DEVELOPMENT OF A REAL-TIME ROAD TRAFFIC ASSESSMENT TOOL FOR KIGALI CITY, RWANDA

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CERTIFICATION

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DEDICATION

To the Almighty God, the Alpha and Omega

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ABSTRACT

Traffic congestion is a significant problem in many urban areas, including Kigali City, Rwanda. This problem is associated with augmented fuel wastage, air pollution, financial losses, delays, and risk of accidents, due to poor traffic control and management. Traffic management efforts such as road widening, speed limit devices, and deployment of control measures to mitigate traffic congestion have not yielded expected results. This is largely due to limited availability of tools that incorporate real-time traffic flow parameters in road traffic assessment for metropolitan cities, such as Kigali. This study, therefore, developed a real-time road traffic assessment tool for Kigali City in Rwanda.

Purposive interviews were conducted with management officers of national roads in Kigali. Preliminary surveys of five national roads (NR1, NR2, NR3, NR4 and NR5) were carried out. Traffic volume data were captured on NR1 and NR2, between 5.00 a.m. and 8.00 p.m., for 30 days, between November 2019 and December 2019, as specified in the Highway Capacity Manual (HCM). Traffic patterns on NR1 and NR2 were analysed using regression models and Macroscopic Fundamental Diagram (MFD). A Traffic Assessment Tool (TAT) for real-time traffic flow analysis was developed based on MFD and regression models. The algorithm for real-time vehicle detection in TAT was designed and implemented using data captured on NR4. The data were analysed using descriptive statistics and t-test at $\alpha_{0.05}$.

The existing roadway, traffic and control conditions of the five national roads in Kigali City were found to be acceptable in accordance with the Rwanda Transport Development Agency Manual. Average daily traffic on NR1, NR2, NR3, NR4 and NR5, with the same design speed of 60 km/h, were 1030, 914, 867,780 and 885, respectively. Free flow traffic only occurred on NR2, with average flow rate of 645 veh/h. A clear transition between two flow regimes (free and congested) existed on NR1, with average flow rate of 1120 veh/h. Analysis of traffic on NR1 at free flow, yielded maximum flow of 3576 veh/h (5005.7 pc/h) (regression) and 3348 veh/h (4687.2pc/h) (MFD). These were greater than HCM recommended capacity of 3600 pc /h for two-lane roadways in a direction resulted in congestion. The critical density was 115 veh/km, which increased to a jam density of 230 veh/km in the congested regime. The mean accuracy of vehicle detection and tracking algorithms of TAT for NR4 was 92.7%. The real-time flow and critical density generated by TAT were 3492 veh/h and 106 veh/km, respectively. The highest coefficient of correlation (R^2 = 0.2787) between flow and density was obtained with MFD, which exhibited a better accuracy than the regression model. There was no significant difference between the flow parameters obtained from the field data and TAT.

The traffic assessment tool developed, provided real-time traffic analysis which could be combined with existing control systems to improve traffic management on national roads in Kigali City.

Keywords: Traffic Assessment Tool, Macroscopic fundamental diagram, Traffic flow, Kigali City

Word count: 472

TABLE OF CONTENTS

LIST OF TABLES

LIST OF FIGURES

LIST OF ABBREVIATIONS

ADB: Asian Development Bank

ADBG :African Development Bank Group

ANPR cameras: Automated number plate recognition cameras

ATIS: Advanced Traffic Information Systems

ATMs: Advanced Traffic Management Systems

ATO: Alternative Transportation Option

CNN: Convolutional Neural Networks

CoK: City of Kigali

ECME: Existing Capacity More Efficiently

FHA: Federal Highway Administration

HCM: Highway Capacity Manual

JICA: Japan International Cooperation Agency

LOS: Level of Service

MININFRA: Ministry of Infrastructure

MWT: Ministry of Work and Transport

NR.: National Road

PHAT: Peak-Hour Automotive Travel

PwC:Price waterhouse coopers

ROI: Region of interest

RRA: Rwanda Revenue Authority

RTDA: Rwanda Transport Development Agency

RURA: Rwanda Utilities Regulatory Authority

T.R.: Transportation Revenue

TAT: Traffic Assessment Tool

UI: University of Ibadan

WBG: World Bank Group

WEF:World Economic Forum

YOLO: You Only look Once

CHAPTER ONE
INTRODUCTION

1.1 Background Study

Improving the traffic flow is essential to the proper function of communities globally (Salini *et. al.,* 2016). Traffic flow measurement is essential in road traffic management to detect traffic congestion and estimate the roadway's capacity (Sun and Qu, 2015). Traffic management necessitates a clear understanding of various strategies to enable the transportation (Yu *et. al.,* 2019). Much research has paid attention to traffic flow improvement using the traffic management tools .Quick mobility is one of the essential traffic assessment tool to improve traffic efficiency and safety (Jarašūniene, 2007). The traffic flow is considered adequate and efficient if the road capacity operates at optimal capacity (Akintayo and Agbede, 2015).

Globally, route traffic blockage is a substantial problem in many cities (FHA, 2004). Traffic congestion is related with significant delays in augmented fuel consumption and financial losses (Gao *et. al.,* 2021). Rwanda is a landlocked territory. Consequently, more than 80% of the goods of Rwanda are transported by road (about 1,400 km) to the nearest maritime port (Dar-Salaam, Tanzania) (MININFRA, 2013). The urban areas all over the country offer many advantages for habitat in terms of transportation facilities (Joshi *et. al*., 2013). The traffic volume growth in Rwandan cities is challenging. The country is characterised by mountainous and vulnerable to natural disasters whose negative impact is mainly deteriorating road transport services (Joshi *et. al.,* 2013).

Traffic congestion and accidents, emissions, and noises in the cities also result in more damage. The Rwandan population increases at 2.8% of the growth rate per year, with more rural people migrating to the towns (WEF and PwC, 2017). The most significant concentration of habitants is fast urbanization, and increased economic activities commonly cause the highest traffic growth in the urban areas (Jarašūniene, 2007).

Kigali represents a high accumulation and concentration of economic activities such as administration, banking, businesses, and professional services. It comprises complex spatial routes that facilitate local and international exchanges of goods and services. It causes the first high town resident and the seat of governance development of the country (Joshi *et. al.*, 2013). As the population grows, the traffic volume increases. Accordingly, urban planning becomes difficult for providing future development (Chao *et. al.*, 2013). It is, therefore, needed to establish efficient and effective traffic congestion control policies. Monitoring road transport-related issues is the central part of transport policy in many countries (Knockaert, 2010). The required policy for transportation decision-makers is to design traffic assessment tool by minimizing delays caused by congestion (Li and Yang, 2017).

The specialist needs to be aware of urban planning organization, future transportation plans, transit development plans, and transportation demand management (Balijepalli *et. al.*, 2014). This involves analyzing traffic through three primary parameters: flow, density, and speed (Batra and Sarode, 2013). Modelling the traffic flow parameters will help in effective transportation planning and establish an outline for mitigation measures for the effects created by development (Amin *et. al.*, 2002). The technology available is the use of cameras to detect the vehicle exceeding the required speed.

Kigali is the capital of Rwanda and is located in the centre of the country. It is divided into three districts: Nyarugenge, Gasabo, and Kicukiro. It is the most densely populated among all Rwandan cities. The characteristics of Kigali's landscape are made by several mountains separated by swamplands in between. It has an altitude that varies between 1,300 m and 1,850 m at the top of Mount Kigali. Kigali's average high temperature is between 25.9°C and 28.2°C. Its average yearly precipitation is 950.9 mm (Bajpai, 2014). Kigali is concentrated with different economic activities, including business, schools, hospitals, and transport systems. It remains the base of administration headquarters and regional offices of many central government agencies. All these activities make it a centre for regional services (Joshi *et. al.*, 2013). Since 2000, the government of Rwanda has put in place urbanization and transport policies to modernize Kigali. It is transformed into an attractive area for development activities, supporting commerce and investments, both within Africa and the world's economy (MININFRA, 2013).

Kigali is quickly developing into an important commercial city due to its central location. Apart from being well-connected to other regions of Rwanda, Kigali as a transit centre has become of fundamental importance in East African road transportation through routes joining neighboring Rwanda countries. After independence in 1962, Rwanda is central economic, cultural, and transport hub (ADBG, 2013). The map location of Kigali city is illustrated in Figure 1.1.

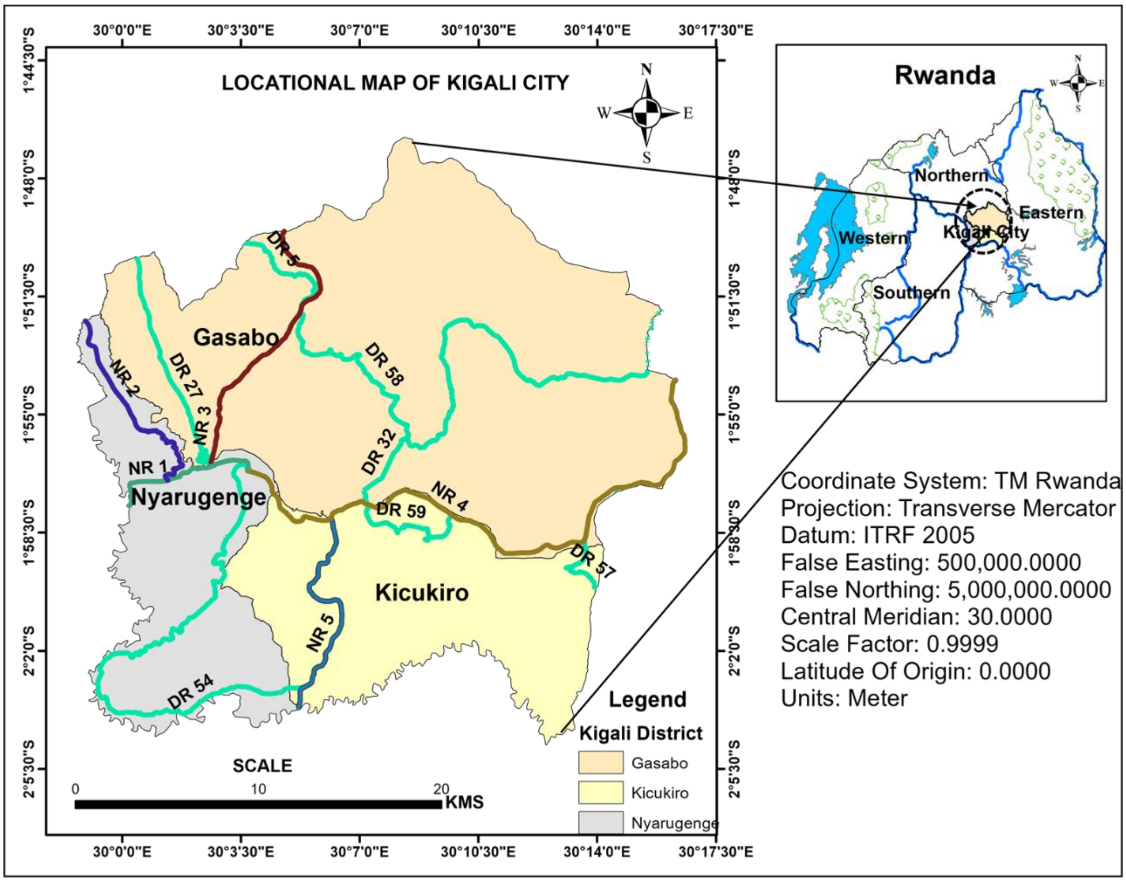

Figure 1.1 The map location of Kigali city

Kigali nowadays has become a city of various circulations due to it being the centre of many activities. In 2018,the road network of Kigali consisted of 2,851 km of roads, of which only 16% were paved by asphalt. They are mainly classified into national and district roads. The national roads are 5 types, namely NR1, NR2, NR3, NR4, and NR5, which are paved by asphalt and are regulated and maintained by the Ministry of Infrastructure(MININFRA). The district roads are partially unpaved and are supported by the city of Kigali. The unpaved roads become inundated in the rainy season and unclean in the dry season (Zyl *et. al.*, 2014).

According to MININFRA (2013), 92% of the population use road as their regular mode of travel for their daily activities.Traffic congestion is emerging in the city due to the high traffic volume. It has started to affect it harmfully, increasing travel time, wastes fuel, air pollution, and risk of accidents (ADBG, 2013). In 2018, the Rwanda National Police reported that about 465 people died and 654 people lived with serious injuries (JICA, 2019).

The decision-makers of Kigali city solve some of these problems by widening some of the roads. Due to Kigali's hilly topography, this strategy has been challenging to reduce road congestion(MININFRA, 2012a).An additional method is to limit the speed by installing an ANPR camera along the roads in Kigali. The ANPR cameras are combined with a system to speed control. A phone number is registered and connected to the car's plate to be recognized for charging messages at any location in Kigali (JICA, 2019).

Therefore, improvements are needed in traffic management by providing an advanced strategy to alleviate the congestion. This study developped a Traffic Assessment Tool (TAT) to improve traffic on significant roads in Kigali. Figure 1.2 shows the National and district roads of Kigali city.

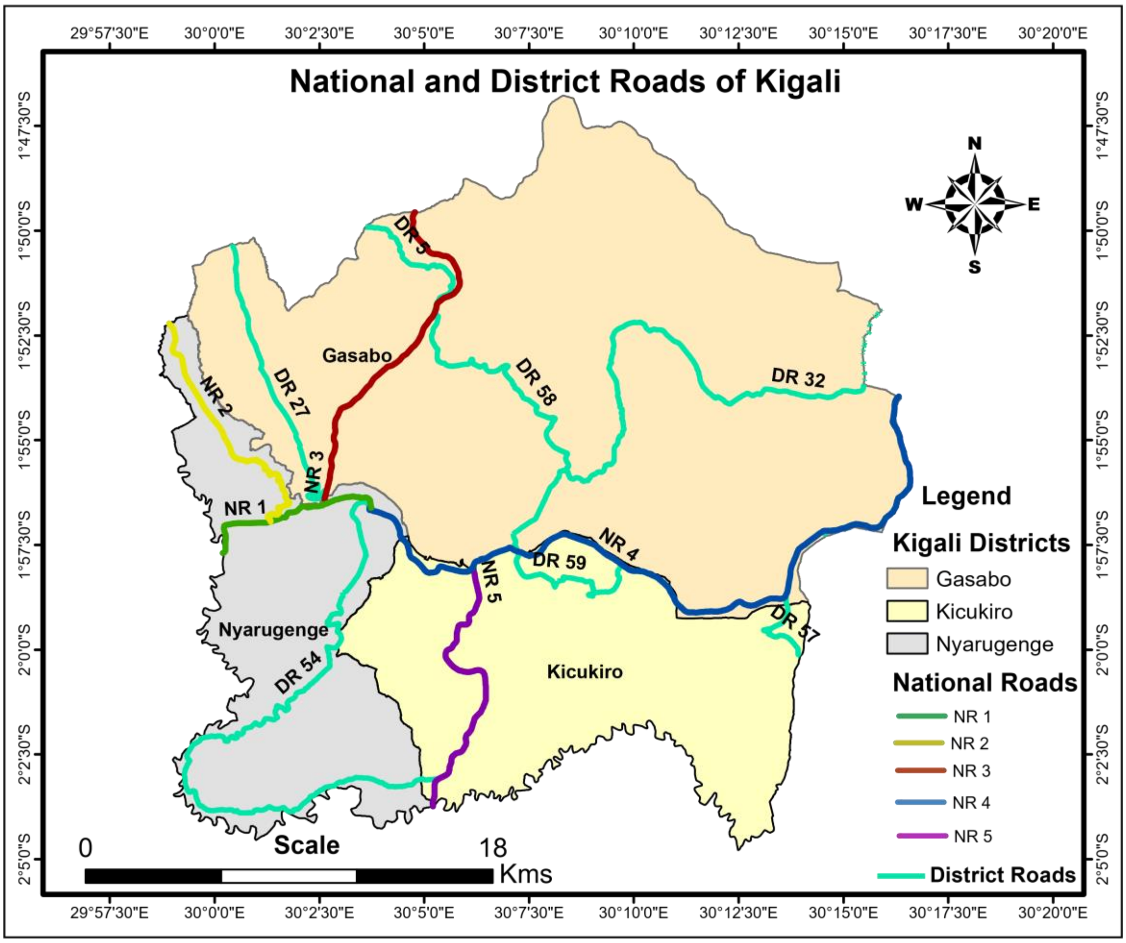

Figure 1.2 Existing national and district roads of Kigali City

1.2 Problem Statement

The traffic congestion effects are challenging in cities all over the world. Traffic congestion affects 10% of the roads in the European Union (Azevedo, 2014). In developing countries, traffic congestion results in augmented fuel wastage and financial losses (Ali and Faraj, 2010). This rise in fuel consumption increases vehicle operating costs, and impairs accessibility to the destination at the schedule (Onyeneke, 2018).The problem is associated with air pollution, economic losses, delays, and possibility of accidents, due to poor traffic management (Wang *et. al.*, 2017)**.**

The negative impacts are mainly due to inadequate road transport assessment tools and reduce the design life of the roads (Chorus *et. al.*, 2013). However, Highway Capacity Manual (HCM) indicates various interventions to manage traffic congestion, such as supply and demand measures. The supply measures, including the development of new infrastructure and road expansion, have been limited success in reducing traffic congestion as they require higher investment and expropriation in urban areas (Allström *et. al.*, 2017).

The demand measures like parking pricing, fuel expenses, and Intelligent Transportation System are emphasized, changing the trip-making behavior of road users *(*Chandana *et. al.*, 2017). They include Traffic Assessment Tool (TAT) which is significant and necessary for the current and upcoming road network, vehicle, and user safety in cities (Jarašūniene, 2007). The combination of TAT with an ANPR camera can monitor the complex situation of traffic to optimize traffic management and reduce traffic congestion with real-time information (Bommes *et. al.*, 2016).

Generally, developing countries experience challenges of the traffic volume growth in which Rwanda is not excluded. People spend a long time traveling from their home location to work due to traffic congestion. Similarly, traffic accidents, emissions, and noises in the cities also result in more damage (FHA, 2004). Kigali City, Rwanda's capital, daily experiences incessant traffic congestion, and more than 79% of accidents occur in the city per year compared to other cities within the country.Also, elevated emissions from vehicles burning fuels and noise produced by circulation cause impediments to the quality of life of the people (Zyl *et. al* ., 2014). The existing strategies, including traffic control device improvements, constructing and expanding roads, are limited to alleviate traffic congestion in Kigali City because of physical barriers and environmental conditions (Joshi *et. al.*, 2013)

More importantly, the lack of proper and well-experimented policies were the reason for the city traffic management plan(MININFRA, 2012b). Also, “Manual control of traffic by a policeman has not proved to be efficient” (Meenakshi *et. al.*, 2017). This, combined with unsuccessful enforcement of road transportation tools, caused the intermittent development of the city (MININFRA, 2013). There is a need to design the traffic management tool, considering traffic growth and congestion (WBG, 2017).

The management of Kigali City has become aware of road transport-related challenges. It has started car-free zones to protect the integrity of transportation systems and reduce the degradation of transportation services (JICA, 2019). It has motivated public transport management by providing e-ticket (Joshi *et. al.*, 2013). Also, new lanes and new roundabouts have been built as the primary measure for reducing traffic jams (Obsu *et. al.*, 2015).On the one hand, this is a reminder that stakeholders respond to traffic congestion for the general public. On the other hand, the last five years' studies showed that new road infrastructure generates fresh circulation and attracts transportation from different routes resulting in congestion before road construction investment (Ali and Faraj, 2010).

Moreover, the ANPR cameras installed in Kigali city to identify the plate number of vehicles passing a specified the roadway to limit speed may cause stress and anxiety to drivers due to automatic charges. Despite the efforts being made by the Kigali road management authority to improve flow on major roads in Kigali city, congested regimes persist for an extended period. The congestion stutus is shown on Figure 1.5. In this study, an TAT was designed to improve flow on selected roads of Kigali city by analyzing traffic flow regimes. Figure 1.3 illustrates the environmental conditions and the construction sites represented by dashed white circles. The ANPR cameras installed in Kigali are shown in Figure 1.4.

Figure 1.3 Environment condition of Kigali city.

Figure 1.4 The existing ANPR cameras installed in Kigali

Figure 1.5 Traffic congestion level in Kigali city

1.3 Aim And Objectives

Aim: To improve traffic flow by carring out the development of a real-time road traffic assessment tool for Kigali city.

The objectives were:

1. To determine the parameters of traffic flow that contribute to congested flow regimes on section of National Road 1 (NR1) and National Road 2 (NR2) in Kigali city.
2. To represent the basic traffic flow parameters through macroscopic models
3. To design an application for optimizing traffic flow management on section of NR1 and NR2 in Kigali city.

1.4 Justification Of The Study

The negative impacts of road traffic congestion are the main problems in urban areas worldwide. Road traffic congestion in Rwanda results in massive delays, stress, anxiety, fuel consumption, and financial losses. Kigali, the capital, is an essential strategic point in the business of the East-African Community, which attracts many people for various opportunities causing an increased traffic volume demand (Bajpai, 2014).

Various traffic flow models, including macroscopic, mesoscopic, and macroscopic models, were described to understand different traffic flow characteristics and provide several congestion mitigations in urban areas. However, macroscopic was preferred over others because fewer parameters were calibrated, hence less demand for computational capacity (Goliya, 2018). Macroscopic models are essential to forecast traffic management in the short range of the period. An additional macroscopic model is combined with congestion control tools to optimize and predict regular traffic flow operations. They can envision observed traffic phenomena like ghost traffic jams applicable to extensive traffic networks (Hueper *et. al*., 2009).

