EFFECT OF RAINFALL ON FUNCTIONAL SERVICE QUALITY DETERIORATION OF DARK ROADWAYS AND ITS IMPLICATION FOR STOPPING SIGHT DISTANCE

By

Opeyemi Oluyemisi MAKINDE
Student No: 216073398

Submitted in fulfilment of the academic requirements for the degree of Doctor of Philosophy in Civil Engineering

College of Agriculture, Engineering and Science,
University of KwaZulu-Natal,
Howard College Campus, Durban.

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Supervisor: Prof. Johnnie Ben-Edigbe

PREFACE

The research contained in this thesis was completed by the candidate while based in the Department of Civil Engineering, School of the College of Agriculture, Engineering and Science, University of KwaZulu-Natal, Howard Campus, Durban, South Africa.

The contents of this work have not been submitted in any form to another university and, except where the work of others is acknowledged in the text, the results reported are due to investigations by the candidate.

Signed: Prof. Johnnie Ben-Edigbe
Date:

DECLARATION 1: PLAGIARISM

I, **Opeyemi Oluyemisi MAKINDE** declare as follows:

(i) the research reported in this dissertation, except where otherwise indicated or acknowledged, is my original work

(ii) this dissertation has not been submitted in full or in part for any degree or examination to any other university;

(iii) this dissertation does not contain other persons' data, pictures, graphs or other information, unless specifically acknowledged as being sourced from other persons;

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a. their words have been re-written, but the general information attributed to them has been referenced;

b. where their exact words have been used, their writing has been placed inside quotation marks, and referenced;

(v) where I have used material for which publications followed, I have indicated in detail my role in the work;

(vi) this dissertation is primarily a collection of material, prepared by me, published as journal articles or presented as a poster and oral presentations at conferences. In some cases, additional material has been included;

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Signed: Opeyemi Oluyemisi Makinde

Date: September 2019.

DECLARATION 2: PUBLICATIONS AND TRAINING

Details of publications that form part and/or include research presented in this thesis.

Publications:

1. Makinde, O. O. and Ben-Edigbe, J. (2019). Effect of Night-time Rainfall on Traffic Stream Characteristic of roads without light. The Open Transportation Journal, 13: pg 84-92, https://benthamopen.com/FULLTEXT/TOTJ-13-84
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2. Makinde, O. O. and Ben-Edigbe, J. (2019). Night-Time Rainfall Effect on Road Service and Travel Time Loss: A Case Study of Roadway Without Light. International Journal of Applied Engineering Research, 14(11), pg 2773-2781 https://www.ripublication.com/ijaer19/ijaerv14n11_32.pdf
3. Ben-Edigbe, J. and Makinde, O. O. (2020). Effect of Night Rainfall on Stopping Sight Distance of Dark Roadways. The Open Transportation Journal, 14:pg 32-37
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Conferences:

1. Makinde, O. O. & Ben-Edigbe, J (2018). Effects of Rainy Darkness Intensity at Two-Lane Highway on Travel Time Differentials. Paper presented at Canadian Society for Engineering Annual Conference, Fredericton, Canada. June 13th – 16th (Presented by Makinde, O. O.)
2. Makinde, O. O. & Ben-Edigbe, J. (2019). Effect of Night-Time Rain on Travel Speed at Two-Lane Highway without Lights. Poster presentation during World Conference on Transport Research (WCTR), Mumbai, India. May 26th – 31st. (Presented by Makinde, O. O.)

Training:

1. 26th International Course on Transport Planning and Traffic Safety held at Indian Institute of Technology, Delhi, India. December 1st – 8th, 2016.

The publications and conference papers presented are based on data collected from the selected study sites in Akure, Ondo State of Nigeria. The empirical data collected were used for the analysis and report presented in all the papers. Paper publication 1 reported the effect of rainy night-time conditions on traffic characteristics of dark roadways while paper publication 2 reported the assessment of road service and travel time loss based on the traffic characteristics earlier investigated in paper 1. Conference paper 1 described the variances in travel time due to the effect of night-time conditions while conference paper 2 highlighted the effect of night-time rain on travel speed.

Signed: Opeyemi Oluyemisi Makinde

Date: September 2019.

DEDICATION

This thesis is dedicated to

My God for His benevolence and love during the programme

and

My family:

Engr Ayodele Stephen Makinde (Husband)
Oluwatofunmi Charles Makinde (D-Boy)
Oluwatokemi Esther Makinde (D-Girl)

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ABSTRACT

Driving in the rain at night is challenging and more so if the roadway has no light. This study aims to ascertain whether rainy dark roadways would have significant influence on functional service quality reduction, and also the associated stopping sight distance implications for road users. Dark roadways are prevalent in Nigeria mainly because of poor energy management and the absence of long term sustained-energy strategic plans. The objectives are to determine the functional service quality in the presence of rainy dark roadways and compare with that taken on dry dark roadways. To that effect a rainy dark roadway impact study was carried out at four (4) selected sites in Nigeria for a period of eight (8) weeks. Based on the circumstances prevalent at the time of the survey, the study assumed that density was a result of speed and flow hence not directly affected by rainfall. This implies that functional service quality was fully the result of speed and travel time changes. Functional service quality describes the assessment of service delivery of roadways based on both road provider (travel speed) and user (travel time) perceptions. Vehicle types, volumes, speeds and rainfall were collected continuously at each surveyed road section for eight weeks and the results analysed. Traffic volume was converted into flow using modified passenger car equivalents values. The results of the analysis show reduction in travel speed with ensuing increase in travel time. Results show that the average travel time increased by 27.1 percent on dark roadways due to night rainfall. Results show that the average travel speed decreased by 18.7 percent on dark roadways due to night rainfall. The results from the analysis were used to establish the stopping sight distance implications of rainy dark roadways for motorists. Results show that on dark roadways the average stopping sight distance (SSD) increased by 25.8 percent due to rainy night. Results from the predicted travel time loss confirm the established evidence that travel time is a significant guide for measuring road effectiveness. Finally, since there is the potential to improve functional service quality output based on efficient and appropriate energy on one hand; effective management of resources on the other, the study concluded that in the presence of rainfall, dark roadways have a significant impact on the functional quality of service and stopping sight distance.

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LIST OF ABBREVIATIONS USED

AASHTO	American Association of State Highways Transportation Officials
ADT	Annual daily traffic
AMS	American Meteorological Society
ANOVA	Analysis of Variance
ARX	Modification of AustRoads94
ATC	Automatic Traffic Counter
AVI	Automatic vehicle identification
AVL	Automatic vehicle location
BD	Braking Distance
CMS	Congestion management strategies
DN	Dry night
DD	Dry Daylight
FMWH	Federal Ministry of Work and Housing
FSQ	Functional Service Quality
GPS	Global Positioning Systems
HCM	Highway Capacity Manual
HR	Heavy rain
HV	Heavy vehicle
LOS	Level of Service
LR	Light rain
LV	Light vehicle
MOE	Measure of effectiveness
MPO	Metropolitan planning organization
MR	Moderate rain
MV	Medium vehicle
MWH	Ministry of Works and Housing
NBRRI	Nigerian Building and Road Research Institute
NITT	Nigerian Institute of Transport Technology

NIMET	Nigerian Meteorological Agency
QOS	Quality of Service
PC	Passenger car
PCE	Passenger car equivalent
PCU	Passenger car unit
R^2	Coefficient of determination
RD	Reaction Distance
RG	Rain gauge
RN	Rainy night
RSU	Roadside Unit
SANRAL	South African National Roads Agency Limited
SNNMI	Spanish National Meteorological Institute
SQ	Service Quality
SS	Study site
SSD	Stopping Sight Distance
TRB	Transport Research Board
US-BPR	United State Bureau of Public Road
VHR	Very heavy rain
WASCAL-FUTA	West African Science Service Centre on Climate Change and Adapted Land Use - Federal University of Technology
WC	Weather condition
WMO	World Meteorological Organisation

LIST OF SYMBOLS & UNITS

Symbol	Meaning	Unit
k_c or k_{crt}	critical density	pce/km
u_Q	speed at capacity	km/h
k_Q	density at capacity Q	pce/km
q_c	flow at capacity	pce/h
Q	capacity / maximum flow	pce/h
u_f	free-flow speed	km/h
T	travel time	Min
%	percentage	
ψ	dummy variable	
u	speed	km/h
k	density	pce/km
t_f	travel time at free-flow speed	Min
ρ	ratio of free flow to speed at capacity	
β	abrupt drop of curve from the free-flow speed	
v/q	volume – capacity ratio	
x	degree of saturation	
i	rainfall intensity	mm/hr
h	headway	S
S	spacing	km/veh
t	reaction time	S
g	Acceleration due to gravity	m/s^2
a	deceleration	m/s^2
Δ	difference	
ave	average	

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CHAPTER ONE

INTRODUCTION

1.1 OVERVIEW

Service quality, according to Ramya *et al.* (2019) is an assessment of how well a delivered service conforms to the client's expectations. From this definition, it is clear that service quality is a reciprocal perception of the service provider and the user. In highway engineering context, service quality may be construed as an assessment of how well a roadway conforms to the road users' expectations. Road users are more interested in the functional quality than the structural quality of roadways. Therefore, the study is skewed toward functional quality of service.

It is globally accepted that road light prevents accidents and increases safety (Beyer and Ker, 2009). Road casualty statistics show that 40 percent of collisions occur in the hours of darkness (Road Safety Factsheet, 2017). Therefore, the provision of light on roadways is important and beneficial to road users. The benefits of road lights vary from road security, the general safety of life, and good road performance due to improved visibility amongst others. Driving on dark roadways at night is challenging as opposed to daylight driving. Driving at night during rainfall on dark roadways is associated with various problems that the drivers must overcome. Rain poses a major hazard with various impacts on road and traffic performances due to its spatiotemporal nature. Probably the most obvious hazard of driving at night in the rain on dark roadways is decreased visibility. Motorists are compelled to reduce their speed and increase the space between vehicles as a safety net against abrupt stopping of the lead vehicle.

This thesis presents studies that investigated the influence of night rainfall on the functional service quality of two-lane dark roadways and its implication on stopping sight distance. The studies were carried out to fill the research gap on rainy night driving on dark roadways and is discussed in seven chapters. This chapter is divided into seven sections with background to the research problem presented in section 1.2. The aim and objectives of the study are presented in section 1.3 whilst the method of the study is in section 1.4. In section 1.5, the research scope and limitations of the study are discussed, while the significance of the study and organisation of the thesis are presented in sections 1.6 and 1.7 respectively.

1.2 Background to the study

Roadway operation is a function of traffic flow and its characteristics, which is used in evaluating the roadway service quality. Service quality over the years has been misconstrued to be the same as level of service and this has led to the erroneous use of service quality and level of service interchangeably. According to HCM 2010, level of service (LOS) is the quantitative stratification of road service into six letter grades. LOS is basically a road provider's perception of assessing road service. As the road provider's mind is fixated on the road design, the end user who is the road user is given little or no consideration. Nevertheless, to evaluate road operation, there is a need to incorporate road users' perception and this is achieved by using service quality as a means of assessing the quality of road service.

Service quality (SQ) or quality of service(QOS) as it may be tagged, is a traveller's implied perception of roadway performance (HCM 2010, Q/LOS Handbook - DOT Florida, 2013). According to Sakai *et al.* (2011), service quality assessment should be considered from two perspectives which are based on the service provider and the customer. However, in considering road service, the service provider is the highway designer while the customer is the road user. The road provider is concerned with "how far and well" a road user can move on the road (speed consideration) under certain conditions, while the road user is concerned with how long it will take to traverse the road (time consideration) under the same conditions. Thus, the road service quality is evaluated using two different service measures as perceived by the road provider and the road user. The service measures are travel speed and travel time respectively. They are basically obtained as road traffic characteristics which are capable of being influenced thereby resulting in changes under varying prevailing roadway conditions. By this, it is possible for road service quality to change under such prevailing road conditions. Thus, the question raised is how the service quality is affected by a change in traffic flow characteristics due to the external influence of night-time rain? What is the extent of the change? What impact does the change in service quality have on other traffic operations such as stopping sight distance? All these questions call for an in-depth study, hence, the need for this study. The main research question for this study is centred on how night rain influences the functional service quality of dark roadways on a two-lane highway. Other challenging issues for the assessment of functional service quality are rainfall intensity, traffic characteristics with its operations and service measures.

The first issue is rainfall. Rain is one of the dominant weather conditions that occur irrespective of time or place. It is spatiotemporal in nature and measured by its intensity which is classified into various classes of light, moderate, heavy, very heavy and storm. The classification method varies globally, and this has made it very difficult to have a universal classification system. Some typical classification methods are the American Meteorological Society (AMS), the World Meteorological Organisation (WMO) and the Spanish National Meteorological Institute (SNMI). In this study, the classification system adopted is the World Meteorological Organisation (WMO) as it replicates the method currently used by the Meteorological body of the study country. Studies have reported that rain affects traffic operations in terms of traffic characteristics, but its effect on service quality is yet to be considered. Therefore, the need for this study.

The second issue is the traffic flow characteristics. Traffic flow characteristics are used in analysing roadway conditions and as a service measure in assessing the service quality delivered by the roadway. The traffic characteristics include flow, density, speed, roadway capacity and headway, while the methods of obtaining them vary from empirical data collection to simulation as the case may be. Flow describes the number of vehicles passing a road section in a time period while density is the number of vehicles occupying a road section. Speed is the distance travelled per unit time by a vehicle while roadway capacity describes the ability of a road to accommodate traffic under safe traffic, roadway and convenient environmental conditions for the discharge of efficient road service delivery. Capacity, as defined by the HCM (2010), is the highest hourly flow rate by which vehicles or persons are expected to traverse a certain point or uniform section of a roadway for a certain period under specific/prevailing roadway, traffic and weather conditions. It is to be noted that a change in any of the characteristics may cause a subsequent change in the service quality of a roadway, hence the need to study the extent of the effect.

Interest in the effect of rain on traffic characteristics and its operations has increased in recent times due to the need to reduce roadway incidences. Many researchers such as (Chung *et al.*; 2006, Alhassan & Ben-Edigbe, 2011a and Angel *et al.*, 2014) have reported rainfall-based studies and its effects on roadway traffic using different approaches. Whilst previous studies on rainfall focused on daylight conditions, this study fills the research gap created by the absence of dark, rainy roadway studies. From the aforementioned, it is clear that initiatives and measures that include research into the influence of dark, rainy roadways on functional service quality have to be taken in order to tackle issues on poor traffic management.

1.3 Research Aim and Objectives

The aim of this study is to investigate the effect of rainfall on functional service deterioration of dark roadways and its implication for stopping sight distanced. It is based on the hypothesis that rainfall will cause functional service quality deterioration with a significant increase in travel time and by association a decrease in average travel speed. Bearing in mind that travel time variability is a key factor that motorists consider when making basic travel decisions, such as route and departure time.

The research objectives are to:

i) Develop a Functional Service Quality (FSQ) criteria table.

ii) Evaluate travel time variability under dry and rainy night-time conditions.

iii) Evaluate travel speed variability under dry and rainy night-time conditions.

iv) Model the kind of relationship that exists between functional service quality and dark, rainy roadways.

v) Examine the extent of stopping sight distance differentials resulting from dark, rainy roadways.

1.4 Method of the Study

The hypotheses set out for this study are outlined below

Hypothesis 1:

- Rainfall affects the functional service quality of a two-lane highway without road light.

Hypothesis 2

- If hypothesis 1 is true, therefore, night-time rain will have a significant effect on stopping sight distance.

The method of study is empirical based with observations and sample surveys taken at various locations in Nigeria. The main criteria for selection are; proximity to rain gauge catchment station, absence of road light, straight and flat single carriageway devoid of pavement distress, functional drainage and attractions like petrol station, rest area, billboards, and roadside parking sections.

The set-up of the study used by Mashros and Ben-Edigbe (2012) was modified and adopted for this study bearing in mind that proximity of rain gauge to the study location is regarded as sacrosanct to the rainfall impact study. The extent of the rain gauge catchment area will first be established, and a standard World Meteorological Organisation rainfall intensity classification method is used for the purpose of global uniformity.

Different methods exist for estimating the quality of service of a road section; however, two main groups can be distinguished as follows: In the first group, quality of service is measured as a function of travel speed and traffic flow (HCM, 2010; Hou *et al,.* 2012 and Mashros *et al.,* 2014). In the second group, (Zhang *et al.,* 1997; Ben-Edigbe *et al*., 2014 and Lu *et al.* 2016) quality of service is measured as a function of travel time and degree of saturation (volume/capacity ratio). However, the two groups are used to assess functional service quality with one group acting as a check on the other.

On a typical road section, all types of vehicles are captured on the automatic traffic counter. The effects of different types of vehicles within a traffic stream is normally accommodated for by way of converting vehicle volumes to passenger car equivalent values. However, observations of vehicles travelling at night on dark roadways during rainfall suggests that the passenger car equivalent values prescribed for dry weather conditions are not appropriate as they could lead to inaccurate assessment.

Consequently, the study modified the passenger car equivalent values prescribed by the Federal Ministry of Works in Nigeria. The extent of functional service quality reduction resulting from dark, rainy roadways is particularly emphasised as the principal aim of the investigation. Nevertheless, a predictive model that relates dark, rainy roadways to aberrant stopping sight distance are presented.

1.5 Research Scope and Limitations

The scope of this study is limited to obtaining empirical data of dark roadways for a two-lane highway without road light. The empirical data required are traffic data and rainfall data for the selected study sites. The traffic data obtained is limited to uninterrupted flow on the roadway at night, while rainfall data is from the rain gauges located close to the selected study sites. The study sites are selected based on certain selection criteria set up to guide against biased data and information. Also, the study is limited to road functional service quality with no consideration given to the structural service quality of the roadways.

The study limitations include the following: funding and manpower. Funding limited the number of study sites for consideration while manpower shortage was experienced during the set-up of the third site. This brought about an increase in the time spent in setting up the equipment. The non-availability of rain weather stations near the selected sites forced the researcher to obtain personal automatic rain gauges for the study. The security of the traffic counter and rain gauges increased the expenses incurred by the researcher despite the dearth of funds. The study sites were visited every other day to check the equipment set-up for proper functioning. Also, there were days when the researcher visited the sites twice due to incidences of leakages and disruption of pneumatic tubes by vehicles.

1.6 Significance of the Study

Past studies (Chung *et al.*, 2006; Alhassan & Ben-Edigbe, 2011a and Angel *et al.*, 2014) had reported rainfall impacts on roadways. However, the studies were mainly carried out during the day with little or no consideration for the night period let alone dark roadways. As driving is a round-the-clock activity, there is a need to understand the operations of traffic on roads at night relative to its service delivery. This therefore makes this study significant as it considers a three-in-one issue that has not received due consideration in the past. The three-in-one issue is rainfall at night on dark roads without light.

Criteria table was been developed to assess the functional service delivery of roads under the conditions studied. This makes the study novel and significant. The criteria table developed takes into consideration the perceptions of both the road providers and the road users. This is a departure from the usual dependence on road providers' perception in assessing road operations.

Past studies (Hogema, 1996; Hranac *et al.*, 2007; Cools *et al.*, 2010 and Mukhlas *et al.*, 2016) were done using the passenger car equivalent values stated in manuals. It is necessary to note that the values stated in the manual were obtained under specific conditions contrary to the conditions under which most of the studies were carried. It could be argued that the use of these PCE values could have resulted in overestimation or underestimation. Thus, in this study, PCE values are modified to reflect the prevailing conditions under which the study is conducted.

Furthermore, the research is significant as the findings could be used in the making of road and traffic policy in terms of management and design. The results of the study could be integrated into the traffic policy used in the Intelligent Transportation System (ITS) for managing traffic flow and safety on highways.

1.7 Organisation of the Thesis

This section presents the arrangement of the thesis in chapter format. Each chapter is presented to address issues raised regarding the research topic. Note that figures, equations and tables are arranged orderly and identified based on the chapter in the order they appear. For example, figure 2.5 refers to the fifth figure in chapter 2, equation 3.9 is the ninth equation in chapter 3 while table 3.3 refers to the third table in chapter 3. The thesis is made up of seven chapters as outlined below:

Chapter 1: Introduction of the research.

Chapter 2: Literature review on service quality with focus on travel time, travel speed and empirical capacity estimation methods. It provides a theoretical and empirical review on stopping sight distance in context.

Chapter 3: Research methodology is presented. The methodology includes the study framework, site selection criteria and set up. Others are data collection equipment and methods. A pilot study for analytical assessment is presented and discussed.

Chapter 4: Empirical survey results for each study site are presented and discussed.

Chapter 5: The roadway service quality is assessed and presented. The service measures in terms of travel speed and travel time are determined and used to set up a functional service quality criteria table for each site. The criteria table is applied for each study site assessment.

Chapter 6: Implication of dark, rainy roadways on stopping site distance is presented.

Chapter 7: Summary of the study findings, conclusions and recommendations for future research are presented.

CHAPTER 2

LITERATURE REVIEW

2.1 Overview

According to Ramya *et al.,* (2019) , service quality is construed as an assessment of how well a delivered service conforms to the client's expectations. From this definition, service quality is a two-way reciprocal perception where the service provider and the user are key players. In highway engineering context, service quality may be construed as an assessment of how well a roadway conforms to road users' expectations. Road users are more interested in the functional quality than the structural quality of roadways. Therefore, the study is skewed towards functional quality of service, keeping in mind that functional quality is influenced by how road users view the service provided regardless of how road providers perceive the quality. It could be stated that services that meet their expectations will result in road user satisfaction. Thus, functional service quality is the *expected* service being realised. When measuring functional service quality, it is often some aspects of road user's satisfaction which is being assessed. In context, travel time is a key parameter used in many literatures to measure road users' satisfaction. It can be mentioned in passing that travel time and travel cost interlink is central to the assessment of road users' satisfaction. However, this study is only interested in travel time and the associated parameters like travel speed, traffic volume and capacity. This study is concerned with the influence of night-time rainfall on the functional service quality of dark roadways and its implication for stopping sight distance. The study assumes that travel time can be used as a proxy for road users' perception of service quality, while travel speed and traffic flow may be used to assess road providers' perception of service quality. Considering that minimum stopping distance is a function of travel speed and the deceleration rate between the tyres and the road surface, the surface traction factor is expected to be different on a wet road surface as opposed to a dry road surface, hence, it would be useful to estimate the stopping sight distance associated with rainy night-time driving on dark roadways as it is yet to be explored.

In light of the foregoing, the rest of this chapter is divided into eight sections as follows: . Section 2.2 reviews literature on roads and traffic in Nigeria. Section 2.3 dwells on rainfall in Nigeria whilst section 2.4 discusses quality of service concepts. Travel time models are discussed in section 2.5 and roadway capacity concepts are explained in section 2.6. The rainy night-time implication on stopping sight distance of dark roadways is discussed in section 2.7. Section 2.8 gives the summary of the chapter.

2.2 Roads and Traffic in Nigeria

Roads are primarily provided to allow movement from one place to another with little or no discomfort. According to TA 79/99 (1999), roads are made up of links, sections and junctions with individual characteristics capable of affecting traffic flow operations and capacity. The individual characteristics are prone to conditions that could force vehicles to experience incidents such as speed reduction, queues, delays, congestion and accidents. This situation irrespective of the type of road and its location may occur at any time of the day. In Nigeria, the major means of transportation is by road. Road development in Nigeria started in 1904 with a mule road while the first motorable road was constructed in 1906 (Anyanwu *et al.,* 1997). Thereafter, road development witnessed an increase from 6,160km in 1937/38 to 44,414km in 1951 to 114,768km with 28,632km tarred surfaces in 1980 (Olamigoke and Emmanuel, 2013). Presently, the total road length in Nigeria is 191,152km (FMPWH, 2016) as presented in table 2.1.

Table 2.1: Summary of total road length in Nigeria

	Trunk A (km)	Trunk B (km)	Trunk C (km)	Total (km)	Percentage (%)
Paved main roads	28,452	10,400		38,852	20
Unpaved main roads	5,888	20,100		25,700	13
Urban roads			21,900	21,900	11
Main rural roads			72,800	72,800	37
Village access roads			35,900	35,900	18
Total	34,341	30,500	130,600	195,152	100
Percentage (%)	18	16	67	100	

Trunk A = Federal road, Trunk B = State road, Trunk C = Local Government road
Source: Revised Inventory of Federal Highways, FMPWH (2016)

The roads in Nigeria are developed and classified under two systems which are functional and administrative systems. The functional system expresses the traffic service provided by the road while the administrative system defines road ownership based on construction and management. The functional system classifies roads as class A for national roads, B for primary roads, C for secondary roads and D for minor roads. Class A roads otherwise known as expressways are roads along rural and metropolitan areas. They are mostly designed as two-lane double carriageway roads. Their design speeds are 100km/h with annual daily traffic (ADT) of 15,000veh/d for rural and 20,000veh/d for metropolitan areas using A1 and A2 designation for each type respectively (FMWH, Highway Part 1: Design, 2013). These roads connect cities and states within the country and serve as border roads with other neighbouring countries by providing mobility as their main function. Class B (primary) are arterial roads with a design speed of 80 - 100km/h and ADT of 8,000 - 10,000veh/d and are found within cities and connect state capitals to one another. They help to deliver traffic from low speed-volume roads to the national roads by providing mobility and access. (FMWH, Highway Part 1: Design, 2013). They are often designed as two-lane highway or single carriageway. A two-lane highway is designed with a single lane in each direction. The other types are low-speed roads – class C (secondary) and class D (minor) with a design speed of 60 - 80km/h and 40km/h respectively. Their ADT is between 500 - 4,000veh/d and are used for movement of vehicles from local roads to the arterial roads. The primary function of class C roads is mobility and access while class D is primarily for access to secondary roads and a link for residential places, local, market and other motorable roads.

From the administrative perspective, roads are classified as trunk A for federal government, trunk B for state government and trunk C for local government roads. Trunk A roads are the roads designed, constructed, controlled, maintained and financed by the Federal Government through the Federal Ministry of Works and Housing (FMWH) while trunk B and C roads are under the jurisdiction of the state and local governments respectively for their design, construction, maintenance and financing through their individual Ministry of Works and Housing (MWH). Nevertheless, roads in Nigeria are identified and described using either their location or the places which the road is connecting, as against the common convention of using alphabet and number. A typical example is Lagos-Ibadan expressway – this shows that the road is linking Lagos and Ibadan cities and is a class A type of road. Akure-Ilesha highway is another type in which the road links Akure and Ilesha. This convention is adopted for this study, and it should be noted that the discussions in this thesis are limited to roads in Nigeria.

Traffic on Nigerian roads is made up of different classes of vehicles which include motorcycle, tricycles, cars, vans, buses, trucks, and trailers with various numbers of axles. The operations of all vehicle types are not limited to a certain type of road though some are more commonly found on a particular road type than the others. Motorcycles and tricycles are commonly found on urban roads while trucks and trailers with various numbers of axles are more common on rural roads and expressways. The operation of each type of vehicle is influenced by other vehicles plying the same road. For example, when a trailer is a lead vehicle, its effect on other vehicles following it is such as to cause delay, platooning, speed reduction and an increase in travel time. Several factors which include vehicular factor, road factor, environmental factor and human factor affect road traffic. The vehicular factor includes vehicle type, size, weight and axle configuration, turning radius and path, acceleration and braking ability. Road factor includes road surface, lighting, road geometry and other road facilities such as traffic signals, signs and road markings. The human factor includes behaviour of drivers, visual acuity, reaction time, psychological factors, physical strength, and demographic characteristics. The environmental factors are rain, fog, snow, ice, daylight and night-time. In general, traffic on Nigerian roads and other features may be said to be in accordance with acceptable standards though there is more room for improvement.

2.2.1 Night-time driving in Nigeria

Driving in the rain at night on dark roadways is intuitively associated with speed reduction, an increase in travel time, reduced stopping sight distance, poor visibility and poor road surface traction. It can also lead to anxiety, fear, and sometimes anger. Night-time is used to describe the absence of visible light which the human eye can see. As the sun is the main source of light on earth, the absence of light from the sun initiates night-time. The sun initiates processes referred to as sunrise and sunset which bring about daylight and night respectively. The daylight is the period when the eyes can see visibly without the use of external light while the night-time is the period of impaired vision in which there is a need for external sources of light to enhance visibility. In Nigeria, sunrise turns into daylight mostly by about 0600hr, while sunset turns into the night-time period mostly by about 1830hr (6.30pm) thereby giving an average of 12½hrs daylight and 11½hrs of darkness. The sunset and sunrise vary from location to location and from season to season. An example of daylight and night-time of a typical day in Akure, Ondo State - a city in Nigeria is presented in figure 2.1. From figure 2.1, the transition period from daylight to night-time is the dusk (three phases of twilight) which allows for the full implementation of the night-time period while the dawn (three phases of twilight) represents the transition period from night-time to daylight.

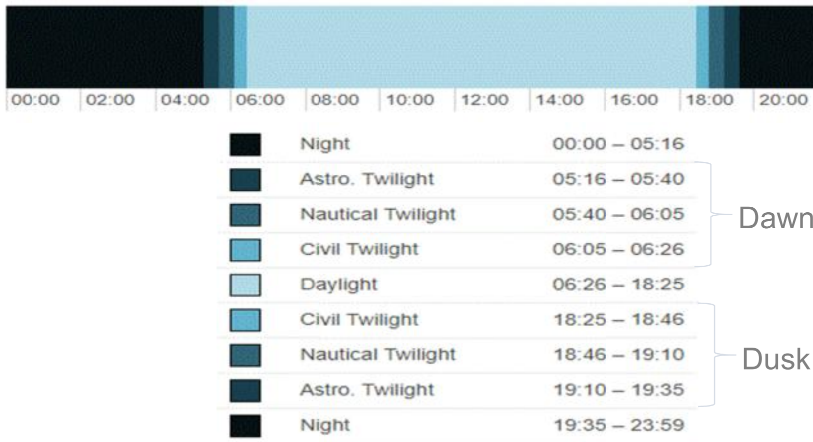


Figure 2.1: Typical graph of day, night and three phases of twilight in Akure, Nigeria.
Source: https://www.timeanddate.com/astronomy/@2350841

Driving at night is a visual task that requires good visibility and to cushion the effect of night-time while driving, vehicle headlamps and road lights are provided for illumination. However, there are times road lights may not be provided and when available may become non-operational, thereby forcing drivers to rely on their car headlamps which at times may malfunction. The headlamp is attached to the front of a vehicle to produce headlight (beam) which illuminates the road, as well as makes other vehicles visible. The use and efficiency of headlamps at night-time on roadways is dependent on their luminance. The higher the headlamp luminance, the brighter the beam and the greater the glare effect (glare is the visual sensation triggered by excessive and uninhibited brightness). The headlight produces both a high and low beam. A low beam with an average of 700 lumens gives light that is controlled to guide against glare and is mostly used when other vehicles are present on the road. On the other hand, a high beam usually gives about 1200 lumens and enhances good visibility but produces too much glare. The use of a high beam under rainy conditions leads to refraction, distortion and reflection of the beam's light which results in glare that makes driving under such conditions dangerous. Glare results in poor visibility, speed reduction and an increase in headway. In addition, use of a high beam under weather conditions such as rainfall and fog cause back dazzle due to retro reflection of water droplets. Against this backdrop, the use of a high beam is limited and more suitable when there are no other vehicles on the road. Reagan *et al.* (2016) reported that only 18 percent of vehicles use a high beam when driving while Sullivan *et al.* (2003) and Stephaine (2014) reported that there is an underuse of a high beam at night. Hence, it can be assumed that most drivers prefer to drive with low beams at night-time to minimise glare and its consequent effect on other road users while still maximising roadway visibility. Within the purview of this study, it is arguably correct to assume that the likely effect of headlamp usage at night-time under rainfall or no rain condition is negligible i.e. no glare effect from beams so as to force drivers to reduce their speed during the period of data collection.

2.3 Rainfall in Nigeria

Nigeria is a tropical country with two well-defined seasons, which are dry and wet seasons. The dry season is characterised with little or no rain, high temperatures and dust-loaded air mass from the Sahara Desert. On the other hand, the wet season is characterised by low temperatures and adequate rain due to the air mass coming from the South Atlantic Ocean and changes in climate. The changes in climate are as a result of differences in humidity and temperature amongst others. In Nigeria, the average relative humidity is low throughout the year though it varies from location to location and from season to season. Usually during the dry season, the northern part of Nigeria experiences very low relative humidity and high temperatures (that could be as high as 42^{o}C) unlike the southern part of Nigeria with high relative humidity which is relatively constant along the coastal areas. The southern part of Nigeria experiences lower temperatures during the dry and wet seasons than the northern area (www.total-facts-about-nigeria.com). The annual average temperature in Nigeria is 27^{o}C though it varies with respect to location, season and time of the day. The Jos Plateau region in central Nigeria is the coldest part with a temperature range of 20^{o}C - 25^{o}C all through the year. The coastal areas in the South-West and South-South zones have an average temperature of 28^{o}C. The months of December and January known as the Harmattan period, has the lowest average temperature while March and April are characterised by very high temperatures. The high temperatures experienced in March and April usher in rainfall for the wet season. The wet season with its significant amount of rainfall is usually from April to October with the rainfall peak in June and August for the southern and northern parts of Nigeria respectively. The northern part of Nigeria made up of the North-West and North-East, has the lowest amount of rainfall annually. Their annual rainfall is between 500-1000mm. The average rainfall along the coastal part of Nigeria varies from 1800mm in the South-West to 4300mm in the Southern Nigeria zones (www.total-facts-about-nigeria.com). The central zone of the nation has an average annual rainfall of 1300mm. In Nigeria, the agency responsible for information regarding climate situations is known as the Nigerian Meteorological Agency (NIMET) and it is saddled with the responsibility of observing, collating, collecting, processing and disseminating all meteorological data and information in Nigeria.

Rain is a precipitated condensed atmospheric water vapour from the cloud whose quantity is measured in millimetres (mm). It is the formation of falling water droplets which interact with each other and the environment (www.nationalgeographic.org/encyclopedia/precipitation). Rain is a typical climatic condition with varying characteristics. It occurs over time and space throughout the year in Nigeria. Rainfall is measured using surface rain gauges, weather radar or satellite imagery. The weather radar and satellite imagery measure rainfall above the earth's surface, while the rain gauge measures rain data on the earth's surface. For this study, the use of a surface rain gauge is considered because traffic interacts with rainfall at a surface level. Measuring of rainfall occurrence could be carried out on-site using a rain gauge or by obtaining rainfall data from rain gauge stations. A rain gauge is a cylindrical drum with a funnel on top to direct rain into the cylinder. The rain gauge could be a manual self-tipping bucket type or an automatic self-logging type. The cylinder bucket is calibrated in millimetres or inches to measure the amount of rainwater in it. The rain gauge is usually placed in an open space with no covering and above ground level to prevent splash water and other contaminants from gaining access to it. Rain gauges are now equipped with sophisticated data loggers capable of measuring rainfall data of high resolution in millimetres per second or millimetres per minute. Rainfall has many characteristics which are measured in terms of quantity, frequency, distribution over an area, time of occurrence and intensity.

Rainfall intensity is defined as the amount of rain that falls per unit of time. Intensity is measured as the water layer height covering the ground in a period and is measured in millimetres per day or hour (mm/day or mm/hr), it depends on raindrop size (Frazer n.d). The bigger the raindrop size, the higher the intensity, the greater the energy impact and the greater the impact on a driver's vision. As the size of raindrops increases, the driver's vision becomes poorer and this subsequently reduces roadway sight distance. Low-intensity rainfall is related with a smaller spherical raindrop size with a radius < 1mm, while the large ones with a radius greater than 4.5mm with a hamburger bun shape are responsible for high-intensity rainfall (Frazer n.d). The differences in raindrop sizes are used to classify rainfall into categories, though this classification had been a contentious issue over time. The classification varies from country to country which makes it difficult to have a universal classification system. Table 2.2 represents the common and acceptable classification system, however, for this study, harmonized rainfall intensity values based on estimations from Table 2.2 taking cognizance of World Meteorological Organisation (WMO) classification system. Pursuance of Table 2.2, light rainfall intensity is 2mm/h to 2.5mm/h with an average intensity of 2.33mm/h > 2mm/h, hence a value of 2.5mm/h is appropriate. Average moderate rainfall intensity (2.5mm/h – 15mm/h) is

9mm/h ± 3.89mm/h; hence a value between 5mm/h and 13mm/h is appropriate. Average heavy rainfall intensity (7.6mm/h – 50mm/h) is 29mm/h ± 12.6mm/h, hence 15mm/h and 42mm/h is appropriate. It can be argued that the impact of rainfall during daylight and darkness is different.

Table 2.2**:** Rainfall intensity classification

Rainfall Category	Intensity *i* (mm/hour)		
	SNMI	WMO	AMS
Light rain	$i < 2.0$	$i < 2.5$	$i < 2.5$
Moderate rain	$2 < i < 15$	$2.5 < i \leq 10$	$2.6 < i < 7.6$
Heavy rain	$15 < i < 30$	$10 < i \leq 50$	$i > 7.6$
Very heavy rain	$30 < i < 60$	$i > 50$	-
Torrential rain	> 60		-

SNNMI - Spanish National Meteorological Institute
WMO - World Meteorological Society
AMS - America Meteorological Society
Source: Ibijola, S. O (2018)

2.4. Quality of Service Concept

Definitions of service quality in the literature centre largely on meeting customers' needs and requirements and how well the delivered service meets customers' expectations (Bateson and Hoffman, 2011). These definitions align with the road user-based method used in this study. However, within researchers and practitioners, there is an acceptable fact that that service quality is an ambiguous and abstract concept that is difficult to describe, define and quantify (Bateson and Hoffman, 2011; Kasper *et al.*, 2006; Kotler and Armstrong, 2010). Quality can be defined in many ways. Service quality is an ephemeral and complex concept. Service quality is descriptive and based on facts whereby customers' perceptions serve as the foundation on which service quality is assessed. Edvardsson (1998) argues that service quality should be approached from the customer's perspective because it is the customer's perception of the outcome that determines the excellence of the service.

According to Kotler and Armstrong (2010) and Sakai *et al.* (2011), quality of service is based on the performance of actual service and the user's perception of quality. In this case, the definition of quality of service by Armstrong and Sakai is presumed to be more encompassing rather than that of the HCM 2010 which recognises only the road user. Kane (2005) opined that measuring performance in terms of service delivery is required to improve transportation services for customers. The performance of a two-lane highway has been limited to the level of service measure which primarily does not put into consideration the user. Measuring the performance of a two-lane highway is not an easy task due to variations in road characteristics (Ghosh *et al.*, 2013). Subsequently, measuring of service delivery has become a critical area of interest to highway designers and planners. In the United States, observed speed/flow data are often superimposed on a predetermined level of service (LOS) chart in order to determine the prevailing LOS. As shown in figure 2.2, LOS would dial from A to F where level A is the highest quality of highway service and level F the lowest; HCM 2010 prescribed the relative densities for each class.

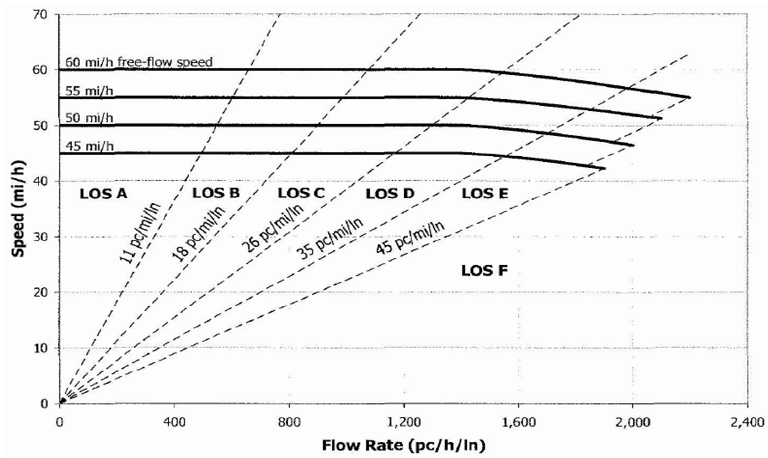


Figure 2.2**:** Typical HCM speed-flow curve and the concept of LOS
Source: HCM 2010

According to the Highway Capacity Manual, HCM 2010, level of service (LOS) is the qualitative assessment of the quality of roadways. The Highway Capacity Manual (HCM) utilises speed/flow as the control variables to describe six LOS experienced by road users. It can be argued that LOS describes road providers' perception not users, since there is nothing in the LOS manual to show that road users' experience was assessed. The HCM 2010 LOS divides the level of traffic flows into six levels ranging from level A to level F with level A representing the highest highway service quality and level F the lowest. Level of service E signifies traffic operation at capacity. According to the HCM 2010 assessment methodology shown below in figure 2.3, the primary measures of service quality are average travel speed and the percent time-spent-following.

The percent time spent following represents the freedom to manoeuvre and the comfort and convenience of travel. It is the average percentage of travel time that vehicles must travel in platoons behind slower vehicles due to an inability to pass. The HCM 2010 based the percentage time-spent-following on the percentage of vehicles travelling with headways of less than three seconds. Percent time spent following is premised on minimising the total time spent to complete passing sight distance. What if the motorist is not interested in overtaking the lead vehicles but still loses time due to other traffic, road or environmental conditions? There is no evidence in the HCM 2010 to suggest that road users' perception is considered.

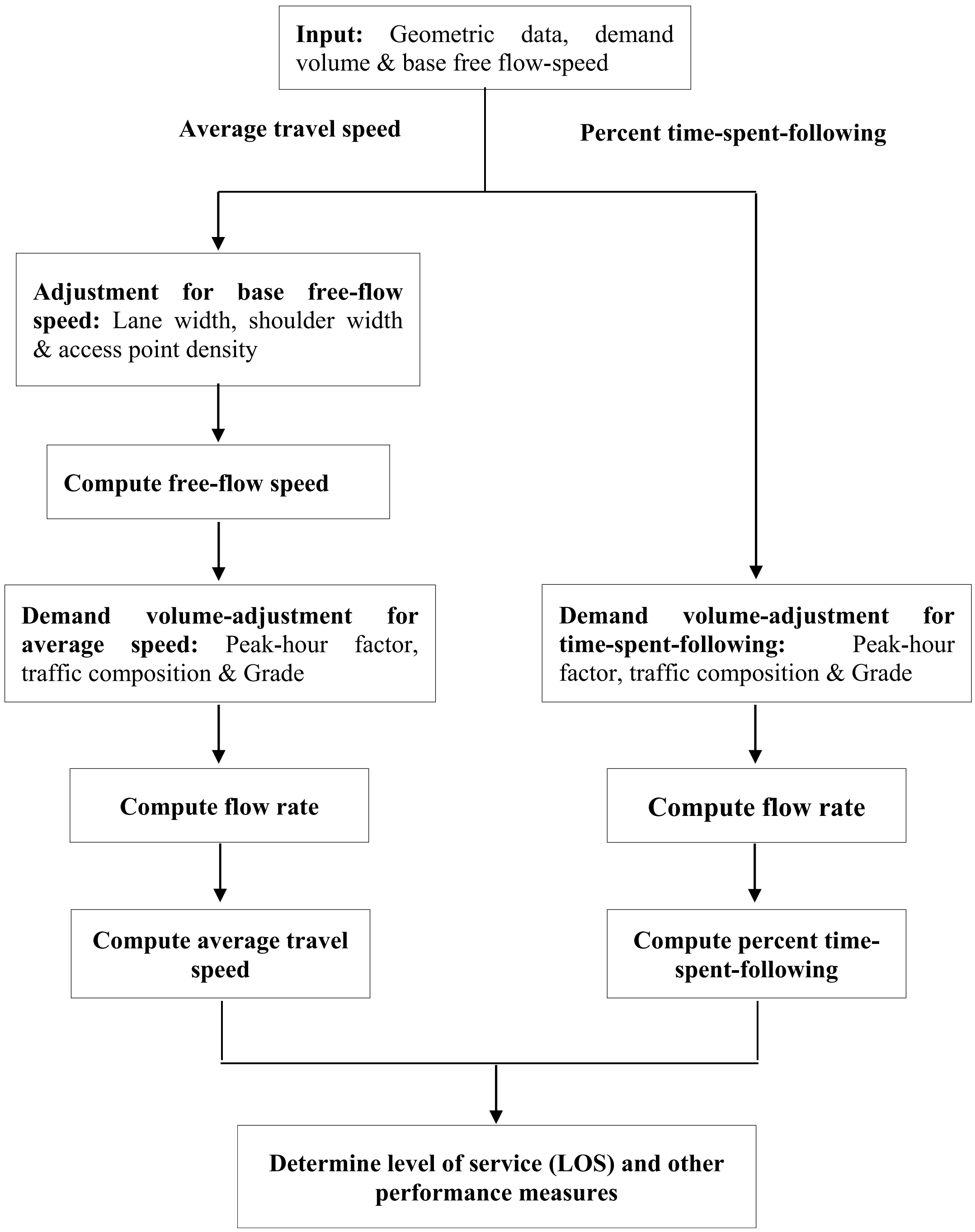


Figure 2.3: HCM-LOS methodology for two-lane highway

2.4.1 Functional Service Quality (FSQ) Concepts

Functional service quality is construed in HCM (2010, p.5-2) as "how well a transportation facility or service operates from the travellers' perspective". Two complementing elements are crucial in functional service quality (FSQ); provision and consumption of a quality product or service. The provider of the service or product is the first line in the quality fitness test before the consumer passes the ultimate service quality judgement. It can be added in passing that an understanding of the road users' perceptions of quality is crucial to rendering an outstanding road infrastructure service. In many studies, speed/flow is often used for qualitative measurements when in fact effectiveness is measured. Measuring effectiveness is not the same as measuring quality. If *effectiveness* is the capability of producing a desired result, then it would be quite appropriate for road providers to measure road service effectiveness with speed and flow; after all speed and traffic flow are key design parameters. If *quality* is the standard of something as measured against other things of a similar kind, the road users are better placed than road providers as a channel for assessing road functional service quality. It can be argued that motorists are more concerned with the generalised time spent on the road than time spent following a lead vehicle. This contradicts the HCM 2010 LOS based on speed and percent time-spent-following.

In presenting functional service quality methodology shown below in figure 2.4, the study modified the HCM LOS methodology for a two-lane highway by way of introducing travel time as a replacement for percent of time following, passenger car equivalent adjustment mechanisms and a road capacity estimation method based on the fundamental diagram. The proposed FSQ assessment methodology uses travel time and degree of saturation as the control variables to describe six qualities experienced by road users. Like the HCM 2010 LOS, FSQ also divides the curve into six levels ranging from level A to level F where level A is the highest quality of highway service and level F, the lowest. FSQ E denotes traffic operation at capacity. FSQ would range from A to F, where level A is the highest service and F is the lowest; FSQ prescribes the relative travel speed for each class. Ben-Edigbe *et al*. (2014) argued that the concept of quality of service is a function of travel speed and volume-capacity ratio. The volume-capacity ratio represents the proportion of traffic passing through a roadway and is otherwise described as a measure of capacity sufficiency. Though there are no basic standards for the volume-capacity ratio distribution, equal distribution is often preferred where the highest ratio is set as 1.0, while others may be set as ≤ 0.25, 0.25 - 0.5, 0.5 - 0.75, 0.75 - 0.85 and 0.85. The 0.85 ratio had been used as the threshold performance by the Transport Research Board

(TRB, 1998), the Highway Capacity Manual (2010) and studies such as those of Hou *et al.* (2012) and Mashros *et al.* (2014).

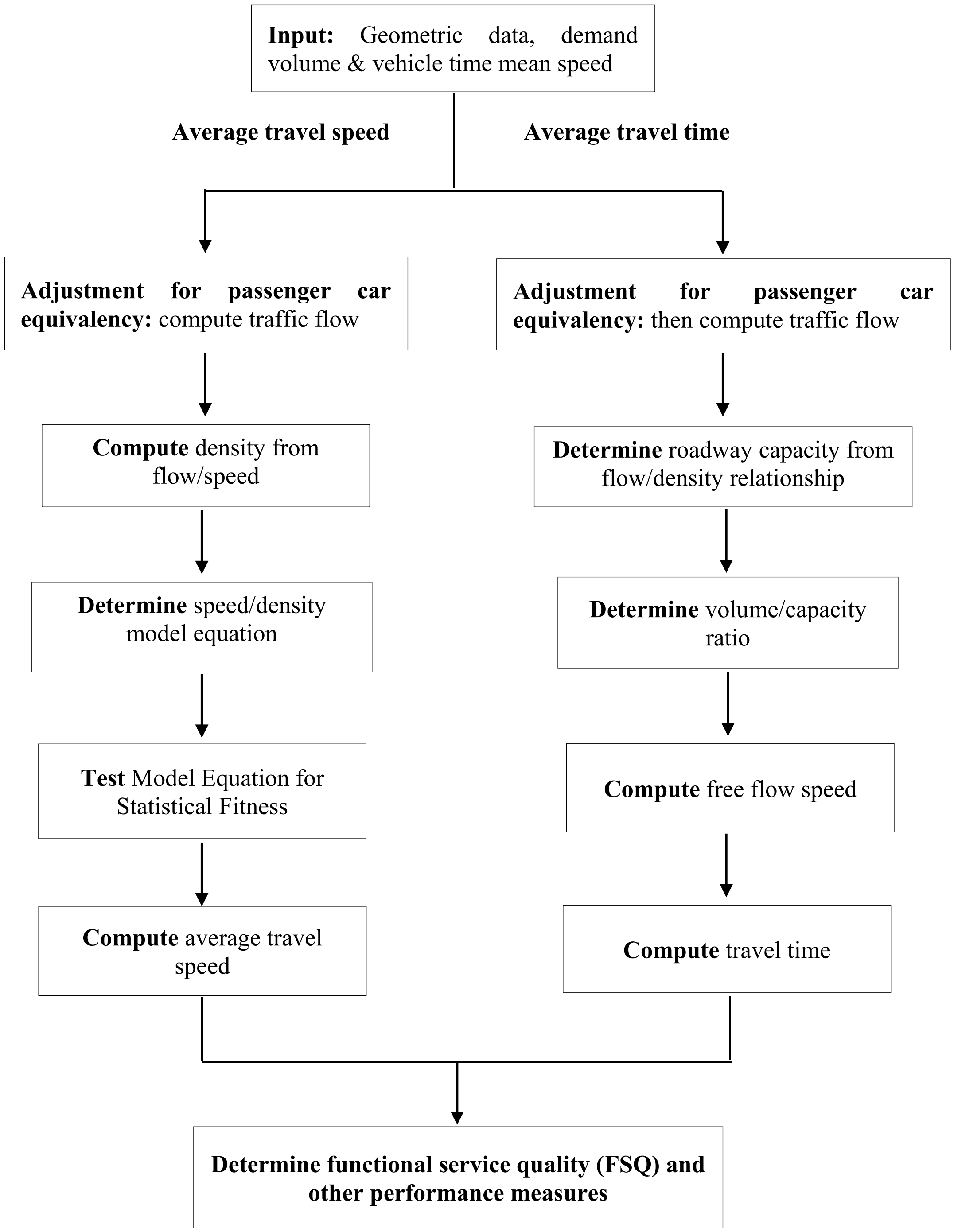


Figure 2.4: Proposed two-lane highway FSQ methodology

The study also proposed adjustments to the HCM LOS speed-flow curve by way of replacing the diagonal lines with horizontal lines. Ben-Edigbe *et al.* (2014) suggested that horizontal lines are more appropriate than diagonal lines because they are more sensitive to speed changes. In any case, there are two intrinsic elements (travel time and roadway capacity) in the proposed two-lane highway functional service quality assessment approach. These are discussed next.

2.4.2 Appraisal of the HCM Quality of Service Method

In the past, the level of service (LOS) based on road providers' perception was used as a measure of effectiveness (MOE) tool for road service delivery. Thereafter, quality of service (QOS) was introduced to support LOS from the perspective of road user. The Transport Research Board (TRB, 2010) committee on highway capacity and quality of service suggested the use of LOS in conjunction with QOS in which QOS is expected to reflect the perception of both road providers and users. This led to erroneous use of LOS and QOS interchangeably overtime. As QOS is a function of service measures such as travel speed, travel time and delay, the vexing issue is how to measure QOS to accommodate the perception of both the road providers and the users.

According to the HCM, QOS is determined on the concept of LOS which is based on average travel speed and the percent time-spent following of vehicles. The HCM QOS is driven by speed alone which often cannot be used by a road user to assess the quality of service rendered by the road. This is presumed to be far from being correct as road users' perception is based on time spent on the road (travel time) whereas road provider's perception is based on the speed (travel speed) at which road users will use the road safely. Therefore, it is correct to say that the assessment of road service quality is dependent on time spent on the road in conjunction with speed associated with the time spent. In meeting up with the challenge of considering both the road user and provider perceptions, functional service quality (FSQ) is introduced in this study for assessing road traffic operations under prevailing roadway and traffic conditions. By this, road users and road providers' perception are considered.

2.5 Travel Time Concepts

Travel time is described as the average time spent in moving through a highway segment (HCM 2010). Travel time, as a vital parameter in transportation studies is defined as the time required to navigate a path between any two considered points. Travel time is a basic idea comprehended and conveyed by a wide variety of personnel which include transportation engineers and planners, alongside others such as travellers, managers, administrators, business personnel, media representatives and consumers. Travel time is described as the time taken to move from the start of a trip to the end of the trip in which the trip range could be an intersection, link, route or highway segment. It is dependent on speed though it varies from time to time, season to season as a result of the macroscopic traffic flow characteristics. It is however to possible to determine travel time directly determined by navigating the path(s) that links the points of interest. Travel time is made of running time which is the time required when the mode of transportation is in motion, and the stopped delay time which is known as the time required when the mode of transport is motionless (or moving slowly as to a likely stop with a supposed speed of less than 8 km/h or 5 mph).

