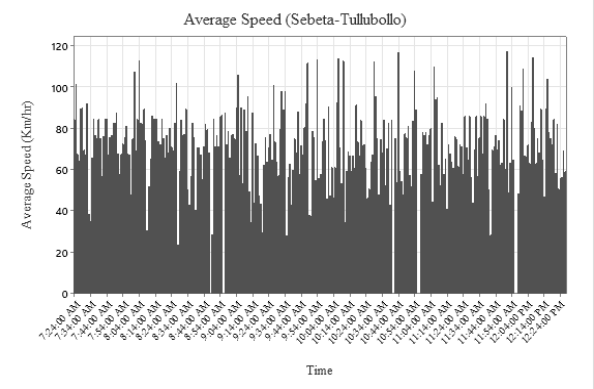
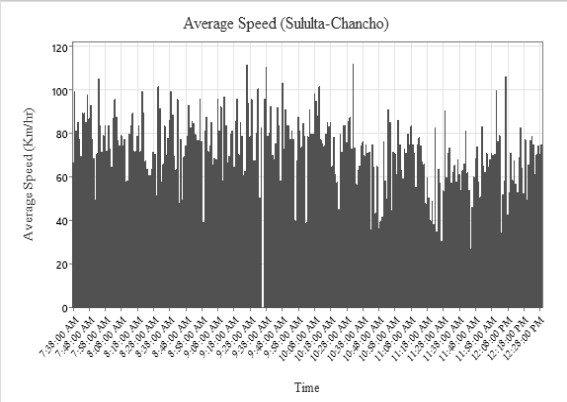
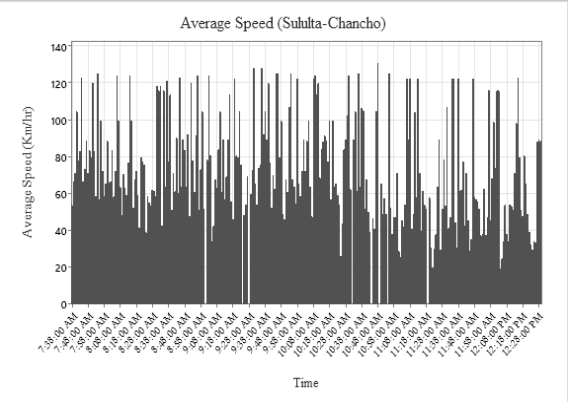
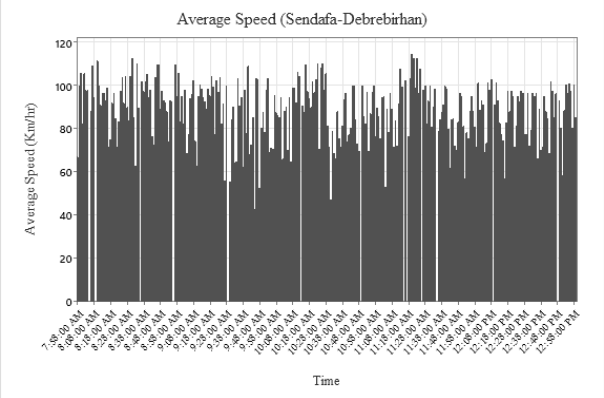
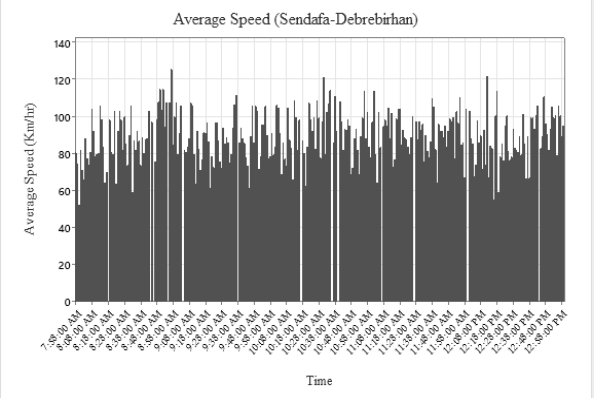
The variation of speed with respect to the time for all study sections was shown on Table 3.2 shown below.

It is observed that from the figure that shows variation in speed with respect to time for Sebeta-Tullubollo section, there was a minimum speed of 36.49 km/hr and maximum speed of 118.52 km/hr towards tullubollo direction and a minimum speed of 23.48 km/hr and maximum speed of 117.23 km/hr towards sebeta direction.

It is observed that from the figure that shows variation in speed with respect to time for Sululta-Chancho section, there was a minimum speed of 26.92 km/hr and maximum speed of 111.52 km/hr towards Sululta direction and a minimum speed of 19.23 km/hr and maximum speed of 130.44 km/hr towards Chancho direction.

It is observed that from the figure that shows variation in speed with respect to time for Sendafa-Debrebirhan section, there was a minimum speed of 42.73 km/hr and maximum speed of 114.3 km/hr towards Sendafa direction and a minimum speed of 52.21 km/hr and maximum speed of 124.94 km/hr towards Debrebirhan direction.

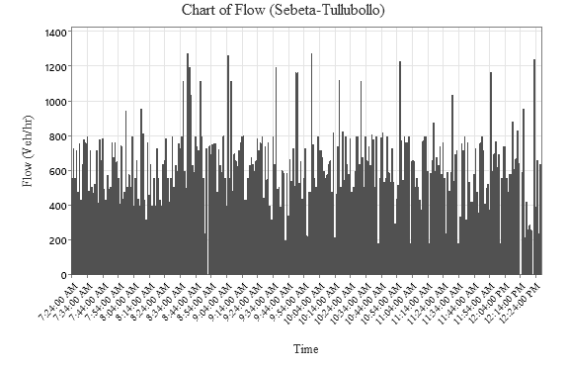
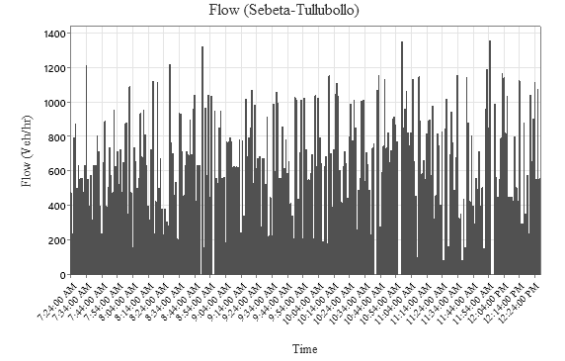
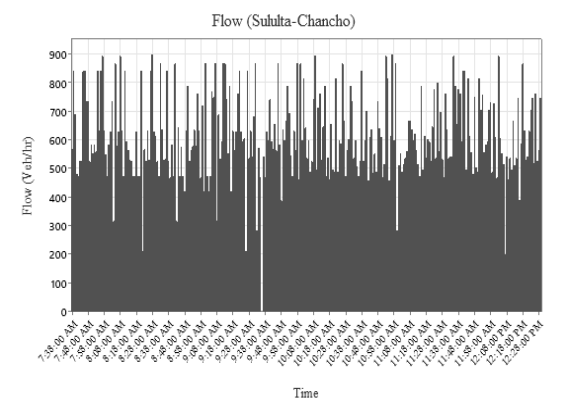
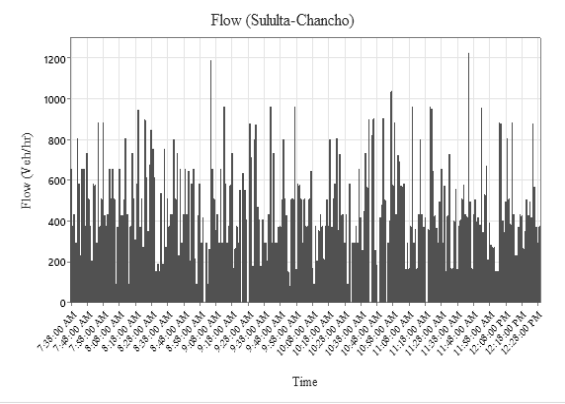
Table 3. 2 Speed variations with respect to time for all sections of the study

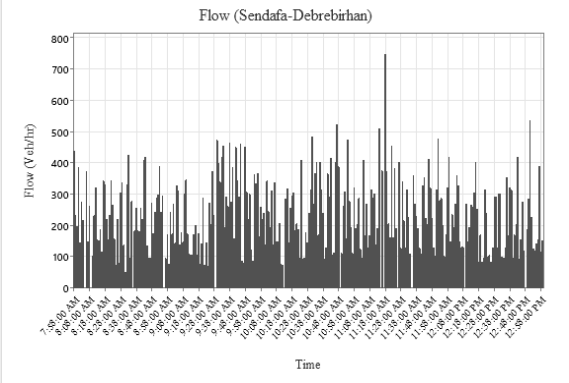
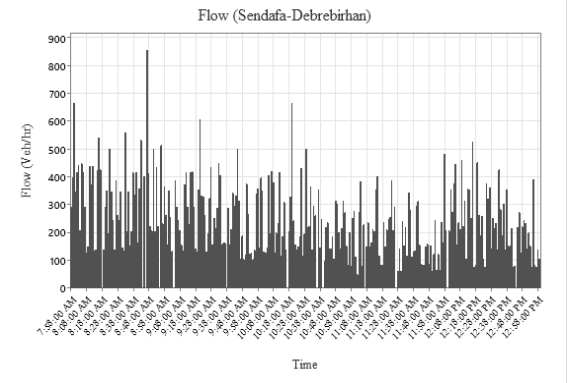
Speed-Density-Flow Variations	
Sebeta-Tullubollo Section	
	
Average speed data measurement for Sebeta-Tullu bollo (towards Tullu bollo direction)	Average speed data measurement for Sebeta-Tullu bollo (towards Sebeta direction)
Sululta-Chancho Section	
	
Average speed data measurement for Sululta-Chancho (towards Sululta direction)	Average speed data measurement for Sululta-Chancho (towards Chancho direction)
Sendafa-Debrebirhan Section	
	
Average speed data measurement for Sendafa-Debrebirhan (towards Sendafa direction)	Average speed data measurement for Sendafa-Debrebirhan (towards Debrebirhan direction)

3.4.3. Flow Data

The hourly traffic flow of the study section was determined by multiplying the number of vehicles that crosses the study section boundary for the given time interval by a factor of 60 as the multiplier changed with respect to the time interval in consideration. The variation of flow with respect to the time was shown on Table 3.3 shown below. The flow value was fluctuating and the maximum flow for the Tullubollo direction was experienced 1267 veh/hr and 1355 veh/hr for the Sebeta direction. The flow value was fluctuating and the maximum flow for the Sululta direction was experienced 898 veh/hr and 1225 veh/hr for the Chancho direction. The flow value was fluctuating and the maximum flow for the Sendafa direction was experienced 746 veh/hr and 855 veh/hr for the Debrebirhan direction.

Table 3. 3 Flow variations with respect to time for all sections of the study

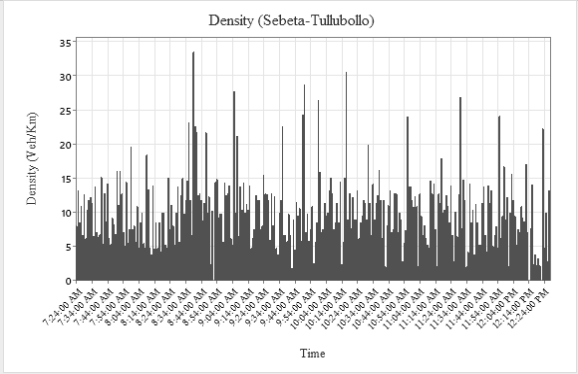
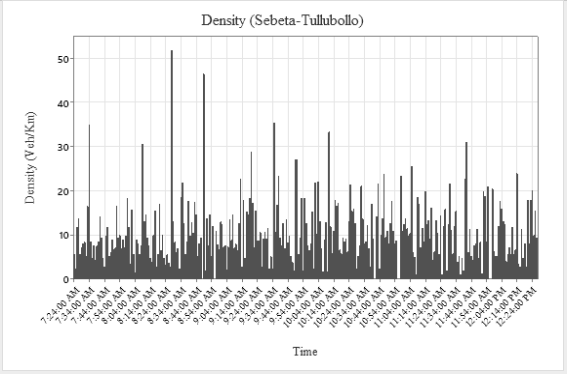
Speed-Density-Flow Variations	
Sebeta-Tullubollo Section	
	
Average flow data measurement for Sebeta-Tullu bollo (towards Tullu bollo direction)	Average flow data measurement for Sebeta-Tullu bollo (towards Sebeta direction)
Sululta-Chancho Section	
	
Average flow data measurement for Sululta-Chancho (towards Sululta direction)	Average flow data measurement for Sululta-Chancho (towards Chancho direction)

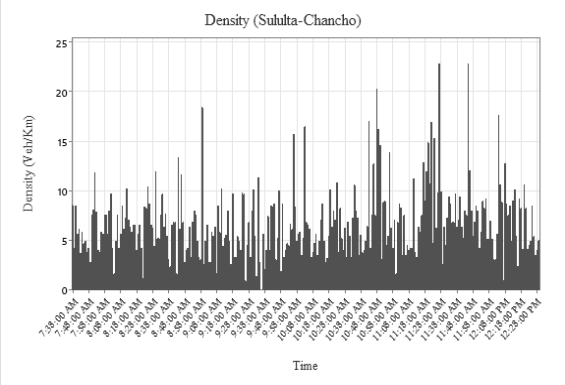
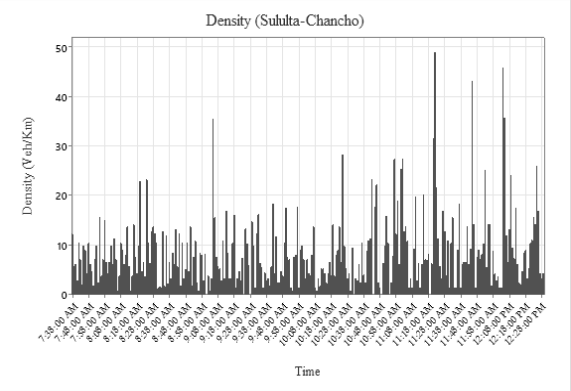
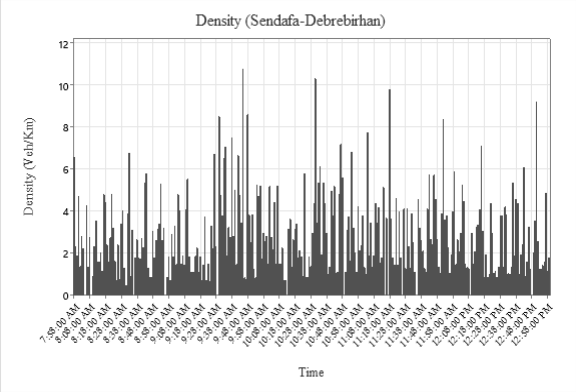
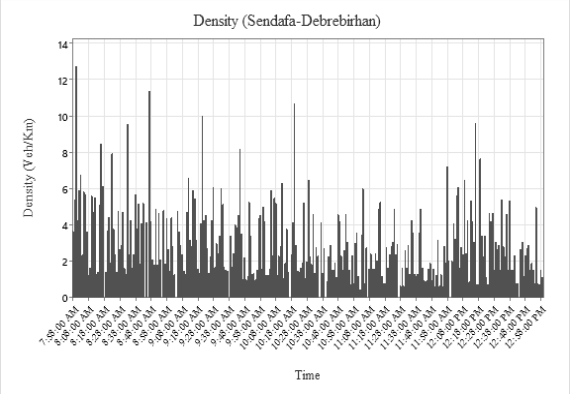
Sendafa-Debrebirhan Section	
	
Average flow data measurement for Sendafa-Debrebirhan (towards Sendafa direction)	Average flow data measurement for Sendafa-Debrebirhan (towards Debrebirhan direction)

3.4.4. Density Data

After the corresponding Speed and the Flow was determined, the Density of the traffic stream was determined based on the steady state equation for a given interval of time. The variation of density with respect to the time for all study sections was shown on Table 3.4 shown below. From the figure on the table, the average density varies between 2 veh/km to 33 veh/km towards Tullubollo direction and 1 veh/km to 52 veh/km towards Sebeta direction. The average density varies between 1 veh/km to 23 veh/km towards Sululta direction and 1 veh/km to 49 veh/km towards Chancho direction. The average density varies between 1 veh/km to 11 veh/km towards Sendafa direction and 1 veh/km to 13 veh/km towards Debrebirhan direction.

Table 3. 4 Density variations with respect to time for all sections of the study

Speed-Density-Flow Variations	
Sebeta-Tullubollo Section	
	
Average density data measurement for Sebeta-Tullu bollo (towards Tullu bollo direction)	Average density data measurement for Sebeta-Tullu bollo (towards Sebeta direction)

Sululta-Chancho Section	
	
Average density data measurement for Sululta-Chancho (towards Sululta direction)	Average density data measurement for Sululta-Chancho (towards Chancho direction)
Sendafa-Debrebirhan Section	
	
Average density data measurement for Sendafa-Debrebirhan (towards Sendafa direction)	Average density data measurement for Sendafa-Debrebirhan (towards Debrebirhan direction)

CHAPTER FOUR: DATA ANALYSIS AND DISCUSSION

4.1. Traffic flow analysis

4.1.1 Introduction

Various classical traffic flow models developed earlier by different scholars were utilized to examine which of the developed models best depicts the actual traffic flow condition of the selected two-lane, two-way rural highways of Ethiopia.

A regression approach is used to discover the better model that represents the actual traffic flow condition of the selected highways. The different classical traffic flow models used in this research for the regression analysis are: Greenshields, Greenberg, Underwood, Drake, May and Schofer (North Western University Model), Drew, Multi-Regime Matrix, and Composite Models. Besides, the researcher derived useful inferences from the collected data by thorough analysis of the unknown parameters of the equations, and the overall model behavior.

4.1.2 Traffic Flow Models: Speed -Density Models

As it is discussed on Chapter-2 of this research paper, various researchers have proposed different models for single-regime, multi-regime or a combination/composite of models which can clearly shows the actual traffic condition of a given road section. For the case of this research paper, single-regime, multi-regime or a combination/composite of models were used to analyze and verify the actual traffic condition of the selected highways. Table 4.1 depicts the various models utilized for the research.

Table 4. 1 Speed flow models

No	Model Name	Equation	Transformation	Unknown Parameters
1	Greenshields Model	$u = u_f\left(1 - \frac{k}{k_j}\right)$	$u = u_f - \frac{u_f}{k_j}k$	u_f, k_j
2	Greenberg's Model	$u = u_o \ln\left(\frac{k_j}{k}\right)$	$u = u_o \ln k_j - u_o \ln k$	u_o, k_j
3	Underwood's Model	$u = u_f \exp\left[-\frac{k}{k_o}\right]$	$\ln u = \ln u_f - \frac{k}{k_o}$	u_f, k_o
4	Drake, May and Schofer's (North Western University) Model	$u = u_f \exp\left[-\frac{1}{2}\left(\frac{k}{k_o}\right)^2\right]$	$\ln u = \ln u_f - \frac{1}{2}\frac{k^2}{{k_o}^2}$	u_f, k_o
5	Drew's Model	$u = u_f\left[1 - \left(\frac{k}{k_j}\right)^{\frac{n+1}{2}}\right]$	$u = u_f - \frac{u_f}{k_j}k^{\frac{n+1}{2}}$	u_f, k_j, n
6	Multi-Regime Matrix Model	NA	NA	NA
7	Composite Models	NA	NA	NA

NA: Not Applicable

4.1.3 Fitting the Curve: Speed -Density Relationship

As it was discussed earlier, in order to check the already developed classical traffic flow models that best suit the actual traffic condition of the highways, a regression analysis (curve fitting technique), which is a powerful tool in data analysis and making predictions about the pattern of the data, helps in determining the best fit line or the model curve that better describes the relationship. Among the curves developed from traffic flow analysis, for the curve fitting technique of this research, the speed-density curve is priorly used for the analysis as it was witnessed from the earlier researches and studies that the speed-density relationship is not difficult to observe mathematically in the real world and various researchers also based their studies form this relationship. As it was discussed in chapter 2, the steady state equation can easily help in determining the speed-flow and flow-density curves after having determined the speed-density relationship.

4.1.4 Regression Analysis Based on One Minute Intervals

According to the Volume-2 of the HCM 2016 (TRB, 2016), because the two directions of traffic interact on a two-lane highway (due to passing movements), the manual suggests analyzing two-lane highways in a separate way. Hence, based on the guideline indicated in

the manual each direction of the selected highways is investigated thoroughly in a separately and in this sub section analysis was done for traffic flow aggregated for a one-minute interval. All outputs of the regression analysis for one-minute interval are specifically indicated in Table A.3-A.5 of Appendix A. Below, the regression analysis of the classical models developed earlier on the traffic data collected for the selected two-lane two-way rural highways was shown accordingly.

4.1.4.1 Greenshields Model

In this particular model, the known parameters are the exponents *m* and *l* which was obtained from the matrix developed by (May & Keller, 1967) which was (m=0 and *l*=2) and the free flow speed u_f and the jam density k_j are the unknown parameters. Figure 4.1 - Figure 4.3 depicts the curve fitting with the Greenshields Model utilizing data that are collected from the actual traffic condition of the selected highways.

Sebeta-Tullobollo's regression analysis yielded the following results:

Towards Tullobollo:	u_f = 91.68 km/hr	k_j= 38.88 veh/km	R^2=0.659
Towards Sebeta:	u_f = 93.49 km/hr	k_j= 46.35 veh/km	R^2=0.663

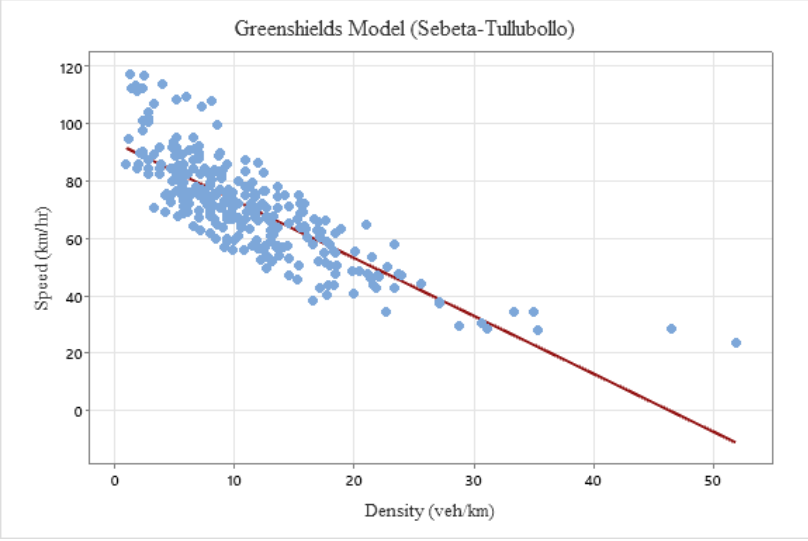


Figure 4. 1 Greenshields Model fitted to data taken on Sebeta-Tullobollo section towards Sebeta direction

Sululta-Chancho's regression analysis yielded the following results:

Towards Chancho:	u_f = 98.10 km/hr	k_j= 33.86 veh/km	R^2=0.596
Towards Sululta:	u_f = 97.87 km/hr	k_j= 26.26 veh/km	R^2=0.705

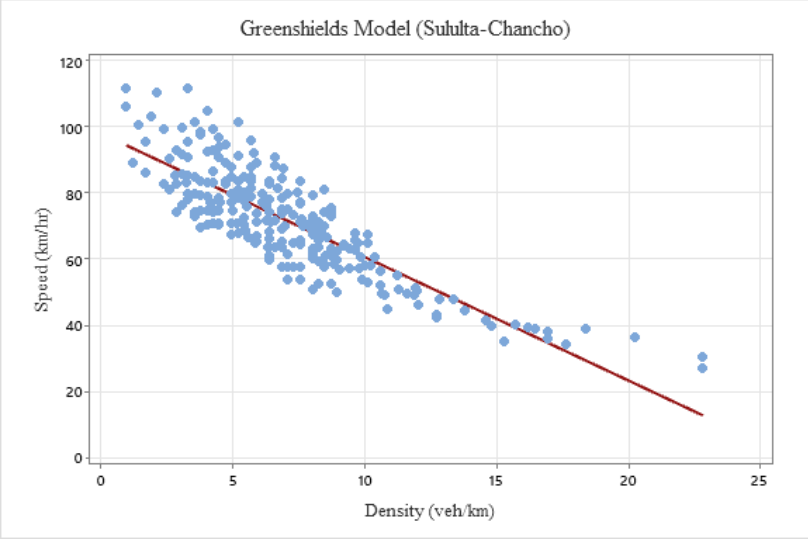


Figure 4. 2 Greenshields Model fitted to data taken on Sululta-Chancho section towards Sululta direction

Sendafa-Debrebirhan 's regression analysis yielded the following results:

Towards Debrebirhan:	u_f = 104.70 km/hr	k_j= 20.11 veh/km	R^2=0.645
Towards Sendafa:	u_f = 107.08 km/hr	k_j= 16.95 veh/km	R^2=0.825

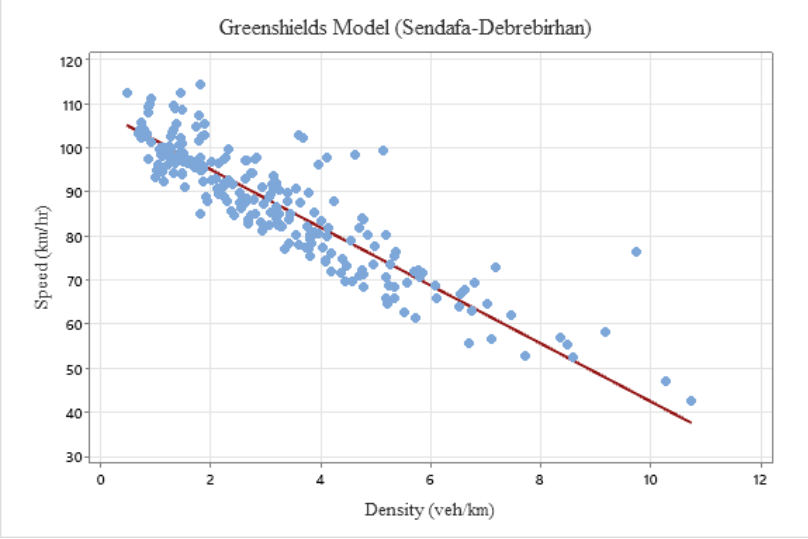


Figure 4. 3 Greenshields Model fitted to data taken on Sendafa-Debrebirhan section towards Sendafa direction

Based on the regression analysis, as an exceptional case for Sendafa-Debrebirhan section specifically towards Sendafa direction which has relatively high value of R^2, lower value of R^2 was obtained on other sections of the study. Looking through the regression figures, despite better estimation of the free flow speed observed on Sendafa-Debrebirhan section specifically towards Sendafa direction, certain areas of the free flow data did not represent by the model better. In addition, the model underestimates the value of speed for low density regime. Based on the foregoing information, it can be deduced that the Greenshields model is insufficient to accurately describing the actual situation of traffic in all study sections under consideration and did not properly reflect the whole range of traffic.

4.1.4.2 Greenberg's Model

In this particular model, the known parameters are the exponents *m* and *l* which was obtained from the matrix developed by (May & Keller, 1967) which was (m=0 and *l*=1) and the free flow speed u_o and the jam density k_j are the unknown parameters. Figure 4.4- B4.6 depicts the curve fitting with the Greenberg's Model utilizing data that are collected from the actual traffic condition of the selected highways.

Sebeta-Tullobollo's regression analysis yielded the following results:

Towards Tullobollo:	u_0 = 24.28 km/hr	k_j= 145.56 veh/km	R^2=0.750
Towards Sebeta:	u_0 = 20.72 km/hr	k_j= 278.21 veh/km	R^2=0.665

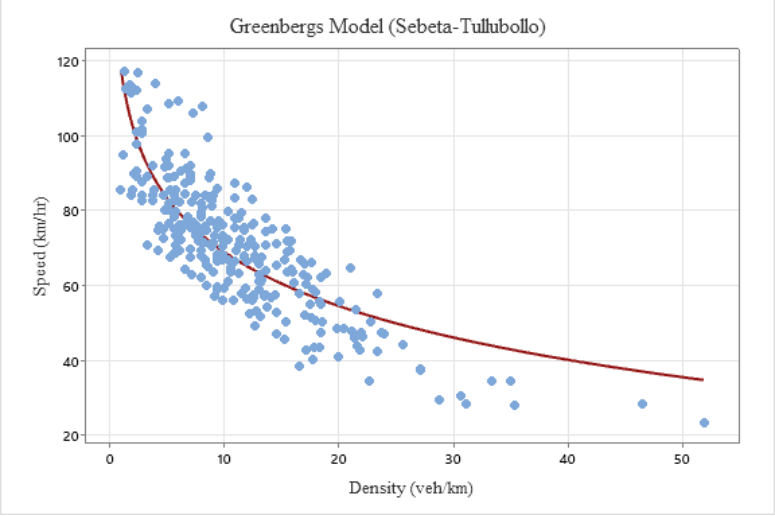


Figure 4. 4 Greenberg's Model fitted to data taken on Sebeta-Tullobollo section towards Sebeta direction

Sululta-Chancho's regression analysis yielded the following results:

Towards Chancho: u_0 = 30.01 km/hr k_j= 70.66 veh/km R^2=0.870
Towards Sululta: u_0 = 24.45 km/hr k_j= 116.65 veh/km R^2=0.662

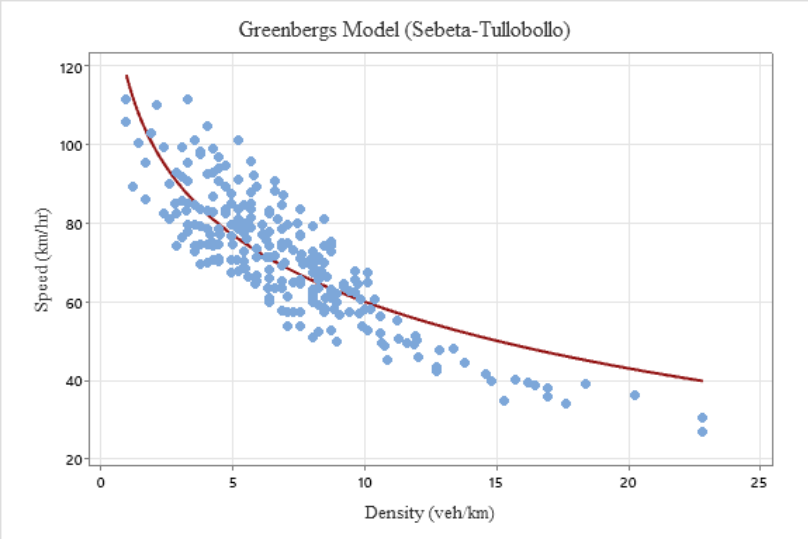


Figure 4. 5 Greenberg's Model fitted to data taken on Sululta-Chancho section towards Sululta direction

Sendafa-Debrebirhan 's regression analysis yielded the following results:

Towards Debrebirhan: u_0 = 15.95 km/hr k_j= 646.43 veh/km R^2=0.650
Towards Sendafa: u_0 = 18.17 km/hr k_j= 314.06 veh/km R^2=0.747

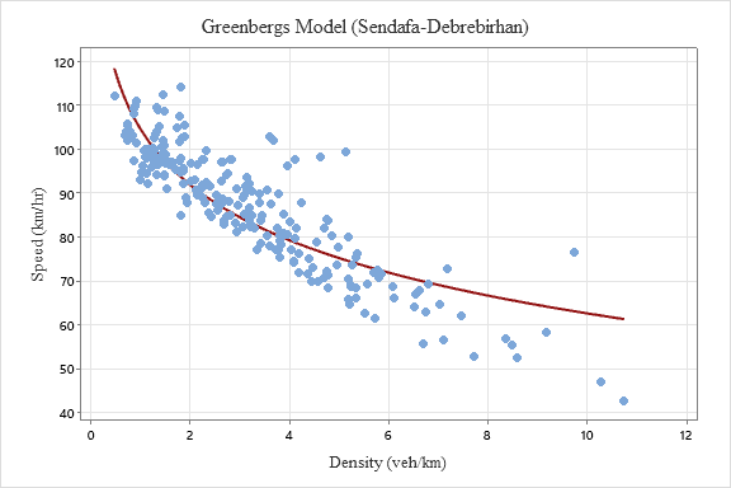


Figure 4. 6 Greenberg's Model fitted to data taken on Sendafa-Debrebirhan section towards Sendafa direction

According to the regression analysis results obtained using Greenberg's model, Greenberg's model relatively better characterizes the data on the lower density regime and fails to represent the data on the high-density regime for all study sections under consideration. The model's regression analysis reveals that it has an unreasonable speed for a zero density. Based on the foregoing information, it can be deduced that the Greenberg's model is insufficient for accurately describing the actual condition of traffic in all study sections under consideration and did not properly reflect the whole range of traffic as the value of $R^2$of the regression analysis also shows a minimum value.

4.1.4.3 Underwood's Model

For this particular model, the known parameters are the exponents *m* and *l* which was obtained from the matrix developed by (May & Keller, 1967) which was (*m=1* and *l=2*) and the free flow speed u_f and the optimum density k_o are the unknown parameters .Figure 4.7- 4.9 depicts the curve fitting with the Underwood's Model utilizing data that are collected from the actual traffic condition of the selected highways.

Sebeta-Tullobollo's regression analysis yielded the following results:

Towards Tullobollo:	u_f = 95.58 km/hr	k_o= 27.77 veh/km	R^2=0.728
Towards Sebeta:	u_f = 99.16 km/hr	k_o=30.30 veh/km	R^2=0.706

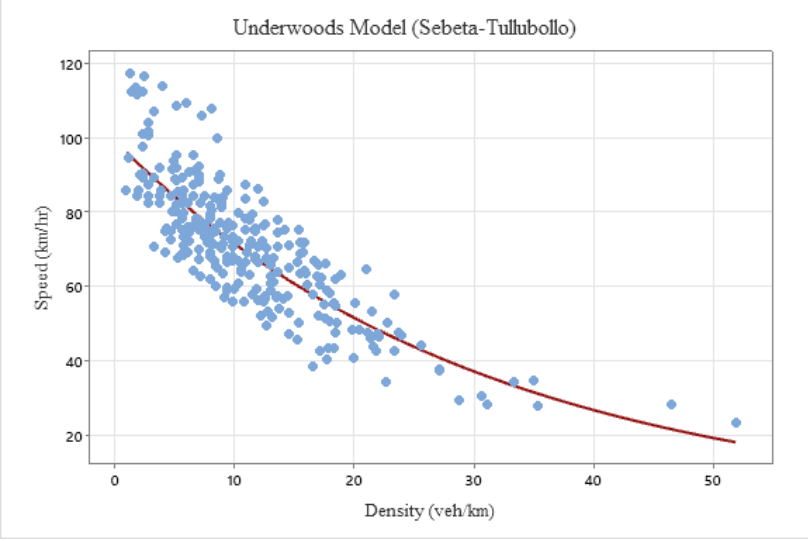


Figure 4. 7 Underwood's Model fitted to data taken on Sebeta-Tullobollo section towards Sebeta direction

Sululta-Chancho 's regression analysis yielded the following results:

Towards Chancho: u_f = 101.03 km/hr k_o= 21.74 veh/km R^2=0.769
Towards Sululta: u_f = 106.16 km/hr k_o= 16.67 veh/km R^2=0.716

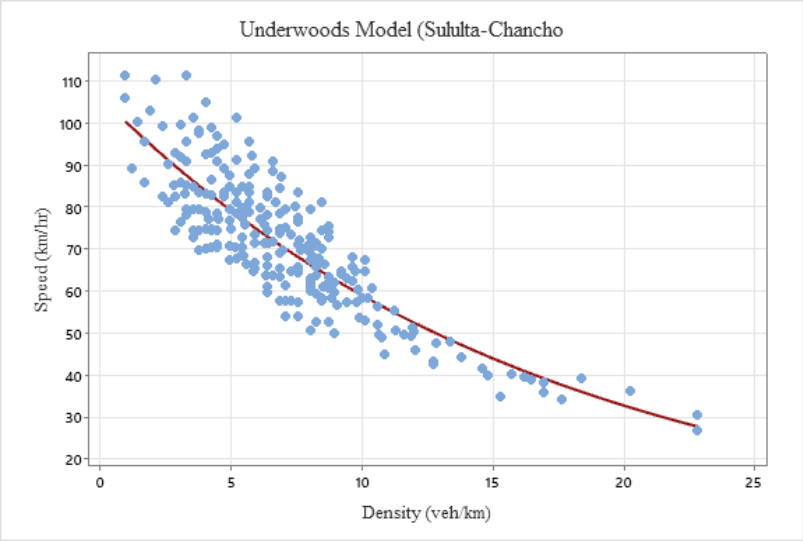


Figure 4. 8 Underwood's Model fitted to data taken on Sululta-Chancho section towards Sululta direction

Sendafa-Debrebirhan 's regression analysis yielded the following results:

Towards Debrebirhan: u_f = 106.33 km/hr k_o= 15.87 veh/km R^2=0.668
Towards Sendafa: u_f = 110.18 km/hr k_o= 12.66 veh/km R^2=0.800

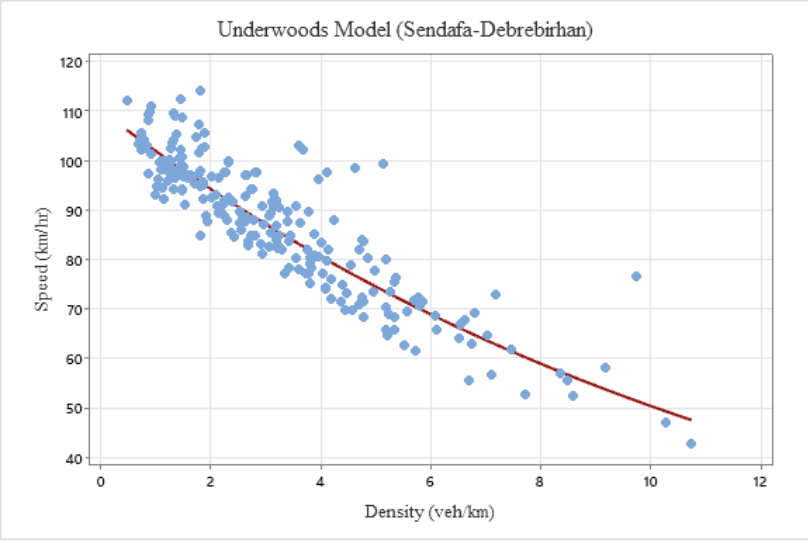


Figure 4. 9 Underwood's Model fitted to data taken on Sendafa-Debrebirhan section towards Sendafa direction

Even though the Underwood's Model depicts a higher value of R^2 than the Greenshields and Greenberg's model and shows a relatively a good representation for the high-density regime data, the model failed to fully represent the low-density data for all sections of the study. Based on this fact, the model was judged inadequate in characterizing the whole traffic range of the study section, despite its greater value of R^2 than Greenshields and Greenberg's model.