This research was intended to develop a real-time road traffic assessment tool on the sections of roads (NR1 and NR2) selected in Kigali. The selection of two roads was based on the interview responses of transport planners.The NR2 accommodates the trucks, big buses, and cars coming from various directions.This makes the road have the highest volume (Nyirajana *et. al.,* 2021). The NR1 goes through primarily residential and commercial areas, connecting Rwanda's southern province.The main characteristics of NR1 are the complex traffic volume movement to and from Kigali city, southern region, northern province of Rwanda,and Burundi *(Chao et. al.,* 2013). This study deeply assessed the state of traffic flow on section of roads NR1 and NR2.

The analysis of the fundamental diagram between flow and traffic density was performed on two selected roads. One specific property of the fundamental diagram is the interaction between vehicles, which are generally motivated by the intention not to hit one another (Neumann *et. al.,* 2013). Free-flow and congested traffic are two regimes of the fundamental diagram. In the free-flow regime, the graph indicates a low traffic flow rate, which increases by increasing density, and the vehicles have the freedom to move at their desired speed (Akintayo and Agbede, 2015). However, the flow rate decreases in the congested regime by increasing density until jam density.The traffic flow is restricted with significant delays in increasing trip time and the surge of vehicles' lines on the roadway (Ye, 2012).

The critical importance of this study was to design the durable solution for improving mobility in Kigali city. Therefore, the TAT was designed to offer traffic control measures to mitigate congestion. The TAT can deliver a warrant of current traffic status, including incident, congestion, travel time, and road network.In such a situation, the driver can choose an alternative road to avoid the unexpected condition of anxiety and crashes (ADB 2019). The combination of TAT with an ANPR camera could monitor the complex situation of traffic to optimize traffic management with real-time information (Bommes *et. al.*, 2016). The TAT was designed to reinforce the use of ANPR cameras to capture the plate number for the charging purpose and provide traffic congestion information.

The representation of parameters that aided in designing TAT was mainly done through Python and Excel with OpenPyX. Python is defined as a programming language used for web applications, software development, and mathematics (Gazoni, 2017). Python can be connected to a database system to accomplish complex mathematics (Sundnes, 2020). It uses new lines to complete the commend different from other programming languages that often use parentheses (Huenerfauth *et. al.,* 2009).

1.5 Scope Of The Study

The study designed a Traffic Assessment Tool (TAT) to be an essential policy instrument for reducing traffic congestion and analyzed the traffic flow of roads of Kigali city in Rwanda through the macroscopic fundamental diagram and regression model. It was limited to national roads (NR1 and NR2). All studied sections of roads were located far from the traffic control facilities to avoid conflict interruption with existing traffic control. The study emphasized on buses, cars, trucks, and minibusses for calculating density and flow to determine the most crucial traffic relation on NR1 and NR2. The traffic volume measurement aided in carrying out the characteristics of roads and representing the main traffic flow parameters of NR1 and NR2.

CHAPTER TWO
LITERATURE REVIEW

2.1 Preamble

The relevant review of traffic flow characteristics, models,and traffic parameters is presented in this chapter. This includes a correlation between speed, density, and flow on selected roads in Kigali. The aspects that affect the traffic flow, particularly the rudimentary theoretical concepts of traffic survey, traffic congestion, and traffic flow models with various traffic measurement and management elements, are mainly discussed.

2.2 Traffic Volume Survey

It is essential to find the number of traffic statistics needed for traffic engineering purposes such as planning, traffic projection, traffic management, and intersection assessment. Data collection in vehicle numbers that pass at the roadway point during a particular duration is called a traffic volume survey. Dependent on the awaited usage of the gathered data, the time can vary from fifteen minutes to a year (Garber and Hoel, 2004). Traffic count is conducted to figure up vehicular or pedestrian traffics passing alongside a roadway, lane, or intersection. The traffic count is generally conducted automatically or manually by surveyors who visually count and add a hand-held electronic device or tally sheet.

These two methods give the traffic data no difference between them. However, a good practice uses the technique to efficiently achieve the required data quality (Salisu and Oyesiku, 2020). Also, Salisu and Oyesiku (2020) mentioned the factors influencing most vehicle counting: climate conditions, the objective, site location, and methods of the traffic count. The level of flow , nature of the road and traffic structure were stated as the factors affecting traffic count.

2.2.1 Manual count

The manual count consists of assigning the workforce to count vehicles as they pass. It is mainly used at the intersection where the number of movements registered distinctly categorizes vehicles. The traffic on each approach for each direction should be counted separately at the junction. It is essential on the road with more than one lane to classify it by direction. Before starting the traffic count, it is recommended to determine the duration of counting. The manual count has a bearing on the quality of data obtained. For example, vehicles passing a point are computed at defined specific interval time (15 minutes, 30 minutes, 45 minutes, 1 hour, etc.). This method provides the total vehicles which are required for the traffic flow computation (Rogers, 2003).

The manual count is usually valid for gathering data for vehicle grouping, turning travels, travel direction, and vehicle occupancy. It also delivers the whole vehicles which are necessary. If there exists data of the past traffic count, it is essential to determine the rate of weighty cars as a percentage of the total traffic, and such portion is helpful to the counted volume to obtain the actual traffic flow. The forms of traffic count should be provided to perform this method, and workers' training is needed before launching it. The following equipment is often utilized in a manual count-based approach: lumber tally method, tally counters, electronic counter boards, laptop computers, and videotape (Al-Sobky and Mousa, 2016).

2.2.2 Automatic count

This method is used to detect vehicular presence and road occupancies by exploiting automatic equipment via wireless communication. The commonly used are detectors inductive loops, pneumatic tubes, sensor types, radar detectors, and video cameras (Garber and Hoel, 2004). Three cyclical variations are helpful to provide traffic flow volumes predictable on the roadway during the specified time: Hourly patterns show how the traffic flow is variable during the day and night time (Muhammad and Faraj, 2013). In cities, they generally describe various peaks such as sunrise time, after lunch, and twilight. The second is day-to-day patterns which define the everyday variation traffic volume through the week. The monthly and annual patterns periodically show periodic variable traffic volume (Pal'o *et. al.*, 2019).

2.3 Traffic Flow

In civil engineering, traffic flow is defined as studying the interaction between vehicles, drivers, and infrastructure, which aims to understand and develop an optimum road network with well-organized traffic movement and minor traffic congestion problems (Obsu *et. al.*, 2015). Measurement of flow is essential in transport management to detect traffic congestion (Ali and Faraj, 2010). It is also vital to evaluate the necessities of a traffic light at a junction and measure the roadway's capacity (Ye, 2012). Traffic flow has various parameters that provide information about the nature and the characteristics of traffic flow. Understanding these parameters helps detect how the flow can vary by space and time (Rao, 2007).

2.3.1 The parameters of traffic flow

An immense literature has been shown that speed, volume, flow, and density are the main parameters to measure the traffic flow (Lu and Meng, 2013). They quantify the change in speed, an essential element of predicted variations in traffic demand(Suresh *et. al.*, 2018). The Highway Capacity Manual (HCM) defines these main parameters based on two different flows: uninterrupted and interrupted. Uninterrupted flow is typically considered by high free-flow speeds, which are continuous at the equivalent level because of the low presence of vehicles on the roadway. The cars are moving in freedom with no obstacles along the road. An example of this facility is a freeway with no obstruction for stopping anywhere (Batra and Sarode, 2013).

In contrast, interrupted flow is characterized by low free-flow speeds where the vehicles are delaying with a long queue at a particular section of roadway. It mentions the situation when the traffic flow on the highway is blocked owed to several obstacles for some reason (Singh and Bansal, 2016).

The speed is mainly applied for the uninterrupted flow and is defined as a length per unit period. In traffic flow measurement, it is assumed that each vehicle has a slightly different speed from those around it on the roadway (Al-Sobky and Mousa, 2016). The average velocity (space mean speed) can be calculated by taking the mean of the single speeds of the vehicle observed in a considered area (Knoop, 2017).

Flow is the rate at which cars pass a specified point on the roadway (the number of vehicles divided by time) (Akintayo and Agbede, 2015). Density is the number of cars observed in a highway distance and is applicable on the uninterrupted flow *(Obsu et. al.*, 2015). High density shows the proximaty of vehicles in a queue different from low density which indicates very large spacing between them (Spiliopoulou *et. al.*, 2015). Knoop (2017) defines the additional characteristic of traffic flow named volume, a common element of traffic flow applied for the uninterrupted and interrupting traffic flow. Volume is well-defined as the number of vehicles observed at a particular road point in an indicated time interval.

2.3.2 Fundamental diagram of traffic flow

A fundamental digram of traffic flow is a drawing that shows the relation between average flow and average traffic density from which authorities can use various information to assess policies and regularities for improving mobility (Li and Zhang, 2011). Recognizing speed, flow, and density relationship is advantageous in the road design and planning process. The general relation between flow, density, and speed is that the flow equals density times average speed. The variables depend on the characteristics of the vehicles and drivers, aspects of the roadway, and environmental issues like weather conditions.

A critical property of the fundamental diagram is the interaction between vehicles, which are generally motivated by not hitting one another (Tang *et. al.*, 2009). The empirical investigations showed that the average speed v in locally homogeneous traffic flow decreases with increasing traffic density (Neumann *et. al.*, 2013). It is expected to find some functional relationship between average speed v and traffic density *k*, for which it can discover $\frac{dv(k)}{dk} < 0$. For very low density, the average speed tends to some limited value $v\max$, whereas for the maximum density($k\max$ *),* no movement is possible when large vehicles are found.

$V(0) = v\max, V(k\max) = 0$

The corresponding flow rate of vehicles $q(k) = kV(k)$ is a function that disappears at $k = o$ and $k = k\max$. Therefore, it has a maximum value of intermediate density (Tang *et. al.*, 2009).

For instance, when the density reaches the top (jam density), the flow is zero because vehicles tend to reduce the speed result in stop-and-go movement (Helbing, 2009). With the coincidence of three parameters, various fundamental diagrams can be plotted. Moreover, all graphs can be grouped into sections with different traffic states of free flow and congestion. If the fundamental diagram is associated with actual traffic, the parameters *k*max and *V*max only prescribe the system's natural length and period scale. The maximum flow is the individual quantity governed by the interactions (Li and Zhang, 2011). HCM 2010 volume 2, provides the capacity 3600 pc/h for two lanes per direction roadway.

2.3.3 Regimes of traffic flow

In the description of the operational characteristics of the traffic flow, two groups of flow regimes are used: free-flow and congested traffic, defined by the two-dimensional zone of the fundamental diagram of the Colombo phase transition model (Akintayo and Lafinhan, 2015). In the free-flow area, the graph indicates a low traffic flow rate, which increases by increasing density, and the vehicles have the freedom to move at their desired speed (Alam, 2015). However, the flow rate decreases in the congested regime by increasing density until jam density (Philip and Jaseela, 2016). The traffic flow is constrained with significant delays in increasing trip time and the surge of vehicles' lines on the roadway (Ye, 2012).

2.3.4 Models and analysis of traffic flow

A model is a simple representation of a part of the system of interest, which emphases certain fundamentals considered important from a specific perspective (Ortúzar and Willumsen, 2011).

Traffic modeling plays a key advantage for researchers in traffic applications like congestion reduction, traffic flow forecasts, accident discovery, and traffic mechanisms. Scientists and Engineers have established a traffic flow model to simplify representations of practical systems by using mathematical demonstrating (Wageningen-kessels, 2013). Modeling traffic flow agrees with the significant variability of different model approaches for some reasons. The traffic flow details can be determined to different degrees, ranging from the dynamics of averaged amounts down to individual vehicle motion.

2.3.5 Classification of traffic flow models

Many types of research have been made to relate to the traffic flow model with authenticity. Traffic flow models are classified into microscopic, macroscopic, and mesoscopic clusters (Shamlitsky *et. al.,* 2023). Based on their properties of the level of detail, the studies define microscopic and macroscopic models in the following way :

Macroscopic traffic models model variables that summarize information about multiple vehicles to describe the traffic condition. These models describe the relationship between density, speed, and flow, which are the main characteristics of traffic*(Puppo et .al.,* 2016). The density defined as the number of vehicles per kilometer and per lane. He also describes traffic flow as the number of cars passing a specified point per hour. Speed is expressed as length per unit time. Macroscopic models have various advantages, their input parameters for macroscopic simulation are reduced, large-scale city networks, modeling is calmer, less computation time is required, and their calibration is more straightforward (Knoop and Daamen, 2017).

Many studies have been made to explain the macroscopic models using the fundamental diagram and regression model .The basic diagrams illustrate a statistical relation between the macroscopic traffic parameters such as flow, density, and speed.

Greenshields early described the MDF as a graph of flow rate versus density and regression relation curve between density and speed (Bellemans, 2002).

Microscopic models model vehicle driver components individually. The drivers in microscopic traffic flows are associated with individual vehicles where each vehicle has its characteristics. The model involves a set of rules describing in what way vehicles journey from one point to another. Microscopic can be divided into two main models:

1. The car following model

This model designates how a vehicle follows preceding vehicles. For instance, the headway a driver reserves between himself and the preceding vehicle and its reaction on acceleration or deceleration of the car in forward-facing of him are described (Velasco and Saavedra, 2012).

2. The overtaking model

It describes the decision of a driver decides to overtake his antecedent. It includes the essentials properties of the vehicle and driver. Given a single car in a lane, the following parameters, such as position (x_i), speed(v_i), and acceleration (a_i), can be observed in a traffic stream.The relationship between then is $v_i = \frac{dx_i}{dt}$ and $a_i = \frac{dv_i}{dt} = \frac{d^2 x_i}{dt}$

Considering two consecutive vehicles in a similar lane in a traffic stream, Sven and Bart (2008) mention the two characteristics of traffic flow, such as space headway and time headway.

Mesoscopic models describe different vehicles, but the interaction between them is released. They are microscopic and macroscopic modeling, as theorized by Nurul and Munzilah (2018).In this model, there are two essential stimulation methods, such as team dispersion and vehicle platoon. The group dispersion consists of a change in distance between vehicles when a platoon travels downstream from an upstream junction. Vehicle platoon behavior consists of a cluster of cars traveling at a short headway and traveling simultaneously. The number of vehicles in a group, the platoon's speed, and its distribution mainly consider modeling platoon behavior. To illustrate this, considering a traffic signal, vehicle platoons are designed once the traffic signal goes to red and vehicles start to queue. The platoon dispersion will be observed while the traffic signal changes from yellow to green, then the cars begin to move by increasing their speed (Azevedo, 2014).

2.3.6 Macroscopic fundamental diagram and regression model comparison

The two methods are important in traffic analysis and are to assess the traffic condition (Li and Zhang, 2011). The comparison of the two tools are mainly based on the collection coefficient R^2. This means that the traffic parameters fit and the sample distribution of the model is precisely efficient and accurate. The closer R^2tended to 1, the better the regression function (Schober and Schwarte, 2018).

2.4 Traffic Congestion

The traffic congestion is defined as a greater demand for traffic than road capacity. Extreme traffic congestion occurs when the vehicles are stationing for a long duration at a low speed (Philip and Jaseela, 2016). Delays characterize this during the journey with long travel times and long queues (Wang, 2018). Some researchers described different elements that can help measure traffic congestion, such as Level of Service (LOS), mean traffic speed, and average delayed time traveling in the congested regime, compared with free-flow traffic perceived on the roadway. Level of Service (LOS) are 6 types classified from A (the best) to F (the worst with stop and go movement) Traffic density is considerably higher in traffic jams than in free flow, while the velocity and flow are shallow, although usually non-vanishing (Muhammad and Faraj, 2013).

2.4.1 Traffic congestion causes

The leading causes of traffic congestion on roads are conflicts inducing traffic turbulences, physical bottlenecks, and operational bottlenecks (Rahane and Saharkar, 2014). Traffic congestion in cities can be affected by the increase of habitats, urbanization, economic growth, and low road capacity (Adigun *et. al.*, 2019). Other potential causes of traffic jams include traffic incidents, weather conditions, traffic control devices, special events, and regular traffic and work areas (Maji and Page, 2017).

2.4.2 Impacts of traffic congestion and mitigation strategies

During congested situations, the travel time is unpredictable, some trips are intentionally canceled, and uncontrolled stress of drivers may lead to accidents (Aschauer and Starkl, 2010). Traffic congestion hurts urban development (Allström *et. al.,* 2017). Many studies highlight the environmental, economic, and personnel impacts. The environmental impact is linked with fuel wasting and rising ecological pollution (Ferguson,1990). Economic disadvantage is mostly happening in the delayed transportation of people and goods. Also, while the goods are transported for commercial issues, they delay reaching the destination, which brings a big problem and conflict between exporters and importers (Ali and Faraj, 2010). The unpredictable travel times, longer trips, and annoying are the primary personnel impacts that cause drivers' stress and anxiety, leading to accidents. Such results come with grave consequences that disturb the worldwide environment and humanity (Scott, 2003).

Recent studies provided different measures, including increase road capacity by constructing and enhancing the ability of the existing roadway as a critical strategy for congestion mitigation. However, that was limited success in different urban areas due to the growth of expropriation costs. Commonly, activity-based travel demand models are recommended to overcome traffic congestion (Darren, 2002). Furthermore, various studies speculated several strategies for dipping the travel demand for peak-period (Suresh and Baraik, 2018). They suggested multiple forms of auto restraint in downtown areas. For example, the prohibition of on-street parking and the banning of non-commercial traffic altogether can help to reduce traffic volume than construct, which requires higher investments (Ye, 2012). Another tactic was stimulating the population for thoughtful law regulation, socialization, social modeling, education and prompts, and economic incentives.

The researchers in 2008 investigated the congestion problems in Los Angeles. They provided ten corresponding recommendations to decrease congestion significantly in the coming five years (Triantis *et. al.,* 2011). The recommendations were proposed to accomplish the following four goals, which are controlling Peak-Hour Automotive Travel (PHAT), raising Transportation Revenue (T.R.), improving Alternative Transportation Option (ATO), and utilizing Existing Capacity More Efficiently

(ECME). The recommendation was linked with policy objectives to be implemented by the policymakers. The first three approvals are mainly to accomplish the use of ECME and support the improvement of ATO are the promotion of investments in signal control improvement, restriction of curbside peak-hour parking, and offering the additional capacity of bus lanes (Systematics, 2008).

The fourth to encourage voluntary drops in driving at businesses and other significant administrations is primarily the improvement of ATO and support managing PHAT. The fifth, mainly to achieve the strategy of working PHAT, using ECME, and improving ATO, could help raise Transportation Revenue (T.R.) (Ali and Faraj, 2010).

Application of mutable curb-parking payment in busy commercial and trade districts was the sixth approval to attain the goals of managing PHAT, raising T.R., and using ECME. The seventh recommendation proposed is to implement the California parking cash outlaw at the public level in towns to succeed, mainly the policy objective of managing PHAT. To accomplish the use of ECME, the following eighth, ninth, and tenth recommendations are proposed: extending Bus Rapid Transit (BRT) facilities, not a motorized lane for bicycle facilities, and motivating public transport by deep discount transit charges bosses. The recommendation is to advance a High-Occupancy Toll Lanes (HOTL) system on expressways and practice remaining income to fund express bus service in the HOTL. Furthermore, in 2012, the Galvin Project suggested 275-Mile-HOTL generate about two-thirds of fee revenues and handle 55% of transportable demand on the recommended roads for increasing mobility in Chicago in projection until 2040 (Systematics, 2008).

2.5 Traffic Assessment Tool

Traffic assessment is applied and useful by traffic engineers in the existing system to analyze and solve various dynamical traffic flow problems (Akintayo and Agbede, 2015). These difficulties are frequently connected with multifaceted processes that cannot willingly be defined in systematic terms (Authors, 2015). Regularly, these processes are categorized by the interface of several system entities.Traffic Assessment Tool (TAT) is significant and necessary for the present and future road network, vehicle, and user safety. It can work with data and technology to improve transportation safety and mobility (Ortúzar and Willumsen, 2011).

The technology of TAT aids in improving the prospects of sustainable transport and traffic management that include congestion reduction. The central part of the tool that collects information from video camera help to get real-time information about traffic condition in the exciting road section(Jarašūniene, 2007). The cars with TAT can predict any vehicle hazards that may reduce the journey time and accidents. The systems are applied to provide real-time traffic conditions and improve driver's capabilities for road awareness and forewarnings which may influence sustainable traffic management, especially in cities with complex traffic (Nkoro and Member, 2014).

The key objective of the TAT is to strengthen the strategies of traffic management and traffic congestion reduction. It is also used to improve the transport operation and transport service profitability and mobility in cities (Kumari *et. al.,* 2017).

A general scheme of TAT consists of two parts. One part with four modules including Wi-Fi modules, ANPR cameras, a database module, and integrated systems. Another aspect for Traffic Density Detection(TDD) describes the procedures and the steps for sending a message to the driver based on the real-time density calculation available from the start to end activity. The concept of Object Tracking is updating the position of a vehicle in subsequent image frames from a video stream using the centroid of the detected object as input. Each car and its centroid (boundary box) is continuously tracked by minimization of Euclidean distance (J. Li *et. al.*, 2018).

The tool can deliver a warrant of current traffic status, including incident, congestion, travel time, and road network. In such a situation, the driver can choose an alternative road to avoid the unexpected condition of anxiety and crashes (ADB, 2019). The representation and integration of context of TAT in future public transport systems characterized the connectivity and collaboration with various integrated systems (Allström *et. al.,* 2017).

2.5.1 Wireless fidelity (Wi-Fi) and its application in traffic flow management

Wi-Fi is defined as a networking technology that permits devices, including computers, mobile phones, and cameras, to interface with an internet connection via a wireless router (Rath, 2018). The technology allows an electronic device to transfer data from one storage to another (Ng *et. al.*, 2018). Wireless networks are new integrative technology arising from wireless communication and tiny sensors (Chandana *et. al.*, 2017). With the reduction of power ingesting and the price of instruments and repairs, it is prepared to install over large-scale traffic areas and monitor roads in a much acceptable method, bringing some advances in traffic monitoring (Badage, 2019).