Travel time according to the HCM (2010) is one of the service measures used in assessing the performance of a roadway in terms of quality of service. Travel time is an important measure of traffic performance on a roadway to road users because the road users are concerned about the time spent in making a trip. It is used for evaluating the efficiency of traffic operation, the performance of transportation facilities relative to traffic management strategies and planning (Zhang *et al.*, 1997; Lu *et al.*, 2016). Travel time studies also make available valuable data in understanding the effectiveness of changed traffic conditions, such as changes in parking regulations, new introduction and installation of traffic signal system, one-way streets, redirecting of bus lines, or flaring or rehabilitating of the street, roads or highway. Travel time studies is useful in providing information on roadway congestion quantitatively and, provision of information regarding causes and amounts of delay using the test car procedure for obtaining the travel time data. The obtained information and results are also useful in calculating possible reductions in travel time based on the changes relative to traffic controls and other physical roadway improvements put in place. The commonly used value with respect to the change in traffic conditions under the existing physical, traffic, and environmental conditions is the mean travel time compared with the travel time before change in the performance of the highway. The merit of this method allow is that it gives room computation of travel time for all traffic directly. Likewise, the median travel time is advantageous on its own because it depicts the corresponding median over-all speed of the traffic since the mean travel time cannot be directly converted to the mean over-all speed of the traffic. For measure of dispersion, the percentile ranges of travel times are useful and adopted because they can be easily converted to over-all speed ranges. The speed ranges are used in setting the timing for coordinated traffic signal systems.

Travel time used together with delay and capacity serves as a guide in evaluating the effectiveness of roadways (Mashros *et al.*, 2012). Overtime, travel time has been used in the modelling of travel demand and measuring traffic performance. The importance and relevance of travel time in road design, planning and management cannot be over-emphasised. Zhang *et al.* (1997) and Lu *et al.* (2016) stated that travel time is used in assessing the efficiency of traffic operation, the performance of traffic management plans, and planning transportation facilities. Therefore, travel time which can either be estimated or predicted is of great importance to both the road providers and users. Estimation of travel time has been mostly carried out using regression models based on many methods such as an origin-destination survey, trip assignment, modal choice amongst others. Nevertheless, it may be correct to say all the methods estimated travel time on an individual basis without consideration to external factors such as road, traffic and weather conditions, thus, there is a need to investigate the weather condition's effect on travel time. According to the US Bureau of Public Roads (US-BPR), travel time over a roadway length can be calculated using equation 2.1.

$$T = t_f\left[1 + \rho(x)^{\beta}\right] = t_f\left[1 + \rho\left(\frac{v}{Q}\right)^{\beta}\right] \qquad 2.1$$

Where; T = predicted time over roadway length

t_f = travel time at free-flow speed$\left(t_f = \frac{d}{u_f}\right)$;

x = degree of saturation (v/Q), v = demand flow;

Q = capacity; ρ = ratio of free flow to speed at capacity, and

β = abrupt drop of curve from the free-flow speed

The 1965 version of the BPR proposed 0.15 and 4 for ρ and β respectively while Dowling and Skabardonis (1993) re-proposed 0.2 and 10 for ρ and β respectively to counter the underestimation of speed. A high value of β will cause the speed to become unresponsive to $"x"$ with the speed dropping when x tends to 1. For this study, the night-time period is a typical off-peak traffic period with a degree of saturation v/Q < 0.9, therefore, the values $\rho = 0.2$ and $\beta = 10$ are acceptable. Equation 2.1 now becomes:

$$T = t_f\left[1 + \rho\left(\frac{v}{Q}\right)^{\beta}\right] \qquad 2.2$$

Bearing in mind that travel time is an essential information for a driver, it also serves as a significant parameter for several purposes, such as the evaluation of delay (vital for economic study), and estimation of emissions, etc. As the link travel time depicts the average traffic conditions considered for a fixed distance, it must be taken that it a constant comparison between 'expected travel times' and 'actual travel times'. Thus, any possible difference between them must be related to past statistical data to show a possible incident. Travel time can either be estimated or predicted. Traffic prediction approaches include statistical model (Davis and Nihan, 1991) or macroscopic models, spectral and cross-spectral analyses (Stathopoulos and Karlaftis, 2001), time series models (Ahmed and Cook, 1982), route choice models based on dynamic traffic assignment (Ben Akiva *et al.*, 1992), neural network techniques (Fu and Rilett, 2000) and cusp catastrophe theory (Phshkar *et al.*, 1995), The key predisposition in these approaches is that they use past statistics from a given location to make estimates for future (usually short-term) traffic behaviour. Furthermore, these methods are generally used for non-urban roads. In the assessment of travel time, there are numerous methods and they are basically divided into five categories as given below:

- Spot speed measurement methods
- Spatial travel time methods
- Probe vehicle technologies
- Regression models
- Neural networks

The spot speed measurement methods are based on the existence of inductance loop detectors (single or dual) for the provision of real time traffic information. Other techniques involve infrared and radar technologies. These systems are only use in measuring the speeds of traffic stream over a short road section at fixed locations along a road. The measurements for the spot speed are used in computing spatial travel times over a whole trip using the estimates of space mean speed. There are new developed methods that relate vehicles based on their lengths (Coifman and Cassidy, 2002; Coifman and Ergueta, 2003). For spatial travel time categories, this method uses fixed location equipment to identify and trace a subset of vehicles in the traffic stream. The trailed using their unique and individual vehicle identifications are matched together at different locations and their spatial travel times are estimated. Typical technologies include automatic vehicle identification (AVI) and license plate video detection systems. For probe vehicle technologies, a sample of probe vehicles are tracked on a second-by-second basis as they move through a link. These technologies include automatic vehicle location (AVL) systems, cellular geo-location and global positioning systems (GPS). Using the probe vehicles give room for numerous samples of travel times to be obtained for all vehicles travelling through the link. van Aerde *et al*, (1993) and Turner and Holdener (1995) reported that the probe vehicle travel time presents the travel times of all vehicles accurately more than other methods employed in estimating travel time. Regression models are the most frequently used technique to assess travel times and are based on regression analysis. Well-established regression procedures include the Wardrop (1968), Takaba *et al.* (1991), Sisiopiku and Rouphail (1994) and Zhang and He (1998) formulas.

Despite the numerous numbers of factors influencing traffic delay, there are no precise mathematical models to describe basically the correlation between the travel time and its influencing factors. Therefore, this makes the estimation of travel time to be a complex problem as a result of the numerous numbers of factors capable of influencing traffic dynamics. However, most of the algorithms identified in the literature are suitable and used more for low density and uniform traffic conditions. Hence, they are suitably used for freeways travel time estimations, but not that suitable for travel time estimations for urban arterials and streets. The main characteristic of urban arterials and streets is the unexpected growth and decay of queues. Such a travel time estimation algorithm should react quickly and accurately in the development of unexpected traffic problems when using dynamic data. Among direct measurements of travel time is the use of a floating car or test vehicle. This method was the commonly used method for collection and estimation of travel time in the early research days. It utilises vehicles such as taxi's or delivery vehicles containing an observer who records cumulative travel time at predefined checkpoints along a travel route. In this method, the measured data is called a floating car data. This method has many advantages which includes the fact that data collection is inexpensive. Since many taxi services and delivery companies automatically gather this data on their vehicles for logistic purposes and can be employed to obtain more accurate travel time when Global Positioning Systems (GPS) is used, it has its disadvantages as well. Firstly, this method generally requires active participation and commitment from vehicle owners, which may compromise personal privacy and secondly, limited data is available, which contributes to less meaningful travel time predictions for a given road link or network.

Since a floating car or test vehicle cannot estimate travel time required in these circumstances, it makes more sense to measure the travel time based on indirect travel time data as most previous studies have used (Oda, 1990; Al-Deek *et al.*, 1998; Roden, 1996; D'Angelo *et al.*, 1999 and Pant *et al.*, 1998). In this method, travel times are usually obtained by using test vehicles which 'float' with traffic, to simulate average traffic characteristics. Each driver is required to stay within the traffic, and to pass as many cars as those passing his vehicle. Travel times are also obtained by taking data on all the vehicles composing a traffic stream. In this procedure, the license number of each vehicle and the times at which it enters and leaves a test section are recorded. Relationships between travel times obtained by the two methods have been reported by Berry and Green (1949). Figure 2.5 shows an example of the relationship between travel time and demand for US-BPR and Dowling *et al.*'s freeway formula known as the 'modified BPR' curve (Kockelman, 2009).

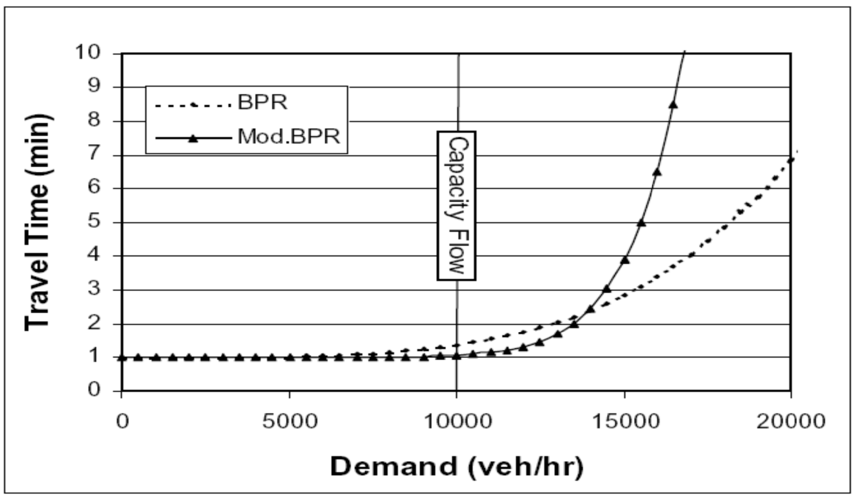


Figure 2.5: Travel Time versus Demand - BPR and Modified-BPR formula
Source: (Kockelman, 2009)

As illustrated in this figure, the actual capacity for a BPR curve is 10,000 veh/hr, c is 8,000 veh/hr, and T_f is 1 minute. If we considered time to traverse a 1km section at a free-flow speed of 100 km/hr and the demand exceeds actual capacity by 30 percent, it would cause doubling of travel times as high as those under free-flow/uncongested conditions. Thus, 2min/km implies speeds of just 50km. While the modified BPR curve differ dramatically from the BPR curve when demand exceeds the actual capacity by more than 50 percent, these curves prove that the assumption of travel time and traffic having a non-linear relationship can be accepted.

2.5.1 Impact of night rain on travel time of dark roadways

Travel time and travel speed are linked. Travel speed is often the first recipient of rainfall impact. According to Alhassan and Ben-Edigbe (2011a), visibility is marred when driving at night thereby reducing efficient sight distance. As the sight distance reduces, drivers are forced to reduce their speed which leads to an increase in travel time. Driving in the rain at night on dark roadways could be challenging. This is due to the possibility of reduced visibility in which road users are forced to rely on their vehicle headlamps. Nevertheless, rain hinders the performance of vehicle headlights by filtering away the luminous power, thus reducing the illuminance on the roadway ahead of the vehicle. Due to its spatiotemporal nature, rainfall affects driver's behaviour and its subsequent traffic operation. The effects include poor visibility and aquaplaning, and reduction in tyre friction. The consequences of these effects may lead to flow contraction, speed reduction, accidents and an increase in travel time.

Many literatures have reported that rainfall, irrespective of its intensity, results in speed reduction and by default travel time increase. Recent studies on travel time are focusing on the understanding of travel time changes due to weather impacts. Stern *et al.* (2003) analysed weather impacts on traffic flow in Washington DC and reported that average travel time increased by 14 percent under adverse weather conditions whereas Mashros *et al*. (2012) suggested that light rain will account for a travel time increase of 0.43minutes per kilometre, while moderate and heavy rain respectively will cause an increase of 0.54 and 0.74 minutes per kilometre. They concluded that rainfall, irrespective of its intensity, has significant impact on travel time. In a study by Tsapakis *et al.* (2013), the effect of weather conditions on travel time was carried out in Greater London, United Kingdom for a period of three months. Using three two-hour periods on weekdays for morning, afternoon and evening, it was reported that travel time increases by 0.1 -2.0 percent for light rain, 1.5 – 3.8 percent for moderate rain and 4.0 – 6.0 percent for heavy rain. Angel *et al.* (2014) in a study carried out on roadways without streetlights reported a speed reduction of 1.6mph under light rainfall with moderate and heavy rainfall having a speed reduction of 1.1mph and 7.5mph respectively.

The HCM 2010 reported a 2km/hr speed reduction in free-flow speed for light rain and 5-7km/hr speed reduction for heavy rain though the rainfall intensity ranges were not specified. Ibrahim and Hall (1994) observed a free-flow speed reduction of 2km/hr for light rain and 5-10km/hr for heavy rain on freeway operation in Canada. Free-flow speed reduction of 2km/hr and 10km/hr for light and heavy rainfall respectively was reported by May (1998). Likewise, Kyte *et al.* (2000) reported a 5km/hr speed drop due to darkness for Brilon and Ponzlet's (1996) study while Liang *et al.* (1998) observed a 1.6km/hr speed reduction during night-time periods. In a study conducted by Chung *et al.* (2006) on weather-induced impacts in Japan, they discovered a free-flow speed reduction of 4.5 percent and 8.2 percent in light and heavy rain respectively. Hranac *et al.* (2007) in a related study, reported free-flow speed reduction in the range of 2-3 percent for light rain, while free flow speed reduction of 4.4 percent, 7.3 percent and 10.6 percent for light, moderate and heavy rain respectively was observed by Wang and Luo (2016).

Similarly, a study in Beijing, China shows speed reduction due to rain. Three classes of road vis-a-vis expressway, major arterial and collector were studied by Zhang *et al.* (2017) for different time periods. Their study revealed travel speed reduction of 7.5, 5.0 and 9.4 percent for the expressway, arterial and collector roads respectively under heavy rain during night-time period. Chung et. al (2005a) selected an approximately 12km route length of the Tokyo Metropolitan Expressway (MEX) to conduct the study on the effect of rainfall on travel time. Going by the history on this route, travel time varies from nine minutes to 70 minutes in free flow condition and severe congestion respectively. However, in the study conducted by Chung *et al.*, density and travel time were computed using ultrasonic detector data from August 1998 to June 2000, and rainfall data monitored by the Japanese Meteorological Agency's meso-scale network of weather stations. The density was estimated by summing flow - in vehicle/5minute divided by vehicle speed obtained at different sections of the route, while travel time was determined from velocity values obtained at different route sections. Based on Chi-squared Automatic Interaction Detector (CHAID) analysis, the results for average travel time for rainy and non-rainy condition show that there is no significant difference in travel time between rainy and non-rainy condition for low density traffic, which implies free flow condition. Even though the relation between rainfall and link travel time has been investigated by Chung et. al (2005a) using indirect travel time data, they do not consider the effects of rain when the traffic flow is at capacity and optimum speed. Also, they do not classify rainfall into different intensity categories. In any case, most of the previous studies on travel time are based on dry/rainy weather and daylight conditions.

In this study, travel time was investigated under dark roadway and rainy night-time conditions. Hypothetically, it is assumed that under rainy night-time conditions, there is speed reduction irrespective of rainfall intensity as illustrated below in figure 2.6 where,

q_D = road capacity under dry conditions, q_R = road capacity under rainy conditions
k_D = density for dry conditions, k_R = density for rainy conditions
u_D = travel speed under dry conditions, u_R = travel speed under rainy conditions

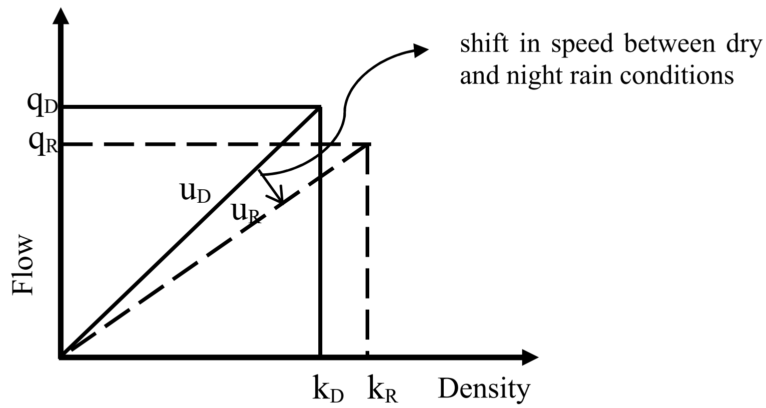


Figure 2.6: Hypothetical shift in travel speed due to rainfall at night

2.5.2 Travel Speed

In order to estimate travel time, average travel speed and the travel distance are required with consideration of the degree of saturation (volume/capacity ratio). The speed over a specified section of highway, being the distance divided by travel time is the average speed. In most countries, road speed limits are used to set the maximum (or minimum in some cases) speed at which road vehicles may move legally on certain sections/segments of the road. Travel speed can be estimated in many ways including percentile spot speed, speed/density relationship, and speed/volume-capacity ratio methods. The spot speed measurement method is based on the existence of inductance loop detectors (single or dual) for the provision of real time traffic information. Other techniques involve infrared and radar technologies. These systems are often use in measuring the traffic stream speeds at certain and fixed location for a short segment along a road. To compute spatial travel speed over a whole trip, these spot speed measurements are adopted using the space mean speed estimates. The 85th percentile speed is a value that is used in many countries for establishing regulatory speed zones. The 85th percentile speed is the speed at or below which 85 percent of the motorists driving on a given road is unaffected by slower traffic or poor weather. This 85th percentile speed designates the reasonable speed in which most motorists on the road are considered under ideal conditions. It is a good guideline in setting the appropriate speed limit for the road. Traffic engineers rely on the 85th percentile rule to help establish speed limits on non-local streets.

Typically, the speed limit is set to the speed that separates the bottom 85 percent of vehicle speeds from the top 15 percent. The theory behind this approach is that most drivers will travel at a speed that is reasonable and prudent for a given roadway segment. The two percentiles often used are the 85th and 15th percentiles, though consideration could be given to the 50th percentile occasionally. The 85th percentile speed is the speed value less than 15 percent of a measured field speed (HCM 2010). Mashros *et al.* (2014) opined that the 85th percentile speed is the speed at or below which 85 percent of vehicles move, the 50th percentile speed represents half of the observed speeds, while the 15th percentile speed is the speed at which 15 percent of vehicles are moving. They further stated that the 85th percentile is used in determining the safe speed of majority of drivers on the road while the 15th percentile speed determines the allowable speed limit on a roadway. The 50th percentile gives the average speed of the traffic stream observed. Furthermore, Hou *et al.* (2012) reported that the 85th percentile speed is used in establishing the speed limit while the 15th percentile speed is for setting the walking speed for signal timing.

As it is important to compare samples in a population, statistical tests are used to assess the significance of different samples. Some of the statistical tests according to Mashros *et al.* (2014) and Hou *et al.* (2012) include nonparametric double bootstrapping, quantile regression, averaging percentiles and a binomial test. They opined that the use of the statistical tests is complex and questionable. However, Hou *et al.* (2012) proposed the use of Cramer's theory of asymptotic distribution of sample quantile as a statistical test for testing the 85th and 15th percentile of a sample. The Cramer's theory is used to establish the normality of data and is expressed mathematically as equation 2.3

$$\frac{(X_{([n0.85])+1} - Y_{([n0.85])+1}) - 0}{1.530\sqrt{\frac{S_x^2}{n_x} + \frac{S_y^2}{n_y}}} \qquad 2.3$$

Where $X_{([n0.85])+1}$ and $Y_{([n0.85])+1}$ are the 85th sample percentiles from independent normal distribution, and S_x^2 and S_y^2 are sample variances.

2.5.3 Volume/Capacity Ratio

Volume-Demand-to-Capacity Ratio (v/c) is a measure use to signals mobility and quality of travel of a facility or a section of a facility. Volume-to-capacity ratio (v/c) is the principal performance measure for the highway-based (non-ferry) critical segments. (v/c) is often associated with defining the performance of a roadway is performing and is also referred to as the level of service. It is a conventional level-of-service measure for roadways, comparing roadway demand (vehicle volumes) with roadway supply (carrying capacity). It is a common measure in assessing performance for the metropolitan planning organization (MPO) and is widely used in congestion management strategies (CMS) and transportation studies. This measure is use in alerting the transportation providers to areas that requires traffic mitigation measures. For example, a v/c of 1.00, the implication is that the roadway facility is operating at its capacity. In the past, a v/c greater than 0.5 was considered a capacity deficiency. However, based on improved technology and accuracy today, a v/c of 0.9 is taken as a better and appropriate threshold due to a greater awareness of environmental issues and limited financial resources, as systems operations begin to deteriorate at this level.

2.6 Roadway Capacity

Roadway capacity is the maximum hourly flow rate at which vehicles or persons are reasonably expected to pass a certain point or uniform section of a roadway for a specified period under specific roadway, traffic, control and environmental conditions (HCM, 2010). Generally, roadway capacity has received attention from many researchers in which the definition of capacity has been queried and recognised to be inadequate and impracticable. Hall and Agyemang-Duah (1991) pointed out that the definition did not cover all situations of roadway traffic for which capacity is required, Minderhoud *et al.* (1996) argued that roadway capacity can only be defined in terms of the quality of traffic flow of a road facility, while Elefteriadou and Lertworawanich (2003) opined that the capacity definition is not adequate for freeway capacity because the roadway becomes congested and 'breakdown' when demand is above specified capacity value. Jia *et al.* (2000) and Sugiarto (2015) suggested that capacity predictions based on physical capacity as given by the HCM (2000) can be misleading.

In a similar manner, Homan (2012) pointed out that the phrase 'reasonable expectation' in the HCM 2000 definition signifies an inconsistency in the numerical value of the maximum number of vehicles. Ben-Edigbe (2009) opined that the HCM 2000 roadway capacity definition proposes section measurement under specific conditions i.e. sections with different conditions will have different capacities thereby indicating that capacity is stochastic in nature (Minderhoud *et al.*, 1997). It can be argued that the stochastic nature of roadway capacity, which is a result of the differences in driver behaviour, and road and weather conditions, is responsible for the inability to give a definite and acceptable definition. Traffic parameters used for estimating roadway capacity are density, speed and flow. The estimation of roadway capacity is important in analysing traffic studies for quantity and quality purposes. According to Suresh and Umadevi (2014), capacity is regarded as an estimate and a probabilistic measurement due to variations occurring from time to time and place to place in similar facilities though the variations cannot be accurately accounted for. Minderhoud *et al.* (1996) stated that capacity is stochastic in nature due to differences in drivers' behaviour, road and weather conditions. *Traffic Flow* involves the movement of drivers and vehicles between two points and the interactions they make with one another. The complexity in operation is due to the various characteristics exhibited by vehicles occupying the road under various driving behaviour. To measure the varying characteristics effect on driving behaviour, the term 'passenger car equivalent' was introduced as a common basis in attaining uniformity for all vehicle types.

2.6.1 Passenger Car Equivalency

Passenger Car Equivalent (PCE) also known as "Passenger Car Unit" (PCU) is a metric unit used to evaluate the traffic flow rate on a roadway by converting different types of vehicles in a mixed traffic volume into an equivalent number of passenger cars. Shalini and Kumar (2014) defined passenger car equivalence as a measure of the effect of a typical mode of transport on traffic variables (such as speed and headway) compared to a passenger car. Passenger car equivalence was first introduced in the HCM (1965) to describe the displacement effects of passenger cars due to the presence of trucks and buses in a traffic stream under prevailing roadway and traffic conditions. The HCM (2010, p. 9-13) further define passenger car equivalent as '*the number of passenger cars that will result in the same operational conditions as a single heavy vehicle of a particular type under specified roadway, traffic, and control conditions*' So, PCE is basically used to describe the impact of a typical mode of transport with respect to road traffic parameters such as speed, headway and density, in comparison with a car. This impact affects the quality and quantity of traffic flow on roadways. The HCM (2010) uses the passenger car equivalent factors to estimate the effect of heavy vehicles in a traffic stream's behaviour under mixed traffic conditions. Also, the passenger car equivalent describes the capacity of a roadway because both are used in stating the quantity of traffic flow rates.

The definition of capacity can be stated in terms of passenger car units (Alhassan and Ben-Edigbe 2012a). It is therefore possible to connect passenger car equivalency values with capacity measurements in a traffic flow. Nevertheless, one may argue that since capacity could be stated in terms of passenger car equivalents, therefore, factors affecting road capacity could also have an impact on passenger car equivalents. It is an acceptable assumption that heavy vehicles are larger than passenger cars thereby occupying more space in a traffic stream. The operating abilities of heavy cars are lesser and more inferior to passenger cars thus making heavy vehicles require longer and higher headways (Ahmed, 2010). Many research efforts have addressed the impact of heavy vehicles on the capacity of a roadway. Mehar, Chandra and Velmurugan (2014) established that passenger car equivalence, which is a function of geometric and traffic conditions present at the time of the survey, is a complex parameter. While Patil and Adavi (2015) opined that factors such as vehicle conditions, traffic stream, roadway, environmental, climatic and control conditions affect passenger car equivalence. Alhassan and Ben-Edigbe (2012a) opined that variations in traffic stream are responsible for the various degrees of instability on roadways which affects the quality and quantity of traffic flow. To cater for the variations in traffic stream, all traffic vehicles are converted into an acceptable common unit known as passenger car equivalent (pce) and expressed as 'pce per hour', 'pce per lane per hour', or 'pce per kilometre' length of the road lane. The passenger car equivalent differs according to vehicle type and road type. Table 2.3 represents the passenger car equivalent values as given by the Federal Ministry of Works and Housing, Nigeria.

Table 2.3: Passenger Car Equivalent Values

Vehicle type	Passenger Car Equivalent values			
	Rural roads	Urban streets	Roundabouts	Traffic signals
Cars and light vans	1.0	1.0	1.0	1.0
Heavy vehicles	3.0	1.75	2.8	1.75
Buses and coaches	3.0	3.0	2.8	2.25
Motorcycles	1.0	0.75	0.75	0.33
Pedal cycles	0.5	0.33	0.5	0.2

Source: Federal Ministry of Works and Housing, Republic of Nigeria, Highway Part 1: Design (2013)

However, the passenger car equivalents stated in table 2.3 above are based on good weather, daylight and level terrain. These values are based on South African National Roads Agency Limited (SANRAL) without guidance for modification to the Nigerian environment, therefore, there is a need to evaluate the appropriateness of the PCE values under the prevailing conditions of this study. The determination of passenger car equivalent values remains a subject of debate due to differences in estimation methods. The headway method is simple. It is the ratio of the average headway of the target vehicle to the average headway of the car. It is expressed mathematically as

$$pce_i = \frac{H_i}{H_c} \qquad 2.4$$

where pce_i = passenger car equivalent of vehicle class *i*

H_i = average headway of vehicle class i (s) and

H_c = average headway of passenger car (s)

The advantage of the headway method is that empirical headway data is easily obtained, simple and easy to calculate. Also, the headway method could be used to separate the effect of congested traffic from free flow traffic. Based on these advantages, the headway method will be adopted for a re-evaluation of passenger car equivalent values in the latter part of this study. Another method is the speed approach method by Chandra and Sikdar (2000), which is based on the physical size of the vehicle as an indicator of vehicle occupancy on road pavement. The speed approach method is expressed mathematically as equation 2.5. The method is suitable for mixed traffic conditions.

$$pcu_i = \frac{V_c/V_i}{A_c/A_i} \qquad 2.5$$

where pcu_i = passenger car unit of the vehicle class *i*

V_c = mean speed of car; V_i = mean speed of vehicle class *i*

A_c = projected rectangular area (length x width) of car on the road

A_i = projected rectangular area (length x width) of vehicle class *i* on the road

The method based on delay employs the expression in equation 2.6 below:

$$pce_{ij} = (D_{ij} - D_{base})/D_{base} \qquad 2.6$$

where pce_{ij} depicts *pce* values of vehicle class i under conditions *j*

D_{ij} denotes delay to passenger cars due to vehicle class i under conditions *j*

D_{base} denotes delay to standard passenger cars due to slower passenger cars

Alternatively, equation 2.7 is used for estimating the passenger car equivalent based on density:

$$E_T = \frac{1}{\sum_1^n P_i}\left[\frac{q_B}{q_M} - 1\right] + 1 \qquad 2.7$$

where P_i depicts proportion of trucks of type i out of all trucks

n = no of trucks in the traffic

q_B = base flow rate (passenger cars only)

q_M = the mixed flow rate

Another method using density is given below as:

$$PCU_i = \frac{k_{car}/W_L}{k_i/W_L} \qquad 2.8$$

where PCU_i = passenger car unit for *i* vehicle in a homogenous traffic behaviour

k_{car} = density of passenger car in homogenous traffic (car/km)

k_i = density of *i* type of vehicle in a homogenous traffic

W_L = lane width of the lane in a homogenous traffic

Note that equation 2.8 is only used in a homogenous traffic condition with a rule of strict lane discipline, cars following and having a constant vehicle fleet in which passenger cars and other vehicle types are assumed to have equal space mean speeds. The HCM (2010) method uses the expression stated in equation 2.9 by using the passenger car equivalent factors to adjust flow rate due to the impact of heavy vehicles in a traffic stream.

$$f_{HV} = \frac{1}{1+P_T(E_T-1)+P_R(E_R-1)} \qquad 2.9$$

where; f_{HV} = HV adjustment factor

E_T, E_R = PCE for trucks/buses and recreational vehicles (RVs) in the traffic stream, respectively;

P_T, P_R = Proportion of trucks/buses and RVs in the traffic stream, respectively;

Keller and Saklas (1984) stated that estimated passenger car equivalents are dependent on traffic volume, vehicle classification and proposed that reduction in capacity is directly related to the additional delay caused by large vehicles in the traffic stream. It is therefore expressed mathematically as:

$$PCE = \frac{TT_i}{TT_0} \quad 2.10$$

where; TT_i = total travel time of vehicle type *i* over the network in hours

TT_0 = total travel time of the base vehicle over the network in hours

Other estimation methods are based on vehicle hours, travel time, platoon formation etc. In general, the passenger car equivalent values of vehicles vary based on the methods employed to evaluate it. The most significant variation is on the heavy vehicles and many research works have been carried out on the effects of the heavy vehicles in a traffic stream. A study of passenger car equivalents for a level freeway operating under moderate and congestion conditions carried out by Ahmed (2010) revealed that passenger car and heavy vehicle headways increased with the presence of heavy vehicles in a traffic stream. He further stated that the PCE factor of 1.76 obtained was higher than the 1.5 stated in the HCM (2010) for level urban freeway sections. Other research efforts estimating passenger car equivalent values include saturation flows (Kimber *et al.* 1985), mixed traffic flow at signalised intersections (Adams *et al.* 2014), capacity loss (Alhassan and Ben-Edigbe, 2012a and b; Ben-Edigbe, 2009), estimation methods of Indian heterogenous traffic context (Metkari *et al.,* 2012), PCE values under rainfall (Alhassan and Ben-Edigbe, 2012c), levels of service for capacity analysis (Mehar *et al.,* 2014), impact of lane width (Khanorkar *et al.*, 2014) and development of passenger car equivalents (Patil and Adavi, 2015).

Tanyel *et al.* (2013) studied the effect of heavy vehicles on traffic circles and found out that different passenger car equivalent values are to be used for minor and major flows when computing the rates of heavy vehicles. Sun *et al.* (2007), while investigating the impact of passenger car equivalents at work zones, reported that the passenger car equivalents for work zones have their own distinct characteristics. As capacity can be expressed in terms of a passenger car equivalence, hence, the opinion that passenger car equivalence is dependent on roadway, traffic and environmental conditions is taken to be true. Thus, it may be right to determine the passenger car equivalent values under its prevailing roadway, traffic and environmental conditions. Consequently, it is necessary to modify the passenger car equivalents under the condition of night-time rainfall for the proper assessment of dark roadway capacity.

2.6.1.1 Appraisal of Passenger Car Equivalent Values

Passenger Car Equivalence is the measure of the effect of the transport mode on traffic variables. It is the displacement impact of passenger cars as a result of medium and heavyweight vehicles in a traffic stream under prevailing roadway and traffic conditions. The prevailing roadway and traffic conditions for the passenger car equivalent (PCE) values stated in the FMWH are different from the conditions considered in this study, thus, a need for modification of the passenger car equivalent (PCE) value is necessary though the values may or may not be significant. The modification of the PCE is done using different methods. For this study, the headway method is adopted since the automatic traffic counter captured the headway information of vehicles. In other to determine if the modified passenger car equivalent (PCE) value is significant or not, two hypotheses were set up. The two hypotheses are as follows

- Null hypothesis (H_0): No difference between the modified and the FMWH PCE values
- Alternate hypothesis (H_1): There is a difference between the modified PCE and the FMWH PCE values

The hypotheses require a statistical test to determine the significance of the modified passenger car equivalent (PCE) values with respect to the FMWH passenger car equivalent values, hence, the use of a chi-square at 95 percent level of confidence is considered. The chi-square test is presented as equation 3.4 below

$$X^2 = \frac{(o-e)^2}{e} \qquad 2.11$$

where X^2 = chi-square

o = observed value

e = expected value

2.6.2 Roadway Capacity Estimation Methods

Minderhoud *et al.* (1996) identified two methods (direct and indirect) of estimating capacity. The direct empirical method, which is of interest to this study, is stochastic in nature and uses data in formulating models to predict traffic flow and estimate road capacity. The empirical methods rely on headway, traffic volume, average speed and density data for capacity estimation. The headway data uses the car-following theory with respect to time while speed data categorises the traffic state into stable, unstable and congested. Due to the shortcomings of traffic volumes estimation methods, other estimation methods were developed. One of these methods involves the use of traffic volumes and speed measurements to describe the state of road capacity. To obtain a good value, the upstream traffic state of the observation point must be known. Three methods are often used; empirical distribution method (EDM), product limit method (PLM) and selection method (SM).

2.6.2.1 Empirical Distribution Method (EDM)

The empirical distribution method assumes that the value of capacity is obtainable from the distribution of capacity measurements. This method depends on the distinct separation of observed flows over the period of observation. The observed flow rate measured from the upstream point is divided into two as portrayed in figure 2.7 below

- free flow measurement i.e. measurements representing traffic demand
- congested flow measurement

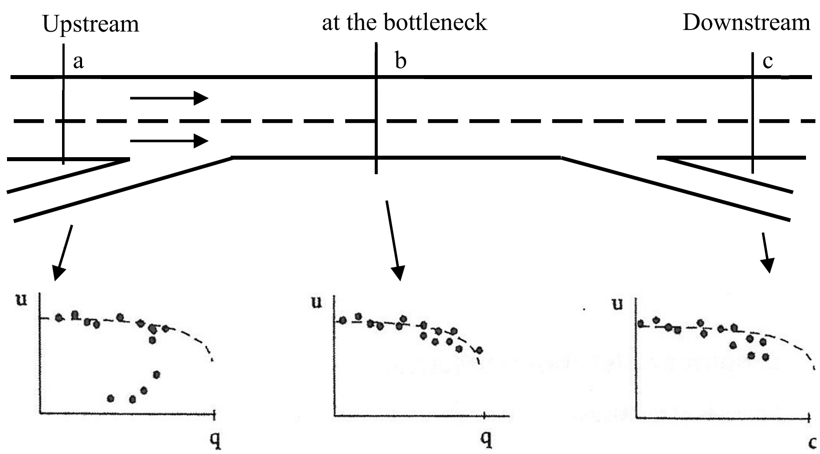


Figure 2.7: Measuring points for the application of Empirical Distribution, Product Limit, Selection Method and corresponding Fundamental Diagram
Source: Minderhoud (1996)

The function of Empirical Capacity Distribution can be determined using equation 2.12 while applying only the intensities that are elements of the capacity set {C}

$$F(q) = Prob\ (q_c \leq q) \qquad q_i \in \{C\} \qquad 2.12$$

Equation 2.12 can be re-written as equation 2.13.

$$F\ (q) = N_c/N \qquad 2.13$$

where $F\ (q)$ = cumulative distribution function of capacity values

q_c = value of capacity

q_i = value of intensity counted at average interval i

N_c = number of observation elements i in set {C} with intensities q_i less than q

N = total number of observation elements in set {C}

{C} = set of observed congested flow measurements

The acceptability of the capacity value derived from the equation above is dependent on the variance of the intensities calculated using equation 2.14.

$$Var\left(F(q)\right) = F(q) \,.\, (1 - F(q))/N \qquad 2.14$$

A major advantage of this method as reported by Minderhoud *et al.* (1997) is the clear and unbiased capacity value with its distribution based on intensity measurements during congestion conditions upstream. However, the method does not encourage the use of capacity values obtained for the free-flow measurements. In summary, the empirical distribution method has a clear meaning of its estimated capacity distribution although the frequent capacity level of the road must be attained to have a good distribution. Homan (2012) carried out a study on some work zones in the Netherlands and reported that the empirical distribution method (EDM) gives a better estimated capacity compared with the product limit method (PLM) values.

2.6.2.2 Product Limit Method (PLM)

Minderhoud (1997) capacity estimation method was modified by Brilon (2005) based on the earlier works of Kaplan and Meier's (1958) product limit method and van Toorenburg's (1986) distribution function. The modified method is written as:

$$F_c(q) = 1 - \prod_{i, q_i \leq q} \frac{k_i - d_i}{k_i}; i \in \{B\} \qquad 2.15$$

where $F_c(q)$ = distribution function of capacity c

q = traffic volume veh/h

q_i = traffic volume in interval i veh/h

k_i = number of intervals with a traffic volume of $q_i \leq q$

d_i = number of breakdowns at a volume q_i

$\{B\}$ = set of breakdown intervals

The product limit method is similar to the empirical distribution method because it also focusses on the separation of flow observations made over the period of observation. In the case of te product limit method, both the free-flow and capacity measurements are used to obtain a better idea of the real capacity value. Note that for the possibility of complete distribution function, there must be maximum observed volume followed by breakdown and recovery, otherwise, the complete distribution function will not be possible because end in a value less than one. Generally, a complete capacity distribution function is hardly achieved; even if attained, for a higher volume, it may not be as reliable as such unless a large quantity of data is gathered.

According to Brilon (2005), product limit method on the other hand does not require the assumption of a specific type of distribution function. Maximum likelihood estimation is a method that determines values for the parameters of a model. The parameter values for this method are obtained such that they maximise the possibility of the process described by the model produces the data that was observed. In general, the maximum likelihood method (according to its name) is a parametric method whose success is dependent on the strength of the distributional assumptions made. A maximum likelihood technique given by Lawless (2003) to estimate the parameters of the distribution functions is given below as:

$$L = \prod_{i=1}^{a} f_c(q_i)^{\delta i} \, [1 - F_c(q_i)]^{1-\delta i} \qquad 2.16$$

where $f_c(q_i)$ = statistical density function of capacity c

$F_c(q_i)$ = cumulative distribution function of capacity c

n = number of intervals

δi = 1, if uncensored (breakdown of classification B)

δi = 0, elsewhere

Transformed into capacity analysis, Log-likelihood function is rewritten as:

$$\ln(L) = \sum_{i=1}^{n} \{\delta i \ln[f_c(q_i)] + (1 - \delta i)\} \ln[1 - F_c(q_i)] \qquad 2.17$$

The drawbacks of this method include the large number of capacity measurements required and its unsuitability for off-peak data collection. Also, the quality of the estimated capacity is doubtful since the product limit method gives no information regarding the capacity distribution. Ben-Edigbe *et al.* (2013) reported that the product limit is weak in estimating capacity because there are inconsistent results arising from the randomness in the selection of capacity values from the cumulative distribution function.

In any case, traffic capacity using product limit method is a "location characteristics of the estimated distribution of capacity" (Minderhoud *et al.,* 1996, p. 36). The location characteristics include the mean, median and a percentile point while the estimated distribution is obtained from the empirical distribution of capacity observations contained in the high-volume free-flow observations information. To use this method, a large database of volume and speed measurements are required, and a bottleneck location to ascertain the capacity state of the road whenever congestion is detected upstream. Equation 2.18 gives the empirical distribution function:

$$G(q) = Prob(q_c > q) \qquad 2.18$$

where $G(q)$ = the probability that capacity value > certain intensity q, and

$F(q)$ is defined as $1 - G(q)$.

The Product limit function is generally expressed as equation 2.19 below:

$$G(q) = \prod_{qi} \frac{K_{qi}-1}{K_{qi}} \qquad q_i \in \{C\} \qquad 2.19$$

Where; K_q = number of observation elements *i* in set {S} with intensity $q_i \geq q$

$\{C\}$ = set of observed congested flow intensities

$\{Q\}$ = set of observed free flow intensities

$\{S\} = \{Q\} \cup \{C\}$, $\{S\}$ is set of all observations *i*

A simple example of the product limit method using a 15-minute averaging interval which was converted into one-hour data is shown below in table 2.4. From the table, column 1 represents the hourly traffic flow observations while column 2 is the flow rates (q_i) at each interval (i). Column 3 represents the traffic categories in which Q stands for free flow while C stands for congested flow. Ranking of the flows in ascending order is presented in column 4. In column 5, the flow intensities that are equal or greater than the threshold capacity values are taken as 1. Thereafter, the discrete functions G(q) and $F(q) = 1 - G(q)$ were calculated. However, the usefulness of the product limit method is questionable because there is no information about the quality (reliability, precision) of the estimated capacity value.

Table 2.4: Product Limit Method calculation

1 interval i	*2* q_i	*3* Set	*4* Order *j*	*5* k q_i	*6* G*(q)*	*7* F*(q)*
1. 15.30 - 15.45	3000	Q	2	-		
2. 15.45 - 16.00	2500	Q	1 lowest	-	1	0
3. 16.00 - 16.15	3500	C	3	6	5/6 = 0.83	0.17
4. 16.15 - 16.30	4000	Q	4	-		
5. 16.30 - 16.45	4000	C	6	3	5/6.3/4.2/3 = 0.41	0.59
6. 16.45 - 17.00	4500	Q	7	-		
7. 17.00 - 17.15	4600	C	8 highest	1	5/6.3/4.2/3.0/1 = 0	1
8. 17.15 - 17.30	4100	C	5	4	5/6.3/4. = 0.62	0.38
2 hours	Average Flow 3775	Total I = 8 i in (Q) = 4 i in (C) = 4				

Source: Minderhoud (1996)

2.6.2.3 Fundamental Diagram Approach

The fundamental diagram gives the relationship between traffic flow, speed and density. It is one of the most important principles in traffic flow theory. The fundamental relationship consisting of flow, density and speed is expressed below as:

$$q = u \,.\, k \Rightarrow u = \frac{q}{k} \Rightarrow k = \frac{q}{u} \qquad 2.20$$

The flow-density relationship can be written as;

$$q = k u_f \left(1 - \frac{k}{k_j}\right) \qquad 2.21$$

The flow-density slope represents the speed;

$$u = q/k \qquad 2.22$$

where u = Speed; q = flow; k = density
u_f = free flow speed; k_j = jam density

The flow-density curve has two sections *viz.* unconstrained (left side) and constrained section (right side). The unconstrained section operates under free-flow speed – a condition where speed oscillates between the unconstraint and constraint ultimate point (q_m), while flow contracts at the constrained section. The flow-density curve has four basic boundary conditions, which are:

- flow is zero when density is zero i.e. $q = 0$ at $k = 0$
- when density is at jam condition, flow is zero i.e. $q = 0$ at $k = k_j$
- speed is equal to free flow when density is zero i.e. $u = u_f$ at $k = 0$
- speed is zero when density isq_i at jam condition i.e. $u = 0$ at $k = k_j$

As flow increases, density also increases till it gets to a maximum point referred to as the critical density. Beyond the critical density traffic flow has entered a congestion section till jam density is reached. At this jam density, the flow of vehicles is hindered as there is a total breakdown. As density increases in the constrained section, the speed reduces and thereafter, becomes zero when the density is at a jam (k_j) i.e. no movement of vehicles.

Speed is an important control index in road planning, and it is also an evaluation index of vehicle operation efficiency. Density reflects the intensity of the vehicles on the road and determines traffic management and control measures. The earliest speed-density model was a linear model proposed by Greenshields *et al.* (1935). The linear model overlaps and classifies the observed data groups, which is proved to be unreasonable, with a narrow range of representations, so there are some deviations between the derived speed-density relation and the actual situation. Later, the relationship between speed and density was studied in greater depth, and the Greenberg logarithmic model, the Edie model, the Underwood exponent model, the Pipes-Munjal model, a modified Greenshields model, the Newell model, and so forth, emerged in turn (Wang *et al.*, 2013; Gupta *et al.*, 2014).

Heydecker and Addison (2011) investigated the relationship between density and speed based on various speed limits and reported that zero speed generates traffic jams, and not the other way around. Ma *et al.* (2015) derived a general logistic model of traffic flow characteristics using several traffic flow parameters with clear physical meanings. The effects of the parameters on speed-density logistic curves were analysed and the experimental results concluded that the model is capable of describing well the traffic flow characteristics in different states. Shao *et al.* (2015) proposed a speed-density model under congested traffic conditions combined with the minimum safety spacing constraint, and the results of the experiment indicated that the absolute error of this model was smaller than that of other models fitting the traffic data of two freeways. Wang *et al.* (2011) proposed a family of speed-density models using a number of parameters with important physical significance and got good performance in the final experiment. Travel speed-density models can be divided into two classes; single regime and multi-regime models. The Greenshields speed-density equation is:

$$u = u_f - \frac{u_f}{k_j} . \mathrm{k} \qquad 2.23$$

Although the function expressions are different, they are more or less similar in the domain $k \in \langle 0, k_j \rangle$ However, some of them do not satisfy the two boundary conditions $v(0) = v_f, (k_j) = 0$ simultaneously. Single regime models describe the relationship between flow, speed and density with a single functional form, whereas multi-regime models usually include two or three regimes to describe different traffic conditions. Typical multi-regime models include the Edie model (1961), the modified Greenberg model and three regime models. Edie (1961) showed that the Greenberg model (1959) in equation 2.24 can be obtained by integration of the car following model in equation 2.25.

$$v = V_m ln\left(\frac{k}{k_j}\right) \qquad 2.24$$

$$w_{\ddot{x}_{n+1}}(t) = \lambda_i \frac{(\dot{x}_n\langle t+\Delta t\rangle - \dot{x}_{n+1}(t+\Delta t))}{(x_n\langle t+\Delta t\rangle - x_{n+1}(t+\Delta t))} \qquad 2.25$$

w = vehicle mass; λ_i = driver sensitivity character coefficient; Δt = Average time lag, a constant, for driver-car system $x_n(t)$, x_{n+1} (t) = the coordinate of front vehicle and the subjective vehicle *wrt* the inertia coordinate system at time *t*, $x_m(t)$, x_{n+1} (t) is the distance headway. It is noted that a constant Δt would not affect the integration. Using the relationship between average distance headway and density,

$$k = 1/y = \frac{1}{x_n - x_{n+1}} \qquad 2.26$$

The boundary condition $v\left(k_j\right) = 0 \; and \; V_m = \lambda_1/W$ is obtained.

Generally, the Greenberg model is obtained by adding parameters for data fitting flexibility:

$$v\,(k) = g_1 + g_2 ln\,\langle\frac{k}{k_j}\rangle \qquad 2.27$$

It is pointed out that the flaw of the Greenberg model is:

$$\lim_{k \to 0} V_m \, ln\frac{k_j}{k} = \infty \qquad 2.28$$

Which means that the model is not suitable for sparse traffic. So, Eddie suggested that a further improvement is needed by stating the following microscopic car-following model for the uncongested traffic.

$$w_{\ddot{x}_{n+1}}(t) = \lambda_i \, \dot{x}_{n+1}(t) \frac{(\dot{x}_n\langle t+\Delta t\rangle - \dot{x}_{n+1}(t+\Delta t))}{(x_n\langle t+\Delta t\rangle - x_{n+1}(t+\Delta t))^2} \qquad 2.29$$

With the boundary condition; $v(0) = v_f$ (free flow) $if \ \frac{1}{x_n - x_{n+1}} = \frac{1}{y} = 0$

Free-flow speed is defined as the speed that occurs when density and flow are zero. Of course, observing zero density and flow does not make much sense because in verbatim, zero density suggests that there is no vehicle at all. However, one can reach the following model noticing the density and headway relationship:

$$k = 1/y, k = k_m ln\left(\frac{v_f}{v}\right); k_m = 1/y_m$$

Or equivalently, $v = v_f exp\left(\frac{-k}{k_m}\right)$ which is exactly the Underwood model (1961) where y_m = the pacing of maximum flow is estimated by minimising the $q(v)$;

k_m = the density of maximum flow

Parameters ω_1 and ω_2 are added for flexibility in the data fitting:

$$v = V(k) = \exp\langle -\omega_1 \frac{k}{k_m} + \omega_2 \rangle \qquad 2.30$$

It is strictly concave for $k \, \epsilon \, \langle 0, 2k_m \rangle$

Those two can be combined in one model as:

$$v\,(k) = \begin{Bmatrix} \exp\left[-\omega_1 \frac{k}{k_j} + \omega_2\right], & k \le k_j \\ g_1 + g_2 ln\langle \frac{k}{k_j} \rangle, & k > k_j \end{Bmatrix} \qquad 2.31$$

The following polynomial model is cited by Zhang (1999) as the one-parameter polynomial model:

$$v = v_f\left(1 - \langle \frac{k}{k_j} \rangle^n\right) \qquad 2.32$$

where; v_f = free-flow speed, k_j = jammed density, n=1 is the Greenshields model (1934).

This model can be considered as a special case of the exponential model used by Hegyi *et al.* (2002)

$$v(k) = v_f \, exp\left(-\frac{1}{\varphi}\langle\frac{k}{k_c}\rangle^{\varphi}\right) \qquad 2.33$$

Where; v_f = free flow speed; φ = model parameter; k_c = critical density, are the same as the k_m used by Eddie. In any case, it generalises somehow the Underwood model. The Greenshields model with meaningful parameters is the simplest of all the models. It also works over a large density range and statistically fits empirical observations of road traffic. The shortcomings include the inability to predict speed at low densities and the need for a specified model for data fitting. It causes the bridging of the macroscopic traffic stream model to a microscopic car-following model. The Greenberg's model assumes that as density approaches zero, speed tends to infinity. The Underwood's model tries to overcome the shortcomings of the Greenberg model by proposing that speed becomes zero when density is at infinity level. Other research works using fundamental diagram includes Alhassan and Ben-Edigbe (2011a,) Ben-Edigbe *et al.* (2013), Alhassan and Ben-Edigbe (2014), Suresh and Umadevi 2014, Mukhlas *et al.* (2016). Khanorkar *et al.* (2014), reported that the fundamental diagram returns a futuristic value thereby making it suitable for all operating conditions of a roadway. According to Ben-Edigbe and Ferguson (2005), equation 2.33 could be presented as equation 2.34 and used for estimating roadway traffic capacity. According to Alhassan and Ben-Edigbe (2014), traffic flow contraction is dependent on rainfall intensity and may lead to platoon formation and bunching of vehicles on the road. The platoon formation and bunching of vehicles result in capacity loss.

$$Q = -\frac{u_f}{k_j}\left(\frac{u_f}{2\left(\frac{u_f}{k_j}\right)}\right)^2 + (u_f)\frac{u_f}{\left(2\frac{u_f}{k_j}\right)} - c \qquad 2.34$$

where; u = space mean speed; u_f = space mean speed for free flow

k_c - critical density = $\frac{u_f}{2\left(\frac{u_f}{k_j}\right)}$; k_j = jam density

If travel time in equation 2.1 is fused with equation 2.34 for roadway capacity, it implies that the travel time model equation can be rewritten as

$$T = \frac{d}{u_f}\left[1 + \rho\left(\frac{v}{-\frac{u_f}{k_j}\left(\frac{u_f}{2\left(\frac{u_f}{k_j}\right)}\right)^2 + (u_f)\frac{u_f}{2\left(\frac{u_f}{k_j}\right)} - c}\right)^{\beta}\right] \qquad 2.35$$

Note that equation 2.35 is suitable for determining travel time for rainy and dry conditions during daylight and at night-time periods. Mashros *et al.* (2012, 2014) opined that using travel time together with speed and flow measures the quality of road service delivery.

2.6.3 Hypothesis on dark roadway capacity shifts due to rainy night-time conditions

Rainfall impact on roadway capacity cannot be overemphasised as it contributes to the inconsistency of the traffic flow rate. The inconsistency ensues from changes in traffic volume and speed. The changes result in capacity loss. Capacity loss is therefore the difference in the flow rate under prevailing conditions. an impact study of environmental factors gained attention after the pioneer study of weather effects on traffic flow by Tanner (1952). Thereafter, several studies on rainfall impact have been carried out. Such studies include traffic volume and behaviour (Hogema, 1996), accidents (Eisenberg, 2004; Keay and Simmonds, 2005), traffic intensity (Cools *et al*., 2010), capacity (Chung *et al.,* 2006). Other rainfall related studies are accident and safety (FHWA, 2008), accident (Changnon, 1996), travel time and demand (Chung *et al.,* 2005a), travel demand and traffic accident (Chung *et al.,* 2005b), traffic parameters (Sandor, 2014; Mukhlas *et al.,* 2016) and surface transportation applications (Pisano *et al.,* 2002), sight distance (Ben-Edigbe *et al.,* 2013), capacity (Alhassan and Ben-Edigbe 2011a), and traffic operation (Xu *et al.,* 2013). Worth noting is the fact that all the studies reported the influence of rainfall on traffic flow characteristics in different proportions and without any trend. A significant change in the macroscopic traffic flow parameters under rainfall condition was evident under varying prevailing conditions. Nevertheless, most of the studies were carried out under daylight conditions while there are few reports on night-time conditions. The few reports on night-time conditions majorly focussed on safety, accident occurrence and visibility. However, as driving is a 24-hour activity, it is therefore a necessity to understand roadway traffic performance under rainy night-time conditions for dark roadways since the impact of night-time rain on traffic cannot be overemphasised.