4.1.4.4 Drake, May, and Schofer's (North Western University) Model

The known parameters are (*m=1* and *l=3*) and the free flow speed u_f and the optimum density k_o are the unknown parameters. Figure 4.10- 4.12 depicts the curve fitting.

Sebeta-Tullobollo's regression analysis yielded the following results:

Towards Tullobollo:	u_f = 83.48 km/hr	k_o= 16.32 veh/km	R^2=0.596
Towards Sebeta:	u_f = 86.52 km/hr	k_o= 18.83 veh/km	R^2=0.636

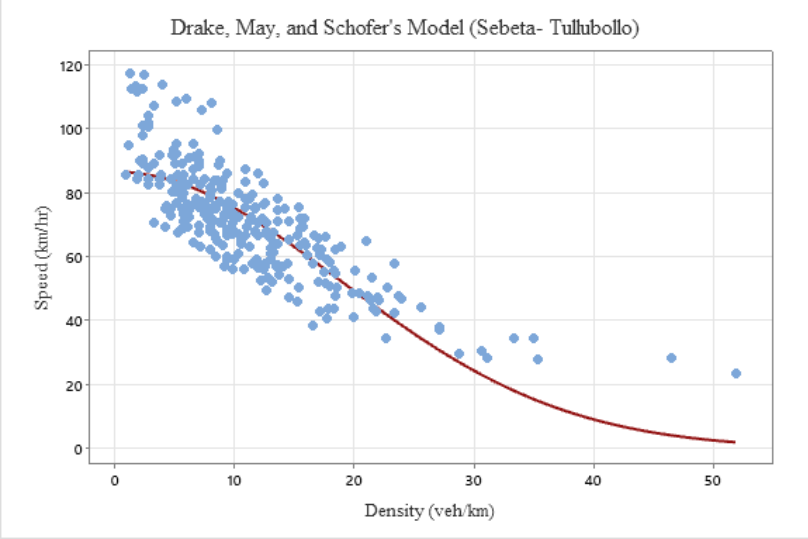


Figure 4. 10 Drake, May, and Schofer's Model fitted to data taken on Sebeta- Tullubollo section towards Sebeta direction

Sululta-Chancho 's regression analysis yielded the following results:

Towards Chancho:	u_f = 99.86 km/hr	k_o= 10.40 veh/km	R^2=0.663
Towards Sululta:	u_f = 88.32 km/hr	k_o= 11.34 veh/km	R^2=0.687

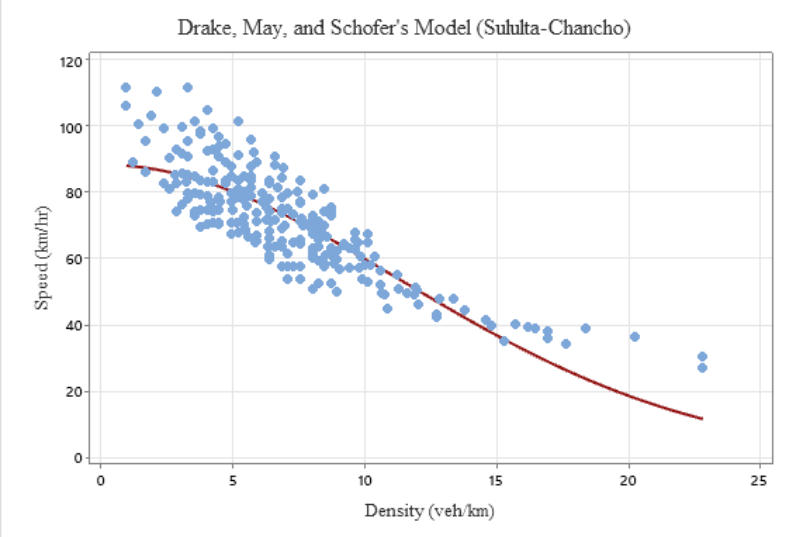


Figure 4. 11 Drake, May, and Schofer's Model fitted to data taken on Sululta- Chancho section towards Sululta direction

Sendafa- Debrebirhan 's regression analysis yielded the following results:

Towards Debrebirhan:	u_f = 97.42 km/hr	k_o= 8.05 veh/km	R^2=0.560
Towards Sendafa:	u_f = 99.01 km/hr	k_o= 6.98 veh/km	R^2=0.731

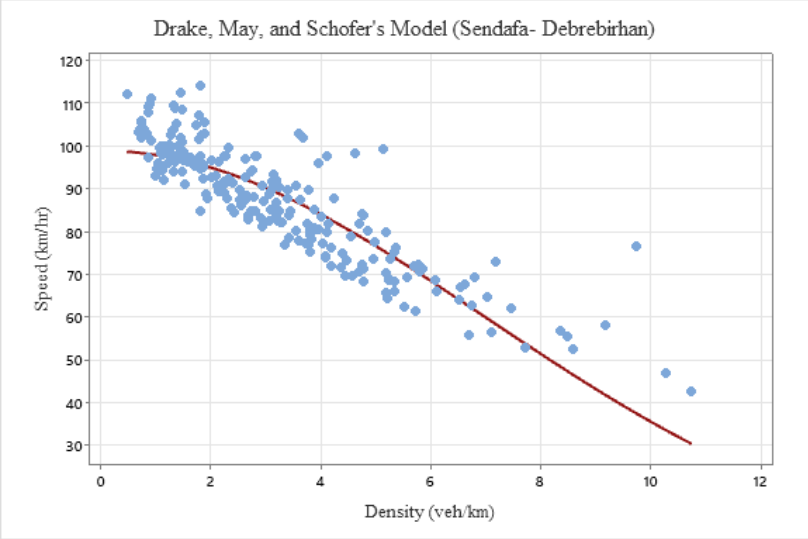


Figure 4. 12 Drake, May, and Schofer's Model fitted to data taken on Sendafa- Debrebirhan section towards Sendafa direction

The model did not fully represent the data on the low-density range and also underestimates the value of the speed for higher density regime for all study section under consideration. In

addition to this it can be noted that the value of R^2 is lower than both the Greenshields and Greenberg's model and hence, it can be concluded that the model cannot be utilized to represent traffic condition of the study sections.

4.1.4.5 Drew's Model

For this model, the known parameters are the exponents *m* and *l* which was obtained from the matrix developed by (May & Keller, 1967) which was (*m=0* and *l=2/3*) and the free flow speed u_f, the jam density k_j, and n values are the unknown parameters. Figure 4.13- 4.15 depicts the curve fitting with the Drew's model utilizing data that are collected from the actual traffic condition of the selected highways.

Sebeta-Tullobollo's regression analysis yielded the following results:

Towards Tullobollo: u_f = 91.67 km/hr k_j= 19.48 veh/km n= 0 R^2=0.656
Towards Sebeta: u_f = 93.49 km/hr k_j= 23.18 veh/km n= 0 R^2=0.662

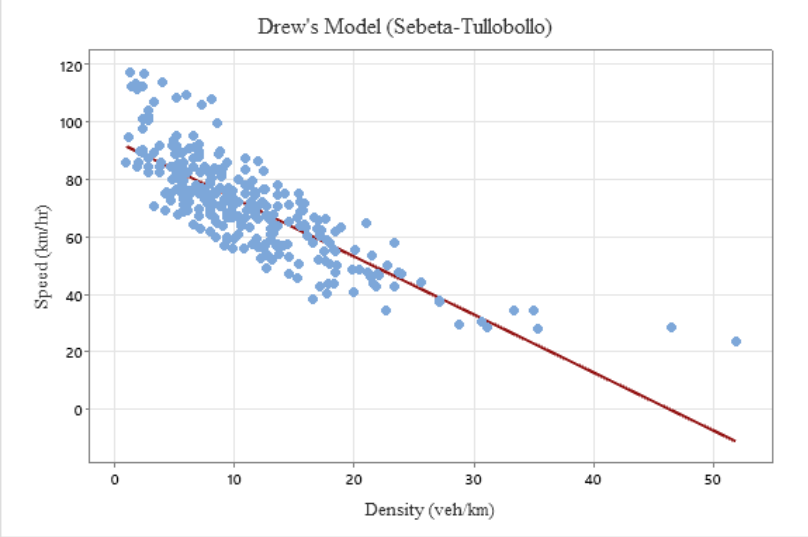


Figure 4. 13 Drew's Model fitted to data taken on Sebeta- Tullubollo section towards Sebeta direction

Sululta-Chancho's regression analysis yielded the following results:

Towards Chancho: u_f = 98.09 km/hr k_j= 16.93 veh/km n= 0 R^2=0.596
Towards Sululta: u_f = 97.87 km/hr k_j= 13.13 veh/km n= 0 R^2=0.705

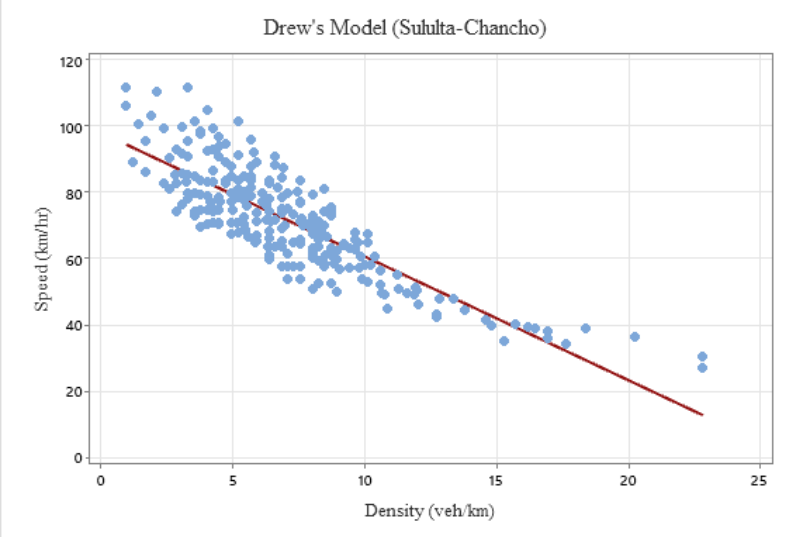


Figure 4. 14 Drew's Model fitted to data taken on Sululta-Chancho section towards Sululta direction

Sendafa-Debrebirhan's regression analysis yielded the following results:

Towards Debrebirhan: u_f = 104.66 km/hr k_j= 10.05 veh/km n= 0 R^2=0.645

Towards Sendafa: u_f = 107.08 km/hr k_j= 8.48 veh/km n= 0 R^2=0.788

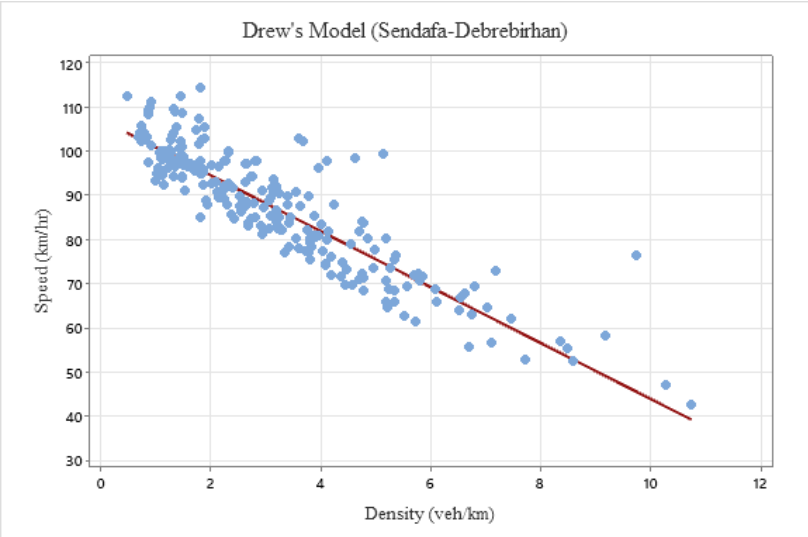


Figure 4. 15 Drew's Model fitted to data taken on Sendafa-Debrebirhan section towards Sendafa direction

Based on the regression analysis, as an exceptional case for Sendafa-Debrebirhan section specifically towards Sendafa direction which has relatively high value of R^2, lower value of R^2 was obtained on other sections of the study. Looking through the regression figures, despite

better estimation of the free flow speed observed on Sendafa-Debrebirhan section specifically towards Sendafa direction, certain areas of the free flow data did not represent by the model better. In addition, the model underestimates the value of speed for low density regime. Based on the foregoing information, it can be deduced that the Drews model is insufficient to accurately describing the actual situation of traffic in all study sections under consideration and did not properly reflect the whole range of traffic.

4.1.4.6 Multi-Regime Matrix Model

Based on the matrix of steady-state flow equations for different *m* and *l* combinations developed by (May & Keller, 1967) an analysis of the actual traffic data was done using the collected data so that to obtain the best equation that better describes the actual traffic condition with the aid of regression technique as it was done on the previous sections.

Given that the model's steady-state flow equations were obtained for different *m* an *l* combination as shown on Table 2.1 five different steady-state flow equations was checked for different *m* an *l* combination. Then, an equation that brings the value of the Coefficient of determination close to 1 or not, visually better describes the data on the different regimes, and that the calibrated parameter values obtained from the regression analysis are consistent with the real conditions was selected accordingly from those five different steady-state flow equations.

With the aid of the solver add-in package of the Excel and Minitab software, a trial-and-error technique was employed to produce a satisfactory result for this specific model since it was noted that different numbers of unknown variables existed on the matrix of steady-state flow equations.

Figure 4.16- 4.18 depicts the curve fitting with the multi-regime matrix model utilizing data that are collected from the actual traffic condition of the selected highways.

Sebeta-Tullobollo's regression analysis yielded the following results:

Towards Tullobollo:

Results of regression analysis for five different steady-state flow equations using *m* and *l* combination was shown as:

Case	*Equation*	*m and l conditions*	k_j	u_f	*c*	*l*	*m*	R^2
I	$u^{1-m} = ck_j{}^{l-1} + ck^{l-1}$	$m<1$ $l<1$, $m<1$ $l>1$	159.47		1278.4	0.98	0.00	0.749
II	$u^{1-m} = u_f{}^{1-m} + ck^{l-1}$	$m>1$ $l<1$, $m>1$ $l>1$		113.0	0.00	1.80	1.00	0.750
III	$u^{1-m} = c\ln(\frac{1}{k_j}) + c\ln(\frac{1}{k})$	$m<1$ $l=1$, $m>1$ $l=1$,	145.43		24.28	1.00	2.00	0.745
IV	$\ln u = c\ln(\frac{1}{k_j}) + c\ln(\frac{1}{k})$	$m=1$ $l=1$	4344736.65		0.32	1.00	1.00	0.721
V	$\ln u = c\ln u_f + ck^{l-1}$	$m=1$ $l>1$		135.7	0.205	1.55	1.00	0.747

From the regression analysis, the data are best depicted by the equation:

$u^{1-m} = u_f{}^{1-m} + ck^{l-1}$ with a condition of $m>1$ and $l>1$

Based on the regression analysis the unknown values are: l= 1.8, m= 1.0014, c= 0.00012, u_f= 113.0 and R^2=0.751

Towards Sebeta:

Results of regression analysis for five different steady-state flow equations using *m* and *l* combination was shown as:

Case	*Equation*	*m and l conditions*	k_j	u_f	*c*	*l*	*m*	R^2
I	$u^{1-m} = ck_j{}^{l-1} + ck^{l-1}$	$m<1$ $l<1$, $m<1$ $l>1$	308.24		1611.04	0.99	0.00	0.662
II	$u^{1-m} = u_f{}^{1-m} + ck^{l-1}$	$m>1$ $l<1$, $m>1$ $l>1$		106.26	0.00	1.87	1.01	0.708
III	$u^{1-m} = c\ln(\frac{1}{k_j}) + c\ln(\frac{1}{k})$	$m<1$ $l=1$, $m>1$ $l=1$,	278.42		20.72	1.00	3.00	0.664
IV	$\ln u = c\ln(\frac{1}{k_j}) + c\ln(\frac{1}{k})$	$m=1$ $l=1$	253740332.23		0.25	1.00	1.00	0.611
V	$\ln u = c\ln u_f + ck^{l-1}$	$m=1$ $l>1$		106.0	0.053	1.82	1.00	0.708

From the regression analysis, the data are best depicted by the equation:

$u^{1-m} = {u_f}^{1-m} + ck^{l-1}$ with a condition of m >1 and l >1

Based on the regression analysis the unknown values are: l= 1.87, m= 1.01, c= 0.000465, u_f= 106.26 and R^2=0.708

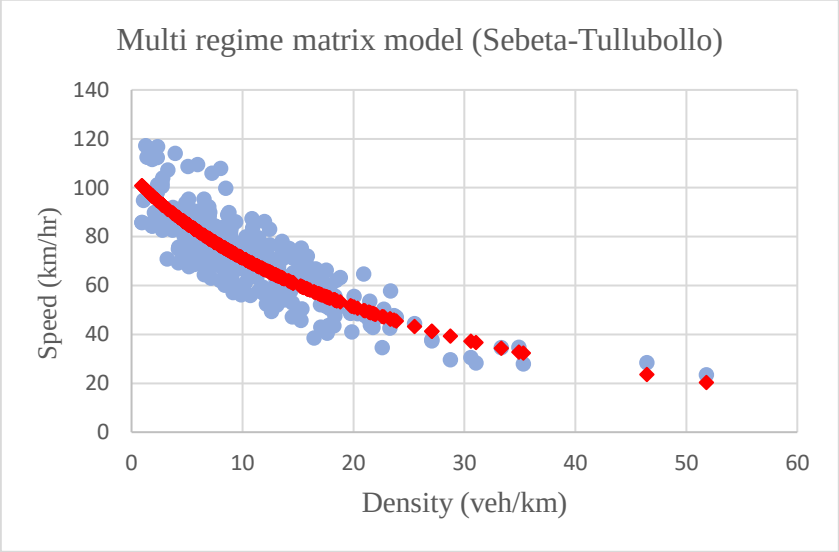


Figure 4. 16 Multi-Regime Matrix's Model fitted to data taken on Sebeta- Tullubollo section towards Sebeta direction

Sululta-Chancho's regression analysis yielded the following results:

Towards Sululta:

Results of regression analysis for five different steady-state flow equations using m and l combination was shown as:

Case	*Equation*	*m and l conditions*	k_j	u_f	*c*	*l*	*m*	R^2
I	$u^{1-m} = ck_j{}^{l-1} + ck^{l-1}$	m<1 l <1, m<1 l >1	127.5		1593.2	0.98	0.00	0.659
II	$u^{1-m} = {u_f}^{1-m} + ck^{l-1}$	m>1 l <1, m>1 l >1		100.3	0.00	2.18	1.01	0.718
III	$u^{1-m} = c\ln(\frac{1}{k_j}) + c\ln(\frac{1}{k})$	m<1 l =1, m>1 l =1,	116.65		24.45	1.0	2.00	0.661
IV	$\ln u = c\ln(\frac{1}{k_j}) + c\ln(\frac{1}{k})$	m=1 l =1	14051210.87		0.29	1.0	1.0	0.605
V	$\ln u = c\ln u_f + ck^{l-1}$	m=1 l >1	100.31		0.0346	2.18	1.0	0.713

From the regression analysis, the data are best depicted by the equation:

$u^{1-m} = {u_f}^{1-m} + ck^{l-1}$ with a condition of m >1 and l >1

Based on the regression analysis the unknown values are: *l*= 2.18, *m*= 1.01, c= 0.00022, u_f= 100.35 and R^2=0.718

Towards Chancho:

Results of regression analysis for five different steady-state flow equations using *m* and *l* combination was shown as:

Case	*Equation*	*m and l conditions*	k_j	u_f	*c*	*l*	*m*	R^2
I	$u^{1-m} = ck_j{}^{l-1} + ck^{l-1}$	*m*<1 *l* <1, *m*<1 *l* >1	99.00		1129.0	0.98	0.11	0.872
II	$u^{1-m} = u_f{}^{1-m} + ck^{l-1}$	*m*>1 *l* <1, *m*>1 *l* >1		215.2	0.01	1.41	1.01	0.871
III	$u^{1-m} = c\ln(\frac{1}{k_j}) + c\ln(\frac{1}{k})$	*m*<1 *l* =1, *m*>1 *l* =1,	70.70		30.01	1.0	3.00	0.870
IV	$\ln u = c\ln(\frac{1}{k_j}) + c\ln(\frac{1}{k})$	*m*=1 *l* =1	792763.62		0.36	1.0	1.0	0.839
V	$\ln u = c\ln u_f + ck^{l-1}$	*m*=1 *l* >1		214.1	0.514	1.40	1.0	0.877

From the regression analysis, the data are best depicted by the equation:
$u^{1-m} = ck^{l-1} - ck_j{}^{l-1}$ with a condition of *m* <1 and *l* <1

Based on the regression analysis the unknown values are: *l*= 0.98, *m*= 0.11, c= 1129.02, k_j=99.00 and R^2=0.872

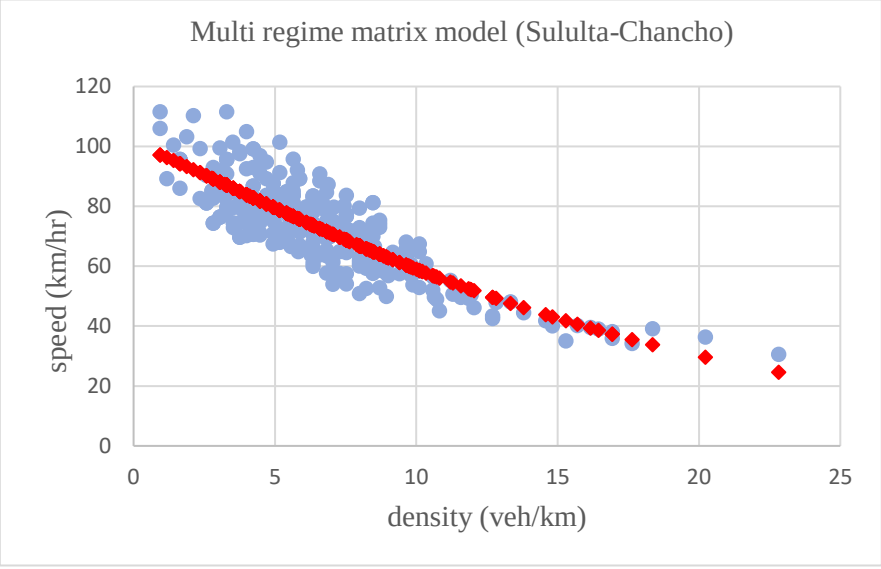


Figure 4. 17 Multi-Regime Matrix's Model fitted to data taken on Sululta- Chancho section towards Sululta direction

Sendafa-Debrebirhan's regression analysis yielded the following results:

Towards Sendafa:

Results of regression analysis for five different steady-state flow equations using *m* and *l* combination was shown as:

Case	*Equation*	*m and l conditions*	k_j	u_f	*c*	*l*	*m*	R^2
I	$u^{1-m} = ck_j{}^{l-1} + ck^{l-1}$	$m<1$ $l<1$, $m<1$ $l>1$	362.28		1445.0	0.99	0.00	0.745
II	$u^{1-m} = u_f{}^{1-m} + ck^{l-1}$	$m>1$ $l<1$, $m>1$ $l>1$		110.5	0.00	2.00	1.01	0.800
III	$u^{1-m} = c\ln(\frac{1}{k_j}) + c\ln(\frac{1}{k})$	$m<1$ $l=1$, $m>1$ $l=1$,	313.85		18.17	1.0	2.00	0.747
IV	$\ln u = c\ln(\frac{1}{k_j}) + c\ln(\frac{1}{k})$	$m=1$ $l=1$	19946946858.28		0.20	1.0	1.0	0.717
V	$\ln u = c\ln u_f + ck^{l-1}$	$m=1$ $l>1$		110.5	0.0797	1.99	1.0	0.795

From the regression analysis, the data are best depicted by the equation:
$u^{1-m} = u_f{}^{1-m} + ck^{l-1}$ with a condition of $m>1$ and $l>1$

Based on the regression analysis the unknown values are: l= 2.00, m= 1.01, c= 0.001026, u_f=110.49 and R^2=0.800

Towards Debrebirhan:

Results of regression analysis for five different steady-state flow equations using *m* and *l* combination was shown as:

Case	*Equation*	*m and l conditions*	k_j	u_f	*c*	*l*	*m*	R^2
I	$u^{1-m} = ck_j{}^{l-1} + ck^{l-1}$	$m<1$ $l<1$, $m<1$ $l>1$	851.97		966.84	0.98	0.00	0.646
II	$u^{1-m} = u_f{}^{1-m} + ck^{l-1}$	$m>1$ $l<1$, $m>1$ $l>1$		108.8	0.00	2.25	3.43	0.677
III	$u^{1-m} = c\ln(\frac{1}{k_j}) + c\ln(\frac{1}{k})$	$m<1$ $l=1$, $m>1$ $l=1$,	646.92		15.95	1.0	3.00	0.648
IV	$\ln u = c\ln(\frac{1}{k_j}) + c\ln(\frac{1}{k})$	$m=1$ $l=1$	488330020396.7		0.17	1.0	1.0	0.628
V	$\ln u = c\ln u_f + ck^{l-1}$	$m=1$ $l>1$		115.7	0.128	1.71	1.0	0.676

From the regression analysis, the data are best depicted by the equation:
$u^{1-m} = {u_f}^{1-m} + ck^{l-1}$ with a condition of m >1 and l >1

Based on the regression analysis the unknown values are: l= 2.25, m= 3.43, c= 1.998E-06, u_f= 108.84 and R^2=0.677

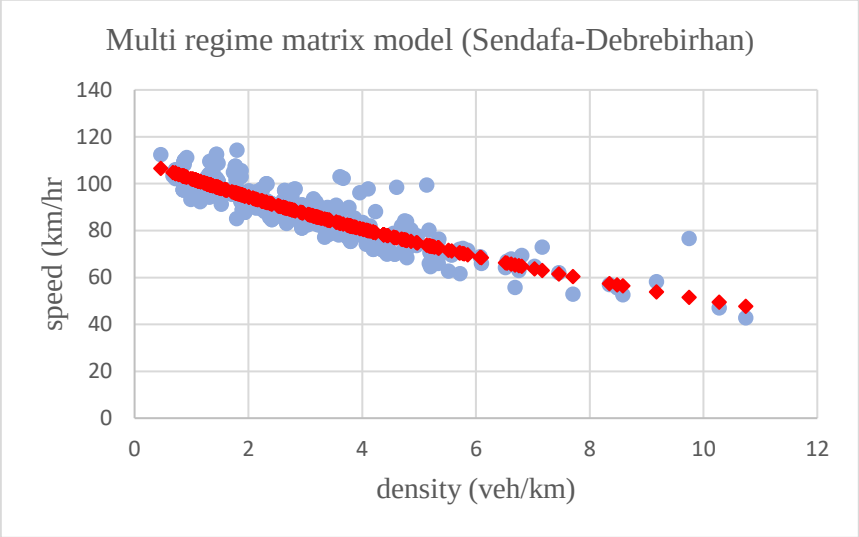


Figure 4. 18 Multi-Regime Matrix's Model fitted to data taken on Sendafa - Debrebirhan section towards Sendafa direction

The Multi-Regime Matrix's model shows a better representation of both the low density and higher density regime than other models in consideration and also have a higher value of R^2 comparing to the other models used for this research. In addition to this the model shows a reasonable free flow speed. In consideration to the above justifications, it can be deduced that the Multi-Regime Matrix's model is sufficient to accurately describe the actual situation of traffic in all study sections under consideration and properly reflect the whole range of traffic.

4.1.4.7 Composite Model

The Sebeta-Tullubollo and Sululta-Chancho sections were examined for a composite model since both traffic situations were seen throughout the data collection and analysis stage of the research. Unfortunately, the traffic condition on Sendafa-Debrebirhan experienced a free-flow regime, hence a composite model is not practicable for this section. For this reason, the composite model was applied for the two above mentioned sections where in this case the Underwood model was selected to represent free-flow/uncongested regime and the Multi

regime matrix was selected to represent the congested regime. For the purpose of this research, in order to get the boundary between the uncongested and congested regime, the density which is in coincident with the maximum capacity of flow for the uncongested regime was used as a separation point based on the fact that after the capacity for the uncongested regime part attained, a rise in density shows the onset of a congested condition. For this specific study, after identifying the candidate sections for the composite model analysis, which showed both traffic regimes both the congested and uncongested regime, a thorough analysis of composite models using the Multi regime matrix model for the free-flow/uncongested regime and the Underwood model for the congested regime was made and the Multi regime matrix model was found to be efficient in representing the traffic conditions of both situations as the value of R^2 is higher when using the Multi regime matrix model than the composite model, and finally the Multi regime matrix model was recommended for the next stage of research.

4.1.4.8 Speed-Density, Flow-Density, and Speed-Flow relationships

In order to arrive on the speed-density-flow relationships for a given time interval t, as it was discussed on the previous section primarily the speed-density relationships were determined because of its simplicity in formulating the relationships, and the corresponding flow-density, and speed-flow relationship for the study sections was determined using the steady state equation (Equation 2.1) of traffic flow. As it was previously stated the speed-density relationships of the traffic flow was best represented by the Multi-regime matrix model and the corresponding flow-density, and speed-flow relationship were derived from the speed-density relationship developed from the Multi-regime matrix model.

Table 4.2 presented an illustration of the multi-regime model describing the speed-density, flow-density and speed-flow relationship for Sebeta-Tullubolo section for both directions. The flow density relationship of this section was developed by using the steady state flow equation on the developed speed-density relationship of the multi-regime matrix model for the time interval under consideration. From the Table below, the maximum flow for Tullubollo direction was 932 veh/hr. The speed-flow relationship was also established using the data and showed on the Table. From the curve of speed-flow relationship the optimum speed of Tullubollo direction gives 35.3 km/hr.