Communication networks, traffic prediction architecture, and algorithms are the central systems used through wireless traffic monitoring (Samih, 2019).

2.5.2 The characteristics of automatic number plate recognition (ANPR)

Various recognition strategies have been generated, and plate numbers are applied for safety and efficiency in traffic flow. ANPR innovation tends to be mainly due to owning license plates in various modes (Bommes *et. al.*, 2016). ANPR is a strategy that uses the optical character to recognize the image to examine the labels on the vehicle. This surveillance can utilize a street standard enforcement camera designed for that action. Authorities mainly use them for monitoring traffic movement. The ANPR is used to supply the cameras; they can be configured to store a driver's photo (Lubna *et. al.*, 2021).

2.6 Critiques Of Previous Studies Of Traffic Flow In Kigali City

Road traffic congestion in Kigali results in massive delays, stress, anxiety, fuel consumption, and financial losses (Bajpai, 2014). Traffic management efforts such as road widening, speed limit devices, and deployment of control measures to mitigate traffic congestion have not yielded expected results (Lombard, 2012). This is largely due to limited availability of tools that incorporate real-time traffic flow parameters in road traffic assessment (Obsu *et. al.*, 2015).

Various traffic flow models, including macroscopic, mesoscopic, and macroscopic models, were described to understand different traffic flow characteristics and provide several congestion mitigations in urban areas. However, macroscopic was preferred over others because fewer parameters were calibrated, hence less demand for computational capacity (Goliya, 2018). Macroscopic models can envision observed traffic phenomena like ghost traffic jams applicable to extensive traffic networks (Hueper *et*. *al*., 2009).

This research was intended to develop a real-time road traffic assessment tool on the roads (NR1 and NR2) selected in Kigali. The selection of two roads was based on the interview responses of transport planners that critilise them having the highest traffic volume based on previous studies which showed that the roads operates between LOS D and LOS F ,and the ratio of volume to capacity varies between 0.5 and 0.75 (Bitangaza & Bwire, 2020). The NR1 goes through primarily residential and commercial areas, connecting Rwanda's southern provinces. The main characteristics of NR1 are the complex traffic volume movement to and from Kigali city, southern region, northern province of Rwanda, and Burundi *(*Chao *et. al.,* 2013).The NR2 connects Kigali with the northern province. The macroscopic fundamental diagram was used to analyse of the relationship between flow and traffic density on RN1 and RN2. The One specific property of the fundamental diagram is the interaction between vehicles, which are generally motivated by the intention not to hit one another (Neumann *et. al.,* 2013). Many studies have been made to explain these macroscopic parameters using the fundamental diagram and regression model. The two methods are important in traffic analysis and for the traffic condition assessment (Li and Zhang, 2011). The comparison of the two tools are mainly based on the collection coefficient R^2. This means that the traffic parameters fit and the sample distribution of the model is precisely efficient and accurate. The closer R^2tended to 1, the better the regression function (Schober and Schwarte, 2018).The critical importance of this study was to design the durable solution for improving mobility in Kigali city. The TAT was designed to offer traffic control measures to mitigate congestion. The TAT can deliver a warrant of current traffic status, including incident, congestion, travel time, and road network. In such a situation, the driver can choose an alternative road to avoid the unexpected condition of anxiety and crashes (ADB, 2019). The combination of TAT with an ANPR camera could monitor the complex situation of traffic to optimize traffic management with real-time information (Bommes *et. al.,* 2016). The representation of parameters that aided in designing TAT was mainly done through Python and Excel with OpenPyX. Python uses new lines to complete the commend different from other programming languages that often use parentheses (Huenerfauth *et. al.,* 2009).

CHAPTER THREE
MATERIALS AND METHODS

3.1 Preamble

The methodology highlights collecting data, data processing, and analysis. It describes the procedures set to represent the parameters of traffic flow using the macroscopic model. The techniques and methods used to perform data analysis and the process designing of TAT were described. Some equations of traffic operation were developed, and the data used were collected using interview and traffic survey techniques.

3.2 Interview Method

The interview intended to obtain information on the daily travel characteristics in Kigali city to understand the current movement of vehicles (a gap of planning, congested roads) and identify the existing traffic congestion mitigation strategies. The interview was performed by distributing the questionnaire to management officers of national roads in Kigali. The nine of ten concerned decision-makers interviewed were the engineers from the Rwanda Transport Development Agency (RTDA), the City of Kigali (CoK), and the Ministry of Infrastructure (MININFRA).

Transport engineers were contacted at work sites at specific hours, such as seven to eight in the morning when getting to the workplace, noon to 2 pm going to break, and 5 to 8 pm after work. The sampling technique was purposive based on targeted engineers in the survey area. The sampling rate was about 90% of the total concerned transport planners in Kigali city. The forms of surveys comprised two sections: a) the primary data of each workplace, i.e., address and work members who were detailed and related to occupation, and the address of the workplace; and b) attitudinal questions that include travel problems facing current traffic situations and existing solutions for traffic improvement.The selected transport engineers (workers) were interviewed; simultaneously, the questionnaires were filled using face-to-face interviews. The interview survey also considered the five essential elements of the outline of the study (objectives, survey details, content, coverage, and methods). The design of the interview survey is shown in Table 3.1.

Table 3.1: Outline of interview survey in Kigali city

Objectives	**Survey details**	**Content**	**Coverage places**	**Methods**
To understand the travel behaviors	primary data of each workplace	address and served data	Workplaces:	Work visit
	work members	Organization	CoK: 3 people	face to face interview by filling the questionnaire
		Position	RTDA: 3 people	
To identify the existing strategies of travel demand forecast			MININFRA:3 people	
	Traffic analysis process, decision-making problems	Travel problems	CoK: 3 people	
		Existing solutions	RTDA: 3 people	
		Planned solution and suggestions	MININFRA:3 people	

3.3 Preliminary Survey

Preliminary surveys were carried out on the section of nationals roads (NR1, NR2, NR3, NR4 and NR5) with respective length of 8.5 km , 12.95 km, 16.45 km, 32.25 km and 13.5 km in Kigali city.Their characteristics were classified into road conditions and traffic control devices. The roads operates between LOS D and LOS F ,and the ratio of volume to capacity varies between 0.5 and 0.75 (Bitangaza & Bwire, 2020) .Table 3.2 shows the preliminary data result on NR1, NR2, NR3, NR4 and NR5.

Table 3.2 Preliminary survey data national roads of Kigali city

	Road name				
	NR1	NR2	NR3	NR4	NR5
Road condition					
Lane width	3.5m	3.5m	3.5m	3.5m	3.5m
Shoulder width	1.5m	1.5m	1.5m	1.5m	1.5m
Design speed	60 km/h	60 km/h	60 km/h	60 km/h	60 km/h
Average Daily Traffic	1030	914	867	780	885
Control devices					
Traffic signals	Good condition	Good condition	Good condition	Good condition	Good condition
Traffic signs	visible	visible	visible	visible	visible
Road marking	visible	visible	visible	visible	visible
On-street parking	sufficient	sufficient	sufficient	sufficient	sufficient

3.4 Traffic Surveys Techniques

The most significant recent method utilized is video recording, which is primarily expensive and lacks footage produced. However, with the evolution in technology, a high-definition video recording can be gotten with a smartphone that can be played at any speed with zooming capability at a very economical fee (Goliya, 2018). The data collected can be examined at any place and time with any number of repetitions (Goliya, 2018). According to Garber and Hoel (2009), a continuous traffic count can be conducted from hour to hour, from day to daytime, and from month to month. The average daily traffic can be calculated by dividing vehicles by the number of days used. The number of cars moving on the sections of national roads, NR1 and NR2, was recorded. The traffic surveys objectives were to find current traffic volume passing on road- section NR1 and NR2 and understand road users' travel characteristics.

The two streets connect different areas of the complex movement of vehicles. The section of NR2 studied has 2 lanes and carriageway width of about 7 m. The primary vehicle types move on NR2 were trucks, big buses, and cars. The NR2 links Kigali city with the Northern province of Rwanda .The NR1 goes through primarily residential and commercial areas, and it connects the town with the Southern province of Rwanda. This road consists of the complex traffic volume movement to and from Kigali, the Southern region, Northern province, and neighboring countries (ADBG, 2013). The section of NR1 studied has 4 lanes.

Two on-road stations DR5 on NR1 and Taba on NR2 shown on Figure 3.1 were taken to conduct a traffic survey to capture the intense traffic flow entering and leaving the city . The traffic survey in this study was taken in 30 days between November 2019 to December 2019 as specified in the Highway Capacity Manual (HCM). The traffic survey was carried out for 15 hours, between 5 am, their workers' workplace time, and 8 pm, to reach destination areas. The number of vehicles was recorded at 15 minutes' intervals times. The method used to capture traffic flow characteristics was video recording using a smartphone. The data were obtained by playback and freezing the video films taken at each location. It can note that this method took time for processing data. The processing time was longer than the field time. The recorded speed was combined according to time intervals to obtain the average speed at a quarter-hour.

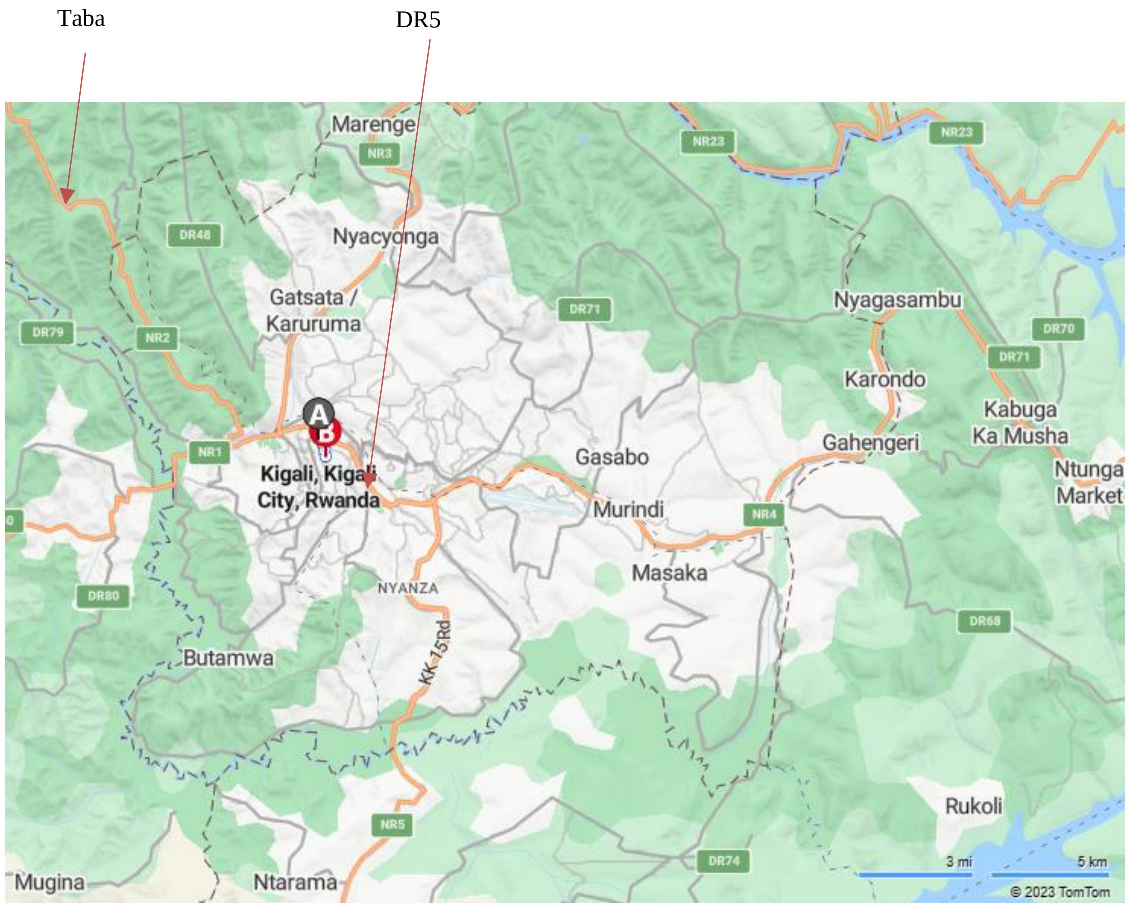

Figure 3.1 Two stations DR5 on NR1 and Taba on NR2 for traffic suvery

The analysis method was based on present traffic conditions on sections of NR2 and NR1 of Kigali city and was performed using a Macroscopic Fundamental Diagram (MFD) of flow versus density and regression model (Li and Zhang, 2011).

3.5 Data Preparation

The data preparation was performed in two steps according to types of data, the method, and the related findings expected for traffic analysis in the study area. The responses were collected together in the same file by conducting an interview face-to-face and filling questionnaires simultaneously. The analysis of these responses demonstrates all questionnaires were answered. The flow rate at each time interval was found by taking all traffic volumes collected at the same time interval divided by the time interval. The average free-flow speeds for each road section in 15 minutes' time intervals were generated using the statistics speed of moving vehicle given by radar for the days under consideration.

At a given period on a roadway, the average speed was obtained by all rates recorded, dividing the traffic volume recorded simultaneously. Direct recorded data processing got the two primary variables: traffic flow speed v and flow q. The measurements of these parameters were combined to 15 minutes time intervals and stored in a data set. The data sets were the basis for all calculations within this thesis and the approach used was macroscopic. This means that the measurement would be not referring to individual vehicle characteristics.

3.6 Mathematical Relation Of The Macroscopic Model

Macroscopic models have become an important tool in traffic flow analysis and investigation to illustrate the multifaceted traffic flow system (Ni, 2011). The importance of macroscopic models is to study the impacts of model parameters to analyze road traffic conditions and predict future traffic (Ardekani and Ghandehari, 2011). The macroscopic variables (aggregated variables) of vehicles such as density, flow, and speed are described as continuum models by comparing the flow of fluids (Tang *et. al*., 2009). The physical characteristics of traffic flow for these parameters combine individual vehicles' attributes and depend on position and time (Zhang *et. al*., 1997).

Some assumption was made to develop the mathematical equations of the macroscopic model. Consider a variable $k\ (x,t)$, k is homogeneous if k is not depending on position therefore $k\ (x,t) = k\ (t)$.The variable k is stationary when independent of time, $k\ (x,t)\ =\ k\ (x)$. Based on two states, two fundemental equations exist in the macroscopic traffic models. The fundamental relation can be generated as $q = kv$. It means the number of vehicles considered as particles (Shamlitsky *et. al., 2023*). Passing a section per unit duration equals the number of cars present per unit length (k) and the distance traveled by those vehicles per unit of the period (v).The second is a partial differential equation, which models the conservation of vehicles equation (Rakha *et. al.*, 1995).

Assuming that the vehicles are following from left to right, the continuity equation can be written as : $\frac{\partial k}{\partial t} + \frac{\partial q}{\partial x} = 0$ … (3.1)

Equation 3.1 indicates departure vehicles are equivalent to entering vehicles plus vehicles stored in the traffic system (Tang *et. al.,* 2009). Where $k\ =\ k(x,t)$ represents the traffic density, describing the number of cars per unit distance of road at instantaneous t and position x; $q\ =\ q(x,t)$ denotes the traffic flow rate, describing the number of vehicles per unit duration. Where x is the longitudinal coordinate in the direction of traffic flow and t is the time.

However, there are two unknowns, $k(x,t)$ and $q(x,t)$,which cannot be calculated by solving one equation. The one possibility is to write two equations from two flow regimes (before and after a bottleneck).

$$k_1v_1 = k_2v_2 \quad \text{… (3.2)}$$

In this relation (equation 3.2), the flow rate before and after will be the same.
Another possibility is to assume that the flow rate q is determined primarily by local density k so that q will be a function of density k. The assumption states that $k(x,t)$ and $q(x,t)$ are not independent. Thus the continuity equation becomes

$$\frac{\partial k(x,t)}{\partial t} + \frac{\partial q(k(x,t))}{\partial x} = 0 \quad \ldots(3.3)$$

There is only one independent variable in equation 3.3, the density when the flow and speed are represented in two and three dimensional. They are considered vectors to describe the average intensity and speed in a specific direction. Consider a function $N(x,t)$ representing the cumulative number of vehicles passing a cross-section x respectively from a random starting instant t. The relation of cumulative flow rate measured at position x during an instant t_1 to t_2 is given in Equation 3.4

$$q(x,t_1t_ot_2) = \frac{N(x,t_2) - N(x,t_1)}{t_2 - t_1} \quad \ldots \ (3.4)$$

The relation of cumulative density measured between position x_1 and x_2 at instant t is given in equation 3.5

$$k(x_1t_ox_2,t) = \frac{N(x_1,t) - N(x_2,t)}{x_2 - x_1} \quad \ldots(3.5)$$

The function $N\ (x,t)$ is a step function since the vehicles are visible. It allows approximating the step function by a smooth process $\tilde{N}(x,t)$ that is continuous and can be differentiated by taking the limit for $(t_2 - t_1)$ to 0 and $lim\ (x_1 - x_2)$ to 0.

The relation 3.4 and 3.5 become : $q(x,t) = \frac{\partial \tilde{N}(x,t)}{\partial t}$ ….. (3.6)

$$k(x,t) = \frac{\partial \tilde{N}(x,t)}{\partial x} \quad \ldots \quad (3.7)$$

The mean speed is therefore defined at position x and time t as: $v(x,t) = \frac{q(x,t)}{k(x,t)}$.

Finally, mean speed, density, and flow rate can be handled as continuous x and t. This property is applicable when developing macroscopic traffic flow models.

From equation (3.7), the number of the vehicle between points a and b is given by

$$N(t)=\int_a^b k\left(x,t\right)dx \qquad \text{....} \quad (3.8)$$

The variation of the number of cars can be calculated by subtracting inflow to outflow:

$$\begin{aligned} &\frac{d}{dt}N(t)=\int_a^b k\left(t\right)dx=q(a)-q(b)=-\int_a^b q(x)dx \\ &\int_a^b k\left(t\right)dx+\int_a^b q(x)dx=0 \end{aligned} \qquad \ldots \quad (3.9)$$

For any value of a and b, the equation (3.9) becomes continuity equation of traffic density:

$$k\left(t\right)+(kv)_x=0 \qquad \ldots \quad (3.10)$$

The initial and boundary conditions must be established to build the various solutions of the continuity equation. The generation of a function $k\ \left(x,\ t\right)$ is needed to incorporate the data as an initial condition into the model.

3.6.1 Fundamental relation of traffic flow

The shape of the fundamental macroscopic relation is based on the principle of two regimes (free flow and congestion). The traffic flow state is either in the free flow regime or the congestion branch for a given time (Monache *et. al.,* 2021). The empirical investigations show that when the density is zero, the flow is also zero because there is no vehicle on the road (Spiliopoulou *et. al.,* 2015). As the density rises, the flow also increases (Knoop and Daamen, 2017). When the density reaches the maximum, usually called the jam density, the flow is zero (Helbing, 2009). There were mainly two cases in a given lane considering the specifics characteristics: critical density, jam density, free-flow speed, and critical speed (Monache *et. al.,* 2021). Note that the critical density was defined as the density at which the free flow zone and the congestion zone of the fundamental relation intersected.

In free flow, the density was equal to or lower than the critical density ($0\leq k\leq kcr$). The traffic flow in the lane was lower than the traffic capacity of the road and it may happen for both lower and higher densities (Singh and Bansal, 2016).

The flow was given by Equation 3.11

$$q = v_f k - \frac{(v_f - v_{cr})}{k_{cr}} k^2 \qquad \text{.... (3.11)}$$

In congestion, the density was more significant than the critical density. It tended to jam density ($k_{cr} \le k \le k_j$), the traffic flow was higher than the road's traffic capacity (Equation 3.12).

$$q = \frac{k_{cr} v_{cr}}{k_j - k_{cr}} (k_j - k\ ) \qquad \text{... (3.12)}$$

With v_f free-flow speed, v_{cr} critical speed, k_{cr} critical density, and k_j jam density. The degree of the efficiency of a road can be valued by analyzing the relationship between three primary descriptors of traffic flow, which directly influence the layout of the road (Pursula and Enberg, 1991). By seeing the flow of traffic along a roadway, three main parameters were considerably significate(Zhang *et. al.*, 2016). The speed and density describe the quality experienced by the stream (H. Yu *et. al.*, 2020). Greenshields suggested the linear relation between speed and density relationship to present MFD as a diagram of flow rate in function of density (Yu *et. al.*, 2016). The linear expression is given in Equation (3.13) $v = v_f - (\frac{v_f}{k_j})k$ ... (3.13)

Where k is density, v is the mean speed at density k, v_f is the free speed, and k_j is the jam density .

Once the relation between speed and density is established, the relationship between density and flow can be derived. Traditionally traffic engineers have estimated density from point measurements, using the relationship $k = \frac{q}{v}$

Knowing that $q = vk$ then by substitution in Equation (3.13):

$$q = kv_f - (\frac{v_f}{k_j})k^2 \qquad \text{...(3.14)}$$

A further vital property of the fundamental diagram is a maximum flow rate, mostly called capacity, which relates to critical density and critical velocity. The attractive boundary conditions are jam density, free-flow speed, and maximum flow. Then differentiate equation (3.14) concerning k and equate it to zero to obtain the density at extreme flow. By solving a following differential equation

$$\frac{dq}{dk} = 0$$

The critical density corresponding to maximum flow is half the jam density, dividing the curve into two regimes: free flow and congested zone. Once the critical density is obtained, the maximum flow can be derived by substituting critical density in equation (3.14)

$$q\max = \frac{k_j v_f}{4} \qquad \text{...(3.15)}$$

This traffic flow analysis on NR1 and NR2 was based on these fundamental equations between density and flow. The equations developed were applicable for the selected roads.The graphical representation of traffic flow analysis was performed by using python and Microsoft Excel working with OpenPyXL.