In considering the mechanisms by which rainfall conditions may possibly influence the quality of highway service, two important groups of factors are considered: the changing composition of traffic and the changing behaviour of drivers. In dry weather and daylight conditions, given a certain traffic density, drivers tend to travel at higher speeds while keeping shorter distances between vehicles ahead without lowering their speed or may choose a different lane of the carriageway (multi-lanes). They may even prefer to change routes or departures times because of improved weather and traffic conditions. In line with the study's aim, questions on roadway capacity and the performance of its parameters under night rain on dark roadways are necessary in achieving the study's objectives. What is the effect of rainfall on traffic flow characteristics such as speed, flow, and travel time? Does the effect generate a corresponding influence on roadway capacity? If it does, to what extent is the effect? How does it affect the overall service delivery of the roadway relative to its functional service quality? These questions are to be answered in this study.

Based on the questions raised, it may be stated hypothetically that irrespective of rainfall intensity, a dark roadway for a two-lane highway without light will experience speed reduction, capacity and travel time loss under rainfall at night. For this hypothesis to hold, it is important to understand the mechanism of traffic operation under dry condition and its equivalent operation under rainfall at night-time using flow-density relationship as shown in figure 2.8 below.

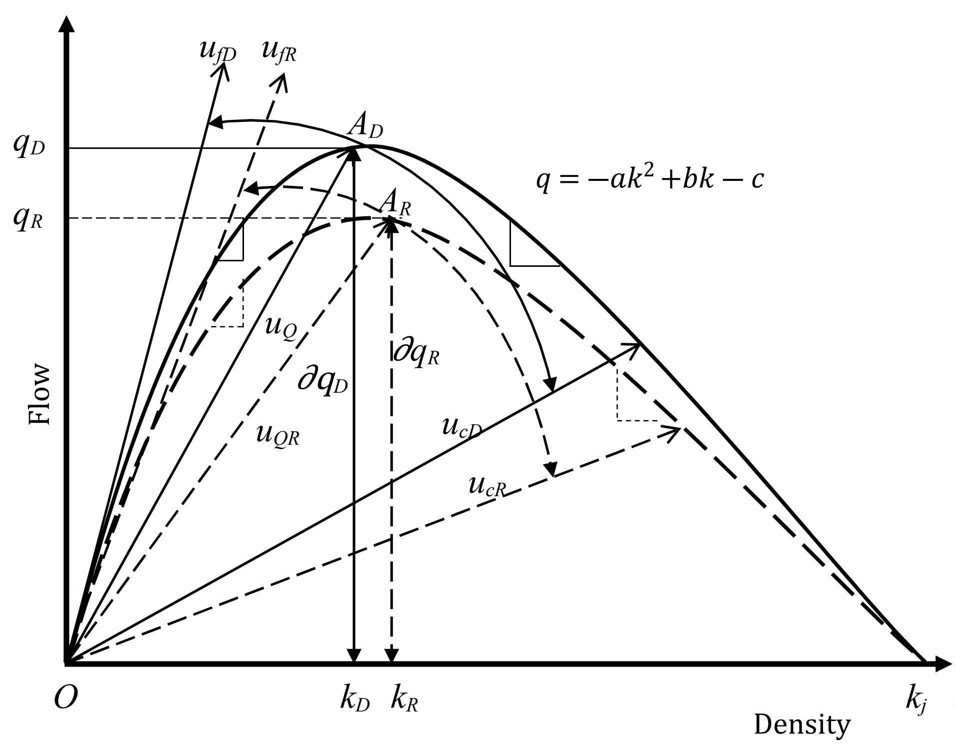


Figure 2.8: Hypothesis on dark roadway capacity shifts due to night rain

According to figure 2.8, OA_DB represents the path of traffic operation under normal and dry conditions. For the traffic operation, two possible traffic conditions are identified, and they are free-flow and congested conditions. At point O, the initial stage of traffic flow, density and flow are zero but as flow increases, density also increases along path OB. When the flow reaches point A_D, traffic is said to be at its maximum flow and its represented as $q_D = q_m$ while its corresponding density is at k_D. Traffic is said to be in a non-congested condition because the traffic is unconstrained and a free-flow speed u_f condition exists within this section until the maximum flow q_m is reached and the flow-density slope (OA_D) represents traffic speed u_{QD} at maximum capacity. Similarly, path OA_RB represents traffic operation under rainy conditions in which its maximum flow is given as q_R with corresponding density k_R and speed at capacity u_{QR}. Note that the free-flow speed is not the same as the ultimate speed as there is a variation in density from the unconstrained section to the constrained section. Traffic operates within the finite boundaries of 0 and k_j but the finite boundaries cannot be divided into equal parts i.e. the concavity is not symmetrical but asymmetrical (Ben-Edigbe, 2009) therefore, the speed at the unconstrained section will not be the same for the constrained section. One advantage of this flow-density fundamental diagram is that it allows the three basic traffic parameters to operate within its envelope such that a change in any of the parameters will influence the remaining parameters. This is supported by the report of Park *et al.* (2010) that the condition of any two parameters in a traffic stream will affect the third parameter. This affects both the quality and quantity of traffic flow.

Many studies have used the flow-density relationship in analysing traffic operations in terms of travel speed, capacity, headway, safety amongst others. Such studies investigated the impacts of rainfall on traffic flow parameters - traffic volume and behaviour (Hogema, 1996), accidents (Eisenberg, 2004; Keay and Simmonds, 2005), traffic intensity (Cools *et al.,* 2010), capacity (Chung *et al.,* 2006). Other rainfall related studies are about accidents and safety (FHWA, 2008), accident (Changnon, 1996), travel time and demand (Chung *et al.,* 2005a), travel demand and traffic accident (Chung *et al.,,* 2005b), traffic parameters (Sandor, 2014) and surface transportation applications (Pisano *et al.,* 2002), sight distance (Ben-Edigbe *et al.,* 2013), and capacity (Alhassan and Ben-Edigbe, 2011a). Greenshield *et al.* (1935), van Aerde (1995) and Wu (2002) used the fundamental diagram to illustrate the behavioural characteristics of traffic relative to its macroscopic parameters. Logghe and Immers (2003) used it to evaluate passenger car equivalent values of heavy vehicles in a traffic stream, while Rahka (2008) used it to study the effect of weather on freeway traffic streams. Billot (2009) studied the effect of inclement weather on traffic using the speed-flow relationship of the fundamental diagram. The fundamental diagram is considered as a better option for verifying the extent of speed reduction occasioned by night rain. Alhassan and Ben-Edigbe (2011a) stated that rain is the main weather element that contributes to the variability of flow rate while its impacts on traffic are due to its spatiotemporal nature. The impacts of rain on traffic flow parameters result in disturbances to roadway traffic and capacity. As drivers are forced to reduce their speed, headway increases with a contraction in traffic flow. This is supported by Alhassan and Ben-Edigbe (2014) that rainfall's effect on flow disruptions affect individual vehicles and the traffic stream which in turn leads to traffic flow contraction and speed reduction. They further stated that flow contraction is dependent on rainfall intensity and may lead to platoon formation and bunching of vehicles on the road. The platoon formation and bunching of vehicles result in capacity reduction.

2.7 Implication of Night Rain on Stopping Sight Distance for Dark Roadway

Rainfall affects traffic flow performances by way of poor visibility and tyre traction among others. Drivers have no control over these factors. In these circumstances, what they can control is how well they handle and react to rainy night-time challenges; especially abrupt stopping. On any rainy day, traffic flow performances are affected by wet surfaces and poor visibility among others. Motorists reduce speed and increase the space between vehicles as a safety net against abrupt stopping. Night-time driving is remarkably different compared to daylight driving. Probably the most obvious hazard of night-time driving is decreased visibility. Imagine night-time driving in the rain on dark roadways without lights and the multitude of associated problems that the drivers must overcome, it can therefore be argued that the night-rain will have an effect on the roadway stopping sight distance. Road lights prevent accidents and increases safety (Rea *et al.*, 2009). Road casualty statistics show that 40 percent of collisions occur in the hours of darkness. Therefore, the provision of lights on roadways is important and beneficial to road users. The benefits vary from road security, the general safety of life, and good road performance to improved visibility amongst others. Rain poses a major hazard with various impacts on road and traffic performances due to its spatiotemporal nature (Alhassan and Ben-Edigbe, 2011a). Wet road surfaces and breaking distance have a clear correlation with vehicle collisions.

There is a clear distinction between wet road surfaces under dry weather conditions and wet road surface during rainfall. When it rains, the road surface becomes slippery due to a loss of friction between the road pavement surface and the tyre. As the vehicle tyre moves over the wet surface, the rainwater acts as a smooth film/cover between the pavement surface and vehicle tyre. This smooth film reduces the '*gripping force*' between the road and tyre surfaces. The gripping force, otherwise known as frictional force, is measured as the skid resistance required in countering road slipperiness. The road slipperiness is measured using braking distance with respect to the coefficient of friction between the road pavement surface and tyre. However, braking distance is a component of stopping sight distance used by road providers for road design and safety purposes. Stopping sight distance (SSD) is the length of roadway that should be visible to ensure that a driver does not hit an object on his/her path. It is an important aspect of road design for safety purposes because it is associated with good visibility which makes it a traffic safety indicator (Ben-Edigbe *et al.,* 2013). It is made up of two component paths; reaction and braking distance. It can be stated that if visibility is blurred irrespective of how it happened, drivers will reduce their approach speed automatically. Since this study is carried out on straight road segments, these three basic equations for uniform acceleration are useful.

$$v = u + at \tag{2.36}$$

$$s = ut + \frac{at^2}{2} \tag{2.37}$$

$$v^2 = u^2 + 2as \tag{2.38}$$

Where; v is final velocity, u is initial velocity, t is time and s is distance covered during acceleration

Stopping distance is made up of reaction distance (the distance the car travels from the point when the driver realises a need to 'brake' and actually start to apply the brake), and braking distance (the distance a vehicle moves from the point when the driver starts to press the brake pedal and when the vehicle comes to a complete halt). Stopping sight distance (SSD) is an important road design parameter consisting of the reaction distance and the braking distance. Years of research and practice have led to vehicle tyre tread which offers good traction under various conditions. Tyre tread channels water away from wet road surfaces thus reduces the tendency to hydroplane. The friction between vehicle's tyres and road surface contributes immensely to acceleration, deceleration and stopping sight distance. Typically, the stopping sight distance (SSD) equation shown below is made of braking and reaction distance.

$$SSD = vt + \frac{v^2}{2a} \quad 2.39$$

Where; *v* denotes vehicle speed; *t* denotes driver reaction time; *a* denotes deceleration.

According to Gerlough and Huber (1975) in earlier car-following research, the driver reaction time is defined as the summation of perception time and foot movement time. Reaction times vary greatly between about 1.5seconds to 3seconds or more. Some accident reconstruction specialists use 1.5seconds. Since human characteristics are dynamic, the estimation of reaction time need not be fixed, however, an assumption of a fixed reaction is permissible in certain circumstances as shown below in General Motor's nonlinear car following model equation:

$$a_n(t + \tau_n) = \alpha \frac{v_n(t+\tau_n)^{\beta}}{[x_{n-1}(t) - x_n(t)]^{\gamma}} [v_{n-1}(t) - v_n(t)] \quad 2.40$$

Where; x (t), v (t), and a (t) = position, speed, and acceleration of the vehicles;

τ_n ~ reaction time fixed value for a certain driver n;

α, β, γ = constant parameters.

Braking distance is a significant basic parameter because it is the overall distance travelled by the vehicle from the onset of brake application to the complete halt of the vehicle. Braking distance is primarily affected by the original speed of the vehicle and the coefficient of friction between the tyres and the type of road surface. Vehicle braking is pre-determined by various factors that differ in their character of impact, intensity and duration. The rate of stopping the car or slowing down the car is deceleration. It is not necessary to specify both the deceleration rate and the coefficient of friction because they both measure the required deceleration rate. However, if deceleration (a) is used as a linear function of friction and initial speed, then the average deceleration for the entire braking process can be expressed as:

$$a = \partial \sqrt{f} + \omega u \quad 2.41$$

Where; ∂ and ω are regression constants; f = coefficient of friction and *u* is speed

The use of deceleration (a) varies from country to country. The American Association of State Highway and Transportation Officials (AASHTO) recommends 3.4 m/s^2. Other countries such as Germany, Ireland, and the United Kingdom recommends 3.7 m/s^2, 3.68 m/s^2 and 2.45 m/s^2 respectively (Van Petegem *et al.* 2014). The variation in deceleration rates is dependent on the coefficient of friction and its associated speed. According to Tromp (1994), on dry surfaces, the friction on porous asphalt is less than on dense asphalt. For newly applied porous asphalt maximum deceleration (locked wheels) for new porous asphalt is 6 m/s^2, for old porous asphalt 7 m/s^2, and 8 m/s^2 for dense asphalt.

The coefficient of friction is the ratio of frictional resistance force to the normal force between the tyre and road surface. This is offered by tyre tread which creates good traction under varying conditions on various road surfaces. The friction generated by vehicles tyres and road surfaces contributes greatly to deceleration, acceleration, braking distance and stopping distance. The coefficient of friction varies for different road surfaces under varying prevailing conditions. For dry surface and wet surfaces, Jones and Childers (2001) reported 0.7 and 0.4 respectively but further stated that the coefficient of friction value could be as high as 0.9 for dry surfaces and as low as 0.1 for the wet surfaces. It is rather unclear whether the wet road is under rainfall or dry weather conditions, nevertheless, it contained enough reasoning to substantiate the admission of 0.7 for dry and 0.4 for wet road surfaces. What is clear from the postulations is that the friction factors for wet and dry road surfaces have different values. Other studies reported 0.28 to 0.4 for wet pavement based on varying design speeds (AASHTO, 2011; Shi, *et al.* 2013). Vejregler (2012) suggested coefficient values of 0.35 for the speed range of 110 to 90 and a coefficient value of 0.35 for 80km/h on wet pavement surfaces. AASHTO (2011) suggested a deceleration rate (a) of 3.4 m/s^2 resulting in a friction coefficient of 0.35 for a wet pavement surface. However, for this study, a distinction must be made between during and post-rainfall wet road surface bearing in mind that during rainfall visibility is an added driving problem. What is clear from the postulations is that the friction factors for wet and dry road surfaces have different values. Therefore, stopping sight distance (SSD) for dry weather condition is presented as;

$$SSD = (0.278v)t + \frac{(0.278v)^2}{2a} \qquad 2.42$$

Where; v ~ speed (m/s), t ~ reaction time (s), a ~ deceleration rate (m/s^2)

The stopping sight distance for rainy night-time conditions takes into consideration the vehicle speed differential relative to time. Therefore, the deceleration rate under rainy night-time conditions is computed using equation 2.43.

$$a_{(t_2)} = \frac{(v_1 - v_2)}{(t_2 - t_1)} \qquad 2.43$$

Where: a denotes deceleration at time t_2, v ~ speed and t ~ time

If equation 2.43 is inserted into equation 2.42, then the model equation for SSD_R during night rainfall on a dark roadway is rewritten as:

$$SSD_R = (0.278v)t + \frac{(0.278v)^2}{2\left|\frac{(u_1-u_2)}{(t_2-t_1)}\right|} \quad 2.44$$

Speed has been shown to have a negative linear relationship with density (Greenshields, 1935).

$$v = v_f - \frac{v_f}{k_j}k \quad 2.45$$

Where; v_f = free-flow speed, k = density, k_j = jam density

If a dummy variable is introduced to equation 2.45 to indicate the presence or absence of night rain on the dark roadway, then, equation 2.45 is written as;

$$u = u_f - \frac{v_f}{k_j}k - \psi \quad 2.46$$

Where; ψ = 1 night-time rainfall, or 0 = night-time dry weather

Then, equation 2.44 can be adjusted as;

$$SSD_R = (0.278v)t + \frac{(0.278v)^2}{2\left|\frac{\psi}{(\Delta t)}\right|} \quad 2.47$$

Such that $\frac{\psi}{(\Delta t)}$ is the deceleration rate for the rainy night-time conditions.

Note that in previous studies simulated wet road surfaces were carried out during daylight conditions, hence the derivatives are associated with dry weather wet pavement. This empirical study was carried out at night on a dark roadway under variable rainfall. This profound difference has numerous outcome implications even though the trend trajectory would likely be similar.

Summarily, in the design of a roadway, sight distance is important as it affects both safety and operation on the road. Stopping sight distance is measured as the available road length for a driver to avoid hitting an object in his path and is estimated using reaction distance and braking distance. It is important to know that stopping sight distance is dependent on speed and is affected by the condition of the road surface. By this, stopping sight distance under rainfall conditions at night is expected to be different than that under a no-rain scenario due to possible changes in speed induced by the prevailing conditions. Thus, it is assumed that stopping sight distance, irrespective of rain intensity will either decrease or increase as speed decreases under rainy night-time conditions.

2.8 Appraisal of Data Collection – Method and Analysis

Collection of empirical traffic data could be done in three ways, namely, collecting data along road length, a moving observer method and collecting data at a point or segment of road. Collecting data along road length is best achieved using aerial photographs. The method measures density but does not give information on speed and traffic volume counts. The moving observer as a second method is reliable in giving information on travel time but deficient in giving accurate speed data. Collection of data at a point or road segment as the third method is reliable because it gives both speed and volume count of vehicles with their time headway. Therefore, in this study, the third method is adopted due to the importance of traffic speed and volume data required. However, traffic data collection irrespective of the method adopted could be done manually or using equipment. The manual method involves the use of human personnel to obtain traffic information. This method is usually used for short duration survey and single parameter survey in most cases, but the method is difficult to achieve and prone to errors. Due to the sensitivity of this research work, the manual method could not be employed. Similarly, video camera as an equipment could not be used for data collection. This is due to possible splash of rain on the camera lens thereby reducing accurate capturing of traffic. Based on the shortcomings of both manual and video camera methods, use of a traffic counter is therefore adopted for data collection in this study.

A traffic counter, either as a permanent counter or portable counter, is useful in collecting traffic data. The permanent counter, which is fixed permanently, is usually expensive and immovable, while a portable counter could be moved from one location to another and is less expensive. Thus, the type of counter to be used depends on cost, number and type of parameters required, the duration and purpose of study. Therefore, a portable counter is employed in this study due to its availability, purpose and the duration of the study. The portable counter used is known as an Automatic Traffic Counter (ATC). The traffic counter is an automatic counting machine comprising of pneumatic tubes and accessories such as nails, figure 8-clamp, tube vent plug amongst others. It can record various traffic information and is suitable for use under all weather-related conditions without interference.

Speed measured as the distance travelled over time, is important in understanding traffic operations on roadways. Many researchers have reported that speed reduces under adverse weather conditions. However, it is not enough to accept such a report, there is a need to verify this statement. On the basis of verifying, various methods had been employed in the past to justify speed reduction. Such methods include speed percentile and other statistical methods such as Quantile-Quantile, Bootstrapping and many more. It is worth noting that all the methods are acceptable but not justified enough to express their suitability. The reason being that only speed information is considered and treated in isolation as a stand-alone aggregated data as opposed to other traffic parameters such as flow and density.

However, a shift from using speed information as a stand-alone aggregated data is employed with the use of the speed-density relationship. The speed-density was first postulated by Greenshields (1935) as a linear relationship such that an increase in density gives a corresponding decrease in speed. However, other researchers (Zhang *et al.,* 2018), overtime have reported a non-linear relationship for the speed-density. In this study, the speed-density linear relationship subjected to a statistical test to determine its suitability and reliability in justifying speed reduction, was adopted for use. Another method of determining travel speed is by using the flow-density relationship which is based on the fundamental relationship of the three basic traffic parameters. The flow-density relationship analysed using different methods is useful in estimating roadway capacity.

The capacity estimation methods include use of headway only, traffic volume only, traffic volume and speed, and the last which is use of traffic volume, speed and density. The rationale behind each type of method depends on available traffic data and the state of traffic which could be at a peak or off-peak period, as a free-flow condition. Note that the method that best relates the traffic situation is a function of the available data. Going by the aim of this study, which is focused primarily on night-time, it is therefore correct to say that the state of traffic at night is under the off-peak period. The two possible methods for estimating roadway capacity in an off-peak scenario are headway and fundamental diagram methods.

Travel time as discussed earlier, is important in measuring road performance, especially from the users' perspective. The Highway Capacity Manual (2010) considers travel time as a service measure introduced to measure the service provided by the roadway. Therefore, the estimation of travel time is important. In this study, the US Bureau of Public Road equation was adopted for travel time estimation as it allows empirical data and information to be related in investigating the effect of rainfall on travel time.

2.9 Summary

In this chapter it is imperative that literature on relevant previous works to this study and theoretic framework are reviewed in order to support arising arguments in later chapters. Five important issues which are night rain, quality of service, travel time, capacity and stopping sight distance were raised and discussed. Relevant literatures on roads and traffic in Nigeria were reviewed and it was opined that two-lane highways are more common in Nigeria than any other road type. Roads as a major mode of transportation cut across the nation with most roads being devoid of light and where present, are not operational. Driving at night is a visual task that requires good visibility but is not easily achieved under dark roadways without light. Road traffic in Nigeria is made up of various vehicle types which constantly interact with each other and other environmental conditions such as night and rain. The interaction with the environment directly or indirectly influences their operations. Rain as a weather condition is known to abound in Nigeria, its occurrence is investigated and known to be prominent between the months of May and September across the nation. The occurrence varies from one location to another with different intensities during the day and the night.

The chapter further elaborated on the concept of service quality and concluded that quality is measured by how well an expected service is received by the end user regardless of the service provider. In relation to roadways, the road user is identified as the end user while the road provider is the service provider. Therefore, the assessment of roadway service delivery is by the road user. The service quality is evaluated functionally to accommodate both the road user and the provider as against the norm of the HCM which focussed on LOS for measure of road effectiveness. The chapter reiterated that functional service quality is best assessed using travel speed as a proxy for the road provider and travel time as a proxy for the road users. The functional service quality adopted the six grades of class A to F in which class A is the best service and class F represents the worst service delivery.

Travel time as a service measure was reviewed such that it was stated that it is used by road users in the assessment of road service quality. Road users are concerned about the time they spend on road; therefore, they judge road performance using travel time. Furthermore, the determination of travel time using the US-BPR formula was investigated. The chapter further reviewed the travel time as service measures in accordance with the Highway Capacity Manual (2010). Travel time loss using the US-BPR formula was reviewed based on capacity obtained from the flow-density relationship. This is required to understand the implication of night-time rainfall on travel time under rainy night-time conditions on a two-lane highway without road lights.

From the literature, the chapter aligned with the view that roadway capacity is stochastic in nature. Several capacity estimation methods were highlighted and reviewed in context based on their strengths and weaknesses in estimating roadway capacity. The two suitable methods identified for the study are headway and fundamental diagram methods due to their suitability for off peak traffic conditions. However, use of the fundamental diagram was preferred because it allows for the use of the three basic traffic parameters in understanding roadway traffic operations. As the study is interested in night-time, which is a typical off-peak scenario, traffic parameters which include flow, speed, density and capacity, and travel time are considered necessary.

Although not considered as the major part of the study, the possible implication of rainfall on stopping sight distance was reviewed. Stopping sight distance is a safety factor made up of braking distance and reaction distance. It is dependent on various factors in which speed is a common parameter for both braking distance and reaction distance. Bearing in mind that rainfall triggers speed reduction with a subsequent increase in travel time, the chapter reiterated that the stopping sight distance under dry surface road conditions is not expected to be same for a wet surface road condition, hence, the need to investigate the influence of night-time rain on the stopping sight distance of dark roadways without light.

CHAPTER THREE

RESEARCH METHODOLOGY

3.1 Overview

In the first chapter, the objectives of this study were set out and it was mentioned that the methodology would be empirical based, with observations and sample surveys taken at various locations in Nigeria. As such, night rainfall on dark roadways, volume and speed of vehicles are considered important. However, the locations to be investigated must be representative of the population for validity of the sample survey, also the selected dark roadways must have sections within the rainfall catchment area. Three types of vehicles were identified: light vehicles (LV), medium vehicles (MV), and heavy vehicles (HV).

Chapter three aims to set out the analytical and empirical background for data collected on the sites discussed in chapter four and analysed in chapters five and six. The estimation of travel time and the computation of travel speed for free flow traffic conditions where capacity seldom occurs, are central to the study.

It has been hypothesised that, 'night rainfall on dark roadways produces functional service quality reduction' as stated earlier in section 1.3. Functional service quality is bi-dimensional as it involves both providers' and user's perceptions of road service delivery. The road providers' perception of measuring service quality is based on travel speed while road users' perception is based on travel time. Thus, the parameters for functional service quality assessment are travel speed and time. In order to determine the influence of night rainfall on dark roadway functional service quality, data is needed to establish the extent of travel time increase and corresponding travel speed reduction. The outcome of these parameters is used to determine the functional service quality for dry night and rainy night on dark roadways.

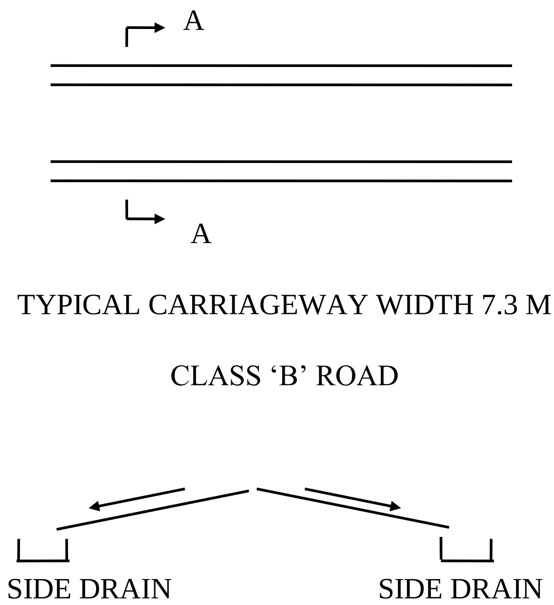
To that effect, the survey data (Table 3.1) and information collected are both qualitative and quantitative. Direct measurements were obtained at four selected sites and supplemented with records from the Ministries of Works and Housing (MWH), the Nigerian Building and Road Research Institute (NBRRI) and the Nigerian Institute of Transport Technology (NITT).

Table 3.1 Sample of a Survey Summary Sheet

ROAD NAME: **STATE:** **DATE:**

START TIME: FINISH TIME:

Carriageway + side-drain



Average Speed km/h

Speed km/h

Volume vehicle/time

Motorcycle

Light vehicles

Medium vehicles

Heavy vehicles

% Motorcycles

% Light vehicles

% Medium vehicles

% Heavy vehicles

Pavement: Flexible **Terrain:** Normal

3.2 Research Methodology Framework

The method of study is empirical with observed and sample surveys taken at selected locations in Nigeria. Figure 3.1 represents the methodology framework of the study. The research approaches are both empirical and analytical. The empirical approach involves estimating traffic parameters such as speed, volume and flow, while the analytical approach involves development of model(s) between the macroscopic traffic flow stream characteristics and rainfall intensities.

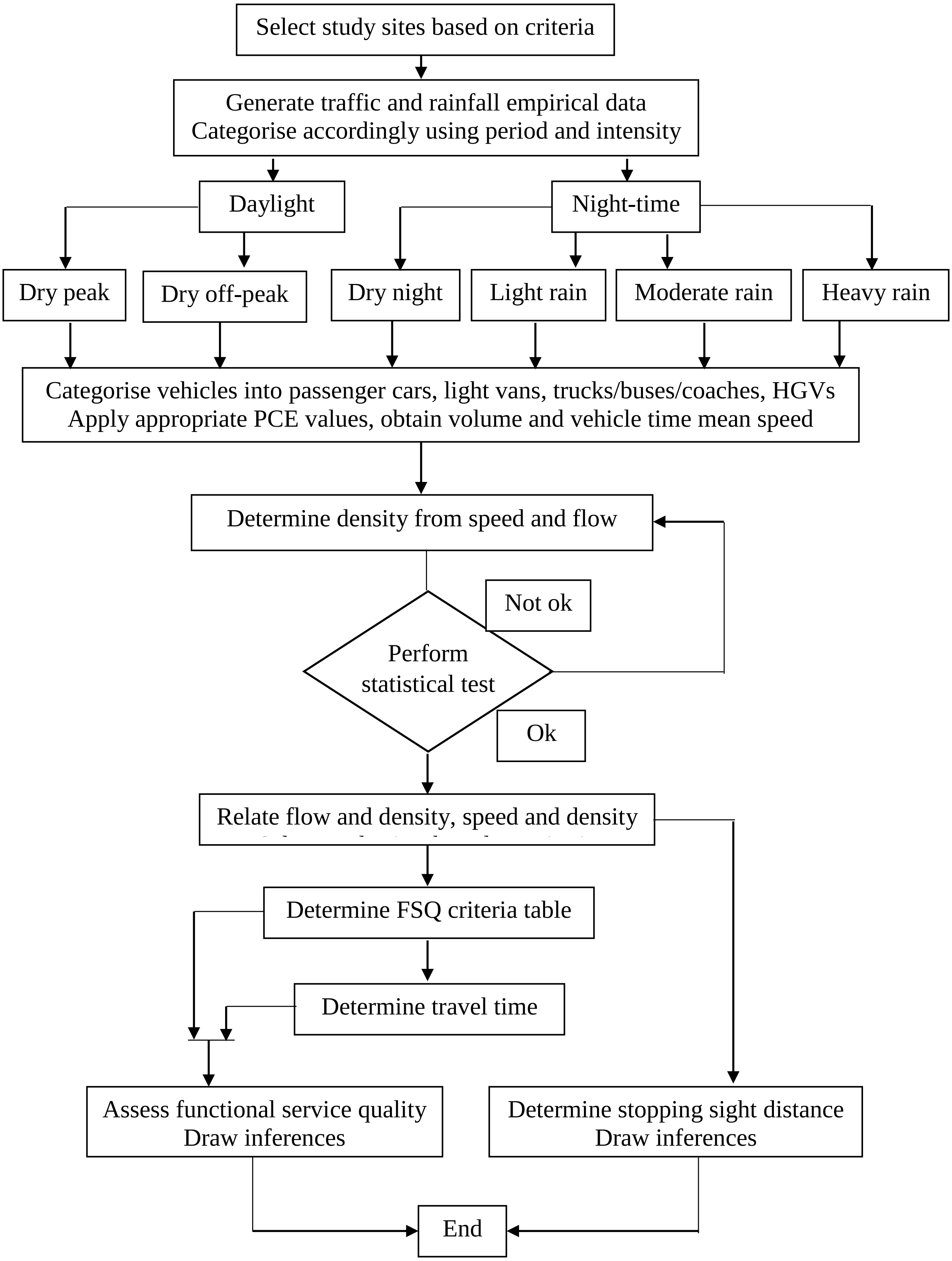


Figure 3.1: Framework of Research Methodology Flowchart

The functional service quality in the context of this study considers the road provider's perception which is based on travel speed and road users' perception based on travel time for assessment of road performance. However, capacity estimation is an important parameter in defining the service quality in terms of travel speed or travel time. Different empirical methods exist for estimating traffic capacity according to Minderhoud *et al.* (1996) as discussed previously in chapter two.

Empirical data were collected for a period of eight weeks across four selected sites that met certain criteria outlined for the study. Traffic data were collected using automatic traffic counters and automatic rain gauges for rainfall data. Both traffic and rain data were synchronised and processed. Traffic volume was converted to traffic flow using appropriate passenger car equivalents (PCE) specified by FMWH. Nevertheless, the PCE values specified by FMWH were estimated under dry daylight conditions, hence, the use may result in errors. The PCE values were modified to conform with the prevailing conditions of the study to avoid biased results. Rain data was categorised into intensities as light rain, moderate rain and heavy rain using the WMO standard. Very heavy rain was not considered in this study due to the possible effect of hydroplaning and drag force which may be difficult to separate. In developing models, the processed data were related with one another using relevant traffic parameters.

For the functional service quality assessment, dry daylight peak period data was used in setting the functional service quality (FSQ) criteria table. Models for dry daylight conditions (off-peak) and night-time conditions of dry and rainfall (using rainfall intensity classification) were also developed. Though not a major part of the study, the dry daylight models were determined and compared with the dry night-time values to establish if dry daylight traffic performance differs significantly from dry night-time performance. However, the main interest of this study is focussed on night-time conditions.

3.3 Study Site

3.3.1 Location and Selection Criteria

Roads in Nigeria are mostly constructed as two-lane roadways except for expressways and metropolitan roads under the administration of the Federal government. Two-lane highways constitute about 78 percent of roads in Nigeria (Revised Inventory of Federal Highways 2016) and carry a high volume of traffic from state to state across the nation. As this study is focused on rural roads based on its primary function as the provider of access, the roads selected for this study connect the western part of Nigeria to both the eastern and northern parts of the nation. The roads are in Akure, Ondo State. The roads carry traffic from neighbouring states such as Osun, Oyo to other states which include Edo, Kogi and the northern part of Nigeria. The roads were specifically chosen because they meet the conditions considered in terms of design, construction and traffic handling. Since this study is centred on night-time rain, three basic elements namely roadway, night-time and rainfall are considered important in achieving the objectives. The roadway is the system on which traffic flow takes place while night-time and rainfall are the environmental and weather conditions under which traffic flow occurs. Hence, it is necessary to put in place certain criteria to assist in guiding against biased information and data. Within the research boundary, roads were selected based on the following criteria:

- Road Geometry ≥ class 'B' road based on FMWH design specifications, clear visibility, straight and level terrain
- Road Link ≥ 500m. The link should be free both ways of influence from road junctions, roundabouts, petrol stations, broken down or parked vehicles, police check points and other roadway/traffic conditions that could cast doubt on traffic data collected
- Dark Roadways must be without streetlights and be wholly within the rainfall catchment area
- Road sections must be well drained to avoid water ponding
- Pavement surfaces of the dark roadways' sections must be free of distress

Based on the criteria listed above, four study sites that meet the criteria are presented and assessed in the next section.

3.3.2 Site Coding and Assessment

As the study sites were carefully selected based on the criteria listed above, it is important to describe the features of each road section. In this regard, selected study sites were coded for easy identification purposes. The coding format used is 'SSyy' where the prefix 'SS' is the acronym for study site and 'yy' - the serial number of sites. For example, 'SS01' means 'study site of serial number 01'. Table 3.2 shows the code for all study sites while their individual assessment is presented in subsequent sections

Table 3.2: Study Site Identification Codes

Site name	Site number	Site code
Akure - Ilesha road	01	SS01
Ilesha - Akure road	02	SS02
Akure - Benin road	03	SS03
Benin - Akure road	04	SS04

3.3.2.1 SS01: Akure - Ilesha Highway

The Akure - Ilesha Highway is a two-lane highway with the two lanes facing one another in opposite directions. It is a typical federal rural highway with an average daily traffic count of 5000 veh/day and a design speed of 80km/h. It is an asphalt paved road with a pavement design life of 20years and a posted speed limit of 100km/h. It is located on a flat terrain with few curves. On this road, the movement of vehicles is from the Akure axis to the Ilesha axis. The road has a lane width of 3.7m with a 1.2m shoulder. The selected road section for the study has a road length of 2250m and is located between Ilaramokin and Igbara-Oke along Akure – Ilesha highway. The road length is greater than the allowable stopping sight distance of 250m and 700m from Ilaramokin and Igbara-Oke respectively. The automatic rain gauge is located within 50m away from the site. Rain data from the rain-gauges were crosschecked with the rainfall data of WASCAL-FUTA due to its proximity. Traffic data for the road section were collected continuously for eight weeks. Traffic composition on this road is made up of all types of vehicle which include motorcycle, light weight vehicles, medium weight vehicles and heavy weight vehicles, but the vehicles are in varying proportions.

3.3.2.2 SS02: Ilesha - Akure Highway

The Ilesha - Akure Highway is the opposite direction of the Akure - Ilesha Highway. It has the same features as that of the Akure - Ilesha Highway. Vehicle movement is from the Ilesha axis towards the Akure axis. The width of the lane is 3.7m with a shoulder of 1.2m. The average daily traffic is about 5000veh/day with a design speed of 80km/hr. The rainfall data collected for SS01 were the same for SS02, but the traffic data varied due to a change in the direction of vehicular movement as captured in the ATC. Traffic composition consists of various types of vehicles in varying proportions.

3.3.2.3 SS03: Akure - Benin Highway

The Akure - Benin Highway is a two-lane highway with the lanes facing one another in opposite directions. It is an asphalt surfaced road located on a flat terrain with few curves and a pavement design life of 20years. This road serves as a major connector road to other parts of the country. It is characterised with a high volume of traffic. It is a federal rural highway with an average daily traffic count of 5000 veh/day and design speed of 80km/h. The lane width is 3.7m with a 1.2m shoulder and a posted speed limit of 100km/h. At SS03, movement of vehicles is from the Akure axis to the Benin axis. The road segment with a road length of 1975m is located between Ilu-Abo and Ogbese. The road length is greater than the allowable stopping sight distance of 750m and 350m from Bolorunduro and Ogbese respectively. The automatic rain-gauge is placed 80m away from the site. Rainfall data from the rain-gauge is verified with data obtained from NIMET at the Akure Domestic Airport due to its proximity. Traffic data along this road is collected continuously for eight weeks.

3.3.2.4 SS04: Benin - Akure Highway

The Benin - Akure Highway is the opposite direction of the Akure - Benin Highway. It has the same features as that of the Akure - Benin highway. On this road lane, vehicles move from the Benin axis and pass through towns such as Owo and Ogbese to Akure and other parts of the country. All vehicles types are well represented on this road.

3.3.2.5 Summary of Selected Study Sites

Based on the assessment of the selected sites as presented in sections 3.3.2.1 – 3.3.2.4, the geometric summary of the sites is presented as table 3.3 below. From table 3.3, it is evident that all study sites meet the criteria listed in section 3.3.1, thus, they are acceptable for the study. Since it is important for empirical data to be collected from the selected road, data collection methods and equipment are discussed in section 3.4

Table 3.3: Summary of Geometric Features of Selected Study Sites

Site features	SS01	SS02	SS03	SS04
Name of Road	Akure - Ilesha Highway	Ilesha - Akure Highway	Akure - Benin Highway	Benin - Akure Highway
Type of road	Federal rural road	Federal rural road	Federal rural road	Federal rural road
Terrain type	Flat	Flat	Flat	Flat
Annual daily traffic	5000veh/d	5000veh/d	5000veh/d	5000veh/d
Number of lanes	2	2	2	2
Lane width	3.7m	3.7m	3.7m	3.7m
Pavement surfacing	Asphalt	Asphalt	Asphalt	Asphalt
Length of road section	2250m	2250m	1975m	1975m
Rain gauge distance to site	50m	50m	80m	80m
Presence of road shoulder	Yes	Yes	Yes	Yes
Width of shoulder	1.2	1.2	1.2	1.2

3.4 Data Collection – Survey Method and Equipment

3.4.1 Sampling

Nigeria has different climate conditions in each of the six geographical zones across the nation. The average annual rainfall amount varies from 1600mm in the west to 4300mm in the east, 1300mm at the central and 500mm in the north. Akure located in the western part of Nigeria has an annual average rainfall of 1455mm (https://en.climate-data.org/africa/nigeria/ondo/akure-46678/), therefore, it gives a good representation of the western part of the nation. The months with frequent rainfall of high intensity for Akure area are April to September, these months represent the general wet season of Nigeria.

Traffic data collected from selected road sections were sorted carefully to exclude data for public holidays. A sample size was considered necessary in order to draw an inference for population estimation. According to the FMWH specification of a two-lane rural road, the expected maximum number of vehicle per hour is 1700 (traffic volume = 1700veh/h), hence, population size was set as 1700veh/h. With this population size, the sample size was thus obtained using equation 3.1 where the confidence interval was taken as 95 percent with a 5 percent margin of error.

$$s = \frac{X^2 NP(1-P)}{d^2(N-1)+X^2P(1-P)} \qquad 3.1$$

where s = required size

X^2 = 3.84 (chi-square value for 1 degree of freedom at desired confidence level)

N = population size

P = population proportion (taken as 0.5 to provide maximum sample size)

d = degree of accuracy or margin of error expressed as proportion = 0.05

Using equation 3.1 in conjunction with its table (Appendix II), the minimum required sample size for a population of 1700veh/h is 313vehicles/h. The sample size of 313vehicles/h is therefore adequate and suitable to represent traffic data for all weather conditions under consideration. Nevertheless, the ATC collected traffic data continuously for eight weeks during the rainy season between June and September. The continuous capturing of traffic data during the period allowed for adequate data which was far above the expected sample size earlier stated.

3.4.2 Survey Team and Equipment

A survey team made up of six people with security personnel (police), was employed during the installation of automatic traffic counters at the selected road sections. Two persons and police were deployed to control the movement of vehicles for safety purposes, while the remaining four people carried out tube installation and traffic counter set up. Each team member was briefed on their expected responsibilities during installation and setting up of the automatic traffic counter. They were also trained in the handling of the equipment from setting up to data downloading. The equipment used include the automatic traffic counter (ATC) and its accessories, hammer, metre rule, rain gauge, laptop computer, road cones, measuring wheel, reflective jackets, nails, padlock, security chain, digger and measuring tape. To install the ATC, stopping sight distance of the road section was first determined as presented below.

Firstly, operating speed was determined during the free-flow period using stopwatches and two cones labelled c_1 and c_2. The two cones (c_1 and c_2) were placed 20m apart along selected road sections. As vehicles passed the first and second cones respectively, the time of passage for each cone (t_{C1} and t_{C2}) was noted and recorded. The difference between the first observed time t_{C1} and the second observed time t_{C2} is the time taken to cover the distance between the two cones. This procedure was repeated randomly for a various number of cars during the free-flow period. The speed of each vehicle was calculated using equation 3.2

$$S_{osi} = \frac{D}{t_i} \qquad 3.2$$

where S_{osi} = operating speed of individual vehicle

D = distance between cones = 20m

t_i = time taken by *ith* vehicle to cover distance D given as $t_{C2} - t_{C1}$

t_{C1} = time at cone 1

t_{C2} = time at cone 2

Thereafter, the 85th percentile of observed operating speeds was determined, and this was taken as the road operating speed. The operating speed was compared with the posted speed of the road, and it was observed that operating speed was lower than the posted speed. Based on this, the obtained operating speed was adopted and used for calculating the stopping sight distance (SSD) using equation 3.3

$$SSD = \frac{u^2}{2gf} + ut \qquad 3.3$$

where *SSD* = stopping sight distance

t = perception-reaction time taken as 2.5s

u = design speed

g = acceleration

f = coefficient of friction

The obtained stopping sight distance was used to install the automatic traffic counter (ATC) across the selected road sections. The automatic traffic counter was installed such that each length of road section from the automatic traffic counter to the end of the road section was greater than the obtained stopping sight distance.

3.4.3 Layout of a Typical Survey Site

The layout of a typical study site is shown in figure 3.2

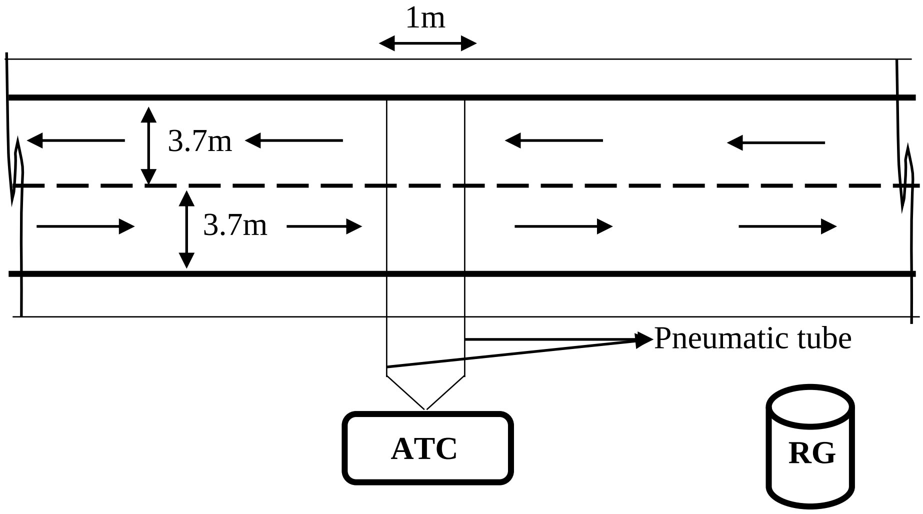


Figure 3.2: Typical layout of a study site

3.4.4 Traffic Data

Traffic data is used in defining vehicles' characteristics relative to their operations on the road. In this study, traffic data was obtained using an automatic traffic counter capable of giving accurate information regarding individual vehicles logged into the counter. The individual information obtainable from the ATC include traffic volume, vehicle speed, headway, gap, vehicle type among others. Section 3.4.4.1 gives a detailed description of the ATC while section 3.4.4.2 describes the installation procedures of the pneumatic tubes and the ATC. The ATC set-up and data downloading from it are presented in sections 3.4.4.3 and 3.4.4.4 respectively. Section 3.4.4.5 describes the typical traffic generated by the ATC.

3.4.4.1 Description of Automatic Traffic Counter (ATC)

The Automatic Traffic Counter is a box-like machine with a dual-air sensor unit opening (A and B) projecting from the machine side as shown in Figure 3.3. The counter has three status LED lights located at its top. The A and B LED lights operate in the Roadside Unit's (RSU) active state. The ATC is operated using replaceable alkaline batteries that can run for 290days at 25^0C in continuous run mode. The machine has 2M RAM capable of logging all type of axle loads.

The Automatic Traffic Counter is accompanied by the accessories shown in Figures 3.4 - 3.8 and described as follows:

- Pneumatic tube: It is black in colour and about 29.9m ± 31mm in length with an outer diameter ranging between 12.7mm - 13.5mm and an inner diameter of 5.3mm - 5.7mm. The tube sends air pulses generated due to a vehicle hitting it to the automatic traffic counter.
- Steel case: this serves as protection for the machine. It is a steel case of 350mm x 124mm x 95mm in dimension.
- Data communication cable: This is a USB cable that allows communication between automatic traffic counter and the computer system during the ATC set up and data downloading.
- Bitumen road tape, Nails, Cleats and Flap: These are fasteners used in holding the pneumatic tubes in place when installed across the road.
- Other accessories include a 4mm ball-driver for screwing and unscrewing, a 6-volt welded battery, protective dust cap for covering the USB port on the counter and tube vent plug for sealing the pneumatic tube end to avoid loss of air.

Figure 3.3: Automatic Traffic Counter

Figure 3.4: Pneumatic tube

Figure 3.5: Communication cable

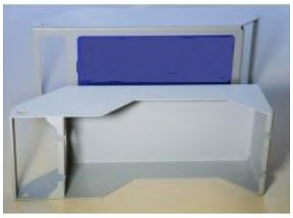


Figure 3.6: Steel case

Figure 3.7: Fasteners

Figure 3.8: Other accessories

3.4.4.2 Installation of Pneumatic Tubes and ATC

Two parallel and equal lengths of the pneumatic tube, one meter apart, were laid across the selected road section and attached to the road pavement at a right angle to the direction of traffic flow. The tube ends to be connected to the ATC were left free while the other ends were firmly knotted to make them airtight. The knotting was done two or three times to ensure that air does not escape from the tube when vehicle pass over it. Tube vent plugs were further inserted into the knotted ends of the tubes to ensure maximum airtightness within the tubes. This guides against the loss of air from the tube and subsequent reduction in the sensitivity of the counter and a loss of data in terms of quality. The double-knotted ends of the tubes were firmly fixed to the road pavement ends using road nails passing through the eyelet of flaps placed across the tubes.

Similarly, the other loose ends of the pneumatic tubes were fastened to the road edge before connecting them to the ATC. To enhance proper installation, the 1m distance between the tubes was double checked at various points along the laid parallel tubes before fastening the loose ends tightly to the road. This is to ensure consistency in tubes spacing towards enhancing the accuracy of the data to be collected. After fastening, the tubes were stretched to 10 percent - 15 percent for tensioning while bitumen tape was used to hold the tubes firmly to the pavement surface at intervals. This was done to avoid shifting of the tubes and minimise lateral movement in the tube positions when vehicles go over it. The tubes were made to pass through the steel casing slots and were connected to the two air-sensor openings A and B appropriately. The connection convention used is such that tube A is hit first by a vehicle travelling in the lane closest to the ATC. The RSU setup was later configured with a laptop for data logging. Lastly, the counter was enclosed with the stainless-steel casing cover, put in a wooden box and placed in a fabricated metal box. The metal box was locked and secured. Figures 3.9 and 3.10 show the installed pneumatic tubes across a road section and the metal box used in securing the automatic traffic counter against theft and weather impacts.

Figure 3.9: Installed tubes

Figure 3.10: Security box for the ATC

3.4.4.3 Setting up of the ATC

After tube installation, the next step is setting up of the automatic traffic counter (ATC) using the software installed on a laptop. On opening the automatic traffic counter software application, the first popped up page is the Roadside Unit Setup. A typical interactive page of the automatic traffic counter software is presented as Figure 3.11

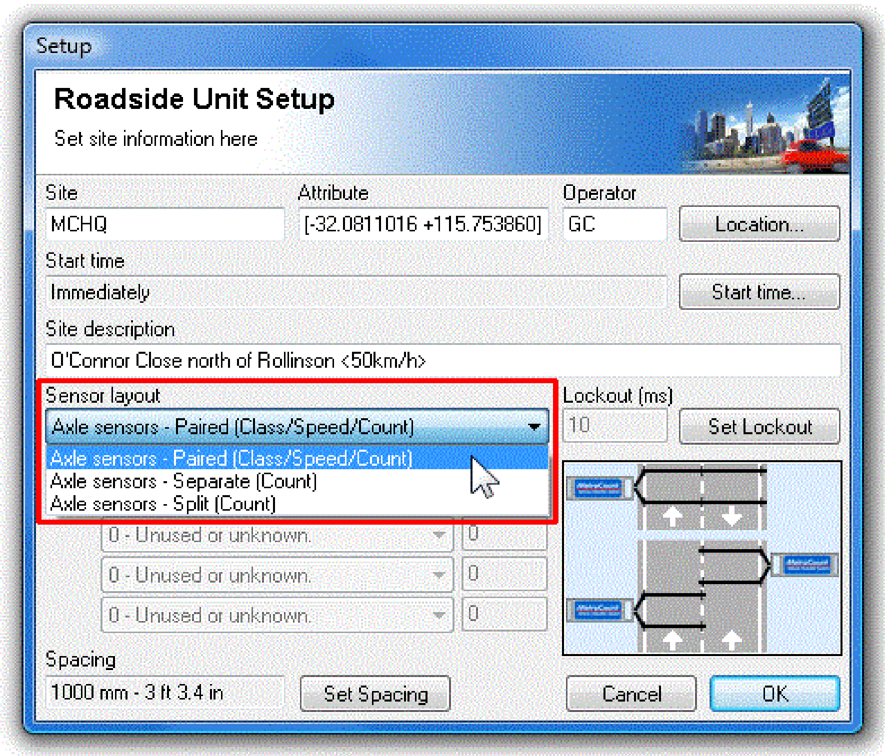


Figure 3.11: Set-up page of the ATC

On the interactive page, site information was logged for identification purposes. The site information logged includes the site name, attributes, lanes, operators, location, direction, debounce A, spacing, debounce B, start time, site description and sensor layout. Other possible options are available in the drop-down section of some of the information sections. After setting up, data logging commenced based on start time inputted during setup. A check was performed by viewing live traffic logging using view (4) icon on the left-hand pane of Figure 3.12. This was necessary to confirm that the counter was working. The view (4) icon has the options of rolling time, vehicle list and axle timing.