Table 4. 2 Speed-Density, Flow-Density and Speed-Flow Relationships for Sebeta-Tullubollo Section

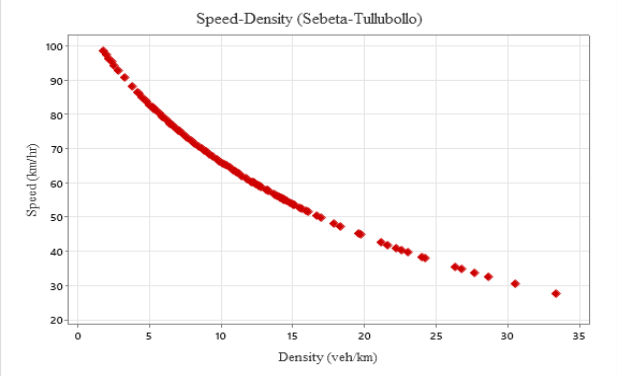
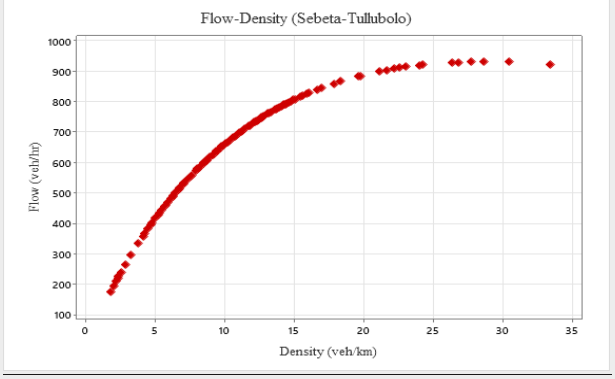
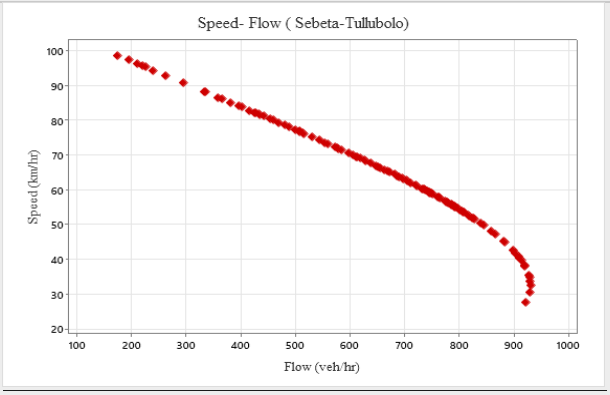
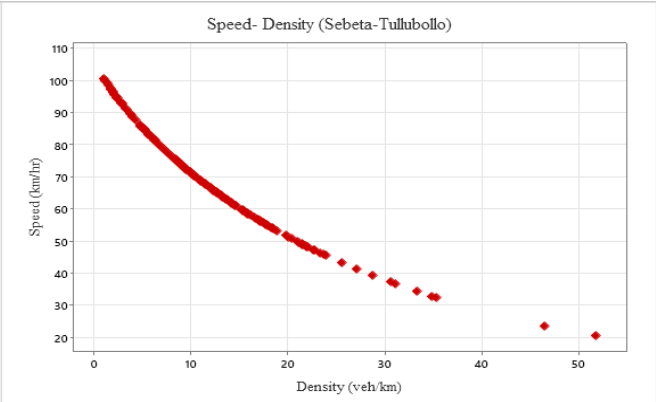
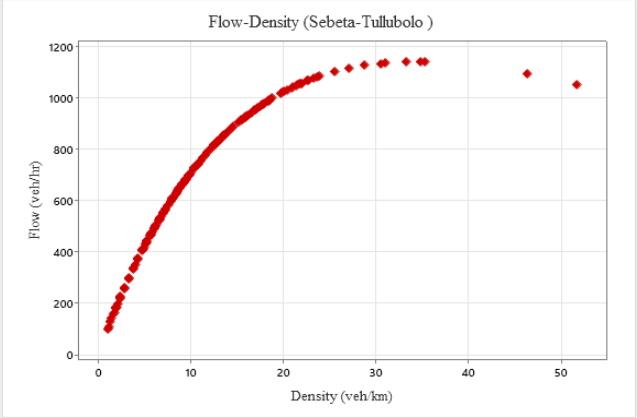
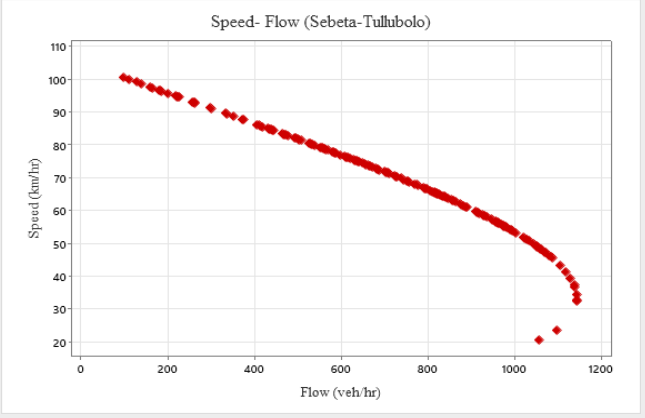
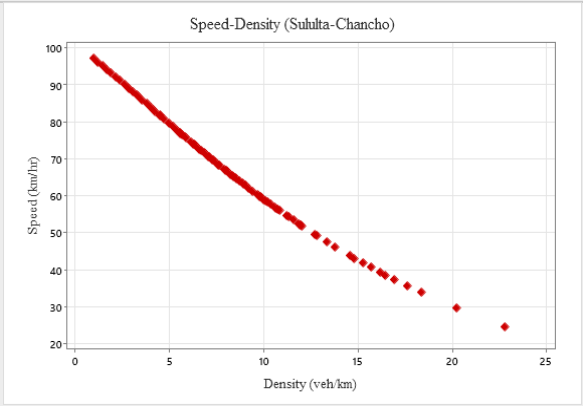
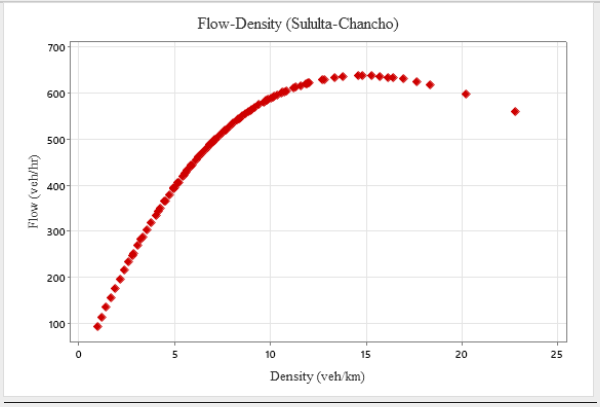
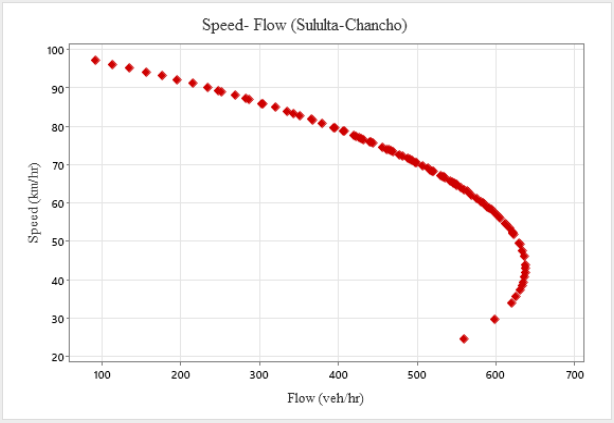
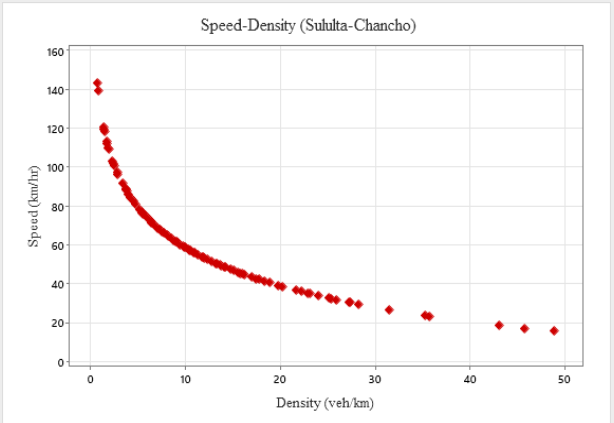
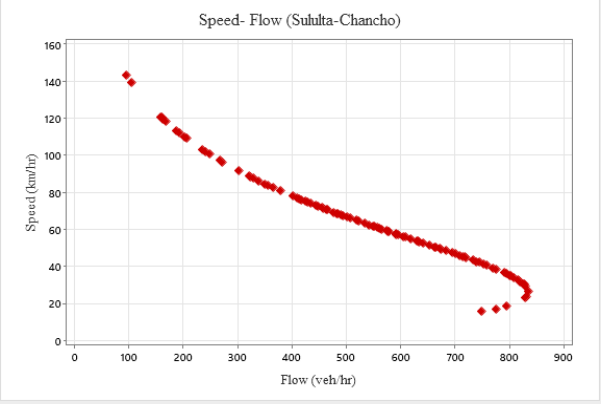
Speed-Density, Flow-Density and Speed-Flow Relationships Sebeta- Tullubollo Section	
	
Speed-Density relationship for traffic on Sebeta-Tullubolo section towards Tullubolo	Flow-Density relationship for traffic on Sebeta-Tullubolo section towards Tullubolo
	
Speed- Flow relationship for traffic on Sebeta-Tullubolo section towards Tullubolo	Speed-Density relationship for traffic on Sebeta-Tullubolo section towards Sebeta
	
Flow-Density relationship for traffic on Sebeta-Tullubolo section towards Sebeta	Speed- Flow relationship for traffic on Sebeta-Tullubolo section towards Sebeta

Table 4.3 presented an illustration of the multi-regime model describing the speed-density, flow-density and speed-flow relationship for Sululta-Chancho section for both directions. The

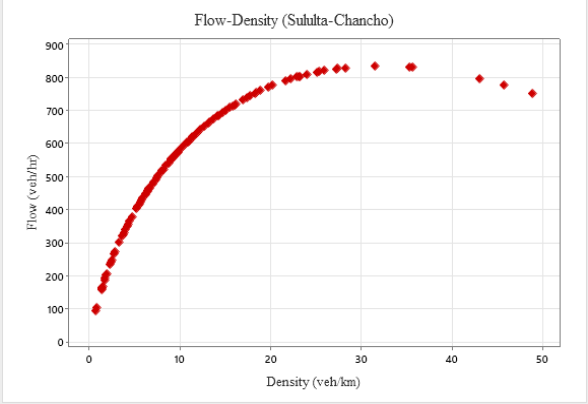
flow density relationship was developed by using the steady state flow equation on the developed speed-density relationship of the multi-regime matrix model for the time interval under consideration. From this relationship, it can be observed that the maximum flow observed in this section is 639 veh/hr for Sululta direction. The speed-flow relationship was also established once more using the data. From the curve of speed-flow relationship the optimum speed of this section observed was 44 km/hr.

Table 4. 3 Speed-Density, Flow-Density and Speed-Flow Relationships for Sululta- Chancho Section

Speed-Density, Flow-Density and Speed-Flow Relationships	
Sululta- Chancho Section	
	
Speed-Density relationship for traffic on Sululta-Chancho section towards Sululta	Flow-Density relationship for traffic on Sululta-Chancho section towards Sululta
	
Speed- Flow relationship for traffic on Sululta-Chancho section towards Sululta	Speed-Density relationship for traffic on Sululta-Chancho section towards Chancho



Speed- Flow relationship for traffic on Sululta-Chancho section towards Chancho

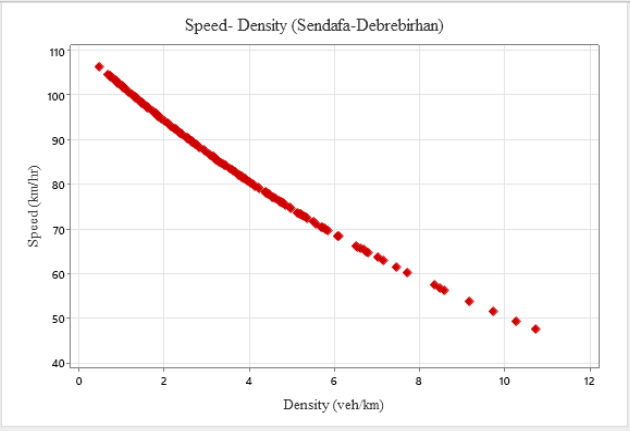


Flow-Density relationship for traffic on Sululta-Chancho section towards Chancho

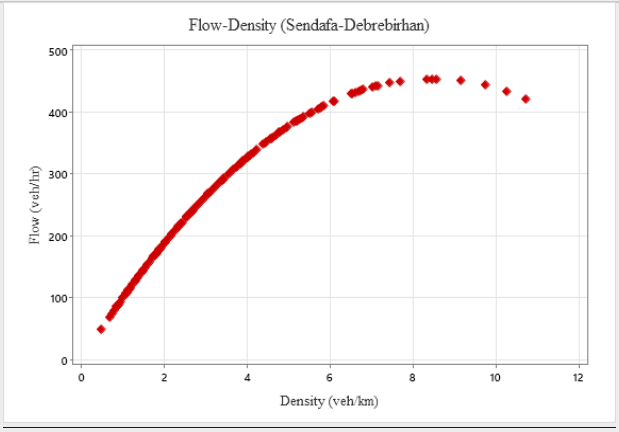
Table 4.4 presented an illustration of the multi-regime model describing the speed-density, flow density and speed-flow relationship for Sendafa-Debrebirhan section for both directions. The flow density relationship was developed by using the steady state flow equation on the developed speed-density relationship of the multi-regime matrix model for the time interval under consideration. From the figure above, it can be observed that the maximum flow observed for Sendafa direction was 454 veh/hr. The speed-flow relationship was also established once more using the data. From the curve of speed-flow relationship the optimum speed of this Sendafa direction gave 54 km/hr.

Table 4. 4 Speed-Density, Flow-Density and Speed-Flow Relationships for Sendafa- Debrebirhan Section

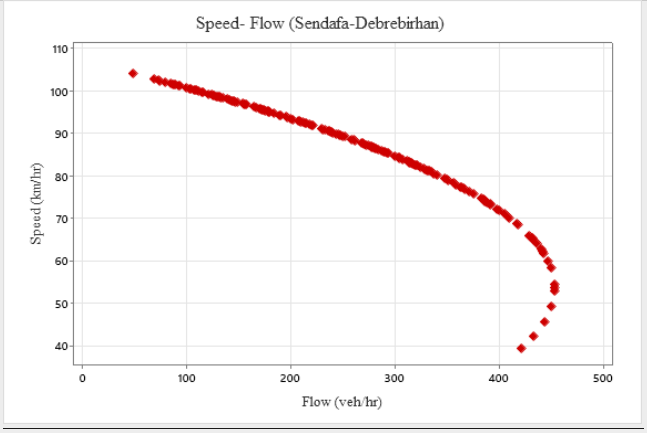
Speed-Density, Flow-Density and Speed-Flow Relationships
Sendafa- Debrebirhan Section



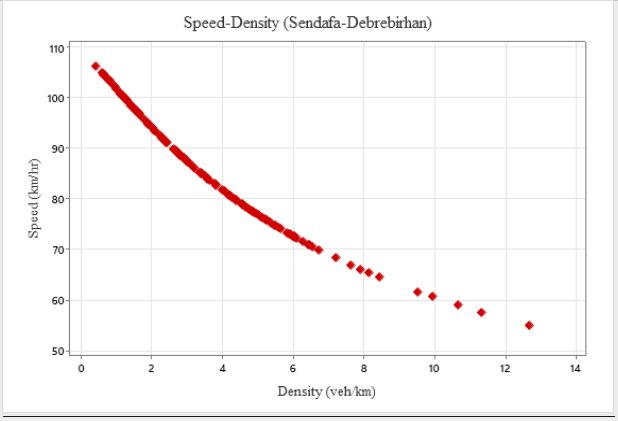
Speed-Density relationship for traffic on Sendafa-Debrebirhan section towards Sendafa



Flow-Density relationship for traffic on Sendafa-Debrebirhan section towards Sendafa



Speed- Flow relationship for traffic on Sendafa-Debrebirhan section towards Sendafa



Speed-Density relationship for traffic on Sendafa-Debrebirhan section towards Debrebirhan

4.1.5 Regression Analysis Based on 15 Minutes Intervals

In this study, in addition to the analysis of the two lane highways using 1 minute interval, analysis based on 15 minute averaged data was conducted to arrive at a conclusion on assessing the better model that describe the actual traffic conditon of the selected two-lane highways, as it was explicitly recommended a 15 min analysis period interval on the Exhibit 15-5 of the (TRB, 2016). The collected data was examined using the classical models outlined in the preceding sections, as it was previously done for 1-minute interval analysis. Finally, the analysis results for each classical model were presented in the Appendix A.

4.1.5.1 Greenshields Model

The regression approach is used again to calculate the unknown parameters of the Greenshields model, the free flow speed u_f and the jam density k_j. Figure 4.19- 4.21 showed the curve fitting with the Greenshields Model using data that was averaged for 15 minutes Sebeta-Tullobollo's regression analysis yielded the following results:

Towards Tullobollo:	u_f = 91.38 km/hr	k_j= 37.65 veh/km	R^2=0.818
Towards Sebeta:	u_f = 99.98 km/hr	k_j= 35.21 veh/km	R^2=0.837

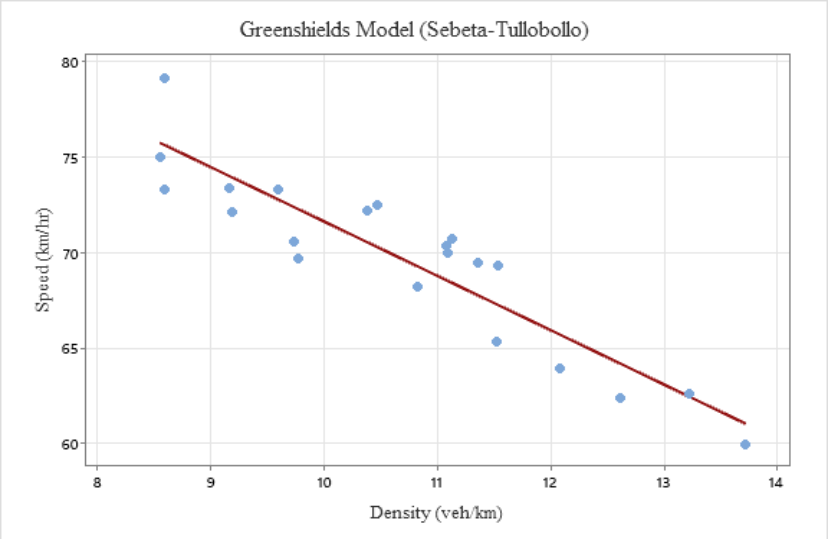


Figure 4. 19 Greenshields Model fitted to 15-min data taken on Sebeta-Tullobollo section towards Sebeta direction

Sululta-Chancho's regression analysis yielded the following results:

Towards Chancho: u_f = 107.3 km/hr k_j= 24.95 veh/km R^2=0.783
Towards Sululta: u_f = 109.3 km/hr k_j= 19.83 veh/km R^2=0.779

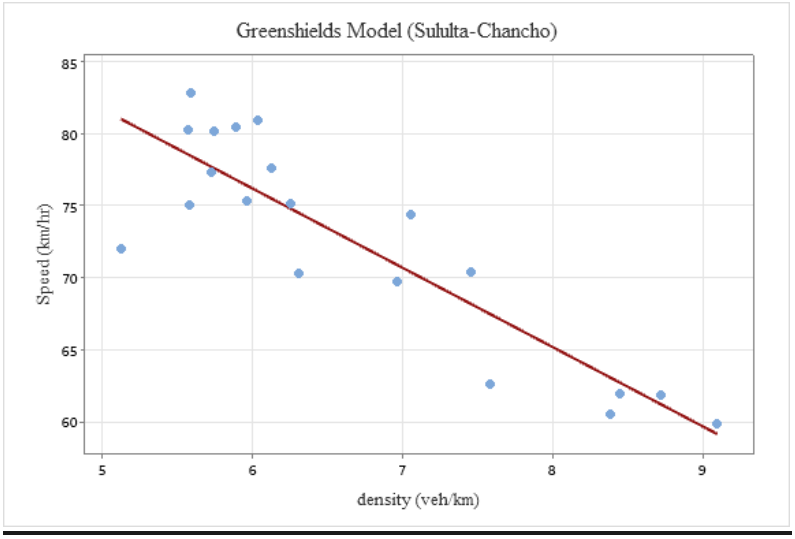


Figure 4. 20 Greenshields Model fitted to 15-min data taken on Sululta-Chancho section towards Sululta direction

Sendafa-Debrebirhan 's regression analysis yielded the following results:

Towards Debrebirhan: u_f = 95.61 km/hr k_j= 26.35 veh/km R^2=0.777
Towards Sendafa: u_f = 101.2 km/hr k_j= 17.29 veh/km R^2=0.768

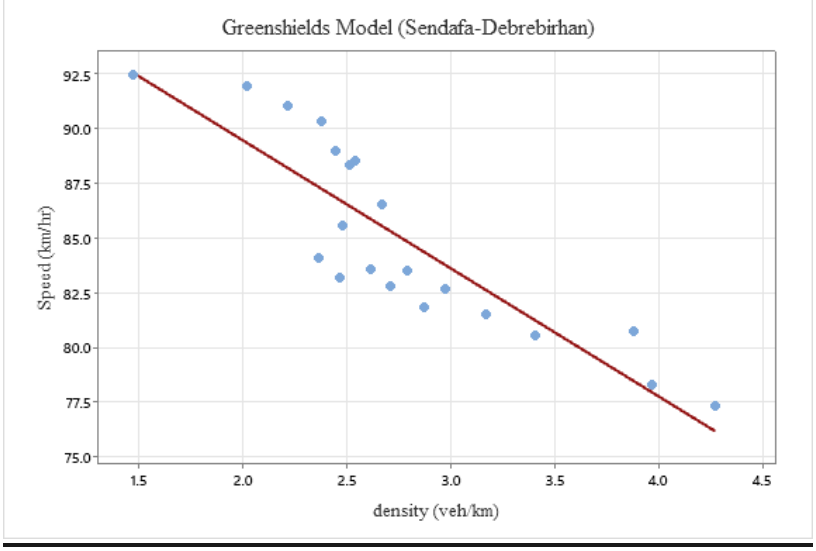


Figure 4. 21 Greenshields Model fitted to 15-min data taken on Sendafa-Debrebirhan section towards Sendafa direction

The Greenshields Model fitted to 15-min data gave a better description of the free flow speed on section of the study. In addition to this, the value jam density shows a realistic value as the value does not have big variation with the value of 1-min analysis. The value of R^2 obtained using regression shows a higher value from the corresponding 1-min analysis on all sections of the study. However, comparing to the other models the value of R^2 is less in describing the data. To this effect, the model was not selected to represent the actual data of the sections.

4.1.5.2 Greenberg's Model

The regression approach is used again to calculate the unknown parameters of the Greenberg model, the optimum speed u_o and the jam density k_j. Figure 4.22- 4.24 showed the curve fitting with the Greenberg's Model using data that was averaged for 15 minutes.

Sebeta-Tullobollo's regression analysis yielded the following results:

Towards Tullobollo:	u_0 = 23.67 km/hr	k_j= 168.61 veh/km	R^2=0.789
Towards Sebeta:	u_0 = 30.10 km/hr	k_j= 107.09 veh/km	R^2=0.819

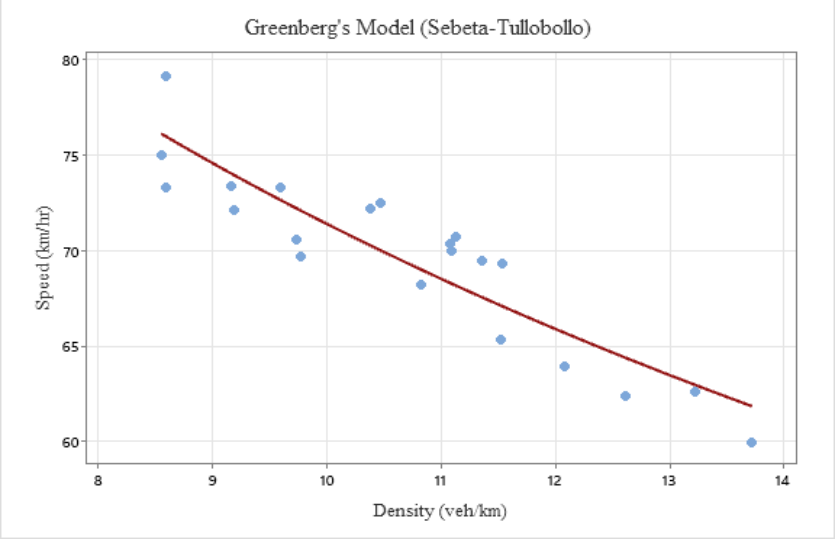


Figure 4. 22 Greenberg's Model fitted to 15-min data taken on Sebeta-Tullobollo section towards Sebeta direction

Sululta-Chancho's regression analysis yielded the following results:

Towards Sululta: u_0 = 37.05 km/hr k_j= 46.734 veh/km R^2=0.749

Towards Chancho: u_0 = 37.9 km/hr k_j= 53.35 veh/km R^2=0.820

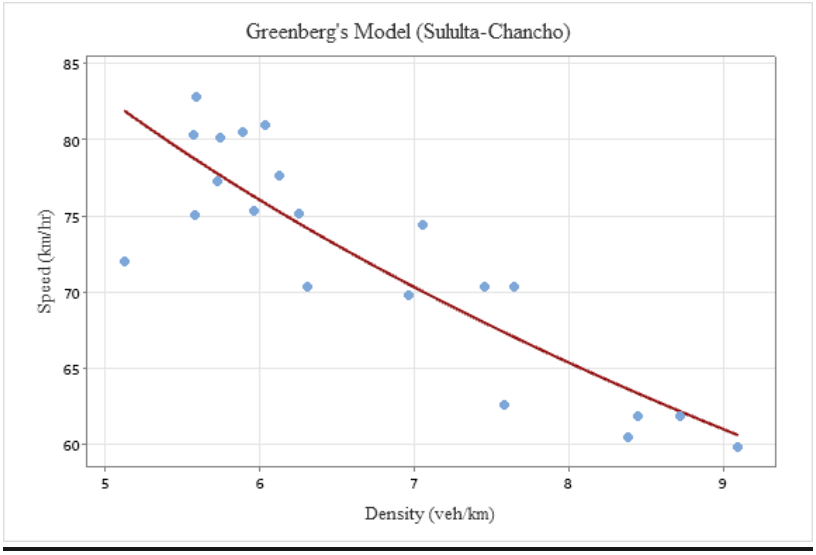


Figure 4. 23 Greenberg's Model fitted to 15-min data taken on Sululta-Chancho section towards Sululta direction

Sendafa-Debrebirhan's regression analysis yielded the following results:

Towards Sendafa: u_0 = 16.39 km/hr k_j= 480.34 veh/km R^2=0.780

Towards Debrebirhan: u_0 = 9.774 km/hr k_j= 16694.52 veh/km R^2=0.665

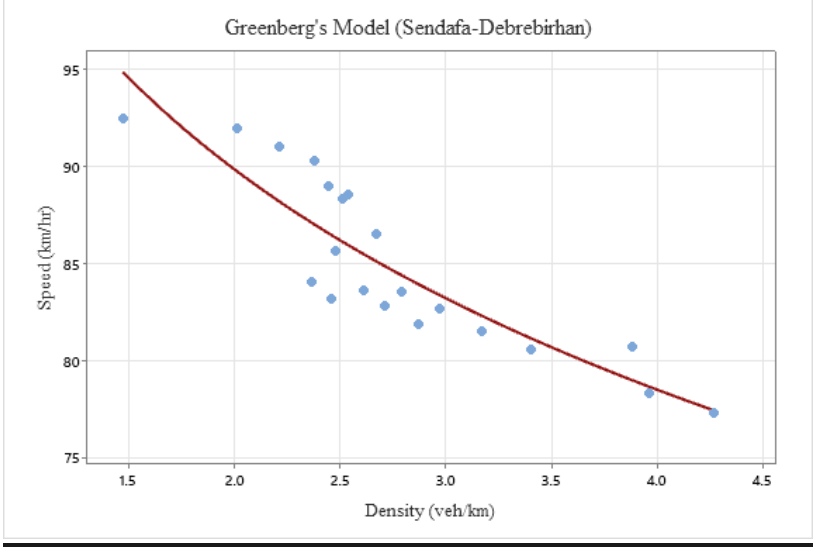


Figure 4. 24 Greenberg's Model fitted to 15-min data taken on Sendafa-Debrebirhan section towards Sendafa direction

Even though, the Greenberg's Model fitted to 15-min data gave a better description of the free flow speed, the value of jam density and optimum speed of Sendafa-Debrebirhan section shows unrealistic value. The value of R^2 obtained using regression shows a higher value from the corresponding 1-min analysis on all sections of the study. However, comparing to the other models the value of R^2 is less in describing the data. To this effect, the model was not selected to represent the actual data of the sections

4.1.5.3 Underwood's Model

The regression approach is used again to calculate the unknown parameters of the Underwood model, the free flow speed u_f and the optimum density k_o. Figure 4.25- 4.27 showed the curve fitting with the Underwood's Model using data that was averaged for 15 minutes.

Sebeta-Tullobollo's regression analysis yielded the following results:

Towards Tullobollo:	u_f = 96.86 km/hr	k_o= 27.03 veh/km	R^2=0.809
Towards Sebeta:	u_f = 108.29 km/hr	k_o= 23.81 veh/km	R^2=0.830

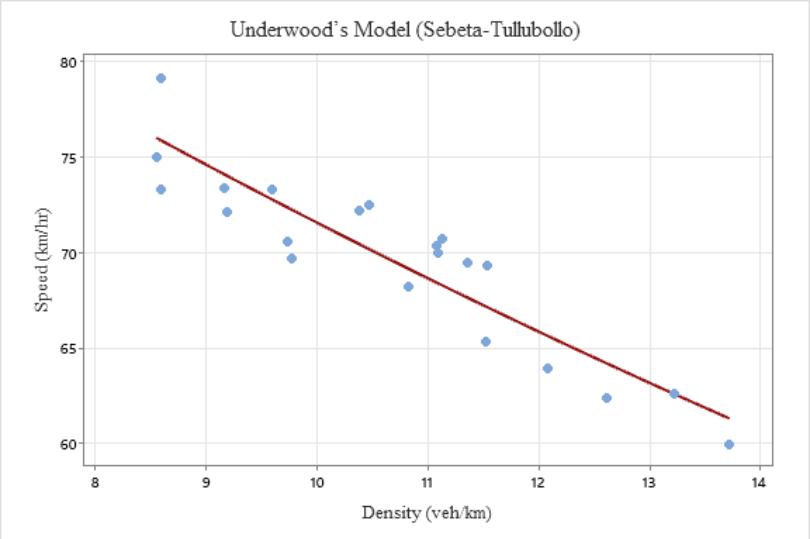


Figure 4. 25 Underwood's Model fitted to 15-min data taken on Sebeta-Tullubollo section towards Sebeta direction

Sululta-Chancho 's regression analysis yielded the following results:

Towards Sululta: u_f = 121.25 km/hr k_o= 12.99 veh/km R^2=0.762

Towards Chancho: u_f = 118.12 km/hr k_o=16.13 veh/km R^2=0.806

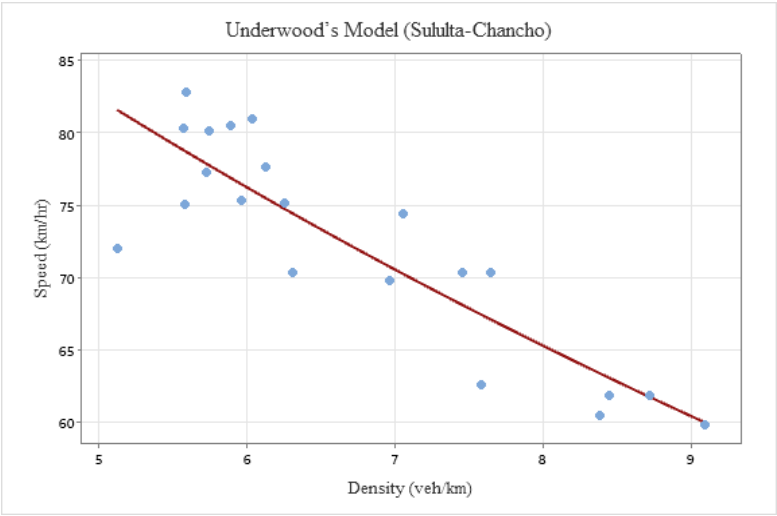


Figure 4. 26 Underwood's Model fitted to 15-min data taken on Sululta-Chancho section towards Sululta direction

Sendafa-Debrebirhan's regression analysis yielded the following results:

Towards Sendafa: u_f = 102.77 km/hr k_o= 14.49 veh/km R^2=0.775

Towards Debrebirhan: u_f = 96.15 km/hr k_o=23.81 veh/km R^2=0.783

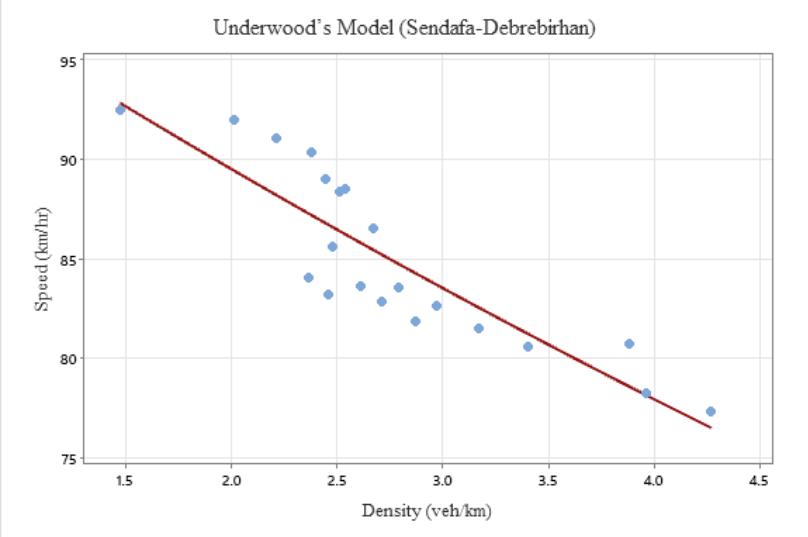


Figure 4. 27 Underwood's Model fitted to 15-min data taken on Sendafa-Debrebirhan section towards Sendafa direction

The Underwood's Model fitted to 15-min data gave a better description of the free flow speed on section of the study. In addition to this, the value optimum density shows a realistic value as the value does not have big variation with the value of 1-min analysis. The value of R^2 obtained using regression shows a higher value from the corresponding 1-min analysis on all sections of the study. However, comparing to the other models the value of R^2 is less in describing the data. To this effect, the model was not selected to represent the actual data of the sections.

4.1.5.4 Drake, May, and Schofer's (North Western University) Model

The regression approach is used again to calculate the unknown parameters of the Underwood model, the free flow speed u_f and the optimum density k_o. Figure 4.28- 4.30 showed the curve fitting with the North Western's Model using data that was averaged for 15 minutes.

Sebeta-Tullobollo's regression analysis yielded the following results:

Towards Tullobollo:	u_f = 80.57 km/hr	k_o= 16.65 veh/km	R^2=0.827
Towards Sebeta:	u_f = 86.69 km/hr	k_o= 16.23 veh/km	R^2=0.843

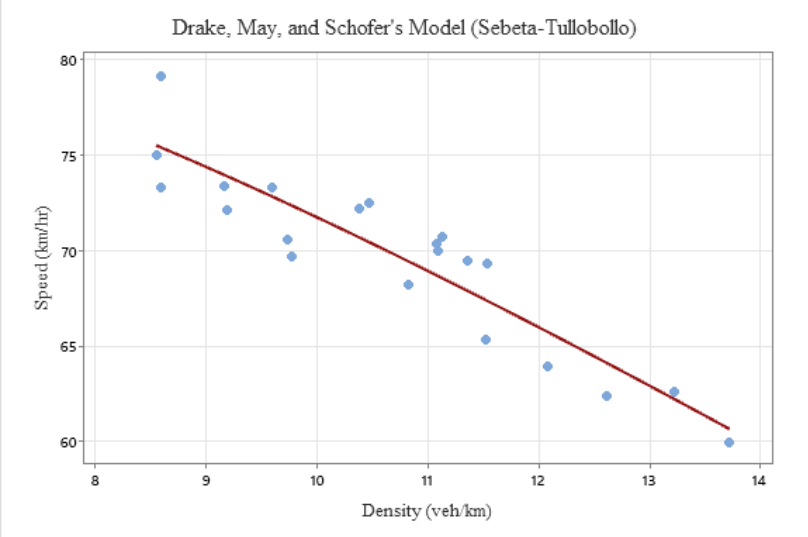


Figure 4. 28 Drake, May, and Schofer's Model fitted to 15-min data taken on Sebeta-Tullobollo section towards Sebeta direction

Sululta-Chancho 's regression analysis yielded the following results:

Towards Sululta: u_f = 79.01 km/hr k_o=5.59 veh/km R^2=0.793
Towards Chancho: u_f = 92.01 km/hr k_o=11.85 veh/km R^2=0.759

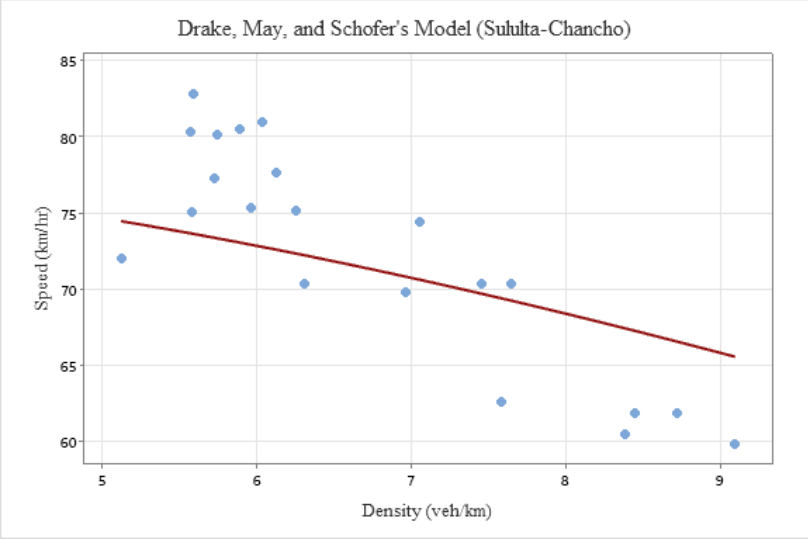


Figure 4. 29 Drake, May, and Schofer's Model fitted to 15-min data taken on Sululta-Chancho section towards Sululta direction

Sendafa-Debrebirhan's regression analysis yielded the following results:

Towards Sendafa: u_f = 93.16 km/hr k_o= 6.59 veh/km R^2=0.729
Towards Debrebirhan: u_f = 90.58 km/hr k_o=8.51 veh/km R^2=0.709

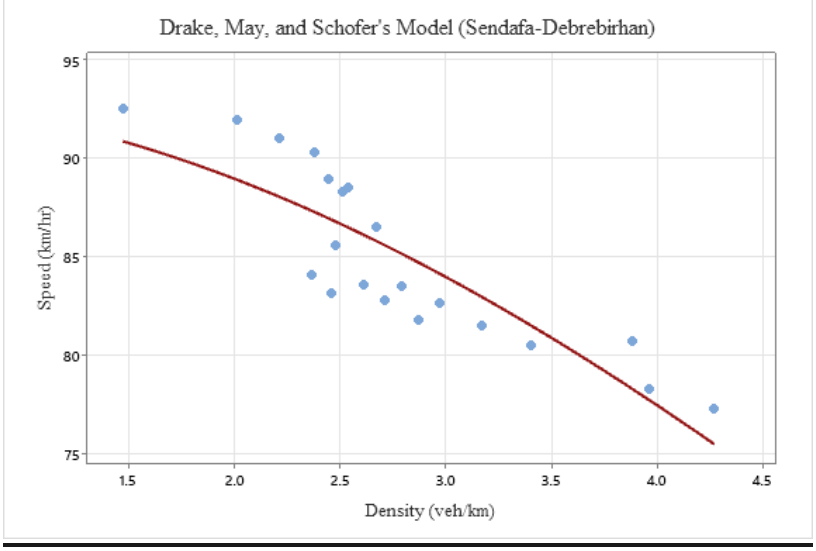


Figure 4. 30 Drake, May, and Schofer's Model fitted to 15-min data taken on Sendafa-Debrebirhan section towards Sendafa direction

The Drake, May, and Schofer's Model exhibits higher value of R^2 than the Greenshields, Greenbergs and Underwoods model for the given data averaged in 15-min interval for all study sections. In addition, the model underestimates the value of free flow speed for Sululta-Chancho section specifically towards Sululta direction. To this effect, the model was not selected to represent the actual data of the sections.