Python was helpful to work with Excel to perform data analytics to handle complex macroscopic mathematics of traffic flow. It was served with OpenPyXL, a Python library that allows python programs to read, write, and modify Excel files. It generated large files of flow, density efficiently and quickly. This library was used to handle and display an Excel dataset of flow, density, and speed (Sundnes, 2020).

3.6.2 Calibration relation of macroscopic traffic flow models.

The calibration process has to be conducted by the filed surveys of the traffic streams (Barua and Hossain, 2017). As it is challenging to determine boundary values free-flow speed(v_f) and jam density(k_j) from various speeds and densities observed, it is better to fit linear equations between them (Shah *et. al.,* 2011). The traffic models deliberated can be used to determine specific parameters, such as the critical speed and critical density at which maximum flow occurs . By involving the collected data on NR1 and NR2, the data were fitted in regression model. It was done by minimizing the squares of the differences between the observed and expected values of a dependent variable.

The linear regression method was used by considering equation $v = a + bk$ (3.16) such that k was density and v was speed.

Where the coefficient parameters a and b, defining the line can be estimated from the sample data using the following equation

$$a = \frac{1}{n}\sum_{i=1}^{n} v_i - \frac{b}{n}\sum_{i=1}^{n} k_i \qquad \text{.... (3.17)}$$

$$b = \frac{\sum_{i=1}^{n} k_i v_i - \frac{1}{n}\sum_{i=1}^{n} k_i (\sum_{i=1}^{n} v_i)}{\sum_{i=1}^{n} k_i^2 - \frac{1}{n}(\sum_{i=1}^{n} k_i)^2} \quad \ldots (3.18)$$

Vi and Ki were the samples of speed and density, respectively; n is the number of samples. For the suitability of an estimated regression function, the collection coefficient was determined from Equation (3.9)

$$R^2 = \sum_{i=1}^{n} (v_i - a - bk_i)^2$$

The closer R^2tended to 1, the better the regression fitted (Schober and Schwarte, 2018).

3.7 Design Of Traffic Assessment Tool

The essential advantage of the Traffic Assessment Tool (TAT) is to manage the traffic by reducing emission, noise, and travel time (Tom, 2014). For this case study, a TAT was designed, linked to synthesizing different data sources and integrating with the macroscopic traffic model (Bassi, 2017). This tool can be designed for providing real-time info direct to drivers (Rath, 2018). It was developed using the congestion control algorithm to support agent's traffic controllers (Eline and Teije, 2015). The TAT would combine different traffic data from existing ANPR cameras installed in Kigali city.

The complex procedures of TAT were performed by using the Click Charts- NCH software. Click chart -NCH software is ideal for presenting data and information to create the perfect charts and diagrams in a meaningful and organized technique. It was used for writing various algorithms to demonstrate the steps of the tool. It was appropriate for analyzing real-time data information to identify the traffic congestion status by optimizing the complex processes of traffic flow on NR1.

3.7.1 Data identification of TAT

Traffic flow data are desirable for traffic management, a control application, and transportation planning operations. Such data can be collected from cameras through a network’s links(ADB, 2019). The TAT was designed to reinforce the existing ANPR cameras' capacity and combine the enormous data required for traffic management and control. The tool intended the architecture flowcharts to establish different procedures for license plate recognition cameras.

The data processing in the system was based on a Wi-Fi module that allowed the ANPR cameras to interface with the internet for enabling data transfer to the database. They used optical character recognition to capture the vehicles as an aggregate name(image) of data collection techniques**.** The method was based on license plate identification and recognition (Allström *et. al.,* 2017). The ANPR camera technology made the new data available for traffic volume to be a considerable amount.

In gathering data, a traffic network would be organized with traffic assessment tool providing real-time traffic data. Technology was essential to deal with the massive amount of data. After the appropriate filtering of data, suitable statistical tools were applied to generate the local information necessary to estimate and predict the short-term evolution of the current traffic state.

3.7.2 Traffic density calculation in the TAT

The density calculation could be performed in ANPR cameras installed in Kigali city. ANPR cameras contained a processor unit for processing the data collected from the various nodes and a Wi-Fi module for sending data to the system. The number of ANPR cameras should be determined according to the general statistics of the traffic volume at each road crossing (Jarašūniene, 2007). This study used three ANPR cameras based on traffic volume determined at the roads NR1 and NR2.The ANPR camera 1 captured a plate number of vehicles as it passed and counted; the number of cars would consider as inflow. Similarly, the ANPR camera 2 calculated the outflow.

The variation of the number(Ni) of vehicles can be calculated by subtracting inflow to outflow. Let consider the length of the queue Li (distance between two cameras)and Ni the number of vehicles in that queue, the segment density (ki) was calculated by using the following equation: $ki = \frac{Ni}{Li}$ (3.20). Camera 3 was intended to deviate the vehicle during unstable flow.

The method focused on using a real-time object detector, You Only Look Once (YOLO), based on Convolutional Neural Networks (CNN), to process data on an image for classification purposes (Jianjun *et. al.,* 2018). This method was highly efficient and fast but required many bounding boxes of objects interest within the picture because the vehicle detection algorithm was executed at every frame. The YOLO model generates vehicle images higher than 45 frames per second (Kolmos *et. al.,* 2013). Through python software, the process of vehicle detection, tracking, and traffic data generation is presented in the following 10 steps.

1. Load Coco labels used in training the YOLO model

2. Derive paths to retrieve YOLO weight and model configuration
3. Load the YOLO Object Detector
4. Initialize video stream and assign desired frame dimension (W, H)
5. Loop over frames

   While true:

   - Read frame from file
   - Create blob to serve as input to YOLO Object Detector
   - Output is array of bounding boxes [], confidences [], and class IDs []
   - Loop through detections to filter out weak predictions

     For detection in the output:

     - Select only if confidence > min confidence and class = desired class
     - Assign bounding boxes and IDs to each selected detection
     - Append array to include on boxes in the region of interest (ROI1 and ROI2)
     - Compute centroid coordinates for the boxes
     - Initialize video writer and pass the frame to it
6. Check to see if tracking was ongoing and update the tracker with coordinates
7. Show frame image in real-time with all required annotations
8. Exit loop when no further frames are found
9. Keep count of boxes finds traffic data of flow in ROI2 per hour
10. Traffic data of flow density was computed by implementing a "transaction algorithm" with the ROI flow data as input. The output is then divided by a calibrated Euclidean distance between ROI1 and ROI2.
11. A data frame of this data was created and continuously updated using pandas' library
12. The generation of the traffic curve in real-time was performed using the Matplotlib library.

3.7.3 Evaluation and validation performance of TAT

The developed tool was based on integrating several technologies algorithms implemented to provide a management tool of traffic monitoring for decision-making processes. Leaning algorithms were used to validate the TAT as the key in addressing challenges in monitoring and managing an urban transport network operating in real-time. Various recordings of traffic were employed to dynamically interpret the large volume and diversity of data to effectively stages of TAT. Data operation recorded using live video aided in evaluating the proposed tool's performance. In this phase, the chosen hours of traffic recording were based on complex traffic congestion scenarios and were tested to the maximum level. The careful identification of data was made to ensure no data interruption to disturb the system's accuracy. The designed TAT was applied on a section of NR4 road of Musanze city to test and evaluate the performance of detection algorithms. Data to validate the TAT were captured on NR4 road of Musanze city and investigated using descriptive statistics and a t-test at $\alpha_{0.05}$.

CHAPTER FOUR
RESULTS AND DISCUSSION

4.1 Preamble

The interview and traffic survey results were conducted to determine the parameters of traffic flow. The proportions of the responses from decision-makers about traffic management, the strategies available, and their effectiveness to mitigate the congestion were presented. The parameters that contributed to congested regimes on NR1 and NR2 were found and represented. There were the strategies available and their effectiveness in alleviating congestion, peak hours, traffic volume, and congestion level. A fundamental traffic flow diagram was used to analyse the flow density relation ship for identifing traffic congestion on NR1 and NR2. An advanced strategy to reduce traffic congestion was proposed through the design of TAT.

4.2 Interview Result

An interview survey was carried out to identify the existing travel demand strategies and the roads with higher volume. The questionnaire included five questions which are presented in appendix A. The main topics of the questionnaire were given as follows: Identification of the road with higher traffic volume in Kigali city helped select routes for traffic analysis (question 1). Critical traffic congestion problems assessed the level of traffic management in Kigali city (question 2). Identify existing solutions and their effectiveness to mitigate traffic congestion to evaluate the gaps for traffic analysis purposes (questions 3 and 5). Assessment of the importance of ANPR cameras was necessary to assess its combination with traffic application (question 4). Using a camera reflected the necessity of traffic analysis in Kigali city as the essence to perform this study.

4.2.1 Identification of the congested natioanl roads

The fundamental elements to identify the congested roads were responses from planners, which are shown in Figure 4.1. They assessed the congested national road of Kigali town and a network-wide qualitative evaluation at the specified routes.

The relevant elements to select the highest congested roads were the planned activities to mitigate traffic congestion. Regarding the most congested roads 33.3 % of transport planners said that NR1 and NR2 characterized the highest traffic volume resulting in traffic congestion. Only 11.1% of Transport planners showed that NR3,NR4 and NR5 were congested.

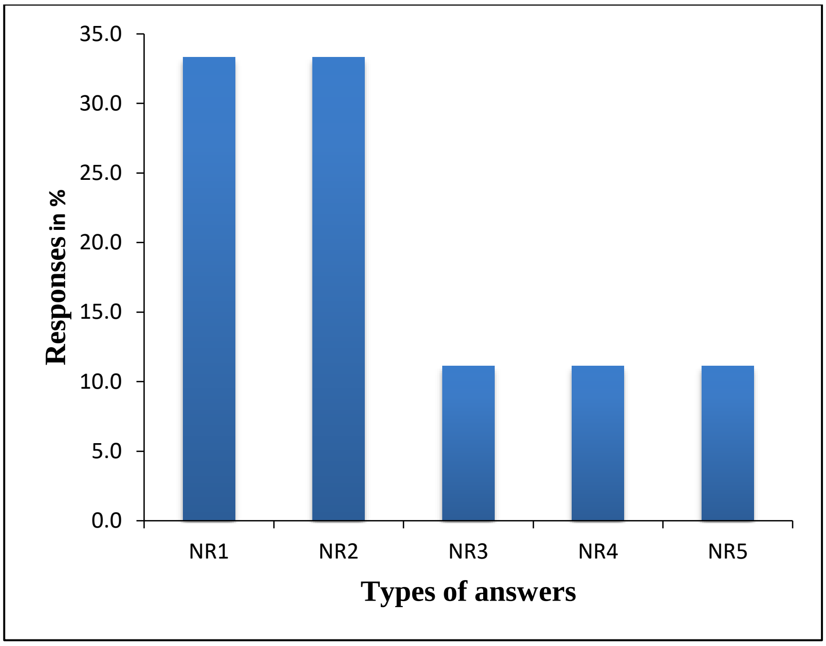

Figure 4.1 Analysis of the congested roads

According to the result (Figure 4.1), the roads NR1 and NR2 were the most congested as they represented the highest percentage of responses. The two streets connect different areas that make them have the complex movement of traffic. The NR2 links Kigali city with northern province of Rwanda.The NR1 goes through primarily residential and commercial areas. This road is the complex traffic volume movement to and from Kigali city, southern region, and Burundi (ADBG, 2013).

4.2.2 Identification of problems' level of traffic congestion in Kigali city

Identifying the problems' level in this sub-section had the purpose of determining and prioritizing congestion assistance involvements. This assessment focused on discussion and questionnaire responses from transport engineers of decision-making in Kigali city. The Transport planners were asked how they critiqued the negatives effect of traffic congestion. 78% of Transport planners said that the congestion occurred at the highest level in Kigali city as the roads operates between LOS D and LOS F ,and the ratio of volume to capacity varies between 0.5 and 0.75 (Bitangaza & Bwire, 2020). Only 22% of responses demonstrated that the congestion problems happened at an average level. No person said that the congestion problems were neither poor nor very poor. Figure 4.2 shows the percentage of answers about critiques on issues of traffic congestion.

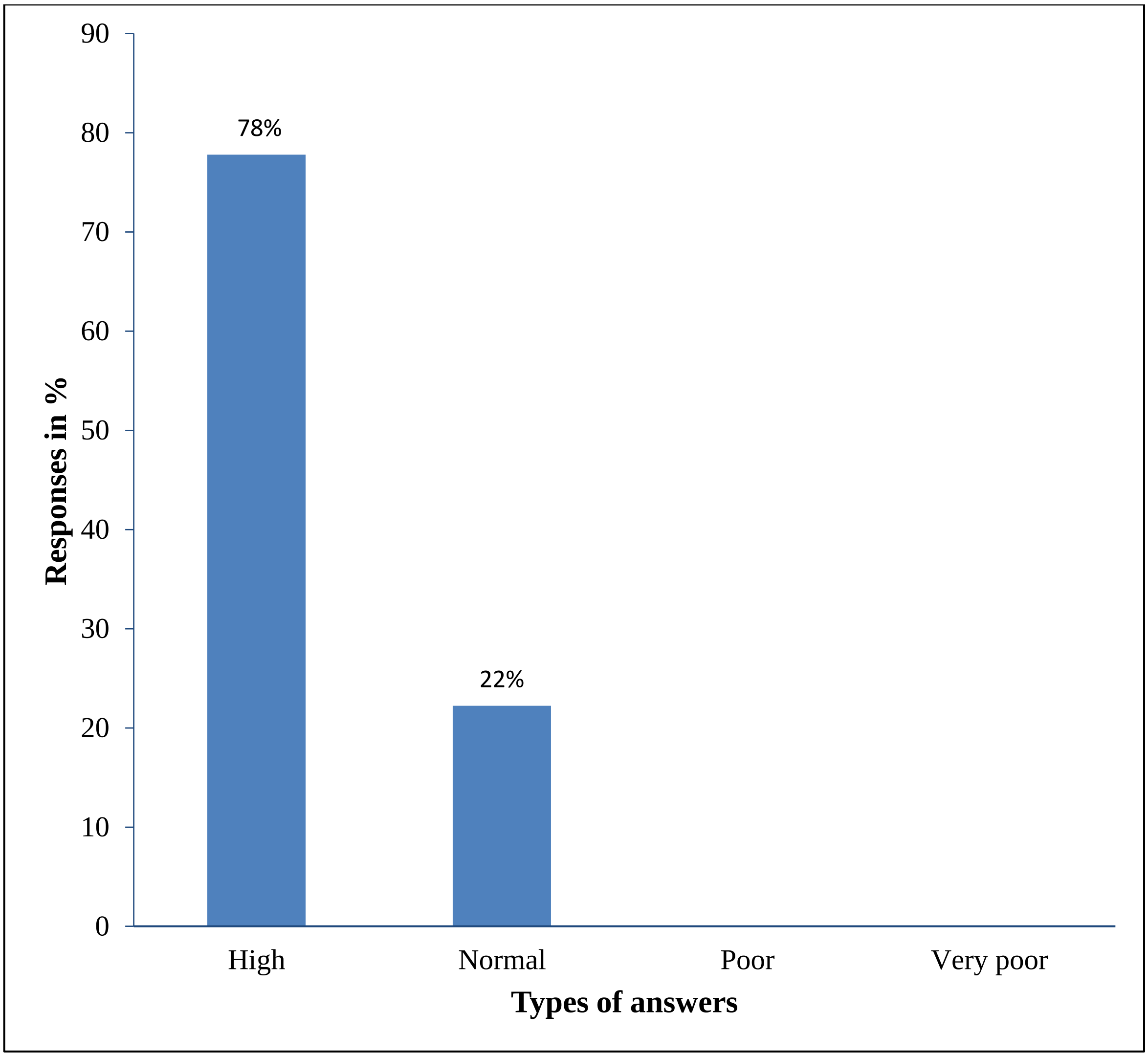

Figure 4.2: Analysis of problems caused by a traffic congestion

The result showed that no one had reacted to neither inadequate nor inferior issues of traffic jams. Traffic congestion in Kigali city can be caused by various reasons such as weather conditions, work regions, incidents, exceptional events, and excessive demand (Chao *et. al.,* 2013).

4.2.3 The existing strategies available for congestion mitigation in Kigali city

The adopted strategies to mitigate traffic volume growth were to promote public transport and extend the existing roads by constructing roundabouts, providing traffic signals, and increasing the width of the carriageway. It was showed that 56% of responses considered road widening as the first strategy to mitigate traffic congestion (Figure 4.3). Again 33% of transport planners responded that it was essential to promote public transport. Only 11% of transport planners reacted that traffic systems were planning to be the strategies, and no one responded according to traffic modelling.

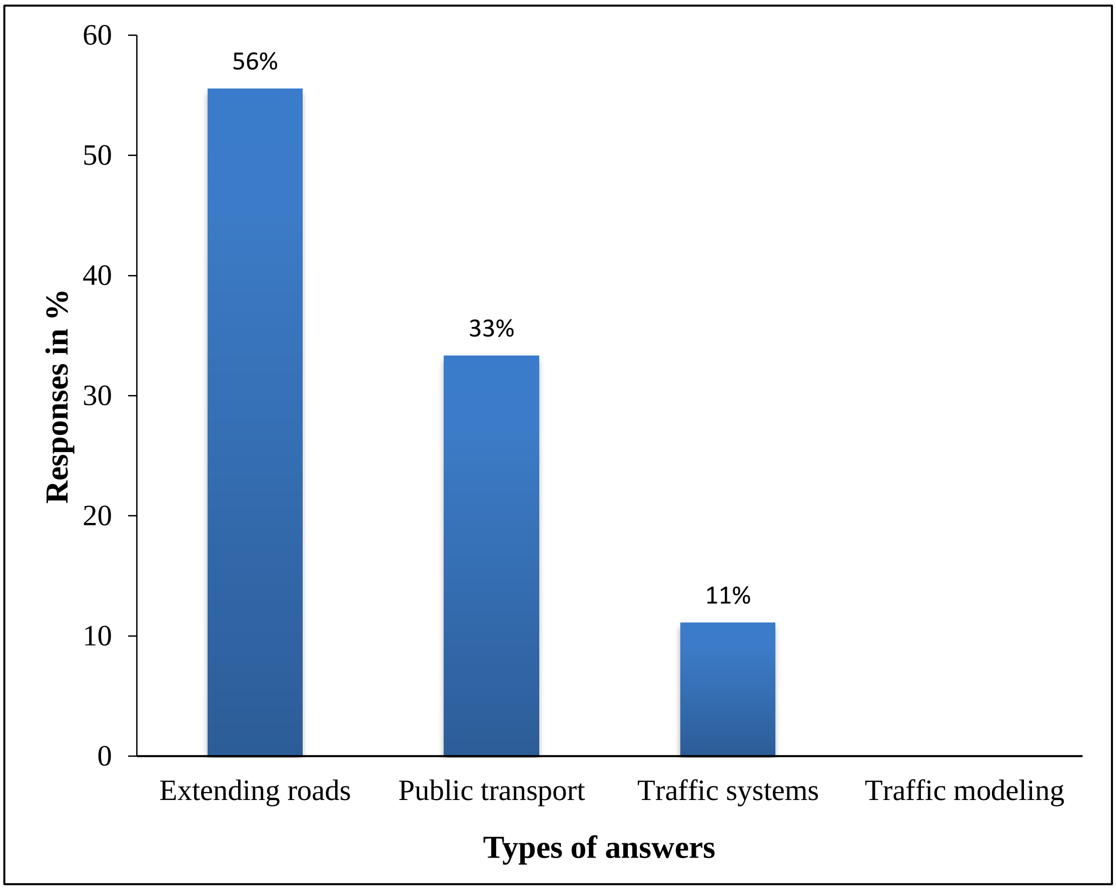

Figure 4.3: Analysis of the solutions to mitigate traffic congestion

The result form Figure 4.3 showed that there was the bid gap in providing the traffic systems that may quickly control the congestion in Kigali city. Concerning the promotion of public transport, the authorities established the use of e-ticket to facilitate payment (ADBG, 2013). Despite the efforts being made by the management authority to improve flow, the long waiting line of passengers remained a challenge of stress and anxiety in Kigali (Chao *et. al.*, 2013). Moreover, the strategy of extending roads has been a difficult challenge to reduce the effects of road congestion due to Kigali's hilly topography(MININFRA, 2012a). It was, therefore, useful to design an assessment traffic tool (WBG, 2017).

4.2.4 The significance utilizing of ANPR cameras in traffic flow in Kigali

In Kigali City, respecting the designed speed on roads was put into practice by installing ANPR cameras. The primary role of the cameras is to capture the vehicle passing at a given point to charge a driver who excessed the provided speed. The use of ANPR cameras to mitigate overspeeding was considered very useful at 67% of responses in traffic flow. 33% of the transport planners showed that the existing cameras were helpful, and no person said that the cameras were neither not useful nor uninterested. The detailed responses are shown in Figure 4.4.