3.4.4.4 Data Downloading from the ATC

Logged traffic data were downloaded from the automatic traffic counter into a computer system based on scheduled time and memory of the automatic traffic counter. The interactive page for the downloading of data is shown in Figure 3.12. The left-hand pane of the initial page consists of the following:

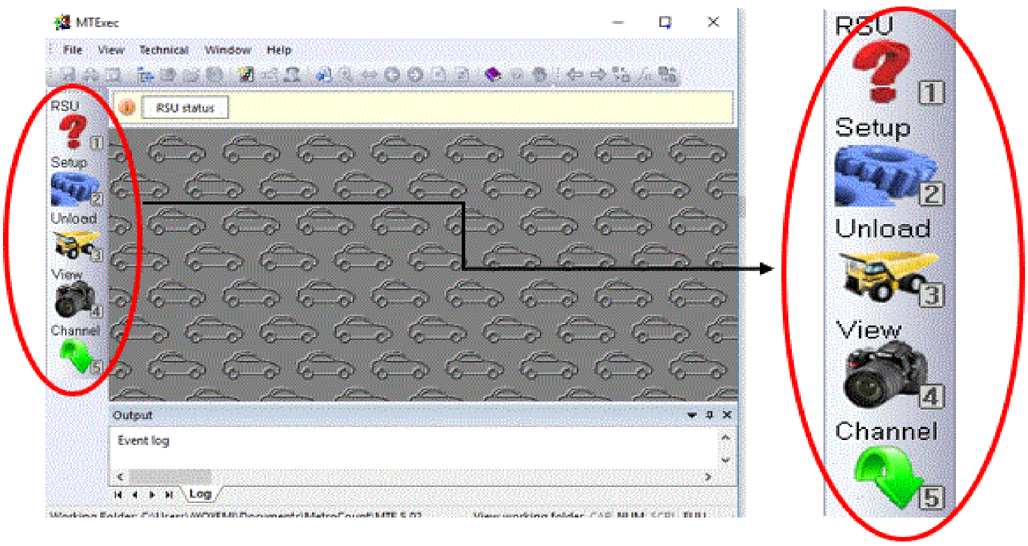


Figure 3.12: An Interactive page of the software

- RSU (1) 

– (Roadside unit) used to identify the status of the ATC in terms of data, status, battery, hits and memory
- Setup (2) 

– used in setting up the ATC for data logging
- Unload (3) 

– used for downloading of stored data in the ATC

- View (4) 

– used for checking the sensor hits as captured by the ATC

Data was downloaded by connecting the ATC to a laptop computer using a provided USB communication cable. After connecting the cable, the device status was first checked using the RSU icon (1) in the set-up toolbar on the screen. The RSU icon (1) was used to check the status of the ATC battery and the memory before downloading data. After the check, the unload button icon (3) was clicked to download data. There are usually two options for unloading, which are ‘unload data and continue’ or ‘unload data and stop’. ‘Unload data and continue’ allows data to be kept in the ATC even after downloading, while ‘unload data and stop’ does not keep downloaded data but requires another set-up after each download. For this study, ’unload data and stop’ was used. This allows for a check on the device status, data quality and loss of data if any. It is noteworthy that during data downloading, the screen displays the stored data in a graphical format using two coloured lines A and B. When the lines are displayed overlapping one another as a blue line, it represents good quality traffic data, otherwise, when displayed as mismatched red and blue lines, it means the quality of the traffic data is poor. In a situation of mismatched lines, the installed tubes were checked for possible errors such as leakages. For easy identification purposes, downloaded data were stored according to information used during the automatic traffic counter set-up described in section 3.4.4.3.

3.4.4.5 Traffic Data Generated by the ATC

The automatic traffic counter captures information such as traffic volume, speed, headway, and time of vehicle passage, among others. Traffic volume is the total number of vehicles that passed the study site for the time considered. As vehicles pass over the tubes, an air pulse is generated and sent to the air sensors of the counter. Each air sensor was counted and recorded. Headway is defined as the time difference between successive vehicles to pass a given point, the automatic traffic counter records headway based on the stated definition. The time difference in which it takes the front axle of a lead vehicle and front axle of a follow vehicle to hit the tube is recorded by the counter as headway. Speed defined as the distance covered per unit time is one of the parameters required in this study. The counter records the speed of a vehicle when the distance travelled over the tubes is divided by the time taken. Note that the distance between the tubes is 1m. The obtained speeds are spot speeds.

Another traffic data generated by the automatic traffic counter is vehicle type. One important use of the counter is its ability to classify vehicles into various classes. Vehicles varying in size from small size to heavy size, are constantly moving on the roads regardless of time and location, therefore, the knowledge of their classification is important. Vehicle classification is also important in converting heterogeneous traffic into homogenous traffic using passenger car equivalent values. The Federal Ministry of Works, Nigeria recognises different classes of vehicles which range from motorcycles, cars, vans, pick-up and minibuses (< 20 seats), buses (> 20 seats) to heavy vehicles of 2, 3-4 and 5+ axles.

There are about twenty-two types of vehicle classifications in the automatic traffic counter system and the nearest in terms of vehicle description to that of Nigeria is the ARX vehicle classification system. Thus, the ARX system was adopted for this study. The ARX is a modification of AustRoads 94. The characteristics of the ARX classification are given in Figure 3.13

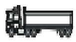
Axles	Groups	Description	Class		Parameters	Dominant Vehicle	Aggregate
2	1 or 2	Very Short - Bicycle or Motorcycle	MC	1	d(1)<1.7m & axles=2		1 (Light)
2	1 or 2	Short - Sedan, Wagon, 4WD, Utility, Light Van	SV	2	d(1)>=1.7m, d(1)<=3.2m & axles=2		
3, 4 or 5	3	Short Towing - Trailer, Caravan, Boat, etc.	SVT	3	groups=3, d(1)>=2.1m, d(1)<=3.2m, d(2) >=2.1m & axles=3,4,5		
2	2	Two axle truck or Bus	TB2	4	d(1)>3.2m & axles=2		2 (Medium)
3	2	Three axle truck or Bus	TB3	5	axles=3 & groups=2		
>3	2	Four axle truck	T4	6	axles>3 & groups=2		
3	3	Three axle articulated vehicle or Rigid vehicle and trailer	ART3	7	d(1)>3.2m, axles=3 & groups=3		3 (Heavy)
4	>2	Four axle articulated vehicle or Rigid vehicle and trailer	ART4	8	d(2)<2.1m or d(1)<2.1m or d(1)>3.2m axles = 4 & groups>2		
5	>2	Five axle articulated vehicle or Rigid vehicle and trailer	ART5	9	d(2)<2.1m or d(1)<2.1m or d(1)>3.2m axles=5 & groups>2		
>=6	>2	Six (or more) axle articulated vehicle or Rigid vehicle and trailer	ART6	10	axles=6 & groups>2 or axles>6 & groups=3		
>6	4	B-Double or Heavy truck and trailer	BD	11	groups=4 & axles>6		
>6	>=5	Double or triple road train or Heavy truck and two (or more) trailers	DRT	12	groups>=5 & axles>6		

Fig 3.13: ARX vehicle classification system
Source: ATC software manual, 2013

According to figure 3.13, the first three groups of vehicles are known as light vehicles (LV) otherwise referred to as passenger cars (PC), the second group consisting of three types of vehicles is the medium vehicles (MV) and the last group made of six types of vehicle is known as heavy vehicles (HV). The data logged in the ATC were downloaded into a laptop computer system with individual vehicles having its own information. Figure 3.14 represents the individual reports of four vehicles as captured by the automatic traffic counter.

DS	Trig Num	Ht	YYYY-MM-DD	hh:mm:ss	Dr	Speed	Wb	Hdwy	Gap	Ax	Gp	Rho	Cl	Nm	Vehicle
00	00000004	04	2017-07-27	11:59:37	N0	82.55	2.62	0.8	0.8	2	2	1.00	2	00000020	SV o o
00	00000008	04	2017-07-27	11:59:40	N0	93.53	2.59	2.6	2.5	2	2	1.00	2	00000010	SV o o
00	0000000c	04	2017-07-27	11:59:56	S1	80.47	2.53	19.3	19.3	2	2	1.00	2	00000010	SV o o
00	00000010	04	2017-07-27	12:00:04	N0	105.44	2.60	23.7	23.6	2	2	1.00	2	00000010	SV o o

Fig 3.14: Typical individual report as captured by the ATC
Source: ATC software

The information logged for each individual vehicle includes the following

- DS – Tagged dataset index
- Trig Number – Dataset axle number
- Ht – Number of axle hits in the vehicle
- YYYY-MM-DD – Date of first axle in the vehicle
- Hh:mm:ss – Time of first axle in the vehicle
- Dr – Direction of travel of vehicle
- Speed – Speed of vehicle
- Wb – Wheelbase of vehicle
- Hdwy – Headway time since the first axle of the last vehicle travelling in the same direction
- Gap – Gap time since last axle of the last vehicle travelling in the same direction
- Ax – Number of axles in the vehicle
- Gp – Number of axle groups in the vehicle
- Rho – Sensor correlation factor
- Cl – Class of vehicle
- Vehicle – Class name and scaled wheel picture of vehicle

The sorting of vehicles and analysis were done based on individual information of vehicles that constitute the traffic stream for the period considered.

3.4.5 Rainfall Data

Rainfall data is vital for this study, hence accurate collection of rainfall data is imperative. Due to the non-availability of weather stations around the selected road sections, in-situ measuring of rainfall was adopted using automatic data logging rain gauges. A typical automatic data-logging rain gauge used is shown in Figure 3.15. The rain gauge has a self-emptying tipping-bucket capable of logging rainfall data automatically. The self-tipping ability of the rain gauge measures rainfall of high resolution in millimetres per minute. Its ability to measure in millimetres per minute justified its suitability in enhancing rainfall intensity classification according to the World Meteorological Organisation's standard.

The automatic self-logging rain gauge was placed within a reasonable radius to each road section based on the stipulated guidelines of the World Meteorological Organisation.

Figure 3.15: Automatic Data Logging Rain Gauge (Insert: data logger)

According to the WMO guideline for a flat terrain, an ideal rain gauge station should cover 600-900 sq.km though 900-3000sq.km is acceptable (Patel *et al.*, 2016). The rain gauges used for this study were located at 50km and 80km radii to the ATC placed across the selected road sections. The area covered by the rain gauges were far smaller compared to the standard specified by the WMO. As such, the rain gauges used covered rainfall events at the selected road sections properly, thus guaranteeing the quality of rainfall data obtained. The rain gauges were positioned on a wooden stool 1.2metres above ground level as shown in Figure 3.16. This is to prevent inflow of splash rain and substances capable of blocking the rain gauge bucket. Also, the rain gauges were placed in an open space free from canopy and shade of any sort.

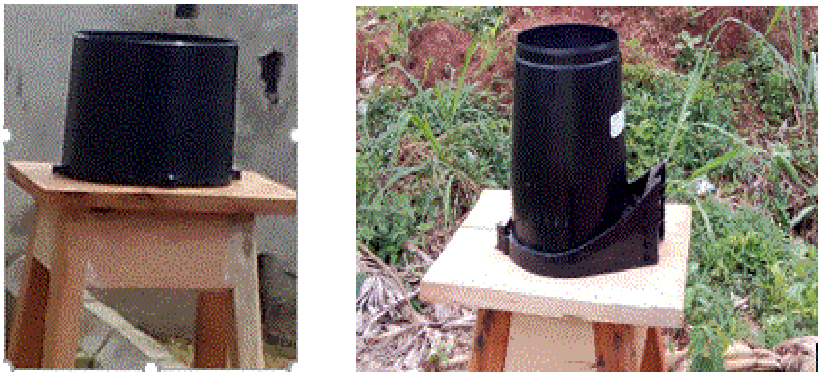


Figure 3.16: Rain gauge placed on a stool above ground level

The rain-gauge collector was set to 0.20mm/tip for logging rain data. The logged rainfall data was downloaded and exported into an excel spreadsheet using five minutes (0.083hr) time intervals. Thereafter, it was converted to intensity by dividing by 0.083 in order to have the intensity in mm/hr. The rainfall data was further classified into light, moderate, heavy and very heavy rain using the World Meteorological Organisation classification system. However, only light, moderate and heavy rainfalls were considered in this study. Very heavy rain was not considered due to aquaplaning and drag force effect on tyres. The rain data with respect to its time of occurrence were synchronised with traffic data and sorted accordingly. A typical example of rainfall intensity estimation is presented thus. For a rainfall amount of 0.2mm in a period of five minutes,

$$intensity\ i = \frac{0.2}{0.083} = 2.40mm/hr$$

Alternative measures were put in place to check the reliability of data obtained by the automatic data-logging rain gauge. The measures include sourcing rainfall data from West African Science Service Centre on Climate Change and Adapted Land Use - Federal University of Technology (WASCAL-FUTA) weather station, and the Nigerian Meteorological Agency (NIMET) - the meteorological body responsible for weather information in Nigeria and lastly getting weather information locally from the study site environment.

3.4.5.1 Rainfall Classification for the Study

The rainfall data collected was converted into intensity and classified using the World Meteorological Organisation’s classification system of light rain (LR) with an intensity less than 2.5mm per hour; moderate rain (MR) with an intensity between 2.5mm/h and 10mm/h; heavy rain (HR) with an intensity between 10mm/h and 50mm/h and very heavy rain (VHR) of intensity greater than 50mm/h. Nevertheless, very heavy rain was not considered in this study.

3.5 Sample Data and Analytical Method

Using a preliminary study referred to as pilot study, typical data and analytical processes were assessed. The importance of a pilot study is to evaluate and test the efficacy of both data collection method and the analytical procedures to be used in the study. It also tests the usefulness of obtained data for adopted procedures. The pilot study also helps in reducing problems while proffering solutions to possible problems that may arise and affect the main study. In addition, results of the pilot study allowed for testing the reliability of the obtained model statistically.

Based on the importance of a pilot study as discussed above, a two-week pilot study was carried out along a section of the Akure road. The pilot study in conformity with the site selection criteria stated in section 3.3.1 is presented in section 3.5.1

3.5.1 Pilot Study

The procedures used in sorting empirical data are listed as follows:

i. Traffic and rainfall data were downloaded from the ATC and the rain gauge logger respectively, into a laptop computer. Individual data of traffic and rainfall were called up and saved appropriately using Microsoft Excel. Note that for traffic data, the data called up is referred to as an ‘individual report’.

ii. Traffic and rainfall data were separated generally using the time convention of 5.30am - 6.30pm for daylight and 6.30pm - 5.30am for night-time. However, for night-time, only data between 7.30pm - 11pm were considered appropriate for use. Traffic data beyond 11pm are usually characterised by long headways, low volume and a high percentage of heavy vehicles.

iii. Rainfall data between 7.30pm - 11pm were separated from the entire rainfall data and sorted based on five-minute intervals. It was converted into intensity (mm/hr) by dividing by 0.083 and grouped accordingly into light, moderate and heavy using the WMO classification.

iv. The separated rainfall data were synchronised with traffic data to obtain their corresponding traffic data. This means that traffic data were separated also using five-minute intervals.

v. The dry equivalent of the sorted data in step (iv) was considered for dry night-time data and they were sorted into another Excel spreadsheet for processing. Motorcycles were filtered out from all the traffic data. This is because motorcycles are not readily found on highways especially at night and in the rain, cyclists stay away from the road.

vi. Passenger car equivalent values was applied to each vehicle classification identified by the ATC. This made the traffic to be homogenous in nature.

vii. Speed and volume values of each separated five-minute traffic data were aggregated, and the mean speed computed. The mean values for parameters such as speed and volume are required. Computed mean speed and aggregated volume were separated into another sheet for further processing. Note that the volume obtained is in $PCE/5min$

viii. The traffic volume was converted from $PCE/5min$ to flow by multiplying with 12 to give PCE/hr.

ix. Using the fundamental equation of flow $q = uk$, the third parameter density was obtained. A sample Excel worksheet shown as figure 3.17 includes many columns where columns A, B, C and D stand for tagged dataset index, serial number, dataset axle number and number of axle hits in the vehicle respectively. Column D and E represent date and time of vehicle axle hit. Column G is vehicle travel direction, column H for vehicle speed, column I is vehicle wheelbase, J is headway and K stands for gap. Other columns include L, M, N and O which stands for number of axles, number of axle group while column P represents the PCE values of each vehicle type, Q stands for type of vehicle. Column R indicates motorcycle only and lastly; column S represents speed excluding all motorcycle speeds.

x. A check on possible speed reduction was first carried out using the speed percentile, followed by relating flow and density and lastly relating speed and density accordingly.

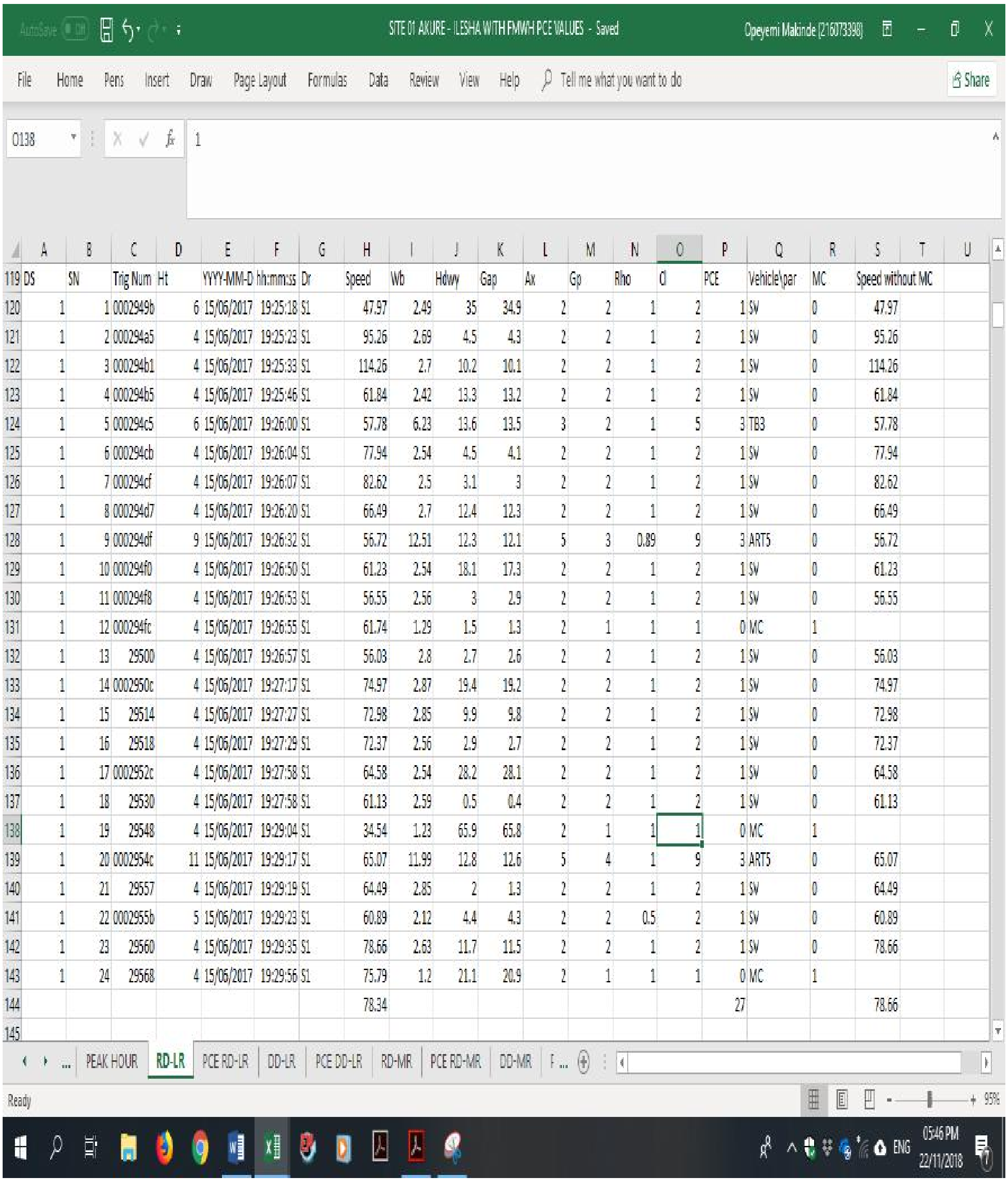
xi. Models based on flow-density relationship were obtained to estimate traffic information such as free-flow speed, speed at capacity, density and capacity for each roadway condition with respect to both dry and rainy conditions.

xii. A functional service quality criteria table was set up using dry daylight traffic parameters as the base condition.

xiii. Individual travel time for each condition considered was estimated using the obtained information in step xi.

xiv. Assessment of roadway functional service quality under rainy night-time was done using the obtained travel time in step xiii in conjunction with FSQ criteria table obtained in step xii. Thereafter, inferences were drawn based on the results obtained.

xv. Speeds and densities were related with the introduction of dummy variable to check the impact of rainfall in terms of its intensity with the dry condition. The relationship was tested statistically for fitness. The speed-density relationship was used to assess the implication of night-time rain on roadway stopping sight distance.



	A	B	C	D	E	F	G	H	I	J	K	L	M	N	O	P	Q	R	S
119	DS	SN	Trig Num	Ht	YYYY-MM-D	hh:mm:ss	Dr	Speed	Wb	Hdwy	Gap	Ax	Gp	Rho	Cl	PCE	Vehicle\par	MC	Speed without MC
120	1	1	0002949b	6	15/06/2017	19:25:18	S1	47.97	2.49	35	34.9	2	2	1	2	1	SV	0	47.97
121	1	2	000294a5	4	15/06/2017	19:25:23	S1	95.26	2.69	4.5	4.3	2	2	1	2	1	SV	0	95.26
122	1	3	000294b1	4	15/06/2017	19:25:33	S1	114.26	2.7	10.2	10.1	2	2	1	2	1	SV	0	114.26
123	1	4	000294b5	4	15/06/2017	19:25:46	S1	61.84	2.42	13.3	13.2	2	2	1	2	1	SV	0	61.84
124	1	5	000294c5	6	15/06/2017	19:26:00	S1	57.78	6.23	13.6	13.5	3	2	1	5	3	TB3	0	57.78
125	1	6	000294cb	4	15/06/2017	19:26:04	S1	77.94	2.54	4.5	4.1	2	2	1	2	1	SV	0	77.94
126	1	7	000294cf	4	15/06/2017	19:26:07	S1	82.62	2.5	3.1	3	2	2	1	2	1	SV	0	82.62
127	1	8	000294d7	4	15/06/2017	19:26:20	S1	66.49	2.7	12.4	12.3	2	2	1	2	1	SV	0	66.49
128	1	9	000294df	9	15/06/2017	19:26:32	S1	56.72	12.51	12.3	12.1	5	3	0.89	9	3	ART5	0	56.72
129	1	10	000294f0	4	15/06/2017	19:26:50	S1	61.23	2.54	18.1	17.3	2	2	1	2	1	SV	0	61.23
130	1	11	000294f8	4	15/06/2017	19:26:53	S1	56.55	2.56	3	2.9	2	2	1	2	1	SV	0	56.55
131	1	12	000294fc	4	15/06/2017	19:26:55	S1	61.74	1.29	1.5	1.3	2	1	1	1	0	MC	1	
132	1	13	29500	4	15/06/2017	19:26:57	S1	56.03	2.8	2.7	2.6	2	2	1	2	1	SV	0	56.03
133	1	14	0002950c	4	15/06/2017	19:27:17	S1	74.97	2.87	19.4	19.2	2	2	1	2	1	SV	0	74.97
134	1	15	29514	4	15/06/2017	19:27:27	S1	72.98	2.85	9.9	9.8	2	2	1	2	1	SV	0	72.98
135	1	16	29518	4	15/06/2017	19:27:29	S1	72.37	2.56	2.9	2.7	2	2	1	2	1	SV	0	72.37
136	1	17	0002952c	4	15/06/2017	19:27:58	S1	64.58	2.54	28.2	28.1	2	2	1	2	1	SV	0	64.58
137	1	18	29530	4	15/06/2017	19:27:58	S1	61.13	2.59	0.5	0.4	2	2	1	2	1	SV	0	61.13
138	1	19	29548	4	15/06/2017	19:29:04	S1	34.54	1.23	65.9	65.8	2	1	1	1	0	MC	1	
139	1	20	0002954c	11	15/06/2017	19:29:17	S1	65.07	11.99	12.8	12.6	5	4	1	9	3	ART5	0	65.07
140	1	21	29557	4	15/06/2017	19:29:19	S1	64.49	2.85	2	1.3	2	2	1	2	1	SV	0	64.49
141	1	22	0002955b	5	15/06/2017	19:29:23	S1	60.89	2.12	4.4	4.3	2	2	0.5	2	1	SV	0	60.89
142	1	23	29560	4	15/06/2017	19:29:35	S1	78.66	2.63	11.7	11.5	2	2	1	2	1	SV	0	78.66
143	1	24	29568	4	15/06/2017	19:29:56	S1	75.79	1.2	21.1	20.9	2	1	1	1	0	MC	1	
144								78.34								27			78.66
145																			

Figure 3.17: Typical Excel worksheet for data processing

3.5.2 Method of Analysis

The procedure of the analytical method adopted in this study is presented in Figure 3.18.

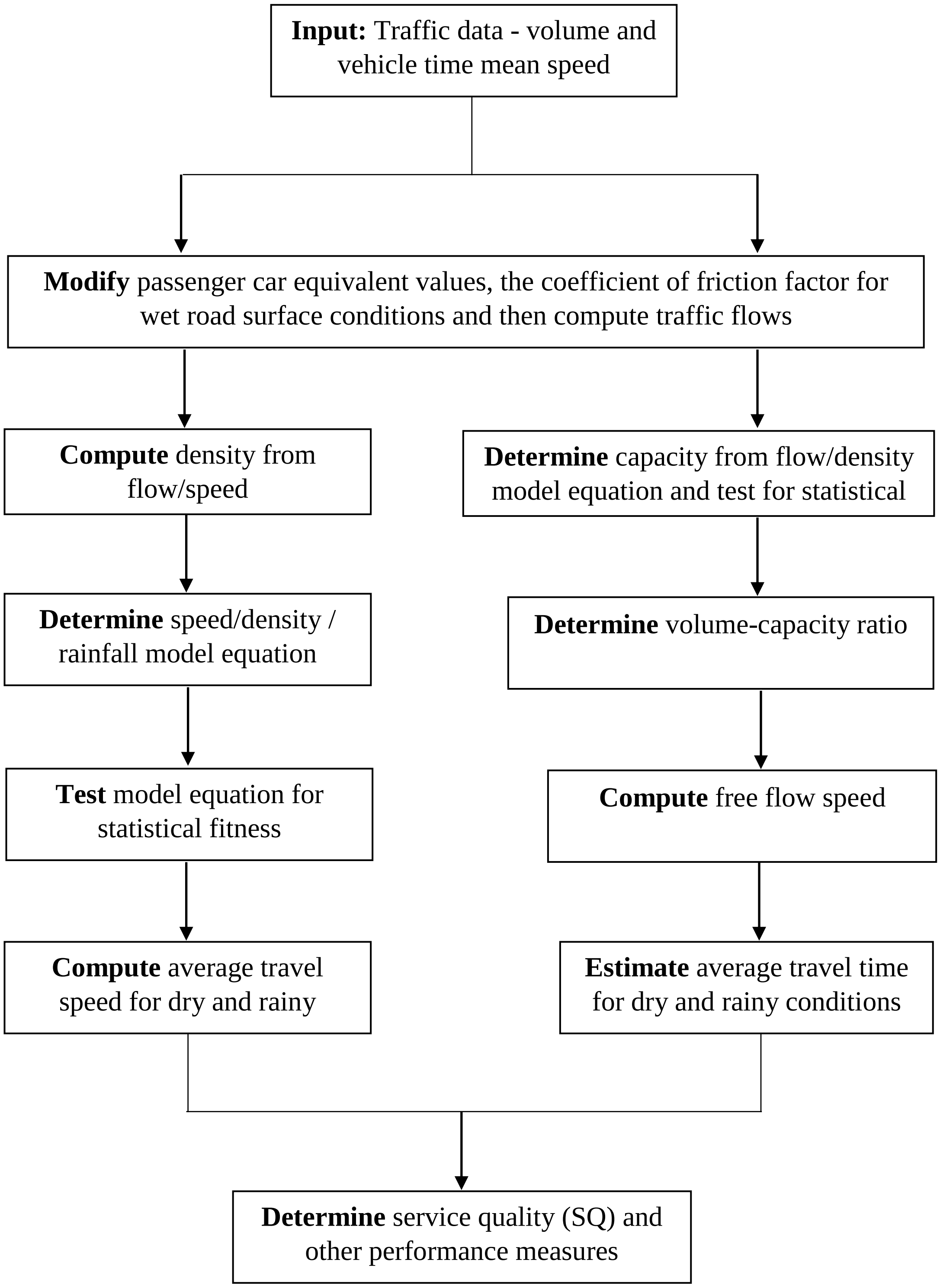


Figure 3.18: Two-Lane Functional Service Quality Assessment Methodology

This method encompasses the analysis of the empirical data obtained for all the weather conditions considered, development of the FSQ criteria table, the assessment of roadway service quality using the criteria table and lastly, implications on other road parameters. The FSQ criteria table is set up using the dry daylight (peak period) data while the assessment of night-time rain is based on the off-peak data for the night-time period. The analysis is centred on travel speed, travel time and roadway capacity.

3.6 Assessment of Functional Service Quality (FSQ) of Pilot Test

3.6.1 Empirical Data

Traffic data was sorted accordingly and separated into the necessary weather scenarios considered. Typical empirical data is presented in table 3.4. This table shows the traffic volume in respect of vehicle composition which are identified as passenger cars (PC), medium vehicles (MV) and heavy vehicles (HV) in columns 1, 2 and 3 respectively. Column 4 is the total volume of vehicles by five-minute count. Columns 5 and 6 represent the conversion of columns 2 and 3 to passenger car by multiplying with the appropriate passenger car equivalent values. Thereafter, traffic volume which is now at a homogenous state of passenger car/5min in column 7 was converted to flow in column 8 by multiplying by 12 to get it to pce/hr.

Table 3.4: Typical Traffic Volume

PC	MV	HV	Total vol (/5min)	MV (/pce)	HV (/pce)	Total vol (pce/5min)	Total flow (pce/hr)
col 1	*col 2*	*col 3*	*col 4* *cols (1 + 2 + 3)*	*col 5* *col 2*3*	*col 6* *col 3*3*	*col 7* *cols (1 + 5 + 6)*	*col 8* *col 7*12*
66	3	5	74	9	15	90	1080
95	4	6	105	12	18	125	1500
95	4	6	105	12	18	125	1500
59	3	4	66	9	12	80	960
54	3	4	61	9	12	75	900
59	3	4	66	9	12	80	960
99	5	7	111	15	21	135	1620
59	3	4	66	9	12	80	960
90	4	6	100	12	18	120	1440
59	3	4	66	9	12	80	960
78	4	5	87	12	15	105	1260
78	4	5	87	12	15	105	1260
76	3	5	84	9	15	100	1200
85	4	6	95	12	18	115	1380

*Note: col 4 = col 1 + col 2 + col 3; col 7 = col 1 +col 5 +col 6; col 8 = col 7 * 12*

Table 3.4 cont'd

PC	MV	HV	Total vol (/5min)	MV (/pce)	HV (/pce)	Total vol (pce/5min)	Total flow (pce/hr)
col 1	*col 2*	*col 3*	*col 4 cols (1 + 2 + 3)*	*col 5 col 2*3*	*col 6 col 3*3*	*col 7 cols (1 + 5 + 6)*	*col 8 col 7*12*
59	3	4	66	9	12	80	960
71	3	5	79	9	15	95	1140
66	3	5	74	9	15	90	1080
45	2	3	50	6	9	60	720
40	2	3	45	6	9	55	660
33	2	2	37	6	6	45	540
50	2	3	55	6	9	65	780
50	2	3	55	6	9	65	780
71	3	5	79	9	15	95	1140
52	2	4	58	6	12	70	840
59	3	4	66	9	12	80	960
40	2	3	45	6	9	55	660
52	2	4	58	6	12	70	840
35	2	3	40	6	9	50	600
35	2	3	40	6	9	50	600
59	3	4	66	9	12	80	960
85	4	6	95	12	18	115	1380
59	3	4	66	9	12	80	960
78	4	5	87	12	15	105	1260
45	2	3	50	6	9	60	720
66	3	5	74	9	15	90	1080
64	3	4	71	9	12	85	1020
71	3	5	79	9	15	95	1140
85	4	6	95	12	18	115	1380
66	3	5	74	9	15	90	1080
54	3	4	61	9	12	75	900
50	2	3	55	6	9	65	780
66	3	5	74	9	15	90	1080
50	2	3	55	6	9	65	780
52	2	4	58	6	12	70	840
76	3	5	84	9	15	100	1200
40	2	3	45	6	9	55	660
97	4	7	108	12	21	130	1560
35	2	3	40	6	9	50	600
40	2	3	45	6	9	55	660
52	2	4	58	6	12	70	840
54	3	4	61	9	12	75	900
59	3	4	66	9	12	80	960

*Note: col 4 = col 1 + col 2 + col 3; col 7 = col 1 +col 5 +col 6; col 8 = col 7 * 12*

Table 3.4 cont'd

PC	MV	HV	Total vol (/5min)	MV (/pce)	HV (/pce)	Total vol (pce/5min)	Total flow (pce/hr)
col 1	*col 2*	*col 3*	*col 4* *cols (1 + 2 + 3)*	*col 5* *col 2*3*	*col 6* *col 3*3*	*col 7* *cols (1 + 5 + 6)*	*col 8* *col 7*12*
50	2	3	55	6	9	65	780
50	2	3	55	6	9	65	780
66	3	5	74	9	15	90	1080
35	2	3	40	6	9	50	600
40	2	3	45	6	9	55	660
52	2	4	58	6	12	70	840
59	3	4	66	9	12	80	960
71	3	5	79	9	15	95	1140
54	3	4	61	9	12	75	900
45	2	3	50	6	9	60	720
66	3	5	74	9	15	90	1080
40	2	3	45	6	9	55	660
40	2	3	45	6	9	55	660
54	3	4	61	9	12	75	900

*Note: col 4 = col 1 + col 2 + col 3; col 7 = col 1 +col 5 +col 6; col 8 = col 7 * 12*

3.6.2 Modification of PCE Values

The PCE values initially used in the analysis were those specified by the FMWH which were estimated under normal dry daylight conditions. There is a need to modify the values to ascertain if they are suitable for other conditions outside normal dry daylight. The modification of the PCE values using the headway method was carried out and tested. The equation of the headway method is presented as equation 3.4

$$PCE_i = \frac{H_i}{H_c} \qquad 3.4$$

Where PCE_i = passenger car equivalent of vehicle class *i*

H_i = average headway of vehicle class *i* (sec)

H_c = average headway of passenger car (sec)

According to Hogema (1996), headway studies under rainfall showed that headway greater than five seconds is not affected by rain, therefore based on this, vehicles with headways greater than five seconds were filtered out, while the remaining headways were used for the PCE modification procedures. For this pilot study, the PCE modification procedure of dry night-time condition is presented thus:

$$Spacing = \frac{1}{Density} km/veh = \frac{1000}{Density} m/veh \qquad 3.5$$

Where density is the value obtained from the model, therefore, spacing becomes

$$Spacing = \frac{1000}{20} = 50m/veh$$

Average speeds of identified vehicles class were considered

Average speed of PC = 82.37km/hr = 22.88m/s (as obtained from ATC)

Average speed of MV = 78.44km/hr = 21.79m/s (as obtained from ATC)

Average speed of HV = 71.37km/hr = 19.83m/s (as obtained from ATC)

Thereafter, average headway of each vehicle class was calculated using

$$h_i = \frac{S}{u_i} \qquad 3.6$$

Where h_i = average headway of vehicle class *i*

S = spacing

u_i= speed of vehicle class *i*

Headway for PC = $50/22.88 = 2.19s$

Headway for MV = $50/21.79 = 2.29s$

Headway for HV = $50/19.83 = 2.52s$

Using equation 3.4 and obtained headway values, PCEs were thus modified as following

PCE for PC = $2.19/2.19 = 1.00$

PCE for MV = $2.29/2.19 = 1.02$

PCE for HV = $2.52/2.19 = 1.15$

The procedures were repeated for moderate and heavy night rain conditions and the summary presented in table 3.5 below

Table 3.5: Summary of modified PCE values

Vehicle Type	DN	LR	MR	HR
Passenger car	1.00	1.00	1.00	1.00
Medium vehicle	1.02	1.05	1.03	1.04
Heavy vehicle	1.15	1.15	1.15	1.17

DN = dry night, LR = light rain, MR = moderate rain, HR = heavy rain

From the table, it is evident that the modified PCE values for medium vehicles and heavy vehicle under night-time conditions are not equal to the PCE values specified by FMWH. The change in the PCE values is as a result of traffic conditions under different weather conditions in which impaired visibility is a major factor. The PCE values for medium vehicles under rainy night-time conditions increased though, without a defined pattern as against its corresponding value for dry night-time conditions. However, for heavy vehicles, the PCE values only changed under heavy night-time rainfall condition. Furthermore, a statistical test using the chi-square at 95 percent level of confidence was performed on the modified PCE and FMWH values for medium and heavy vehicles. The test determines if there is a significant difference between the modified PCE and FMWH values. Two hypotheses were made as follows:

- Null hypothesis (H_0): No difference between the modified PCE and FMWH PCE values
- Alternate hypothesis (H_1): There is a difference between the modified PCE and FMWH values

Chi-square equation is given as

$$X^2 = \frac{(o-e)^2}{e} \qquad 3.7$$

Where X^2 = chi-square,

o = observed value

e = expected value

The test was carried out at a 95 percent level of confidence for one degree of freedom where $X^2 = 3.84$ as taken from chi-square distribution table (see appendix). If $X^2 < 3.84$, it means no significant difference between the PCE variables hence the null hypothesis (H_0) is accepted, but if otherwise such as $X^2 > 3.84$, the alternate hypothesis (H_1) is accepted that is there is a significant difference between the PCE variables.

For medium vehicles (MV) with a modified PCE value of 1.02 under dry night-time conditions and FMWH PCE value of 3

$$X^2 = \frac{(1.02-3)^2}{3} = 1.31 < 3.84$$

The null hypothesis (H_0) is thus accepted since $1.31 < 3.84$ and the alternate hypothesis (H_1) is rejected. The result shows no statistical difference between the modified PCE and FMWH values at a 95 percent level of confidence for one degree of freedom. Therefore, since there is no significant difference, either FMWH PCE or modified PCE could be used. For this study, preference is given to the modified PCE values since it reflects the prevailing conditions of the study. A typical summary of flow, speed and density is shown in Table 3.6

Table 3.6: Typical Summary of Flow-Speed-Density

vol (pce/5 min)	q (pce/ hr	u (km/ h)	k (pce/ km)	vol (pce/5 min)	q (pce/ hr	u (km/ h)	k (pce/ km)	vol (pce/5 min)	q (pce/ hr	u (km/ h)	k (pce/ km)
90	1080	70	15.4	55	660	57	11.6	70	840	69	12.2
125	1500	81	18.5	95	1140	76	15.0	100	1200	53	22.6
125	1500	80	18.8	70	840	46	18.3	130	1560	70	22.3
80	960	70	13.7	80	960	67	14.3	50	600	56	10.7
75	900	87	10.3	55	660	80	8.3	55	660	56	11.8
80	960	62	15.5	70	840	65	12.9	70	840	55	15.3
135	1620	75	21.6	50	600	66	9.1	75	900	50	18.0
80	960	66	14.5	50	600	61	9.8	80	960	55	17.5
120	1440	60	24.0	80	960	62	15.5	65	780	65	12.0
80	960	68	14.1	115	1380	64	21.6	65	780	48	16.3
105	1260	75	16.8	80	960	60	16.0	90	1080	75	14.4
105	1260	81	15.6	105	1260	56	22.5	50	600	51	11.8
100	1200	66	18.2	60	720	45	16.0	55	660	55	12.0
115	1380	77	17.9	90	1080	59	18.3	70	840	78	10.8
80	960	65	14.8	85	1020	82	12.4	80	960	76	12.6
95	1140	72	15.8	95	1140	51	22.4	95	1140	64	17.8
90	1080	68	15.9	115	1380	65	21.2	75	900	55	16.4
60	720	63	11.4	90	1080	82	13.2	60	720	79	9.1
55	660	66	10.0	75	900	64	14.1	90	1080	60	18.0
45	540	56	9.6	65	780	64	12.2	55	660	60	11.0
65	780	63	12.4	90	1080	72	15.0	55	660	52	12.7
65	780	58	13.4	65	780	76	10.3	75	900	90	10.0

Note that, q denotes flow, u denotes speed and k denotes density where $q = uk$

The procedure for obtaining flow, density and speed data was carried out for dry daylight (peak and of-peak) conditions and night conditions of dry, light rain, moderate rain and heavy rain.

Table 3.7 represents the empirical data summary both the peak and off-peak periods of dry daylight conditions while Table 3.8 is the dry night-time conditions and Tables 3.9, 3.10 and 3.11 are the empirical data for light rainy night-time conditions, moderate rainy night-time conditions and heavy rainy night-time condition respectively.

Table 3.7: Empirical Data for Dry Daylight (Peak and Off-Peak Periods)

Period	Dry daylight (peak)			Dry daylight (off-peak)		
	u (km/h)	q (pce/h)	k (pce/km)	u (km/h)	q (pce/h)	k (pce/km)
1	67	1348	20	65	1288	20
2	79	1275	16	72	1438	20
3	60	1658	28	90	1337	15
4	79	1575	20	83	1113	13
5	75	1425	19	70	1387	20
6	67	1649	25	88	1062	12
7	72	1573	22	83	1137	14
8	83	1425	17	95	1489	16
9	74	1725	23	70	1594	23
10	73	1510	21	58	1578	27
11	70	1599	23	87	1413	16
12	69	1425	21	84	1200	14
1hr	ave = 72			ave = 79		

u = speed, q = flow, k = density, ave = average

Table 3.8: Empirical Data for Dry Night-Time

Period	u (km/h)	q (pce/h)	k (pce/km)
1	106	1050	10
2	98	750	8
3	85	940	11
4	80	1165	15
5	87	900	10
6	79	825	10
7	76	975	13
8	77	1090	14
9	70	1125	16
10	95	675	7
11	90	715	8
12	78	1015	13
1hr	ave = 85		

u = speed, q = flow, k = density, ave = average

Table 3.9: Empirical Data for Light Night-Time Rain

Period	u (km/h)	q (pce/h)	k (pce/km)
1	60	480	8
2	68	383	6
3	67	443	7
4	72	300	4
5	57	503	9
6	58	413	7
7	50	975	19
8	68	240	4
9	70	825	12
10	57	600	11
11	61	865	14
12	70	315	5
1hr	ave = 63		

u = speed, q = flow, k = density, ave = average

Table 3.10: Empirical Data for Moderate Night-Time Rain

Period	u (km/h)	q (pce/h)	k (pce/km)
1	49	715	15
2	50	1050	21
3	35	1125	32
4	52	900	17
5	60	750	13
6	62	450	7
7	50	675	14
8	64	775	12
9	56	525	9
10	57	725	13
11	53	600	11
12	57	415	7
1hr	ave = 54		

u = speed, q = flow, k = density, ave = average

Table 3.11: Empirical Data for Heavy Night-Time Rain

Period	u (km/h)	q (pce/h)	k (pce/km)
1	50	520	10
2	55	825	15
3	65	300	5
4	45	900	20
5	52	790	15
6	61	450	7
7	43	975	23
8	52	450	9
9	60	375	6
10	58	675	12
11	52	815	17
12	64	350	6
1hr	ave = 55		

u = speed, q = flow, k = density, ave = average

3.6.3 Analysis and Discussion

Stepwise analysis was adopted due to its simplicity and clarity for the pilot study. The analysis is presented as follows:

Step 1: Application of the speed percentile test to determine whether the percentile speed curve has shifted because of night-time rainfall on dark roadways. A speed percentile test using 15th, 50th and 85th was first carried out on the speed data of each condition to verify the possibility of speed reduction under night-time rain conditions. The 15th percentile speed is the speed at which 15 percent of the vehicles are moving, while the 50th percentile speed represents half of the observed speeds and the 85th-percentile speed is the speed value less than 15 percent of a measured field speed. The graph of the speed percentile is given as Figure 3.19. The results of the speed percentile show that at the 15th, speed drops from 75km/h to 54km/h, 46km/h and 41km/h for light, moderate and heavy rain respectively while for the 85th percentile, speed reduced from 95km/h to 68km/h, 61km/h and 64km/h for light, moderate and heavy rain respectively. It is clear from the speed cumulative graph that speed reduction is attributed to night-time rainfall on dark roadways. The next stage is to develop a functional service quality assessment criteria table bearing in mind that the functional service quality (FSQ) criteria table is developed from the roadway's peak performance, however, for the purpose of assessing the influence of nigh-time rainfall on dark roadway's functional service, off-peak performance was considered. This is needed in order to remove the influence of peak traffic flow in the study's outcomes and ensure that night-time rainfall on dark roadways could be held accountable for functional service quality reduction.

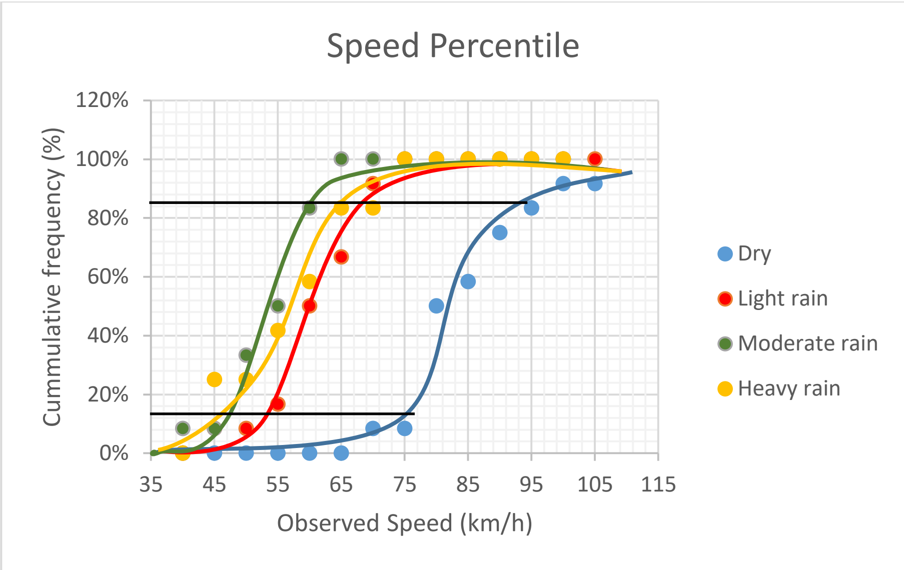


Figure 3.19: Speed percentile graph for dry and rainy night-time conditions

Step 2: Development of the functional service quality (FSQ) criteria table

In this study, functional service quality is described as a bi-dimensional assessment depending on both travel time for road users and travel speed for road providers. It is on this basis, that the FSQ criteria table is developed. Travel time is the time requires to travel the entire length of the observed path. Travel time ratio is defined as a proportion between the travel time at peak hours and the travel time at off-peak hours for a particular road section. Whereas degree of saturation, often interchangeably used as volume/capacity ratio, is a measures of traffic flow demand relative to the roadway capacity. For the purpose of quantitative assessment traffic flow is the objective function and density is the independent parameter. However, for the purpose of qualitative assessment, travel speed or travel time is the objective function and volume/capacity ratio the independent parameters. All variables are tied together in the fundamental diagram where roadway capacity is construed in many literatures as the maximum hourly rate at which persons or vehicles can move in a reasonable order of a point or a lane of road, during a period of time under the prevailing conditions of path, traffic and control. Note that $q = uk$ and

Speed, $u_i = u_f - bk$; then, Capacity, $Q = ku_f - bk^2$

$$\frac{\partial q}{\partial k} = u_f - 2bk = 0;\ k_Q = \frac{u_f}{2b}$$

Speed at capacity, $u_Q = \frac{2b(ku_f - bk^2)}{u_f}$

Where, q = flow, u = speed, k = density, u_f = free flow speed, Q = capacity, k_Q = density at capacity, u_Q = speed at capacity

Using peak traffic data, the flow/density model is given as

$$q_{DDpeak} = -2.2687k^2 + 132.22k - 262.85 \qquad R^2 = 0.9224 \qquad 3.8$$

The flow-density model has the correct sign convention with a coefficient of determination $R^2 = 0.9224$. The R^2 value shows that the model is good for prediction.

Differentiating *q* with respect to *k* in equation 3.8

$$\frac{dq}{dk} = -2 * 2.2687k + 132.22 = 0$$

$$k_Q \approx 29\ veh/km$$

Substituting obtained k_Q into equation 3.8 to obtain capacity Q, gives

$$Q = -2.2687(29)^2 + 132.22(29) - 132.22$$

$$Q \approx 1664 pce/h$$

Plugging the values of k_Q and q into the fundamental equation, $q = ku$, speed at maximum flow is thus obtained as

$$u_Q = \frac{q}{k} = \frac{1664}{29} \approx 57 km/h$$

The obtained capacity $Q \approx 1664 pce/h$ is approximated as 1700pce/h and divided into six to reflect the classes for the FSQ criteria table. The classes are designated as class A-F where Class A represents the best service quality while class F is the worst service quality. Class E is the capacity class where volume-capacity ratio is 100 percent which is the borderline between congested and uncongested section of the flow-density curve while class F is the congested section of the curve. With class E as capacity class of 100 percent, divide 100 percent into four equal parts to give 25 percent (0.25), 50 percent (0.5), 75 percent (0.75) and 100 percent (1). Introduce the threshold of 85 percent (0.85), therefore, the classes are now class A = 0.25, class B = 0.5, class C = 0.75, class D = 0.85 which is known as the threshold class, class E = 1 and class F >1.

Step 3: Determination of travel time and travel speed for functional service quality levels

Using US-BPR formula presented as equation 3.9, calculate travel time for each class

$$T = t_f\left[1 + \rho(x)^{\beta}\right] = t_f\left[1 + \rho\left(\frac{v}{q}\right)^{\beta}\right] \qquad 3.9$$

where T = predicted time over roadway length; t_f = travel time at free-flow speed

v = demand traffic volume, *q* = capacity

ρ = ratio of free flow to speed at capacity (*ρ = 0.15 or 0.2)*

β = abrupt drop of curve from the free-flow speed (*β = 4 or 10)*

x = degree of saturation ($\frac{v}{Q}$) = volume capacity ratio

When $\frac{v}{q} = 1, \beta = 4$ and $\rho = 0.15$ and when $\frac{v}{q} < 0.9,\ \beta = 10$ and $\rho = 0.2$

For class E, $\frac{v}{q} = 1$

Speed at capacity u_Q = 57km/h, its equivalent time, $t_E = 60/57 = 1.05min$

Where $\frac{v}{q} = 1, \beta = 4$ and $\rho = 0.15$, travel time for class E is calculated as

$$T_E = \frac{60}{57}[1 + 0.15(1)^4]$$

$$T_E = 1.22min$$

For class A to D, $\frac{v}{q} < 0.9$

Speed for class A = 130km/h, hence its equivalent time, $t_E = 60/130 = 0.46min$

Where $\frac{v}{q} < 0.9,\ \beta = 10$ and $\rho = 0.2$, travel time for class A is calculated as

$$T_A = \frac{60}{130}[1 + 0.2(0.9)^{10}]$$

$$T_A = 0.49min$$

As speed is evenly distributed, speed for each class is distributed between the free-flow speed of 130km/h for class A and speed at capacity of 57km/h for class E. The speed is used to calculate its time and expected travel time, thereafter, the criteria table for service quality is set up. Thus,

Class A (0.25) = 0.25 * 1700 = 425pce/h ≈ 500pce/h

Class B (0.50) = 0.50 * 1700 = 850pce/h ≈ 900pce/h

Class C (0.75) = 0.75 * 1700 = 1275pce/h ≈ 1300pce/h

Class D (0.85) = 0.85 * 1700 = 1445pce/h ≈ 1500pce/h

Class E (1.0) = 1700pce/h and

Class F (> 1) = < 1700pce/h

Based on the obtained travel time for each class capacity and its subsequent travel speed, the functional service quality criteria table is presented as Table 3.12

Table 3.12: Pilot Study FSQ Criteria Table

CLASS	T (min)	U (km/h)	Q (pce/h)	K (veh/km)	h (s)
A	< 0.49	> 130	< 500	< 4	7.2
B	0.58	110	900	8	4.0
C	0.71	90	1300	14	2.8
D	0.92	70	1500	21	2.4
E	1.25	55	1700	31	2.1
F	> 1.25	< 55	< 1700	> 31	< 2.1

T = travel time, u = speed (± 20%), q = flow rate, k = density, h = headway

Step 4: Measurement of Influence of rainfall on dark roadway FSQ

The roadway functional service quality assessment is investigated using the free flow speed values of the models earlier developed in step 1 of this section for each condition considered. The flows and densities of each condition considered were related and their individual model presented as follows:

$$q_{DD} = -2.5553k^2 + 128.51k - 86.082 \qquad R^2 = 0.7044 \qquad 3.10$$

$$q_{DN} = -2.9998k^2 + 119.80k - 9.9669 \qquad R^2 = 0.8426 \qquad 3.11$$

$$q_{LR} = -1.3197k^2 + 78.652k - 29.078 \qquad R^2 = 0.9584 \qquad 3.12$$

$$q_{MR} = -1.2447k^2 + 77.584k - 74.622 \qquad R^2 = 0.9479 \qquad 3.13$$

$$q_{HR} = -1.1703k^2 + 70.467k - 17.920 \qquad R^2 = 0.9796 \qquad 3.14$$

For all the models, coefficient of determination R^2 was greater than 0.5 which shows that the models are good for prediction. From the model equations, free flow speeds and their corresponding travel times are computed for various scenarios. According to all the models obtained, the coefficients of "k" in the models represent the traffic free-flow speed. Take for example the dry daylight quadratic equation shown below;

$$q_{DD} = -2.5553k^2 + 128.51k - 86.082 \qquad R^2 = 0.7044$$

Therefore, the free flow speed is; $u_f = 128.5km/h$, Equivalent free flow time, $t_{uf} = 60/128.5 = 0.47min$

Where; $\frac{v}{q} < 0.9,\ \beta = 10$ and $\rho = 0.2$,

Computed travel time is, $$T_{DD} = \frac{60}{128.5}[1 + 0.2(0.9)^{10}]$$

$$T_{DD} = 0.5min$$

From table 3.12, for travel time of 0.5min, the functional service quality is class B

For dry night-time, free flow speed, $u_f = 119.8km/h$,

Equivalent time, $t_{uf} = 60/119.8 = 0.5min$

Where $\frac{v}{q} < 0.9,\ \beta = 10$ and $\rho = 0.2$,

Computed travel time is, $$T_{DN} = \frac{60}{119.8}[1 + 0.2(0.9)^{10}]$$

$$T_{DN} = 0.54min$$

From table 3.12, for travel time of 0.54min, the functional service quality is class B

For light night rain, free flow speed, $u_f = 78.7km/h$,

Equivalent free flow time, $t_{uf} = 60/78.7 = 0.76min$

Where $\frac{v}{q} < 0.9,\ \beta = 10$ and $\rho = 0.2$,

Computed travel time is, $$T_{LR} = \frac{60}{78.7}[1 + 0.2(0.9)^{10}]$$

$$T_{LR} = 0.81min$$

From table 3.12, for travel time of 0.81min, the functional service quality is class C

For moderate night rain, free flow speed, $u_f = 77.6km/h$,

Equivalent free flow time, $t_{uf} = 60/77.6 = 0.77min$

Where $\frac{v}{q} < 0.9,\ \beta = 10$ and $\rho = 0.2$,

Computed travel time is, $$T_{MR} = \frac{60}{77.6}[1 + 0.2(0.9)^{10}]$$

$$T_{MR} = 0.83min$$

From table 3.12, for travel time of 0.83min, the functional service quality is class D

For heavy night rain, free flow speed, $u_f = 70.5km/h$,

Equivalent free flow time, $t_{uf} = 60/70.5 = 0.85min$

Where $\frac{v}{q} < 0.9,\ \beta = 10$ and $\rho = 0.2$,

Computed travel time is, $$T_{HR} = \frac{60}{70.5}[1 + 0.2(0.9)^{10}]$$

$$T_{HR} = 0.91min$$

From table 3.12, for travel time of 0.91min, the functional service quality is class D.