4.1.5.5 Drew's Model

The regression approach is used again to calculate the unknown parameters of the Drew model, the free flow speed u_f, the jam density k_j, and n values. Figure 4.31- 4.33 showed the curve fitting with the North Western's Model using data that was averaged for 15 minutes interval.

Sebeta-Tullobollo's regression analysis yielded the following results:

Towards Tullobollo:	u_f = 79.04 km/hr	k_j= 18.19 veh/km	n= 1.037	R^2=0.828
Towards Sebeta:	u_f = 81.36 km/hr	k_j= 17.53 veh/km	n= 1.592	R^2=0.848

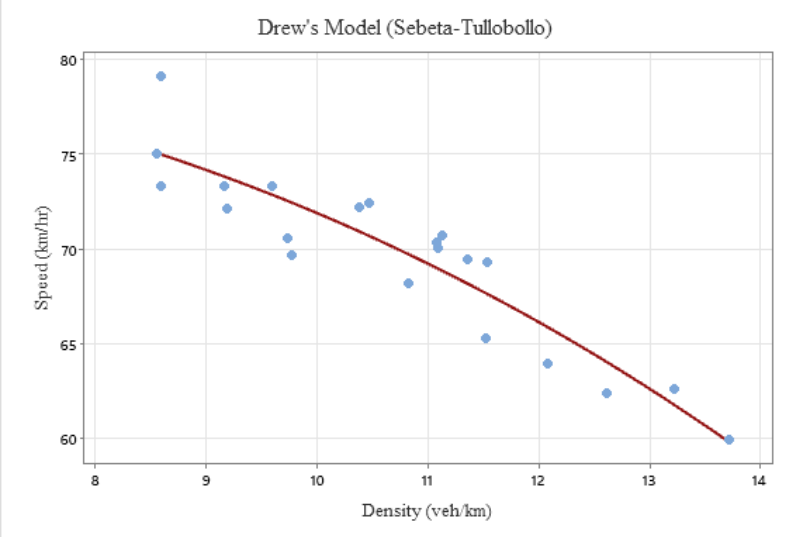


Figure 4. 31 Drew's Model fitted to 15-min data taken on Sebeta-Tullobollo section towards Sebeta direction

Sululta-Chancho's regression analysis yielded the following results:

Towards Sululta: u_f = 85.69 km/hr k_j= 10.69 veh/km n= 1.657 R^2=0.785
Towards Chancho: u_f = 107.26 km/hr k_j= 12.47 veh/km n= 0 R^2=0.783

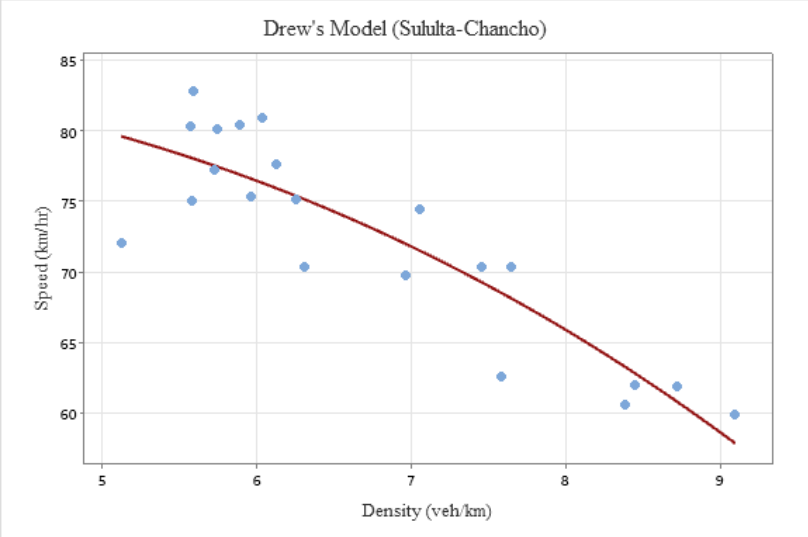


Figure 4. 32 Drew's Model fitted to 15-min data taken on Sululta-Chancho section towards Sululta direction

Sendafa-Debrebirhan's regression analysis yielded the following results:

Towards Sendafa: u_f = 101.16 km/hr k_j= 8.64 veh/km n= 0 R^2=0.768
Towards Debrebirhan: u_f = 95.61 km/hr k_j= 13.18 veh/km n= 0 R^2=0.777

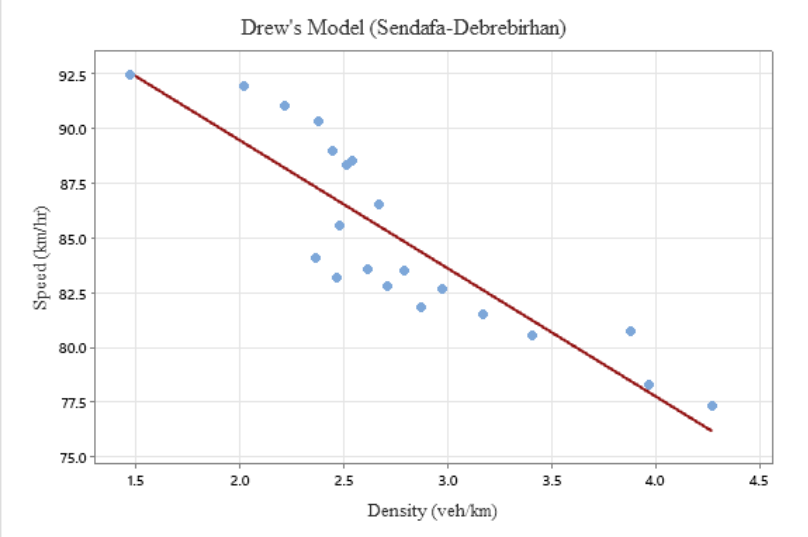


Figure 4. 33 Drew's Model fitted to 15-min data taken on Sendafa-Debrebirhan section towards Sendafa direction

The drew's model showed highest value of R^2 than all the models under consideration except the multi-regime matrix model which shows a better representation of the actual data with high value of R^2 than other models. To this effect, the model was not selected to represent the actual data of the sections.

4.1.5.6 Multi- Regime matrix's Model

Based on the matrix of steady-state flow equations for various m and l combinations developed by (May & Keller, 1967), actual traffic data was analyzed in order to find the optimal equation that, when integrated with regression technique, better captures the current traffic condition. As it was noted that varying numbers of unknown variables existed on the matrix of steady-state flow equations, a trial-and-error technique was used to generate a good outcome for this particular model using the solver add-in package of the Excel and Minitab software. Figure 4.34- 4.36 depicted the curve fitting with the multi-regime matrix model utilizing data that was averaged for 15 minutes.

Sebeta-Tullobollo's regression analysis yielded the following results:

Towards Tullobollo:

Case	*Equation*	*m and l conditions*	k_j	u_f	*c*	*l*	*m*	R^2
I	$u^{1-m} = ck_j{}^{l-1} + ck^{l-1}$	$m<1$ $l<1$, $m<1$ $l>1$	183.02		1119.9	0.98	0.00	0.788
II	$u^{1-m} = u_f{}^{1-m} + ck^{l-1}$	$m>1$ $l<1$, $m>1$ $l>1$		113.00	0.00	1.80	1.00	0.802
III	$u^{1-m} = c\ln(\frac{1}{k_j}) + c\ln(\frac{1}{k})$	$m<1$ $l=1$, $m>1$ $l=1$,	168.57		23.67		2.00	0.789
IV	$\ln u = c\ln(\frac{1}{k_j}) + c\ln(\frac{1}{k})$	$m=1$ $l=1$	2067898.70		0.34			0.776
V	$\ln u = c\ln u_f + ck^{l-1}$	$m=1$ $l>1$		77.99	0.0005	3.43		0.829

From the regression analysis, the data are best depicted by the equation:
$\ln(\frac{u_f}{u}) = ck^{l-1}$ with a condition of $m=1$ and $l>1$

Based on the regression analysis the unknown values are: l= 3.43, c= 0.000537, u_f= 77.96 and R^2=0.829

Towards Sebeta:

Case	*Equation*	*m and l conditions*	k_j	u_f	*c*	*l*	*m*	R^2
I	$u^{1-m} = ck_j{}^{l-1} + ck^{l-1}$	$m<1$ $l<1$, $m<1$ $l>1$	112.39		1783.8	0.98	0.00	0.819
II	$u^{1-m} = u_f{}^{1-m} + ck^{l-1}$	$m>1$ $l<1$, $m>1$ $l>1$		110.55	0.00	1.94	1.01	0.829
III	$u^{1-m} = c\ln(\frac{1}{k_j}) + c\ln(\frac{1}{k})$	$m<1$ $l=1$, $m>1$ $l=1$,	107.06		30.10		3.00	0.819
IV	$\ln u = c\ln(\frac{1}{k_j}) + c\ln(\frac{1}{k})$	$m=1$ $l=1$	226200.62		0.43			0.810
V	$\ln u = c\ln u_f + ck^{l-1}$	$m=1$ $l>1$		80.35	9.27834 E-05	4.08		0.848

From the regression analysis, the data are best depicted by the equation:
$\ln(\frac{u_f}{u}) = ck^{l-1}$ with a condition of $m=1$ and $l>1$

Based on the regression analysis the unknown values are: l= 4.08, m= 1.0014, c= 9.27834E-05, u_f= 80.35 and R^2=0.848

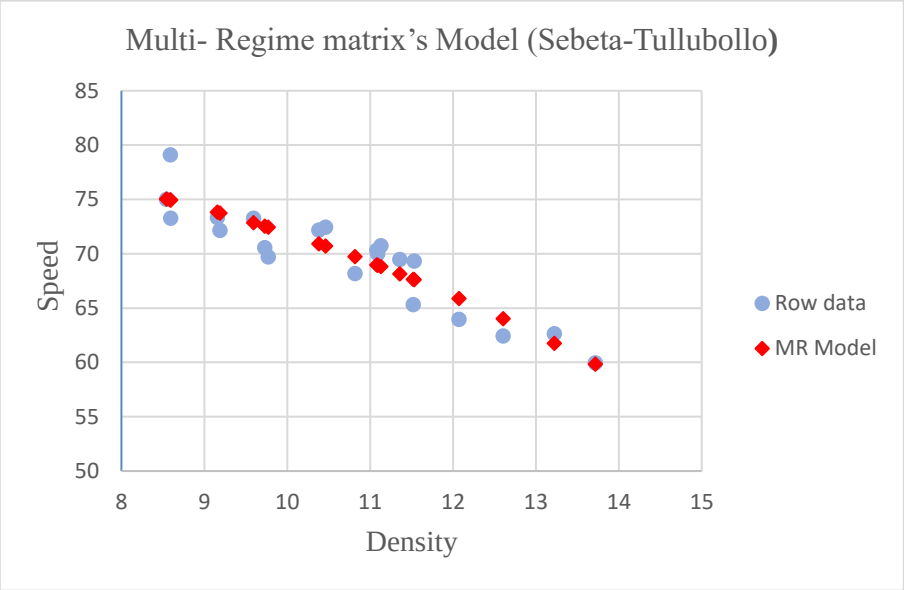


Figure 4. 34 Multi- Regime matrix's Model fitted to 15-min data taken on Sebeta-Tullobollo section towards Sebeta direction

Sululta-Chancho's regression analysis yielded the following results:

Towards Sululta:

Case	*Equation*	*m and l conditions*	k_j	u_f	*c*	*l*	*m*	R^2
I	$u^{1-m} = ck_j{}^{l-1} + ck^{l-1}$	*m*<1 *l* <1, *m*<1 *l* >1	48.58		1923.7	0.98	0.00	0.749
II	$u^{1-m} = u_f{}^{1-m} + ck^{l-1}$	*m*>1 *l* <1, *m*>1 *l* >1		84.14	0.00	4.31	1.03	0.787
III	$u^{1-m} = c\ln(\frac{1}{k_j}) + c\ln(\frac{1}{k})$	*m*<1 *l* =1, *m*>1 *l* =1,	46.75		37.05		2.00	0.749
IV	$\ln u = c\ln(\frac{1}{k_j}) + c\ln(\frac{1}{k})$	*m*=1 *l* =1	28758.19		0.51			0.735
V	$\ln u = c\ln u_f + ck^{l-1}$	*m*=1 *l* >1		84.19	0.0002	4.28		0.787

From the regression analysis, the data are best depicted by the equation:
$\ln(\frac{u_f}{u}) = ck^{l-1}$ with a condition of *m* =1 and *l* >1

Based on the regression analysis the unknown values are: l= 4.28, c= 0.000265, u_f= 84.19 and R^2=0.788

Towards Chancho:

Case	*Equation*	*m and l conditions*	k_j	u_f	*c*	*l*	*m*	R^2
I	$u^{1-m} = ck_j{}^{l-1} + ck^{l-1}$	*m*<1 *l* <1, *m*<1 *l* >1	73.50		1099.2	0.98	0.14	0.822208
II	$u^{1-m} = u_f{}^{1-m} + ck^{l-1}$	*m*>1 *l* <1, *m*>1 *l* >1		843.44	0.02	1.44	1.65	0.826
III	$u^{1-m} = c\ln(\frac{1}{k_j}) + c\ln(\frac{1}{k})$	*m*<1 *l* =1, *m*>1 *l* =1,	53.35		37.90		3.00	0.820
IV	$\ln u = c\ln(\frac{1}{k_j}) + c\ln(\frac{1}{k})$	*m*=1 *l* =1	21674.6		0.54			0.826
V	$\ln u = c\ln u_f + ck^{l-1}$	*m*=1 *l* >1		2516.59	2.59	1.15		0.826

From the regression analysis, the data are best depicted by the equation:
$u^{1-m} = ck^{l-1} - ck_j{}^{l-1}$ with a condition of *m* <1 and *l* <1

Based on the regression analysis the unknown values are: *l*= 0.98, *m*=0.14, *c*= 1099.2, u_f= 73.50 and R^2=0.822

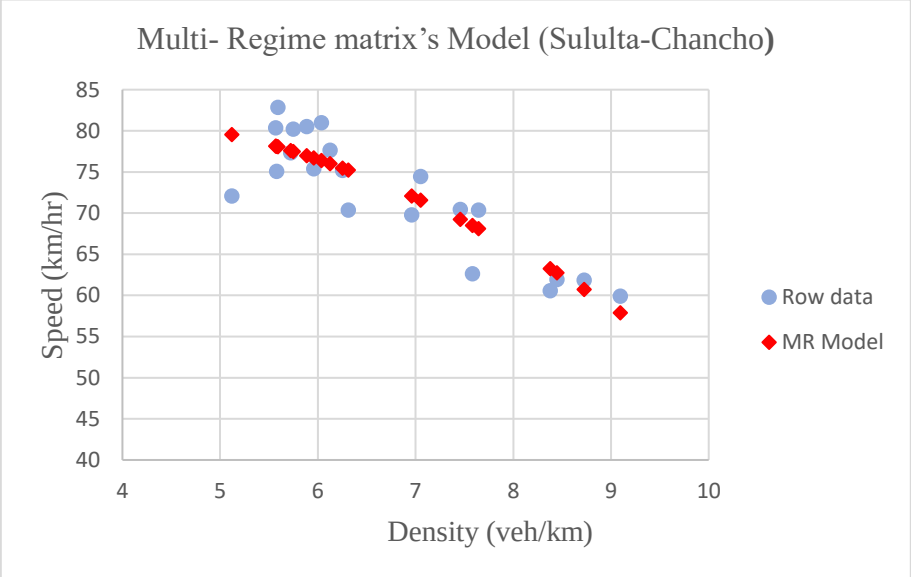


Figure 4. 35 Multi- Regime matrix's Model fitted to 15-min data taken on Sululta-Chancho section towards Sululta direction

Sendafa-Debrebirhan's regression analysis yielded the following results:

Towards Sendafa:

Case	*Equation*	*m and l conditions*	k_j	u_f	*c*	*l*	*m*	R^2
I	$u^{1-m} = ck_j{}^{l-1} + ck^{l-1}$	*m*<1 *l* <1, *m*<1 *l* >1	516.65		1024.2	0.98	0.00	0.779
II	$u^{1-m} = u_f{}^{1-m} + ck^{l-1}$	*m*>1 *l* <1, *m*>1 *l* >1		126.16	0.00	1.49	1.01	0.783
III	$u^{1-m} = c\ln(\frac{1}{k_j}) + c\ln(\frac{1}{k})$	*m*<1 *l* =1, *m*>1 *l* =1,	481.91		16.38	1.00	2.00	0.780
IV	$\ln u = c\ln(\frac{1}{k_j}) + c\ln(\frac{1}{k})$	*m*=1 *l* =1	34424731338.5		0.19	1.00	1.00	0.775
V	$\ln u = c\ln u_f + ck^{l-1}$	*m*=1 *l* >1		124.93	0.233	1.50	1.00	0.783

From the regression analysis, the data are best depicted by the equation:
$\ln(\frac{u_f}{u}) = ck^{l-1}$ with a condition of *m* =1 and *l* >1

Based on the regression analysis the unknown values are: l= 1.504, c= 0.23299, u_f= 124.94 and R^2=0.783

Towards Debrebirhan:

Case	*Equation*	*m and l conditions*	k_j	u_f	*c*	*l*	*m*	R^2
I	$u^{1-m} = ck_j{}^{l-1} + ck^{l-1}$	*m*<1 *l* <1, *m*<1 *l* >1	1652.37		679.09	0.98	0.00	0.804
II	$u^{1-m} = u_f{}^{1-m} + ck^{l-1}$	*m*>1 *l* <1, *m*>1 *l* >1		108.46	0.00	2.26	3.46	0.796
III	$u^{1-m} = c\ln(\frac{1}{k_j}) + c\ln(\frac{1}{k})$	*m*<1 *l* =1, *m*>1 *l* =1,	16740.78		9.77	1.00	3.00	0.804
IV	$\ln u = c\ln(\frac{1}{k_j}) + c\ln(\frac{1}{k})$	*m*=1 *l* =1	18750334		0.11	1.00	1.00	0.803
V	$\ln u = c\ln u_f + ck^{l-1}$	*m*=1 *l* >1	1.00	140.83	0.397	1.23	1.00	0.805

From the regression analysis, the data are best depicted by the equation:
$\ln(\frac{u_f}{u}) = ck^{l-1}$ with a condition of *m* =1 and *l* >1

Based on the regression analysis the unknown values are: l= 1.23, c= 0.3977, u_f= 140.83 and R^2=0.805

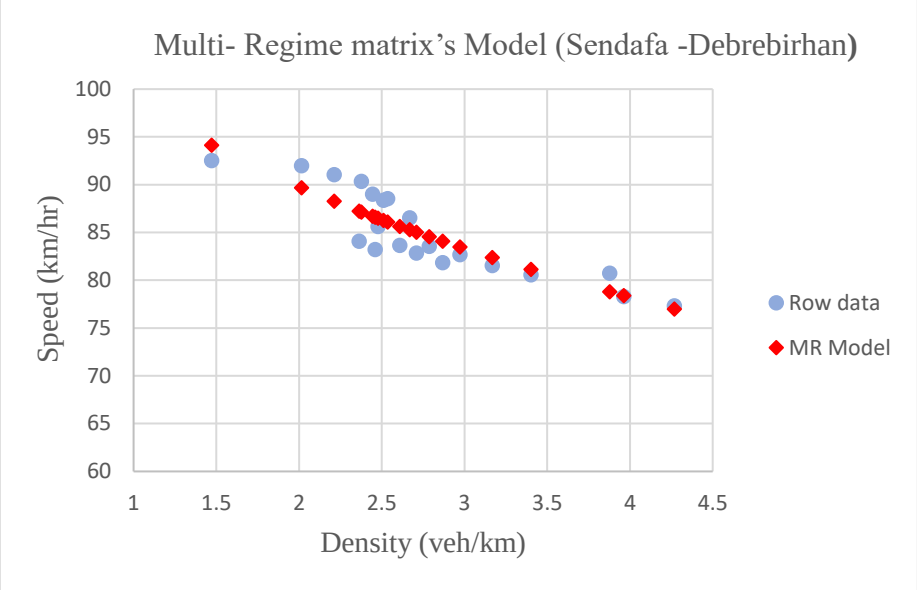


Figure 4. 36 Multi- Regime matrix's Model fitted to 15-min data taken on Sendafa-Debrebirhan section towards Sendafa direction

When comparing the value of R^2 of all models utilized for this research, the multi-regime matrix model has shown a higher value of R^2 on all sections of this study.as it was observed on the other models, the R^2 value obtained during 15-min interval analysis was greater than the 1-min interval analysis. To this end, among the models considered for this research, as it was selected before for the 1-min interval analysis, the multi-regime matrix model was selected to represent the actual traffic condition of the selected study sections.

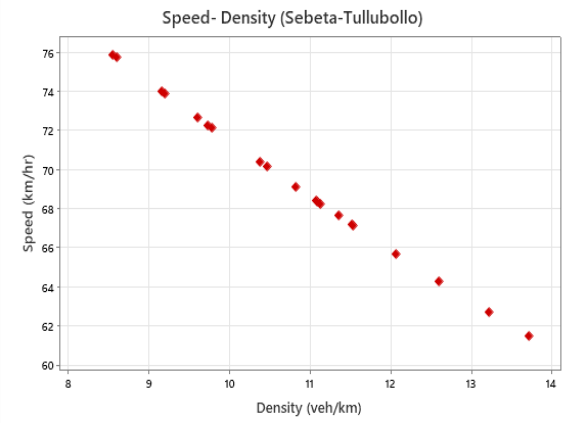
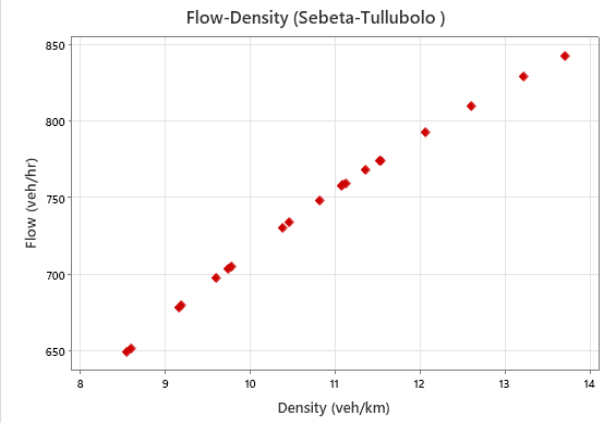
4.1.5.7 Composite Model

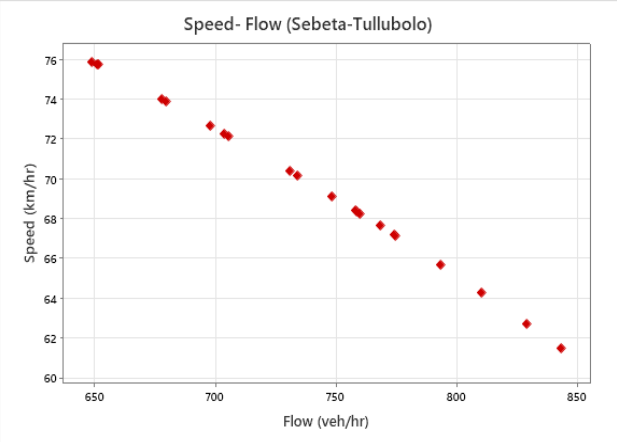
As it was previously mentioned; the composite model is a type of traffic model that considers combining two different models to describe the free flow regime and the congested regime of a traffic flow in order to produce a better representation of the traffic stream for both traffic conditions. As it was easily observed from the regression data of the models, there was a reduction of data especially for high density regime, as the data was averaged using the 15-min interval time. To this effect applying the composite model was impractical for the given time interval. As it was previously indicated the Multi regime matrix model was found to be efficient in representing the traffic conditions of both situations, and it was recommended for the next stage of research for this specific time interval.

4.1.5.8 Speed-Density, Flow-Density, and Speed-Flow relationships

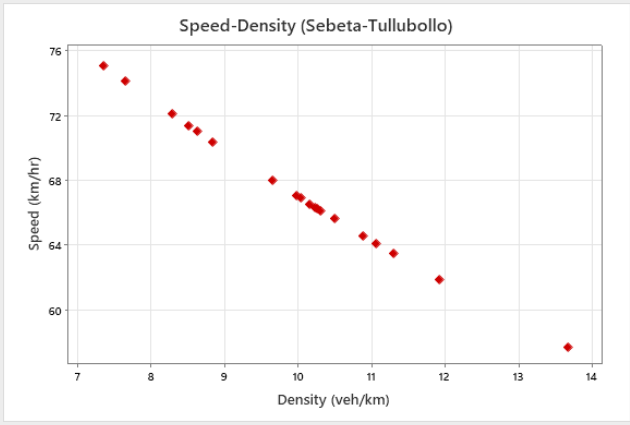
As it was previously stated during 1-min interval case, in order to arrive on the speed-density-flow relationships for a given time interval t, the speed-density relationships were determined because of its simplicity in formulating the relationships, and the corresponding flow-density, and speed-flow relationship for the study sections was determined using the steady state equation (Equation 2.1) of traffic flow. As it had been previously mentioned, the speed-density relationships of the traffic flow were best represented by the multi-regime matrix model and the corresponding flow-density, and speed-flow relationship were derived from the speed-density relationship developed from the multi-regime matrix model. Below the diagrammatical representation and the description of those relationships was presented. Table 4.5 presented an illustration of the multi-regime model describing the speed-density, flow-density and speed-flow relationship for Sebeta-Tullubolo section for both directions. The flow density relationship of this section was developed by using the steady state flow equation on the developed speed-density relationship of the multi-regime matrix model for the time interval under consideration. From the Table, it can be shown that observing the maximum flow in this section is not possible due to the insufficient data observed when the data averaged to 15-min interval. The speed-flow relationship was also established once more using the data.

Table 4. 5 Speed-Density, Flow-Density and Speed-Flow Relationships for Sebeta- Tullubollo Section (15-min)

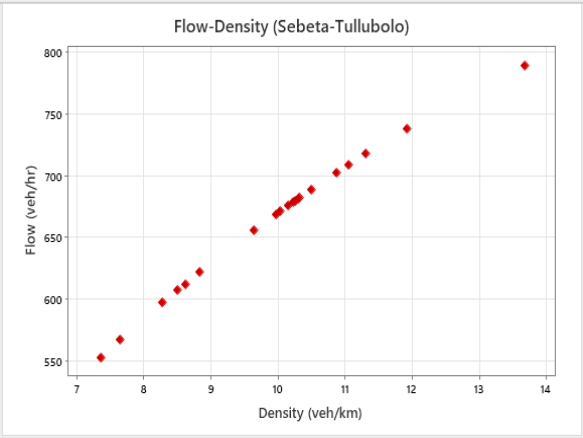
Speed-Density, Flow-Density and Speed-Flow Relationships	
Sebeta- Tullubollo Section	
	
Speed-Density relationship for traffic on Sebeta-Tullubolo section towards Sebeta	Flow-Density relationship for traffic on Sebeta-Tullubolo section towards Sebeta



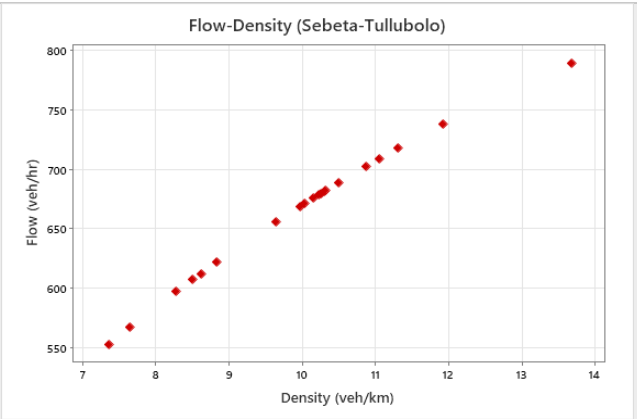
Speed- Flow relationship for traffic on Sebeta-Tullubolo section towards Sebeta



Speed-Density relationship for traffic on Sebeta-Tullubolo section towards Tullubolo



Flow-Density relationship for traffic on Sebeta-Tullubolo section towards Tullubolo



Speed- Flow relationship for traffic on Sebeta-Tullubolo section towards Tullubolo

Table 4.6 presented an illustration of the multi-regime model describing the speed-density, flow-density and speed-flow relationship for Sululta- Chancho section for both directions. The flow density relationship of this section was developed by using the steady state flow equation on the developed speed-density relationship of the multi-regime matrix model for the time interval under consideration. From the Table, it can be observed that the maximum flow observed towards Sululta direction was 530 veh/hr which is lesser compared with the 1-min analysis for similar section under consideration. The speed-flow relationship was also established once more using the data. From the speed-flow relationship the optimum speed of this direction gave 62.75 km/hr which is greater than the optimum speed obtained when implementing the 1-min averaged data for similar section under consideration.

Table 4. 6 Speed-Density, Flow-Density and Speed-Flow Relationships for Sululta- Chancho Section (15-min)

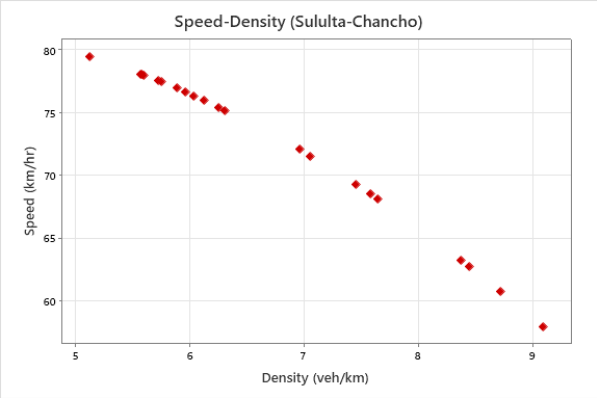
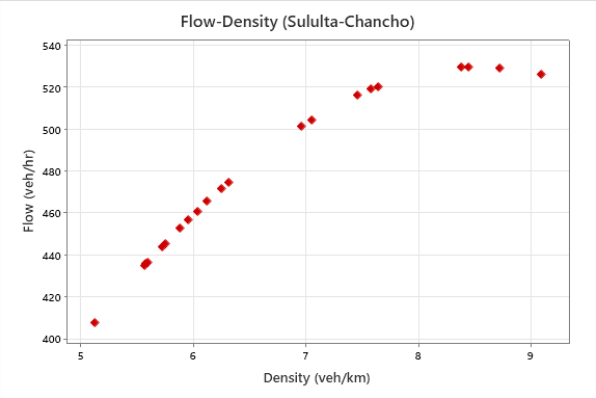
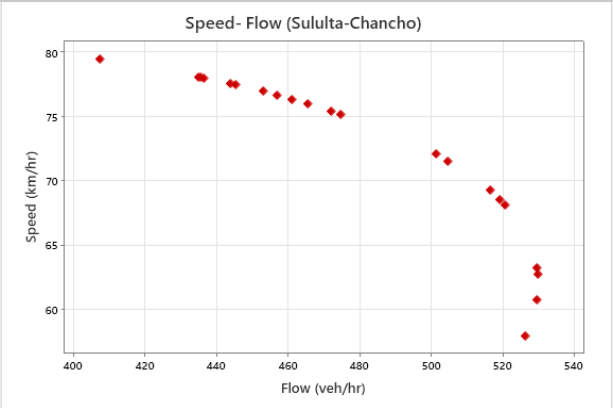
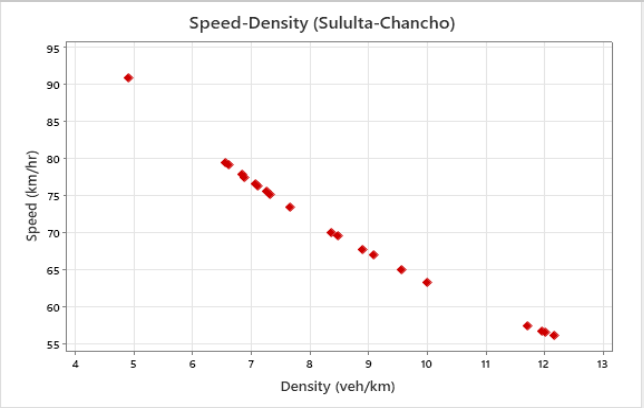
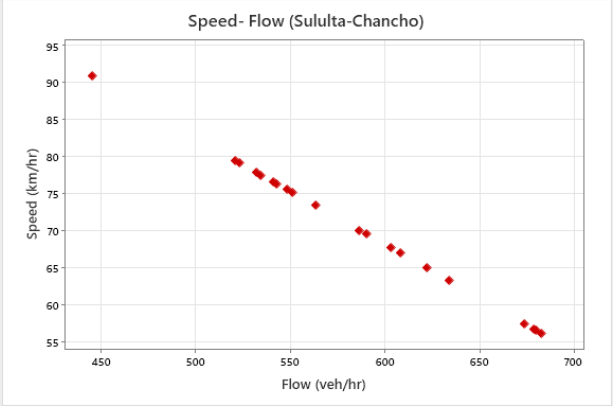
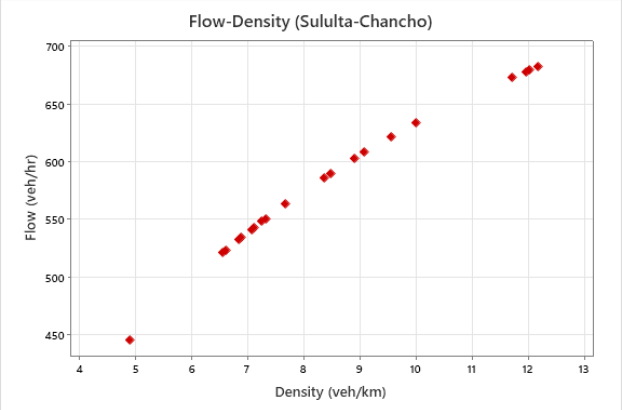
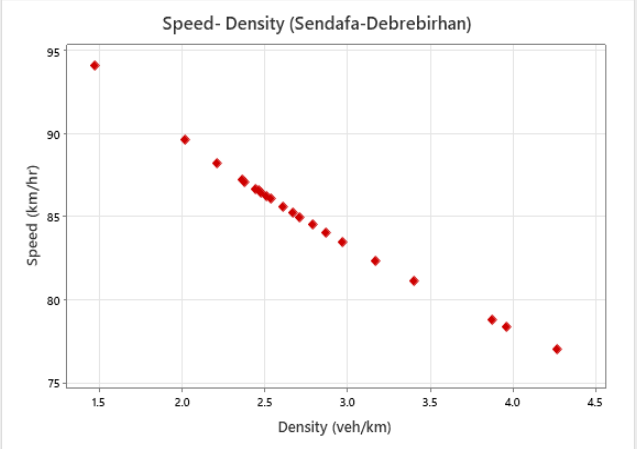
Speed-Density, Flow-Density and Speed-Flow Relationships	
Sululta- Chancho Section	
	
Speed-Density relationship for traffic on Sululta-Chancho section towards Sululta	Flow-Density relationship for traffic on Sululta-Chancho section towards Sululta
	
Speed- Flow relationship for traffic on Sululta-Chancho section towards Sululta	Speed-Density relationship for traffic on Sululta-Chancho section towards Chancho
	
Speed- Flow relationship for traffic on Sululta-Chancho section towards Chancho	Flow-Density relationship for traffic on Sululta-Chancho section towards Chancho

Table 4.7 presented an illustration of the multi-regime model describing the speed-density, flow-density and speed-flow relationship for Sendafa- Debrebirhan section for both directions. The flow density relationship of this section was developed by using the steady state flow equation on the developed speed-density relationship of the multi-regime matrix model for the time interval under consideration. From the Table, it can be shown that observing the maximum flow in this section is not possible due to the insufficient data observed when the data averaged to 15-min interval. The speed-flow relationship was also established once more using the data.