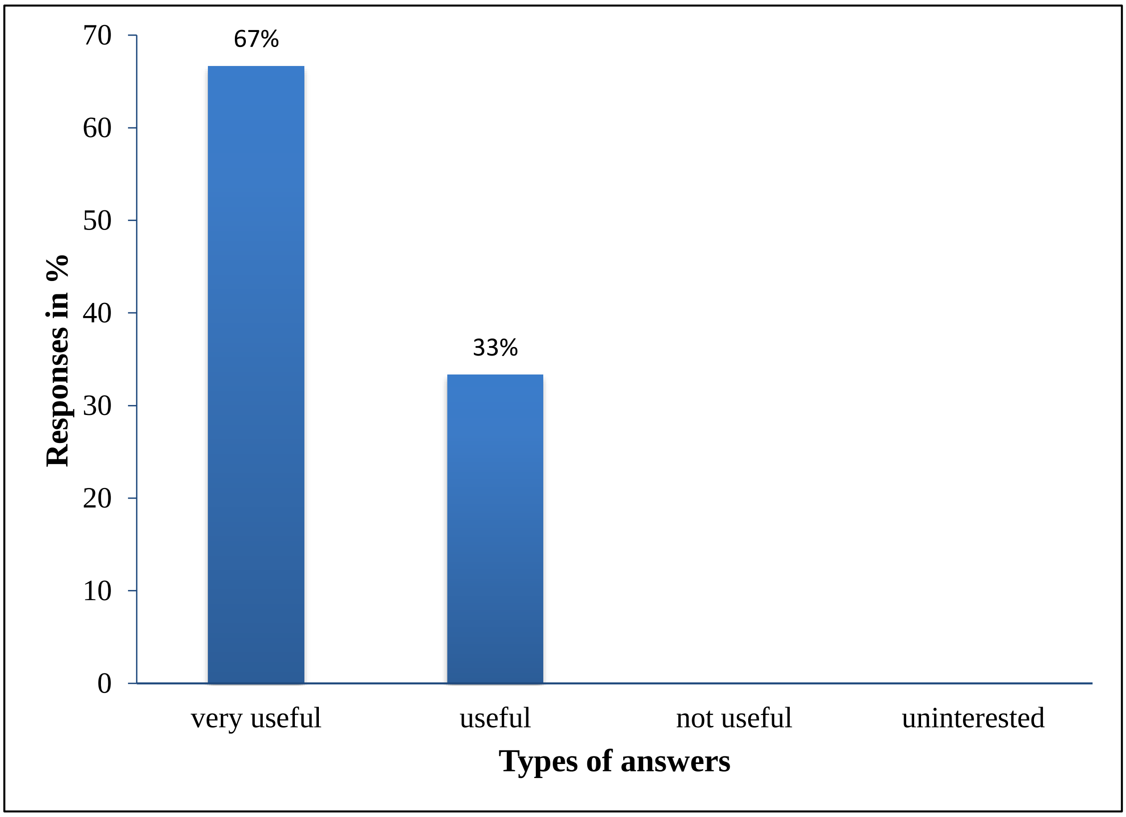

Figure 4.4: Analysis of the significant use of ANPR cameras in traffic flow

The responses significantly impacted choosing cameras installed in Kigali as an essential tool to design the traffic application. The cameras provide an effective solution to help the authorities identify vehicles that disrupt the speed limit (JICA, 2019). In such a situation, they would have the role of capturing the image of cars passing at a specified point for the charge driver and warning him the awareness of jam location (Bhatia and Goyal, 2016). The combination of the ANPR cameras with a designed a traffic assessment tool would be essential to fast mitigation of congestion (Nkoro and Member, 2014).

4.2.5 Effectiveness of existing solution available for congestion control

According to Figure 4.5, the strategies to alleviating traffic congestion were considered very effective at 33.3%. Also, 22.2% of transport planners answered that they were effective, and 44.4% said they were somehow ineffective in mitigating traffic jams. No one had reacted to the indifferent response.

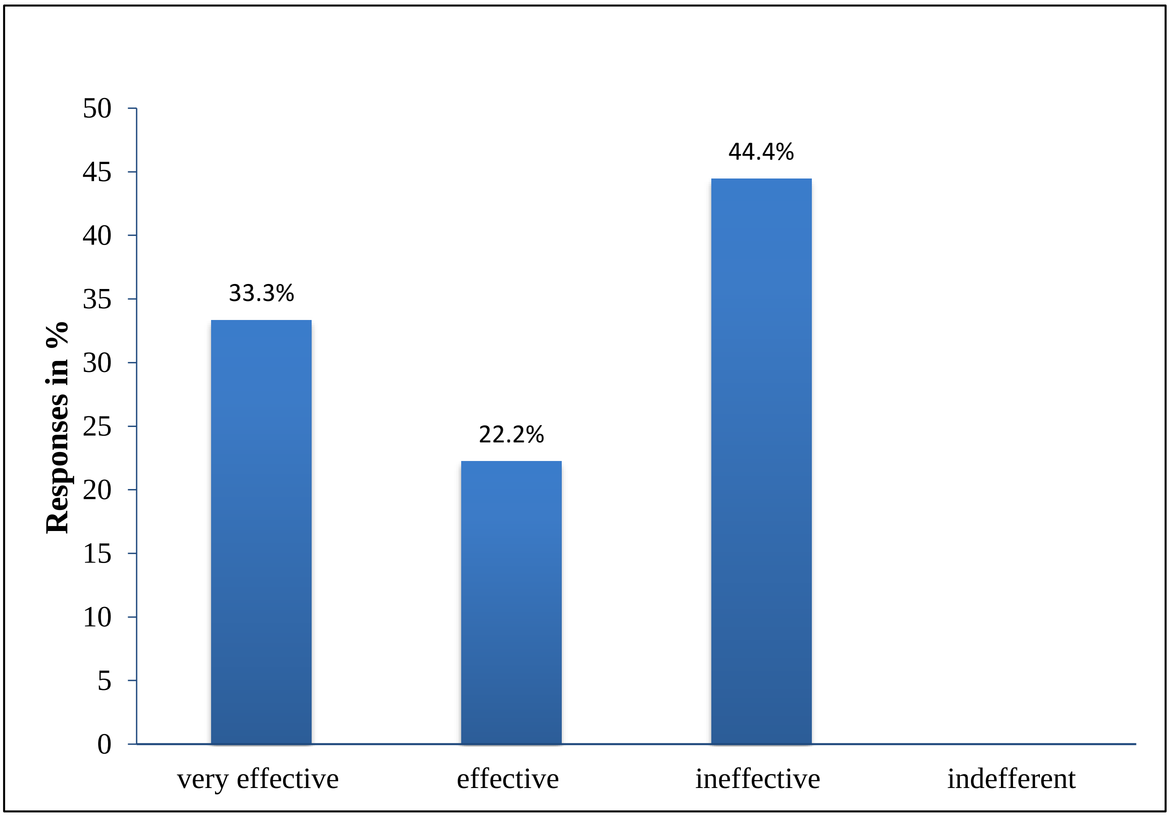

Figure 4.5: Analysis of the effectiveness of solutions to reduce congestion

By analysing these results (Figure 4.5), it was observed that they were gaps in mitigating traffic congestion. It was, therefore, helpful to provide a durable solution, which was the design of TAT (Amin *et. al.*, 2002).

4.3 Traffic Survey Results

This section presents traffic count results performed on standpoints of NR1 and NR2. It emphasized buses, cars, trucks, and minibuses for density and flow rate calculation to determine the most crucial traffic relation on NR1 and NR2. The variation of urbanization and land use of Kigali city was considered in surveying to identify significant urban transit flows of road freight transport. Survey points and methods of analysis were decided based on the current traffic condition. The traffic volume results counted from 5 am to 8 pm were presented to determine the peak hours and the MFD of flow rate and density. It was regular to use a great effort to collect traffic count data with reasonable accuracy.

The methodology steps were detailed to secure the targeted objective of finding a reliable data set. The following measurements were typically obtained and extracted from the traffic count data. The traffic volume average and variation within the survey period of 15 hours for each count station per type of vehicle was presented. Each site's peak hour traffic volume was extracted by detecting the highest traffic volume available in the survey period. The time of the day in which the traffic reached the peaks was identified. The traffic volume based on the counted data was estimated in traffic volume per hour. The percentage of each vehicle type in the traffic flow was expressed as a percentage for each count station.

4.3.1 Preliminary survey result

According to the Rwanda Transport Development Agency (RTDA) manual, road marking and signs were visible to facilitate the comfortability of drivers. The on-street parking was observed in good conditions. The characteristics of vehicles moving in Kigali city were appreciated in good condition. The traffic signals at the intersection provided well information to convey road users in their directions .The existing roadway, traffic and control conditions of the five national roads in Kigali City were found to be acceptable in accordance with the Rwanda Transport Development Agency Manual.

4.3.2 Traffic survey adjustment

Traffic data was collected between November 2019 and December 2019. However, one week of November 2019 traffic survey was disturbed by weather conditions. Resurvey was conducted in December 2019. The result of the traffic survey on NR2 showed the following aspects:

The traffic volume of motorcycles counted between November 2019 and December 2019 was 25%. The traffic volume of private cars was 24 % . The traffic volume of public transport minibuses and buses were 22%, and 23% respectively. The number of trucks counted was 6%. The traffic result between November 2019 and December 2019 on NR2 is indicated in Table 4.1.

Table 4.1 Traffic survey result on NR2

Types of vehicles	Traffic volume	Proportion
Motorcycle	4279	25%
Cars	3986	24%
Minibus	3713	22%
Bus	3875	23%
Truck	952	6%

The result of the traffic survey on NR1 revealed the following aspects:
The number of motorcycles counted was 29%. The traffic volume of private cars and minibuses were 21% and 17% respectively. The traffic volume result between November 2019 and December 2019 on NR1 are shown in Table 4.3.

The variation in traffic volume found on NR1 and NR2 was due to the number of vehicles available and the period of traffic survey. Kalašová and Stacho (2006) showed the similar result a significant variation of the number of vehicles in a period of surveying.The traffic flow data analysed on NR1 and NR2 involved identifying peak hours, traffic distribution by vehicle types, and analysing density, speed, and flow relationships.

4.3.3 Traffic volume and peak hours on NR2

The traffic count was recorded at 15 minutes intervals for 15 hours (Garber and Hoel, 2004), summed up to one hour. The average vehicular flow was 645.3 veh/h per lane. Figure 4.6 shows the survey outcome of the traffic volume per type of vehicle. The findings on NR2 showed that the primary vehicles that were highly significant were motorcycles and cars, occupying respectively 25% and 24%. The highest percentage of traffic volume was 25%, which presented the number of motorcycles available at that chosen station. The rate of bus and minibus were respectively 22% and 23%. The minor proportion was 6% which showed the number of trucks counted on-road NR2.
According to British standard approach, traffic movements approach unstable states for traffic flows above 1100 veh/h for two-way uban roads. On this road NR2 ,the traffic flow average was 645.4 veh/h and the drivers had the freedom to select their desired speeds. The rate of 24% and 25% showed cars and motorcycles were respectively main mode of transport (Figure 4.6). The highest percentage of traffic volume was 25%, which presented the number of motorcycles is reasonable as the service of motorcycle taxies occupied 13% of other public transport in Kigali . They are taken as the faster mode to reach the destination on time (JICA,2019).

Table 4.2 Traffic survey result on NR1

Types of vehicles	**Traffic volume**	**Proportion**
Motorcycle	3331	29%
Cars	2461	21%
Minibus	1895	17%
Bus	2936	26%
Truck	770	7%

The hourly distribution in traffic volume per type of vehicle on NR2 is shown in Figure 4.7. It was obtained that in from 6 am to 8 am, the traffic volume was high, varying between 120 to 200, it started to decrease from 9 am to be moderate up to 4 pm. Between 5 pm to 8 pm represented the highest traffic volume, fluctuating from 100 to 190. Therefore, the extracted hours of congestion were observed from in the morning 6 to 8 and evening 5 to 8.

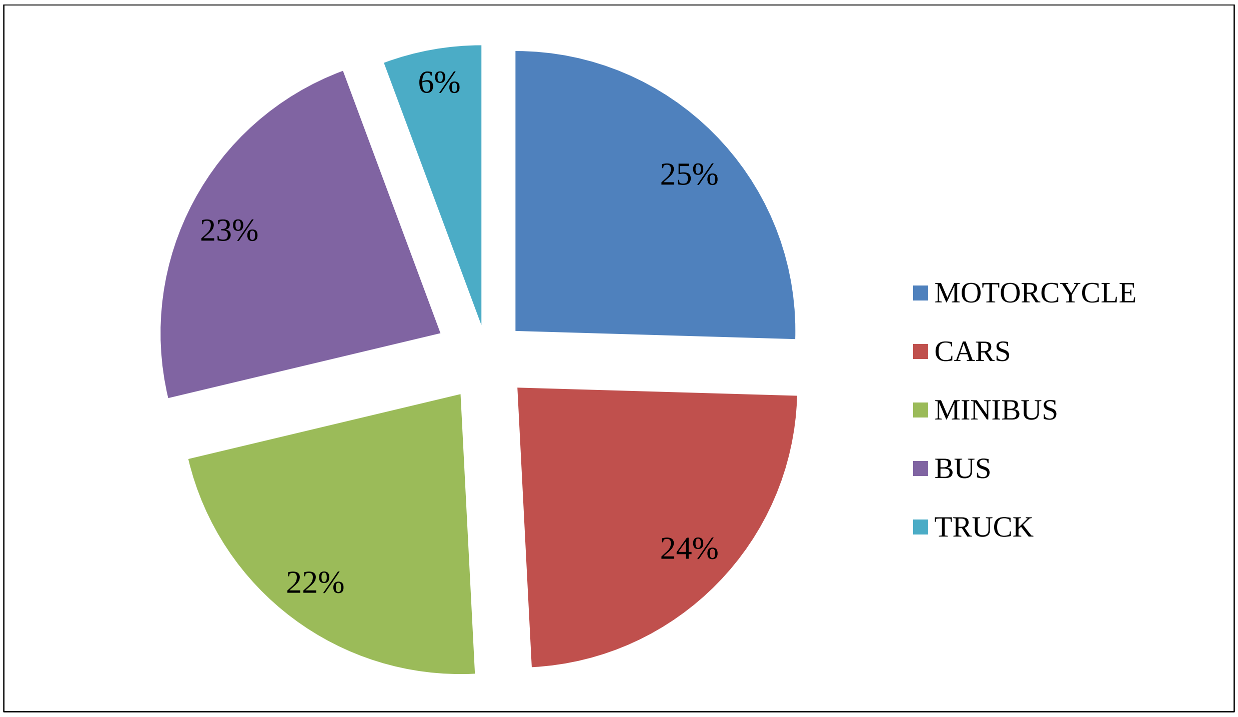

Figure 4.6: Compositions of traffic volume on NR2

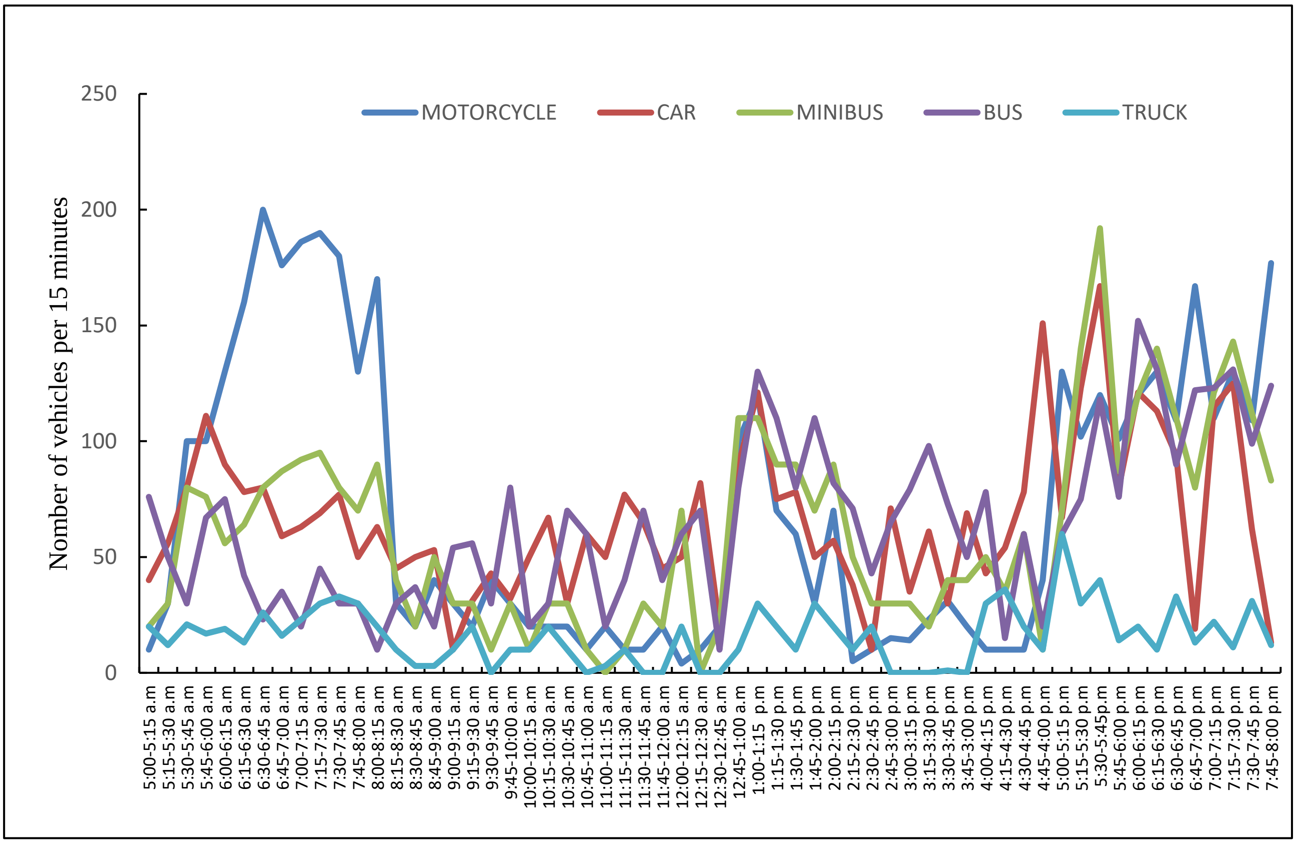

Figure 4.7: Hourly compositions of vehicular traffic on NR2

In the graphical formats of hourly traffic volume, the peak volumes were from 6 a.m. to 8 a.m. and 5 p.m. to 8 p.m. It was contingent that daily market, work, and school trips were mainly responsible for the peaks. If such data are gathered daily for one year, the hourly variations may be similar, while the actual volume may not be identical from day to day (Soriguera *et. al.*, 2017).

4.3.4 Traffic volume and peak hours on NR1

The traffic volumes moving in each direction were counted for 15 minutes intervals. The average vehicular flow was 1120.3veh/h per lane. Figure 4.8 shows the traffic volume per vehicle type on road NR1. The findings showed that the primary vehicles which were highly significant were motorcycles occupying 29%. The rate of buses, cars, and minibuses were respectively 26%,21%, and 17%. The minor proportion was 7% which showed the number of trucks counted on-road NR1. The vehicle types having different sizes were converted into equivalent passenger car units (PCU) which are adopted as per standard practice of Rwanda. The PCU factors for motocycles ,cars,minibus ,bus and truck are respectively 1, 2, 2 and 3.5 (MININFRA, 2016). Using the PCU factors and percentage of vehicle , the factors to attribute to maximum flow rate found for four lanes is 29%*0.5 + 26%* 1+21%*2+17%*2+7%*3.5=1.4.

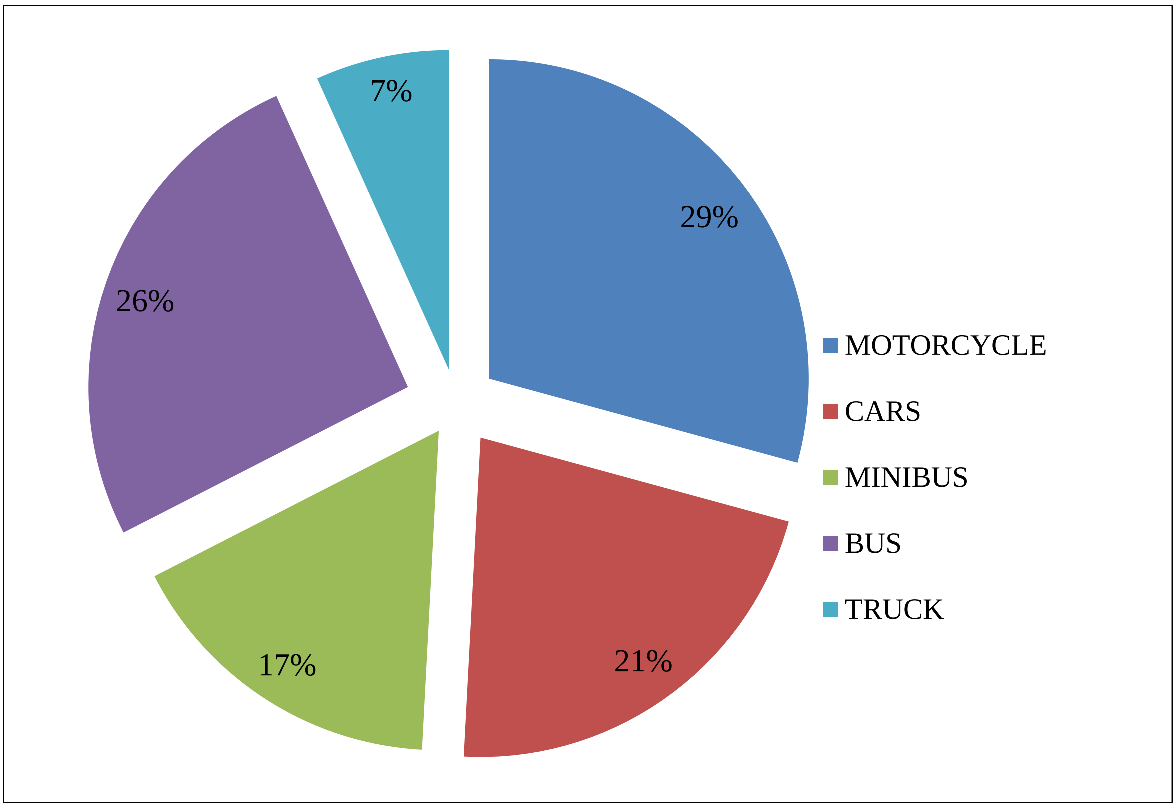

Figure 4.8: Compositions of traffic volume on NR1

According to British standard approach, traffic movements approach unstable states for traffic flows above 1100 veh/h for two-way uban roads.The case of the flow on NR1 of 1120.3veh /h, the drivers had not the freedom to choose the desired speeds in case of restricted movement. The primary vehicles on NR1 that were highly significant were motorcycles occupying 29% (Figure 4.8). Similar results appeared in the study done in Indonesia, where the composition of motorcycles was about 32 %, while the light vehicles and heavy vehicles occupied 68 % (Putranto and Setyarini, 2011). The highest percentage is rational as this road connects markets and banks, and the users admire motorcycles as fleet vehicles for daily transport. According to a JICA (2019) study, motorcycles occupied the highest percentage of 60% of road accidents in Kigali city in 2017. It should be avoided by promoting public transport in the city of Kigali.