The summary of the functional service quality analysis is presented as Table 3.13. From the table, free-flow speed dropped by 7 percent from 129km/h under dry daylight conditions to 120km/h under dry night-time conditions. The travel time increased by 87 percent from 0.5min to 0.54min. This confirms that as speed reduces, travel time increases and vice-versa. The comparative assessment of dry night with rainy night-time conditions shows that the free-flow speed of 120km/h under dry night conditions reduced to 79km/h, 78km/h and 70km/h for light, moderate and heavy rain respectively. However, the travel time under dry night increased from 0.54min to 0.81min for light rain (50.1%), 0.83min (53.8%) for moderate rain and 0.92min (70.5%). These changes in both travel speed and travel time under the scenarios are evident in terms of functional service quality of the road.

Table 3.13: Summary of Functional Service Quality Assessment for Pilot Study

Weather condition	Model	u_f (km/h)	t_f (min)	$\rho\left(\frac{v}{q}\right)^{\beta}$	1 + col 5	T (min)	FSQ
1	2	3	4	5	6	7	8
Dry day	$-2.5553k^2 + 128.51k - 86.082$	129	0.47	0.07	1.07	0.50	B
Dry night	$-2.9998k^2 + 119.80k - 9.9669$	120	0.50	0.07	1.07	0.54	B
Light rain	$-1.3197k^2 + 78.652k - 29.078$	79	0.76	0.07	1.07	0.81	C
Moderate rain	$-1.2447k^2 + 77.584k - 74.622$	78	0.78	0.07	1.07	0.83	D
Heavy rain	$-1.1703k^2 + 70.467k - 19.920$	70	0.86	0.07	1.07	0.92	D

*u_f = free-flow speed, t_f = travel time at u_f, T = travel time, ρ = ratio of free-flow to speed at capacity, β = abrupt drop of curve from the free-flow speed, v/q = volume-capacity ratio, col 7 = col 4*col 6*

The functional service quality of the dry conditions (both day and night) remains at class B, this signifies that there is no influence whatsoever that is significant enough to alter the roadway service quality despite the increase in travel time and its associated reduction in free-flow speed. It is therefore evident that it is the 'night condition' that triggered the reduction in free-flow speed. Comparing the dry night with rainy night-time conditions, there is a significant change in the functional service quality of the dark roadway. The functional service quality under light rainy night-time conditions is class C while for moderate and heavy rainy night-time conditions, FSQ is class D. The summary of the pilot test is that the functional service quality deteriorates significantly due to night-time rain.

3.7 Implication on Stopping Sight Distance

Stopping sight distance as a safety measure on the road is important in assessing road traffic performance. Based on the hypothesis that night-time rain on dark roadways for a two-lane road without light influences the roadway functional service quality, it may be correct to say that stopping sight distance of dry and wet road surfaces will not be the same. Hence, there is a need to investigate the impact of the rainy night on stopping sight distance of the dark roadway.

Stopping sight distance (SSD) is estimated as following

$$SSD_i = RD_i + BD_i \tag{3.15}$$

Where;

BD denotes braking distance and RD denotes reaction distance;

i = weather condition of either dry night (DN) or rainy night-time condition (RN)

3.7.1 Reaction Distance (RD)

Reaction distance is expressed as

$$RD = u_{fi}t = 0.278u_{fi} * t \tag{3.16}$$

Where

u_{fi} = free-flow speed,

i = weather condition of dry night-time or rainy night-time

Average reaction time, *t* = 2.5s

If 2.5s is plugged into equation 3.16, thus,

$$RD_i = 0.278u_{fi} * 2.5 = 0.695u_{fi} \tag{3.17}$$

3.7.2 Braking Distance (BD)

Braking distance is expressed as

$$BD_i = \frac{(u_{fi})^2}{2a} \qquad 3.18$$

Where

u_f = free-flow speed (m/s), a = deceleration m/s^2

i = weather condition of dry night-time or rainy night-time

It has been shown in previous studies that deceleration distance increases with an increase in vehicle speed in all vehicle types. This implies that during a deceleration (a) manoeuvre from a higher speed to a stop condition, drivers traverse more distance as compared to a deceleration manoeuvre from lower speed ranges. Deceleration distance and time are similar in behaviour; vehicle deceleration time also increases with their maximum speed. Where g denotes gravitational force, note that friction factor, $f = \frac{a}{g}$

For deceleration, $$a_{t_2} = \frac{\Delta v}{\Delta t} = \frac{(v_1 - v_2)}{(t_2 - t_1)} \qquad 3.19$$

Therefore, braking distance equation can be rewritten as;

$$BD_i = \frac{(0.278uf_i)^2}{2 * \left|\frac{(v_1 - v_2)}{(t_2 - t_1)}\right|} \qquad 3.20$$

Therefore, generalised SSD equation is rewritten as

$$SSD_i = 0.695u_{fi} + \frac{(0.278u_{fi})^2}{2 * \left|\frac{(v_1 - v_2)}{(t_2 - t_1)}\right|} \qquad 3.21$$

Using the stepwise analysis, the stopping sight distance of the pilot study is presented thus.

Step 1: Determine the linear model equations for a dark roadway. A dummy variable (ψ) was introduced to assess the impact of rainfall (irrespective of its intensity) on the dry conditions. The introduction of a dummy variable (ψ) is to indicate whether there will be a shift in speed in the absence or presence of rainfall. This was done by combining speed and density under dry night and night rain conditions with dummy variable. The dummy variable conditions are such that ψ = 0 for dry conditions and ψ = 1 for rainfall conditions. Table 3.14 represents the combined speed-density data with a dummy variable (ψ) while Figure 3.22 is the statistical result.

Table 3.14: Dry and Light Rainy Night-Time Conditions with Dummy Variable (ψ)

Weather condition	u (km/h)	k (pce/km)	ψ (1 or 0)
Light night rain	60	8.0	1
	68	5.6	1
	67	6.6	1
	72	4.2	1
	57	8.8	1
	58	7.1	1
	50	19.5	1
	68	3.5	1
	70	11.8	1
	57	10.5	1
	61	14.2	1
	70	4.5	1
Dry night	106	9.9	0
	98	7.7	0
	85	11.1	0
	80	14.6	0
	87	10.3	0
	79	10.4	0
	76	12.9	0
	77	14.1	0
	70	16.1	0
	95	7.1	0
	90	7.9	0
	78	13.0	0

u = speed, k = density, ψ = dummy variable

SUMMARY OUTPUT

Regression Statistics	
Multiple R	0.89358
R Square	0.79848
Adjusted R Squar	0.77929
Standard Error	6.65265
Observations	24

ANOVA

	df	*SS*	*MS*	*F*	*gnificance F*
Regression	2	3682.62	1841.31	41.6042	5E-08
Residual	21	929.412	44.2577		
Total	23	4612.03			

	Coefficients	*tandard Err*	*t Stat*	*P-value*	*Lower 95%*	*Upper 95%*	*ower 95,0%*	*pper 95,0%*
Intercept	102.635	4.52644	22.6745	3E-16	93.2216	112.048	93.2216	112.048
X Variable 1	-10.868	2.87156	-9.0083	1.2E-08	-31.839	-19.896	-31.839	-19.896
X Variable 2	-1.5595	0.36414	-4.2827	0.00033	-2.3168	-0.8022	-2.3168	-0.8022

Figure 3.20: Statistical result of Table 3.14

The ensuing linear model equation for Table 3.14 is:

$$u_{LR} = 102.63 - 1.5595k - 10.868 \qquad R^2 = 0.7985 \qquad 3.22$$

The coefficient of determinant (R^2) is greater than 0.5, thus, the relationship is valid and acceptable. A statistical test was carried on the combination of both dry night-time and light night-time rain conditions to determine the suitability of the obtained model. The statistical result of the test performed at a 95 percent level of confidence is attached in Figure 3.20. The t-test is greater than 2.2 suggesting that the variables are significant, while the F-stat is greater than F-critical at 4.84 which means that the equation did not occur by chance. In summary, the models are valid and could be used for prediction.

The process was repeated for moderate night-time rain (*MR*) and heavy night-time rain (*HR*) conditions. The models obtained with the introduction of a dummy variable are given as

$$u_M = 99.114 - 1.2467k - 12.617 \qquad R^2 = 0.8826 \qquad 3.23$$

$$u_H = 101.14 - 1.4271k - 14.395 \qquad R^2 = 0.8895 \qquad 3.24$$

The model equations obtained have the expected signs of a negative linear regression which by implication means that a decrease in speed results in an increase in density.

Step 2: Based on the linear model equation 3.22 in step 1, determine the free flow speed for both dry and rainy night conditions and its speed differential.

Free-flow speed for dry night condition $u_{fDN} = 102.63km/h$ $(28.5m/s)$

Free-flow speed differential, $\Delta u_f = 10.87km/h(2.961m/s)$

Free-flow speed, light night rain, $u_{fDN} = 102.63 - 10.87 = 91.76km/h(25.51m/s)$

Step 3: Obtain the time equivalent of each free-flow speed and its differential. Using both the time and speed differential, determine the deceleration value using equation 3.19

The time equivalent for dry night condition $t_{DN} = 100/28.5 = 3.50s$

The time equivalent for light night rain, $t_{LR} = 100/25.50 = 3.94s$

Change in time equivalent $\Delta t = 3.94 - 3.50 = 0.44s$

Thus, deceleration is obtained as following

$$a_{LR} = \frac{\Delta v}{\Delta t} = \frac{2.961}{0.44} = 6.7m/s^2$$

Step 4: Based on the linear model equation 3.22 in step 1, determine the reaction distance *(RD)* for dry night and light night rainfall on a dark roadway using equation 3.17

Where reaction distance, $RD_i = 0.695u_{fi}$,

Reaction distance for dry night, $RD_{DN} = 0.695u_{fDN} = 0.695 * 102.63 = 71.33m$

Reaction distance for light night rain, $RD_{LR} = 0.695u_{fLR} = 0.695 * 91.76 = 63.77m$

Step 5: Based on the linear model equation 3.22 in step 1, determine braking distance *(BD)* for dry night and light night rainfall on a dark roadway. Note that the deceleration value obtained in step 3 is used to determine the braking distance for both dry and rainy night conditions.

$$BD_{DN} = \frac{(0.278u_{fi})^2}{2a} = \frac{(0.278*102.63)^2}{2*6.7} = 60.75m$$

$$BD_{LR} = \frac{(0.278u_{fi})^2}{2a} = \frac{(0.278*91.76)^2}{2*6.7} = 48.24m$$

Step 6: Using results from step 4 and step 5, determine the stopping sight distance (SSD) for dry night and light night rainfall on a dark roadway such that

$$SSD_i = RD_i + BD_i$$

For dry night on dark roadway $SSD_{DN} = 71.33m + 60.75m = 132.08m$

For light rainy night on dark roadway $SSD_{LR} = 63.77m + 48.24m = 112.01m$

Step 5: Determine the influence of night-time rainfall on a dark roadway by computing the SSD differences. Thus, for light rainy night conditions on a dark roadway, its stopping sight distance for dry conditions is 132.08m but decreased to 112.01m under rainfall. The change in stopping sight distance due to rainfall effect is 20m.

Steps 2 - 6 were repeated for moderate and heavy rainy night-time conditions respectively. The rainy night-time conditions are summarised and presented as Table 3.15

Table 3.15: Summary of Stopping Sight Distance for Pilot Study

Rain	Model equation	u_{fDN}	u_{fRN}	a	SSD_{DN}	SSD_{RN}	Δ
LR	102.63 - 1.56k – 10.86	102.6	91.8	0.44	132.08	112.01	20.07
MR	99.114 - 1.25k – 12.62	99.1	86.5	0.53	125.53	103.25	22.28
HR	101.14 - 1.43k – 14.39	101.1	86.7	0.59	129.28	103.69	25.59

LR = light rain, MR = moderate rain, HR = heavy rain, DN = dry night, RN = rainy night, a = deceleration, f = friction factor, SSD= stopping sight distance (m), Δ = difference

From Table 3.15, the percentage difference for the stopping sight distance between dry night conditions and rainy night conditions relative to its intensity is such that light rainy night (LR) $= 20.07/132.08 = 15.3\%$; moderate rainy night (MR) $= 22.28/125.53 = 17.7\%$ and heavy rainy night (HR) $= 25.59/129.28 = 19.7\%$. Also, from the table, it is observed that free flow speed under night rain conditions reduced irrespective of rainfall intensity. This led to a decrease in stopping sight distance under rainy night-time conditions in comparison with dry night condition. The decrease is a function of the negative effect of rainfall on free flow speed. It is worthy to note that breaking distance has a more significant impact on stopping sight distance due to rain compared to the reaction distance. It can be assumed that as speed is reduced due to impaired visibility during rainfall, drivers require lesser distance in bringing their vehicles to a halt under rainy conditions. Bearing in mind that the functional service quality deteriorates significantly under heavy night-time rain intensity, this trend is also followed by stopping sight distance. The decrease in stopping sight distance is more evident with heavy rain intensity as against light rain intensity.

It is evident that rainfall has a significant impact on stopping sight distance. Based on the pilot study analysis, the following are adopted for the selected four sites.

- There is evidence of speed reduction using speed percentile.
- Based on the submission that there is no significant difference in the modified PCE values and FMWH values, the modified PCE values are adopted for this study.
- The setting up of a criteria table for functional service quality is important in analysing and understanding traffic performance under rainy conditions.
- The flow-density relationship is adopted for estimating the impact of rainfall at night-time on roadway capacity. This relationship is adopted because it encompasses the three basic traffic parameters empirically obtained to analyse travel speed, traffic capacity and travel time.

- Use of speed-density relationship with a dummy variable is possible in understanding the implication of night rain on stopping sight distance.

3.8 SUMMARY

The method of collecting the required traffic and rainfall data was presented in this chapter. The chapter also highlighted the criteria for selection of the study site and the geometric features of selected road sections. The traffic data collection method, site coding for identification purposes, and the survey team were well stated. The automatic traffic counter was identified as the most appropriate equipment and used for traffic data collection. Automatic rain gauges were used for rainfall data collection but were subjected to external rainfall data for validation and reliability purposes. Three rainfall classes which are light rain, moderate rain and heavy rain in increasing order of intensity were identified for use.

Furthermore, the chapter described the stepwise method of analysing data for model formulation. The pilot study presented in the chapter was used to confirm and ascertain the suitability of all analysis procedures proposed. Nevertheless, there are questions to be answered in this study. Consequently, the data begs several questions on the influence of rainfall at night-time on roadway capacity loss. The questions are

- Does night-time rain have an influence on functional service quality of dark roadways?
- If yes, to what extent is the influence?
- What is the implication of night rain on stopping sight distance of dark roadways?

Based on the questions raised above, data for the four selected study sites are analysed in chapter 4 and investigated in chapter 5 for functional road service quality assessment, while in chapter 6, the implications of rainfall on stopping sight distance is investigated.

CHAPTER FOUR

EMPIRICAL RESULTS OF STUDY SITES

4.1 Overview

In the previous chapter, it was stated that the method of study is empirical based, therefore, both traffic and rainfall data are fundamental data required in achieving the study objectives. The previous chapter described required traffic and rainfall data with their respective method of collection. The traffic data gives information such as speed, volume, headway, type of vehicle and time of vehicle movement as captured by the ATC under prevailing conditions of dry and rainfall periods for both day and night times. Other information such as density are derived using the fundamental relationship of flow while traffic composition is analysed from the raw data. The rainfall data obtained are time of rainfall occurrence and amount of rainfall event per time, which is further converted into intensity. The rainfall data is synchronised with traffic data to obtain required data for both dry and rainy conditions at night. Thus, this chapter focusses on the empirical data required for analysis.

The organisation of this chapter is as follows: a summary of geometric information of the four sites is presented in section 4.2. In addition to the geometric information, typical rainfall information and individual site report as obtained from the ATC for all the study sites are presented in section 4.3. The individual site report is presented in the following order: flow-time profile, volume-density graph, speed-density graph, traffic composition, hourly traffic volume and speed for each weather scenario. In section 4.4, the chapter is summarised.

4.2 Summary of Surveyed Sites Data

Four roadways in Nigeria were selected for the study. The roads located in Ondo State serves as connecting links to other part of the country. The study was carried out at night-time period with and without rainfall since the study is anchored on the impact of night rainfall. The data for rain and traffic were collected simultaneously using rain gauges and ATC respectively between June and August 2017 for eight weeks continuously. The collected data aims to show how rainfall at night-time could influence the service quality of dark roadways. Manual collection of traffic and rainfall data were carried out at specific periods to check the quality of data collected automatically. Table 4.1 is a summary of the four study site features while Table 4.2 represents the data collection schedule. Rainfall information is presented in section 4.3.1 while sections 4.3.2.1 - 4.3.2.4 represent the empirical traffic data of the study sites.

Table 4.1: Summary of Selected Sites Features

	SS01	SS02	SS03	SS04
Name of road	Akure – Ilesha	Ilesha - Akure	Akure - Benin	Benin – Akure
Type of road	Rural road	Rural road	Rural road	Rural road
Number of lanes	2	2	2	2
Road width	3.7m	3.7m	3.7m	3.7m
Pavement surfacing	Asphalt	Asphalt	Asphalt	Asphalt
Directional Flow	60/40	60/40	60/40	60/40
Length of road section	2250m	2250m	1975m	1975m
Rain gauge distance to site	50m	50m	80m	80m
Presence of road shoulder	Yes	Yes	Yes	Yes

Table 4.2: Data Collection Schedule

Site Coding	Survey Site	Direction	Highway Name	Field Data Collection	No. of days
SS01	Akure	Ilaramokin	Akure - Ilesha	8th June - 25th August 2017	78
SS02	Akure	Igbara-Oke	Ilesha - Akure	8th June - 25th August 2017	78
SS03	Akure	Ilu-Abo	Akure - Benin	8th June - 25th August 2017	78
SS04	Akure	Ogbese	Benin - Akure	8th June - 25th August 2017	78

4.3 Rainfall Information and Individual Site Report

4.3.1 Rainfall Data

Rainfall data for all the selected sites is explained accordingly. Figure 4.1 is a typical rainfall graph obtained from the rain gauge used for rain data collection. Rainfall data was collected simultaneously with traffic data. The rain precipitation was obtained in intervals of five minutes and converted into intensity by dividing the rain precipitation value with the rain duration. A typical example of rain precipitation of 0.4mm in a period of five minutes (0.083h) gives an intensity of 4.82mm/h as follows

$$Rainfall\ intensity\ i = \frac{0.4}{0.083} = 4.82mm/h$$

The night-time rainfall conditions are separated into three classes *viz* light rain with intensity (i < 2.5mm/h), moderate rain whose intensity is greater than 2.5mm/h but less than or equal to 10mm/h, and heavy rain with intensity greater than 10mm/h but lesser than or equal to 50mm/h as the case may be. Consideration was not given to rainfall intensity greater than 50mm/h to avoid the effect of aquaplaning and drag force. Rainfall data for SS02 is the same as that of SS01 while the rainfall data for SS03 is the same for SS04.

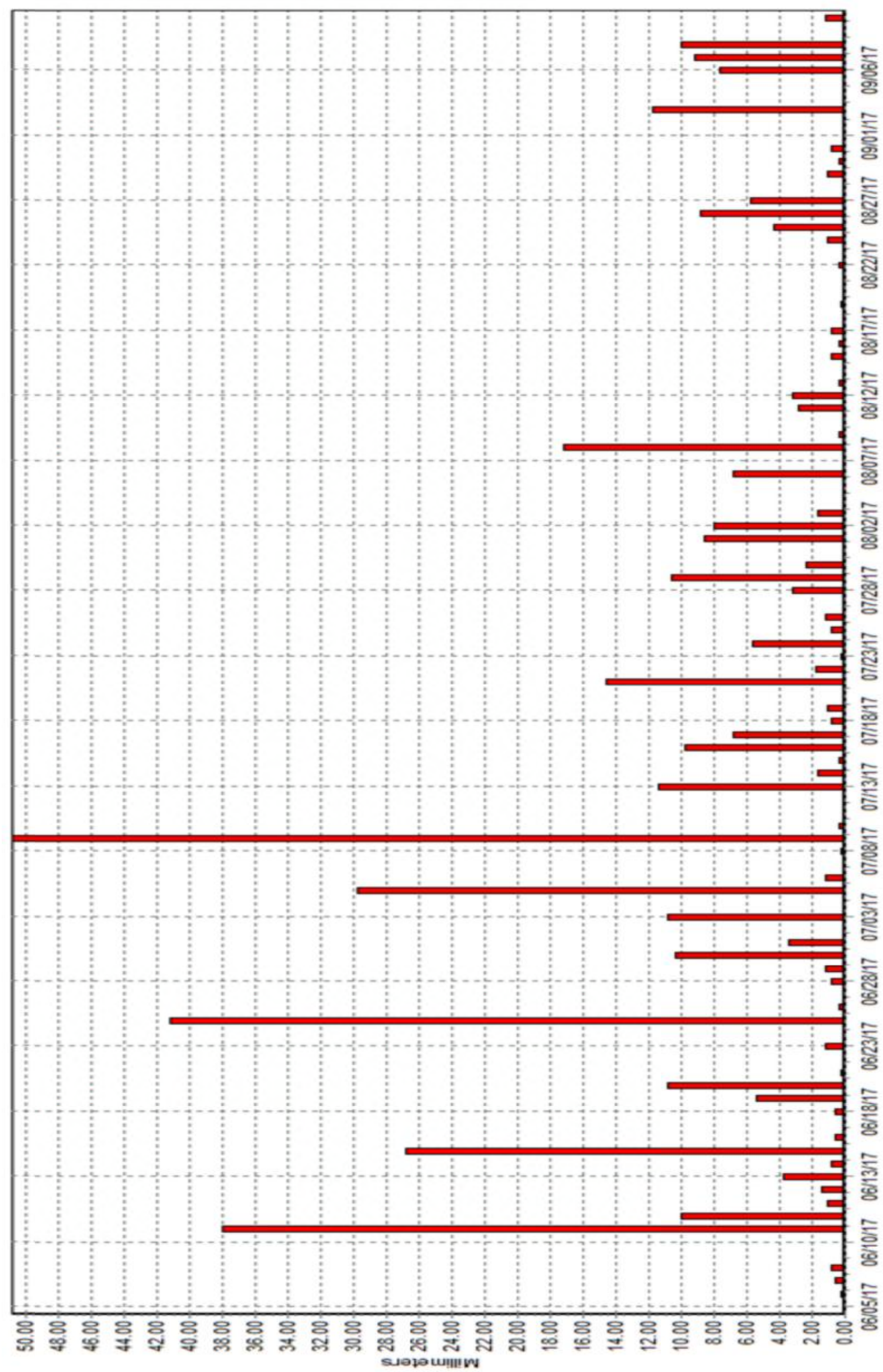


Figure 4.1: Typical Rainfall Data

4.3.2 Individual Site Report

4.3.2.1 SS01: Akure - Ilesha Highway

The Akure - Ilesha road according to section 3.3.2 is coded as SS01. It is an asphalt paved road with a pavement design life of 20years and posted speed limit of 100km/h. It is located on a flat terrain with few curves. It is a typical federal rural highway with an average daily traffic above 6000veh/day and a design speed of 80km/h. It has a lane with 3.7m width and a shoulder of 1.2m. On this road, the movement of vehicles is from Akure axis to Ilesha axis. The selected road section for the study is located between Ilaramokin and Igbara-Oke along Akure – Ilesha highway with a road length of 2250m. The road length is greater than the allowable stopping sight distance of 250m and 700m from Ilaramokin and Igbara-Oke respectively. Traffic data for the road section was collected continuously for eight weeks between June and August 2017. The automatic rain gauge is located within 50m away from the site. Rain data from the rain-gauges was crosschecked with rainfall data of WASCAL-FUTA due to its proximity. Traffic composition on this road is made up of all types of vehicle but in various proportions. The flow/time profile from the ATC is presented as Figure 4.2.

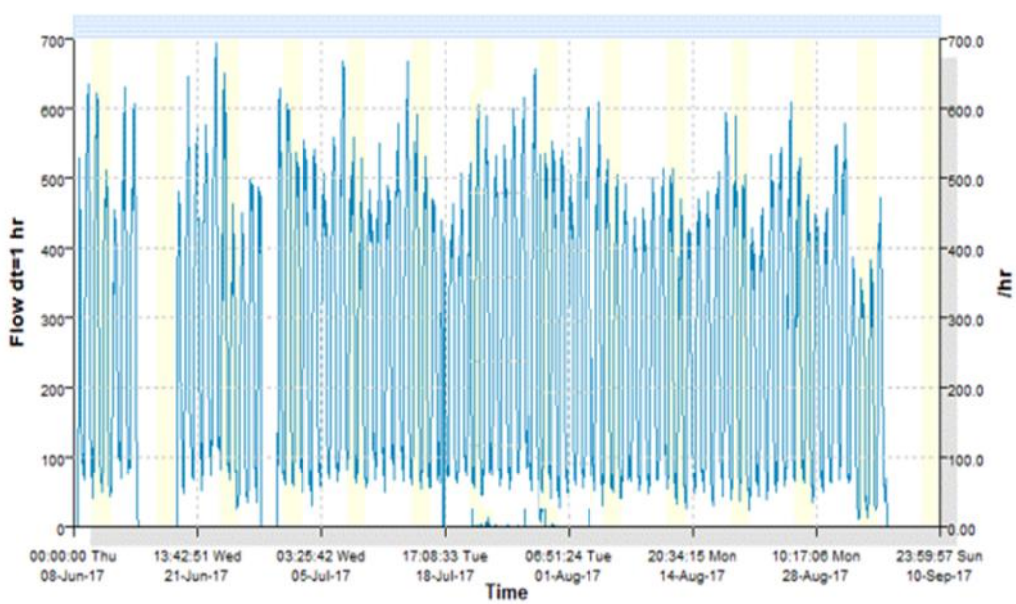


Figure 4.2: Flow/time profile of SS01

The flow/time profile shows that traffic data was collected from 8th June to 25th August 2017. The date of the data collection relates to the vehicular flow rate. From the traffic flow/time profile, it is noted that the flow of traffic varied with time each day. Also, there is no definite pattern to traffic flow across the week i.e. the peak period varies over the week, however, Sundays recorded lower traffic flow to other days. Note that the areas without lines in Figure 4.2 depict periods when traffic data was not logged data due to loss of impulse to the automatic traffic counter sensor. The traffic data loss was caused by puncturing and breakage of pneumatic tubes by vehicles. The inability to log data was discovered and corrected appropriately. Nevertheless, the loss of data for those periods did not affect the quality of data obtained.

Similarly, the volume-density and speed-density plots are given as Figures 4.3 and 4.4 respectively. The plot dispersion in Figure 4.3 follows a parabolic curve pattern which conforms with the shape of flow-density relationship of the fundamental diagram. It also agrees with the unconstrained section of the fundamental diagram. However, it must be noted that the plot is made up of various vehicles in the traffic stream.

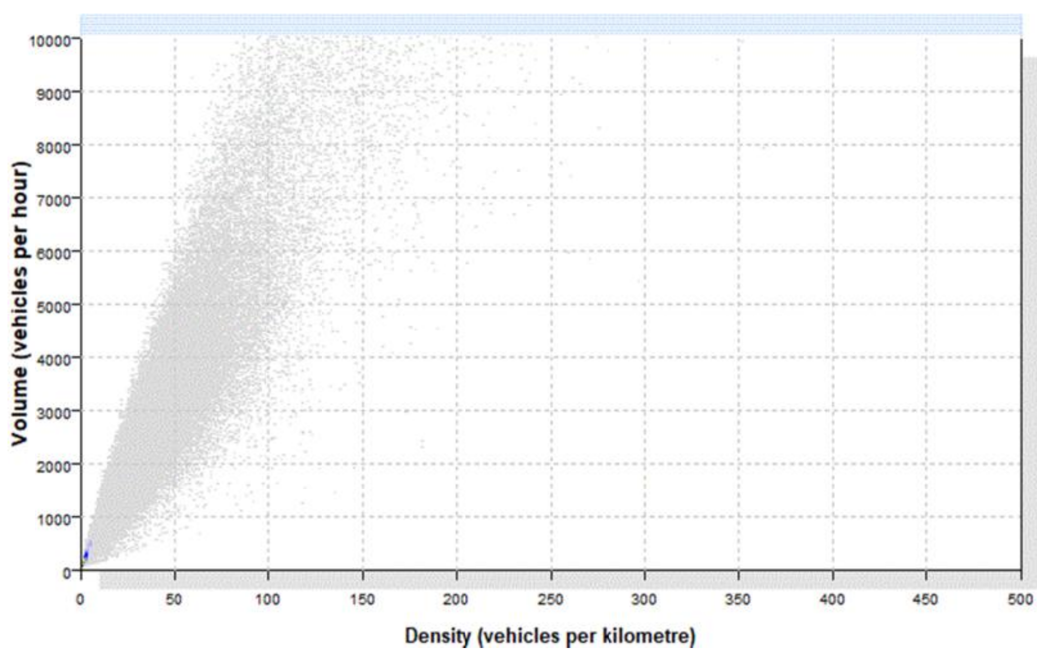


Figure 4.3: Volume-density plot of SS01

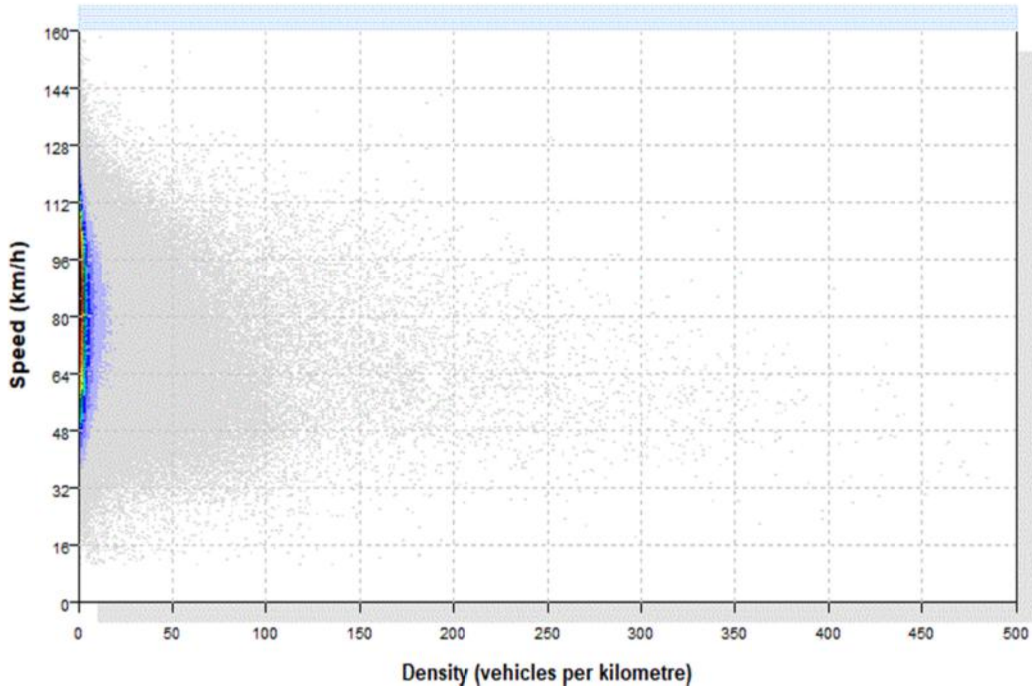


Figure 4.4: Speed-density plot of SS01

Four classes of vehicles were identified for both dry and rainy night-time conditions at SS01. They are motorcycles (MC), light vehicles (LV) known as passenger cars (PC), medium vehicles (MV) and heavy vehicles (HV), however, motorcycles were not considered in data analysis as earlier stated. The reasons for the exclusion of motorcycles is the near total absence of motorcycles on the road at night-time and when it rains, most motorcycle riders stay off the road totally. Also, motorcycle do not have vehicle following influence in the traffic stream. The percentage composition of individual vehicle types with respect to varying night-time conditions is presented as Table 4.3.

Table 4.3: Typical Percentage of Traffic Composition - SS01

Vehicle class	Percentage composition at night-time (%)				Average %	DD
	DN	LR	MR	HR		
Motorcycles	1.2	0.3	0.0	0.0	0.4	8
Light vehicles	82.9	81.4	79.9	85.4	82.4	81.9
Medium vehicles	10.4	10.4	15.2	10.9	11.7	6.2
Heavy vehicles	5.5	7.9	4.9	3.7	5.5	3.9

DD – dry daylight, DN – dry night, LR – light rain, MR – moderate rain, HR – heavy rain

The average traffic composition for the night-time is made up of 0.4 percent motorcycles, 82.4 percent light vehicles, 11.7 percent for medium vehicles while heavy vehicles account for 5.5 percent of the total vehicles. The light vehicles are the dominant vehicle type for SS01 while motorcycles constitute the least for the night-time period considered. The equivalent traffic composition for dry daylight conditions of SS01 is given as follows - motorcycles represent 8.0 percent, light vehicle is 81.9 percent, medium vehicle 6.2 percent and heavy vehicle is 3.9 percent. The hourly traffic volume and speed data for each vehicle class at SS01 are presented as Table 4.4 - 4.9 for dry daylight (peak), dry daylight (off-peak), dry night-time and night-time conditions of light rain, moderate rain and heavy rain respectively.

Table 4.4: SS01 Traffic Volume and Speed for Dry Daylight (Peak Period)

Period	LV per 5mins	MV per 5mins	HV per 5mins	Total per 5mins	u (km/h)
1	85	10	5	100	72
2	102	8	8	118	67
3	107	6	6	119	71
4	91	11	9	111	69
5	98	6	8	112	65
6	119	6	4	129	68
7	95	9	10	114	80
8	106	10	8	124	75
9	106	10	8	124	75
10	104	12	10	126	62
11	85	9	5	99	70
12	123	6	8	137	63
1hr	1221	103	89	1413	Ave = 70

LV – light vehicle, MV – medium vehicle, HV – heavy vehicle, u - speed

Table 4.5: SS01 Traffic Volume and Speed for Dry Daylight (Off-Peak)

Period	LV per 5mins	MV per 5mins	HV per 5mins	Total per 5mins	u (km/h)
1	91	8	9	108	67
2	80	10	11	101	79
3	107	12	13	132	60
4	102	15	9	126	79
5	98	11	6	115	75
6	110	11	11	132	67
7	107	7	12	126	72
8	94	11	9	114	83
9	117	7	14	138	74
10	105	10	7	122	73
11	115	10	5	130	70
12	99	9	7	115	69
1 hr	1225	121	113	1459	Ave = 72

LV – light vehicle, MV – medium vehicle, HV – heavy vehicle, u – speed, ave = average

Table 4.6: SS01 Traffic Volume and Speed for Dry Night-Time Conditions

Period	LV per 5mins	MV per 5mins	HV per 5mins	Total per 5mins	u (km/h)
1	72	7	4	83	73
2	91	5	4	100	58
3	56	4	7	67	82
4	60	10	5	75	70
5	84	5	7	96	66
6	68	5	5	78	80
7	52	3	3	58	84
8	42	2	2	46	78
9	83	9	5	97	74
10	72	8	6	86	68
11	69	6	4	79	71
12	58	2	4	64	80
1 hr	807	66	56	929	Ave = 74

LV – light vehicle, MV – medium vehicle, HV – heavy vehicle, u - speed, ave = average

Table 4.7: SS01 Traffic Volume and Speed for Light Rainy Night-Time Conditions

Period	LV per 5mins	MV per 5mins	HV per 5mins	Total per 5mins	u (km/h)
1	69	6	4	79	49
2	81	6	9	96	45
3	59	5	3	67	65
4	86	8	6	100	68
5	75	5	5	85	73
6	62	4	4	70	62
7	72	5	5	82	70
8	45	2	2	49	62
9	70	5	5	80	57
10	37	2	2	41	69
11	76	6	5	87	60
12	85	7	6	98	49
1 hr	817	61	56	934	Ave = 61

LV – light vehicle, MV – medium vehicle, HV – heavy vehicle, u - speed, ave = average

Table 4.8: SS01 Traffic Volume and Speed for Moderate Rainy Night-Time Conditions

Period	LV per 5mins	MV per 5mins	HV per 5mins	Total per 5mins	u (km/h)
1	44	8	7	59	59
2	48	1	3	52	68
3	91	9	6	106	57
4	97	6	8	111	67
5	72	4	5	81	43
6	40	6	7	53	70
7	22	3	2	27	71
8	63	5	7	75	72
9	63	4	4	71	77
10	47	7	4	58	59
11	95	7	7	109	51
12	62	8	6	76	41
1 hr	744	68	66	878	Ave = 61

LV – light vehicle, MV – medium vehicle, HV – heavy vehicle, u - speed, ave = average

Table 4.9: SS01 Traffic Volume and Speed for Heavy Rainy Night-Time Conditions

Period	LV per 5mins	MV per 5mins	HV per 5mins	Total per 5mins	u (km/h)
1	20	4	5	29	66
2	71	3	5	79	55
3	68	2	2	72	51
4	55	3	3	61	40
5	66	2	5	73	43
6	40	1	2	43	56
7	61	2	1	64	59
8	47	3	2	52	51
9	87	3	4	94	57
10	81	4	3	88	39
11	74	3	6	83	59
12	68	2	2	72	56
1 hr	738	32	40	810	Ave = 53

LV – light vehicle, MV – medium vehicle, HV – heavy vehicle, u - speed, ave = average

4.3.2.2 SS02: Ilesha - Akure Highway

Ilesha - Akure highway is the opposite direction of Akure - Ilesha Highway. It has same features as that of Akure - Ilesha Highway. Vehicle movement is from Ilesha axis towards Akure axis. The width of the lane is 3.7m with a 1.2m shoulder. The average daily traffic is 8000veh/day with a design speed of 80km/hr. The road section for traffic survey is between Igbara-Oke and Ilaramokin with a road length of 2250m. The rainfall data collected for site 01 is the same for site 02 but the traffic data varies due to change in direction of vehicular movement as captured in the ATC. Both traffic and rainfall data collection for the site was from 8th June to 25th August 2017. The traffic composition consists various types of vehicles in different percentages. The traffic data for this site was separated from the entire traffic data based on direction as indicated in the downloaded data collected by the ATC. The traffic flow/time profile, volume-density and speed-density plots of SS02 are presented as Figures 4.5, 4.6 and 4.7 respectively.

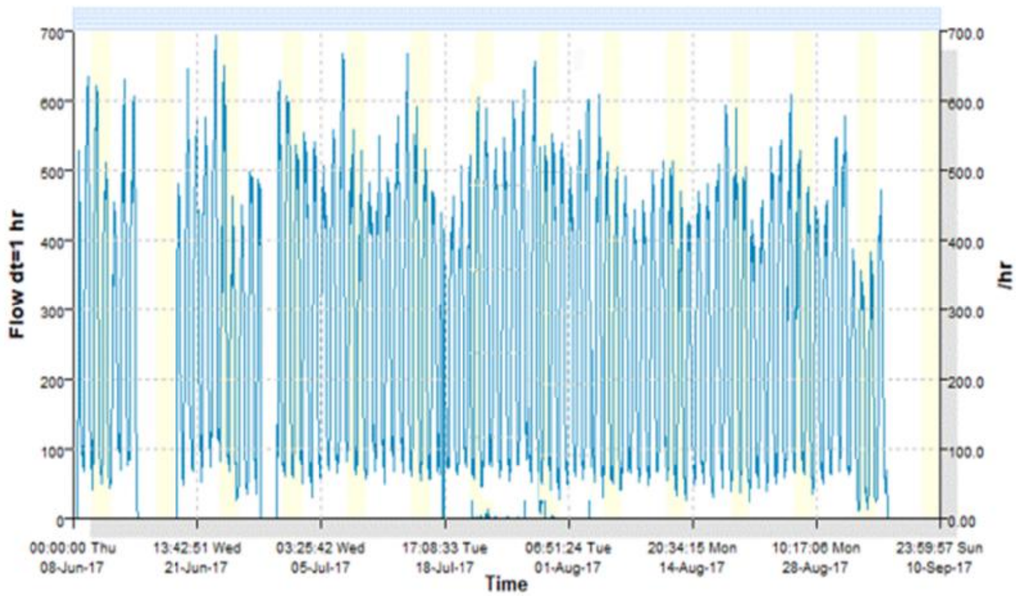


Figure 4.5: Flow/time profile of SS02

In Figure 4.5, the areas without lines show periods when no traffic data was logged by the counter due to disturbances on the pneumatic tubes. The disturbances were as a result of tube breakages and puncturing caused by moving vehicles. The tubes were promptly replaced with a spare while the damaged one was later repaired for further use. However, it should be noted that the quality of data collected was not affected. Considering the traffic flow/time profile, there is an evident variation of traffic flow regardless of day and time. Traffic movement did not follow a definite pattern as the peak flow varies across days and time of the day. The volume-density and speed-density plots are given as Figures 4.6 and 4.7. The plot dispersion in Figure 4.6 follows a parabolic curve pattern as expected of the flow-density relationship of the fundamental diagram. However, the plot is made up of various types of vehicle class as earlier identified. The speed-density plot (Figure 4.7) aligned with the speed-density shape of the fundamental diagram.

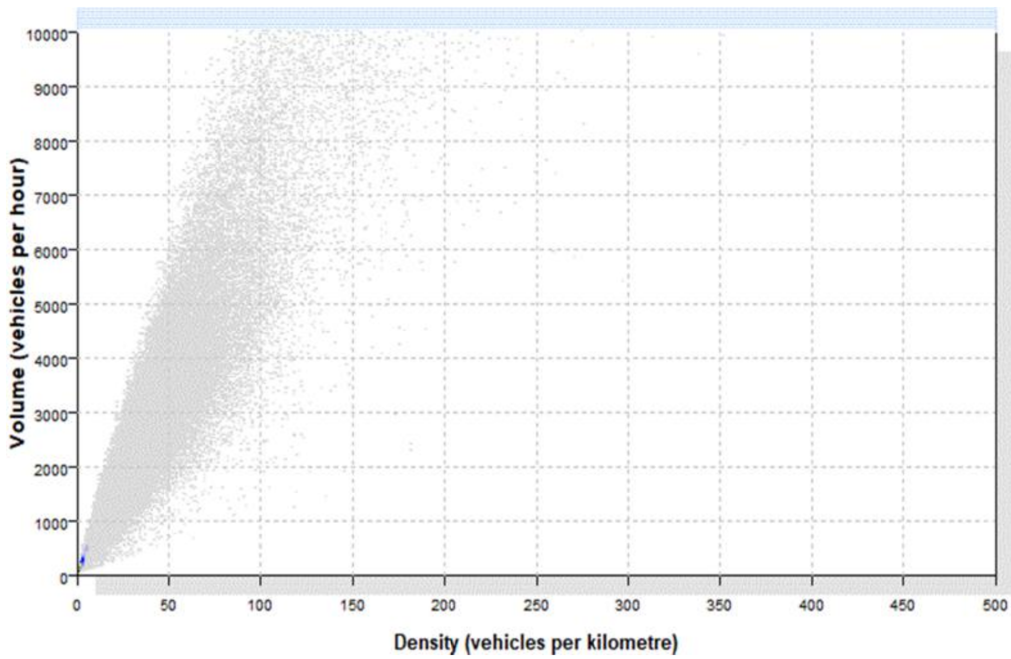


Figure 4.6: Volume-density plot of SS02

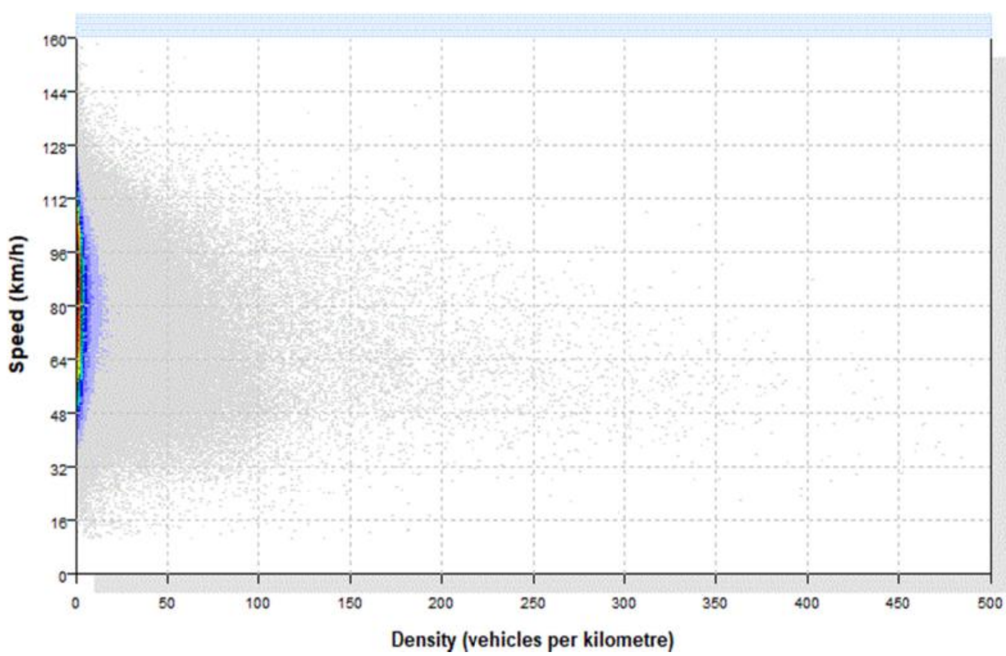


Figure 4.7: Speed-density plot of SS02

For SS02, the traffic composition is heterogeneous in nature. The traffic data was categorised into four classes of vehicles which are motorcycle, light vehicle, medium vehicle and heavy vehicle as captured by the ATC. The percentage traffic composition of vehicles at SS02 at night-time is presented as Table 4.10

Table 4.10: Typical Percentage of Traffic Composition - SS02

Vehicle class	Percentage composition at night-time (%)				Average %	DD
	DN	LR	MR	HR		
Motorcycles	1.9	0.4	0.1	0.0	0.6	7.2
Light vehicles	83.1	81.8	79.9	82.4	81.8	81.1
Medium vehicles	11.7	12.4	13.2	13.7	12.8	6.8
Heavy vehicles	3.3	5.4	6.8	3.9	4.9	4.8

DD – dry daylight, DN – dry night, LR – light rain, MR – moderate rain, HR – heavy rain

From the table, the percentage of each vehicle class varies from one weather condition to another. For example, under dry night-time conditions, the percentage of light vehicles is 83.1 percent, reduced to 81.8 percent and 79.9 percent under light and moderate rainy night-time conditions respectively but increased to 82.4 percent under heavy rainy night-time conditions. Medium vehicles from 11.7 percent under dry night-time conditions increased to 12.4 percent under light rainy night-time, 13.2 percent under moderate rainy night-time and 13.7 percent under heavy rainy night-time conditions. Thus, the average traffic composition is 0.6 percent for motorcycles, 81.8 percent for light vehicles, 12.8 percent for medium vehicles and 4.9 percent for heavy vehicles. The corresponding traffic composition for its dry daylight period is 7.2 percent for motorcycles, 81.1 percent for light vehicles while medium and heavy vehicles are 6.8 percent and 4.8 percent respectively. It is therefore evident that light vehicles constitute the highest volume of traffic both at night-time and daytime. Table 4.11 represents the hourly traffic volume and speed data for dry daylight (peak), Table 4.12 for dry daylight (off-peak) while the hourly traffic volume and speed for night conditions are presented as Tables 4.11 – 4.16 in the order of dry night, light night rain, moderate night rain and heavy night rain. Motorcycle was however excluded from the traffic analysis due to its no vehicle following influence and absence under rainfall condition.

Table 4.11: SS02 Traffic Volume and Speed for Dry Daylight (Peak Period)

Period	LV per 5mins	MV per 5mins	HV per 5mins	Total per 5mins	u (km/h)
1	99	7	4	110	81
2	87	8	6	101	78
3	111	9	6	126	64
4	93	5	4	102	80
5	104	15	9	128	71
6	84	4	7	95	81
7	93	10	9	112	70
8	90	6	7	103	79
9	98	10	9	117	78
10	93	9	10	112	83
11	82	11	7	100	75
12	94	9	6	109	77
1 hr	1128	103	84	1315	76

LV – light vehicle, MV – medium vehicle, HV – heavy vehicle, u - speed, ave = average

Table 4.12: SS02 Traffic Volume and Speed for Dry Daylight (Off-Peak)

Period	LV per 5mins	MV per 5mins	HV per 5mins	Total per 5mins	u (km/h)
1	81	9	8	98	75
2	71	6	4	81	82
3	113	12	8	133	65
4	82	8	5	95	77
5	94	8	10	112	83
6	104	15	9	128	75
7	84	4	7	95	81
8	87	8	6	101	78
9	99	7	4	110	83
10	83	9	5	97	73
11	90	6	7	103	79
12	93	5	4	102	80
1 hr	1081	97	77	1255	Ave = 78

LV – light vehicle, MV – medium vehicle, HV – heavy vehicle, u - speed, ave = average

Table 4.13: SS02 Traffic Volume and Speed for Dry Night-Time Conditions

Period	LV per 5mins	MV per 5mins	HV per 5mins	Total per 5mins	u (km/h)
1	58	7	3	68	81
2	55	7	2	64	73
3	79	5	6	90	71
4	58	7	2	67	80
5	73	7	4	84	72
6	76	7	5	88	71
7	72	8	5	85	70
8	79	8	5	92	63
9	68	4	2	74	70
10	67	5	4	76	69
11	63	4	7	74	72
12	75	2	3	80	76
1 hr	823	71	48	942	Ave = 72

LV – light vehicle, MV – medium vehicle, HV – heavy vehicle, u - speed, ave = average

Table 4.14: SS02 Traffic Volume and Speed for Light Rainy Night-Time Conditions

Period	LV per 5mins	MV per 5mins	HV per 5mins	Total per 5mins	u (km/h)
1	88	10	5	103	62
2	59	5	3	67	66
3	58	4	3	65	57
4	54	2	0	56	74
5	88	2	5	95	51
6	70	2	2	74	56
7	54	9	1	64	53
8	68	3	5	76	75
9	77	4	6	87	55
10	83	7	2	92	62
11	74	4	2	80	43
12	43	2	2	47	70
1 hr	816	54	36	906	Ave = 60

LV – light vehicle, MV – medium vehicle, HV – heavy vehicle, u - speed, ave = average

Table 4.15: SS02 Traffic Volume and Speed for Moderate Rainy Night-Time Conditions

Period	LV per 5mins	MV per 5mins	HV per 5mins	Total per 5mins	u (km/h)
1	49	7	4	60	66
2	39	3	1	43	67
3	71	6	5	82	61
4	71	3	2	76	66
5	60	3	4	67	57
6	80	7	3	90	43
7	59	4	0	63	55
8	57	0	0	57	52
9	78	4	6	88	51
10	69	3	5	77	61
11	62	1	5	68	54
12	56	6	2	64	53
1 hr	751	47	37	835	Ave = 57

LV – light vehicle, MV – medium vehicle, HV – heavy vehicle, u - speed, ave = average

Table 4.16: SS02 Traffic Volume and Speed for Heavy Rainy Night-Time Conditions

Period	LV per 5mins	MV per 5mins	HV per 5mins	Total per 5mins	u (km/h)
1	59	5	3	67	45
2	65	6	7	78	48
3	48	1	3	52	55
4	41	4	1	46	59
5	71	4	7	82	55
6	65	8	3	76	55
7	73	3	2	78	53
8	64	3	1	68	54
9	55	1	4	60	50
10	55	3	3	61	55
11	75	3	4	82	52
12	77	5	2	84	46
1 hr	748	46	40	834	Ave = 52

LV – light vehicle, MV – medium vehicle, HV – heavy vehicle, u - speed, ave = average

4.3.2.3 SS03: Akure - Benin Highway

The code of Akure - Benin is SS03. Akure - Benin highway is a two-lane highway with the lanes facing one another in opposite direction. This road serves as a major connector road to other parts of the country. It is characterised with a high volume of traffic. It is a federal rural highway with an average daily traffic above 8000 veh/day and design speed of 80km/h. It is an asphalt surfaced road located on a flat terrain with few curves and a pavement design life of 20years. The lane width is 3.7m with a 1.2m shoulder and posted speed limit of 100km/h. At site 03, movement of vehicles is from Akure axis to Benin axis. The selected road segment for the study is between Ilu-Abo and Ogbese. The road length which is 1975m is greater than the allowable stopping sight distance of 750m and 350 from Bolorunduro and Ogbese respectively. The automatic rain-gauge is placed 80m away from the site. Rainfall data from the rain-gauge is verified with data obtained from NIMET at Akure Domestic Airport due to its proximity. Traffic and rainfall data along this road were collected continuously for eight weeks. Traffic data for SS03 was collected from 8th June 2017 - 28th August 2017 using ATC. The traffic flow/time profile as related by the ATC software is shown as Figure 4.8 while Figure 4.9 is the volume-density plot and the speed-density plot is presented as Figure 4.10.