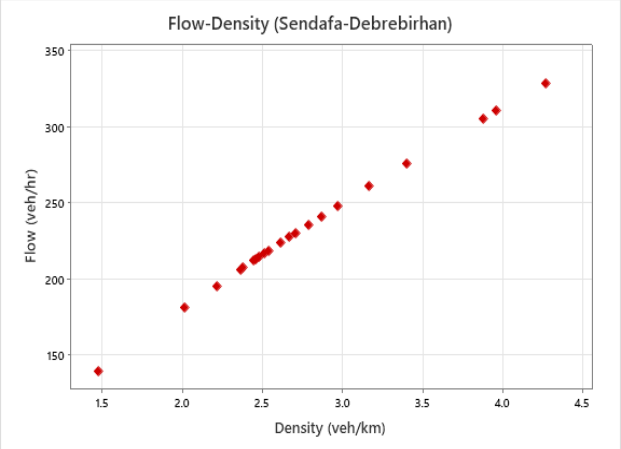
Table 4. 7 Speed-Density, Flow-Density and Speed-Flow Relationships for Sendafa-Debrebirhan Section (15-min)

Speed-Density, Flow-Density and Speed-Flow Relationships

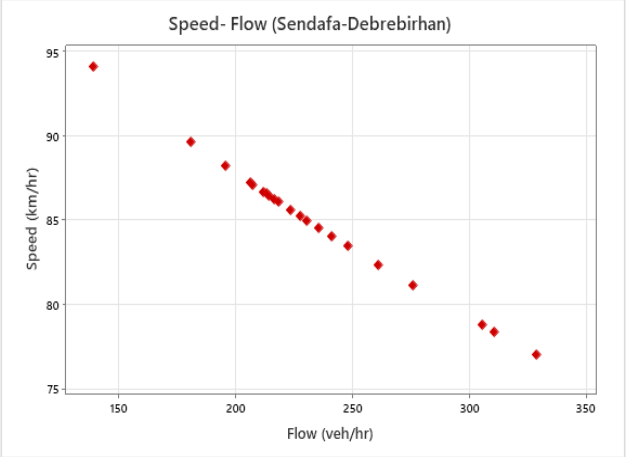
Sendafa- Debrebirhan Section



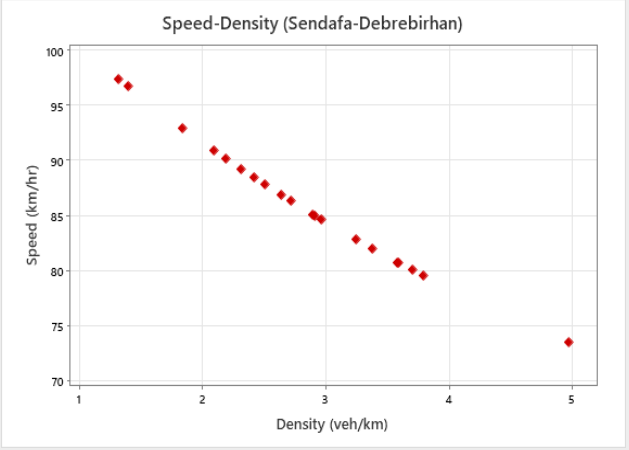
Speed-Density relationship for traffic on Sendafa-Debrebirhan section towards Sendafa



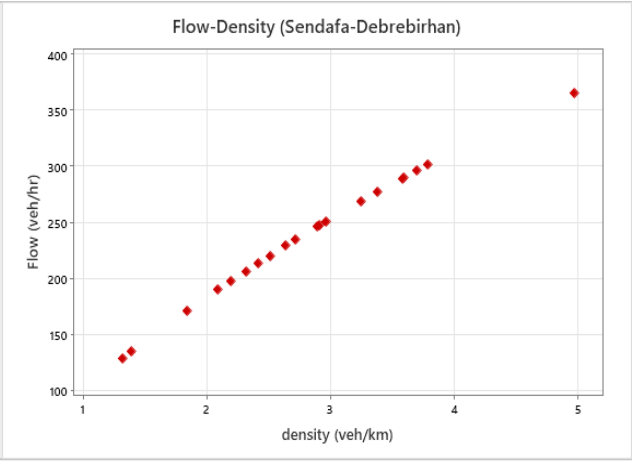
Flow-Density relationship for traffic on Sendafa-Debrebirhan section towards Sendafa



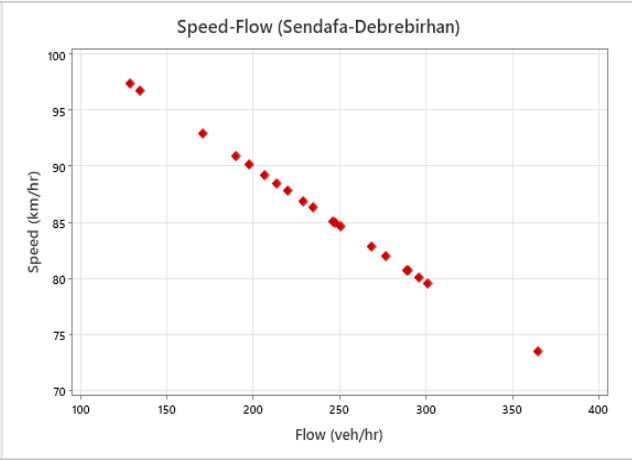
Speed- Flow relationship for traffic on Sendafa-Debrebirhan section towards Sendafa



Speed-Density relationship for traffic on Sendafa-Debrebirhan section towards Debrebirhan



Flow-Density relationship for traffic on Sendafa-Debrebirhan section towards Debrebirhan



Speed- Flow relationship for traffic on Sendafa-Debrebirhan section towards Debrebirhan

4.2. Travel time relationship

The most easily detectable parameter in traffic stream quality characteristics is travel time (Guerin, 1958). In addition to identifying relationships between traffic flow parameters, this study examined the relationships between travel time and other traffic parameters, such as density and flow, on selected two-lane two-way rural highways of Ethiopia. Based on the curves created by (Rothrock and Keefer ,1957), which were simply an inversion of the Normann curve that described the relationship between travel time and volume (Guerin, 1958) investigated the travel time and traffic flow parameter's relationship that was conducted on two two-lane highways of Washington Boulevard and Temple Street located in USA. Owing to the presence of congested and free-flow situations, (Guerin, 1958) proposed utilizing a boundary curve in defining the relationship between travel time and density, which has the general formula shown below:

$$T = \frac{a * K^2}{\sqrt{(b-k)}} + c \qquad (4.1)$$

Where:

a= a constant such that 2a is equal to the curvature of the time density curve at zero density

b= a constant equal to the maximum density obtained under bumper to bumper conditions

c= a constant equal to the minimum travel time.

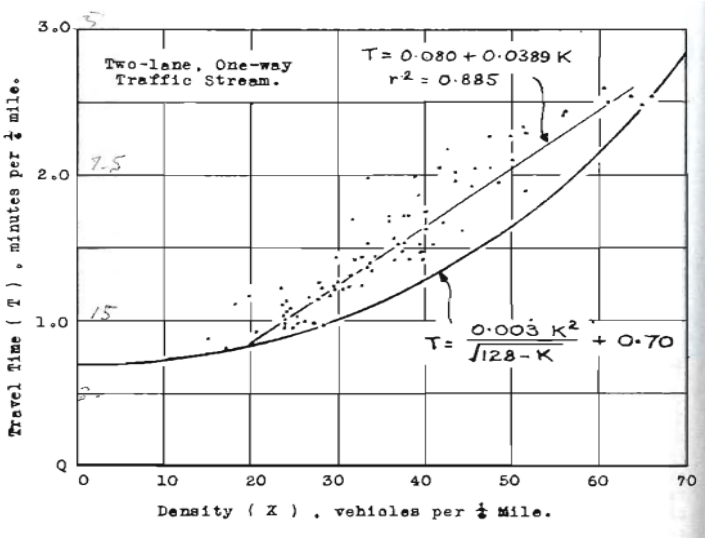


Figure 4. 37 Travel time-density relationship on Washington Boulevard street in USA (Guerin, 1958)

Guerin (1958) considered using the expression developed by (Rothrock and Keefer ,1957) in order to establish the relationship between the travel time and flow after the travel time-density relationships was attained by using the formula of boundary curved discussed previously. The expression developed by (Rothrock and Keefer ,1957) was shown as:

$$\text{Density} = \text{Flow} * \text{Average Travel Time} \qquad (4.2)$$

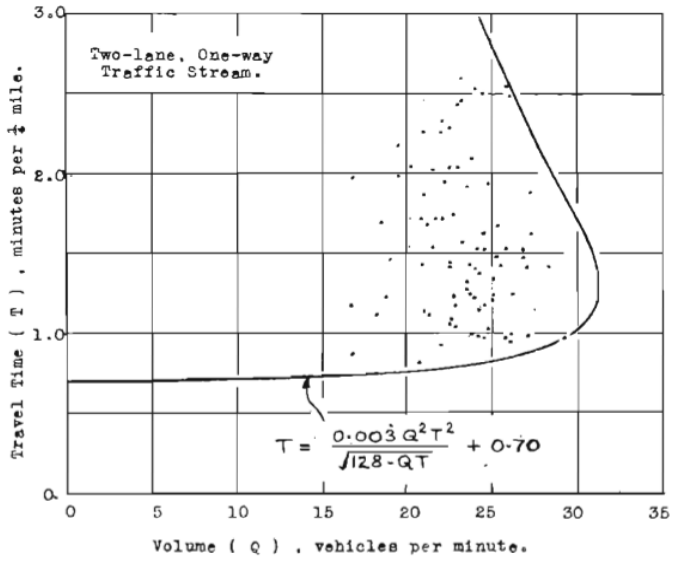


Figure 4. 38 travel time-flow relationship on Washington Boulevard street in USA (Guerin, 1958)

In order to examine and demonstrate the travel time-density relationship for this particular research, the sululta-chancho section, towards Chancho direction was utilized. For this research, the linear regression for the travel time density relationship, the boundary curve relationship developed by (Guerin, 1958), and other relationships was applied on the data in order to examine the relationship that describes the travel time-density data of the section under the study. In light of this, looking in to the relationship of the travel time and density of this section, the linear relationship yielded a greater value of R^2 than the boundary curve developed by (Guerin, 1958). In his work, (Guerin, 1958) proposed that for low volumes and densities, the travel time against volume or density should have zero slope and constant curvature. Along with including (Underwood, 1961) in his study on the Merritt Parkway to look at the speed-density, speed-volume, travel time-density, and travel time-volume relationships, (Underwood, 1961) suggested employing curves rather than linear relationships to show the relationship between travel time-density and travel time-volume as the use of the curves satisfy the actual traffic condition observed. Figure 4.39 shows the travel time-density relationship based on the linear relationship and the boundary curve developed by (Guerin, 1958) on Sululta-Chancho section.

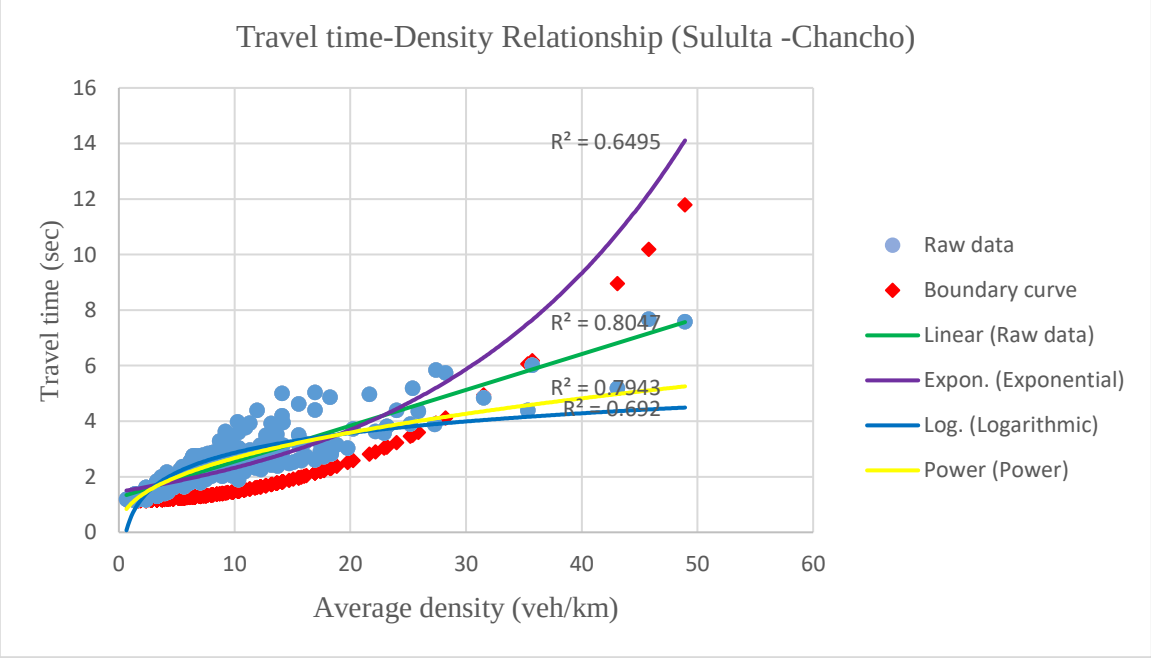


Figure 4. 39: Travel time-Density relationships on Sululta-Chancho section

After regression analysis was done to identify the unknown parameters of the boundary curve, the equation of the boundary curve looks like:

$$T = \frac{0.0315 * k^2}{\sqrt{(99 - k)}} + 1.132$$

According to the regression analysis's findings, even though the value of R^2 is lower when using the boundary curve than it is when using a linear relationship with ($R^2 = 0.805$), as can be seen by the efforts of several scholars on the topic, the boundary curve presented a more accurate depiction of the actual traffic situation than the linear one. In this study, in addition to the linear relationship, the exponential, logarithmic, and the power relationships were examined as shown on the figure above to study the relationship of travel time-density and showed lesser relationships when compared to the linear relationship. The boundary curve begins with zero slope and continues to move upwards from the lowest travel time, which in this case is 1.132 seconds, at a rate proportionate to the square of the density, as shown in the Figure above. As the value of density grows, the value of travel time climbs to a boundless travel time as the value of density approaches the jammed density, where vehicles are compelled to a complete standstill. The travel time -flow relationship of this section was derived using the methodology set by (Guerin, 1958), where he thought of utilising the expression developed by Rothrock and Keefer (1957) once the travel time-density relationships had been established by applying the boundary curve. The travel time-flow relationship of this section was shown in Figure 4.40 below.

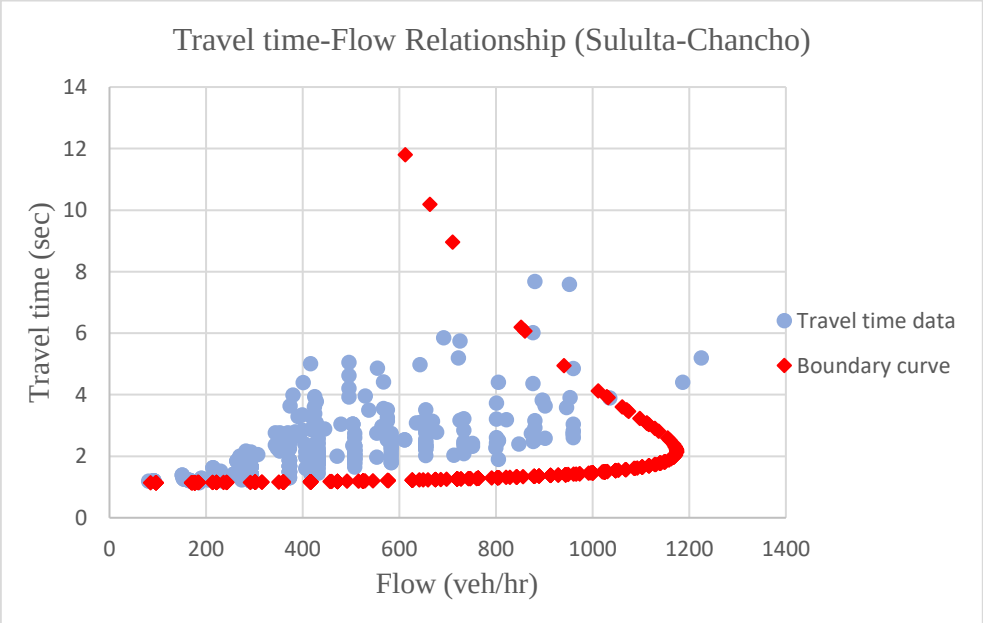


Figure 4. 40**:** Travel time-Density relationships on Sululta-Chancho section

The equation of the boundary curve based on the equation of looks like:

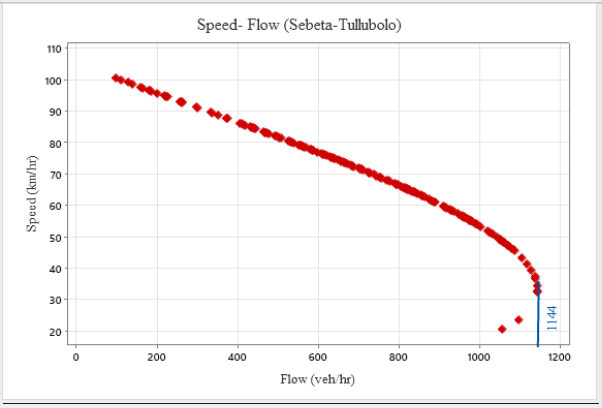
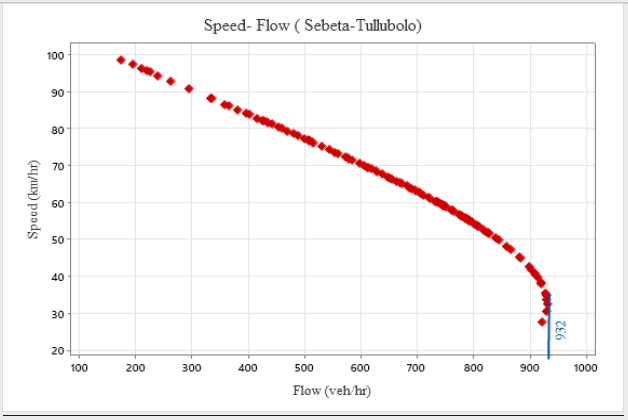
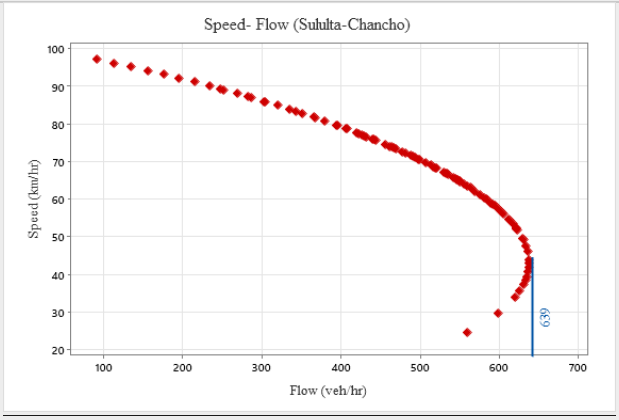
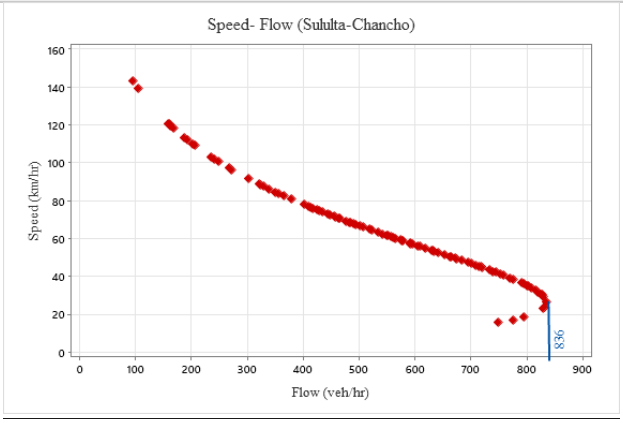
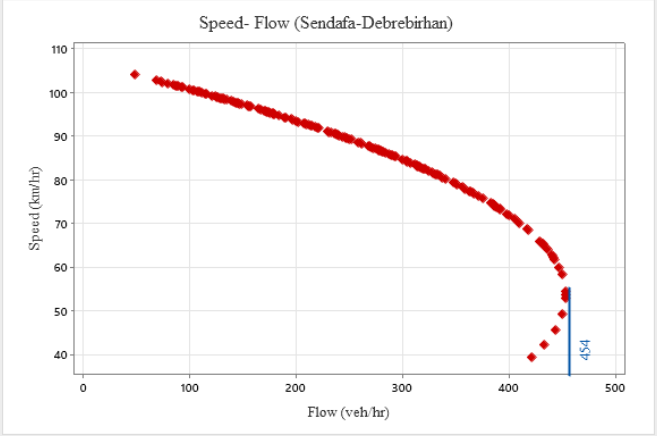
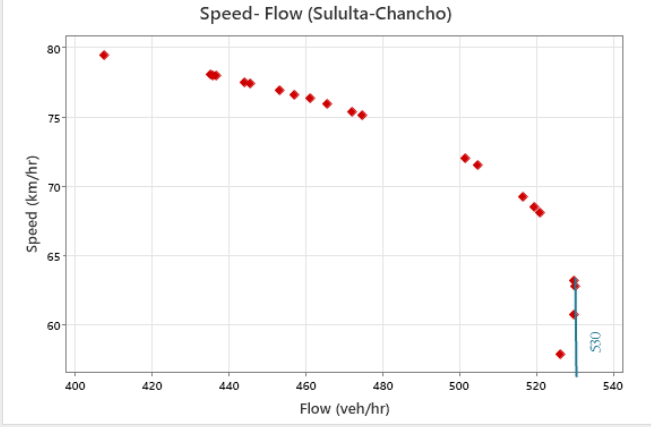
$$T = \frac{0.0315 * Q^2 * T^2}{\sqrt{(99 - Q * T)}} + 1.132$$

In a similar way like the travel time-density curve, the curve commences with a zero slope but gradually climbs to the maximum flow and then increases to an infinite travel time as the flow approaches to zero. In addition to this, it can be observed that applying a linear relationship is not possible because of the existence of nonlinear data pattern for the travel time-flow relationship. Finally, it can be deduced from the preceding discussions that the trend observed for the travel time - density and travel time - flow relationship of the selected section of this study was similar to previous researches, especially with the classical researches conducted by (Guerin, 1958) and (Underwood, 1961).

4.3. Capacity determination

The capacity of a highway is the highest number of cars that may flow through a road in a particular period of time. The speed-flow relationship derived from the actual traffic condition is a tool that aids in the examination of the highway traffic condition's capacity, congestion and level of service. (TRB,2016) recommends a two-lane highway may have 1,700 pc/h in one direction and a maximum of 3,200 pc/h in both directions under the base condition of the highway facility. Since the conditions observed on the selected highway sections of this study are close to the base conditions stated under (TRB,2016), a comparison was carried out between both the obtained capacity values of this study and the capacity values specified on (TRB,2016). For the purposes of this study, the previously derived speed-flow relationships were utilized in order to analyze the capacity of the highway sections under consideration. Table 4.8 below depicts the capacity value of the study sections under consideration, with a capacity value of 1144 veh/hr for Sebeta -Tullubollo section towards Sebeta direction, 836 veh/hr for Sululta -Chancho section towards Chancho direction,and 454 veh/hr for Sendafa - Debrebirhan section towards Sendafa direction.

Table 4. 8 Speed-Flow relationship depicting capacity value

Speed-Flow relationship depicting capacity value	
Sebeta-Tullubollo Section	
	
Capacity value for 1-min. time intervals on Sebeta-Tullubollo section towards Sebeta direction	Capacity value for 1-min. time intervals on Sebeta-Tullubollo section towards Tullubollo direction
Sululta-Chancho Section	
	
Capacity value for 1-min. time intervals on Sululta-Chancho section towards Sululta direction	Capacity value for 1-min. time intervals on Sululta-Chancho section towards Chancho direction
Sendafa-Debrebirhan Section	
	
Capacity value for 1-min. time intervals on Sendafa-Debrebirhan section towards Sendafa direction	Capacity value for 15-min. time intervals on Sululta-Chancho section section towards Sululta direction

From the figures shown above on the table , the value of capacity obtained for those two lane highways of this research was lesser than the value 1700 veh/hr which is the (TRB,2016)'s recommended maximum capacity value for a two-lane highway facility under the base condition.

From the figure shown above on the table, the value of capacity obtained for Sululta-Chancho section using the 15-min interval analysis was lesser than the value 1700 veh/hr which is the (TRB,2016)'s recommended maximum capacity value for a two-lane highway facility under the base condition.

CHAPTER FIVE: CONCLUSIONS AND RECOMMENDATIONS

5.1. Chapter Introduction

In this last chapter of the study, conclusions pertaining to the entire research work are presented based on the research work 's findings, and recommendations for additional research further into the topic are suggested.

5.2. Conclusions

In light of the data gathered for this study and the data analysis made, the following conclusion was drawn:

- In this research, an analysis of the traffic composition of the traffic stream was conducted so that the effects of the heavy vehicles could be mitigated. Based on this fact, the analysis shows that, as per the (ERA, 2013) vehicle classification, the Pick-up/4-wheel drive type contributes the major part of the vehicle composition for all study sections, and passenger cars have the second largest contribution. Next to both types, small trucks and 3-axled trucks contribute to the share of the traffic composition of the study sections. From the results, it can be deduced that the contribution of a 2-axled trailer and a 3-axled trailer is less.
- In this research, in comparison to other fundamental traffic flow relationships, the speed-density relationship is seen to be simple and easy to explain mathematically and was selected and examined by aggregating the data on 1-minute and 15-minute time intervals. The reason 1-minute average data was used was, various researchers had implemented the use of this interval for analysis of their specific traffic condition and 15-minute time interval as it is recommended by HCM. Based on this relationship, the data collected from the three sections of this study was utilized to obtain the parameters associated with the equation with the aid of regression analysis (curve fitting technique) using the Microsoft Excel solver add-in and Minitab software, whereby the values of free flow speed, speed corresponding to the maximum flow, jam density, and the density corresponding to the maximum flow were obtained for all classical models utilized for this research.

- Given the fact that there is no common standard to assess if a model adequately represents the data because the value of the parameters obtained from the different classical models with the aid of regression analysis was different, and the value of R^2 (Coefficient of determination) which was used to quantify the overall adequacy of the model and did not fully demonstrate whether the data are sufficiently represented by a given model, the approach used to assess whether a model better describes the data or not was to first check whether the value of the Coefficient of determination was close to 1 or not, then to visually examine whether the model better describes the data on the different regimes, namely the congested and uncongested regimes, and to ensure that the calibrated parameter values obtained from the regression analysis are consistent with the real conditions. In accordance with the criteria described above, the classical models used in this study were compared to one another, and the best fitting model was chosen.

- For the case of data averaged over a 1-min interval, by aiming to obtain a model that better represents the whole traffic range, namely the congested and uncongested parts of the data, a combination of composite models was applied, where in this case the underwood model was selected for the uncongested regime and the multi-regime matrix model was selected for the congested regime. However, the composite model does not represent the whole data,as each individual model did not fully represent the specific regimes, and especially less data was observed for the congested regime of the data. In this case, (i.e., the multi-regime model) better describes the data than the composite model with a higher value of the coefficient of determination, realistic parameter values, and a better visual representation of both regimes.
- For the case of data averaged over a 15-min interval, as it was witnessed that the time interval is higher than the 1-min interval analysis, a small data was observed especially for the congested regime/higher density data. Due to this reason, application of the composite model is totally not feasible and again similarly with the 1-min time interval analysis, the multi-regime matrix model relatively was better to represent the data satisfying a higher value of the coefficient of determination, and realistic parameter values.
- In both the 1-min and 15-min time interval analyses for all three sections of the study, the value of capacity obtained for those two-lane highways in this research was less than the value of 1700 veh/hr which is the (TRB,2016)'s recommended maximum capacity value

for a two-lane highway facility under the base condition The reason for this could relate to our pavement's quality, since roads with damaged pavement lower capacity, the absence of experienced drivers and driving behaviour, and lane discipline.Since the HCM maximum capacity value for a two-lane highway facility was derived from the analysis made on a 15-min time interval, in this case, the Sululta-Chancho section satisfies the capacity condition with a value of 530 vehicles per hour, which is far less than the HCM maximum capacity value. Besides, it can be deduced that looking at the capacity value for the same section (i.e., the Sululta-Chancho section), the value of capacity obtained during the 15-min time interval analysis (i.e., 530 veh/hr) is lesser than the 1-min time interval analysis (i.e., 639 veh/hr).

- It can be deduced that the trend observed for the travel time - density and travel time - flow relationship of the selected section of this study was similar to previous researches, especially with the classical researches conducted by (Guerin, 1958) and (Underwood, 1961).
- In south Africa, similar researches were conducted by (Roux, 2001) on freeways, where the analysis was done for only 1-min interval for data collected for three hours, and also (Twagirimana,2013) on Two-lane Two-Way highways, where the analysis was done for 1-min and 5-min time interval for a data collected for around two hours. However, in this study analysis was done for both 1-min and 15-min time intervals, utilizing data collected for around five hours for each study section as this makes this research focused on applying the approaches used by those researchers and HCM recommendation by employing both 1-min and 15-min time interval analysis and utilizing data collected for five hours for each section of the study.

5.3. Recommendations

- Despite its better precision, the data collection mechanism being utilized for this research was time-consuming and laborious, starting from the video recording to the data conversion. In order to obtain better results, save time and effort, it is better to adopt different technologies such as CCTV cameras, loop detectors, etc., especially when there is a need to study for a longer duration with a broader scope.

- An investigation of various scenarios was necessary in order to reach a conclusion as this study was performed on flat terrain, a straight section, day time, and in dry weather.

- In this study, three two-lane, two-way highways in Ethiopia were chosen for the examination of speed-flow-density relationships, capacity, travel time-flow relationships, and travel time-density relationships. In order to draw conclusions, other highways located throughout the country should also be examined for the same considerations.

- In this study, the capacity values were determined from the speed-flow curve developed based on the analysis made on data averaged on 1-min time and 15-min time interval. Because of the reduction in data as the data are averaged to 15-min time interval, only the Sululta-Chancho section attains the capacity value. In order to verify the capacity for other sections using the 15-min time interval, the data should be collected for an extended period.

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APPENDIX- A

Travel time, Speed, Density, Flow Measurements and Regression Analysis data

Table A. 1 Measurements of Travel time, Speed, Flow, and Density conducted for the data averaged on 1-min interval on Sebeta-Tullubollo section

Time	Average travel time (sec)		Average speed (km/hr)		Average flow (veh/hr)		Average density (veh/km)	
	Towards Sebeta	Towards Tullubolo	Towards Sebeta	Towards Tullubollo	Towards Sebeta	Towards Tullubollo	Towards Sebeta	Towards Tullubollo
7:24:00 AM	1.75	2.13	84.33	69.45	476.10	555.45	5.65	8.00
7:25:00 AM	1.46	2.68	101.19	55.11	238.05	726.05	2.35	13.17
7:26:00 AM	2.19	2.25	67.46	65.59	793.50	555.45	11.76	8.47
7:27:00 AM	2.31	2.24	63.97	65.99	872.85	714.15	13.64	10.82
7:28:00 AM	1.65	2.04	89.25	72.28	503.87	476.10	5.65	6.59
7:29:00 AM	1.64	2.46	89.95	59.99	634.80	752.85	7.06	12.55
7:30:00 AM	2.13	2.11	69.45	70.06	555.45	428.49	8.00	6.12
7:31:00 AM	2.20	2.41	67.04	61.33	559.75	634.80	8.35	10.35
7:32:00 AM	1.60	2.24	91.99	65.86	476.10	776.30	5.18	11.79
7:33:00 AM	3.83	2.38	38.55	62.04	634.80	756.80	16.47	12.20
7:34:00 AM	4.26	2.10	34.67	70.27	1210.62	793.50	34.92	11.29
7:35:00 AM	2.25	1.98	65.59	74.67	555.45	481.11	8.47	6.44
7:36:00 AM	1.75	2.82	84.33	52.34	396.75	714.15	4.70	13.64
7:37:00 AM	1.93	2.06	76.42	71.73	575.29	504.75	7.53	7.04
7:38:00 AM	1.97	1.98	74.96	74.37	317.40	465.98	4.23	6.27
7:39:00 AM	1.75	1.91	84.33	77.29	634.80	519.62	7.53	6.72
7:40:00 AM	1.97	3.12	74.96	47.26	634.80	712.93	8.47	15.09
7:41:00 AM	2.60	1.91	56.78	77.45	801.44	409.15	14.11	5.28
7:42:00 AM	1.94	2.44	75.89	60.61	714.15	776.38	9.41	12.81
7:43:00 AM	1.75	1.95	84.33	75.73	396.75	654.64	4.70	8.64
7:44:00 AM	1.75	2.69	84.33	54.97	238.05	779.91	2.82	14.19
7:45:00 AM	2.20	1.88	67.04	78.64	651.95	490.98	9.73	6.24
7:46:00 AM	1.95	1.82	75.56	81.08	888.72	430.10	11.76	5.30
7:47:00 AM	1.93	2.35	76.66	62.78	396.75	572.81	5.18	9.12
7:48:00 AM	1.79	2.45	82.38	60.14	503.87	490.98	6.12	8.16
7:49:00 AM	1.79	1.97	82.55	74.85	737.96	505.84	8.94	6.76
7:50:00 AM	1.69	3.10	87.34	47.55	575.29	757.29	6.59	15.93
7:51:00 AM	2.19	2.41	67.46	61.12	476.10	675.09	7.06	11.05
7:52:00 AM	2.55	3.10	57.82	47.55	952.20	757.29	16.47	15.93
7:53:00 AM	2.19	2.89	67.43	51.11	627.27	648.64	9.30	12.69
7:54:00 AM	2.04	1.88	72.28	78.71	714.15	555.45	9.88	7.06
7:55:00 AM	1.96	1.82	75.36	81.13	525.64	407.21	6.97	5.02
7:56:00 AM	1.82	2.87	81.22	51.47	726.05	739.62	8.94	14.37
7:57:00 AM	2.19	1.84	67.46	80.25	476.10	436.12	7.06	5.43

7:58:00 AM	2.20	2.33	67.04	63.25	651.95	476.10	9.73	7.53
7:59:00 AM	3.10	3.08	47.57	47.93	872.85	939.28	18.35	19.60
8:00:00 AM	1.97	2.21	74.88	66.93	880.79	503.87	11.76	7.53
8:01:00 AM	1.38	2.05	107.22	71.93	353.11	575.29	3.29	8.00
8:02:00 AM	2.13	1.65	69.26	89.25	1089.50	503.87	15.73	5.65
8:03:00 AM	1.75	2.01	84.33	73.33	476.10	793.50	5.65	10.82
8:04:00 AM	1.31	1.75	112.44	84.33	158.70	396.75	1.41	4.70
8:05:00 AM	1.79	2.25	82.55	65.59	737.96	555.45	8.94	8.47
8:06:00 AM	1.80	2.23	81.85	66.26	654.64	654.64	8.00	9.88
8:07:00 AM	1.65	1.84	89.25	80.25	503.87	436.12	5.65	5.43
8:08:00 AM	2.00	1.75	73.79	84.33	555.45	396.75	7.53	4.70
8:09:00 AM	4.84	2.84	30.53	51.89	933.65	952.20	30.58	18.35
8:10:00 AM	2.84	2.42	51.97	60.87	681.33	810.35	13.11	13.31
8:11:00 AM	2.26	1.62	65.29	91.07	952.20	428.49	14.59	4.70
8:12:00 AM	1.72	1.75	86.01	84.33	809.37	317.40	9.41	3.76
8:13:00 AM	1.75	2.71	84.33	54.41	634.80	756.28	7.53	13.90
8:14:00 AM	1.75	1.51	84.33	97.82	396.75	460.23	4.70	4.70
8:15:00 AM	1.75	1.97	84.33	74.96	317.40	634.80	3.76	8.47
8:16:00 AM	2.01	1.75	73.48	84.33	726.05	396.75	9.88	4.70
8:17:00 AM	2.05	2.25	72.06	65.59	1118.84	555.45	15.53	8.47
8:18:00 AM	1.75	1.58	84.33	93.70	238.05	396.75	2.82	4.23
8:19:00 AM	1.96	2.01	75.19	73.48	424.52	726.05	5.65	9.88
8:20:00 AM	2.24	2.63	65.82	56.22	1114.87	555.45	16.94	9.88
8:21:00 AM	1.93	1.78	76.50	82.79	503.87	428.49	6.59	5.18
8:22:00 AM	2.16	1.75	68.26	84.33	674.48	396.75	9.88	4.70
8:23:00 AM	1.84	3.50	80.12	42.16	380.84	634.80	4.75	15.06
8:24:00 AM	2.08	1.70	70.81	86.96	229.55	654.64	3.24	7.53
8:25:00 AM	2.14	2.08	68.85	70.85	382.59	781.08	5.56	11.02
8:26:00 AM	1.79	2.13	82.61	69.45	306.07	555.45	3.70	8.00
8:27:00 AM	1.45	1.84	101.89	80.25	283.12	417.07	2.78	5.20
8:28:00 AM	6.29	2.63	23.48	56.22	1216.74	555.45	51.83	9.88
8:29:00 AM	2.50	2.54	59.01	58.16	765.18	793.50	12.97	13.64
8:30:00 AM	1.76	1.65	83.99	89.25	700.14	503.87	8.34	5.65
8:31:00 AM	1.94	2.92	76.26	50.59	459.11	628.98	6.02	12.43
8:32:00 AM	1.91	3.72	77.11	39.73	535.63	594.16	6.95	14.96
8:33:00 AM	1.65	1.92	89.22	77.02	206.60	754.14	2.32	9.79
8:34:00 AM	2.93	2.39	50.39	61.73	933.52	726.05	18.52	11.76
8:35:00 AM	3.44	2.71	42.89	54.40	933.52	793.50	21.77	14.59
8:36:00 AM	2.59	3.06	56.91	48.19	711.62	1110.90	12.50	23.05
8:37:00 AM	1.79	2.92	82.61	50.60	459.11	595.13	5.56	11.76
8:38:00 AM	1.95	1.98	75.73	74.67	631.27	494.40	8.34	6.62
8:39:00 AM	3.65	3.88	40.47	38.01	714.66	1269.60	17.66	33.40