The hourly fluctuation of traffic volume per type of vehicle on NR1 for 15 hours starting at 6 am till 8 pm is indicated in Figure 4.9. It was obtained that from 6 am to 8 am, the traffic volume was high, varying between 70 to 132 vehicle types, it started to decrease from 9 am to be moderate up to 4 pm and the traffic volume 4 to 40 vehicle types. The time between 5 pm to 8 pm represented the highest traffic volume, fluctuating between 72 and 230 vehicle types counted in 15minutes. Therefore, the extracted peak hours were from 6 am to 8 am and from 5 pm to 8 pm (Figure 4.9).

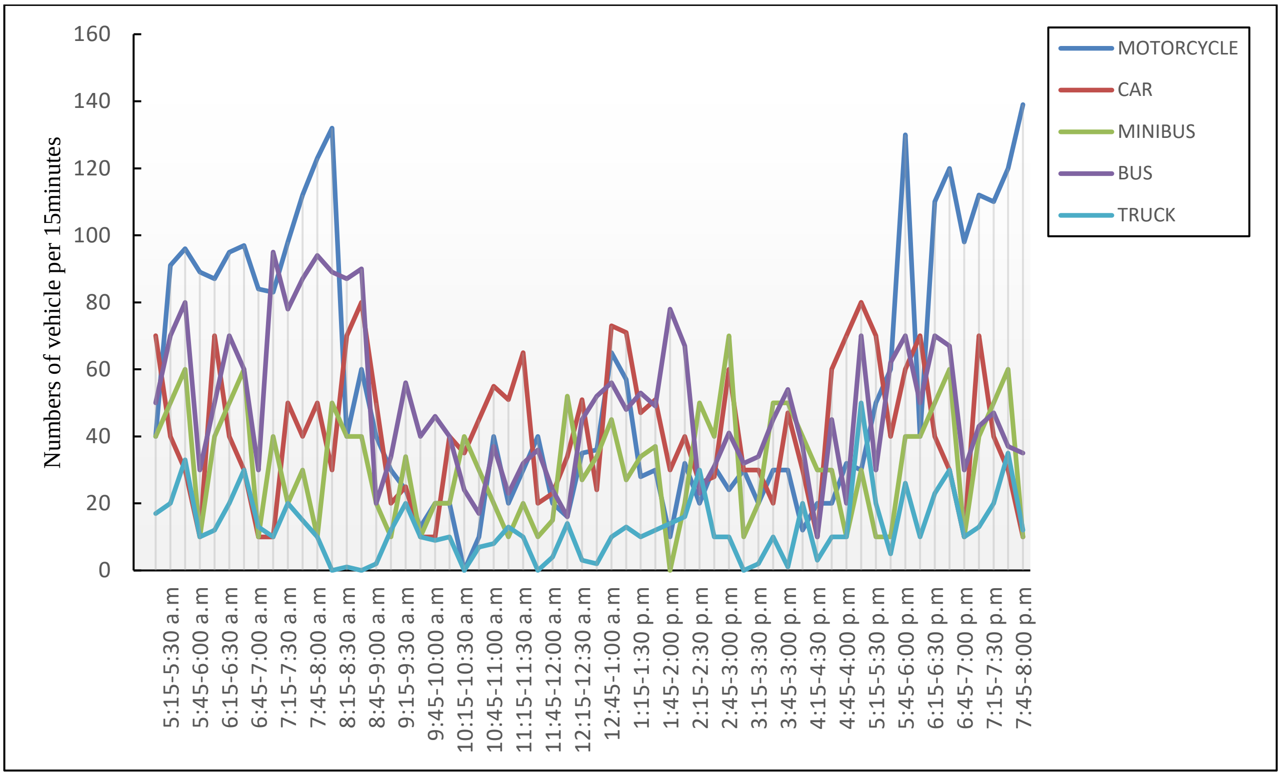

Figure 4.9 Compositions of traffic volume on NR1

In the graphical formats of hourly traffic volume (Figure 4.9), the peak volumes started 6 a.m. to 8 a.m. and 5 p.m. to 8 p.m. A similar result was obtained by Harilimana *et. al.* (2019), where the peak hours were morning 6 to 9 and evening 4 to 8 in Kigali city. It was contingent that daily market, work, and school trips were mainly responsible for the peaks. The public transport promotion and reinforcement of e-commerce and e-learning were proposed to mitigate congestion. If such data are gathered daily for one year, the hourly variations may be similar, while the actual volume may not be identical from day to day (Soriguera *et. al.*, 2017).

4.3.5 Flow- density relationship on NR2

The traffic volume counted on NR2 was used to find the flow rate at an interval time of 15 minutes. The flow rate was found by converting the traffic volume seen in a quarter hour to one hour. Then using average speed recorded at the same interval time, the density was calculated as the flow rate divided speed. The diagram between two parameters, flow, and density, is shown in Figure 4.10. Through the curve, the traffic flow increased concerning an increase in traffic density. For instance, when only one car travelled along a section of road, the density and flow were by characterization close to zero since the speed corresponding to the density mentioned above was called free speed (vf) since no vehicles were on the road. As more vehicles moved on the roadway, the density and flow grew simultaneously (Figure 4.10), with noticeable traffic on NR2.

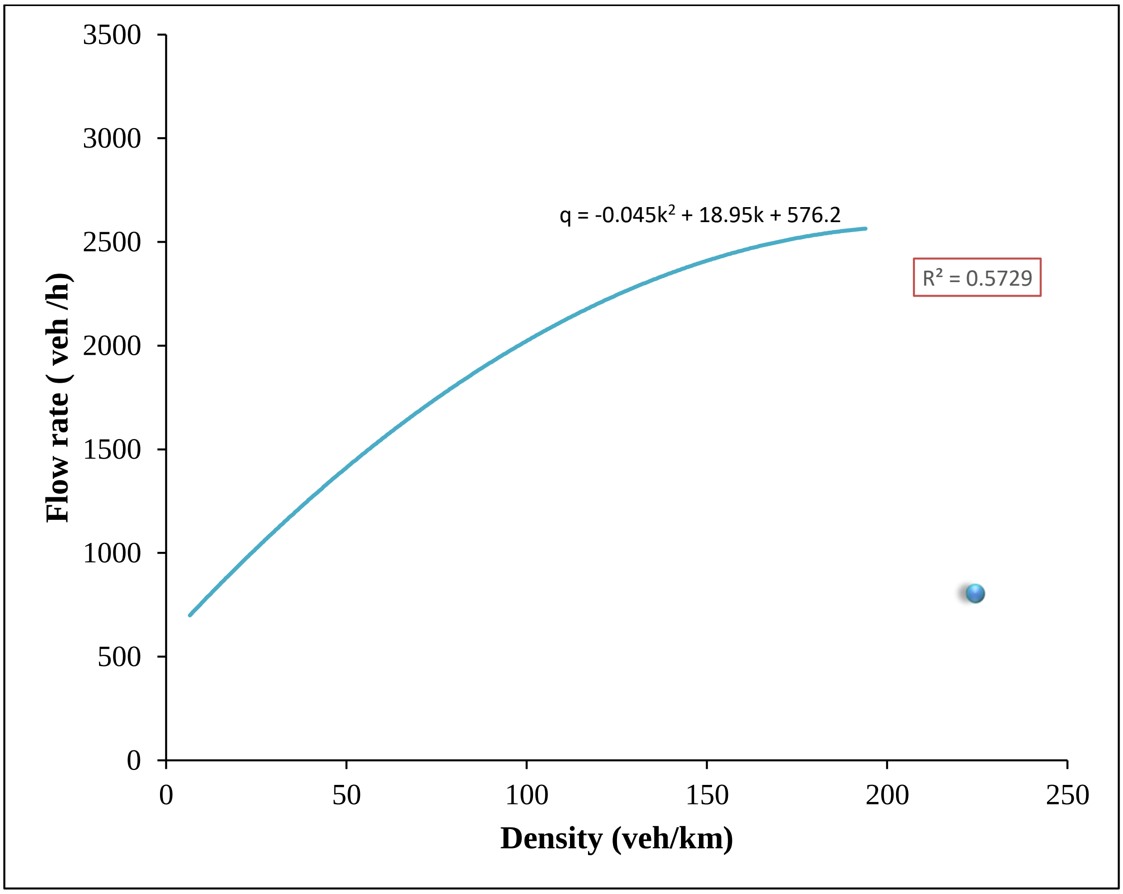

Figure 4.10 Flow-density relationship on-road NR2

The analysis of the result was based on Equation 3.14, illustrated in chapter three. The equation $q = -0.045k^2 + 18.95k + 576.2$ has different structure from Equation (3.14) so that to get the extreme flow (qmax) and the corresponding critical density (kcr) was complex. It showed that there was no clear transition between free-flow and congested regimes Through the curve, the traffic flow increased concerning an increase in traffic density. The study revealed that the flow rate and the corresponding density were acceptable for free traffic wich is similar to the study made by Akintayo and Lafinhan (2015) that showed an increase of flow rate concerning an increase of density in free flow regime . This result also was comparable to the findings from the study carried out in India, where an increase in traffic flow may happen for both lower and higher densities (Singh and Bansal, 2016). It was due to the existence of the faster vehicles which passing on another connected to that station.

4.3.6 Flow - density relationship on NR1

The traffic volume counted on NR1 was used to find the flow rate at an interval time of 15 minutes. Then using average speed recorded at the same interval time, the density was calculated as the flow rate divides speed. The diagram between two parameters, flow, and density, is shown in Figure 4.11.

The findings found from MFD on NR1 (Figure 4.11) empirically showed the following: Referring to equation 3.13, the free speed and jam density ratio was 0.253, where 58.23 km/h was free speed. Therefore, the jam density, the critical density, and maximum flow were respectively 230 veh/km, 115 veh/km, 3348veh/h (Tang *et. al.,* 2009). When the density tended to zero through the diagram, the flow was zero since no vehicles were on the road. The car moved at the desired speed. When the number of cars progressively increased, the density and flow grew until it reached a maximum flow of 3348 veh/h. Again this corresponded to the critical density, and beyond this point, the flow rate decreased until it reached a jam density of 230veh/km. Once supplementary vehicles were added, it resembled a situation where cars couldn't move. There was a stop-and-go movement with the unstable flow (Helbing, 2009).

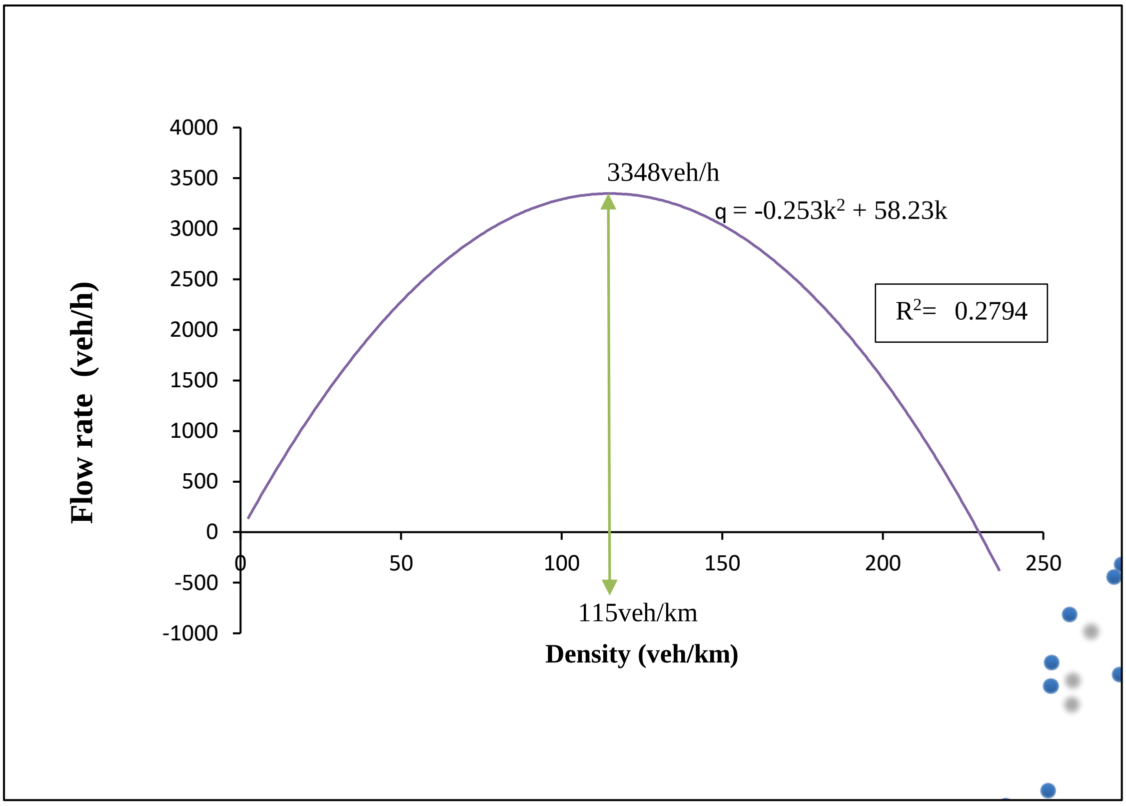

Figure 4.11 Flow- density relationship on-road NR1

The existence of concavity in Figure 4.11 showed Equation (3.14) fitting to represent the Macroscopic Fundamental Diagram (MFD) of flow versus density (Knoop and Daamen, 2017). The graph showed a clear transition between the free-flow and congested zone. A critical point separated the two regimes with a crucial coordinate density of 115 veh/km and maximum traffic flow of 3348veh/h, which were comparable to a study made by Kachroo and Özbay (2018). Their findings showed that the critical density should be between 70 veh /km and 270 veh /km. HCM 2010 volume 2 provides the capacity of two lanes in one direction of 3600 pc/h. Using the PCU factor of 1.4 ,the maximum flow rate found was 4684.4 pc/h. NR1 demand exceeded the capacity which resuted in LOS F. The movement on NR1 was restricted and the deviation of vehicles to different routes to reduce intense traffic volume was desirable and was performed by using the TAT designed in chapter four.

4.3.7 Comparison of MFD and the linear regression model

In the previous subsection, the basic diagram (MFD) has shown the relationship between density and the corresponding traffic flow on road NR1. In analyzing the concavity of the curve (Figure 4.11), the following argument was assumed: When the density on NR1 was 0, the flow was also 0 since no vehicle was traveling on NR1. It followed that as the density increased from 0, the flow also increased from 0 to a maximum value. Further continuous increases in density resulted in a constant decrease in flow rate. When the density reached its highest value, called the congestion density, the flow rate. was zero (Monache *et. al.*, 2021). The data collected on NR1 tended to confirm the argument postulated above and was used to validate the regression analysis when fitting the velocity and density data to the macroscopic model discussed in Chapter Three. When comparing the Greenshields expression (Equation 3.13) to the estimated regression function (Equation 3.16), velocity was represented by v, free velocity v_f by a, and the ratio of free speed to congestion density by b.

Table 4.3 Density and speed data captured on NR1

Number of observation (n)	**Speed(km/h),** v_i	**Density(veh/km),** k_i	$v_i k_i$	k_i^2
1	82.3	20.95	1724	438.8083
2	61.0	34.03	2076	1158.231
3	55.7	2.30	128	5.287246
4	62.3	2.31	144	5.336841
5	71.0	23.21	1648	538.7629
6	70.3	28.61	2012	818.3396
7	71.7	27.40	1964	751.0149
8	59.7	28.36	1692	804.1502
9	46.7	48.00	2240	2304
10	45.7	39.42	1800	1553.626
11	42.7	48.84	2084	2385.712
12	66.0	20.67	1364	427.1111
13	65.7	22.66	1488	513.471
14	55.7	27.38	1524	749.5136
15	34.7	64.96	2252	4220.001
16	34.0	54.35	1848	2954.242
17	46.3	23.40	1084	547.358
18	32.0	35.00	1120	1225
19	11.3	162.35	1840	26358.48
20	5.5	181.82	1000	33057.85
21	22.7	112.94	2560	12755.71
22	33.0	109.33	3608	11953.78
23	19.7	170.85	3360	29188.85
24	11.0	236.36	2600	55867.77
25	20.0	148.00	2960	21904
26	44.7	70.84	3164	5017.714
27	63.7	29.84	1900	890.6006
28	69.7	36.86	2568	1358.751
29	74.7	44.57	3328	1986.612
30	75.3	28.30	2132	800.9401
31	75.0	43.84	3288	1921.946
32	60.0	49.53	2972	2453.551
33	58.0	56.76	3292	3221.541
34	53.0	61.13	3240	3737.131
35	56.7	64.09	3632	4108.056
36	66.7	44.40	2960	1971.36
37	69.0	50.61	3492	2561.24
38	80.7	37.19	3000	1383.102
39	78.0	32.31	2520	1043.787
40	50.0	57.84	2892	3345.466
41	60.0	40.80	2448	1664.64

Number of observation (n)	**Speed(km/h),** v_i	**Density(veh/km),** k_i	$v_i k_i$	$k_i^{\,2}$
42	80.7	39.17	3160	1534.567
43	78.7	37.12	2920	1377.794
44	46.0	69.65	3204	4851.425
45	42.3	68.03	2880	4628.284
46	33.0	67.88	2240	4607.53
47	34.0	60.12	2044	3614.131
48	21.7	132.92	2880	17668.54
49	28.0	89.00	2492	7921
50	15.0	138.67	2080	19228.44
51	8.0	170.00	1360	28900
52	42.0	59.05	2480	3486.621
53	42.3	68.03	2880	4628.284
54	33.0	67.88	2240	4607.53
55	34.0	60.12	2044	3614.131
56	21.7	132.92	2880	17668.54
57	28.0	89.00	2492	7921
58	15.0	138.67	2080	19228.44
59	8.0	170.00	1360	28900
60	42.0	59.05	2480	3486.621
Sum	$\sum_{i=1}^{60} v_i = 2814.8$	$\sum_{i=1}^{60} k_i = 4139.7$	$\sum_{i=1}^{60} v_i k_i = 139144$	$\sum_{i=1}^{60} k_j^{\,2} = 437825.7$

The coefficients a and b were obtained using the following parameters:

$$\sum_{i=1}^{60} v_i = 2814.8$$

$$\sum_{i=1}^{60} k_i = 4139.7$$

$$\sum_{i=1}^{60} v_i k_i = 139144$$

$$\sum_{i=1}^{60} k_j^{\;2} = 437825.7$$

The mean speed was given by $\frac{1}{60}\sum_{i=1}^{60} v_i = 46.9$

The mean densitywas given by $\frac{1}{60}\sum_{i=1}^{60} k_i = 69.0$

The coefficient b was calculated by using equation 3.18

$$b = \frac{(139144 - \frac{1}{60} * 4139.7 * 2814.8)}{437825.7 - \frac{1}{60} * 4139.7^2} = -0.361$$

The coefficient a was calculated by using equation 3.17

$$a = 46.9 + 0.36 * 69.0 = 71.74$$

Since $a = 71.74$ and $b = -0.361$, the linear equation was constructed using the founded coefficient *a* and *b*. Therefore $v = 71.74 - 0.361\ \mathrm{k}$, then $v_f = 71.87$ km/h

$v_f / k_j = 0.361$ and so $k_j = 199$ veh/km.

The maximum flow was obtained as $qmax = \frac{(71.87 * 199.3)}{4} = 3575.5$ veh/h

Using PCU factor of 1.4 ,the new maximum flow obtained was 5005.7 pc/h.In the estimated regression function, the velocity was represented by *v* in the Greenshields expression and density by *k*. The mean free velocity v_f was represented by *a*, and the value of the mean free velocity v_f divided by the jam density k_j was represented by *b*. Linear regression analysis was performed to determine the values of *a* and *b* in the estimated regression function. When entering the velocity and density data in Table 4.3

in the excel spreadsheet, the summary output was displayed in Table 4.4. Under the coefficient column, a constant represented by (intercept) was estimated in the regression function as 71. 87**.** A constant *b* was represented by (X variable1) in the same column, which was -0.361, resulting in a regression formula for finding velocity as a density function. The summary output is shown in Table 4.4.