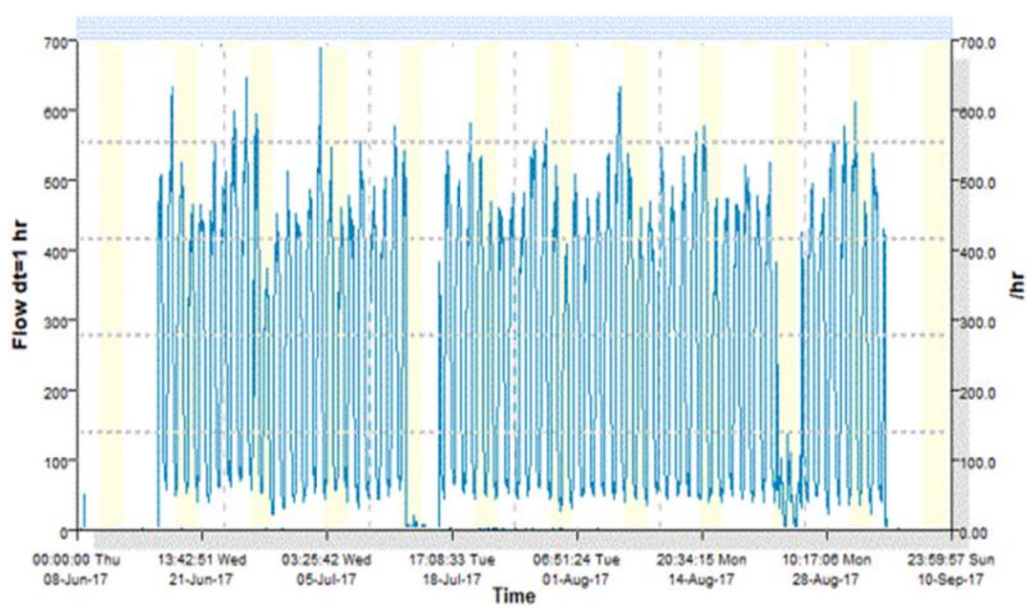


Figure 4.8: Flow/time profile of SS03

According to the flow/time profile, there was no data logged in the first week of installing the machine. This was due to the inability of the tubes to send vehicle hit impulses to the ATC sensor. Other areas without data lines are as a result of cut tubes and breakages. The breakages were promptly attended to by replacing damaged tubes with spare tubes. This was done to guard against losing too much data. The loss of data within that period has no effect on the quality of data collected. From the volume profile plot, it is evident that the movement of vehicles is higher during the week though there is no specific pattern for the peak periods. There is a decrease in the volume of vehicles during the weekend. The volume-density plot (Figure 4.9) imitates the unconstrained section of the fundamental diagram earlier discussed. Similarly, Figure 4.10 represents the speed-density plot of the collected traffic data and this aligned with fundamental diagram graph of the speed-density relationship.

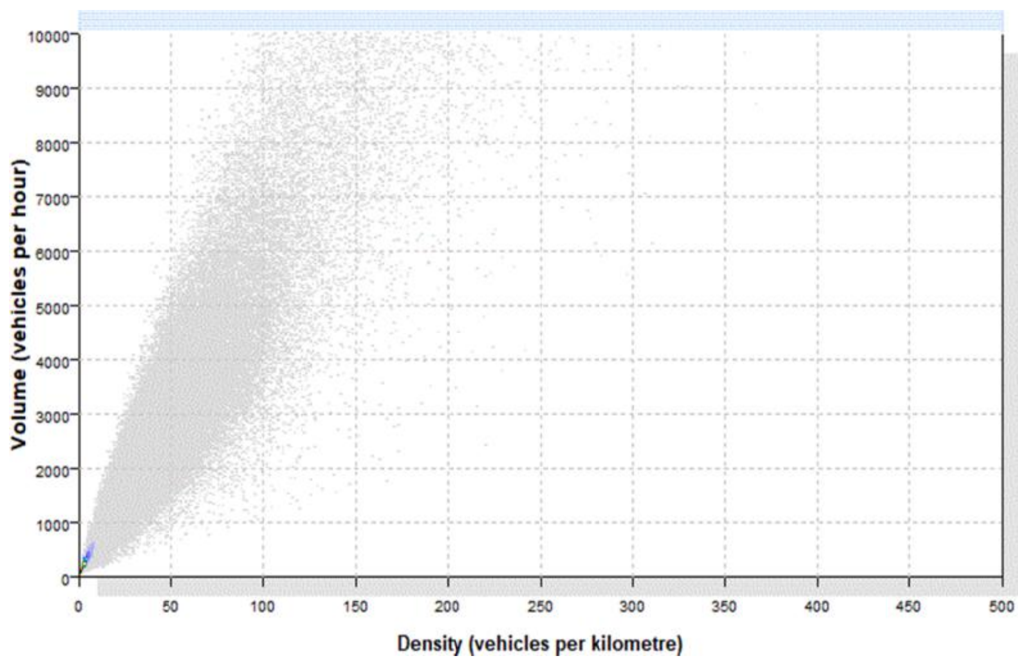


Figure 4.9: Volume-density plot of SS03

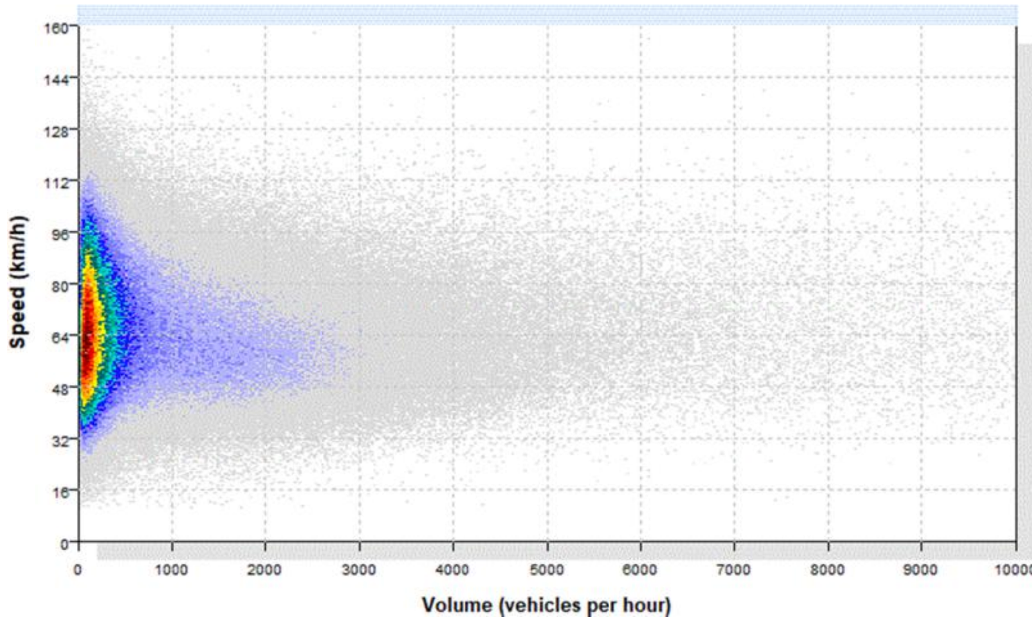


Figure 4.10: Speed-density plot at SS03

The traffic composition of SS03 is presented as Table 4.17. Four classes of vehicles are identified in the table. The classes are motorcycles, light vehicles, medium vehicles and heavy vehicles. The light vehicle is the dominant car for all weather conditions with an average of 83.7 percent. Medium vehicles represent 8.5 percent while heavy vehicles average 7.6 percent. The traffic composition of its dry daylight condition is 7.6 percent for motorcycles, 78.9 percent for light vehicles while 7.3 percent and 6.2 percent are for medium and heavy vehicles respectively.

Table 4.17: Typical Percentage of Traffic Composition - SS03

Vehicle class	Percentage composition at night-time (%)				Average %	DD
	DN	LR	MR	HR		
Motorcycles	0.9	0.3	0.0	0.0	0.3	7.6
Light vehicles	83.2	80.9	83.5	87.0	83.7	78.9
Medium vehicles	8.1	10.1	9.3	6.5	8.5	7.3
Heavy vehicles	7.8	8.7	7.2	6.5	7.6	6.2

DD – dry daylight, DN – dry night, LR – light rain, MR – moderate rain, HR – heavy rain

Tables 4.18 - 4.23 is the hourly traffic volume and speed data for dry daylight (peak), dry daylight (off-peak), dry night-time and rainy night-time conditions respectively.

Table 4.18: SS03 Traffic Volume and Speed for Dry Daylight (Peak Period)

Period	LV per 5mins	MV per 5mins	HV per 5mins	Total per 5mins	u (km/h)
1	98	11	6	115	75
2	110	10	15	135	74
3	107	7	12	126	72
4	95	15	8	118	69
5	110	11	11	132	67
6	115	10	5	130	70
7	107	12	13	132	60
8	94	11	9	114	83
9	105	10	7	122	73
10	80	10	11	101	79
11	102	15	9	126	79
12	91	8	9	108	67
1 hr	1214	130	115	1459	72

LV – light vehicle, MV – medium vehicle, HV – heavy vehicle, u – speed, ave = average

Table 4.19: SS03 Traffic Volume and Speed for Dry Daylight

Period	LV per 5mins	MV per 5mins	HV per 5mins	Total per 5mins	u (km/h)
1	123	6	8	137	63
2	119	6	4	129	68
3	106	10	8	124	78
4	104	12	10	126	68
5	98	6	8	112	65
6	107	6	6	119	69
7	95	9	10	114	80
8	91	11	9	111	69
9	106	10	8	124	68
10	102	8	8	118	67
11	84	5	3	92	73
12	85	10	5	100	72
1 hr	1220	99	87	1406	Ave = 70

LV – light vehicle, MV – medium vehicle, HV – heavy vehicle, u – speed, ave = average

Table 4.20: SS03 Traffic Volume and Speed for Dry Night-Time Conditions

Period	LV per 5mins	MV per 5mins	HV per 5mins	Total per 5mins	u (km/h)
1	63	7	3	73	46
2	45	3	3	51	86
3	36	4	1	41	64
4	35	3	3	41	66
5	70	4	4	78	73
6	50	3	3	56	77
7	54	4	2	60	85
8	46	5	2	53	75
9	49	0	5	54	72
10	45	4	4	53	75
11	71	3	6	80	41
12	46	4	0	50	77
1 hr	610	44	36	690	Ave = 69

LV – light vehicle, MV – medium vehicle, HV – heavy vehicle, u - speed, ave = average

Table 4.21: SS03 Traffic Volume and Speed for Light Rainy Night-Time Conditions

Period	LV per 5mins	MV per 5mins	HV per 5mins	Total per 5mins	u (km/h)
1	24	4	2	30	73
2	28	1	3	32	73
3	35	3	3	41	70
4	65	5	4	74	58
5	38	3	4	45	82
6	37	3	2	42	70
7	30	7	0	37	75
8	34	6	4	44	65
9	52	1	7	60	64
10	33	2	4	39	75
11	49	4	2	55	75
12	40	2	2	44	78
1 hr	465	41	37	543	Ave = 72

LV – light vehicle, MV – medium vehicle, HV – heavy vehicle, u - speed, ave = average

Table 4.22: SS03 Traffic Volume and Speed for Moderate Rainy Night-Time Conditions

Period	LV per 5mins	MV per 5mins	HV per 5mins	Total per 5mins	u (km/h)
1	34	2	4	40	69
2	41	4	1	46	57
3	38	5	0	43	59
4	41	2	5	48	59
5	53	2	3	58	62
6	41	4	1	46	66
7	32	0	1	33	72
8	49	4	2	55	68
9	28	0	1	29	69
10	30	3	3	36	70
11	70	2	2	74	70
12	57	6	7	70	51
1 hr	514	34	30	578	Ave = 64

LV – light vehicle, MV – medium vehicle, HV – heavy vehicle, u - speed, ave = average

Table 4.23: SS03 Traffic Volume and Speed for Heavy Rainy Night-Time Conditions

Period	LV per 5mins	MV per 5mins	HV per 5mins	Total per 5mins	u (km/h)
1	59	3	3	65	45
2	64	5	7	76	41
3	55	3	3	61	51
4	47	5	5	57	55
5	68	5	1	74	52
6	56	1	4	61	58
7	48	6	1	55	65
8	30	3	3	36	65
9	29	0	4	33	65
10	36	2	4	42	56
11	51	3	1	55	65
12	41	2	5	48	55
1 hr	584	38	41	663	Ave = 56

LV – light vehicle, MV – medium vehicle, HV – heavy vehicle, u - speed, ave = average

4.3.2.4 SS04: Benin - Akure Highway

The Benin - Akure highway is the opposite lane of Akure - Benin (SS03) in which the geometry is the same as SS03. It is a federal rural highway with an average daily traffic above 8000 veh/day and design speed of 80km/h. It is an asphalt surfaced road located on a flat terrain with a pavement design life of 20years. It is characterised with a high volume of traffic. The lane width is 3.7m with a 1.2m shoulder and posted speed limit of 100km/h. At site 04, vehicle movement is from Benin axis to Akure axis. The selected road segment for the study is between Ogbese and Ilu-Abo. The automatic rain-gauge is placed 80m away from the site. Rainfall data from the rain-gauge is verified with data obtained from NIMET at Akure Domestic Airport due to its proximity. The traffic and rainfall data were collected between 8th of June to 28th of August 2017. The traffic flow/time profile is shown as Figure 4.11 while Figure 4.12 is the volume-density plot. The speed-density is presented as Figure 4.13.

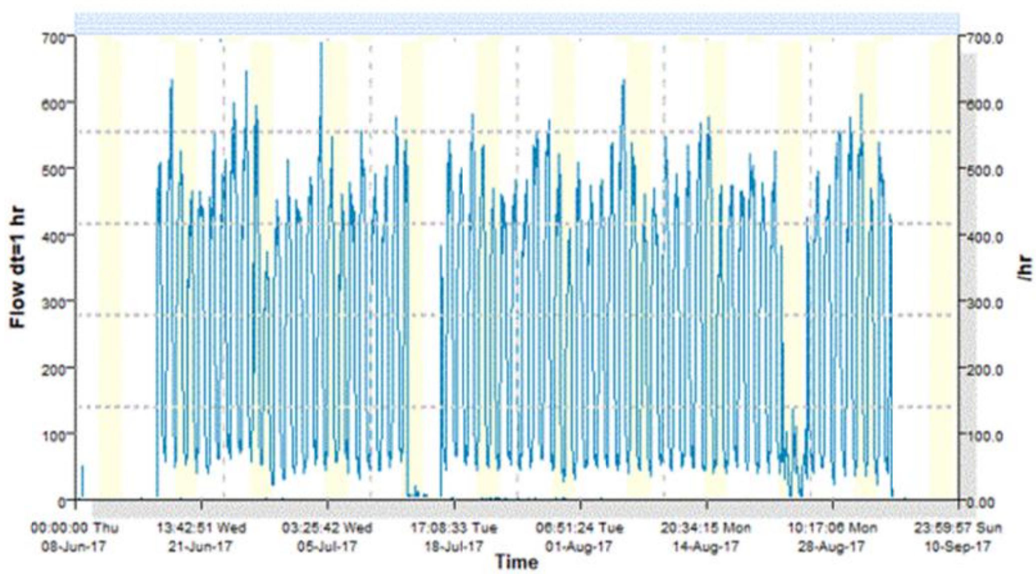


Figure 4.11: Flow/time profile at SS04

From the profile, there was no data logged in the first week of installing the machine. This was due to an inability of the machine to send hit impulses through the tube to the sensor. Also, the areas without data was the period of cut tube incidences. The loss of data within that period has no effect on the overall quality of the data collected. From the profile plot, it is evident that movement of vehicles is higher during weekdays, though, no specific pattern for peak period. There is a decrease in the number of vehicles during the weekend. The volume-density plot pattern conforms with the unconstrained section of the fundamental diagram.

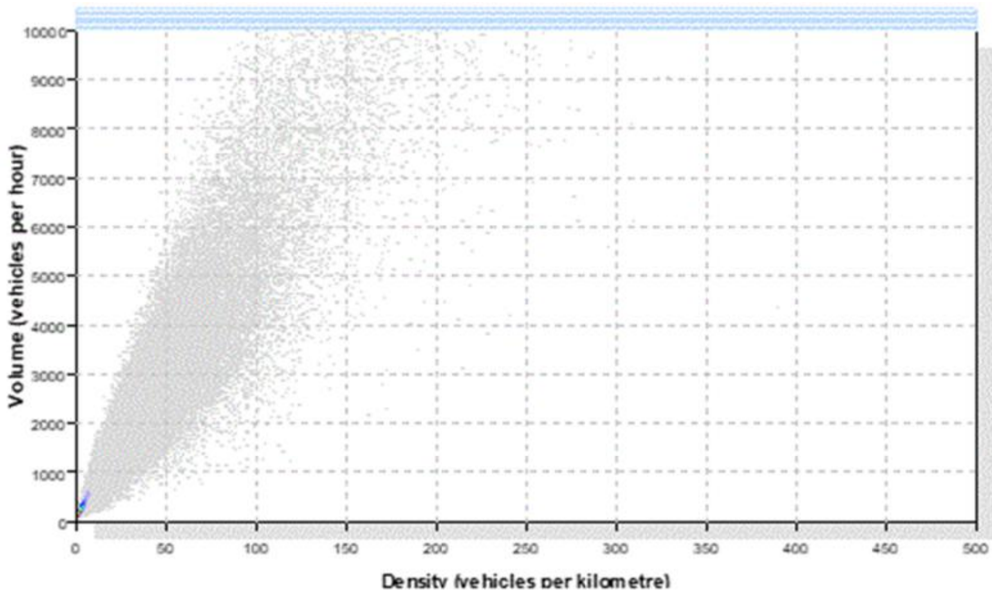


Figure 4.12: Volume-density plot at SS04

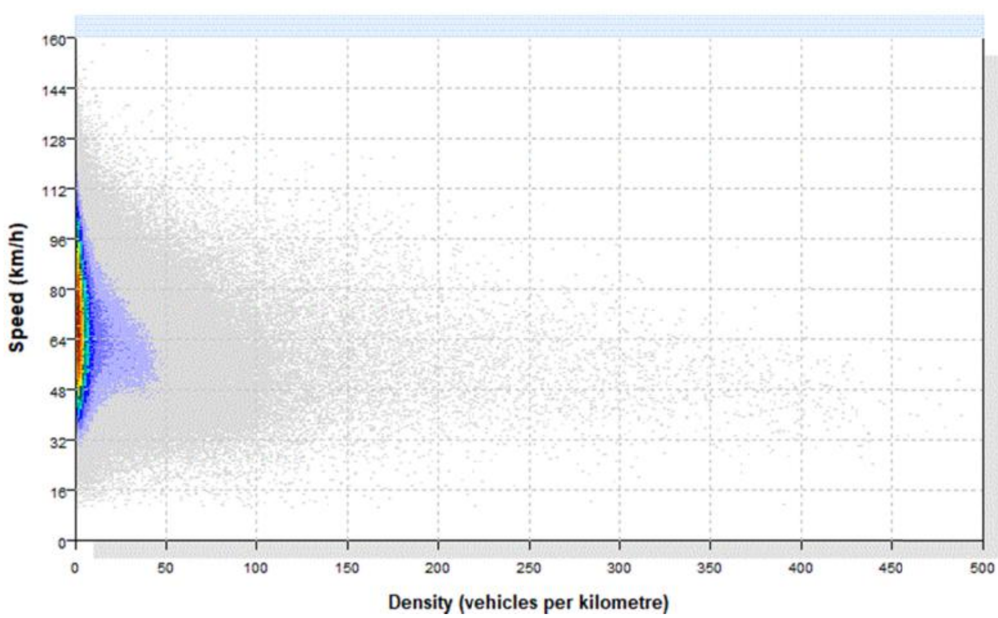


Figure 4.13: Speed-density plot of SS04

Table 4.24 represents the traffic composition of SS04 for each weather scenario considered. The traffic composition of SS04 is heterogeneous in nature with four classes of vehicles identified *viz-a-viz* motorcycles, light vehicles (passenger car), medium weight and heavy weight vehicles.

Table 4.24: Percentage of Traffic Composition - SS04

Vehicle class	Percentage composition at night-time (%)				Average %	DD
	DN	LR	MR	HR		
Motorcycles	1.0	0.2	0.1	0.0	0.3	6.4
Light vehicles	81.9	81.6	79.0	80.8	80.8	80.6
Medium vehicles	11.3	11.9	14.3	10.7	12.1	7.5
Heavy vehicles	5.8	6.3	6.7	8.5	6.8	5.5

DD – dry daylight, DN – dry night, LR – light rain, MR – moderate rain, HR – heavy rain

From the table, the percentage of each vehicle class varies under each weather condition. Under dry night-time conditions, the percentage of light vehicle is 81.9 percent, but reduced to 81.6 percent, 79 percent and 80.8 percent under light, moderate and heavy night rain respectively. Medium vehicles increased from 11.3 percent under dry night-time conditions to 11.9 percent and 14.3 percent under light and moderate rainy night-time conditions but reduced to 10.7 percent under heavy rainy night-time conditions. However, the average traffic composition is 0.3 percent for motorcycles, 80.8 percent for light vehicles, 12.1 percent for medium vehicles and 6.8 percent for heavy vehicles. The corresponding traffic composition for its dry daylight period is 6.4 percent for motorcycles, 80.6 percent for light vehicles while moderate and heavy vehicles are 7.5 percent and 5.5 percent respectively. It is therefore evident that light vehicles constitute the highest volume of traffic both at night-time and daytime. Note that motorcycles were not considered in the analysis because of its near zero percentage under rainfall condition at night. Tables 4.25 and 4.26 are the hourly traffic volume and speed data for both peak and off-peak dry daylight, Table 2.27 for dry night-time conditions, while the night-time conditions for light, moderate and heavy rain are presented as Tables 4.28, 4.29 and 4.30 respectively.

Table 4.25: SS04 Traffic Volume and Speed for Daylight (Peak Period)

Period	LV per 5mins	MV per 5mins	HV per 5mins	Total per 5mins	u (km/h)
1	84	7	6	97	77
2	94	6	4	104	80
3	82	6	6	94	86
4	96	7	4	107	81
5	100	9	4	113	77
6	107	8	4	119	63
7	106	8	5	119	63
8	107	2	7	116	73
9	109	5	10	124	60
10	100	7	8	115	77
11	98	16	9	123	70
12	93	8	3	104	72
1 hr	1176	89	70	1335	72

LV – light vehicle, MV – medium vehicle, HV – heavy vehicle, u - speed, ave = average

Table 4.26: SS04 Traffic Volume and Speed for Daylight (Off-Peak)

Period	LV per 5mins	MV per 5mins	HV per 5mins	Total per 5mins	u (km/h)
1	65	10	5	80	70
2	118	10	6	134	62
3	100	7	8	115	67
4	93	8	3	104	73
5	82	6	6	94	70
6	100	9	4	113	77
7	109	5	10	124	60
8	84	7	6	97	65
9	106	8	5	119	63
10	107	2	7	116	73
11	96	7	4	107	72
12	94	6	4	104	63
1 hr	1154	85	68	1307	Ave = 68

LV – light vehicle, MV – medium vehicle, HV – heavy vehicle, u - speed, ave = average

Table 4.27: SS04 Traffic Volume and Speed for Dry Night-Time Conditions

Period	LV per 5mins	MV per 5mins	HV per 5mins	Total per 5mins	u (km/h)
1	72	10	3	85	60
2	88	6	6	100	68
3	69	6	4	79	82
4	36	4	0	40	98
5	58	7	2	67	85
6	65	1	9	75	90
7	79	7	5	91	68
8	48	6	1	55	84
9	52	3	3	58	90
10	76	5	2	83	72
11	41	4	1	46	79
12	58	9	5	72	79
1 hr	742	68	41	851	Ave = 79

LV – light vehicle, MV – medium vehicle, HV – heavy vehicle, u - speed, ave = average

Table 4.28: SS04 Traffic Volume and Speed for Light Rainy Night-Time Conditions

Period	LV per 5mins	MV per 5mins	HV per 5mins	Total per 5mins	u (km/h)
1	78	9	4	91	69
2	78	4	6	88	75
3	77	1	7	85	66
4	52	3	3	58	78
5	72	5	5	82	71
6	86	6	3	95	60
7	62	4	4	70	62
8	77	8	1	86	62
9	65	4	4	73	67
10	69	6	4	79	55
11	58	0	1	59	79
12	69	8	0	77	72
1 hr	843	58	42	943	Ave = 68

LV – light vehicle, MV – medium vehicle, HV – heavy vehicle, u - speed, ave = average

Table 4.29: SS04 Traffic Volume and Speed for Moderate Rainy Night-Time Conditions

Period	LV per 5mins	MV per 5mins	HV per 5mins	Total per 5mins	u (km/h)
1	75	9	4	88	62
2	68	9	3	80	43
3	70	2	2	74	70
4	72	3	2	77	55
5	52	1	7	60	60
6	77	6	3	86	46
7	60	1	1	62	66
8	59	5	3	67	67
9	39	3	1	43	68
10	42	2	2	46	70
11	45	2	2	49	69
12	98	8	4	110	60
1 hr	757	51	34	842	Ave = 61

LV – light vehicle, MV – medium vehicle, HV – heavy vehicle, u - speed, ave = average

Table 4.30: SS04 Traffic Volume and Speed for Heavy Rainy Night-Time Conditions

Period	LV per 5mins	MV per 5mins	HV per 5mins	Total per 5mins	u (km/h)
1	34	5	3	42	50
2	40	6	0	46	55
3	28	0	5	33	65
4	60	3	4	67	62
5	20	4	5	29	68
6	43	2	5	50	48
7	25	6	2	33	65
8	29	2	0	31	69
9	69	6	4	79	58
10	26	0	4	30	54
11	73	8	4	85	35
12	35	1	1	37	54
1 hr	482	43	37	562	Ave = 57

LV – light vehicle, MV – medium vehicle, HV – heavy vehicle, u - speed, ave = average

The summary of the one-hour recorded volume of vehicles across the four sites is presented as Table 4.31

Table 4.31: Summary of One-Hour Recorded Vehicle Volume

Weather condition	SS01	SS02	SS03	SS04
Dry daylight	1459	1255	1406	1307
Dry night	929	942	690	851
Light rain	934	906	543	943
Moderate rain	878	835	578	842
Heavy rain	810	834	663	562

From the summary of the empirical results as presented in Table 4.31, SS01 with 1459 vehicles has the highest recorded volume of vehicles during the one-hour daylight duration count while SS02 recorded the lowest with 1255 vehicles. SS02 with 942 vehicles has the highest recorded volume of vehicles during the one-hour dry night-time duration count while SS03 recorded the lowest at 690 vehicles. Irrespective of rainfall intensity, SS01 and SS04 have the highest recorded volume of 934 vehicles under rainy night-time duration while SS03 with 543 vehicles has the lowest recorded volume under rainy night-time conditions.

4.4 Summary

The geometry survey and empirical results for the four selected sites are presented in this chapter. The geometry of the selected sites is within the specification of the site selection criteria. All the roadways fall within the specification of FMWH for a two-lane highway. Furthermore, rainfall data obtained for the sites which varied with respect to time, day and site was presented. The number of rainy days was higher at SS03 and SS04 as opposed to SS01 and SS02. The individual rainfall data was converted into density and classified accordingly into light ($i < 2.5$mm/h), moderate (2.5mm/h $< i \leq 10$mm/hr), heavy (10mm/hr $< i \leq 50$mm/hr) and very heavy ($i > 50$mm/hr), however the very heavy rain intensity data was not considered in this study.

Similarly, traffic data for all selected sites was presented graphically in terms of vehicle flow profiles, volume-density and speed-density. Four types of traffic vehicles *vis-à-vis* motorcycles, light vehicles (passenger car), moderate vehicles and heavy vehicles were identified by the ATC for each site. Nevertheless, the traffic composition of the various vehicle types varied from site to site. Motorcycles were excluded due to its near total absence on the road at night-time during rainfall. Also, motorcycle do not have vehicle following influence in the traffic stream.

Generally, light vehicles known as passenger cars are dominant across the four sites with an average of 82.2 percent irrespective of weather conditions. The medium vehicles accounted for 11.3 percent while 6.2 percent represented the heavy vehicles. In all the cases, there is a substantial drop in vehicle speeds during heavy rainfall. The data presented in this chapter are analysed further in the next chapter towards achieving the study aim and objectives.

CHAPTER FIVE

ROADWAY SERVICE QUALITY ANALYSIS

5.1 Overview

In this chapter, the empirical data presented in chapter four is analysed in order to determine the influence of night-time rain on dark roadways' functional service quality for a two-lane highway. Functional service quality has two complementing parameters (travel time and travel speed). These parameters are used to draw up the functional service quality criteria table. The criteria table is based on daylight and dry weather conditions; it is then used to assess service quality under the prevailing conditions.

Travel time was determined from a modified US Bureau of Public Roads (US-BPR) equation, whilst travel speed relied on the fundamental diagram. Roadway capacity is a common parameter and was determined using a flow and density relationship, whereas a speed and density relationship was used to ascertain the prevailing travel speed. In the flow/density relationship, density is used as the control parameter and flow is the objective function. In the speed/density relationship, density is used as the control parameter and speed is the objective function. The validity of the model equations is based on coefficient of determination. The coefficient of determination relates the estimated and actual y-values, and coefficient of determination values ranges from 0 to 1. If it is 1, thus a perfect correlation exists in the sample - there is no difference between the estimated y-values and the actual y-value. However, if the coefficient of determination is 0, the quadratic equation is not useful in predicting a y-value, and thus cannot be utilised for predictions. However, before road capacity can be estimated it is important that the effect of mixed traffic is taken into consideration and this was done by converting volume into passenger car equivalent (PCE) values. Because of the wide variance in PCE adopted by many scholars it is difficult to directly compare numerical results. Although the calibration of the PCE values is significant to estimations, it would not affect the outcome of the study.

Against the backdrop of discussions thus far, the remainder of this chapter is such that section 5.2 deals with assessment of PCE values. Section 5.3 is on generalised criteria table determination, bearing in mind that the criteria table is based on dry weather and daylight conditions. In section 5.4, functional service quality (FSQ) is assessed for surveyed roadways under daylight and dry weather conditions using modified PCE values. In section 5.5, functional service quality (FSQ) is assessed for dark roadways without night rainfall using modified PCE values. Section 5.6 focuses on dark roadways with night rainfall using modified PCE values. In section 5.7 the influence of night rainfall on the functional service quality of dark roadways is discussed and section 5.8 concludes the chapter.

5.2 Passenger Car Equivalent Values

The application of passenger car equivalency values from the Nigerian Design Manual is doubtful because their derivation is based on the Highway Capacity Manual 2000 and SANRAL where it is obvious there are clear differences in terrain, driving population and pattern, lane width and lateral clearance. The study used a simplistic method using vehicle headways from the database of the research survey. The method of calculating PCE was presented by Greenshields (1934) and was based on measurement of headway between vehicles under saturated flow conditions. However, Zhao (1998) concludes that Greenshields' method of determining the headways combined with the regression method calculation of PCE is applicable to developing countries. According to Seguin, Crowley and Zwieg (1982), PCEs is defined as the ratio of the mean lagging headway of a subject vehicle which is divided by the mean lagging headway of the basic passenger car. Lagging headway is defined as the time or space from the rear of the lead vehicle to the rear of the subject vehicle; it consists of the length of the inter-vehicular gap and the subject vehicle. However, PCEs is estimated as:

$$PCE_{ij} = H_{ij}/H_{pcj} \qquad 5.1$$

Where; PCE_{ij} is the PCE of vehicle type i under conditions j, and

H_{ij}, H_{pcj} is the average headway for vehicle type i and light car (LV) for conditions j.

i Headway = Spacing (m/veh) / Speed (m/sec) HCM (2010)

ii Spacing = (1000m/km) / Density (veh/km) HCM (2010)

The computed densities per roadway section and their relative average speed were plugged into the equations above for different types of vehicle (LVs, MVs and HVs). For example,

At site SS01: where spacing = 1000 / 34 = 29.41 m/veh, the individual headways for each vehicle class is calculated thus

Headway (LV) = 29.41 / 21.29 = 1.38 sec / veh

Headway (MV) = 29.41 / 20.59 = 1.43 sec / veh

Headway (HV) = 29.41 / 18.01 = 1.63 sec / veh

The passenger car equivalent values for each class of vehicle is thus calculated as follows:

PCE (LV) = 1.38 / 1.38 = 1.0 unit

PCE (MV) = 1.43 / 1.38 = 1.04 unit

PCE (HV) = 1.63 / 1.38 = 1.18 unit

Note that the estimated PCE values in Tables 5.1 and 5.2 were calculated for the purpose of this study and may not be relied on for more widespread adoption without modifications.

Table 5.1: Average Modified PCE Values

	Dry night	Light rain	Moderate rain	Heavy rain	Average
Light vehicle	1.00	1.00	1.00	1.00	1.00
Medium vehicle	1.08	1.12	1.24	1.15	1.15
Heavy vehicle	1.24	1.56	1.29	1.27	1.34

Table 5.2: Summary of Modified PCE Values

Site	WC	VC	K	s	u	h	PCE
SS01	DD	PC	34.00	29.41	21.29	1.38	1.00
		MV			20.59	1.43	1.04
		HV			18.01	1.63	1.18
	LR	PC	34.00	29.41	19.75	1.49	1.00
		MV			21.20	1.39	0.93
		HV			16.14	1.82	1.23
	MR	PC	32.00	31.25	18.59	1.68	1.00
		MV			16.99	1.84	1.10
		HV			16.59	1.88	1.12
	HR	PC	32.00	31.25	15.61	2.00	1.00
		MV			13.62	2.29	1.15
		HV			13.71	2.28	1.14
SS02	DD	PC	34.00	29.41	22.65	1.30	1.00
		MV			21.10	1.39	1.07
		HV			18.10	1.62	1.25
	LR	PC	32.00	31.25	23.29	1.34	1.00
		MV			19.73	1.58	1.18
		HV			8.95	3.49	2.60
	MR	PC	33.00	30.30	15.93	1.90	1.00
		MV			13.00	2.33	1.23
		HV			11.65	2.60	1.37
	HR	PC	30.00	33.30	22.46	1.48	1.00
		MV			18.60	1.79	1.21
		HV			16.91	1.97	1.33
SS03	DD	PC	37.00	27.03	21.79	1.24	1.00
		MV			19.72	1.37	1.10
		HV			18.49	1.46	1.17
	LR	PC	32.00	31.25	19.83	1.58	1.00
		MV			15.52	2.01	1.28
		HV			16.28	1.92	1.22
	MR	PC	32.00	31.25	22.13	1.41	1.00
		MV			16.48	1.90	1.34
		HV			16.59	1.88	1.33
	HR	PC	33.00	30.30	14.18	2.14	1.00
		MV			11.08	2.73	1.28
		HV			11.49	2.64	1.23
SS04	DD	PC	37.00	27.03	22.88	1.18	1.00
		MV			20.85	1.30	1.10
		HV			16.98	1.59	1.35
	LR	PC	35.00	28.57	20.78	1.37	1.00
		MV			19.39	1.47	1.07
		HV			17.64	1.62	1.18
	MR	PC	32.00	31.25	25.05	1.25	1.00
		MV			19.75	1.58	1.27
		HV			18.85	1.66	1.33
	HR	PC	31.00	32.26	17.90	1.80	1.00
		MV			18.58	1.74	0.97
		HV			13.22	2.44	1.36

WC = weather condition, VC = vehicle class, PC passenger car, MV = medium vehicle, HV = heavy vehicle. k = density, s = spacing, h = headway, u = speed

5.2.1 Comment on Estimated PCE Values

As shown in Tables 5.1 and 5.2, the estimated PCE values vary from site to site under each condition. This shows that the PCE values are not fixed but dynamic depending on the prevailing conditions of both traffic and road. PCE values as mentioned earlier are employed in highway capacity analysis to determine the number of passenger cars displaced in the traffic flow by MVs and HVs under the prevailing roadway and traffic conditions. Within the context of this study, traffic is free flowing, the terrain is flat, and the roadway is dark with and without night rainfall. If the definition of PCE values is to hold, their values will be significantly different under free flow condition.

As mentioned earlier, the Nigerian PCE values were adopted from the Highway Capacity Manual without modifications to local conditions, or recalculation. Besides, traffic conditions in most developing countries are considerably different from those in the USA. Consequently, the PCE values of the Highway Capacity Manual cannot be transferred without thorough evaluation. So, it is distorting to claim that 3.0 light vehicles (LVs) are displaced by MVs and HVs. Further research is needed to ascertain the PCE values of vehicle types in Nigeria. In this study headway was estimated from spacing and speed, it would be useful to conduct a separate headway distribution survey for vehicle types under varying road and traffic conditions. However, under night rainfall and dark roadway conditions, PCE values are near uniform; note also that PCE values of MVs and HVs are slightly more than 1.0. From observations at survey sites, light cars sometimes force HVs to slow down especially when they are platoon leaders because of their manoeuvrability difficulties on dark roads with rainfall. These observations further validate the definition of PCE values and to some extent the reason why the PCE values of HVs and MVs are slightly more than 1.0. It is worth noting that the PCE value is not a fixed value attached to the vehicle type, rather it depends on three main factors; the roadway, weather conditions and the traffic composition.

5.3 Generalised Functional Service Quality Criteria Table

Functional service quality is based on two parameters which are travel time and travel speed. These parameters are used in setting up the criteria table for the assessment of roadway functional service quality. In this study, the criteria table is set up using the peak period empirical data of dry and daylight conditions on the road. The peak period traffic data is used in the determination of the criteria table. This is necessary to allow the worst scenario of the roadway to be used, bearing in mind that the road attains its maximum capacity under the peak period with equivalent traffic performance. The criteria table for each of the selected sites is thus presented using the stepwise analysis in Figure 5.1. The stepwise analysis is adopted due to its clarity and simplicity.

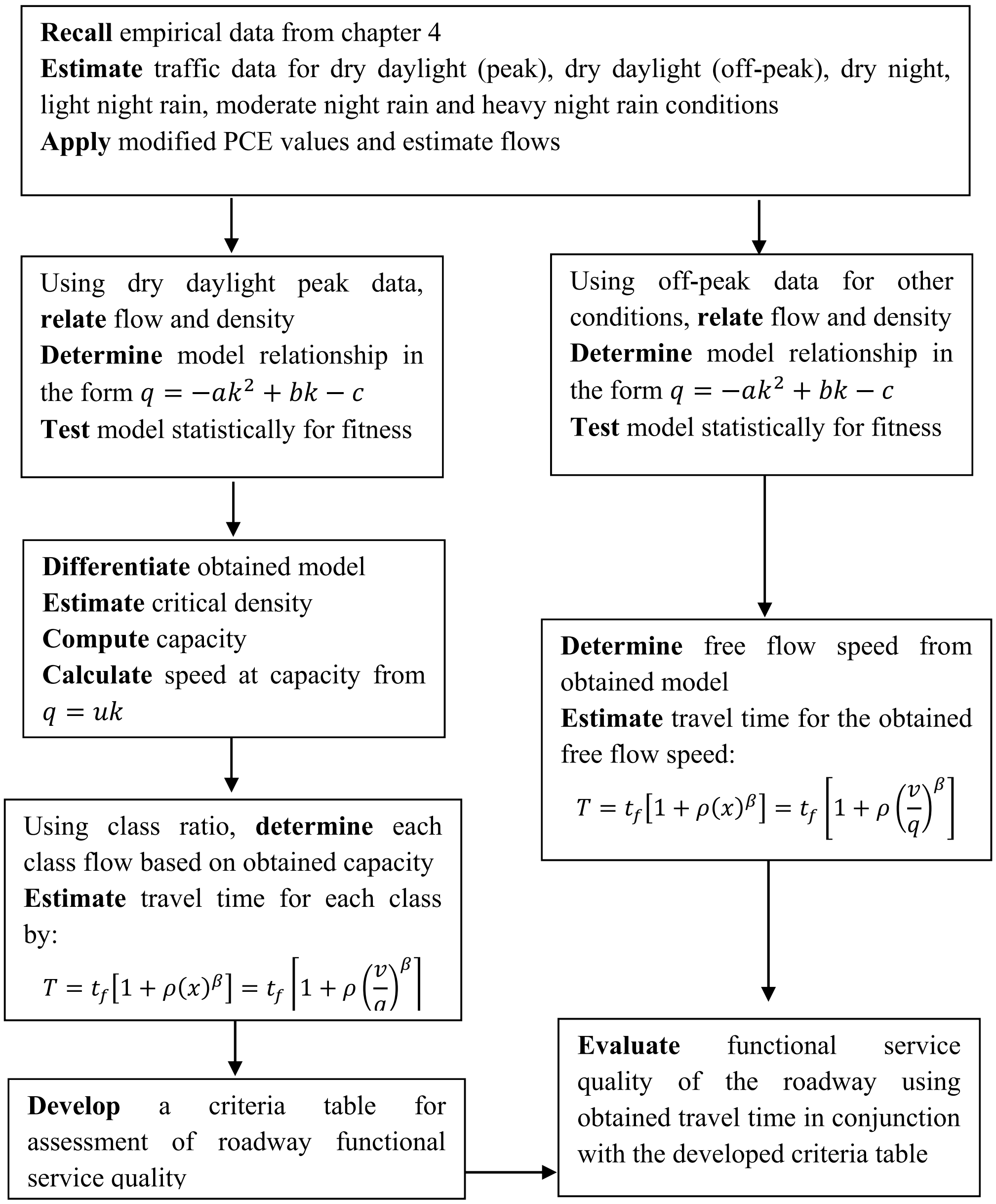


Figure 5.1: Schematic procedure of FSQ analysis

5.3.1 FSQ Criteria Table Determination – SS01

Step 1: Recall empirical results for dry daylight (peak) in chapter 4, the five-minute vehicle volumes obtained are converted into passenger car equivalents by applying average the modified PCE values given as PC = 1, MV = 1.15 HV = 1.34. The total flow/5-min is multiplied by 12 to obtain flow rate in pce/hour. The process of obtaining flow is summarised and presented in Table 5.3. With obtained flow and speed, density is calculated using the fundamental equation, $q = uk$.

Table 5.3: Computed Flow and Density for Dry Daylight (Peak) – SS01

Period	PC	MV	HV	vol	MV	HV	q	q	u	k
1	*2*	*3*	*4*	*5*	*6*	*7*	*8*	*9*	*10*	*11*
					*3*1.15*	*4*1.34*	*2+6+7*	*8 *12*		*9/10*
1	85	10	5	100	11.5	6.70	103	1238	72	17
2	102	8	8	118	9.2	10.72	122	1463	67	22
3	107	6	6	119	6.9	8.04	122	1463	71	21
4	91	11	9	111	12.7	12.06	116	1389	69	20
5	98	6	8	112	6.9	10.72	116	1387	65	21
6	119	6	4	129	6.9	5.36	131	1575	68	23
7	95	9	10	114	10.4	13.40	119	1425	80	18
8	106	10	8	124	11.5	10.72	128	1539	75	21
9	106	10	8	124	11.5	10.72	128	1539	75	21
10	104	12	10	126	13.8	13.40	131	1574	62	25
11	85	9	5	99	10.4	6.70	102	1225	70	17
12	123	6	8	137	6.9	10.72	141	1687	63	27

1, 2, 3...11 = column numbers, column 2 – 5 = volume by 5mins, column 6 - 8 = flow (pce/5mins), q = total flow (pce/h), u = speed (km/h), k = density (pce/km), PC = passenger car, MV = medium vehicle, HV = heavy vehicle

Step 2: Using the model adapted from Minderhoud *et al.* (1996) and Ben-Edigbe (2005), flow and density were related using Microsoft Excel to obtain the flow-density relationship in the form of equation 5.2 presented as follows.

$$q = -ak^2 + bk - c \qquad 5.2$$

The obtained speed-density model shown in Figure 5.2 is presented in equation 5.3.

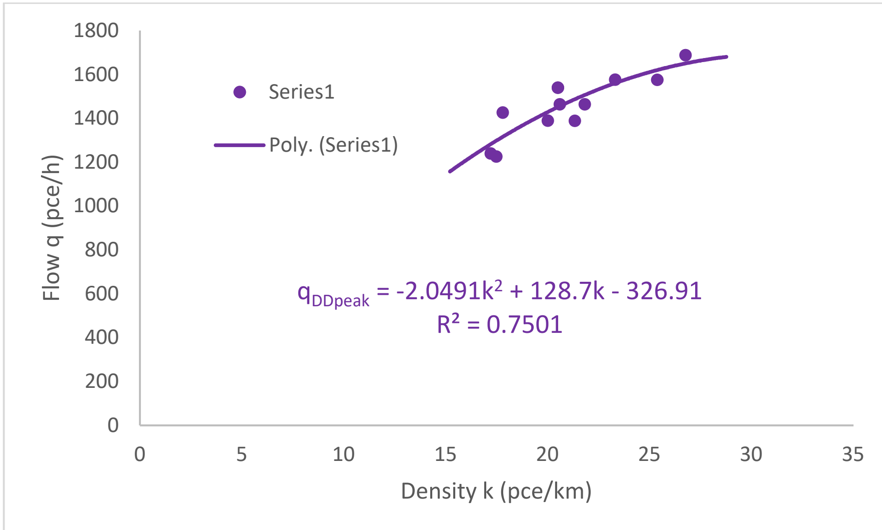


Figure 5.2: Flow-density graph of SS01

$$q_{DDpeak} = -2.0491k^2 + 128.70k - 326.91 \qquad R^2 = 0.7501 \qquad 5.3$$

The model coefficients have expected sign conventions while the coefficients of determination (R^2) is greater than 0.5 suggesting that the models could be used for prediction of capacity for the site. The value of R^2 is 0.7501 which signifies that a strong relationship exists between flow and density. At ten degree of freedom, value of F-observed statistics is greater than F-critical (4.94) which signifies that the relationship did not occur by chance. Also, the t-observed statistic value tested at five percent significance level, is greater than 2, this implies that when estimating flow, density is an important variable. The statistical values were taken directly from the Microsoft Excel worksheet. Note that the coefficient of "k" represents the free-flow speed, therefore, the free-flow speed of at SS01 is approximately 130km/h. The model is used in estimating critical density, capacity and speed at capacity in step 3.

Step 3: Using equation 5.3, critical density, capacity and speed at maximum flow were determined

$$q_{DDpeak} = -2.0491k^2 + 128.70k - 326.91 \qquad R^2 = 0.7501$$

Differentiating q with respect to k,

$$\frac{dq}{dk} = -2 * 2.0491k + 128.70 = 0$$

$$k_{crt} = k_Q = 31.4pce/km \approx 31pce/km$$

Substituting obtained k_{crt} into equation 5.3 to obtain capacity Q, gives

$$Q = q_{DDpeak} = -2.0491(31.4)^2 + 128.70(31.4) - 326.91$$

$$q_{DDpeak} = 1693.9pce/h \approx 1694pce/h$$

Plugging the values of k_{crt} and q into the fundamental equation $q = ku$, speed at maximum flow is thus obtained as

$$u_Q = \frac{q}{k} = \frac{1694}{31} = 54.6km/h \approx 55km/h$$

The maximum flow otherwise referred to as capacity is 1694pce/h with a corresponding speed at capacity, u_Q = 55km/h

Step 4: With the obtained capacity $Q = 1694pce/h$ which is approximated as 1700pce/h, flow rate for each class is thus calculated using ratio 0.25 for class A, 0.5 for class B, 0.75 for class C, 0.85 for class D, 1 for class E and class F > 1.

Class A (0.25) = 0.25 * 1700 = 425pce/h ≈ 500pce/h

Class B (0.50) = 0.50 * 1700 = 850pce/h ≈ 900pce/h

Class C (0.75) = 0.75 * 1700 = 1275pce/h ≈ 1300pce/h

Class D (0.85) = 0.85 * 1700 = 1445pce/h ≈ 1500pce/h

Class E (1.0) = 1700pce/h

Class F (> 1) = < 1700pce/h

Step 5: With the US-BPR formula in equation 5.4, travel time for each class is calculated

$$T = t_f\left[1 + \rho(x)^\beta\right] = t_f\left[1 + \rho\left(\frac{v}{q}\right)^\beta\right] \quad 5.4$$

where T = predicted time over roadway length; t_f = travel time at free-flow speed

v = demand traffic volume, q = capacity

ρ = ratio of free flow to speed at capacity (*ρ = 0.15 or 0.2)*

β = abrupt drop of curve from the free-flow speed (*β = 4 or 10)*

x = degree of saturation ($\frac{v}{Q}$) = volume capacity ratio

With $\frac{v}{q} = 1, \beta = 4$ and $\rho = 0.15$ while $\frac{v}{q} < 0.9,\ \beta = 10$ and $\rho = 0.2$

Recall

Speed at capacity u_Q = 55km/h for class E, its equivalent time, $t_E = 60/55 = 1.09min$

Where $\frac{v}{q} = 1, \beta = 4$ and $\rho = 0.15$, travel time for class E is calculated as

$$T_E = \frac{60}{55}[1 + 0.15(1)^4]$$

$$T_E = 1.25min$$

For class A to D, $\frac{v}{q} < 0.9$

Speed for class A = 130km/h, hence its equivalent time, $t_E = 60/130 = 0.46min$
Where $\frac{v}{q} < 0.9,\ \beta = 10$ and $\rho = 0.2$, travel time for class A is calculated as

$$T_A = \frac{60}{130}[1 + 0.2(0.9)^{10}]$$

$$T_A = 0.49min$$

As speed is evenly distributed, speed for each class is distributed between the free-flow speed of 130km/h for class A and speed at capacity of 55km/h for class E. The speed is used to calculate its time and expected travel time, thereafter, the criteria table for service quality is set up. Table 5.4 represents the functional service quality criteria table for SS01.

Table 5.4: Functional Service Quality Criteria Table – SS01

CLASS	T (min)	u (km/h)	q (pce/h)	k (veh/km)	h (s)
A	< 0.49	> 130	< 500	< 4	7.2
B	0.58	110	900	8	4.0
C	0.71	90	1300	14	2.8
D	0.92	70	1500	21	2.4
E	1.25	55	1700	31	2.1
F	> 1.25	< 55	< 1700	> 31	< 2.1

T = travel time, u = speed (± 20%), q = flow rate, k = density, h = headway

For the avoidance of repetition, the FSQ criteria table determination for the remaining three sites is summarised using the stepwise analysis method

5.3.2 FSQ Criteria Table Determination – SS02

Step 1: Analysis of empirical data in Table 5.5

Table 5.5: Computed Flow and Density for Dry Daylight (Peak) – SS02

Period	PC	MV	HV	vol	MV	HV	q	q	u	k
1	*2*	*3*	*4*	*5*	*6*	*7*	*8*	*9*	*10*	*11*
					*3*1.15*	*4*1.34*	*2+6+7*	*8 *12*		*9/10*
1	99	7	4	110	8.1	5.4	112.4	1349	81	17
2	87	8	6	101	9.2	8.0	104.2	1251	78	16
3	111	9	6	126	10.4	8.0	129.4	1553	64	24
4	93	5	4	102	5.8	5.4	104.1	1249	80	16
5	104	15	9	128	17.3	12.1	133.3	1600	71	23
6	84	4	7	95	4.6	9.4	98.0	1176	81	14
7	93	10	9	112	11.5	12.1	116.6	1399	70	20
8	90	6	7	103	6.9	9.4	106.3	1275	79	16
9	98	10	9	117	11.5	12.1	121.6	1459	78	19
10	93	9	10	112	10.4	13.4	116.8	1401	83	17
11	82	11	7	100	12.7	9.4	104.0	1248	75	17
12	94	9	6	109	10.4	8.0	112.4	1349	77	18

1, 2, 3…11 = column numbers, column 2 – 5 = volume by 5mins, column 6 - 8 = flow (pce/5mins), q = total flow (pce/h), u = speed (km/h), k = density (pce/km), PC = passenger car, MV = medium vehicle, HV = heavy vehicle

Step 2: Flow-density model relationship obtained as equation 5.5 from Figure 5.3.

$$q_{DDpeak} = -3.2061k^2 + 165.25k - 548.93 \qquad R^2 = 0.8809 \qquad 5.5$$

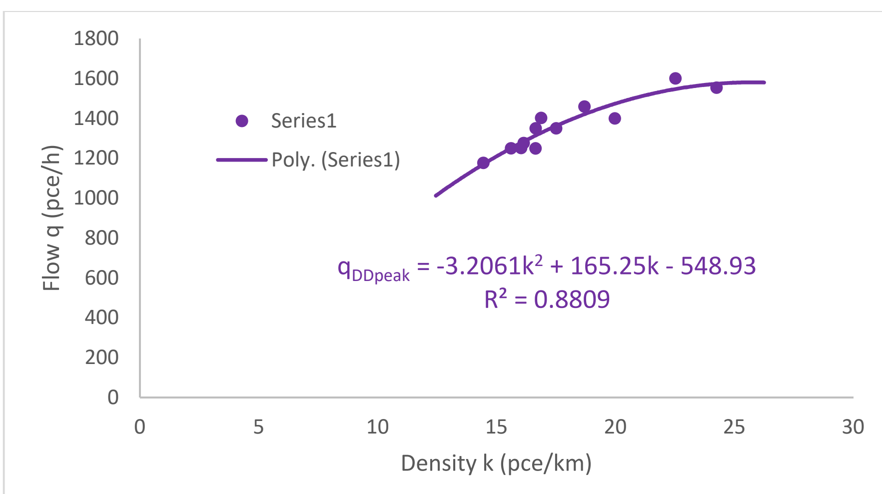


Figure 5.3: Flow-density graph of SS02

Step 3: Critical density, capacity, speed at maximum flow determined using equation 5.5.

$$q_{DDpeak} = -3.2061k^2 + 165.25k - 548.93$$

$$\frac{dq}{dk} = -2 * 3.2061k + 165.25 = 0$$

$$k_{crt} = k_Q = 25.8pce/km \approx 26pce/km$$

$$Q = q_{DDpeak} = -3.2061(25.8)^2 + 165.25(25.8) - 548.93$$

$$q_{DDpeak} = 1580.4pce/h \approx 1580pce/h$$

$$u_Q = \frac{q}{k} = \frac{1580}{26} = 60.8km/h \approx 60km/h$$

Capacity, maximum flow = 1580pce/h, speed at capacity u_Q = 60km/h, free flow speed u_f = 165.25km/h assumed to be 160km/h

Step 4: Flow rate for each class is calculated as

Class A (0.25)	=	0.25 * 1700 = 425pce/h ≈ 500pce/h
Class B (0.50)	=	0.50 * 1700 = 850pce/h ≈ 900pce/h
Class C (0.75)	=	0.75 * 1700 = 1275pce/h ≈ 1300pce/h
Class D (0.85)	=	0.85 * 1700 = 1445pce/h ≈ 1500pce/h
Class E (1.0)	=	1700pce/h
Class F (> 1)	=	< 1700pce/h

Step 5: Calculation of travel time for each class using the US-BPR formula.