8:40:00 AM	2.09	2.80	70.61	52.70	694.12	1190.25	9.83	22.58
8:41:00 AM	2.09	3.10	70.58	47.66	896.66	1031.55	12.70	21.64
8:42:00 AM	2.20	2.92	67.08	50.59	694.31	628.98	10.35	12.43
8:43:00 AM	2.68	3.20	55.15	46.19	960.14	585.07	17.41	12.67
8:44:00 AM	2.07	2.19	71.27	67.46	1039.49	793.50	14.59	11.76
8:45:00 AM	1.80	1.77	82.03	83.48	424.52	734.10	5.18	8.79
8:46:00 AM	1.86	2.33	79.37	63.25	634.80	714.15	8.00	11.29
8:47:00 AM	2.16	2.88	68.23	51.33	634.65	1110.90	9.30	21.64
8:48:00 AM	0.00	0.00	0.00	80.31	0.00	793.50	0.00	9.88
8:49:00 AM	5.19	3.25	28.45	45.41	1322.19	555.45	46.47	12.23
8:50:00 AM	1.75	1.46	84.33	101.19	158.70	238.05	1.88	2.35
8:51:00 AM	2.08	2.08	70.95	70.85	968.07	722.87	13.64	10.20
8:52:00 AM	1.93	0	76.42	0.00	575.29	0.00	7.53	0.00
8:53:00 AM	2.07	2.87	71.27	51.47	1039.49	739.62	14.59	14.37
8:54:00 AM	1.73	3.16	85.42	46.77	447.02	691.33	5.23	14.78
8:55:00 AM	1.71	1.82	86.21	81.13	1033.09	746.77	11.98	9.20
8:56:00 AM	0.00	0.00	0.00	77.02	0.00	754.14	0.00	9.79
8:57:00 AM	1.69	1.92	87.33	77.02	950.03	754.14	10.88	9.79
8:58:00 AM	2.05	1.75	71.92	84.33	558.84	476.10	7.77	5.65
8:59:00 AM	1.89	2.92	78.23	50.59	527.87	721.06	6.75	14.25
9:00:00 AM	2.24	2.92	65.81	50.59	852.24	628.98	12.95	12.43
9:01:00 AM	1.93	3.20	76.41	46.19	950.03	585.07	12.43	12.67
9:02:00 AM	1.92	2.57	77.06	57.34	558.84	797.09	7.25	13.90
9:03:00 AM	1.97	1.63	74.85	90.81	566.07	555.45	7.56	6.12
9:04:00 AM	1.64	1.93	89.90	76.66	186.28	396.75	2.07	5.18
9:05:00 AM	1.39	3.25	105.95	45.42	768.41	1258.58	7.25	27.71
9:06:00 AM	2.59	2.63	57.05	56.22	768.41	555.45	13.47	9.88
9:07:00 AM	1.64	2.81	89.90	52.47	791.70	1110.90	8.81	21.17
9:08:00 AM	2.79	1.98	52.98	74.67	768.41	481.11	14.51	6.44
9:09:00 AM	1.66	2.92	88.94	50.59	624.00	694.10	7.02	13.72
9:10:00 AM	1.88	2.33	78.48	63.25	624.00	654.64	7.95	10.35
9:11:00 AM	1.55	3.39	95.30	43.49	624.00	623.49	6.55	14.34
9:12:00 AM	2.99	2.04	49.41	72.28	624.00	714.15	12.63	9.88
9:13:00 AM	4.27	2.17	34.57	67.91	781.69	760.67	22.61	11.20
9:14:00 AM	1.69	1.93	87.59	76.66	245.82	793.50	2.81	10.35
9:15:00 AM	3.38	2.57	43.62	57.34	775.27	797.09	17.77	13.90
9:16:00 AM	2.03	1.62	72.77	91.07	340.36	428.49	4.68	4.70
9:17:00 AM	2.21	2.11	66.78	70.06	1016.93	428.49	15.23	6.12
9:18:00 AM	3.13	2.00	47.17	73.79	684.20	555.45	14.51	7.53
9:19:00 AM	3.39	2.92	43.54	50.59	794.18	628.98	18.24	12.43
9:20:00 AM	4.99	2.57	29.60	57.34	851.45	672.56	28.76	11.73
9:21:00 AM	2.37	2.73	62.32	53.97	1070.53	634.80	17.18	11.76

9:22:00 AM	1.96	1.87	75.47	79.06	529.46	595.13	7.02	7.53
9:23:00 AM	2.32	1.80	63.71	81.85	983.27	654.64	15.43	8.00
9:24:00 AM	2.09	2.93	70.78	50.30	617.13	778.84	8.72	15.48
9:25:00 AM	1.91	2.63	77.21	56.22	673.23	714.15	8.72	12.70
9:26:00 AM	2.28	2.46	64.85	59.99	684.45	756.37	10.55	12.61
9:27:00 AM	1.47	2.19	100.52	67.46	276.77	793.50	2.75	11.76
9:28:00 AM	2.01	1.98	73.35	74.37	673.23	439.50	9.18	5.91
9:29:00 AM	2.31	2.54	63.79	58.09	673.23	737.96	10.55	12.70
9:30:00 AM	2.59	2.17	57.05	67.91	523.62	546.39	9.18	8.05
9:31:00 AM	1.86	2.40	79.55	61.45	912.60	756.85	11.47	12.32
9:32:00 AM	1.51	1.75	97.80	84.33	224.41	396.75	2.29	4.70
9:33:00 AM	1.66	1.75	88.91	84.33	448.82	317.40	5.05	3.76
9:34:00 AM	1.51	1.84	97.80	80.31	224.41	793.50	2.29	9.88
9:35:00 AM	5.28	2.73	27.94	53.97	987.40	634.80	35.33	11.76
9:36:00 AM	2.64	2.80	55.98	52.70	600.29	1190.25	10.72	22.58
9:37:00 AM	2.35	1.98	62.82	74.67	1058.74	494.40	16.85	6.62
9:38:00 AM	3.46	1.93	42.62	76.50	992.78	503.87	23.29	6.59
9:39:00 AM	2.46	2.16	59.88	68.36	559.41	391.56	9.34	5.73
9:40:00 AM	1.97	2.39	74.86	61.72	559.41	598.22	7.47	9.69
9:41:00 AM	2.17	1.68	67.91	87.77	856.47	580.09	12.61	6.61
9:42:00 AM	1.68	1.33	88.11	111.09	617.28	195.78	7.01	1.76
9:43:00 AM	2.57	2.24	57.53	65.83	779.31	580.09	13.55	8.81
9:44:00 AM	2.06	1.93	71.49	76.30	585.09	341.69	8.18	4.48
9:45:00 AM	2.21	2.55	66.87	57.92	655.86	663.48	9.81	11.46
9:46:00 AM	1.84	2.58	80.35	57.10	412.80	538.10	5.14	9.42
9:47:00 AM	1.61	2.15	91.89	68.57	343.36	725.11	3.74	10.57
9:48:00 AM	1.32	1.67	111.51	88.62	208.33	507.58	1.87	5.73
9:49:00 AM	3.90	3.08	37.88	47.88	1026.22	1160.18	27.09	24.23
9:50:00 AM	3.96	3.64	37.31	40.51	1010.79	1160.18	27.09	28.64
9:51:00 AM	1.88	1.98	78.47	74.57	439.81	525.71	5.60	7.05
9:52:00 AM	1.95	2.19	75.58	67.33	706.01	652.60	9.34	9.69
9:53:00 AM	2.69	1.94	54.95	75.96	1010.06	435.07	18.38	5.73
9:54:00 AM	1.30	2.00	113.11	73.79	210.67	555.45	1.86	7.53
9:55:00 AM	2.65	2.20	55.73	67.09	1021.40	726.05	18.33	10.82
9:56:00 AM	2.56	1.68	57.72	87.88	725.64	222.11	12.57	2.53
9:57:00 AM	2.01	1.75	73.31	84.33	546.18	476.10	7.45	5.65
9:58:00 AM	1.75	2.63	84.38	56.22	550.08	476.10	6.52	8.47
9:59:00 AM	2.00	3.06	73.92	48.19	585.19	1269.60	7.92	26.35
10:00:00 AM	3.23	3.14	45.72	47.07	698.60	748.16	15.28	15.90
10:01:00 AM	1.63	1.88	90.48	78.71	210.67	555.45	2.33	7.06
10:02:00 AM	3.11	2.21	47.42	66.93	1037.74	503.87	21.89	7.53
10:03:00 AM	2.42	2.10	61.09	70.27	626.36	793.50	10.25	11.29

10:04:00 AM	3.17	1.94	46.51	75.89	1023.20	714.15	22.00	9.41
10:05:00 AM	2.42	2.04	61.04	72.28	795.86	714.15	13.04	9.88
10:06:00 AM	1.60	2.88	92.16	51.20	643.71	674.48	6.98	13.17
10:07:00 AM	1.30	3.72	113.48	39.73	191.63	594.16	1.69	14.96
10:08:00 AM	2.09	3.38	70.55	43.73	624.21	555.45	8.85	12.70
10:09:00 AM	2.76	1.93	53.38	76.42	683.61	575.29	12.81	7.53
10:10:00 AM	1.31	1.97	112.40	74.96	181.64	634.80	1.62	8.47
10:11:00 AM	4.27	2.55	34.54	57.97	1151.08	654.64	33.33	11.29
10:12:00 AM	2.49	2.63	59.30	56.22	703.14	476.10	11.86	8.47
10:13:00 AM	2.15	2.61	68.64	56.46	390.63	814.67	5.69	14.43
10:14:00 AM	2.22	1.62	66.61	91.07	726.58	214.25	10.91	2.35
10:15:00 AM	2.50	1.81	58.95	81.52	1045.17	460.23	17.73	5.65
10:16:00 AM	2.21	3.01	66.83	49.01	1109.40	737.96	16.60	15.06
10:17:00 AM	2.44	4.04	60.40	36.50	1031.28	1113.48	17.07	30.51
10:18:00 AM	1.62	2.62	91.19	56.37	605.48	503.87	6.64	8.94
10:19:00 AM	2.01	2.29	73.44	64.39	417.98	823.24	5.69	12.79
10:20:00 AM	2.21	2.07	66.64	71.44	624.86	545.07	9.38	7.63
10:21:00 AM	1.76	2.28	83.74	64.87	714.86	793.50	8.54	12.23
10:22:00 AM	2.06	2.08	71.53	71.01	644.55	634.80	9.01	8.94
10:23:00 AM	2.04	2.29	72.23	64.35	445.32	575.29	6.17	8.94
10:24:00 AM	2.43	2.48	60.75	59.40	796.21	780.34	13.11	13.14
10:25:00 AM	3.19	1.90	46.22	77.84	988.89	476.10	21.40	6.12
10:26:00 AM	2.92	2.48	50.50	59.50	775.61	503.87	15.36	8.47
10:27:00 AM	2.32	2.33	63.63	63.25	1012.65	595.13	15.91	9.41
10:28:00 AM	2.19	2.19	67.28	67.46	850.32	793.50	12.64	11.76
10:29:00 AM	1.31	2.10	112.30	70.27	262.83	793.50	2.34	11.29
10:30:00 AM	1.55	2.08	95.34	71.01	490.87	634.80	5.15	8.94
10:31:00 AM	1.97	2.63	74.83	56.22	560.44	1110.90	7.49	19.76
10:32:00 AM	3.09	2.47	47.71	59.73	1004.92	674.48	21.06	11.29
10:33:00 AM	1.98	1.93	74.60	76.50	1012.65	503.87	13.57	6.59
10:34:00 AM	2.17	2.63	68.00	56.22	541.11	793.50	7.96	14.11
10:35:00 AM	1.76	2.02	83.95	73.23	707.31	654.64	8.43	8.94
10:36:00 AM	2.82	2.26	52.40	65.35	637.74	737.96	12.17	11.29
10:37:00 AM	2.11	2.92	69.91	50.59	490.87	628.98	7.02	12.43
10:38:00 AM	1.79	2.95	82.57	50.00	231.91	803.64	2.81	16.07
10:39:00 AM	3.44	2.24	42.92	65.86	733.23	776.30	17.08	11.79
10:40:00 AM	1.76	1.79	84.03	82.38	757.68	503.87	9.02	6.12
10:41:00 AM	0.00	0.00	0.00	67.46	0.00	793.50	0.00	11.76
10:42:00 AM	1.96	1.65	75.22	89.64	1068.41	178.69	14.20	1.99
10:43:00 AM	2.76	2.13	53.56	69.45	1150.71	555.45	21.49	8.00
10:44:00 AM	1.26	2.06	116.74	71.73	277.00	786.58	2.37	10.97
10:45:00 AM	2.49	2.39	59.27	61.75	590.66	814.83	9.97	13.20

10:46:00 AM	2.72	1.96	54.17	75.33	745.46	531.65	13.76	7.06
10:47:00 AM	3.10	2.00	47.65	73.79	1127.86	555.45	23.67	7.53
10:48:00 AM	1.91	2.36	77.25	62.46	733.23	793.50	9.49	12.70
10:49:00 AM	1.96	3.20	75.39	46.19	822.85	585.07	10.92	12.67
10:50:00 AM	1.83	1.96	80.79	75.33	651.76	531.65	8.07	7.06
10:51:00 AM	2.57	2.01	57.34	73.48	721.54	726.05	12.58	9.88
10:52:00 AM	2.87	2.48	51.50	59.47	904.32	531.65	17.56	8.94
10:53:00 AM	1.77	1.42	83.60	104.00	912.47	293.60	10.92	2.82
10:54:00 AM	1.37	1.84	107.87	80.25	867.19	436.12	8.04	5.43
10:55:00 AM	1.66	2.10	88.87	70.26	772.22	515.26	8.69	7.33
10:56:00 AM	0.00	0.00	0.00	51.02	0.00	1224.97	0.00	24.01
10:57:00 AM	0.00	0.00	0.00	56.46	0.00	771.59	0.00	13.67
10:58:00 AM	2.56	3.74	57.76	39.43	1348.82	543.48	23.35	13.78
10:59:00 AM	1.89	2.19	78.21	67.46	849.45	793.50	10.86	11.76
11:00:00 AM	1.93	2.08	76.66	70.85	957.56	760.29	12.49	10.73
11:01:00 AM	1.89	2.40	78.11	61.45	1060.52	756.85	13.58	12.32
11:02:00 AM	2.04	2.01	72.22	73.33	823.70	793.50	11.40	10.82
11:03:00 AM	1.93	1.65	76.36	89.64	746.48	178.69	9.78	1.99
11:04:00 AM	1.85	2.86	79.83	51.53	823.70	654.64	10.32	12.70
11:05:00 AM	3.33	2.12	44.37	69.57	1132.59	654.64	25.52	9.41
11:06:00 AM	1.35	1.93	109.45	76.50	653.82	503.87	5.97	6.59
11:07:00 AM	1.57	2.13	93.74	69.45	458.19	555.45	4.89	8.00
11:08:00 AM	1.56	1.79	94.80	82.38	102.96	503.87	1.09	6.12
11:09:00 AM	2.38	1.78	62.07	82.79	1145.85	428.49	18.46	5.18
11:10:00 AM	2.83	1.89	52.09	78.19	887.63	373.91	17.04	4.78
11:11:00 AM	1.79	2.80	82.39	52.65	585.03	768.86	7.10	14.60
11:12:00 AM	2.56	2.36	57.74	62.46	663.27	793.50	11.49	12.70
11:13:00 AM	2.27	2.63	64.95	56.22	552.58	793.50	8.51	14.11
11:14:00 AM	3.60	1.87	40.99	79.06	815.01	595.13	19.88	7.53
11:15:00 AM	2.05	1.65	72.12	89.64	887.63	178.69	12.31	1.99
11:16:00 AM	2.18	3.20	67.58	46.19	895.70	585.07	13.25	12.67
11:17:00 AM	2.32	2.55	63.75	57.97	576.28	654.64	9.04	11.29
11:18:00 AM	2.43	3.02	60.67	48.82	976.40	872.85	16.09	17.88
11:19:00 AM	1.95	2.45	75.76	60.23	322.78	595.13	4.26	9.88
11:20:00 AM	1.97	2.27	74.74	65.16	459.96	674.48	6.15	10.35
11:21:00 AM	2.40	2.92	61.49	50.59	815.01	628.98	13.25	12.43
11:22:00 AM	2.05	2.16	72.17	68.19	744.54	737.96	10.32	10.82
11:23:00 AM	2.08	2.17	71.03	67.93	403.47	575.29	5.68	8.47
11:24:00 AM	2.56	2.71	57.73	54.41	829.33	756.28	14.37	13.90
11:25:00 AM	1.72	1.75	85.73	84.33	82.11	555.45	0.96	6.59
11:26:00 AM	2.09	1.75	70.65	84.33	845.76	238.05	11.97	2.82
11:27:00 AM	2.29	2.52	64.43	58.52	1018.19	588.85	15.80	10.06

11:28:00 AM	1.72	1.98	85.73	74.67	164.22	481.11	1.92	6.44
11:29:00 AM	2.63	3.16	56.06	46.77	697.95	587.21	12.45	12.55
11:30:00 AM	3.37	3.84	43.82	38.46	944.29	1031.55	21.55	26.82
11:31:00 AM	2.13	2.10	69.33	70.26	763.64	536.11	11.01	7.63
11:32:00 AM	1.72	3.16	85.73	46.77	492.67	691.33	5.75	14.78
11:33:00 AM	2.61	2.43	56.59	60.72	677.43	714.15	11.97	11.76
11:34:00 AM	1.96	1.65	75.29	89.64	1153.68	178.69	15.32	1.99
11:35:00 AM	1.72	1.83	85.73	80.54	328.45	332.58	3.83	4.13
11:36:00 AM	2.18	2.76	67.74	53.53	352.33	753.46	5.20	14.08
11:37:00 AM	1.72	1.75	85.73	84.33	82.11	714.15	0.96	8.47
11:38:00 AM	1.61	1.93	91.74	76.66	439.30	793.50	4.79	10.35
11:39:00 AM	1.75	1.75	84.33	84.33	158.70	317.40	1.88	3.76
11:40:00 AM	2.94	2.17	50.28	67.91	1143.74	760.67	22.75	11.20
11:41:00 AM	5.20	2.35	28.36	62.92	880.79	532.37	31.05	8.46
11:42:00 AM	2.13	1.84	69.41	80.25	424.52	417.07	6.12	5.20
11:43:00 AM	2.08	1.84	70.98	80.25	801.44	417.07	11.29	5.20
11:44:00 AM	1.93	2.90	76.66	50.95	396.75	575.29	5.18	11.29
11:45:00 AM	2.13	2.77	69.34	53.21	293.60	726.05	4.23	13.64
11:46:00 AM	1.99	2.04	74.31	72.28	559.42	476.10	7.53	6.59
11:47:00 AM	2.38	1.77	62.14	83.39	496.94	353.11	8.00	4.23
11:48:00 AM	2.33	2.71	63.25	54.41	714.15	756.28	11.29	13.90
11:49:00 AM	1.75	2.10	84.33	70.27	396.75	793.50	4.70	11.29
11:50:00 AM	2.46	2.74	60.09	53.82	505.39	710.21	8.41	13.20
11:51:00 AM	1.26	1.82	117.23	81.13	151.67	407.21	1.29	5.02
11:52:00 AM	3.04	1.98	48.59	74.67	960.14	494.40	19.76	6.62
11:53:00 AM	2.33	2.25	63.25	65.57	1190.25	519.71	18.82	7.93
11:54:00 AM	1.48	1.89	99.76	78.19	847.14	373.91	8.49	4.78
11:55:00 AM	2.28	3.05	64.71	48.32	1355.42	1162.22	20.95	24.05
11:56:00 AM	0.00	0.00	0.00	97.30	0.00	595.13	0.00	6.12
11:57:00 AM	0.00	0.00	0.00	73.79	0.00	694.31	0.00	9.41
11:58:00 AM	3.04	3.21	48.50	46.00	988.33	765.84	20.38	16.65
11:59:00 AM	1.63	2.15	90.69	68.79	564.76	614.96	6.23	8.94
12:00:00 PM	1.66	2.59	88.68	57.05	451.81	692.55	5.10	12.14
12:01:00 PM	1.36	1.65	108.63	89.64	553.46	178.69	5.10	1.99
12:02:00 PM	2.22	2.63	66.51	56.22	790.66	555.45	11.89	9.88
12:03:00 PM	2.23	3.14	66.29	47.07	1163.40	734.35	17.55	15.60
12:04:00 PM	2.05	2.35	71.97	62.74	1140.81	737.96	15.85	11.76
12:05:00 PM	2.35	2.50	62.89	59.03	818.90	555.45	13.02	9.41
12:06:00 PM	1.78	1.60	82.98	91.99	1033.51	476.10	12.45	5.18
12:07:00 PM	1.29	1.93	114.01	76.42	451.81	575.29	3.96	7.53
12:08:00 PM	1.85	1.81	79.81	81.52	451.81	575.29	5.66	7.06
12:09:00 PM	2.34	1.82	62.95	81.21	451.54	879.25	7.17	10.83

12:10:00 PM	1.96	2.25	75.19	65.59	424.52	603.59	5.65	9.20
12:11:00 PM	2.17	1.92	68.14	76.82	801.44	665.38	11.76	8.66
12:12:00 PM	1.65	3.03	89.25	48.70	503.87	828.15	5.65	17.01
12:13:00 PM	2.29	1.63	64.45	90.50	424.52	636.86	6.59	7.04
12:14:00 PM	3.14	0.00	47.01	0.00	1122.70	0.00	23.88	0.00
12:15:00 PM	1.66	1.91	89.15	77.13	293.60	587.59	3.29	7.62
12:16:00 PM	1.42	2.19	104.00	67.54	293.60	950.54	2.82	14.07
12:17:00 PM	1.89	1.58	78.00	93.33	880.79	214.05	11.29	2.29
12:18:00 PM	1.97	1.34	75.05	110.37	353.11	418.24	4.70	3.79
12:19:00 PM	2.05	1.25	71.93	118.53	575.29	256.64	8.00	2.17
12:20:00 PM	1.75	1.68	84.33	87.80	238.05	285.16	2.82	3.25
12:21:00 PM	2.54	1.25	58.14	118.53	1039.49	256.64	17.88	2.17
12:22:00 PM	1.80	0.00	81.85	0.00	654.64	0.00	8.00	0.00
12:23:00 PM	2.92	2.65	50.60	55.68	904.59	1235.70	17.88	22.19
12:24:00 PM	2.65	1.79	55.60	82.64	1115.52	388.82	20.06	4.70
12:25:00 PM	2.63	2.23	56.22	66.26	555.45	654.64	9.88	9.88
12:26:00 PM	2.14	1.75	68.99	84.33	1071.23	238.05	15.53	2.82
12:27:00 PM	2.50	3.06	59.03	48.19	555.45	634.80	9.41	13.17

Table A. 2 Measurements of Travel time, Speed, Flow, and Density conducted for the data averaged on 15-min interval on Sebeta-Tullubollo section

Time		Average travel time (sec)		Average speed (km/hr)		Average flow (veh/hr)		Average density (veh/km)	
From	To	Towards Sebeta	Towards Tullubollo	Towards Sebeta	Towards Tullubollo	Towards Sebeta	Towards Tullubollo	Towards Sebeta	Towards Tullubollo
7:24:00 AM	7:38:00 AM	2.19	2.26	73.28	66.07	703.21	637.52	9.60	9.65
7:39:00 AM	7:53:00 AM	2.00	2.40	74.99	63.88	640.82	655.43	8.55	10.26
7:54:00 AM	8:08:00 AM	1.94	2.10	79.10	72.33	679.63	598.83	8.59	8.28
8:09:00 AM	8:23:00 AM	2.19	2.14	72.17	73.20	749.22	631.00	10.38	8.62
8:24:00 AM	8:38:00 AM	2.41	2.41	69.45	64.54	788.89	713.70	11.36	11.06
8:39:00 AM	8:53:00 AM	2.24	2.31	62.41	56.66	786.91	775.33	12.61	13.68
8:54:00 AM	9:08:00 AM	1.81	2.30	73.27	64.48	629.69	769.33	8.59	11.93
9:09:00 AM	9:23:00 AM	2.65	2.33	62.62	65.95	828.13	675.05	13.23	10.24
9:24:00 AM	9:38:00 AM	2.33	2.27	70.73	66.84	787.34	701.54	11.13	10.50
9:39:00 AM	9:53:00 AM	2.28	2.24	70.31	69.97	779.09	697.84	11.08	9.97
9:54:00 AM	10:08:00AM	2.22	2.44	72.44	64.22	757.99	698.86	10.46	10.88
10:09:00 AM	10:23:00 AM	2.27	2.39	69.32	64.84	799.63	705.50	11.54	10.88
10:24:00 AM	10:38:00 AM	2.24	2.36	70.00	63.77	776.59	721.11	11.09	11.31
10:39:00 AM	10:53:00 AM	2.16	1.98	63.96	71.89	772.20	634.90	12.07	8.83
10:54:00 AM	11:08:00 AM	1.66	1.92	70.55	67.31	686.60	693.98	9.73	10.31
11:09:00 AM	11:23:00 AM	2.32	2.38	65.30	64.41	752.47	664.22	11.52	10.31
11:24:00 AM	11:38:00 AM	2.14	2.35	72.14	66.93	662.92	679.91	9.19	10.16
11:39:00 AM	11:53:00 AM	2.38	2.20	68.17	69.02	737.61	586.85	10.82	8.50
11:54:00 AM	12:08:00 PM	1.68	2.03	69.70	68.94	681.26	691.66	9.77	10.03
12:09:00 PM	12:23:00 PM	2.10	1.63	73.34	72.78	671.67	535.10	9.16	7.35
12:24:00 PM	12:38:00 PM	2.48	2.21	59.96	70.35	822.66	537.88	13.72	7.65

Table A. 3 Summary of regression analysis for Sebeta-Tullubollo section for the data averaged on 1-min time interval

Model	Equation	Direction	*m*	*l*	u_f	k_j	u_o	k_o	*C*	*n*	R^2
Greenshields	$u = u_f\left(1-\frac{k}{k_j}\right)$	Sebeta	0	*2*	93.49	38.88					0.659
		Tullubollo	0	*2*	91.68	46.35					0.663
Greenberg	$u = u_o \ln\left(\frac{k_j}{k}\right)$	Sebeta	0	*1*		278.21	20.72				0.665
		Tullubollo	0	*1*		145.56	24.28				0.750
Underwood	$u = u_f \exp\left[-\frac{k}{k_o}\right]$	Sebeta	1	*2*	99.16			30.30			0.728
		Tullubollo	1	*2*	95.58			27.77			0.706
Drake et al.	$u = u_f \exp\left[-\frac{1}{2}\left(\frac{k}{k_0}\right)^2\right]$	Sebeta	1	*3*	86.52			18.83			0.596
		Tullubollo	1	*3*	83.48			16.32			0.636
Drew	$u = u_f\left[1-\left(\frac{k}{k_j}\right)^{\frac{n+1}{2}}\right]$	Sebeta	0	*2/3*	93.49	19.48				0	0.656
		Tullubollo	0	*2/3*	91.67	23.18				0	0.662
Multi-regime Matrix	$u^{1-m} = u_f^{1-m} + ck^{l-1}$ $u^{1-m} = u_f^{1-m} + ck^{l-1}$	Sebeta	1.01	1.87	106.26				0.000465		0.708
		Tullubollo	1.0014	1.8	113.0				0.00012		0.751

Table A. 4 Summary of regression analysis for Sululta-Chancho section for the data averaged on 1-min time interval

Model	Equation	Direction	*m*	*l*	u_f	k_j	u_o	k_o	*C*	*n*	R^2
Greenshields	$u = u_f\left(1-\frac{k}{k_j}\right)$	Sululta	0	*2*	97.87	33.86					0.705
		Chancho	0	*2*	98.10	26.26					0.596
Greenberg	$u = u_o \ln\left(\frac{k_j}{k}\right)$	Sululta	0	*1*		116.65	24.45				0.662
		Chancho	0	*1*		70.66	30.01				0.870
Underwood	$u = u_f \exp\left[-\frac{k}{k_o}\right]$	Sululta	1	*2*	106.16			16.67			0.716
		Chancho	1	*2*	101.03			21.74			0.769
Drake et al.	$u = u_f \exp\left[-\frac{1}{2}\left(\frac{k}{k_0}\right)^2\right]$	Sululta	1	*3*	88.32			11.34			0.687
		Chancho	1	*3*	*99.86*			10.40			0.663
Drew	$u = u_f\left[1-\left(\frac{k}{k_j}\right)^{\frac{n+1}{2}}\right]$	Sululta	0	*2/3*	97.87	13.13				*0*	0.705
		Chancho	0	*2/3*	98.09	16.93				*0*	0.596
Multi-regime Matrix	$u^{1-m} = u_f^{1-m} + ck^{l-1}$ $u^{1-m} = ck^{l-1} - ck_j^{l-1}$	Sululta	1.01	2.18	100.35				0.00022		0.718
		Chancho	0.11	0.98		99.00			1129.02		0.872

Table A. 5 Summary of regression analysis for Sendafa-Debrebirhan section for the data averaged on 1-min time interval

Model	Equation	Direction	*m*	*l*	u_f	k_j	u_o	k_o	*C*	*n*	R^2
Greenshields	$u = u_f\left(1-\frac{k}{k_j}\right)$	Sendafa	0	*2*	99.98	35.21					0.837
		Deb/birhan	0	*2*	91.38	37.65					0.818
Greenberg	$u = u_o \ln\left(\frac{k_j}{k}\right)$	Sendafa	0	*1*		107.09	30.10				0.819
		Deb/birhan	0	*1*		168.61	23.67				0.789
Underwood	$u = u_f \exp\left[-\frac{k}{k_o}\right]$	Sendafa	1	*2*	108.29			23.81			0.830
		Deb/birhan	1	*2*	96.86			27.03			0.809
Drake et al.	$u = u_f \exp\left[-\frac{1}{2}\left(\frac{k}{k_o}\right)^2\right]$	Sendafa	1	*3*	86.69			16.23			0.827
		Deb/birhan	1	*3*	80.57			16.65			0.843
Drew	$u = u_f\left[1-\left(\frac{k}{k_j}\right)^{\frac{n+1}{2}}\right]$	Sendafa	0	*2/3*	81.36	17.53				1.592	0.848
		Deb/birhan	0	*2/3*	79.04	18.19				1.037	0.828
Multi-regime Matrix	$\ln(\frac{u_f}{u}) = ck^{l-1}$	Sendafa	1	4.08	80.35				9.27834E-05		0.848
	$\ln(\frac{u_f}{u}) = ck^{l-1}$	Deb/birhan	1	3.43	77.96				0.000537		0.829

Table A. 6 Summary of regression analysis for Sebeta-Tullubollo section for the data averaged on 15-min time interval

Model	Equation	Direction	*m*	*l*	u_f	k_j	u_o	k_o	*C*	*n*	R^2
Greenshields	$u = u_f\left(1-\frac{k}{k_j}\right)$	Sebeta	0	*2*	107.08	16.95					0.645
		Tullubollo	0	*2*	104.70	20.11					0.825
Greenberg	$u = u_o \ln\left(\frac{k_j}{k}\right)$	Sebeta	0	*1*		314.06	18.17				0.747
		Tullubollo	0	*1*		646.43	15.95				0.650
Underwood	$u = u_f \exp\left[-\frac{k}{k_o}\right]$	Sebeta	1	*2*	110.18			12.66			0.800
		Tullubollo	1	*2*	106.33			15.87			0.668
Drake et al.	$u = u_f \exp\left[-\frac{1}{2}\left(\frac{k}{k_o}\right)^2\right]$	Sebeta	1	*3*	99.01			6.98			0.560
		Tullubollo	1	*3*	97.42			8.05			0.731
Drew	$u = u_f\left[1-\left(\frac{k}{k_j}\right)^{\frac{n+1}{2}}\right]$	Sebeta	0	*2/3*	107.08	8.48				*0*	0.788
		Tullubollo	0	*2/3*	104.66	10.05				*0*	0.645
Multi-regime Matrix	$u^{1-m} = u_f^{1-m} + ck^{l-1}$	Sebeta	1.01	2.00	110.49				0.001026		0.800
	$u^{1-m} = u_f^{1-m} + ck^{l-1}$	Tullubollo	3.43	2.25	108.84				1.998E-06		0.677

Table A. 7 Summary of regression analysis for Sululta-Chancho section for the data averaged on 15-min time interval

Model	Equation	Direction	*m*	*l*	u_f	k_j	u_o	k_o	*C*	*n*	R^2
Greenshields	$u= u_f\left(1-\frac{k}{k_j}\right)$	Sululta	0	*2*	109.3	19.83					0.783
		Chancho	0	*2*	107.3	24.95					0.779
Greenberg	$u = u_o \ln\left(\frac{k_j}{k}\right)$	Sululta	0	*1*		53.35	37.9				0.820
		Chancho	0	*1*		46.734	37.05				0.749
Underwood	$u = u_f \exp\left[-\frac{k}{k_o}\right]$	Sululta	1	*2*	118.12			16.13			0.806
		Chancho	1	*2*	121.25			12.99			0.762
Drake et al.	$u = u_f \exp\left[-\frac{1}{2}\left(\frac{k}{k_o}\right)^2\right]$	Sululta	1	*3*	86.69			16.23			0.843
		Chancho	1	*3*	80.57			16.65			0.827
Drew	$u = u_f\left[1-\left(\frac{k}{k_j}\right)^{\frac{n+1}{2}}\right]$	Sululta	0	*2/3*	81.36	17.53				1.592	0.848
		Chancho	0	*2/3*	79.04	18.19				1.037	0.828
Multi-regime Matrix	$\ln(\frac{u_f}{u}) = ck^{l-1}$ $u^{1-m} = ck^{l-1} - ck_j^{l-1}$	Sululta	1	4.28	84.19				0.000265		0.788
		Chancho	0.14	0.98	73.50				1099.2		0.822