Table 4.4 Validation of the macroscopic model

Regression Statistics				
Multiple R	0.838735265			
R Square	0.703476845			
Adjusted R Square	0.698364377			
Standard Error	12.03177108			
Observations	60			
	Coefficients	***Standard Error***	***t Stat***	***P-value***
Intercept	71.87289931	2.634423624	27.28221	8.85998E-35
X Variable 1	-0.361759702	0.030839732	-11.7303	6.04544E-17

The regression statistics in Table 4.5 show that the standard error was around 12.032, and the R square was 0.7. The data of density and speed were fitted the regression model; this meant that the sample distribution of the model was precisely efficient and accurate (Schober and Schwarte, 2018)

The standard error found shows that the velocity and density relation can be found with greater precision. A similar result was found in the research made by Atanasova *et. al.* (2017).

Comparing the result from the MFD (Figure 4.11) and regression analysis (Table 4.5) of the two parameters, the free speed(vf) and the ratio (vf/kj) had different values. Consequently, the maximum flow rate calculated was different. The two alternative top flow rates, 5005.6 pc/h and 4687.2 pc/h were different and the difference ratio was 0.067. The two results founded were greater than the capacity of 3600 pc/h provided by HCM 2010 volume 2 and resulted to traffic congestion.

4.4 Design Of Traffic Assessment Tool (TAT)

The key objective of the TAT was to provide convenience tools to strengthen the existing strategies of traffic management and control in Kigali city. It was also expected to improve the transport operation and mobility in Kigali city.

A general scheme of TAT consists of two parts. One part with five modules that acted and generated the functionalities of TAT. The modules were ANPR camera 1 and 2 and ANPR camera 3, Wi-Fi modules, a database module, and integrated systems.The second part was the Traffic Density Detection (TDD) that described the procedures and the steps for sending a message to the driver based on the real-time density calculation available

The tool was designed into a flowchart based on the functions of each module (Figure 4.12). The tool worked with three cameras; ANPR camera 1 and 2 that monitored the traffic data for inflow and outflow points of the global region of interest. While the ANPR camera three, located at the point of a possible road diversion, was used to randomly divert vehicles to minimize flow into the inflow point of the global region of interest. The system started counting cars by capture the plate number using the two cameras. It checked the traffic jams by calculating density on the road, which equaled the difference between the number of vehicles passed on two cameras divided by the distance between them.

The plate number would be sent to the database via the Wi-Fi module when the density was between the half jam density (kj/2) and jam density (kj). Whereas in contrast, they would still calculate density to determine the status of congestion. Once the system received the plate number, the next step was to check the car's driver and send the message based on the plate number captured. Once the plate number did not match any vehicle's registered driver, the TAT would connect with other integrated systems such as the Rwanda Revenue Authority (RRA) and Rwanda Utilities Regulatory Authority (RURA). If the car driver also was not found, the system left the plate number without any message. The tool sent the message to selected drivers based on the density calculated, which determined the congestion status. It provided alternative roads based on the density level available on streets, and then the driver chose the route (ADB, 2019). A detailed description of TAT its main parts are shown in Figure 4.12.

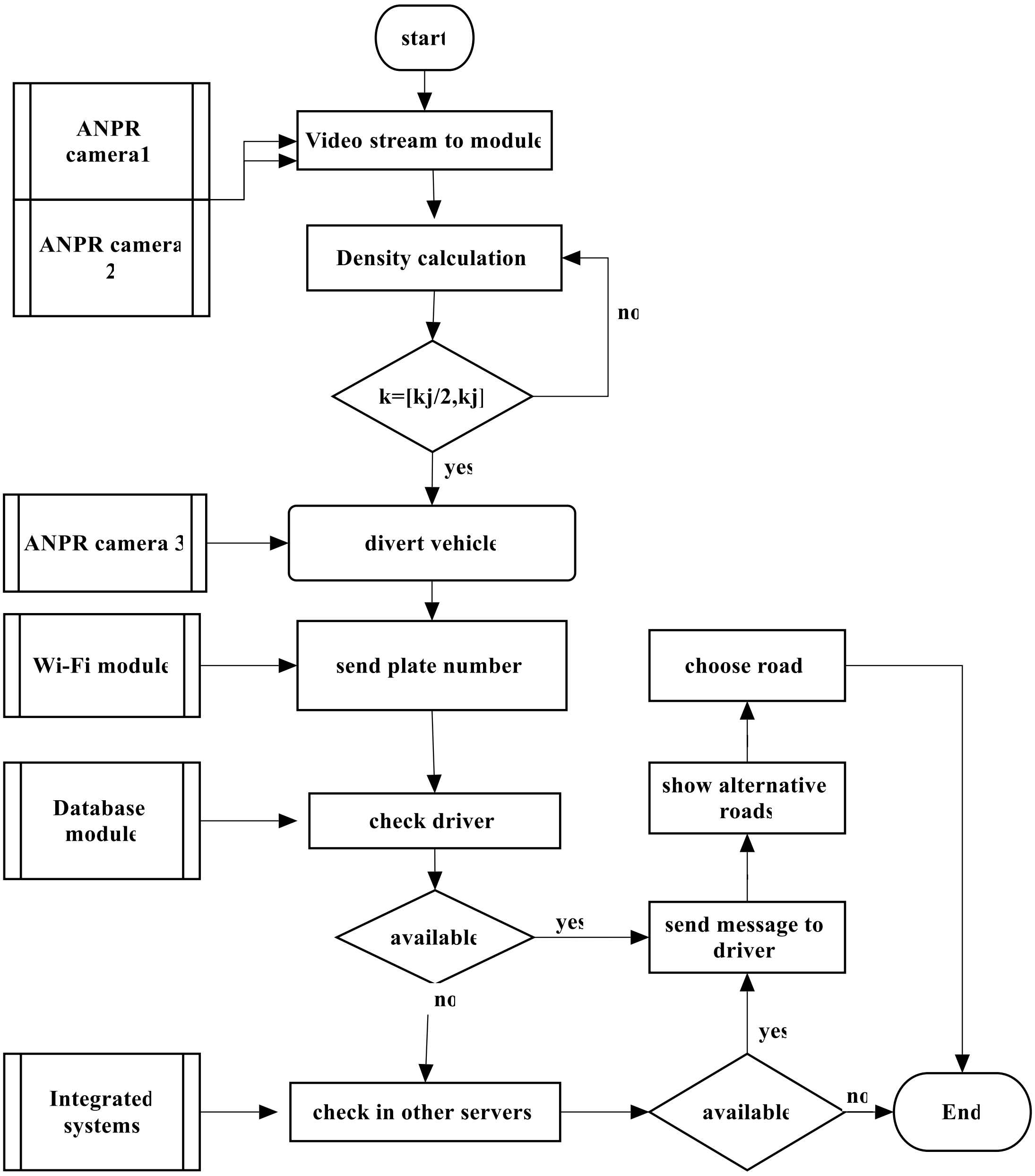

Figure 4.12 Flowchart of the TAT

It was shown that the combination of TAT with an ANPR camera could monitor the tasks of the complex situation of traffic compared to other methods. Due to the various techniques of the TAT, it could optimize traffic management and reduce traffic congestion with real-time information (Bommes *et. al.*, 2016).

A methodological was combining several data performed by defining the following three steps. The existing ANPR camera identifying the license plate of vehicles provided the number of vehicle counts in travel length at a given time measurement. The use of two cameras for calculating the traffic density in real-time was required for the tool. The help of density calculated on NR1 would be needed to design TAT in the real-time design of the current traffic state. The data from various vehicles like cars would be collected through installed ANPR cameras that produce data in a dynamic context (Ortúzar and Willumsen, 2011)..

Different ANPR cameras kept changing in terms of location, speed, orientation, and light. A car interacted with many external entities like pedestrians, roads, time, space, and other vehicles like buses, motorcycles, and trucks. The information gathered is valid for only one minute for cars to complete their trip. The one minute should be updated every time (Bhatia and Goyal, 2016). Once the data has been acquired, the storage system (database) receives them for processing activities. The data stored is indexed on every attribute so that the access information would be fast to better processing performance (Jun *et. al.,* 2015). The ANPR camera had two parts process unit that received the image from the capture unit that took a picture of the car moving at a specific roadway point. One or more capture units could be controlled simultaneously by the processing unit.

It was found that the ANPR camera can control four lanes in the same carriageway (Gupta *et. al.,* 2020). The system of ANPR camera uses infrared lighting to allow cameras taking the photo any time of a day. It consisted of five steps of plate recognition: capturing of vehicle image, preprocessing, extracting of the plate number, segmenting, and recognizing character. Once the plate number was collected, it was processed to pass to the central platform registered in the Database (DB). It was showed that the capturing method has a 90% extraction rate for 50 images taken (Lubna; *et. al.*, 2021).

4.4.1 Real-time congestion control using TAT

The design of TAT on NR1 and NR2 emphasized on-demand strategies of Kigali to reinforce ANPR cameras for speed limits and congestion location awareness. The basic concepts of the strategy to manage and control traffic were reducing traffic delays and increasing road safety.

The traffic control was summarized in the fundamental traffic flow diagram on NR1 and the designed TAT (Figure 4.13). When the traffic flow on road NR1 was approaching capacity at a maximum flow rate of 3348veh/h, and above capacity levels (maximum flow rate started to reduce steadily to turn to zero), the speed decreased. The density varied from 115veh/km to 230veh/km, resulting in movement stop-go with unstable and obstruction on-road services. When such a condition has occurred, the TAT stopped further interruption on NR1 by redirecting the driver to NR2 to control the traffic congestion on RN1.

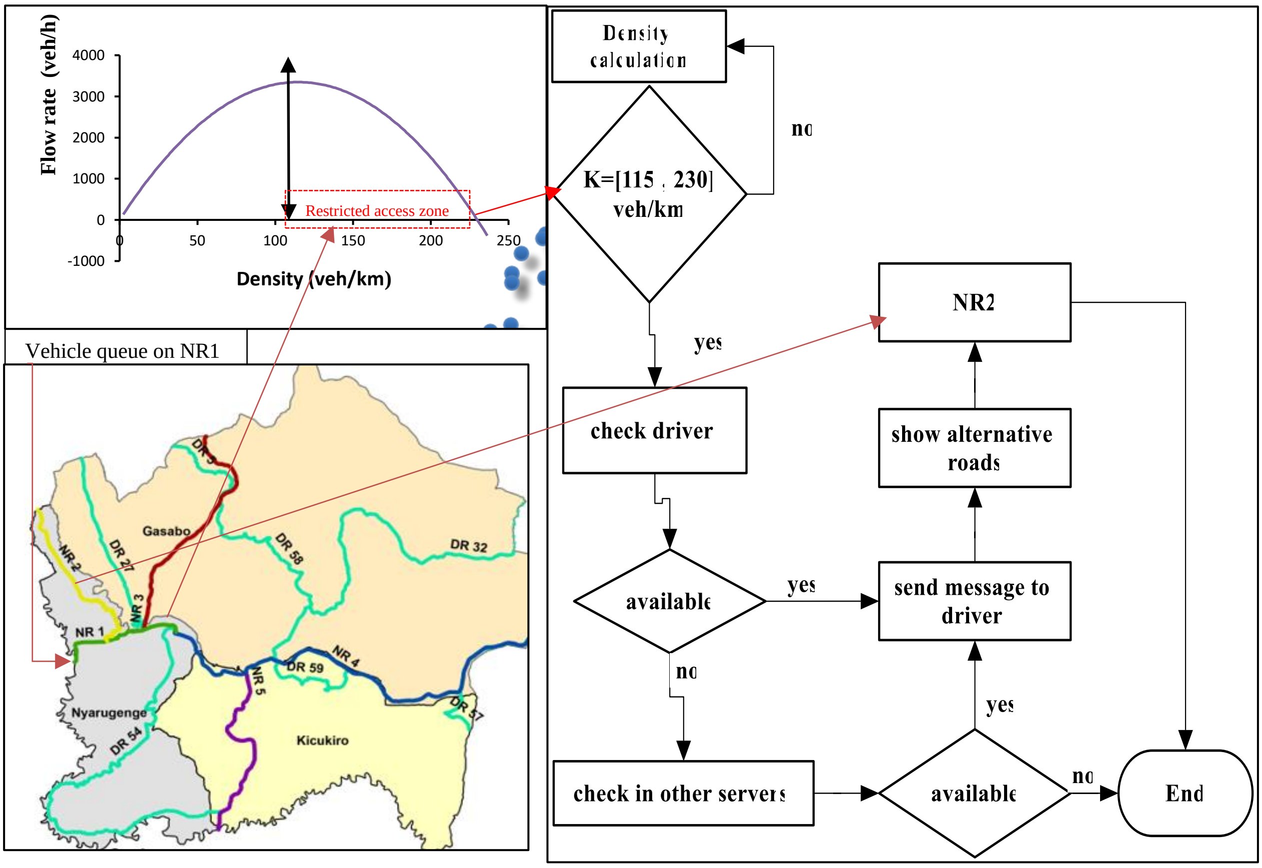

Figure 4.13 Traffic congestion control through re-routing technique

Harmonizing traffic volume was key to keeping the traffic flow stable, preventing the capacity drop, and interrupting further breakdown (Allström *et. al.,* 2017). According to figure 4.13, when the traffic flow on road NR1 was approaching capacity levels and above the capacity (restricted access zone), the road situation typically becomes unstable with velocity variation resulting in stop-and-go movement. When the capacity in such dangerous conditions tended to drop, it was recognized as a traffic jam phenomenon. The traffic volume reduction strategies could be performed by providing information about the congested periods and shifting the road users (drivers) to other roads available in their direction (Royani *et. al.,* 2010). The designed tool optimized traffic flow by sending variable messages of basic info directly to the car driver.

4.4.2 Prototype development of TAT

The TAT prototype was developed based on three components: object detection, Multiple Object Tracking, and implementation of a Decision Tree. Object detection was a process of identifying instances of a class in an image(Al-Sobky and Mousa, 2016).
In this study, the object class detected vehicles passing on NR4. The algorithms used a bounding box around the car to locate it within the image in the detection approach. The concept of Object Tracking was updating the position of a vehicle in subsequent image frames from a video stream using the centroid of the detected object as input. Each car and its centroid (boundary box) were continuously tracked by minimization of Euclidean distance. The object detection and tracking algorithms were then used to generate real-time data of flow (veh/h) and density (veh/km) by focusing on a Region of Interest(ROI) (J. Li *et. al.,* 2018).
The result became inputs for the decision tree and was served into the computational model developed in this research. Decision tree implementation was based on fuzzy logic attending to several cases predicted to occur in the region. The algorithm of vehicle detection, tracking, and traffic data generation is as follow:

Start of algorithm

```
# import the necessary packages/libraries

labelsPath = os.path.cwd/coco.name

LABELS = open(labelsPath)

COLORS = random(0, 255, size=(len(LABELS), 3))
```

```
weightsPath = os.path.cwd/yolov3.weights

configPath = os.path.cwd/yolov3.cfg

net = cv2.dnn.readNetFromDarknet(configPath, weightsPath)

ln = net.getLayerNames()

ln = [ln[i[0] - 1] for i in net.getUnconnectedOutLayers()]

vs = VideoCapture(input)

writer = None

(W, H) = (None, None)

ct = CentroidTracker(maxDisappeared=5)

trackers = []

Create dictionary for TrackableObjects

Red_alert_density range = (input range of density for congestion)

totalFrames = 0

totalDown_in = 0

totalDown_out = 0

frameCount = 0

Road_Length = (input calibrated road length between ROIs)

n_frames_skip = (input number)

df=new_pandas_dataframe(columns=["TotalCount_in","CummD_totalDown_in","TotalCount_out","CummD_totalDown_out","Density_Down"])

while True:

    (grabbed, frame) = vs.read()

    if not grabbed:

        break

    frame = (frame, width=1920)
```

```
rgb = Color(frame, COLOR_BGR2RGB)
if W is None or H is None:
    (H, W) = frame.shape[:2]
rects = []
if count "skip_frames" != n_frames_skip:
    status = "Detecting"
    trackers = []
    blob = dnn.blobFromImage
    net.setInput(blob)
    start = time.time()
    layerOutputs = net.forward(ln)
    end = time.time()
    boxes = []
    confidences = []
    classIDs = []
    for output in layerOutputs:
        for detection in output:
            scores = detection[5:]
            classID = max(scores)
            confidence = scores[classID]
            if confidence > "min_confidence":
                box = detection[0:4] * array([W, H, W, H])
                (centerX, centerY, width, height
                x = int(centerX - (width / 2))
```

```
                y = int(centerY - (height / 2))
                boxes.append([x, y, int(width), int(height)])
                confidences.append(float(confidence))
                classIDs.append(classID)
    # apply non-maxima suppression to suppress weak, overlapping
    # bounding boxes
    idxs = NMS(boxes, confidences, "confidence", "threshold")
    if len(idxs) > 0:
        for i in idxs.flatten():
            (x, y) = (boxes[i][0], boxes[i][1])
            (w, h) = (boxes[i][2], boxes[i][3])

            tracker = dlib.correlation_tracker()
            rect = dlib.rectangle(x, y, x+w, y+h)
            tracker.start_track(rgb, rect)
            trackers.append(tracker)
else:
    for tracker in trackers:
        status = "Tracking"
        tracker.update(rgb)
        pos = tracker.get_position()
        startX = int(pos.left())
        startY = int(pos.top())
        endX = int(pos.right())
```

```
        endY = int(pos.bottom())
        rects.append((startX, startY, endX, endY)
line1 ----> (frame, (0, H // 3), (W, H // 3), (0, 255, 255), 2)
line2 ----> (frame, (0, H // 2), (W, H // 2), (0, 255, 255), 2)
objects = ct.update(rects)
for (objectID, centroid) in objects.items():
    to = trackableObjects.get(objectID, None)
    Out = trackableObjects2.get(objectID, None)
    if to is None:
        to = TrackableObject(objectID, centroid)
    else:
        y = [c[1] for c in to.centroids]
        direction = centroid[1] - np.mean(y)
        to.centroids.append(centroid)
        if not to.counted:
            if direction < 0 and centroid[1] < line1:
                totalUp_out += 1
                to.counted = True
            elif direction > 0 and centroid[1] > line1:
                totalDown_in += 1
                to.counted = True
    trackableObjects[objectID] = to
     if Out is None:
        Out = TrackableObject2(objectID, centroid)
```

```
        else:
            y = [c[1] for c in Out.centroids]
            direction = centroid[1] - np.mean(y)
            Out.centroids.append(centroid)
            if not Out.counted:
                if direction < 0 and centroid[1] < line2:
                    totalUp_in += 1
                    Out.counted = True
                elif direction > 0 and centroid[1] > line2:
                    totalDown_out += 1
                    Out.counted = True
        trackableObjects2[objectID] = Out
        text = "ID {}".format(objectID)
        putText---->(frame, text, (centroid[0] - 10, centroid[1] - 10), FONT_HERSHEY_SIMPLEX, 0.5, (0, 255, 0), 2)
        circle---->(frame, (centroid[0], centroid[1]), 4, (0, 255, 0), -1)
    info = [("Up", totalUp), ("Down", totalDown), ("Status", status)
    for (i, (k, v)) in enumerate(info):
        text = "{}: {}".format(k, v)
        putText---->(frame, text, (10, H - ((i * 20) + 20)),  FONT_HERSHEY_SIMPLEX, 0.6, (0, 0, 255), 2)
    #calculate flow rate and display value in frame
    if frameCount % frames_PS == 0:
        df.loc[z] = [totalDown_in, (totalDown_in - df.iloc[(z-1, 0)]), totalDown_out, (totalDown_out - df.iloc[(z-1, 2)]), (totalDown_in - totalDown_out)]
```

```
print (df)
cv2.putText(frame, "Flow_Rate_in (Veh/h): " + str(df.iloc[(z, 1)]), (10, H - ((i * 20) + 40)), cv2.FONT_HERSHEY_SIMPLEX, 0.6, (0, 0, 255), 2)
cv2.putText(frame, "Flow_Rate_out (Veh/h): " + str(df.iloc[(z, 3)]), (W // 2, H - ((i * 20) + 40)), cv2.FONT_HERSHEY_SIMPLEX, 0.6, (0, 0, 255), 2)
cv2.putText(frame, "Density_Down (Veh/km): " + str(df.iloc[(z, 4)]), (W // 2, H // 2 - ((i * 20) + 40)), cv2.FONT_HERSHEY_SIMPLEX, 0.6, (0, 0, 255), 2)
mem_flow_rate_down_in = df.iloc[(z, 1)]
mem_flow_rate_down_out = df.iloc[(z, 3)]
mem_Density_down = df.iloc[(z, 4)]
z +=1
#show a plot of flow against density
plt.scatter(df["CummD_totalDown_out"],df["Density_Down"], label = "My Test")
plt.title("Flow Curve")
plt.xlabel("Density(Veh/km)")
plt.ylabel("Flow(Veh/h)")
plt.draw()
plt.pause(0.001)
#implement traffic diversion script if conditions are met
if df.iloc[(z,4)] == Red_alert_density range:
    sys.execute traffic_diversion.py
if writer is None:
    fourcc = VideoWriter_fourcc(*"MJPG")
    writer = VideoWriter(cwd/output, fourcc, 30, (frame.shape[1], frame.shape[0]), True)
writer.write(frame)
```

```
    imageshow---->("Frame", frame)

    key = waitKey(1) and 0xFF

    if key == ord("q"):

        break

    totalFrames += 1

    fps.update()

#export data for video stream to storage in csv format

df.to_csv("Flow_Data.csv")

writer.release()

vs.release()

destroyAllWindows()
```

End of algorithm

The TAT was developed to overcome the drawbacks of the exiting ANPR cameras installed in Kigali city, enhancing them for better traffic control and management. The number of vehicles counted was represented in traffic density calculated in the YORO model. The model was refreshingly simple, trained on the full image, and optimized detection performance. This method was highly efficient and fast to process images' data (Redmon *et. al.*, 2016).