Speed at capacity for class E u_Q = 60km/h, its equivalent time, $t_E = 60/60 = 1.0min$

Where $\frac{v}{q} = 1, \beta = 4$ and $\rho = 0.15$ travel time for class E is calculated

$$T_E = \frac{60}{60}[1 + 0.15(1)^4]$$

$$T_E = 1.15min$$

Speed for class A = 160km/h, its equivalent time, $t_E = 60/160 = 0.38min$

Where $\frac{v}{q} < 0.9,\ \beta = 10$ and $\rho = 0.2$, travel time for class A is calculated

$$T_A = \frac{60}{160}[1 + 0.2(0.9)^{10}]$$

$$T_A = 0.40min$$

Thus, the criteria table for service quality of SS02 is presented in Table 5.6

Table 5.6: Functional Service Quality Criteria Table – SS02

CLASS	T (min)	u (km/h)	q (pce/h)	k (veh/km)	H (s)
A	< 0.40	> 160	< 500	< 4	7.2
B	0.48	135	900	8	4.0
C	0.58	110	1300	14	2.8
D	0.76	85	1500	21	2.4
E	1.15	60	1700	31	2.1
F	> 1.15	< 60	< 1700	> 31	< 2.1

T = travel time, u = speed (± 25%), q = flow rate, k = density, h = headway

5.3.3 FSQ Criteria Table Determination – SS03

Step 1: Analysis of empirical data in table 5.7

Table 5.7: Computed Flow and Density for Dry Daylight (Peak) – SS03

Period	PC	MV	HV	vol	MV	HV	q	q	u	k
1	*2*	*3*	*4*	*5*	*6*	*7*	*8*	*9*	*10*	*11*
					*3*1.15*	*4*1.34*	*2+6+7*	*8 *12*		*9/10*
1	98	11	6	115	12.7	8.0	118.7	1424	75	19
2	110	10	15	135	11.5	20.1	141.6	1699	74	23
3	107	7	12	126	8.1	16.1	131.1	1574	72	22
4	95	15	8	118	17.3	10.7	123.0	1476	69	21
5	110	11	11	132	12.7	14.7	137.4	1649	67	25
6	115	10	5	130	11.5	6.7	133.2	1598	70	23
7	107	12	13	132	13.8	17.4	138.2	1659	60	28
8	94	11	9	114	12.7	12.1	118.7	1425	83	17
9	105	10	7	122	11.5	9.4	125.9	1511	73	21
10	80	10	11	101	11.5	14.7	106.2	1275	79	16
11	102	15	9	126	17.3	12.1	131.3	1576	79	20
12	91	8	9	108	9.2	12.1	112.3	1347	67	20

1, 2, 3...11 = column numbers, column 2 – 5 = volume by 5mins, column 6 - 8 = flow (pce/5mins), q = total flow (pce/h), u = speed (km/h), k = density (pce/km), PC = passenger car, MV = medium vehicle, HV = heavy vehicle

Step 2: Flow-density model relationship obtained as equation 5.6 from Figure 5.4

$$q_{DDpeak} = -2.2909k^2 + 134.03k - 273.28 \qquad R^2 = 0.7231 \qquad 5.6$$

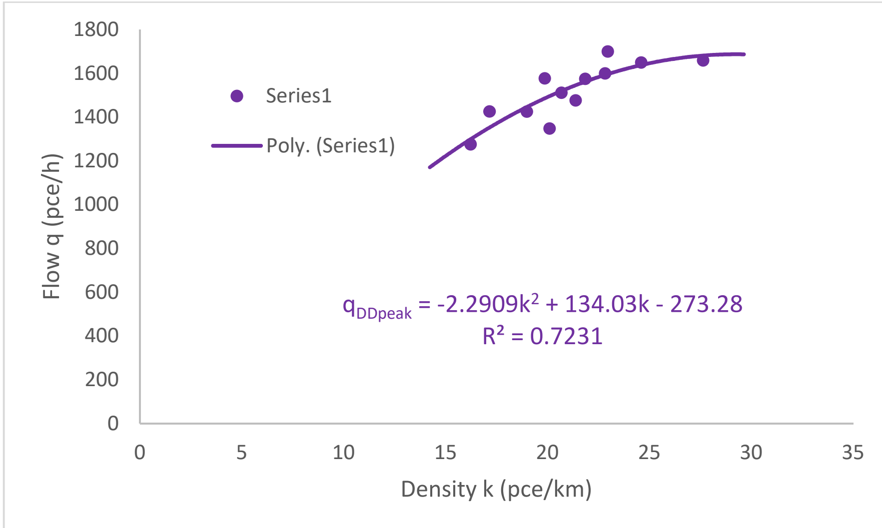


Figure 5.4: Flow-density graph of SS03

Step 3: Determine critical density, capacity, speed at maximum flow using equation 5.6

$$q_{DDpeak} = -2.2909k^2 + 134.03k - 273.28$$

$$\frac{dq}{dk} = -2 * 2.2909k + 134.03 = 0$$

$$k_{crt} = k_Q = 29.3pce/km$$

$$Q = q_{DDpeak} = -2.2909(29.3)^2 + 134.03(29.3) - 273.28$$

$$q_{DDpeak} = 1687.1pce/h \approx 1687pce/h$$

$$u_Q = \frac{q}{k} = \frac{1687}{29.3} = 57.5km/h \approx 57km/h$$

Capacity, maximum flow = 1687pce/h approximated as 1700pce/h, speed at capacity u_Q = 57km/h, free flow speed u_f = 134.03km/h assumed to be 130km/h

Step 4: Flow rate for each class is calculated as

Class A (0.25) = 0.25 * 1700 = 425pce/h ≈ 500pce/h

Class B (0.50) = 0.50 * 1700 = 850pce/h ≈ 900pce/h

Class C (0.75) = 0.75 * 1700 = 1275pce/h ≈ 1300pce/h

Class D (0.85) = 0.85 * 1700 = 1445pce/h ≈ 1500pce/h

Class E (1.0) = 1700pce/h

Class F (> 1) = < 1700pce/h

Step 5: Calculation of travel time for each class using the US-BPR formula.

Speed at capacity for class E u_Q = 60km/h, its equivalent time, $t_E = 60/55 = 1.09min$

Where $\frac{v}{q} = 1, \beta = 4$ and $\rho = 0.15$ travel time for class E is calculated

$$T_E = \frac{60}{55}[1 + 0.15(1)^4]$$

$$T_E = 1.25min$$

Speed for class A = 160km/h, its equivalent time, $t_E = 60/130 = 0.46min$

Where $\frac{v}{q} < 0.9,\ \beta = 10$ and $\rho = 0.2$, travel time for class A is calculated

$$T_A = \frac{60}{130}[1 + 0.2(0.9)^{10}]$$

$$T_A = 0.49min$$

Thus, the criteria table for service quality of SS03 is presented in Table 5.8

Table 5.8: Functional Service Quality Criteria Table – SS03

CLASS	T (min)	U (km/h)	Q (pce/h)	k (veh/km)	h (s)
A	< 0.49	> 130	< 500	< 4	7.2
B	0.58	110	900	8	4.0
C	0.71	90	1300	14	2.8
D	0.92	70	1500	21	2.4
E	1.25	55	1700	31	2.1
F	> 1.25	< 55	< 1700	> 31	< 2.1

T = travel time, u = speed (± 20%), q = flow rate, k = density, h = headway

5.3.4 FSQ Criteria Table Determination – SS04

Step 1: Analysis of empirical data in Table 5.9

Table 5.9: Computed Flow and Density for Dry Daylight (Peak) – SS04

Period	PC	MV	HV	vol	MV	HV	q	q	u	k
1	*2*	*3*	*4*	*5*	*6*	*7*	*8*	*9*	*10*	*11*
					*3*1.15*	*4*1.34*	*2+6+7*	*8 *12*		*9/10*
1	84	7	6	97	8.1	8.0	100.1	1201	77	16
2	94	6	4	104	6.9	5.4	106.3	1275	80	16
3	82	6	6	94	6.9	8.0	96.9	1163	86	14
4	96	7	4	107	8.1	5.4	109.4	1313	81	16
5	100	9	4	113	10.4	5.4	115.7	1389	77	18
6	107	8	4	119	9.2	5.4	121.6	1459	63	23
7	106	8	5	119	9.2	6.7	121.9	1463	63	23
8	107	2	7	116	2.3	9.4	118.7	1424	73	20
9	109	5	10	124	5.8	13.4	128.2	1538	60	26
10	100	7	8	115	8.1	10.7	118.8	1425	77	19
11	98	16	9	123	18.4	12.1	128.5	1542	70	22
12	93	8	3	104	9.2	4.0	106.2	1275	72	18

1, 2, 3...11 = column numbers, column 2 – 5 = volume by 5mins, column 6 - 8 = flow (pce/5mins), q = total flow (pce/h), u = speed (km/h), k = density (pce/km), PC = passenger car, MV = medium vehicle, HV = heavy vehicle

Step 2: Flow-density model relationship obtained in equation 5.7 from Figure 5.5

$$q_{DDpeak} = -2.2987k^2 + 121.39k - 78.648 \qquad R^2 = 0.8859 \qquad 5.7$$

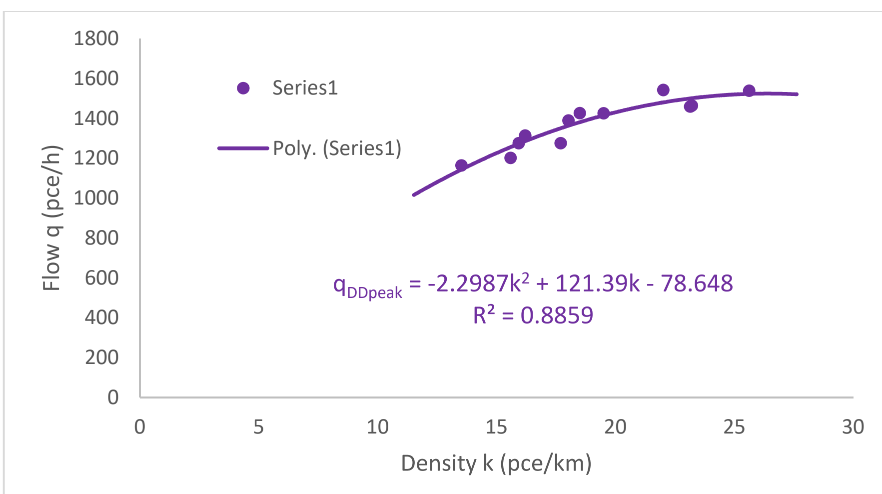


Figure 5.5: Flow-density graph of SS04

Step 3: Determine critical density, capacity, speed at maximum flow using equation 5.7

$$q_{DDpeak} = -2.2987k^2 + 121.39k - 78.648$$

$$\frac{dq}{dk} = -2 * 2.2987k + 121.39 = 0$$

$$k_{crt} = k_Q = 26.4pce/km$$

$$Q = q_{DDpeak} = -2.2987(26.4)^2 + 121.39(26.4) - 78.648$$

$$q_{DDpeak} = 1524pce/h$$

$$u_Q = \frac{q}{k} = \frac{1524}{26.4} = 57.7km/h \approx 58km/h$$

Capacity, maximum flow = 1524pce/h approximated as 1600pce/h, speed at capacity u_Q = 57km/h, free flow speed u_f = 121.39km/h assumed to be 120km/h

Step 4: Flow rate for each class is calculated as

Class A (0.25) = 0.25 * 1600 = 400pce/h

Class B (0.50) = 0.50 * 1600 = 800pce/h

Class C (0.75) = 0.75 * 1600 = 1200pce/h

Class D (0.85) = 0.85 * 1600 = 1360pce/h ≈ 1400pce/h

Class E (1.0) = 1600pce/h

Class F (> 1) = < 1600pce/h

Step 5: Calculation of travel time for each class using the US-BPR formula

Speed at capacity for class E u_Q = 50km/h, its equivalent time, $t_E = 60/50 = 1.2min$

With $\frac{v}{q} = 1, \beta = 4$ and $\rho = 0.15$ travel time for class E is calculated

$$T_E = \frac{60}{50}[1 + 0.15(1)^4]$$

$$T_E = 1.38min$$

Speed for class A = 120km/h, its equivalent time, $t_E = 60/120 = 0.5min$

With $\frac{v}{q} < 0.9,\ \beta = 10$ and $\rho = 0.2$, travel time for class A is calculated

$$T_A = \frac{60}{120}[1 + 0.2(0.9)^{10}]$$

$$T_A = 0.53min$$

Thus, the criteria table for service quality of SS04 is presented in Table 5.10

Table 5.10: Functional Service Quality Criteria Table – SS04

CLASS	T (min)	u (km/h)	q (pce/h)	k (veh/km)	h (s)
A	< 0.53	> 120	< 400	< 3	9.0
B	0.64	100	800	8	4.5
C	0.80	80	1200	15	3.0
D	1.07	60	1400	23	2.6
E	1.38	50	1600	32	2.3
F	> 1.25	< 50	< 1600	> 32	< 2.3

T = travel time, u = speed (± 20%), q = flow rate, k = density, h = headway

The functional service quality criteria table for SS01 – SS04 are presented in Tables 5.4, 5.6, 5.8 and 5.10 respectively. From the tables, there is evidence of differences in travel time and the associated speed across the four study sites for the various FSQ classes. This is an evidence that despite the same scenario of dry and daylight conditions across the sites, each site responds to its own traffic and roadway operations. The criteria tables are to be used in the assessment of each site's service quality respectively in other sections of this chapter. The remaining sections analyse the off-peak period of both dry daylight conditions and night-time conditions with and without rainfall.

5.4 Impact of Dry Daytime Conditions on Roadway Functional Service Quality (FSQ)

In this section, the assessment of the surveyed roadways under the dry daylight is presented using the off-peak empirical data. The off-peak dry daylight empirical data are presented in Tables 5.11 - 5.14 respectively for the four study sites. For this analysis, the stepwise analysis adopted in section 5.3 is used in this section. The analysis is thus presented as follows:

5.4.1 Dry Daylight (off-peak)

Step 1: Analysis of empirical data for each site

Table 5.11: Computed Flow and Density for *Dry Daylight* – SS01

Period	PC	MV	HV	vol	MV	HV	Q	Q	u	k
1	*2*	*3*	*4*	*5*	*6*	*7*	*8*	*9*	*10*	*11*
					*3*1.15*	*4*1.34*	*2+6+7*	*8 *12*		*9/10*
1	91	8	9	108	9.20	12.06	112.26	1347	67	20
2	80	10	11	101	11.50	14.74	106.24	1275	79	16
3	107	12	13	132	13.80	17.42	138.22	1658	60	28
4	102	15	9	126	17.25	12.06	131.31	1575	79	20
5	98	11	6	115	12.65	8.04	118.69	1425	75	19
6	110	11	11	132	12.65	14.74	137.39	1649	67	25
7	107	7	12	126	8.05	16.08	131.13	1573	72	22
8	94	11	9	114	12.65	12.06	118.71	1425	83	17
9	117	7	14	138	8.05	18.76	143.81	1726	74	23
10	105	10	7	122	11.50	9.38	125.88	1510	73	21
11	115	10	5	130	11.50	6.70	133.20	1599	70	23
12	99	9	7	115	10.35	9.38	118.73	1425	69	21

1, 2, 3...11 = column numbers, column 2 – 5 = volume by 5mins, column 6 - 8 = flow (pce/5mins), q = total flow (pce/h), u = speed (km/h), k = density (pce/km), PC = passenger car, MV = medium vehicle, HV = heavy vehicle

Table 5.12: Computed Flow and Density for *Dry Daylight* – SS02

Period	PC	MV	HV	vol	MV	HV	Q	q	u	k
1	*2*	*3*	*4*	*5*	*6*	*7*	*8*	*9*	*10*	*11*
					*3*1.15*	*4*1.34*	*2+6+7*	*8 *12*		*9/10*
1	81	9	8	98	10.35	10.72	102.07	1225	75	16
2	71	6	4	81	6.90	5.36	83.26	1000	82	12
3	113	12	8	133	13.8	10.72	137.52	1650	64	26
4	82	8	5	95	9.20	6.70	97.90	1175	77	15
5	94	8	10	112	9.20	13.40	116.60	1400	83	17
6	104	15	9	128	17.25	12.06	133.31	1600	75	21
7	84	4	7	95	4.60	9.38	97.98	1175	81	14
8	87	8	6	101	9.20	8.04	104.24	1250	78	16
9	99	7	4	110	8.05	5.36	112.41	1350	81	17
10	83	9	5	97	10.35	6.70	100.05	1200	78	15
11	90	6	7	103	6.90	9.38	106.28	1275	79	16
12	93	5	4	102	5.75	5.36	104.11	1250	80	16

1, 2, 3…11 = column numbers, column 2 – 5 = volume by 5mins, column 6 - 8 = flow (pce/5mins), q = total flow (pce/h), u = speed (km/h), k = density (pce/km), PC = passenger car, MV = medium vehicle, HV = heavy vehicle

Table 5.13: Computed Flow and Density for *Dry Daylight* – SS03

Period	PC	MV	HV	vol	MV	HV	Q	q	u	k
1	*2*	*3*	*4*	*5*	*6*	*7*	*8*	*9*	*10*	*11*
					*3*1.15*	*4*1.34*	*2+6+7*	*8 *12*		*9/10*
1	123	6	8	137	6.90	10.72	140.62	1688	63	27
2	119	6	4	129	6.90	5.36	131.26	1575	68	23
3	106	10	8	124	11.5	10.72	128.22	1538	80	19
4	104	12	10	126	13.8	13.40	131.20	1575	62	25
5	98	6	8	112	6.90	10.72	115.62	1388	65	21
6	107	6	6	119	6.90	8.04	121.94	1463	69	21
7	95	9	10	114	10.35	13.40	118.75	1425	80	18
8	91	11	9	111	12.65	12.06	115.71	1388	69	20
9	106	10	8	124	11.50	10.72	128.22	1538	75	21
10	102	8	8	118	9.20	10.72	121.92	1463	67	22
11	84	5	3	92	5.75	4.02	93.77	1125	75	15
12	85	10	5	100	11.5	6.70	103.20	1238	72	17

1, 2, 3...11 = column numbers, column 2 – 5 = volume by 5mins, column 6 - 8 = flow (pce/5mins), q = total flow (pce/h), u = speed (km/h), k = density (pce/km), PC = passenger car, MV = medium vehicle, HV = heavy vehicle

Table 5.14: Computed Flow and Density for *Dry Daylight* – SS04

Period	PC	MV	HV	vol	MV	HV	Q	q	u	k
1	*2*	*3*	*4*	*5*	*6*	*7*	*8*	*9*	*10*	*11*
					*3*1.15*	*4*1.34*	*2+6+7*	*8 *12*		*9/10*
1	65	10	5	80	11.5	6.70	83.20	999	72	14
2	118	10	6	134	11.5	8.04	137.54	1650	53	31
3	100	7	8	115	8.05	10.72	118.77	1425	67	21
4	93	8	3	104	9.20	4.02	106.22	1275	73	17
5	82	6	6	94	6.90	8.04	96.94	1163	70	17
6	100	9	4	113	10.35	5.36	115.71	1388	72	19
7	109	5	10	124	5.75	13.40	128.15	1538	55	28
8	84	7	6	97	8.05	8.04	100.09	1201	75	16
9	106	8	5	119	9.20	6.70	121.9	1463	50	29
10	107	2	7	116	2.30	9.38	118.68	1425	73	20
11	96	7	4	107	8.05	5.36	109.41	1313	72	18
12	94	6	4	104	6.90	5.36	106.26	1275	63	20

1, 2, 3...11 = column numbers, column 2 – 5 = volume by 5mins, column 6 - 8 = flow (pce/5mins), q = total flow (pce/h), u = speed (km/h), k = density (pce/km), PC = passenger car, MV = medium vehicle, HV = heavy vehicle

Step 2: Using the flow and density values in Tables 5.11 - 5.14, the flow-density model for each site was determined accordingly. The models are presented in equations 5.8 - 5.11

SS01	$q_{DD} = -2.2294k^2 + 132.51k - 269.84$	$R^2 = 0.7108$	5.8
SS02	$q_{DD} = -2.9480k^2 + 163.55k - 588.96$	$R^2 = 0.9514$	5.9
SS03	$q_{DD} = -2.1348k^2 + 129.44k - 297.07$	$R^2 = 0.7735$	5.10
SS04	$q_{DD} = -2.0907k^2 + 124.27k - 282.61$	$R^2 = 0.8722$	5.11

From equations 5.8 – 5.11, all the model coefficients have expected sign convention and coefficients of determination (R^2) greater than 0.5 suggesting that the models could be used for capacity prediction. The values of their R^2 ranges are between 0.7108 and 0.9514 signifying that a strong relationship exists between flow and density. At ten degrees of freedom, values of F-observed statistics are much greater than F-critical (4.94) which signify that their relationship did not occur by chance. Also, the t-observed statistic values tested at a five percent significance level are greater than 2, this implies that when estimating flow, density is an important variable. All the statistical values were taken directly from the Microsoft Excel worksheet. The coefficients of "k" represents the free-flow speeds which are used in the next step for analysing travel time.

Step 3: Using the US-BPR formula, travel time of each site was obtained based on their individual free-flow speed as shown in the flow-density model in step 2. Thereafter, the roadway service quality was determined accordingly from their corresponding functional service quality criteria table as earlier determined in section 5.3.

At SS01

Free flow speed is, $u_f = 132.5km/h$,

Its equivalent free flow time is, $t_{uf} = 60/132.5 = 0.45min$

Where $\frac{v}{q} < 0.9$, $\beta = 10$ and $\rho = 0.2$,

Computed travel time is, $T_{DD} = \frac{60}{132.5}[1 + 0.2(0.9)^{10}]$

$$T_{DD} = 0.48min$$

Using Table 5.4, travel time of 0.48min has a functional service quality A.

At SS02

Free flow speed is, $u_f \ = \ 163.55km/h$,

Its equivalent free flow time is, $t_{uf} = 60/163.55 \ = \ 0.37min$

Where $\frac{v}{q} < 0.9$, $\beta = 10$ and $\rho = 0.2$,

Computed travel time is, $T_{DD} = \frac{60}{163.55}[1 + 0.2(0.9)^{10}]$

$$T_{DD} = 0.39min$$

From Table 5.6, travel time of 0.39min has a functional service quality A

At SS03

Free flow speed is, $u_f \ = \ 129.44km/h$,

Its equivalent free flow time, $t_{uf} = 60/129.44 \ = \ 0.46min$

Where $\frac{v}{q} < 0.9$, $\beta = 10$ and $\rho = 0.2$,

Computed travel time is, $T_{DD} = \frac{60}{129.44}[1 + 0.2(0.9)^{10}]$

$$T_{DD} = 0.49min$$

From Table 5.8, travel time of 0.49min has a functional service quality A.

At SS04

Free flow speed is, $u_f \ = \ 124.27km/h$,

Its equivalent free flow time, $t_{uf} = 60/124.27 \ = \ 0.48min$

Where $\frac{v}{q} < 0.9$, $\beta = 10$ and $\rho = 0.2$,

Computed travel time is, $T_{DD} = \frac{60}{124.27}[1 + 0.2(0.9)^{10}]$

$$T_{DD} = 0.51min$$

Using Table 5.10, travel time of 0.51min has a functional service quality A.

The dry daylight analysis of the four sites is summarised and presented in Table 5.15.

Table 5.15: Summary of Travel Time and FSQ of Dry Daylight (Off-Peak Period)

SS	Model	u_f (km/h)	t_f (min)	$\rho\left(\frac{v}{q}\right)^{\beta}$	1 + col 5	T (min)	FSQ
1	*2*	*3*	*4*	*5*	*6*	*7*	*8*
01	$-2.2294k^2 + 132.51k - 269.84$	132.5	0.45	0.07	1.07	0.48	A
02	$-2.9480k^2 + 163.55k - 588.96$	163.5	0.37	0.07	1.07	0.39	A
03	$-2.1348k^2 + 129.44k - 297.07$	129.4	0.46	0.07	1.07	0.49	A
04	$-2.0907k^2 + 124.27k - 282.61$	124.3	0.48	0.07	1.07	0.51	A

*SS = study site, u_f = free-flow speed, t_f = travel time at u_f, T = travel time, ρ = ratio of free-flow to speed at capacity, β = abrupt drop of curve from free-flow speed, v/q = volume-capacity ratio, col 4 = 60/col 3, col 7 = col 4 * col 6*

From the table, the FSQ of all four sites under dry daylight conditions in the off-peak period is class A. The off-peak period is the period drivers can choose their speed without any consideration for incidences that may force them to alter their speed. The result of the analysis showed that the roadway and traffic operations do not in any way affect road users' (drivers) decision in terms of their travel time with respect to their travel speed. Therefore, the FSQ obtained for dry daylight conditions is justified under the prevailing conditions of this study. However, having understood the service quality delivery under dry daylight conditions, there is a need to look further into its equivalent dry night-time conditions to ascertain if the service quality will be maintained or changed under the influence of night-time conditions. Thus, section 5.5 investigates the impact of dry night-time conditions on functional service quality of dark roadways.

5.5 Impact of Dry Night-Time Conditions on Dark Roadway Functional Service Quality (FSQ)

In this section, the dry night-time condition of the roadway is considered and analysed to understand if night-time conditions will influence dark roadways. However, bearing in mind that night-time is also an off-peak traffic period, as the dry daylight condition analysed in section 5.4, there is still a need to investigate further the impact on functional service quality. The empirical traffic data assessment for the dry night condition of the surveyed roadways are presented in Tables 5.16 - 5.19 respectively for SS01 - SS04. The stepwise analysis adopted in section 5.4 is applicable in this section and the analysis presented as follows:

5.5.1 Dry Night

Step 1: Analysis of empirical data for each site

Table 5.16: Computed Flow and Density for *Dry Night* – SS01

Period	PC	MV	HV	vol	MV	HV	Q	q	u	k
1	*2*	*3*	*4*	*5*	*6*	*7*	*8*	*9*	*10*	*11*
					*3*1.15*	*4*1.34*	*2+6+7*	*8 *12*		*9/10*
1	72	7	4	83	8.05	5.36	85.41	1025	73	14
2	91	5	4	100	5.75	5.36	102.11	1225	58	21
3	56	4	7	67	4.60	9.38	69.98	840	82	10
4	60	10	5	75	11.50	6.70	78.20	938	70	13
5	84	5	7	96	5.75	9.38	99.13	1190	66	18
6	68	5	5	78	5.75	6.70	80.45	965	80	12
7	52	3	3	58	3.45	4.02	59.47	713	84	8
8	42	2	2	46	2.30	2.68	46.98	563	78	7
9	83	9	5	97	10.35	6.70	100.05	1201	74	16
10	72	8	6	86	9.20	8.04	89.24	1075	68	16
11	69	6	4	79	6.90	5.36	81.26	975	71	14
12	58	2	4	64	2.30	5.36	65.66	788	80	10

1, 2, 3...11 = column numbers, column 2 – 5 = volume by 5mins, column 6 - 8 = flow (pce/5mins), q = total flow (pce/h.), u = speed (km/h), k = density (pce/km), PC = passenger car, MV = medium vehicle, HV = heavy vehicle

Table 5.17: Computed Flow and Density for *Dry Night* – SS02

Period	PC	MV	HV	vol	MV	HV	Q	q	u	k
1	*2*	*3*	*4*	*5*	*6*	*7*	*8*	*9*	*10*	*11*
					*3*1.15*	*4*1.34*	*2+6+7*	*8 *12*		*9/10*
1	58	7	3	68	8.05	4.02	70.07	840	81	10
2	55	7	2	64	8.05	2.68	65.73	788	73	11
3	79	5	6	90	5.75	8.04	92.79	1113	71	16
4	58	7	2	67	8.05	2.68	68.73	825	80	10
5	73	7	4	84	8.05	5.36	86.41	1038	72	14
6	76	7	5	88	8.05	6.70	90.75	1088	71	15
7	72	8	5	85	9.20	6.70	87.90	1055	70	15
8	79	8	5	92	9.20	6.70	94.90	1138	63	18
9	68	4	2	74	4.60	2.68	75.28	903	70	13
10	67	5	4	76	5.75	5.36	78.11	938	69	14
11	63	4	7	74	4.60	9.38	76.98	924	72	13
12	75	2	3	80	2.30	4.02	81.32	975	76	13

1, 2, 3...11 = column numbers, column 2 – 5 = volume by 5mins, column 6 - 8 = flow (pce/5mins), q = total flow (pce/h), u = speed (km/h), k = density (pce/km), PC = passenger car, MV = medium vehicle, HV = heavy vehicle

Table 5.18: Computed Flow and Density for *Dry Night* – SS03

Period	PC	MV	HV	vol	MV	HV	Q	q	u	k
1	*2*	*3*	*4*	*5*	*6*	*7*	*8*	*9*	*10*	*11*
					*3*1.15*	*4*1.34*	*2+6+7*	*8 *12*		*9/10*
1	63	7	3	73	8.05	4.02	75.07	900	46	20
2	45	3	3	51	3.45	4.02	52.47	630	86	7
3	36	4	1	41	4.60	1.34	41.94	503	64	8
4	35	3	3	41	3.45	4.02	42.47	510	66	8
5	70	4	4	78	4.60	5.36	79.96	960	73	13
6	50	3	3	56	3.45	4.02	57.47	690	77	9
7	54	4	2	60	4.60	2.68	61.28	735	85	9
8	46	5	2	53	5.75	2.68	54.43	653	75	9
9	49	0	5	54	0	6.70	55.70	668	72	9
10	45	4	4	53	4.60	5.36	54.96	660	75	9
11	71	3	6	80	3.45	8.04	82.49	990	41	24
12	46	4	0	50	4.60	0	50.60	608	77	8

1, 2, 3...11 = column numbers, column 2 – 5 = volume by 5mins, column 6 - 8 = flow (pce/5mins), q = total flow (pce/h), u = speed (km/h), k = density (pce/km), PC = passenger car, MV = medium vehicle, HV = heavy vehicle

Table 5.19: Computed Flow and Density for *Dry Night* – SS04

Period	PC	MV	HV	vol	MV	HV	Q	q	u	k
1	*2*	*3*	*4*	*5*	*6*	*7*	*8*	*9*	*10*	*11*
					*3*1.15*	*4*1.34*	*2+6+7*	*8 *12*		*9/10*
1	72	10	3	85	11.5	4.02	87.52	1050	60	18
2	88	6	6	100	6.90	8.04	102.94	1235	68	18
3	69	6	4	79	6.90	5.36	81.26	975	82	12
4	36	4	0	40	4.60	0	40.60	488	98	5
5	58	7	2	67	8.05	2.68	68.73	825	85	10
6	65	1	9	75	1.15	12.06	78.21	938	90	10
7	79	7	5	91	8.05	6.70	93.75	1125	68	17
8	48	6	1	55	6.90	1.34	56.24	675	84	8
9	52	3	3	58	3.45	4.02	59.47	713	90	8
10	76	5	2	83	5.75	2.68	84.43	1013	72	14
11	41	4	1	46	4.60	1.34	46.94	563	79	7
12	58	9	5	72	10.35	6.70	75.05	901	79	11

1, 2, 3...11 = column numbers, column 2 – 5 = volume by 5mins, column 6 - 8 = flow (pce/5mins), q = total flow (pce/h), u = speed (km/h), k = density (pce/km), PC = passenger car, MV = medium vehicle, HV = heavy vehicle

Step 2: Using the flow and density values in Tables 5.16 - 5.19, the flow-density model for each site was determined accordingly. The models are presented as following:

SS01	$q_{DN} = -2.5854k^2 + 119.84k - 142.27$	$R^2 = 0.9643$	5.12
SS02	$q_{DN} = -1.8619k^2 + 99.252k - 22.681$	$R^2 = 0.9242$	5.13
SS03	$q_{DN} = -2.8017k^2 + 110.96k - 98.442$	$R^2 = 0.8344$	5.14
SS04	$q_{DN} = -2.8009k^2 + 117.80k - 60.601$	$R^2 = 0.9469$	5.15

All the model coefficients have expected sign conventions with coefficients of determination (R^2) greater than 0.5, therefore, suggesting that the models could be used for capacity prediction. The R^2 ranges between 0.8344 and 0.9643 signifying that a strong relationship exists between flow and density. Both the t-test and F-test for all the models are satisfactory and significant. All the statistical values were taken from the Microsoft Excel worksheet. The coefficients of "k" in the models represent the free-flow speeds under the prevailing condition and they are used in analysing the travel time.

Step 3: Using the US-BPR formula, travel time of each site was obtained based on their individual free-flow speed in the flow-density model obtained in step 2. Thereafter, the roadway functional service quality was determined accordingly from their corresponding functional service quality criteria table as earlier determined in section 5.3.

At SS01

Free flow speed is, $u_f = 119.84km/h$,

Its equivalent free flow time, $t_{uf} = 60/119.84 = 0.50min$

Where $\frac{v}{q} < 0.9$, $\beta = 10$ and $\rho = 0.2$,

Computed travel time is, $T_{DN} = \frac{60}{119.84}[1 + 0.2(0.9)^{10}]$

$$T_{DN} = 0.54min$$

From Table 5.4, travel time of 0.54min has a functional service quality B.

At SS02

Free flow speed is, $u_f = 99.25km/h$,

Its equivalent free flow time, $t_{uf} = 60/99.25 = 0.61min$

Where $\frac{v}{q} < 0.9$, $\beta = 10$ and $\rho = 0.2$, Computed travel time is, $T_{DN} = \frac{60}{99.25}[1 + 0.2(0.9)^{10}]$

$$T_{DN} = 0.65min$$

From Table 5.6, travel time of 0.65min has a functional service quality C.

At SS03

Free flow speed is, $u_f = 110.96km/h$,

Its equivalent free flow time, $t_{uf} = 60/110.96 = 0.54min$

Where $\frac{v}{q} < 0.9$, $\beta = 10$ and $\rho = 0.2$,

Computed travel time is, $T_{DN} = \frac{60}{110.96}[1 + 0.2(0.9)^{10}]$

$$T_{DN} = 0.58min$$

From Table 5.8, travel time of 0.58min has a functional service quality B

At SS04

Free flow speed is, $u_f = 117.8km/h$,

Its equivalent free flow time, $t_{uf} = 60/117.8 = 0.51min$

Where $\frac{v}{q} < 0.9$, $\beta = 10$ and $\rho = 0.2$,

Computed travel time is, $T_{DN} = \frac{60}{117.8}[1 + 0.2(0.9)^{10}]$

$$T_{DN} = 0.55min$$

From Table 5.10, travel time of 0.55min has a functional service quality B.

The dry night analysis of the four study sites is summarised and presented in Table 5.20.

Table 5.20: Summary of Travel Time and FSQ Assessment of Dry Night-Time Conditions

SS	Model	u_f (km/h)	t_f (min)	$\rho\left(\frac{v}{q}\right)^\beta$	1 + col 5	T (min)	FSQ
1	*2*	*3*	*4*	*5*	*6*	*7*	*8*
01	$-2.5854k^2 + 119.84k - 142.27$	119.8	0.50	0.07	1.07	0.54	B
02	$-1.8619k^2 + 99.252k - 22.681$	99.3	0.61	0.07	1.07	0.65	C
03	$-2.8017k^2 + 110.96k - 98.442$	110.9	0.54	0.07	1.07	0.58	B
04	$-2.8009k^2 + 117.80k - 60.601$	117.8	0.51	0.07	1.07	0.55	B

*SS = study site, u_f = free-flow speed, t_f = travel time at u_f, T = travel time, ρ = ratio of free-flow to speed at capacity, β = abrupt drop of curve from free-flow speed, v/q = volume-capacity ratio, col 4 = 60/col 3, col 7 = col 4 * col 6*

According to Table 5.20, the functional service quality under dry night-time conditions at the sites is class B except SS02 that has FSQ of class C. The functional service quality under dry night-time conditions is different from the functional service quality of dry daylight conditions, bearing in mind that the two conditions are at off-peak periods. The change is significant enough to state that night-time has an influence on traffic performance of dark roadways. Furthermore, for comparison purposes, the dry daylight (off-peak) condition is compared with the dry night-time condition graphically in Figures 5.6 - 5.9 using the flow-density relationship of each site as shown in the Excel spreadsheet.

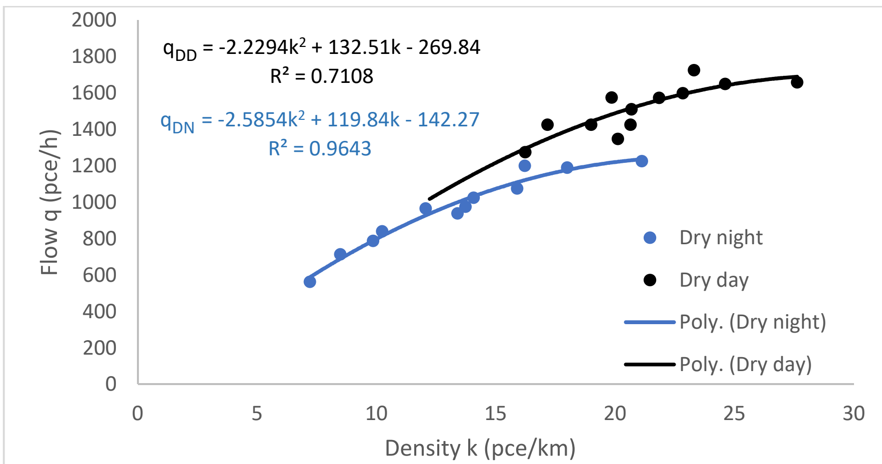


Figure 5.6: Flow-density graph of dry daylight and dry night at SS01

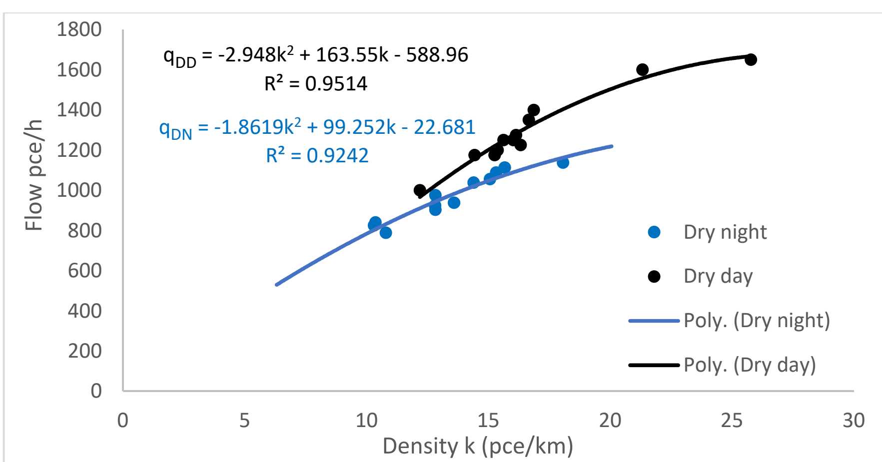


Figure 5.7: Flow-density graph of dry daylight and dry night at SS02

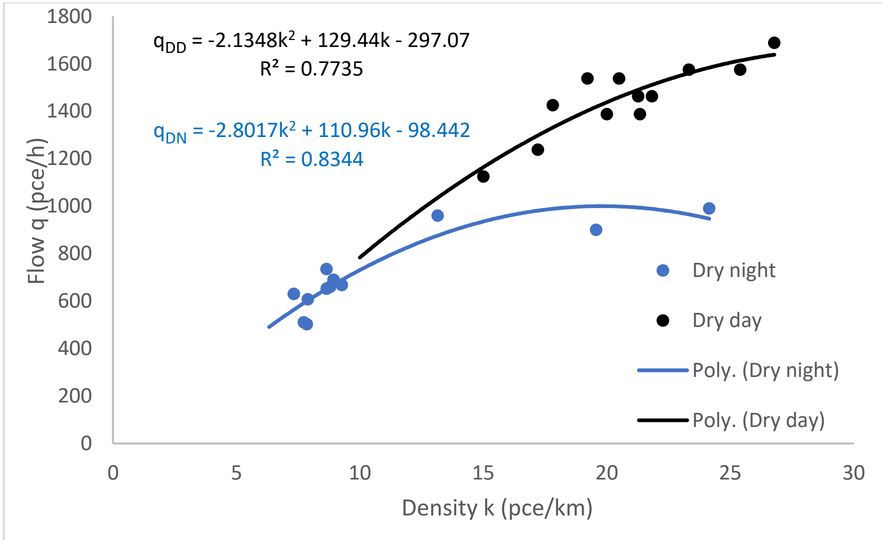


Figure 5.8: Flow-density plot of dry daylight and dry night of SS03

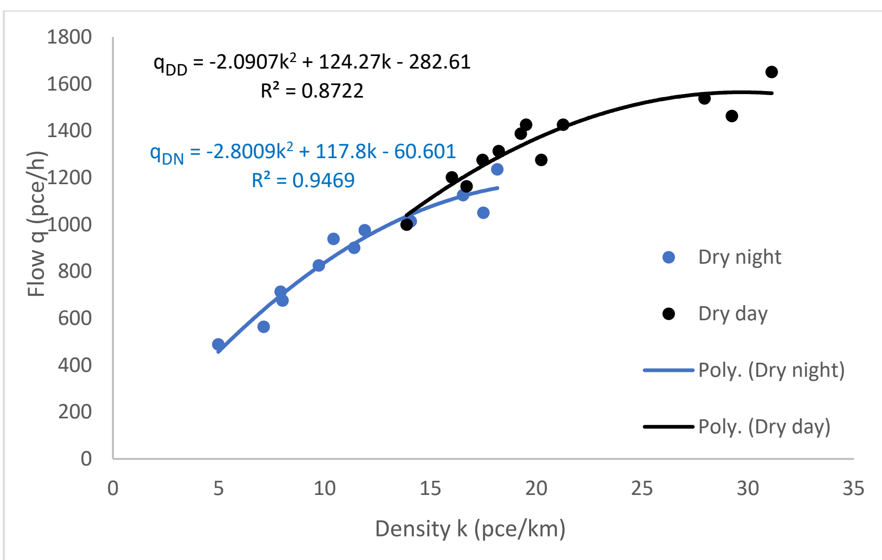


Figure 5.9: Flow-density plot dry daylight and dry night of SS04

For identification purposes, colour code notations are adopted for the graphs. The black colour represents dry daylight conditions while blue colour is for dry night-time conditions. Across the four graphs, there is a significant change in the position of the trendlines for the two different conditions. The dry night conditions shift downward and backward from the dry daylight conditions as shown on the graph for the four sites. Despite being an off-peak traffic period, the backward and downward shifts of the dry night-time conditions confirm that night as a climatic condition has an influence on traffic and roadway operations on dark roadways. As earlier opined, driving at night is challenging, the night-time influence is assumed to cause drivers to reduce their travel speed at night and more so on roadways without light. The reduction in speed results in an increase in time spent on the roadway.

This influence is translated into the travel speeds as portrayed in the model equations and travel time results. With the change in travel time, the functional service quality of the roadway also under dry daylight conditions changed from class A to class B for SS01, SS03 and SS04 and class C for SS02 under dry night conditions. However, as this study is focussed on night-time rain, it is necessary to investigate the influence of night-time rain on the functional service quality of the dark roadways. The investigation is presented in section 5.6.

5.6 Impact of Night Rainfall on Dark Roadways Functional Service Quality

In this section, the impact of night rain on functional service quality on dark roadways is investigated and presented. The rain intensities considered in this study are light, moderate and heavy based on the World Meteorological Organisation system. The empirical traffic data assessment of the surveyed roadways under light, moderate and heavy night rain conditions are presented and analysed for SS01 - SS04. However, it is to be noted that the stepwise analysis adopted in section 5.5 is applicable in this section. The analysis is presented such that light rainy night conditions for all the sites were first analysed, followed by the moderate night rain and lastly, heavy night rain.

5.6.1 Light Rainy Night-Time Conditions

Step 1: Analysis of empirical data for each site using Tables 5.21 - 5.24

Table 5.21: Computed Flow and Density for *Light Night Rain* – SS01

Period	PC	MV	HV	vol	MV	HV	q	q	u	k
1	*2*	*3*	*4*	*5*	*6*	*7*	*8*	*9*	*10*	*11*
					*3*1.15*	*4*1.34*	*2+6+7*	*8 *12*		*9/10*
1	69	6	4	79	6.9	5.36	81.26	975	49	20
2	81	6	9	96	6.9	12.06	99.96	1200	45	27
3	59	5	3	67	5.75	4.02	68.77	825	65	13
4	86	8	6	100	9.2	8.04	103.24	1238	68	18
5	75	5	5	85	5.75	6.7	87.45	1050	73	14
6	62	4	4	70	4.6	5.36	71.96	863	62	14
7	72	5	5	82	5.75	6.7	84.45	1013	70	14
8	45	2	2	49	2.3	2.68	49.98	600	62	10
9	70	5	5	80	5.75	6.7	82.45	990	57	17
10	37	2	2	41	2.3	2.68	41.98	503	69	7
11	76	6	5	87	6.9	6.7	89.6	1075	60	18
12	85	7	6	98	8.05	8.04	101.09	1213	49	25

1, 2, 3...11 = column numbers, column 2 – 5 = volume by 5mins, column 6 - 8 = flow (pce/5mins), q = total flow (pce/h), u = speed (km/h), k = density (pce/km), PC = passenger car, MV = medium vehicle, HV = heavy vehicle

Table 5.22: Computed Flow and Density for *Light Night Rain* – SS02

Period	PC	MV	HV	vol	MV	HV	q	q	u	k
1	*2*	*3*	*4*	*5*	*6*	*7*	*8*	*9*	*10*	*11*
					*3*1.15*	*4*1.34*	*2+6+7*	*8 *12*		*9/10*
1	88	10	5	103	11.5	6.70	106.20	1275	62	21
2	59	5	3	67	5.75	4.02	68.77	825	66	13
3	58	4	3	65	4.60	4.02	66.62	800	57	14
4	54	2	0	56	2.30	0	56.30	675	74	9
5	88	2	5	95	2.30	6.70	97.00	1163	51	23
6	70	2	2	74	2.30	2.68	74.98	900	56	16
7	54	9	1	64	10.35	1.34	65.69	788	53	15
8	68	3	5	76	3.45	6.70	78.15	938	75	13
9	77	4	6	87	4.60	8.04	89.64	1075	55	20
10	83	7	2	92	8.05	2.68	93.73	1125	62	18
11	74	4	2	80	4.60	2.68	81.28	975	43	23
12	43	2	2	47	2.30	2.68	47.98	575	70	8

1, 2, 3...11 = column numbers, column 2 – 5 = volume by 5mins, column 6 - 8 = flow (pce/5mins), q = total flow (pce/h), u = speed (km/h), k = density (pce/km), PC = passenger car, MV = medium vehicle, HV = heavy vehicle

Table 5.23: Computed Flow and Density for *Light Night Rain* – SS03

Period	PC	MV	HV	vol	MV	HV	q	q	u	k
1	*2*	*3*	*4*	*5*	*6*	*7*	*8*	*9*	*10*	*11*
					*3*1.15*	*4*1.34*	*2+6+7*	*8 *12*		*9/10*
1	24	4	2	30	4.6	2.68	31.28	375	73	5
2	28	1	3	32	1.15	4.02	33.17	398	73	5
3	35	3	3	41	3.45	4.02	42.47	510	70	7
4	65	5	4	74	5.75	5.36	76.11	913	58	16
5	38	3	4	45	3.45	5.36	46.81	563	82	7
6	37	3	2	42	3.45	2.68	43.13	518	70	7
7	30	7	0	37	8.05	0	38.05	458	75	6
8	34	6	4	44	6.90	5.36	46.26	555	65	9
9	52	1	7	60	1.15	9.38	62.53	750	64	12
10	33	2	4	39	2.30	5.36	40.66	488	75	7
11	49	4	2	55	4.60	2.68	56.28	675	75	9
12	40	2	2	44	2.30	2.68	44.98	540	78	7

1, 2, 3...11 = column numbers, column 2 – 5 = volume by 5mins, column 6 - 8 = flow (pce/5mins), q = total flow (pce/h), u = speed (km/h), k = density (pce/km), PC = passenger car, MV = medium vehicle, HV = heavy vehicle

Table 5.24: Computed Flow and Density for *Light Night Rain* – SS04

Period	PC	MV	HV	vol	MV	HV	q	q	u	k
1	*2*	*3*	*4*	*5*	*6*	*7*	*8*	*9*	*10*	*11*
					*3*1.15*	*4*1.34*	*2+6+7*	*8 *12*		*9/10*
1	78	9	4	91	10.35	5.36	93.71	1125	69	16
2	78	4	6	88	4.60	8.04	90.64	1088	75	15
3	77	1	7	85	1.15	9.38	87.53	1050	66	16
4	52	3	3	58	3.45	4.02	59.47	713	78	9
5	72	5	5	82	5.75	6.70	84.45	1013	71	14
6	86	6	3	95	6.90	4.02	96.92	1163	60	19
7	62	4	4	70	4.60	5.36	71.96	863	62	14
8	77	8	1	86	9.20	1.34	87.54	1050	62	17
9	65	4	4	73	4.60	5.36	74.96	900	67	13
10	69	6	4	79	6.90	5.36	81.26	975	55	18
11	58	0	1	59	0	1.34	59.34	713	79	9
12	69	8	0	77	9.2	0	78.20	938	72	13

1, 2, 3...11 = column numbers, column 2 – 5 = volume by 5mins, column 6 - 8 = flow (pce/5mins), q = total flow (pce/h), u = speed (km/h), k = density (pce/km), PC = passenger car, MV = medium vehicle, HV = heavy vehicle

Step 2: Using the flow and density values in Tables 5.21 - 5.24, the flow-density model for each site was determined accordingly. The models are presented as follows:

SS01	$q_{LR} = -2.2599k^2 + 113.22k - 222.38$	$R^2 = 0.8675$	5.16
SS02	$q_{LR} = -1.5753k^2 + 86.049k - 9.2806$	$R^2 = 0.7644$	5.17
SS03	$q_{LR} = -2.0415k^2 + 91.419k - 25.297$	$R^2 = 0.9595$	5.18
SS04	$q_{LR} = -2.4354k^2 + 109.06k - 80.767$	$R^2 = 0.8119$	5.19

The model coefficients have the expected sign convention with coefficients of determination (R^2) greater than 0.5. The R^2 values between 0.7644 and 0.9595 signified that a strong relationship exist between flow and density, and that the models are suitable for prediction. Other statistical test results such as F-observed values and t-observed values as taken directly from the Microsoft Excel worksheet signified that the relationship did not occur by chance and that when estimating flow, density is an important variable. The coefficients of "k" represent the free-flow speeds under light rainy night-time conditions and were used in travel time analysis in the next step.

Step 3: Using the US-BPR formula, travel time of each site was obtained based on their individual free-flow speed according to models obtained in step 2. Thereafter, the functional service quality was determined from their corresponding functional service quality criteria table as earlier determined in section 5.3

At SS01

Free flow speed is, $u_f = 113.2km/h$,

Its equivalent free flow time, $t_{uf} = 60/113.2 = 0.53min$

Where $\frac{v}{q} < 0.9$, $\beta = 10$ and $\rho = 0.2$,

Computed travel time is, $T_{LR} = \frac{60}{113.2}[1 + 0.2(0.9)^{10}]$

$$T_{LR} = 0.57min$$

From Table 5.4, travel time of 0.57min has a functional service quality B.