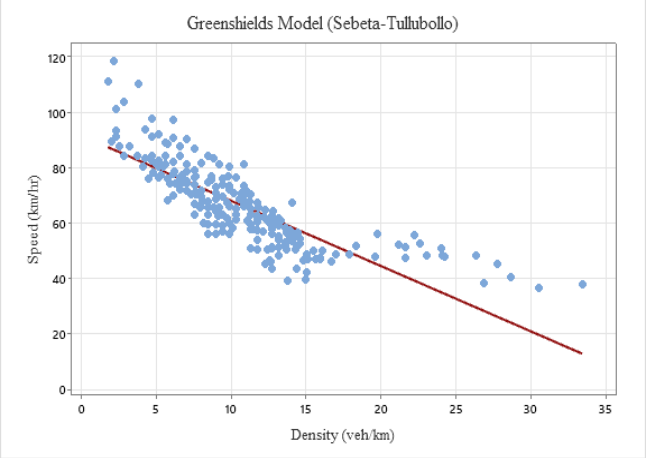
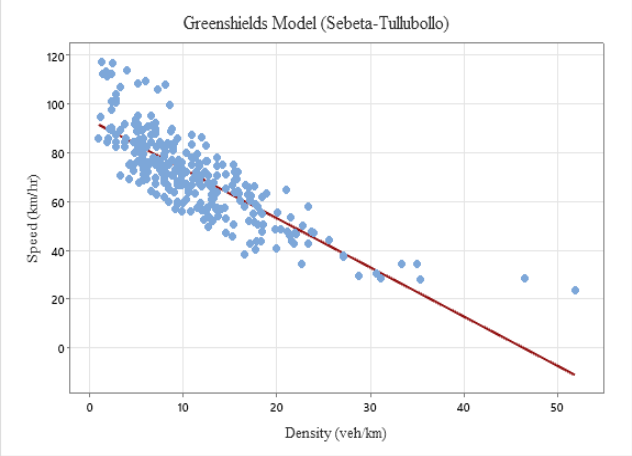
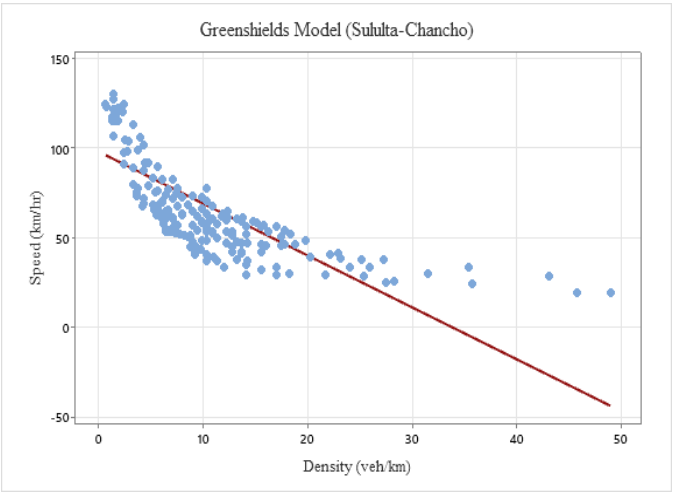
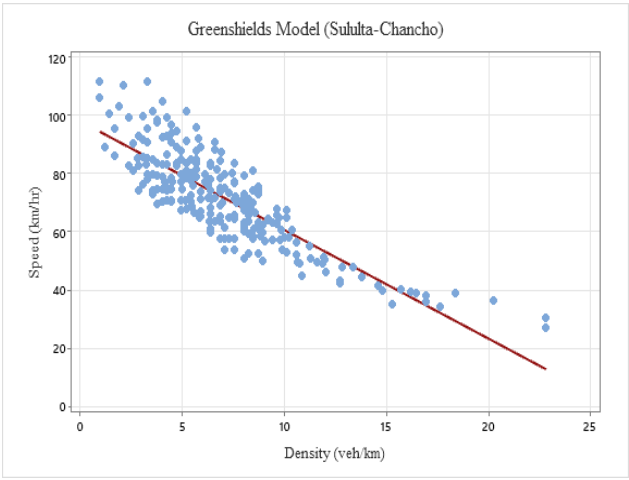
Table A. 8 Summary of regression analysis for Sendafa-Debrebirhan section for the data averaged on 15-min time interval

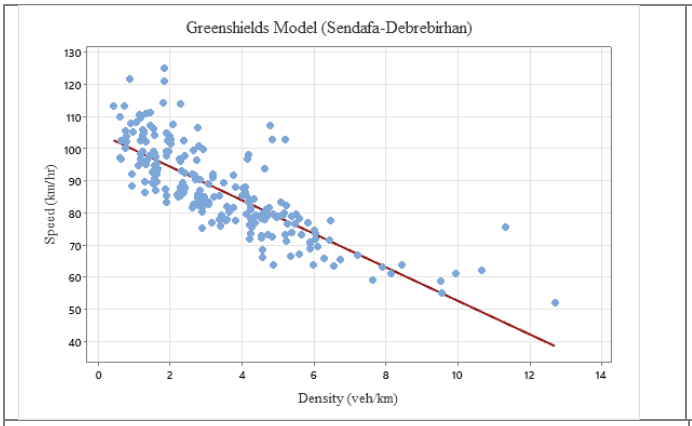
Model	Equation	Direction	*m*	*l*	u_f	k_j	u_o	k_o	*C*	*n*	R^2
Greenshields	$u= u_f\left(1-\frac{k}{k_j}\right)$	Sendafa	0	*2*	101.2	17.29					0.768
		Debrebirhan	0	*2*	95.61	26.35					0.777
Greenberg	$u = u_o \ln\left(\frac{k_j}{k}\right)$	Sendafa	0	*1*		16694.52	9.774				0.665
		Debrebirhan	0	*1*		480.34	16.39				0.780
Underwood	$u = u_f \exp\left[-\frac{k}{k_o}\right]$	Sendafa	1	*2*	96.15			23.81			0.783
		Debrebirhan	1	*2*	102.77			14.49			0.775
Drake et al.	$u = u_f \exp\left[-\frac{1}{2}\left(\frac{k}{k_o}\right)^2\right]$	Sendafa	1	*3*	90.58			8.51			0.709
		Debrebirhan	1	*3*	93.16			6.59			0.729
Drew	$u = u_f\left[1-\left(\frac{k}{k_j}\right)^{\frac{n+1}{2}}\right]$	Sendafa	0	*2/3*	101.16	8.64				*0*	0.768
		Debrebirhan	0	*2/3*	95.61	13.18				*0*	0.777
Multi-regime Matrix	$\ln(\frac{u_f}{u}) = ck^{l-1}$ $\ln(\frac{u_f}{u}) = ck^{l-1}$	Sendafa	1	1.504	124.94				0.23299		0.783
		Debrebirhan	1	1.23	140.83				0.3977		0.805

APPENDIX- B

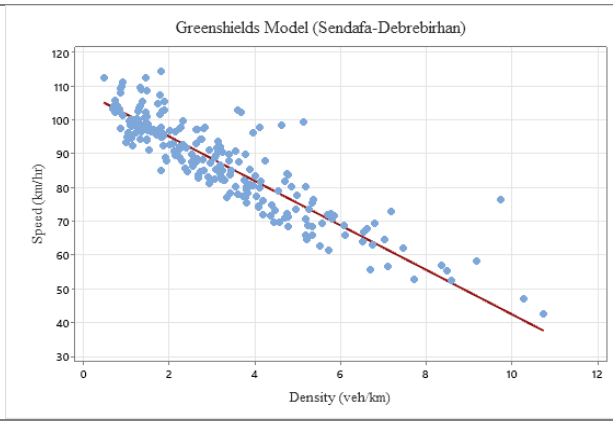
Speed-Density Models Fitted to Data Averaged on 1-min and 15-min Time Interval

Table B. 1 Speed-Density Models Fitted to Data Averaged on 1-min Time Interval

Speed-Density Models	
Greenshields Model	
	
Sebeta-Tullobollo section towards Tullobollo	Sebeta-Tullobollo section towards Sebeta
	
Sululta-Chancho section towards Chancho direction	Sululta-Chancho section towards Sululta direction

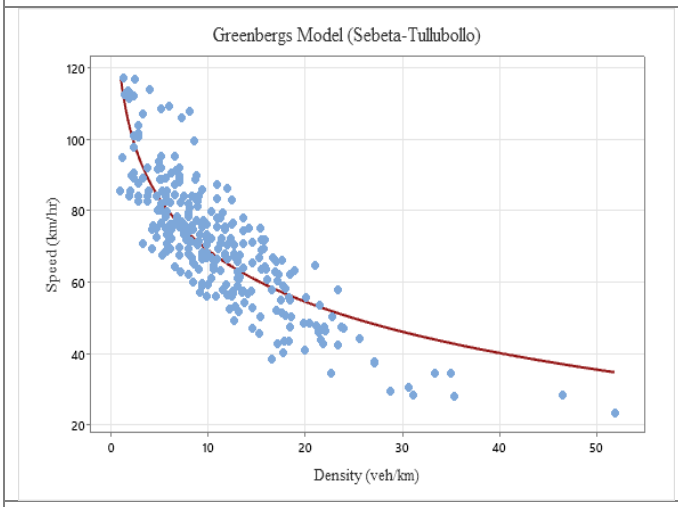


Sendafa-Debrebirhan section towards Debrebirhan direction



Sendafa-Debrebirhan section towards Sendafa direction

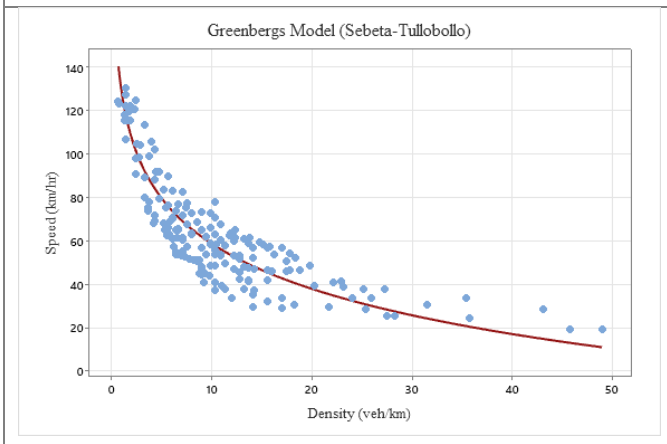
Greenbergs Model



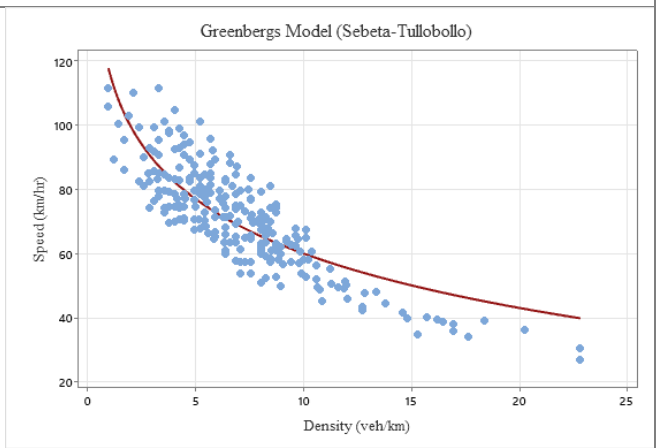
Sebeta-Tullobollo section towards Sebeta direction



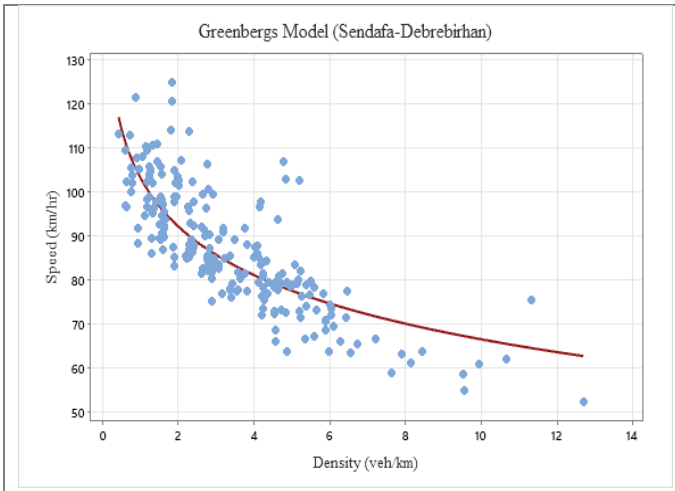
Sebeta-Tullobollo section towards Tullobollo direction



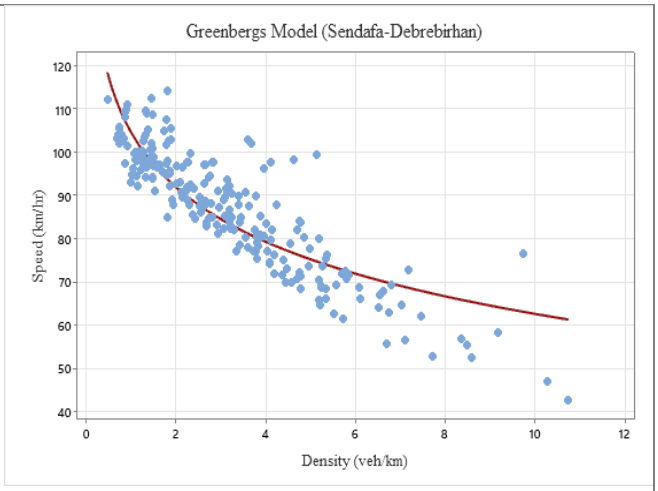
Sululta-Chancho section towards Chancho direction



Sululta-Chancho section towards Sululta direction

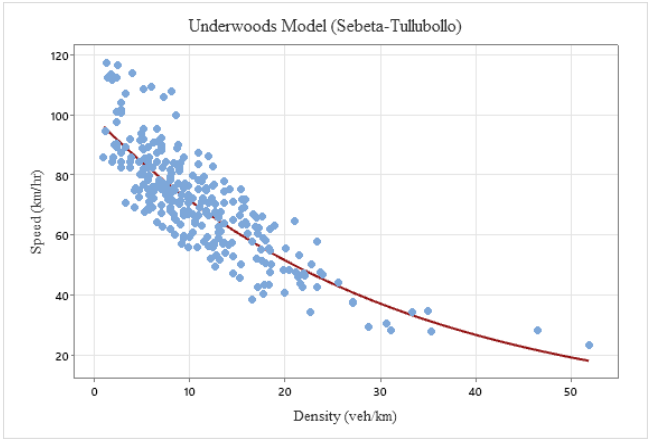


Sendafa-Debrebirhan section towards Debrebirhan direction

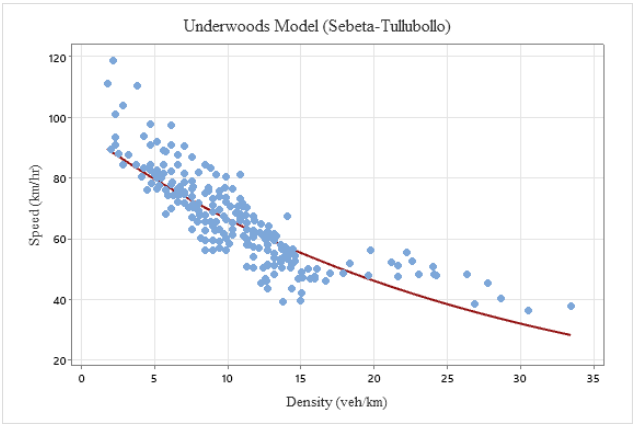


Sendafa-Debrebirhan section towards Sendafa direction

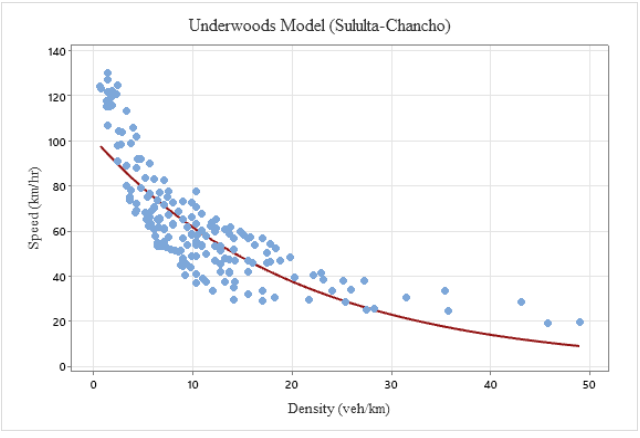
Underwoods Model



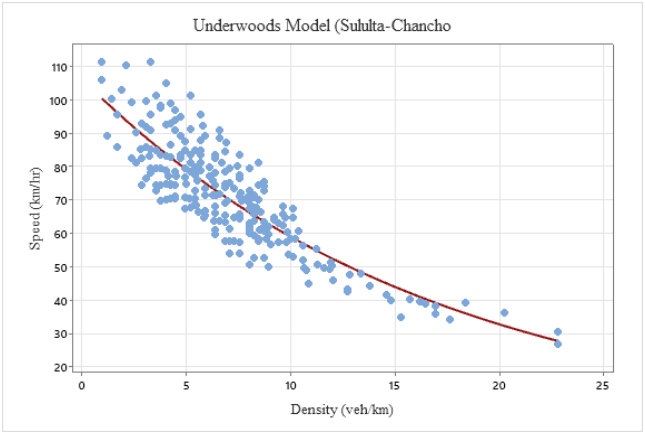
Sebeta-Tullobollo section towards Sebeta direction



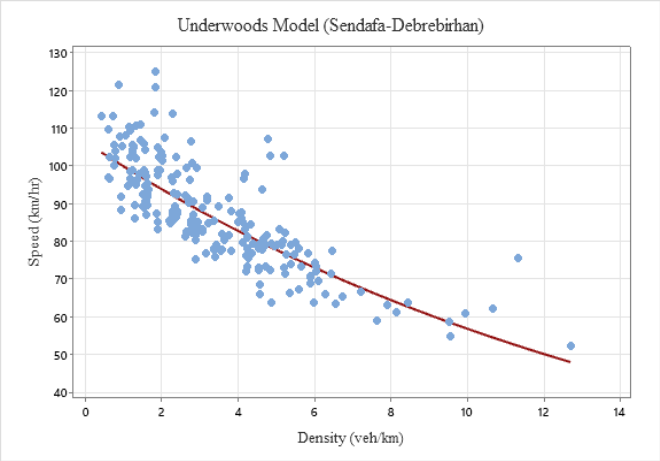
Sebeta-Tullobollo section towards Tullobollo direction



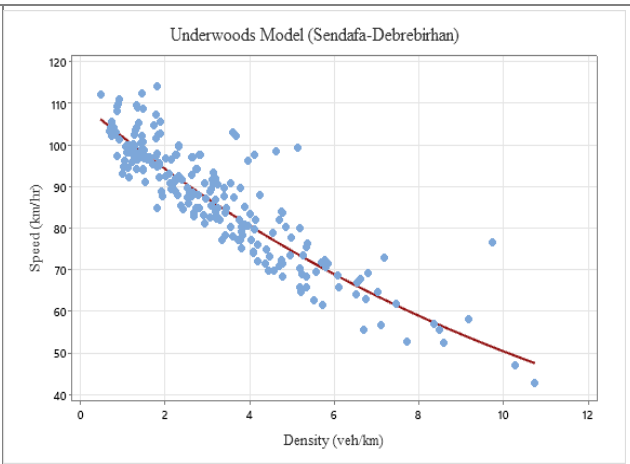
Sululta-Chancho section towards Chancho direction



Sululta-Chancho section towards Sululta direction

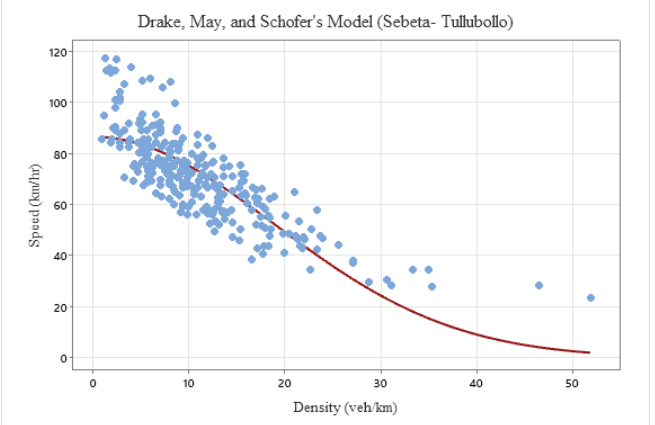


Sendafa-Debrebirhan section towards Debrebirhan direction

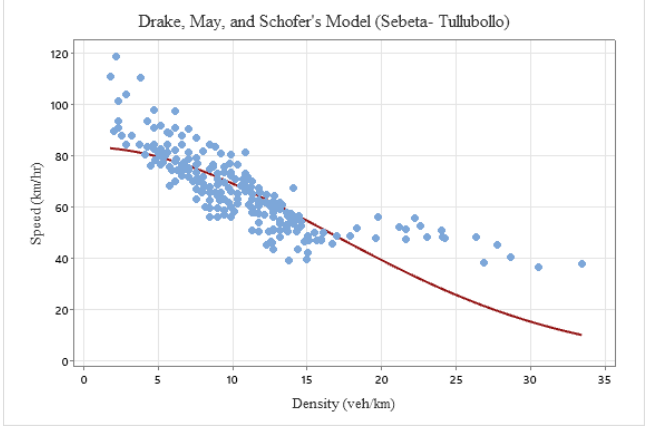


Sendafa-Debrebirhan section towards Sendafa direction

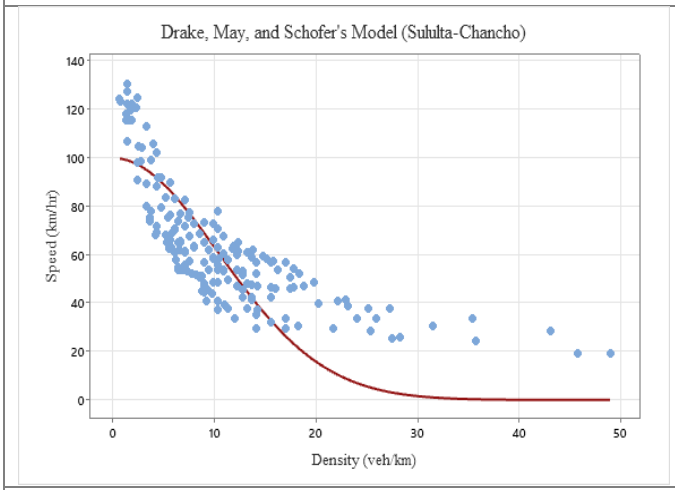
Drake, May, and Schofer's Model



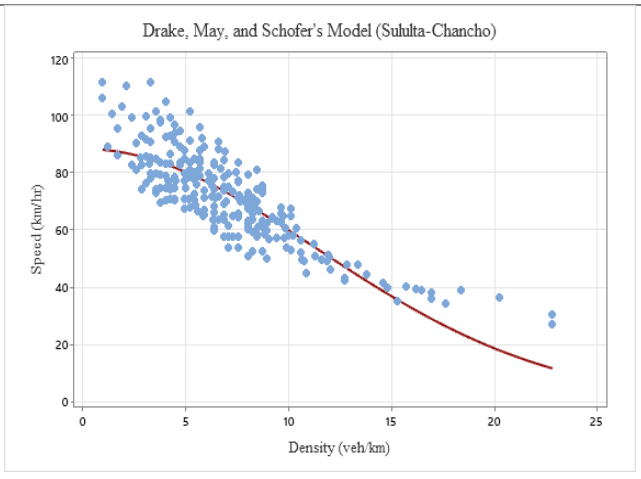
Sebeta- Tullubollo section towards Sebeta direction



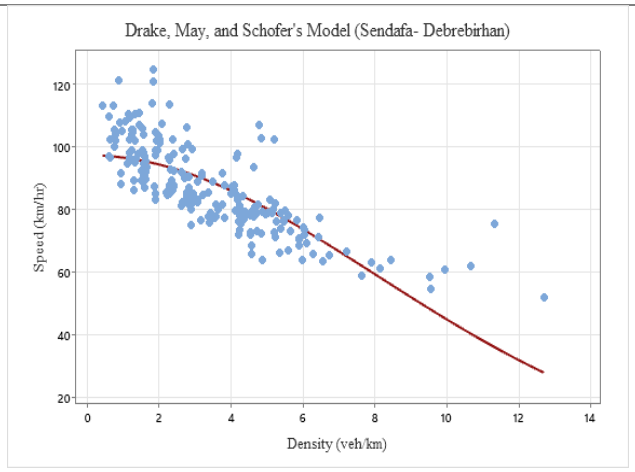
Sebeta- Tullubollo section towards Tullubollo direction



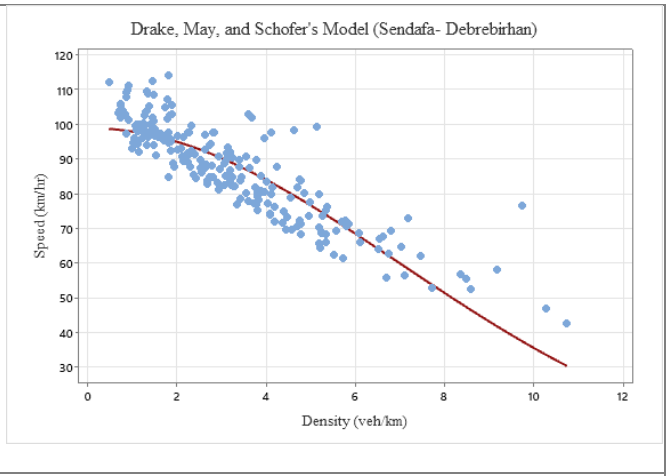
Sululta- Chancho section towards Chancho direction



Sululta- Chancho section towards Sululta direction

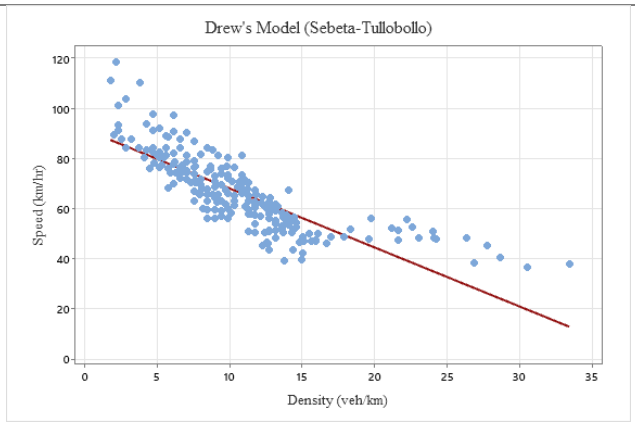


Sendafa- Debrebirhan section towards Debrebirhan direction

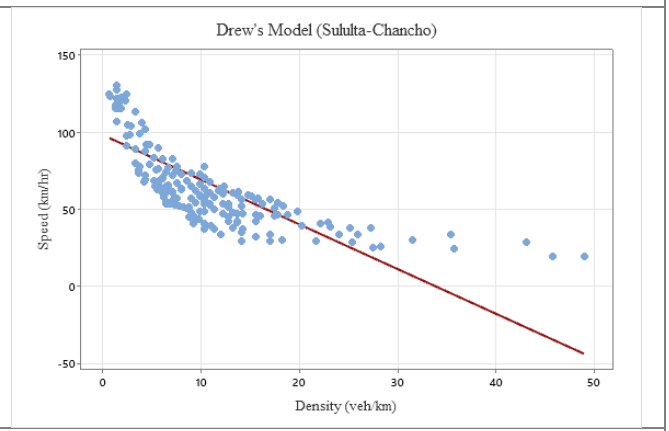


Sendafa- Debrebirhan section towards Sendafa direction

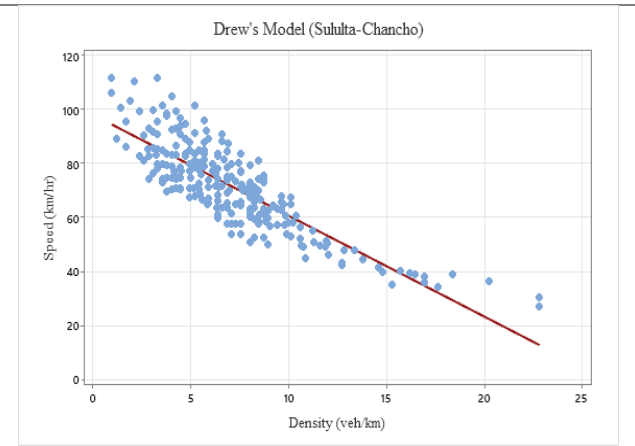
Drew's Model



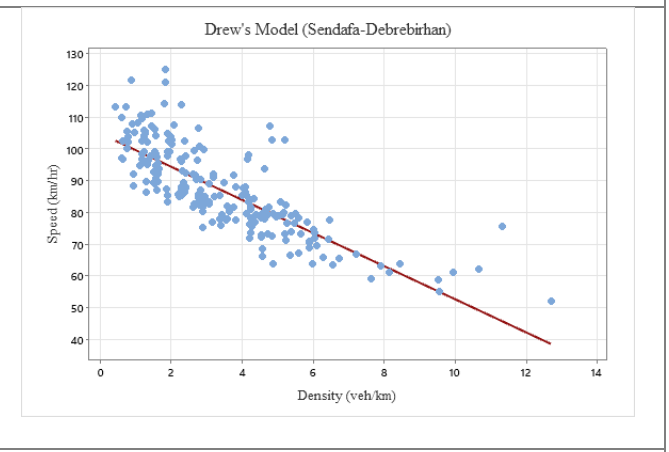
Sebeta- Tullubollo section towards Sebeta direction



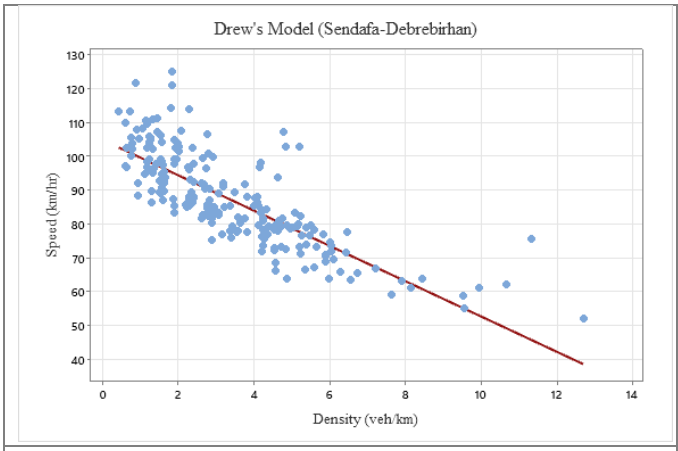
Sebeta- Tullubollo section towards Tullubollo direction



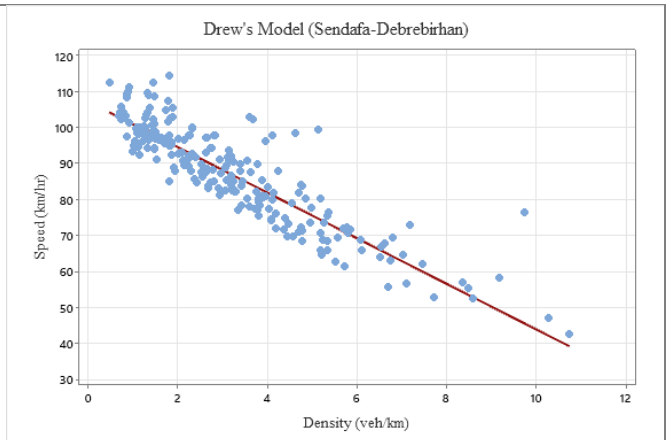
Sululta-Chancho section towards Chancho direction



Sululta-Chancho section towards Sululta direction

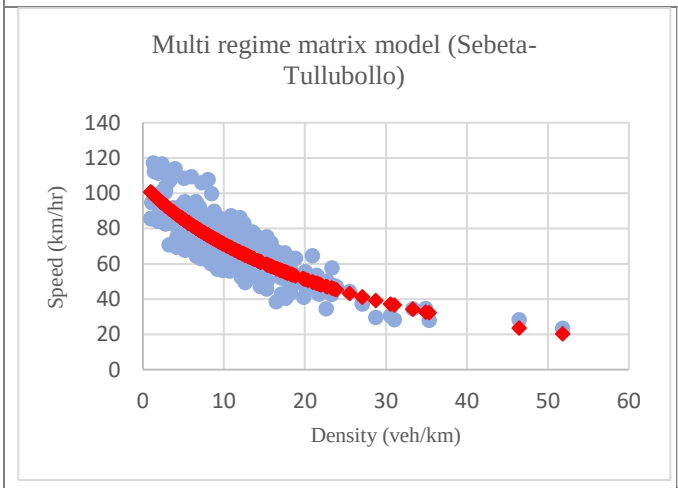


Sendafa-Debrebirhan section towards Debrebirhan direction

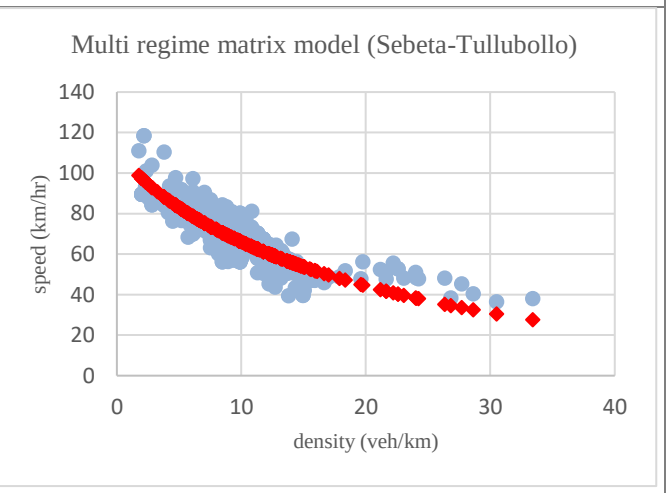


Sendafa-Debrebirhan section towards Sendafa direction

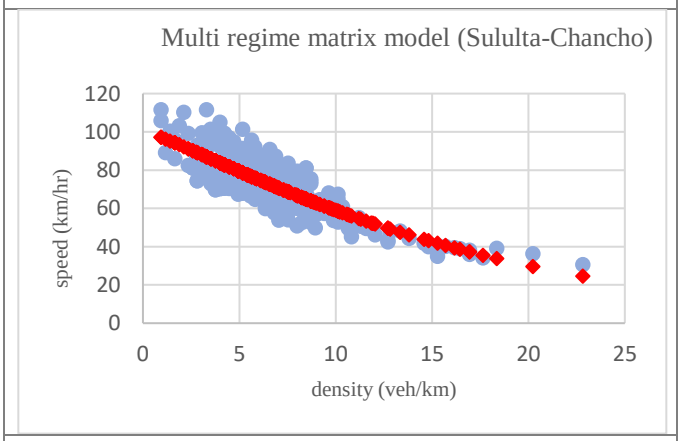
Multi-Regime Matrix's Model



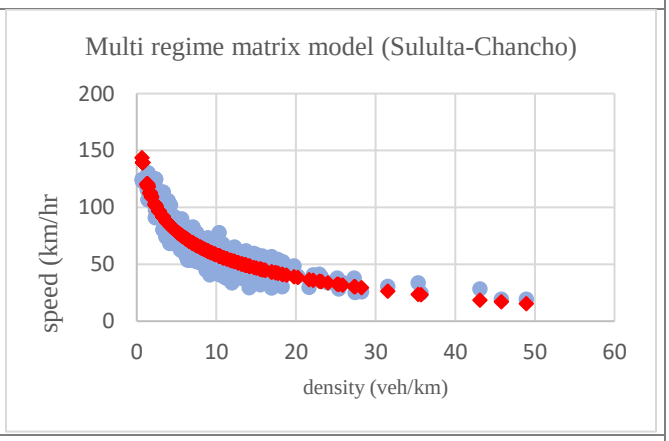
Sebeta- Tullubollo section towards Sebeta direction