4.4.3 Performance evaluation and validation of TAT

The source code for the TAT object recognition had a couple of modifications to allow for the video recording conditions used. The proposed TAT was to have intelligent cameras recording and upload their data to a central network and implement the fuzzy logic decision tree based on the observed traffic conditions (Wageningen-kessels, 2013).The NR4 road traffic analysis was achieved by concatenating all video streams before running through the developed algorithm. The MFD between flow and density was analysed to give a better perception of traffic conditions. The TAT vehicle detection and tracking algorithms generated real-time flow and density data for NR4. Using Inflow count and Outflow Count, the real-time flow and critical density generated by

TAT were 3492veh/h (4888.8pc/h) and (106veh/km), respectively.The mean accuracy of vehicle detection and tracking algorithms of TAT for NR4 was 92.7%. The highest coefficient of correlation ($R^2 = 0.2787$) between flow and density was obtained with MFD (Figure 4-14) .

The regression model between flow and density generated the coefficient of correlation ($R^2 = 0.0276$). The regression statistics on NR4 is shown on Table 4.5 .

The coefficient of correlation found with MFD is greater than that generated in regression model which exhibited a better accuracy of MFD than the regression model. This high accuracy found on NR4 road reflected the highest precision of the ANPR Cameras installed with a higher resolution of vehicle detection. The result showed that the TAT allows for quick real-time information for optimizing traffic management (Ortúzar and Willumsen, 2011).

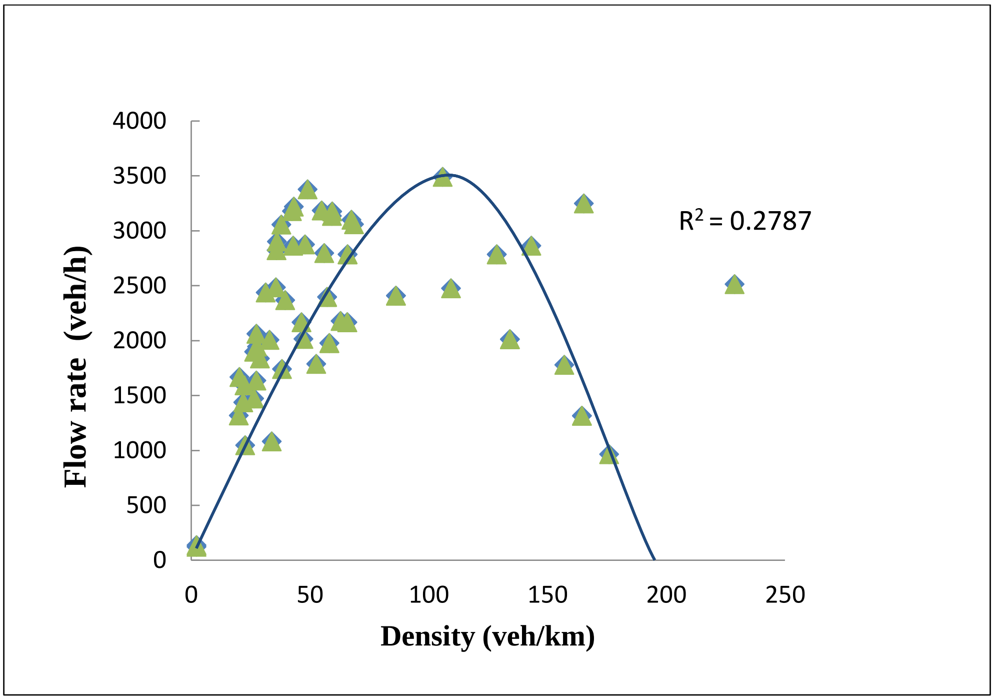

Figure 4.14: MFD of flow -density relationship on NR4

Table 4.5: Regression model validation of TAT vehicle detection on NR4

Regression Statistics				
Multiple R	0.16627718			
R Square	0.0276481			
Adjusted R Square	0.01088341			
Standard Error	752.79734			
Observations	60			
	df	*SS*	*MS*	*F*
Regression	1	934600.4	934600.4	1.649187
Residual	58	32868822	566703.8	
Total	59	33803423		
	Coefficients	*Standard Error*	*t Stat*	*P-value*
Intercept	2067.80965	164.7469	12.55144	3.56E-18
X Variable 1	2.56027279	1.993661	1.284207	0.204176

Where **df** is Degree of Freedom**, SS** is Sum of Squares**, F:** the ratio of two variance**s MS:** Mean Squares

CHAPTER FIVE

CONCLUSION AND RECOMMENDATIONS

5.1 Conclusion

The traffic jam is a substantial challenge in many cities, including Kigali city, Rwanda. Traffic congestion is associated with augmented fuel wastage, air pollution, financial losses, delays, and risk of accidents due to poor traffic control management. Traffic management efforts such as road widening, speed limit devices, and deployment of control measures to mitigate traffic congestion have not yielded expected results . This study, therefore, developed a real-time road traffic assessment tool for Kigali City in Rwanda.

Purposive interviews were conducted with Kigali road management officers in charge of the national roads. Preliminary survey on national roads NR1, NR2, NR3, NR4 and NR5 were carried out. The analysis of the traffic flow on selected national roads, NR1 and NR2, was performed. Traffic volume data were captured on NR1 and NR2 between 5.00 a.m. and 8.00 p.m. for 30 days between November 2019 and December 2019 as specified in the Highway Capacity Manual (HCM). Traffic patterns on NR1 and NR2 were analyzed using regression models and Macroscopic Fundamental Diagram (MFD). A Traffic Assessment Tool (TAT) for real-time traffic flow analysis based on MFD and regression model was developed. The algorithm for real-time vehicle detection in TAT was performed using Python programming. Data to validate the TAT was captured on national road NR4. The data were analyzed using descriptive statistics and a t-test at $\alpha_{0.05}$.

The existing roadway, traffic, and control conditions of the five national roads in Kigali city were found acceptable in accordance with Rwanda Transport Development Agency Manual. The interview results showed that the strategy of extending roads was unsatisfactory to mitigate congestion at 50% of responses. It was confirmed by the 78% rate of the transport planners who responded that the congestion occurred at the highest level in Kigali city.

Average daily traffic on NR1, NR2, NR3, NR4 and NR5, with the same design speed of 60 km/h, were 1030, 914, 867,780 and 885, respectively. Free flow traffic only occurred on NR2, with average flow rate of 645 veh/h. A clear transition between two flow regimes (free and congested) existed on NR1, with average flow rate of 1120 veh/h. Analysis of traffic on NR1 at free flow, yielded maximum flow of 3576 veh/h (5005.7 pc/h) (regression) and 3348 veh/h (4687.2pc/h) (MFD). These were greater than HCM recommended capacity of 3600 pc /h for two-lane roadways in a direction resulted in congestion. The critical density was 115 veh/km, which increased to a jam density of 230 veh/km in the congested regime. The mean accuracy of vehicle detection and tracking algorithms of TAT for NR4 was 92.7%. The real-time flow and critical density generated by TAT were 3492(4888.8 pc/h) veh/h and 106 veh/km, respectively. The highest coefficient of correlation ($R^2 = 0.2787$) between flow and density was obtained with MFD, which exhibited a better accuracy than the regression model. There was no significant difference between the flow parameters obtained from the field data and TAT.

The traffic Assessment tool developed provides real-time traffic analysis which in combination with existing controlled system could be used to improve traffic flow on the national roads in Kigali city.

5.2 Recommendations

This study proposed further research to extend similar research to all roads of Rwanda to mitigate traffic congestion based to flow- density relationship. It should be better to provide a computerized system of traffic flow data in Rwanda, especially in Kigali, to facilitate research.

5.3 Contributions To Knowledge

The findings contributed to fill the gap in the academic literature of transport systems through a paper published in the recognized journal. This research analyzed the traffic flow of selected roads in Kigali city by developing TAT, an advanced tool to mitigate the congestion. TAT vehicle detection provided the traffic situation to the driver, which is essential for traffic management and helpful to other transport stakeholders and Governmental Organizations.

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APPENDIX

A. QUESTIONNAIRE

INTERVIEW GUIDE

I thank you for your kind contribution to the interview of all about academics.

I am researching "**DEVELOPMENT OF A REAL-TIME ROAD TRAFFIC ASSESSMENT TOOL FOR KIGALI CITY, RWANDA"** at the University of Ibadan, which requires a deep analysis of road traffic flow. I kindly request your essential and helpful participation to this interview for realizing this study.This questionnaire is required strictly for research purposes. The interview will take between 20-30 minutes.

I. General information of the respondent

Organization:

Department:

Position:

For how long:

Responsibilities:

………………………………………………………………………………………
……

II.Traffic analysis process, decision-making problems

Questions	A	B	C	D	E
1. What are the roads which are the most congested in Kigali city?	**NR1**	**NR2**	**NR3**	**NR4**	**NR5**
2. How do you critique the problems caused by traffic congestion in Kigali city?	**High**	**normal**	**poor**	**Very poor**	
3. What are the solutions available to solve congestion problems in Kigali city?	**Extending roads**	**Public transport**	**Traffic systems**	**Traffic modeling**	
4. Did the ANPR cameras installed in Kigali city give effective solutions to traffic congestion?	**Very useful**	**useful**	**Not useful**	**Uninterested**	
5. How do you expect the solutions' effectiveness to mitigate congestion problems in Kigali city?	**Very effective**	**Effective**	**ineffective**	**Indifferent**	

B. TRAFFIC COUNT DATA

Traffic data surveyed on NR2

HOURS	*MOTORCYCLE*	*CAR*	*MINIBUS*	*BUS*	*TRUCK*	TOTAL
5:00-5:15 a.m	10	40	20	76	20	**166**
5:15-5:30 a.m	30	56	30	50	12	**178**
5:30-5:45 a.m	100	80	80	30	21	**311**
5:45-6:00 a.m	100	111	76	67	17	**371**
6:00-6:15 a.m	230	90	56	75	19	**370**
6:15-6:30 a.m	160	78	64	42	13	**357**
6:30-6:45 a.m	200	80	80	23	26	**409**
6:45-7:00 a.m	176	59	87	35	16	**373**
7:00-7:15 a.m	186	63	92	20	23	**384**
7:15-7:30 a.m	190	69	95	45	30	**429**
7:30-7:45 a.m	180	77	80	30	33	**400**
7:45-8:00 a.m	230	50	70	30	30	**310**
8:00-8:15 a.m	170	63	90	10	20	**353**
8:15-8:30 a.m	30	45	40	30	10	**155**
8:30-8:45 a.m	20	50	20	37	3	**230**
8:45-9:00 a.m	40	53	50	20	3	**166**
9:00-9:15 a.m	30	10	30	54	10	**134**
9:15-9:30 a.m	20	31	30	56	20	**157**
9:30-9:45 a.m	40	43	10	30	0	**123**
9:45-10:00 a.m	30	32	30	80	10	182
10:00-10:15 a.m	20	50	10	20	10	110
10:15-10:30 a.m	20	67	30	30	20	167
10:30-10:45 a.m	20	30	30	70	10	160
10:45-11:00 a.m	10	60	10	60	0	140
11:00-11:15 a.m	20	50	0	20	3	93
11:15-11:30 a.m	10	77	10	40	10	147
11:30-11:45 a.m	10	65	30	70	0	175
11:45-12:00 a.m	20	45	20	40	0	125
12:00-12:15 a.m	4	50	70	60	20	204
12:15-12:30 a.m	10	82	0	70	0	162
12:30-12:45 a.m	20	20	20	10	0	70
12:45-1:00 a.m	100	90	110	80	10	390
1:00-1:15 p.m	120	121	110	230	30	511
1:15-1:30 p.m	70	75	90	110	20	365
1:30-1:45 p.m	60	78	90	80	10	318
1:45-2:00 p.m	30	50	70	110	30	290
2:00-2:15 p.m	70	57	90	82	20	319
2:15-2:30 p.m	5	38	50	71	10	174
2:30-2:45 p.m	10	10	30	43	20	113
2:45-3:00 p.m	15	71	30	65	0	181
3:00-3:15 p.m	14	35	30	79	0	158

3:15-3:30 p.m	23	61	20	98	0	202
3:30-3:45 p.m	31	30	40	73	1	175
3:45-3:00 p.m	20	69	40	50	0	179
4:00-4:15 p.m	10	43	50	78	30	211
4:15-4:30 p.m	10	54	35	15	36	150
4:30-4:45 p.m	10	78	60	60	20	228
4:45-4:00 p.m	40	151	10	20	10	231
5:00-5:15 p.m	230	67	70	60	60	387
5:15-5:30 p.m	102	123	140	75	30	470
5:30-5:45p.m	120	167	192	118	40	637
5:45-6:00 p.m	101	80	87	76	14	358
6:00-6:15 p.m	120	121	120	152	20	533
6:15-6:30 p.m	230	113	140	131	10	524
6:30-6:45 p.m	109	94	110	90	33	436
6:45-7:00 p.m	167	19	80	122	13	401
7:00-7:15 p.m	110	115	121	123	22	491
7:15-7:30 p.m	230	125	143	131	11	540
7:30-7:45 p.m	109	62	112	99	31	413
7:45-8:00 p.m	177	13	83	124	12	409
TOTAL	4279	3986	3713	3875	952	16805

Traffic survey data on NR1

HOURS	*MOTORCYCLE*	*CAR*	*MINIBUS*	*BUS*	*TRUCK*	TOTAL
5:00-5:15 a.m	40	70	40	50	17	**217**
5:15-5:30 a.m	91	40	50	70	20	**271**
5:30-5:45 a.m	96	30	60	80	33	**299**
5:45-6:00 a.m	89	10	10	30	10	**149**
6:00-6:15 a.m	87	70	40	50	12	**259**
6:15-6:30 a.m	95	40	50	70	20	**275**
6:30-6:45 a.m	97	30	60	60	30	**277**
6:45-7:00 a.m	84	10	10	30	13	**147**
7:00-7:15 a.m	83	10	40	95	10	**238**
7:15-7:30 a.m	98	50	20	78	20	**266**
7:30-7:45 a.m	112	40	30	87	15	**284**
7:45-8:00 a.m	123	50	10	94	10	**287**
8:00-8:15 a.m	132	30	50	89	0	**301**
8:15-8:30 a.m	40	70	40	87	1	**238**
8:30-8:45 a.m	60	80	40	90	0	**270**
8:45-9:00 a.m	40	50	20	20	2	**132**
9:00-9:15 a.m	30	20	10	34	12	**106**
9:15-9:30 a.m	24	25	34	56	20	**159**
9:30-9:45 a.m	13	10	10	40	10	**83**
9:45-10:00 a.m	20	10	20	46	9	**105**
10:00-10:15 a.m	20	40	20	40	10	**230**
10:15-10:30 a.m	0	35	40	24	0	**99**
10:30-10:45 a.m	10	45	30	17	7	**109**
10:45-11:00 a.m	40	55	20	37	8	**160**
11:00-11:15 a.m	20	51	10	23	13	**117**
11:15-11:30 a.m	30	65	20	32	10	**157**
11:30-11:45 a.m	40	20	10	36	0	**106**
11:45-12:00 a.m	20	23	15	24	4	**86**
12:00-12:15 a.m	16	34	52	16	14	**132**
12:15-12:30 a.m	35	51	27	45	3	**161**
12:30-12:45 a.m	36	24	34	52	2	**148**
12:45-1:00 a.m	65	73	45	56	10	**249**
1:00-1:15 p.m	57	71	27	48	13	**216**
1:15-1:30 p.m	28	47	34	53	10	**172**
1:30-1:45 p.m	30	51	37	49	12	**179**
1:45-2:00 p.m	10	30	0	78	14	**132**
2:00-2:15 p.m	32	40	20	67	16	**175**
2:15-2:30 p.m	20	26	50	23	30	**149**
2:30-2:45 p.m	31	28	40	31	10	**140**
2:45-3:00 p.m	24	60	70	41	10	**205**
3:00-3:15 p.m	30	30	10	32	0	**102**
3:15-3:30 p.m	20	30	20	34	2	**106**

3:30-3:45 p.m	30	20	50	45	10	**155**
3:45-3:00 p.m	30	47	50	54	1	**182**
4:00-4:15 p.m	12	30	40	37	20	**139**
4:15-4:30 p.m	20	10	30	10	3	**73**
4:30-4:45 p.m	20	60	30	45	10	**165**
4:45-4:00 p.m	32	70	10	20	10	**142**
5:00-5:15 p.m	30	80	30	70	50	**260**
5:15-5:30 p.m	50	70	10	30	20	**180**
5:30-5:45p.m	60	40	10	62	5	**177**
5:45-6:00 p.m	230	60	40	70	26	**326**
6:00-6:15 p.m	40	70	40	50	10	**210**
6:15-6:30 p.m	110	40	50	70	23	**293**
6:30-6:45 p.m	120	30	60	67	30	**307**
6:45-7:00 p.m	98	10	10	30	10	**158**
7:00-7:15 p.m	112	70	40	43	13	**278**
7:15-7:30 p.m	110	40	50	47	20	**267**
7:30-7:45 p.m	120	30	60	37	35	**282**
7:45-8:00 p.m	139	10	10	35	12	**206**
Total	**3331**	**2461**	**1895**	**2936**	**770**	**11393**

Source: Author ,2021

NATIONAL ROAD (NR2)

Time interval(min)	speed(km/h)	volume(vehicles)	flow rate(veh/h)	Density(veh/km)
15	20.0	420	1680	84.00
15	30.0	550	2200	73.33
15	20.0	709	2836	141.80
15	10.0	370	1480	148.00
15	74.7	123	492	6.59
15	15.0	258	1032	68.80
15	75.0	214	856	11.41
15	60.0	183	732	12.20
15	46.3	136	544	11.74
15	32.0	294	1176	36.75
15	11.3	180	720	63.53
15	10.7	172	688	64.50
15	22.7	98	392	17.29
15	33.0	234	936	28.36
15	19.7	276	1104	56.14
15	11.0	245	980	89.09
15	20.0	243	972	48.60
15	14.0	230	920	65.71
15	63.7	123	492	7.73
15	69.7	215	860	12.34
15	58.0	205	820	14.14
15	53.0	211	844	15.92
15	56.7	164	656	11.58
15	66.7	192	768	11.52
15	60.0	215	860	14.33
15	20.0	247	988	49.40
15	28.0	234	936	33.43
15	40.0	220	880	22.00
15	30.0	450	1800	60.00
15	20.0	405	1620	81.00
15	60.0	674	2696	44.93
15	35.0	704	2816	80.46
15	32.0	405	1620	50.63
15	30.0	604	2416	80.53
15	25.0	607	2428	97.12
15	15.0	501	2004	133.60
15	10.0	391	1564	156.40
15	20.0	412	1648	82.40
15	20.0	380	1520	76.00
15	30.0	564	2256	75.20
15	69.7	320	1280	18.37
15	12.0	582	2328	194.00

15	72.3	302	1208	16.70
15	23.0	788	3152	137.04
15	74.0	325	2300	17.57
15	20.0	415	1660	83.00
15	80.3	351	1404	17.48
15	30.0	567	2268	75.60
15	74.7	292	1168	15.64
15	20.0	806	3224	161.20
15	57.7	288	1152	19.98
15	23.0	778	3112	135.30
15	45.7	323	1292	28.29
15	47.7	312	1248	26.18
15	40.7	272	1088	26.75
15	66.0	202	808	12.24
15	65.7	185	740	11.27
15	55.7	233	932	16.74
15	34.7	167	668	19.27
15	34.0	225	900	26.47

NATIONAL ROAD (NR1)				
Time(min)	speed(km/h)	volume(vehicles)	flow rate(veh/h)	Density(veh/km)
15	82.3	431	1724	20.95
15	61.0	519	2076	34.03
15	55.7	32	128	2.30
15	62.3	36	144	2.31
15	71.0	412	1648	23.21
15	70.3	503	2012	28.61
15	71.7	491	1964	27.40
15	59.7	423	1692	28.36
15	46.7	560	2240	48.00
15	45.7	450	1800	39.42
15	42.7	521	2084	48.84
15	66.0	341	1364	20.67
15	65.7	372	1488	22.66
15	55.7	381	1524	27.38
15	34.7	563	2252	64.96
15	34.0	462	1848	54.35
15	46.3	271	1084	23.40
15	32.0	280	1120	35.00
15	11.3	460	1840	162.35
15	5.5	250	1000	181.82
15	22.7	640	2560	112.94
15	33.0	902	3608	109.33
15	19.7	840	3360	170.85
15	11.0	650	2600	236.36
15	20.0	740	2960	148.00
15	44.7	791	3164	70.84
15	63.7	475	1900	29.84
15	69.7	642	2568	36.86
15	74.7	832	3328	44.57
15	75.3	533	2132	28.30
15	75.0	822	3288	43.84
15	60.0	743	2972	49.53
15	58.0	823	3292	56.76
15	53.0	810	3240	61.13
15	56.7	908	3632	64.09
15	66.7	740	2960	44.40
15	69.0	873	3492	50.61
15	80.7	750	3000	37.19
15	78.0	630	2520	32.31
15	50.0	723	2892	57.84
15	60.0	612	2448	40.80
15	80.7	790	3160	39.17

15	78.7	730	2920	37.12
15	46.0	801	3204	69.65
15	42.3	720	2880	68.03
15	33.0	560	2240	67.88
15	34.0	511	2044	60.12
15	21.7	720	2880	132.92
15	28.0	623	2492	89.00
15	15.0	520	2080	138.67
15	8.0	340	1360	170.00
15	42.0	620	2480	59.05
15	42.3	720	2880	68.03
15	33.0	560	2240	67.88
15	34.0	511	2044	60.12
15	21.7	720	2880	132.92
15	28.0	623	2492	89.00
15	15.0	520	2080	138.67
15	8.0	340	1360	170.00
15	42.0	620	2480	59.05

Source: Author ,2021