Sebeta- Tullubollo section towards Tullubollo direction



Sululta- Chancho section towards Sululta direction



Sululta- Chancho section towards Chancho direction

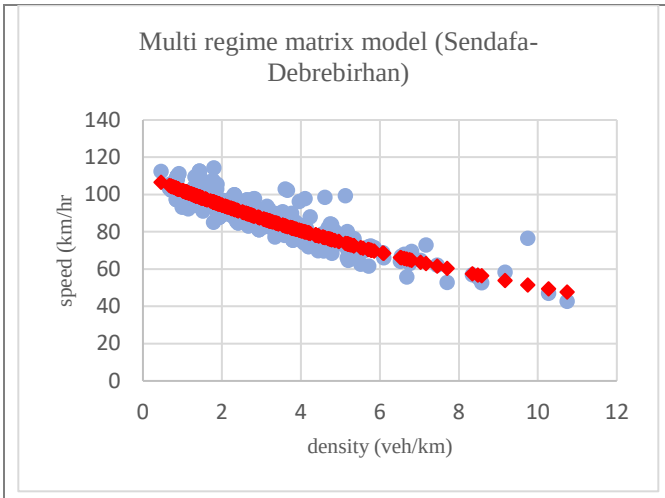
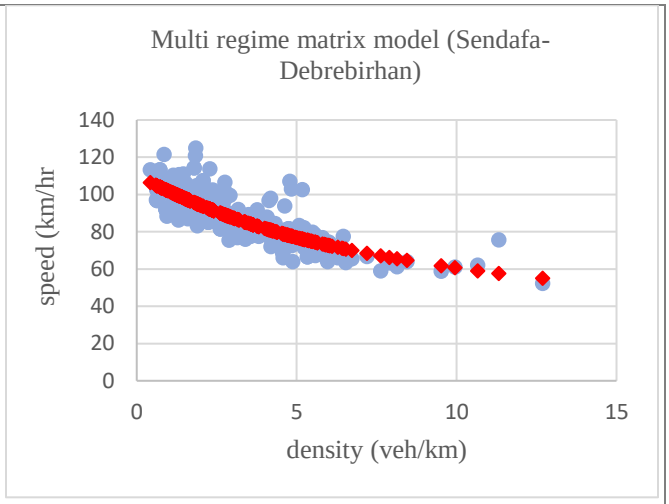
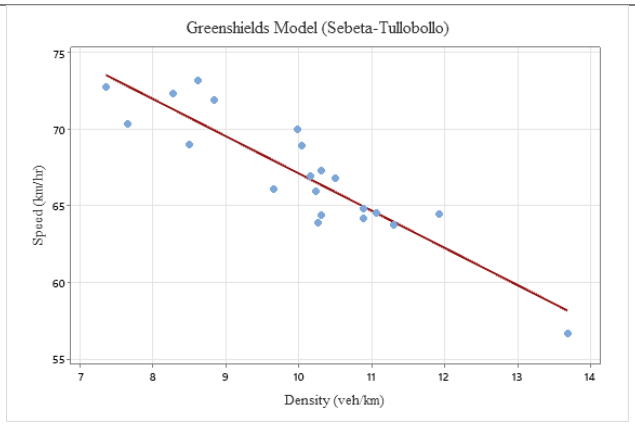
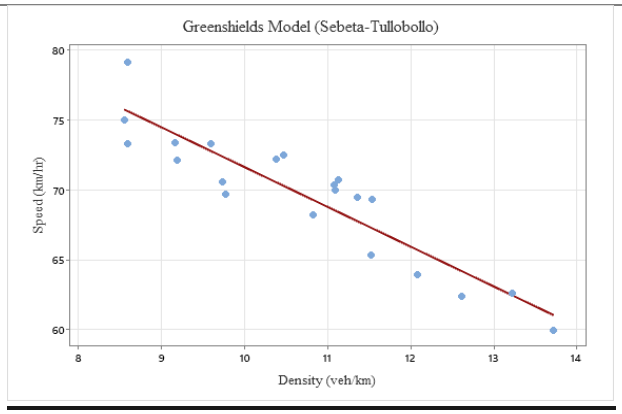
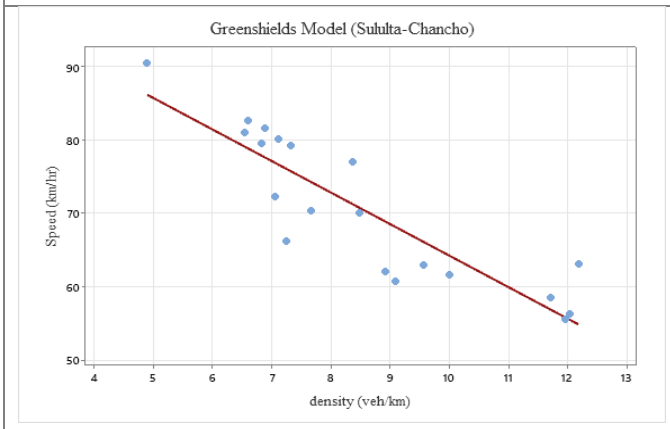
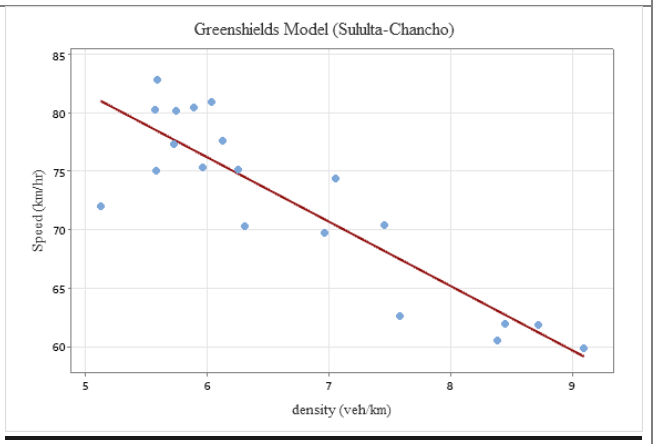
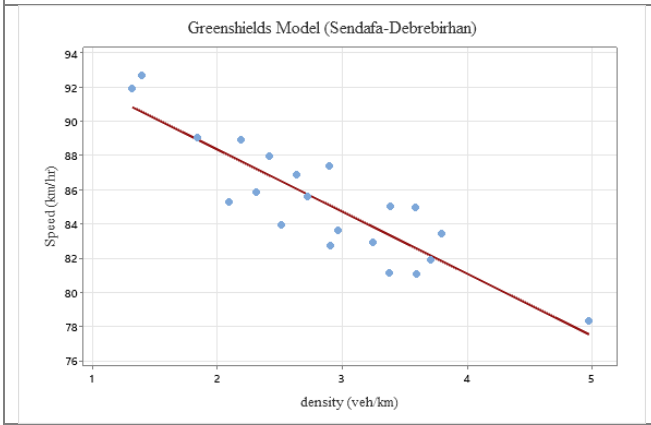
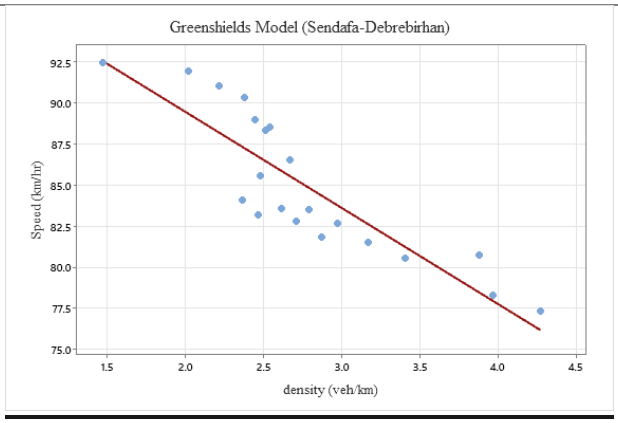
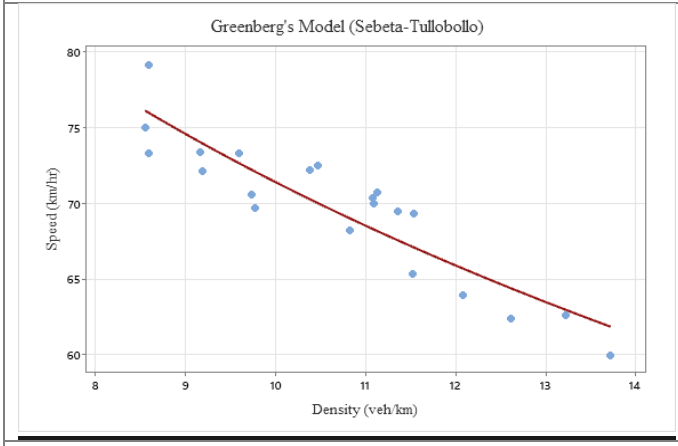
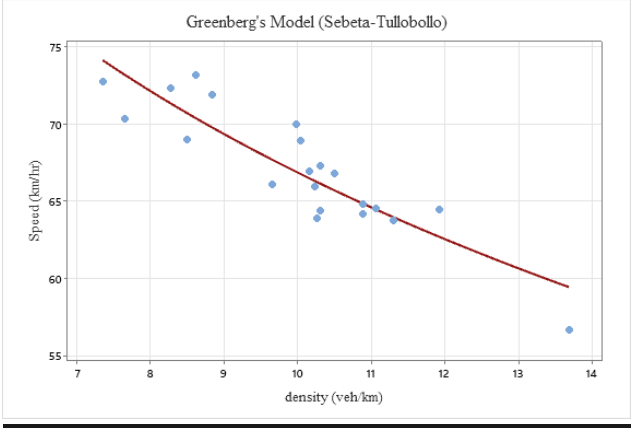
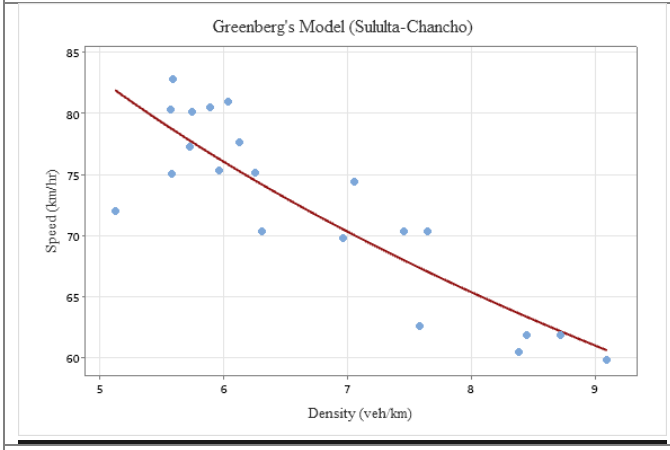
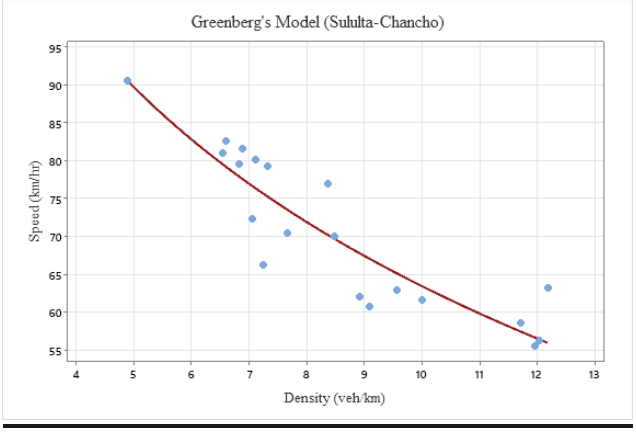
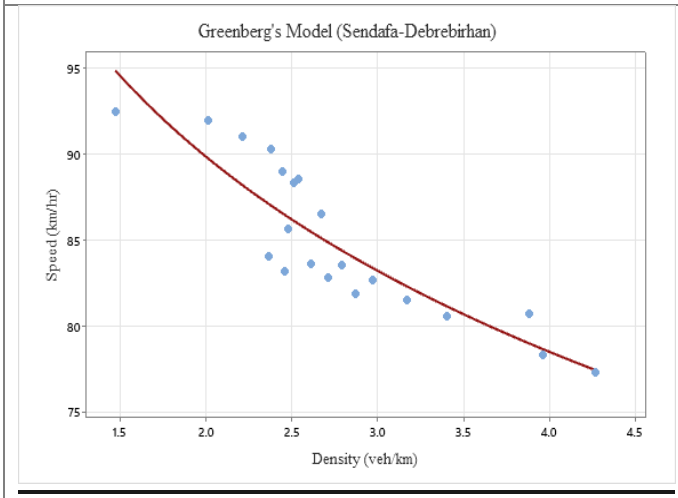
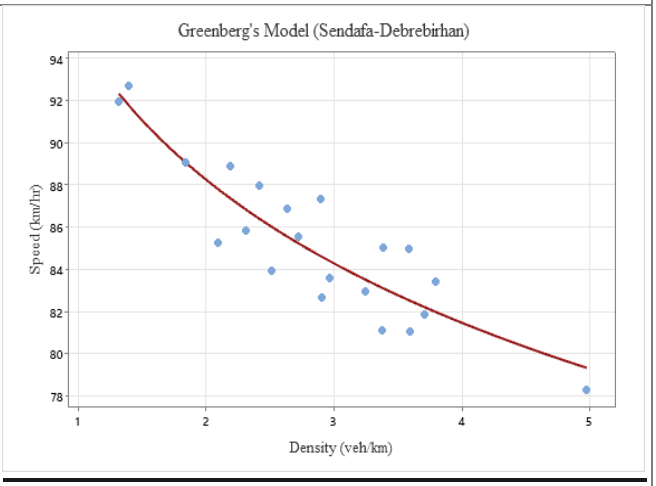
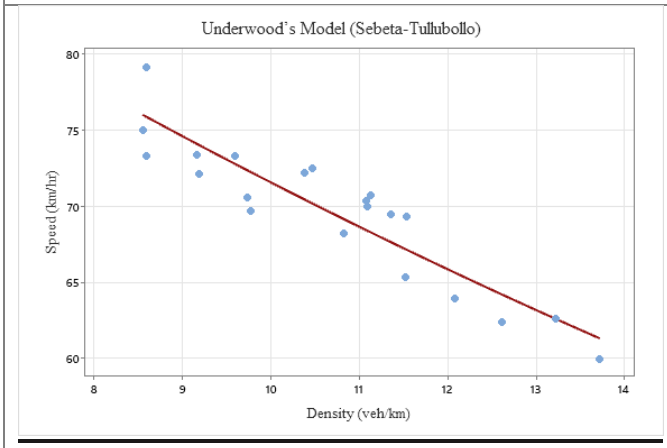
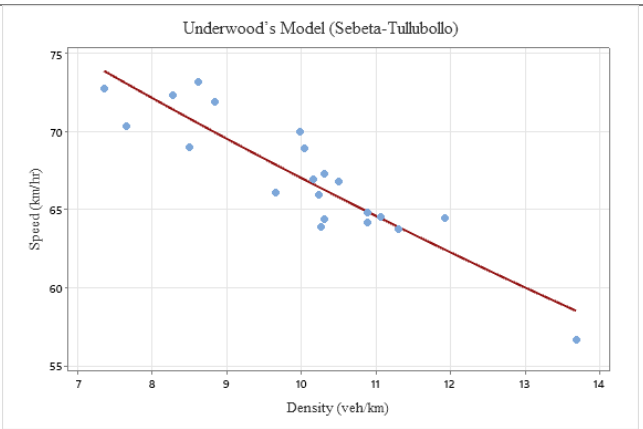
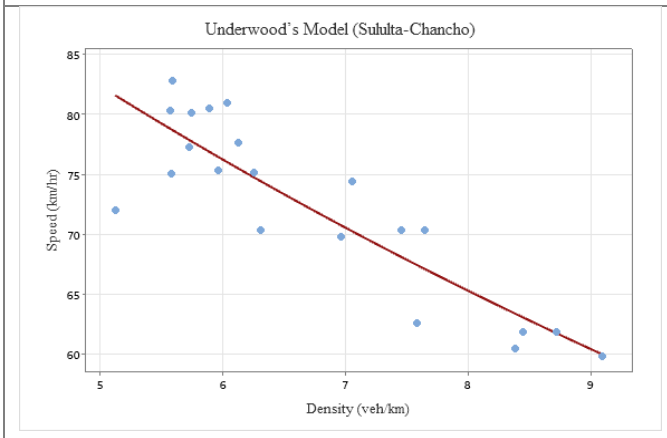
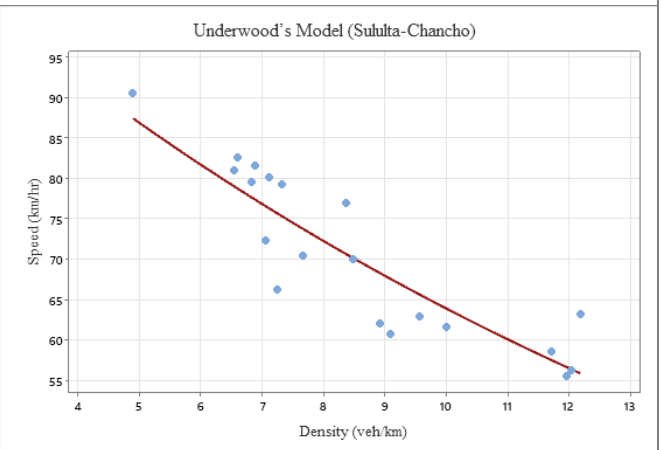
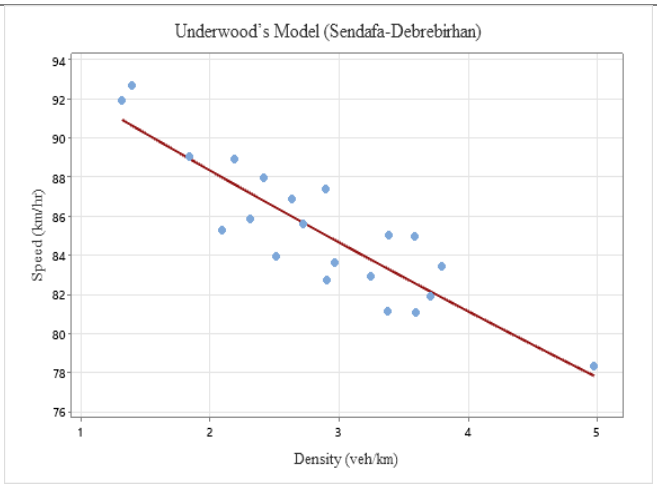
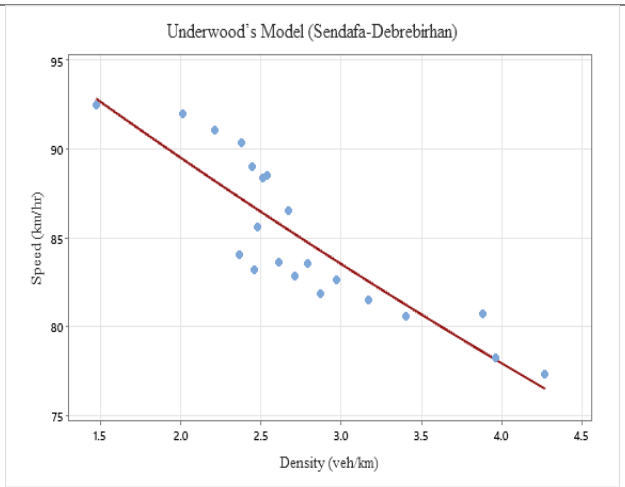
	
Sendafa - Debrebirhan section towards Sendafa direction	Sendafa - Debrebirhan section towards Debrebirhan direction

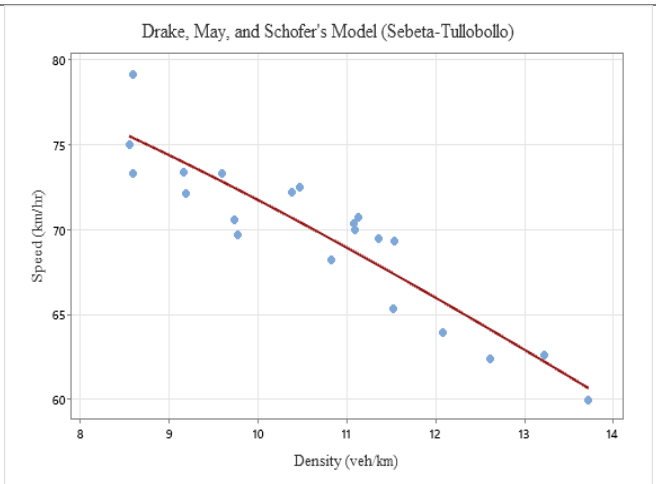
Table B. 2 Speed-Density Models Fitted to Data Averaged on 15-min Time Interval

Speed-Density Models	
Greenshields Model	
	
Sebeta-Tullobollo section towards Tullobollo	Sebeta-Tullobollo section towards Sebeta
	
Sululta-Chancho section towards Chancho direction	Sululta-Chancho section towards Sululta direction
	
Sendafa-Debrebirhan section towards Debrebirhan direction	Sendafa-Debrebirhan section towards Sendafa direction

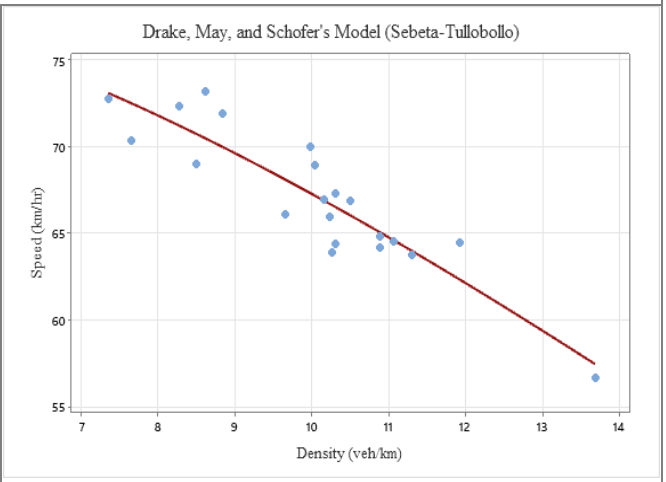
Greenbergs Model	
	
Sebeta-Tullobollo section towards Sebeta direction	Sebeta-Tullobollo section towards Tullobollo direction
	
Sululta-Chancho section towards Chancho direction	Sululta-Chancho section towards Sululta direction
	
Sendafa-Debrebirhan section towards Debrebirhan direction	Sendafa-Debrebirhan section towards Sendafa direction

Underwoods Model	
	
Sebeta-Tullobollo section towards Sebeta direction	Sebeta-Tullobollo section towards Tullobollo direction
	
Sululta-Chancho section towards Chancho direction	Sululta-Chancho section towards Sululta direction
	
Sendafa-Debrebirhan section towards Debrebirhan direction	Sendafa-Debrebirhan section towards Sendafa direction

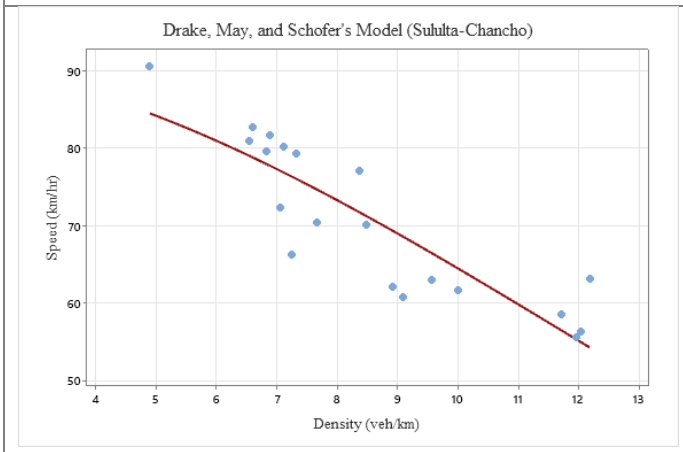
Drake, May, and Schofer's Model



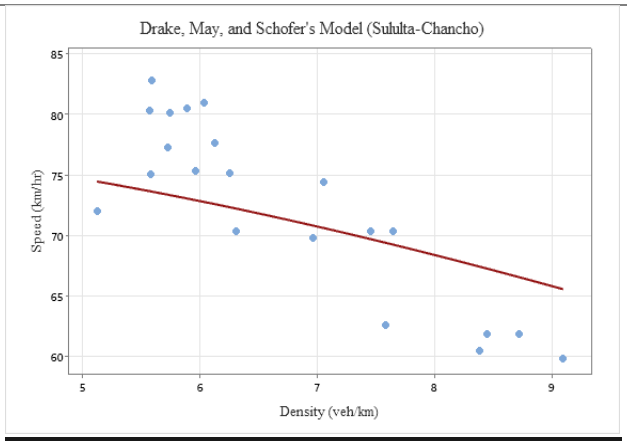
Sebeta- Tullubollo section towards Sebeta direction



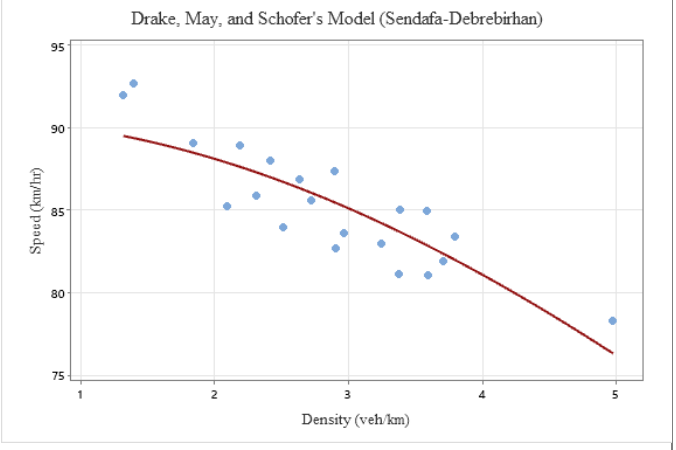
Sebeta- Tullubollo section towards Tullubollo direction



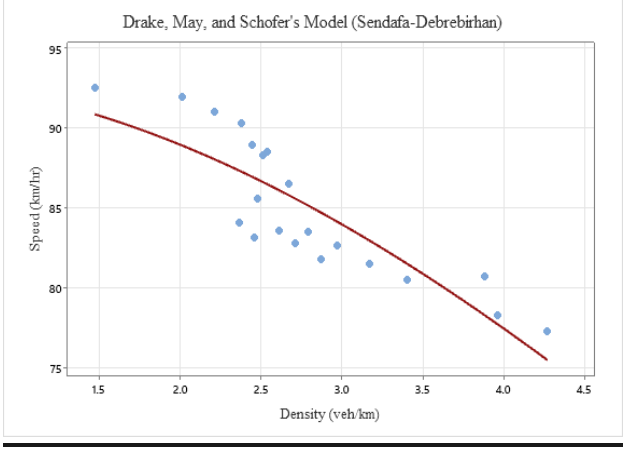
Sululta- Chancho section towards Chancho direction



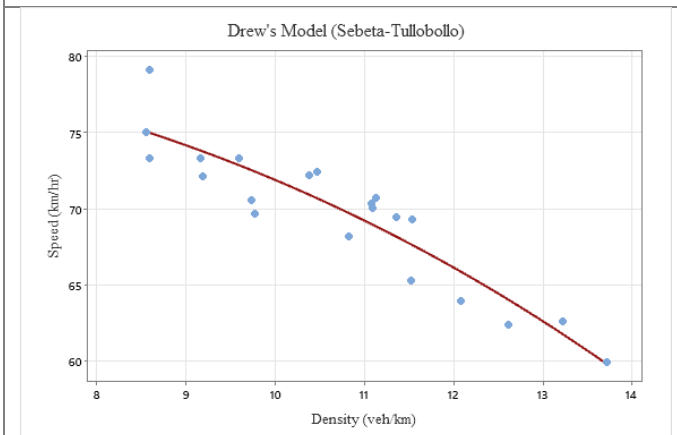
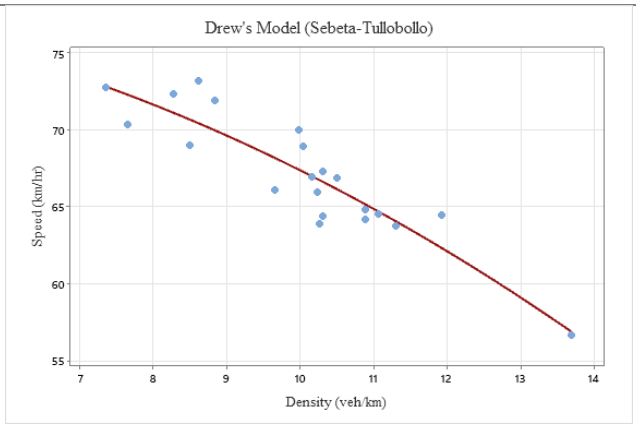
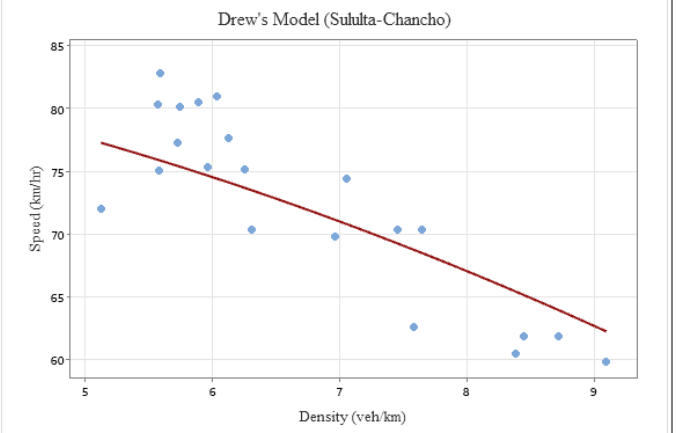
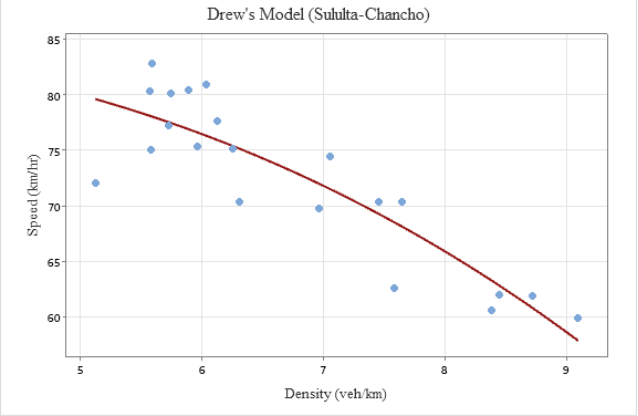
Sululta- Chancho section towards Sululta direction

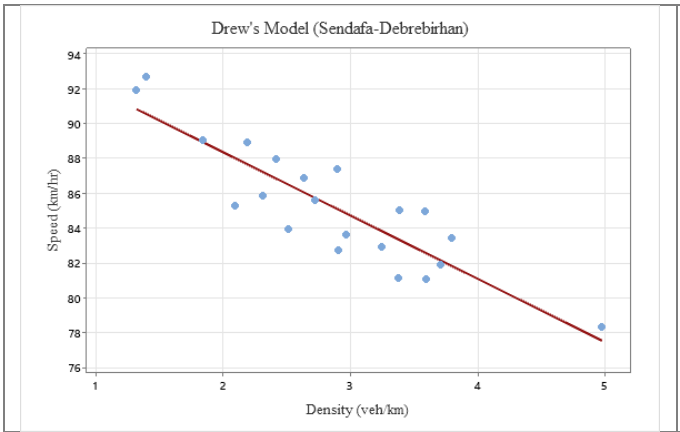
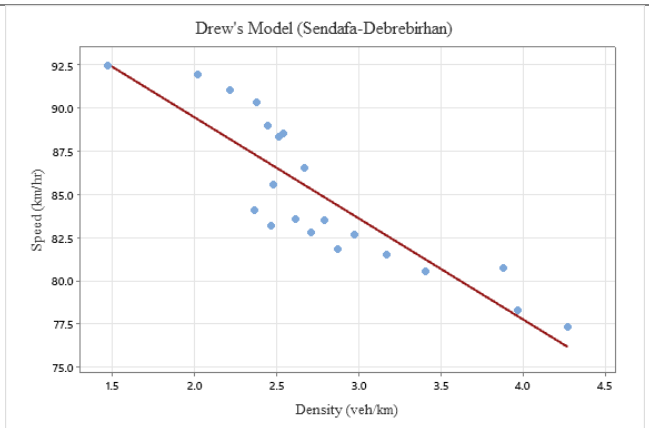


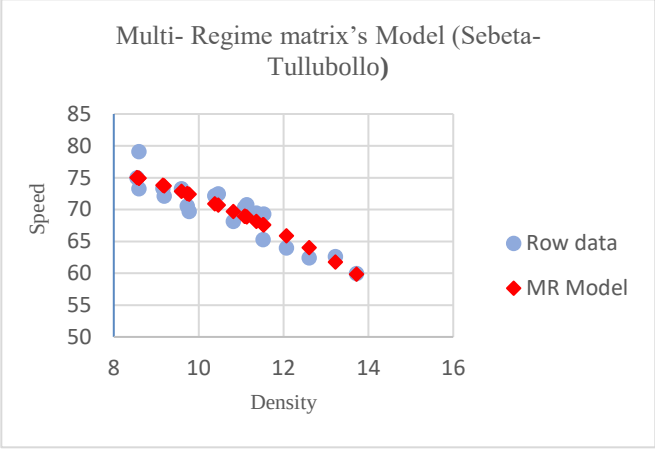
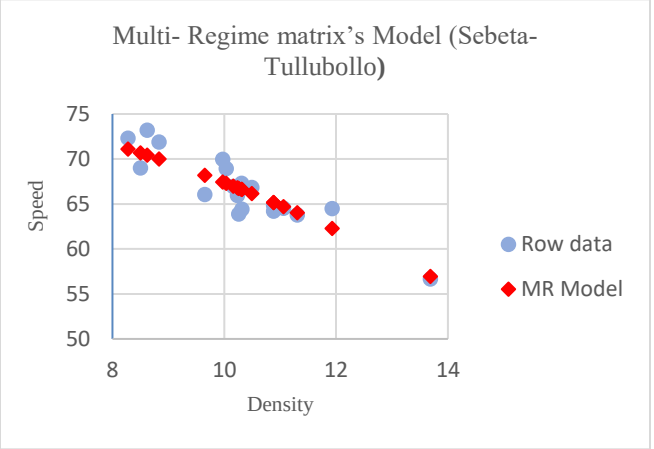
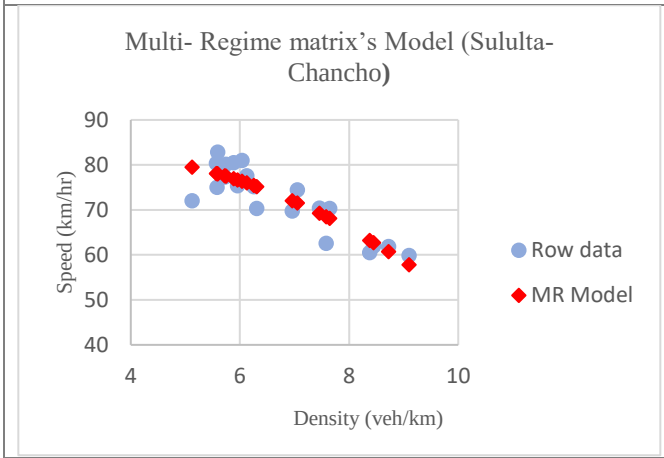
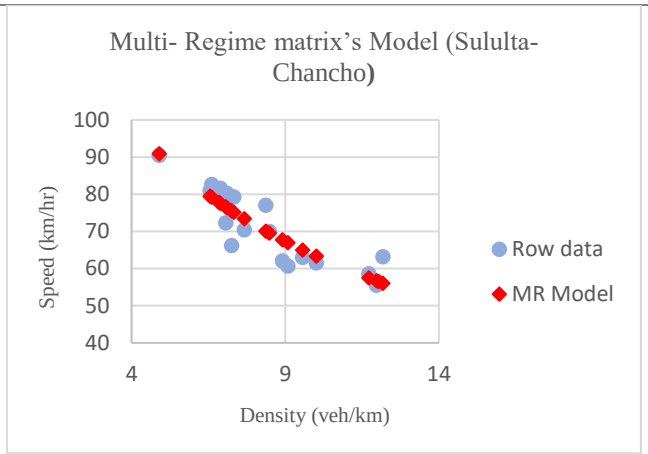
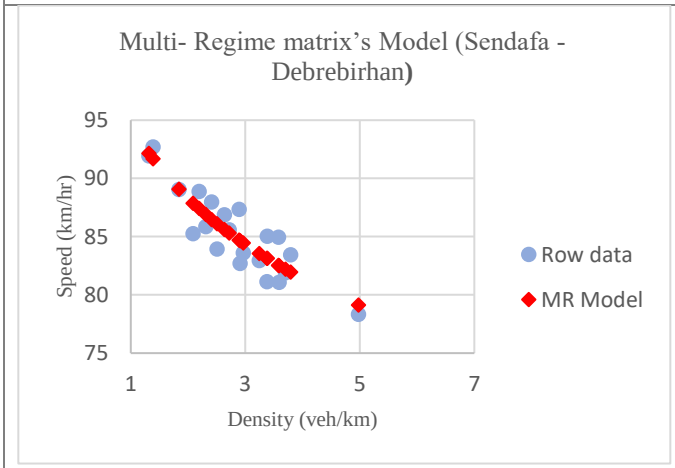
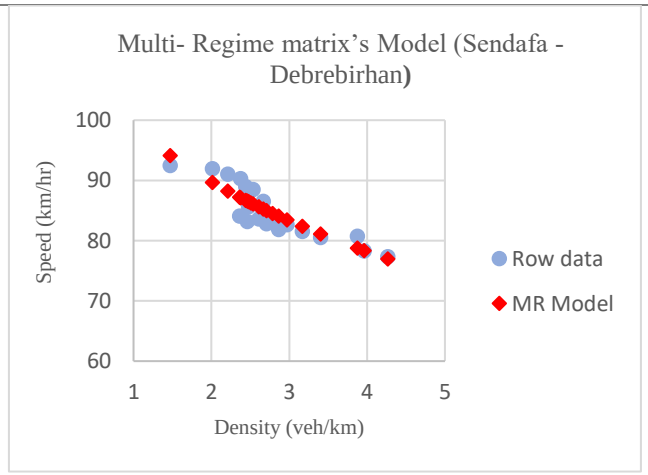
Sendafa- Debrebirhan section towards Debrebirhan direction



Sendafa- Debrebirhan section towards Sendafa direction

Drew's Model	
	
Sebeta- Tullubollo section towards Sebeta direction	Sebeta- Tullubollo section towards Tullubollo direction
	
Sululta-Chancho section towards Chancho direction	Sululta-Chancho section towards Sululta direction

	
Sendafa-Debrebirhan section towards Debrebirhan direction	Sendafa-Debrebirhan section towards Sendafa direction

Multi-Regime Matrix's Model	
	
Sebeta- Tullubollo section towards Sebeta direction	Sebeta- Tullubollo section towards Tullubollo direction
	
Sululta- Chancho section towards Sululta direction	Sululta- Chancho section towards Chancho direction
	
Sendafa - Debrebirhan section towards Sendafa direction	Sendafa - Debrebirhan section towards Debrebirhan direction