At SS02

Free flow speed is, $u_f = 86.05km/h$,

Its equivalent free flow time, $t_{uf} = 60/86.05 = 0.70min$

Where $\frac{v}{q} < 0.9$, $\beta = 10$ and $\rho = 0.2$, Computed travel time is, $T_{LR} = \frac{60}{86.05}[1 + 0.2(0.9)^{10}]$

$$T_{LR} = 0.75min$$

From Table 5.6, travel time of 0.75min has a functional service quality D

At SS03

Free flow speed is, $u_f = 91.4km/h$,

Its equivalent free flow time, $t_{uf} = 60/91.4 = 0.66min$

Where $\frac{v}{q} < 0.9$, $\beta = 10$ and $\rho = 0.2$,

Computed travel time is, $T_{LR} = \frac{60}{91.4}[1 + 0.2(0.9)^{10}]$

$$T_{LR} = 0.70min$$

From Table 5.8, travel time of 0.70min has a functional service quality C.

At SS04

Free flow speed is, $u_f = 109.1km/h$,

Its equivalent free flow time, $t_{uf} = 60/109.1 = 0.55min$

Where $\frac{v}{q} < 0.9$, $\beta = 10$ and $\rho = 0.2$,

Computed travel time is, $T_{LR} = \frac{60}{109.1}[1 + 0.2(0.9)^{10}]$

$$T_{LR} = 0.59min$$

From Table 5.10, travel time of 0.59min has a functional service quality B.

Analysis of the light rainy night-time condition of the four study sites is summarised and presented in Table 5.25

Table 5.25: Summary of Travel Time and FSQ for Light Rainy Night-Time Conditions

SS	Model	u_f (km/h)	t_f (min)	$\rho\left(\frac{v}{q}\right)^{\beta}$	1 + col 5	T (min)	FSQ
1	*2*	*3*	*4*	*5*	*6*	*7*	*8*
01	$-2.2599k^2 + 113.22k - 222.38$	113.2	0.53	0.07	1.07	0.57	B
02	$-1.5753k^2 + 86.049k - 9.2806$	86.1	0.70	0.07	1.07	0.75	D
03	$-2.0415k^2 + 91.419k - 25.297$	91.4	0.66	0.07	1.07	0.70	C
04	$-2.4354k^2 + 109.06k - 80.767$	109.1	0.55	0.07	1.07	0.59	B

*SS = study site, u_f = free-flow speed, t_f = travel time at u_f, T = travel time, ρ = ratio of free-flow to speed at capacity, β = abrupt drop of curve from free-flow speed, v/q = volume-capacity ratio, col 4 = 60/col 3, col 7 = col 4 * col 6*

According to Table 5.25, the functional service quality at SS01 and SS04 is class B though their travel time and travel speed are different, while at SS02, the functional service quality is class D and level C at SS03 under light rainy night-time conditions. Based on the difference in functional service quality across the four study sites, it is correct to say each roadway operation is a function of its traffic composition despite operating under the same weather conditions of light night-time rain. The moderate night-time rain is considered in the next section.

5.6.2 Moderate Rainy Night-time Conditions

Step 1: Analysis of empirical data for each site using Tables 5.26 - 5.29

Table 5.26: Computed Flow and Density for *Moderate Night Rain* – SS01

Period	PC	MV	HV	vol	MV	HV	q	q	u	K
1	*2*	*3*	*4*	*5*	*6*	*7*	*8*	*9*	*10*	*11*
					*3*1.15*	*4*1.34*	*2+6+7*	*8 *12*		*9/10*
1	44	8	7	59	9.20	9.38	62.58	750	59	13
2	48	1	3	52	1.15	4.02	53.17	638	68	9
3	91	9	6	106	10.35	8.04	109.39	1313	57	19
4	97	6	8	111	6.90	10.72	114.62	1375	67	16
5	72	4	5	81	4.60	6.70	83.3	1000	43	23
6	40	6	7	53	6.90	9.38	56.28	675	70	10
7	22	3	2	27	3.45	2.68	28.13	338	71	5
8	63	5	7	75	5.75	9.38	78.13	938	72	14
9	63	4	4	71	4.60	5.36	72.96	875	77	12
10	47	7	4	58	8.05	5.36	60.41	725	59	12
11	95	7	7	109	8.05	9.38	112.43	1350	51	26
12	62	8	6	76	9.20	8.04	79.24	950	41	23

1, 2, 3...11 = column numbers, column 2 – 5 = volume by 5mins, column 6 - 8 = flow (pce/5mins), q = total flow (pce/h), u = speed (km/h), k = density (pce/km), PC = passenger car, MV = medium vehicle, HV = heavy vehicle

Table 5.27: Computed Flow and Density for *Moderate Night Rain* – SS02

Period	PC	MV	HV	vol	MV	HV	q	q	u	K
1	*2*	*3*	*4*	*5*	*6*	*7*	*8*	*9*	*10*	*11*
					*3*1.15*	*4*1.34*	*2+6+7*	*8 *12*		*9/10*
1	49	7	4	60	8.05	5.36	62.41	750	66	11
2	39	3	1	43	3.45	1.34	43.79	525	67	8
3	71	6	5	82	6.90	6.70	84.60	1015	61	17
4	71	3	2	76	3.45	2.68	77.13	925	66	14
5	60	3	4	67	3.45	5.36	68.81	825	57	14
6	80	7	3	90	8.05	4.02	92.07	1105	43	26
7	59	4	0	63	4.60	0	63.60	763	55	14
8	57	0	0	57	0	0	57.00	683	52	13
9	78	4	6	88	4.60	8.04	90.64	1088	51	21
10	69	3	5	77	3.45	6.70	79.15	950	61	16
11	62	1	5	68	1.15	6.70	69.85	838	54	16
12	56	6	2	64	6.90	2.68	65.58	788	53	15

1, 2, 3...11 = column numbers, column 2 – 5 = volume by 5mins, column 6 - 8 = flow (pce/5mins), q = total flow (pce/h), u = speed (km/h), k = density (pce/km), PC = passenger car, MV = medium, vehicle, HV = heavy vehicle

Table 5.28: Computed Flow and Density for *Moderate Night Rain* – SS03

Period	PC	MV	HV	vol	MV	HV	q	q	u	K
1	*2*	*3*	*4*	*5*	*6*	*7*	*8*	*9*	*10*	*11*
					*3*1.15*	*4*1.34*	*2+6+7*	*8 *12*		*9/10*
1	34	2	4	40	2.30	5.36	41.66	500	69	7
2	41	4	1	46	4.60	1.34	46.94	563	57	10
3	38	5	0	43	5.75	0	43.75	525	59	9
4	41	2	5	48	2.30	6.7	50	600	59	10
5	53	2	3	58	2.30	4.02	59.32	713	62	12
6	41	4	1	46	4.60	1.34	46.94	563	66	9
7	32	0	1	33	0	1.34	33.34	400	72	6
8	49	4	2	55	4.60	2.68	56.28	675	68	10
9	28	0	1	29	0	1.34	29.34	352	69	5
10	30	3	3	36	3.45	4.02	37.47	450	70	6
11	70	2	2	74	2.30	2.68	74.98	900	70	13
12	57	6	7	70	6.90	9.38	73.28	879	51	17

1, 2, 3...11 = column numbers, column 2 – 5 = volume by 5mins, column 6 - 8 = flow (pce/5mins), q = total flow (pce/h), u = speed (km/h), k = density (pce/km), PC = passenger car, MV = medium vehicle, HV = heavy vehicle

Table 5.29: Computed Flow and Density for *Moderate Night Rain* – SS04

Period	PC	MV	HV	vol	MV	HV	q	q	u	k
1	*2*	*3*	*4*	*5*	*6*	*7*	*8*	*9*	*10*	*11*
					*3*1.15*	*4*1.34*	*2+6+7*	*8 *12*		*9/10*
1	75	9	4	88	10.35	5.36	90.71	1088	62	18
2	68	9	3	80	10.35	4.02	82.37	988	43	23
3	70	2	2	74	2.30	2.68	74.98	900	70	13
4	72	3	2	77	3.45	2.68	78.13	938	55	17
5	52	1	7	60	1.15	9.38	62.53	750	60	13
6	77	6	3	86	6.90	4.02	87.92	1055	46	23
7	60	1	1	62	1.15	1.34	62.49	750	66	11
8	59	5	3	67	5.75	4.02	68.77	825	67	12
9	39	3	1	43	3.45	1.34	43.79	525	68	8
10	42	2	2	46	2.30	2.68	46.98	563	70	8
11	45	2	2	49	2.30	2.68	49.98	600	69	9
12	98	8	4	110	9.20	5.36	112.56	1350	60	23

1, 2, 3…11 = column numbers, column 2 – 5 = volume by 5mins, column 6 - 8 = flow (pce/5mins), q = total flow (pce/h), u = speed (km/h), k = density (pce/km), PC = passenger car, MV = medium vehicle, HV = heavy vehicle

Step 2: Using the flow and density values in Tables 5.26 - 5.29, the flow-density model for each site was determined accordingly. The models are as follows:

SS01 $q_{MR} = -1.6450k^2 + 92.589k - 66.269$ $R^2 = 0.8020$ 5.20

SS02 $q_{MR} = -1.4586k^2 + 83.446k - 55.411$ $R^2 = 0.8500$ 5.21

SS03 $q_{MR} = -1.8819k^2 + 88.476k - 54.061$ $R^2 = 0.9607$ 5.22

SS04 $q_{MR} = -2.1757k^2 + 106.07k - 162.36$ $R^2 = 0.8545$ 5.23

The model coefficients have the expected sign convention with coefficients of determination (R^2) greater than 0.5. The R^2 values between 0.8020 and 0.9607 signify that a strong relationship exists between flow and density, and that the models are suitable for prediction. Other statistical test results such as F-observed values and t-observed values as taken directly from the Excel worksheet signify that the relationship did not occur by chance and that when estimating flow, density is an important variable. The coefficients of "k" represent the free-flow speeds under moderate rainy night-time conditions and were used in the travel time analysis in the next step.

Step 3: Using the US-BPR formula, travel time of each site was obtained based on their individual free-flow speed in the flow-density models obtained in step 2. Thereafter, the functional service quality was determined from their corresponding functional service quality criteria table as earlier determined in section 5.3

At SS01

Free flow speed is, $u_f = 92.6km/h$,

Its equivalent free flow time, $t_{uf} = 60/92.6 = 0.65min$

Where $\frac{v}{q} < 0.9$, $\beta = 10$ and $\rho = 0.2$,

Computed travel time is, $T_{MR} = \frac{60}{92.6}[1 + 0.2(0.9)^{10}]$

$$T_{MR} = 0.69min$$

From Table 5.4, travel time of 0.69min has a functional service quality C.

At SS02

Free flow speed is, $u_f = 83.5km/h$,

Its equivalent free flow time, $t_{uf} = 60/83.5 = 0.72min$

Where $\frac{v}{q} < 0.9$, $\beta = 10$ and $\rho = 0.2$,

Computed travel time is, $T_{MR} = \frac{60}{83.5}[1 + 0.2(0.9)^{10}]$

$$T_{MR} = 0.77min$$

From Table 5.6, travel time of 0.77min has a functional service quality D.

At SS03

Free flow speed is, $u_f = 88.5km/h$,

Its equivalent free flow time, $t_{uf} = 60/88.5 = 0.68min$

Where $\frac{v}{q} < 0.9$, $\beta = 10$ and $\rho = 0.2$,

Computed travel time is, $T_{MR} = \frac{60}{88.5}[1 + 0.2(0.9)^{10}]$

$$T_{MR} = 0.73min$$

From Table 5.8, travel time of 0.73min has a functional service quality C.

At SS04

Free flow speed is, $u_f = 106.1km/h$,

Its equivalent free flow time, $t_{uf} = 60/106.1 = 0.57min$

Where $\frac{v}{q} < 0.9$, $\beta = 10$ and $\rho = 0.2$,

Computed travel time is, $T_{MR} = \frac{60}{106.1}[1 + 0.2(0.9)^{10}]$

$$T_{MR} = 0.61min$$

From Table 5.10, travel time of 0.61min has a functional service quality B.

The analysis and assessment of the moderate rainy night-time conditions of the four study sites is summarised and presented in Table 5.30.

Table 5.30: Summary of Travel Time and FSQ for Moderate Rainy Night-Time Conditions

SS	Model	u_f (km/h)	t_f (min)	$\rho\left(\frac{v}{q}\right)^{\beta}$	1 + col 5	T (min)	FSQ
1	*2*	*3*	*4*	*5*	*6*	*7*	*8*
01	$-1.6450k^2 + 92.589k - 66.269$	92.6	0.65	0.07	1.07	0.69	C
02	$-1.4586k^2 + 83.446k - 55.411$	83.5	0.72	0.07	1.07	0.77	D
03	$-1.8819k^2 + 88.476k - 54.061$	88.5	0.68	0.07	1.07	0.73	C
04	$-2.1757k^2 + 106.07k - 162.36$	106.1	0.57	0.07	1.07	0.61	B

*SS = study site, u_f = free-flow speed, t_f = travel time at u_f, T = travel time, ρ = ratio of free-flow to speed at capacity, β = abrupt drop of curve from free-flow speed, v/q = volume-capacity ratio, col 4 = 60/col 3, col 7 = col 4 * col 6*

The FSQ at SS01 and SS03 according to Table 5.30 is class C, while at SS02 and SS04, their respective FSQ is D and B under moderate rain conditions. The influence of moderate night-time rain is significantly more at SS02 while SS04 has the least impact. However, at SS01 and SS03 with the same FSQ, it was observed that their travel time and travel speed values are not the same. This aligns with the opinion that the response of traffic on roadways depends on its composition and operation in order to cause a significant change in the functional service delivery expected of a roadway.

5.6.3 Heavy Rainy Night-Time Conditions

Step 1: Analysis of empirical data for each site using Tables 5.31 - 5.34

Table 5.31: Computed Flow and Density for *Heavy Night Rain* – SS01

Period	PC	MV	HV	vol	MV	HV	q	q	u	K
1	*2*	*3*	*4*	*5*	*6*	*7*	*8*	*9*	*10*	*11*
					*3*1.15*	*4*1.34*	*2+6+7*	*8 *12*		*9/10*
1	20	4	5	29	4.60	6.70	31.30	375	66	6
2	71	3	5	79	3.45	6.70	81.15	975	55	18
3	68	2	2	72	2.30	2.68	72.98	875	51	17
4	55	3	3	61	3.45	4.02	62.47	750	40	19
5	66	2	5	73	2.30	6.70	75.00	900	43	21
6	40	1	2	43	1.15	2.68	43.83	525	56	9
7	61	2	1	64	2.30	1.34	64.64	775	59	13
8	47	3	2	52	3.45	2.68	53.13	638	51	13
9	87	3	4	94	3.45	5.36	95.81	1150	57	20
10	81	4	3	88	4.60	4.02	89.62	1075	39	28
11	74	3	6	83	3.45	8.04	85.49	1026	59	17
12	68	2	2	72	2.30	2.68	72.98	876	56	16

1, 2, 3.,.11 = column numbers, column 2 – 5 = volume by 5mins, column 6 - 8 = flow (pce/5mins), q = total flow (pce/h), u = speed (km/h), k = density (pce/km), PC = passenger car, MV = medium vehicle, HV = heavy vehicle

Table 5.32: Computed Flow and Density for *Heavy Night Rain* – SS02

Period	PC	MV	HV	vol	MV	HV	q	q	u	k
1	*2*	*3*	*4*	*5*	*6*	*7*	*8*	*9*	*10*	*11*
					*3*1.15*	*4*1.34*	*2+6+7*	*8 *12*		*9/10*
1	59	5	3	67	5.75	4.02	68.77	825	45	18
2	65	6	7	78	6.90	9.38	81.28	975	48	20
3	48	1	3	52	1.15	4.02	53.17	638	55	12
4	41	4	1	46	4.60	1.34	46.94	563	59	10
5	71	4	7	82	4.60	9.38	84.98	1020	55	19
6	65	8	3	76	9.20	4.02	78.22	938	55	17
7	73	3	2	78	3.45	2.68	79.13	950	53	18
8	64	3	1	68	3.45	1.34	68.79	825	54	15
9	55	1	4	60	1.15	5.36	61.51	738	50	15
10	55	3	3	61	3.45	4.02	62.47	750	55	14
11	75	3	4	82	3.45	5.36	83.81	1005	52	19
12	77	5	2	84	5.75	2.68	85.43	1025	46	22

1, 2, 3...11 = column numbers, column 2 – 5 = volume by 5mins, column 6 - 8 = flow (pce/5mins), q = total flow (pce/h), u = speed (km/h), k = density (pce/km), PC = passenger car, MV = medium vehicle, HV = heavy vehicle

Table 5.33: Computed Flow and Density for *Heavy Night Rain* – SS03

Period	PC	MV	HV	vol	MV	HV	q	q	u	k
1	*2*	*3*	*4*	*5*	*6*	*7*	*8*	*9*	*10*	*11*
					*3*1.15*	*4*1.34*	*2+6+7*	*8 *12*		*9/10*
1	59	3	3	65	3.45	4.02	66.47	798	45	18
2	64	5	7	76	5.75	9.38	79.13	950	41	23
3	55	3	3	61	3.45	4.02	62.47	750	51	15
4	47	5	5	57	5.75	6.70	59.48	713	55	13
5	68	5	1	74	5.75	1.34	75.09	901	52	17
6	56	1	4	61	1.15	5.36	62.51	750	58	13
7	48	6	1	55	6.90	1.34	56.24	675	65	10
8	30	3	3	36	3.45	4.02	37.47	450	65	7
9	29	0	4	33	0	5.36	34.36	412	65	6
10	36	2	4	42	2.30	5.36	43.66	524	56	9
11	51	3	1	55	3.45	1.34	55.79	670	65	12
12	41	2	5	48	2.30	6.70	50	600	55	11

1, 2, 3...11 = column numbers, column 2 – 5 = volume by 5mins, column 6 - 8 = flow (pce/5mins), q = total flow (pce/h), u = speed (km/h), k = density (pce/km), PC = passenger car, MV = medium vehicle, HV = heavy vehicle

Table 5.34: Computed Flow and Density for *Heavy Night Rain* – SS04

Period	PC	MV	HV	vol	MV	HV	q	q	u	k
1	*2*	*3*	*4*	*5*	*6*	*7*	*8*	*9*	*10*	*11*
					*3*1.15*	*4*1.34*	*2+6+7*	*8 *12*		*9/10*
1	34	5	3	42	5.75	4.02	43.77	525	50	11
2	40	6	0	46	6.90	0	46.9	563	55	10
3	28	0	5	33	0	6.70	34.7	415	65	6
4	60	3	4	67	3.45	5.36	68.81	825	62	13
5	20	4	5	29	4.60	6.70	31.3	375	68	6
6	43	2	5	50	2.30	6.70	52	625	48	13
7	25	6	2	33	6.90	2.68	34.58	415	65	6
8	29	2	0	31	2.30	0	31.3	375	69	5
9	69	6	4	79	6.90	5.36	81.26	975	58	17
10	26	0	4	30	0	5.36	31.36	375	54	7
11	73	8	4	85	9.20	5.36	87.56	1050	35	30
12	35	1	1	37	1.15	1.34	37.49	450	54	8

1, 2, 3...11 = column numbers, column 2 – 5 = volume by 5mins, column 6 - 8 = flow (pce/5mins), q = total flow (pce/h), u = speed (km/h), k = density (pce/km), PC = passenger car, MV = medium vehicle, HV = heavy vehicle

Step 2: Using the flow and density values in Tables 5.31 - 5.34, the flow-density model for each site was determined accordingly. The models are presented in equations 5.24 - 5.27

SS01	$q_{HR} = -1.4170k^2 + 80.664k - 68.973$	$R^2 = 0.8174$	5.24
SS02	$q_{HR} = -1.3475k^2 + 82.164k - 119.44$	$R^2 = 0.8953$	5.25
SS03	$q_{HR} = -1.5355k^2 + 76.252k - 4.7990$	$R^2 = 0.9257$	5.26
SS04	$q_{HR} = -1.2897k^2 + 75.660k - 41.761$	$R^2 = 0.9252$	5.27

All the model coefficients have expected sign conventions with coefficients of determination (R^2) greater than 0.5. This suggests that the models could be used for prediction. The R^2 values are between 0.8174 and 0.9257 signifying that a strong relationship exists between flow and density. Other statistical test results such as F-observed values and t-observed values, as taken directly from the Excel worksheet signify that the relationship did not occur by chance and that when estimating flow, density is an important variable. The coefficients of "k" represent the free-flow speeds under heavy rainy night-time conditions and were used in the travel time analysis in the next step

Step 3: Using the US-BPR formula, travel time of each site was obtained based on their individual free-flow speed according to the models obtained in step 2. Thereafter, the roadway functional service quality is determined from their corresponding functional service quality criteria table as earlier determined in section 5.3

At SS01

Free flow speed is, $u_f = 80.7km/h$,

Its equivalent free flow time, $t_{uf} = 60/80.7 = 0.74min$

Where $\frac{v}{q} < 0.9$, $\beta = 10$ and $\rho = 0.2$,

Computed travel time is, $$T_{HR} = \frac{60}{80.7}[1 + 0.2(0.9)^{10}]$$

$$T_{HR} = 0.80min$$

From Table 5.4, travel time of 0.80min has a functional service quality D.

At SS02

Free flow speed is, $u_f \ = \ 82.2km/h$,

Its equivalent free flow time, $t_{uf} = 60/82.2 \ = \ 0.73min$

Where $\frac{v}{q} < 0.9$, $\beta = 10$ and $\rho = 0.2$,

Computed travel time is, $T_{HR} = \frac{60}{82.2}[1 + 0.2(0.9)^{10}]$

$$T_{HR} = 0.78min$$

From Table 5.6, travel time of 0.78min has a functional service quality D.

At SS03

Free flow speed is, $u_f \ = \ 76.3km/h$,

Its equivalent free flow time, $t_{uf} = 60/76.3 \ = \ 0.79min$

Where $\frac{v}{q} < 0.9$, $\beta = 10$ and $\rho = 0.2$,

Computed travel time is, $T_{HR} = \frac{60}{76.3}[1 + 0.2(0.9)^{10}]$

$$T_{HR} = 0.84min$$

From Table 5.8, travel time of 0.84min has a functional service quality D.

At SS04

Free flow speed is, $u_f \ = \ 75.7km/h$,

Its equivalent free flow time, $t_{uf} = 60/75.7 \ = \ 0.79min$

Where $\frac{v}{q} < 0.9$, $\beta = 10$ and $\rho = 0.2$,

Computed travel time is, $T_{HR} = \frac{60}{75.7}[1 + 0.2(0.9)^{10}]$

$$T_{HR} = 0.85min$$

From Table 5.10, travel time of 0.85min has a functional service quality C.

Analysis of the heavy night rain conditions of the four study sites is summarised and presented in Table 5.35.

Table 5.35: Summary of Travel Time and FSQ for Heavy Rainy Night-Time Conditions

SS	Model	u_f (km/h)	t_f (min)	$\rho\left(\frac{v}{q}\right)^{\beta}$	1 + col 5	T (min)	FSQ
1	*2*	*3*	*4*	*5*	*6*	*7*	*8*
01	$-1.4170k^2 + 80.664k - 68.973$	80.7	0.74	0.07	1.07	0.80	D
02	$-1.3475k^2 + 82.164k - 119.44$	82.2	0.73	0.07	1.07	0.78	D
03	$-1.5355k^2 + 76.252k - 4.7990$	76.3	0.79	0.07	1.07	0.84	D
04	$-1.2897k^2 + 75.660k - 41.761$	75.7	0.79	0.07	1.07	0.85	C

*SS = study site, u_f = free-flow speed, t_f = travel time at u_f, T = travel time, ρ = ratio of free-flow to speed at capacity, β = abrupt drop of curve from free-flow speed, v/q = volume-capacity ratio, col 4 = 60/col 3, col 7 = col 4 * col 6*

From Table 5.35, the functional service quality at SS01, SS02 and SS03 is D and C at SS04. According to the results obtained for the heavy night-time rain conditions, it is evident that heavy rain intensity has a significant influence on roadway performance as to cause significant change in service quality. With the same functional service quality across SS01, SS02 and SS03, their travel time and travel speed values are different.

In light of the results obtained for rainy night-time conditions, there is a need to compare these with the dry night-time conditions. The comparison is presented graphically using the flow-speed relationship for all the sites. The graphs are taken from Microsoft Excel and presented in Figures 5.10 - 5.13. For ease of identification, colour code notations are adopted. The blue is for dry night condition while red, green and yellow represent light, moderate and heavy rain conditions respectively.

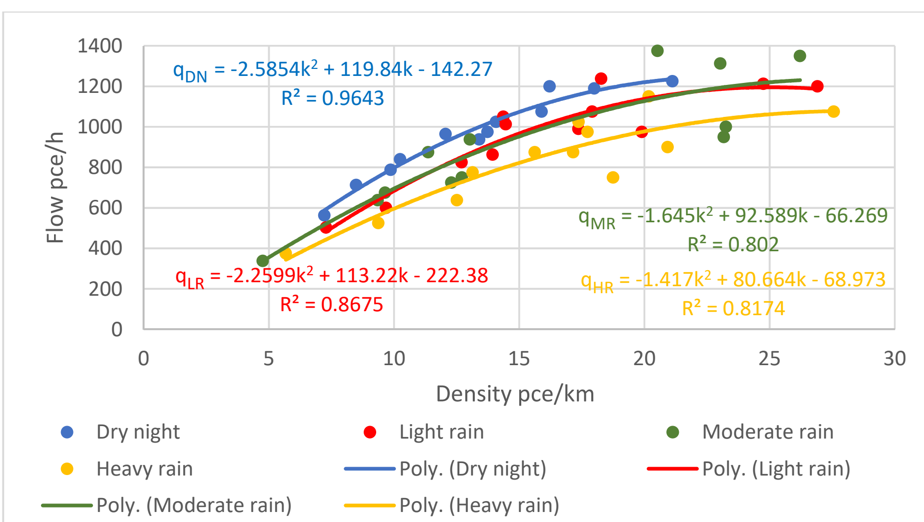


Figure 5.10: Flow-density graph of dry night and rainy night conditions at SS01

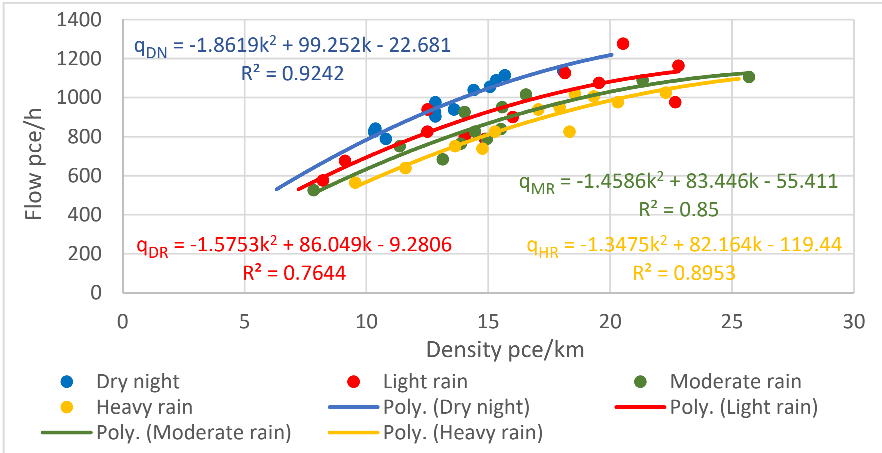


Figure 5.11: Flow-density graph of dry night and rainy night conditions at SS02

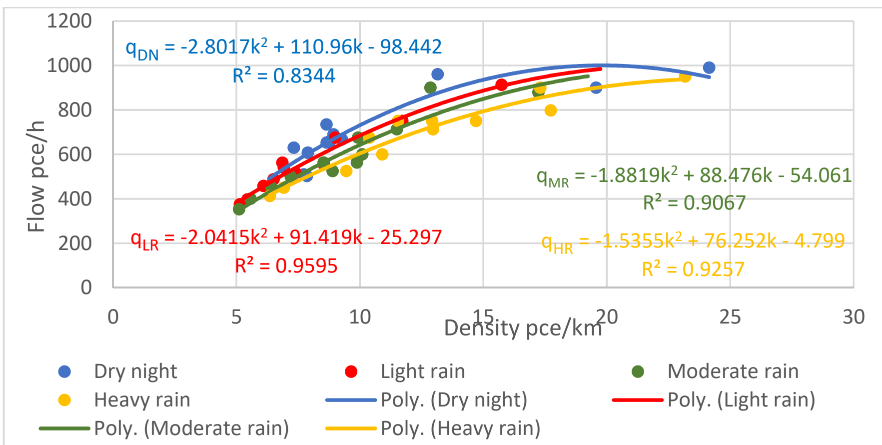


Figure 5.12: Flow-density plot of for dry night and rainy night conditions at SS03

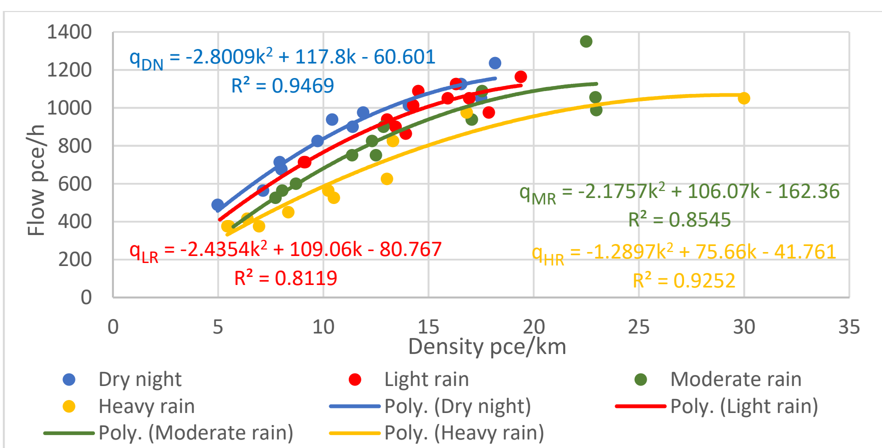


Figure 5.13: Flow-density plot of for dry night and rainy night conditions at SS04

From Figures 5.10 - 5.13, the graphs show that there is a downward shift from dry night condition (blue trendline) to rainy night-time conditions (red, green and yellow trendlines) irrespective of the rainfall intensity. The trio of red, green and yellow coloured trendlines are positioned beneath the blue trendline – this implies a change in flow-density parameters of traffic flow operation on the roadways under the influence of night rain. The change in traffic flow as shown in the flow-density relationship is evident in the variabilities in travel time and travel speed presented in Table 5.36

Table 5.36: Summary of Travel Time, Travel Speed and Their Variabilities

Site	WC	u_f (km/h)	Δu_f	Δu_f (%)	Δu_f	Δu_f (%)	T (min)	ΔT	ΔT (%)	ΔT	ΔT (%)
01	DD	132.5					0.48				
	D	116.8	15.7	11.8			0.55	-0.07	-14.6		
	LR	113.2			3.6	3.1	0.57			-0.02	-3.6
	MR	90.6			26.2	22.4	0.71			-0.16	-29.1
	HR	80.7			36.1	30.9	0.8			-0.25	-45.5
02	DD	163.6					0.39				
	D	99.3	64.3	39.3			0.64	-0.25	-64.1		
	LR	86.1			13.2	13.3	0.75			-0.11	-17.2
	MR	83.5			15.8	15.9	0.77			-0.13	-20.3
	HR	82.2			17.1	17.2	0.78			-0.14	-21.9
03	DD	129.4					0.50				
	D	110.9	18.5	14.3			0.58	-0.08	-16.0		
	LR	91.4			19.5	17.6	0.71			-0.13	-22.4
	MR	88.5			22.4	20.2	0.73			-0.15	-25.9
	HR	76.3			34.6	31.2	0.85			-0.27	-46.6
04	DD	124.3					0.51				
	D	117.8	6.5	5.2			0.55	-0.04	-7.8		
	LR	109.1			8.7	7.4	0.59			-0.04	-7.3
	MR	106.1			11.7	9.9	0.76			-0.21	-38.2
	HR	75.7			42.1	35.7	0.81			-0.26	-47.3

WC = weather condition, u_f = free flow speed, T = travel time, Δ = difference, % = percentage

From Table 5.36, there is evidence of travel time differential between dry daylight conditions and dry night-time conditions. At SS01, the travel time under dry daylight conditions increased from 0.48min to 0.55min (14.6% loss) while its travel speed reduced from 132.5km/h for dry daylight conditions to 112.5kmhr for dry night-time conditions. The change under dry scenarios for both travel time and travel speed were evident at all the study sites, though the changes vary randomly.

From the table, there is evidence of a variation in travel time irrespective of rainfall intensity across the four sites. At site 01, the finding shows travel loss of 3.1 percent under light rainy night-time conditions while for moderate and heavy rainy night-time conditions, the loss is 29.1 percent and 45.5 percent respectively. The travel speed however increased by 3.1 percent for light night rain, 22.4 percent for moderate night rain and 30.9 percent for heavy night rain. At site 02, the travel time loss is 17.2 percent, 20.3 percent and 21.9 percent for light, moderate and heavy night rain respectively, while the corresponding increase in travel speed variation is 13.3 percent, 15.9 percent and 17.2 percent for the light, moderate and heavy rainy night-time conditions respectively.

Travel time loss at SS03 is 22.4 percent in light rain, 25.9 percent in moderate rain and 46.6 percent in heavy rain with a corresponding increase in travel speed of 17.6 percent, 20.2 percent and 31.2 percent for light, moderate and heavy rain respectively. At SS04, travel time loss of 7.3 percent for light rain, 38.2 percent for moderate rain and 47.3 percent for heavy rain were recorded with a corresponding travel speed increase of 7.4 percent, 9.9 percent and 35.7 percent under light, moderate and heavy night rain conditions. Generally, the average travel time increase due to night rain is 27.1 percent while the average travel speed reduction is 18.7 percent. However, the change in both travel time and travel speed do not follow any trend, but their variation is aberrant irrespective of the rain intensity. The anomaly observed in the results of the travel speed and travel time may be attributed to differences in traffic composition and driver behaviour, and the difficulty in drawing a borderline between rainfall occurrences with respect to its intensity for classification purpose. Rainfall may start out as light, swift to heavy, moderate and revert to light within a short period without any pattern in the change.

Summarily, Table 5.37 shows the flow-density models, travel time, travel speed and functional service quality of the four study sites while Table 5.38 is the generalised summary of the FSQ across the four sites.

Table 5.37: Summary of Travel Time, Travel Speed and FSQ for All Sites

WC	SS	Model	T (min)	u_f (km/h)	FSQ
Dry Daylight	01	$-2.2294k^2 + 132.51k - 269.84$	0.48	132.5	A
	02	$-2.9480k^2 + 163.55k - 588.96$	0.39	163.6	A
	03	$-2.1348k^2 + 129.44k - 297.07$	0.49	129.4	A
	04	$-2.0907k^2 + 124.27k - 282.61$	0.51	124.3	A
Dry Night	01	$-2.5854k^2 + 119.84k - 142.27$	0.54	116.8	B
	02	$-1.8619k^2 + 99.252k - 22.681$	0.65	99.3	C
	03	$-2.8017k^2 + 110.96k - 98.442$	0.58	110.9	B
	04	$-2.8009k^2 + 117.80k - 60.601$	0.54	117.8	B
Light night rain	01	$-2.2599k^2 + 113.22k - 222.38$	0.57	113.2	B
	02	$-1.5753k^2 + 86.049k - 9.2806$	0.75	86.1	D
	03	$-2.0415k^2 + 91.419k - 25.297$	0.70	91.4	C
	04	$-2.4354k^2 + 109.06k - 80.767$	0.59	109.1	B
Moderate night rain	01	$-1.6450k^2 + 92.589k - 66.269$	0.69	92.6	C
	02	$-1.4586k^2 + 83.446k - 55.411$	0.77	83.5	D
	03	$-1.8819k^2 + 88.476k - 54.061$	0.73	88.5	C
	04	$-2.1757k^2 + 106.07k - 162.36$	0.61	106.1	B
Heavy night rain	01	$-1.4170k^2 + 80.664k - 68.973$	0.80	80.7	D
	02	$-1.3475k^2 + 82.164k - 119.44$	0.78	82.2	D
	03	$-1.5355k^2 + 76.252k - 4.7990$	0.84	76.3	D
	04	$-1.2897k^2 + 75.660k - 41.761$	0.85	75.7	C

WC = weather condition, SS = study site, T = travel time, u_f = free-flow speed, FSQ = service quality

Table 5.38: Summary of Functional Service Quality Assessment by Study Sites

Weather Condition	SS01	SS02	SS03	SS04
Dry daylight	A	A	A	A
Dry night	B	C	B	B
Light night rain	B	D	C	B
Moderate night rain	C	D	C	B
Heavy night rain	D	D	D	C

As shown in Tables 5.37 and 5.38, the FSQ of the roadways varies under different conditions due to the variabilities in travel time and travel speed. The increase in travel time with a consequent reduction in travel speed leads to a deterioration in the roadway functional service quality. Under dry daylight conditions, the functional service quality across the four sites is class A while for dry night-time conditions, the functional service quality deteriorates to class B for SS01, SS0 and SS04 but class C for SS02. For light rainy night-time conditions, the functional service quality was B at SS01 and SS04 while SS02 and SS03 deteriorates to class D and C respectively. For moderate rainy night-time conditions, both SS01 and SS03 had their functional service quality deteriorate to class C, while SS02 and SS04 maintained the functional service quality obtained for light rainy night-time conditions. However, for heavy rainy night-time condition, the functional service quality for SS01, SS02 and SS03 deteriorated to class D while SS04 deteriorated to class C. Based on these findings, it is evident that rainfall, irrespective of its intensity affects road service quality as to cause significant changes. It is however to be noted that roads may be operating under the same service quality for different conditions, but their travel time will be different depending on the traffic characteristics. The deterioration in FSQ under rainy night-time conditions shows that rainfall has a significant impact on traffic operations. The reduction in service quality due to rainfall influence does not follow any trend relative to rainfall intensity. However, the impact of heavy night-time rain is more prominent than other rainfall intensities.

5.7 Influence of Night Rainfall on Functional Service Quality (FSQ)

Based on the evidence presented in section 5.6, it is therefore necessary to use the speed-density relationship to further substantiate the influence of night rain on functional service quality. The speed-density relationship for the dry night and rainy conditions are related using Microsoft Excel and the graphs with their model equations presented accordingly. A stepwise analysis was employed for the speed-density relationship

5.7.1 Speed - Density Relationship

Using the empirical data presented in sections 5.5.1, 5.6.1, 5.6.2 and 5.6.3 for dry night, light night rain, moderate night rain and heavy night rain respectively, their speeds and corresponding densities were linearly related using Microsoft excel. The linear relationship is based on the postulation of Greenshield (1935) which is expressed as

$$u = u_f - ak \qquad 5.28$$

The speed-density relationship models for all the sites in terms of each weather condition are presented thus as follows:

Dry Night

SS01	$u_{DN} = -1.6782k + 96.040$	$R^2 = 0.8089$	5.29
SS02	$u_{DN} = -1.7509k + 96.031$	$R^2 = 0.7203$	5.30
SS03	$u_{DN} = -2.2231k + 94.252$	$R^2 = 0.7413$	5.31
SS04	$u_{DN} = -2.2759k + 105.71$	$R^2 = 0.7978$	5.32

Light Night rain

SS01	$u_{LR} = -1.2558k + 81.371$	$R^2 = 0.6031$	5.33
SS02	$u_{LR} = -1.5490k + 85.010$	$R^2 = 0.6189$	5.34
SS03	$u_{LR} = -1.7124k + 85.291$	$R^2 = 0.6056$	5.35
SS04	$u_{LR} = -1.9640k + 96.365$	$R^2 = 0.6878$	5.36

Moderate Night rain

SS01	$u_{MR} = -1.2542k + 81.099$	$R^2 = 0.5765$	5.37
SS02	$u_{MR} = -1.2462k + 76.315$	$R^2 = 0.6031$	5.38
SS03	$u_{MR} = -1.3468k + 77.100$	$R^2 = 0.5841$	5.39
SS04	$u_{MR} = -1.3530k + 81.235$	$R^2 = 0.7242$	5.40

Heavy Night rain

SS01	$u_{MR} = -1.0727k + 70.188$	$R^2 = 0.5500$	5.41
SS02	$u_{MR} = -0.8258k + 65.917$	$R^2 = 0.5300$	5.42
SS03	$u_{MR} = -1.4871k + 75.177$	$R^2 = 0.7837$	5.43
SS04	$u_{MR} = -1.1172k + 69.287$	$R^2 = 0.6297$	5.44

From all the speed-density models obtained, the model coefficients have the correct signs with coefficient of determination R^2 greater than 0.5. The R^2 implies that there exists a strong relationship between speed and density, hence, the models are statistically fit and significant for the prediction of speed. Note that the constant of each model represents the free-flow speed. The graphical representations of the speed-density relationships for each site showing both dry night and rainy night conditions are presented in Figures 5.14 - 5.17

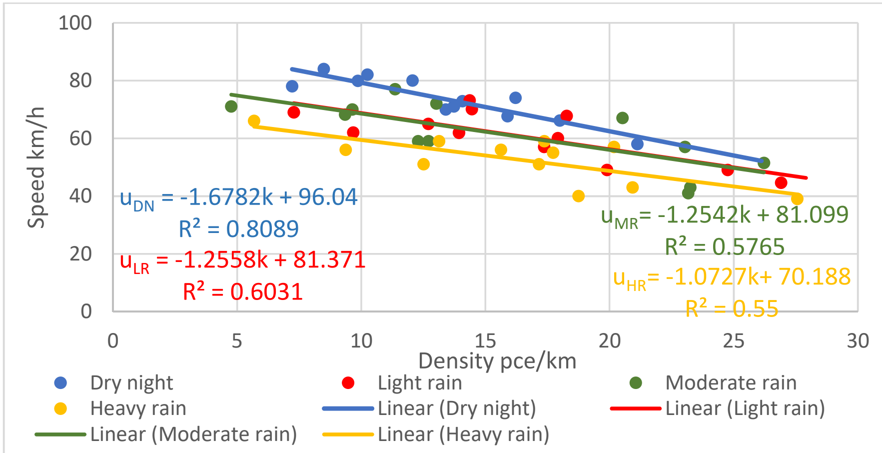


Figure 5.14: Speed-density graph of dry night and rainy night conditions at SS01

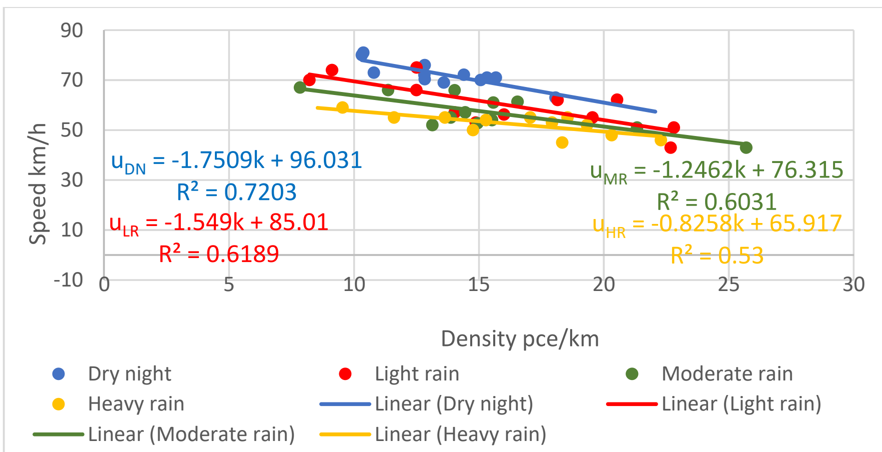


Figure 5.15: Speed-density graph of dry night and rainy night conditions at SS02

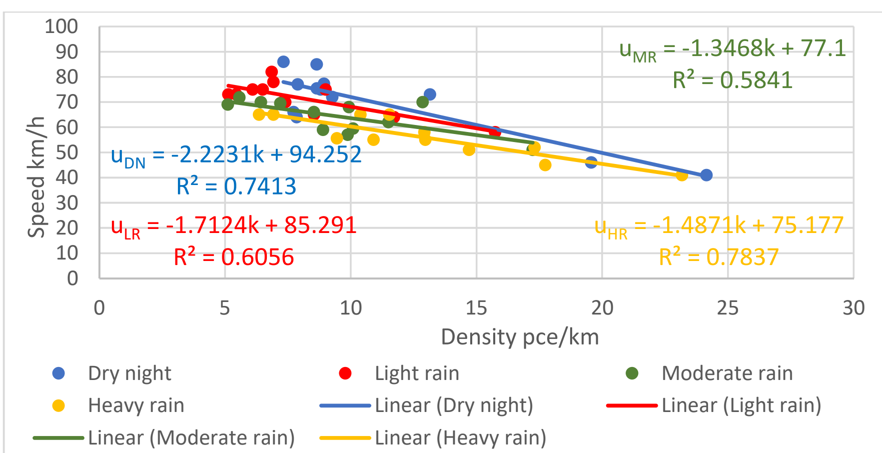


Figure 5.16: Speed-density graph of dry night and rainy night conditions at SS03

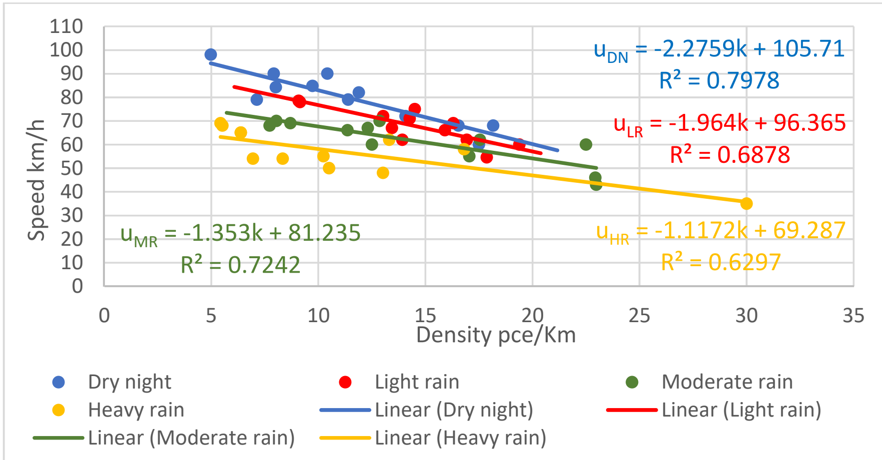


Figure 5.17: Speed-density plot of dry night and rainy night conditions at SS04

The colour notations adopted earlier are applicable to Figures 5.14 - 5.17 where blue represents dry night, red for light rain, green for moderate rain and yellow for heavy rain conditions. The figures show a downward shift from dry night-time conditions to rainy night-time conditions. This shows that rainfall impact on the speed-density relationship is the reason for the downward shift. The relationship has a negative linearity such that as speed increases, density reduces and vice versa.

5.7.2 Speed/Density Relationship with a Dummy variable

Based on the evidence of the speed-density relationship, a dummy variable (ψ) was introduced to assess the impact of rainfall (irrespective of its intensity) on the dry conditions. The introduction of a dummy variable (ψ) is to indicate whether there will be a change in speed in the absence or presence of rainfall. This was done by combining speed and density under dry night-time and rainy night-time conditions using a dummy variable. The dummy variable's conditions are such that $\psi = 0$ for dry conditions, otherwise 1 for rainfall conditions. The speed-density dummy based relationship is presented thus as

$$u = u_f - ak \pm \psi \qquad 5.45$$

With the empirical data presented in sections 5.5.1, 5.6.1, 5.6.2 and 5.6.3 for dry night-time, light night rain, moderate night rain and heavy night rain conditions respectively, the speeds and their respective densities are regressed with the dummy variable using 0 for dry night and 1 for rainy night conditions irrespective of its intensity. Tables 5.39 - 5.42 represent the speed-density with dummy variables while Figures 5.18 - 5.21 are their respective statistical results as obtained from Microsoft Excel.

Table 5.39: Dry Night with Light Rainy Night-Time – SS01

Weather condition	u	k	ψ
Light night rain	49	20	1
	45	27	1
	65	13	1
	68	18	1
	73	14	1
	62	14	1
	70	14	1
	62	10	1
	57	17	1
	69	7	1
	60	18	1
	49	25	1
Dry night	73	14	0
	58	21	0
	82	10	0
	70	13	0
	66	18	0
	80	12	0
	84	8	0
	78	7	0
	74	16	0
	68	16	0
	71	14	0
	80	10	0

u = speed, k = density, ψ = dummy variable (0 or 1)

SUMMARY OUTPUT

Regression Statistics	
Multiple R	0.89478
R Square	0.80064
Adjusted F	0.78165
Standard E	4.93381
Observatic	24

ANOVA

	df	*SS*	*MS*	*F*	*gnificance F*
Regressior	2	2052.97	1026.49	42.1685	4.4E-08
Residual	21	511.192	24.3425		
Total	23	2564.16			

	Coefficient:	*andard Err*	*t Stat*	*P-value*	*Lower 95%*	*Upper 95%*	*ower 95.0%*	*pper 95.0%*
Intercept	92.3089	3.1805	29.0234	2E-18	85.6947	98.9231	85.6947	98.9231
X Variable	-1.39888	0.21286	-6.57172	1.7E-06	-1.84155	-0.95621	-1.84155	-0.95621
Dummy	-8.5815	2.11969	-4.04847	0.00058	-12.9896	-4.17337	-12.9896	-4.17337

Figure 5.18: Statistical test result for Table 5.39

Table 5.40: Dry Night with Light Rainy Night-Time – SS02

Weather condition	u	k	ψ
Light night rain	62	21	1
	66	13	1
	57	14	1
	74	9	1
	51	23	1
	56	16	1
	53	15	1
	75	13	1
	55	20	1
	62	18	1
	43	23	1
	70	8	1
Dry night	81	10	0
	73	11	0
	71	16	0
	80	10	0
	72	14	0
	71	15	0
	70	15	0
	63	18	0
	70	13	0
	69	14	0
	72	13	0
	76	13	0

u = speed, k = density, ψ = dummy variable (0 or 1)

SUMMARY OUTPUT

Regression Statistics	
Multiple R	0.88506
R Square	0.78333
Adjusted F	0.76269
Standard E	4.71741
Observatic	24

ANOVA

	df	*SS*	*MS*	*F*	*gnificance F*
Regressior	2	1689.55	844.775	37.9607	1.1E-07
Residual	21	467.333	22.254		
Total	23	2156.88			

	Coefficients	*andard Err*	*t Stat*	*P-value*	*Lower 95%*	*Upper 95%*	*ower 95.0%*	*pper 95.0%*
Intercept	93.8114	3.77859	24.8271	4.8E-17	85.9534	101.669	85.9534	101.669
X Variable	-1.58654	0.26097	-6.07949	4.9E-06	-2.12925	-1.04383	-2.12925	-1.04383
Dummy	-8.20382	2.02565	-4.04997	0.00058	-12.4164	-3.99125	-12.4164	-3.99125

Figure 5.19: Statistical test result for Table 5.40

Table 5.41: Dry Night with Light Rainy Night-Time – SS03

Weather condition	u	k	ψ
Light night rain	73	5	1
	73	5	1
	70	7	1
	58	16	1
	82	7	1
	70	7	1
	75	6	1
	65	9	1
	64	12	1
	75	7	1
	75	9	1
	78	7	1
Dry night	46	20	0
	86	7	0
	64	8	0
	66	8	0
	73	13	0
	77	9	0
	85	9	0
	75	9	0
	72	9	0
	75	9	0
	41	24	0
	77	8	0

u = speed, k = density, ψ = dummy variable (0 or 1)

SUMMARY OUTPUT

Regression Statistics	
Multiple R	0.84298
R Square	0.71061
Adjusted F	0.68305
Standard E	6.00279
Observatic	24

ANOVA

	df	*SS*	*MS*	*F*	*gnificance F*
Regressior	2	1858.12	929.06	25.7833	2.2E-06
Residual	21	756.703	36.0335		
Total	23	2614.82			

	Coefficients	*andard Err*	*t Stat*	*P-value*	*Lower 95%*	*Upper 95%*	*ower 95.0%*	*pper 95.0%*
Intercept	92.9191	3.66864	25.3279	3.2E-17	85.2897	100.548	85.2897	100.548
X Variable	-2.10184	0.29406	-7.14765	4.8E-07	-2.71337	-1.49031	-2.71337	-1.49031
Dummy	-4.49193	2.59894	-1.72837	0.0986	-9.89672	0.91285	-9.89672	0.91285

Figure 5.20: Statistical test result for Table 5.41

Table 5.42: Dry Night with Light Rainy Night-Time – SS04

Weather condition	u	k	ψ
Light night rain	69	16	1
	75	15	1
	66	16	1
	78	9	1
	71	14	1
	60	19	1
	62	14	1
	62	17	1
	67	13	1
	55	18	1
	79	9	1
	72	13	1
Dry night	60	18	0
	68	18	0
	82	12	0
	98	5	0
	85	10	0
	90	10	0
	68	17	0
	84	8	0
	90	8	0
	72	14	0
	79	7	0
	79	11	0

u = speed, k = density, ψ = dummy variable (0 or 1)

SUMMARY OUTPUT

Regression Statistics	
Multiple R	0.91168
R Square	0.83116
Adjusted F	0.81508
Standard E	4.69652
Observatic	24

ANOVA

	df	*SS*	*MS*	*F*	*gnificance F*
Regressio	2	2280.31	1140.15	51.6905	7.7E-09
Residual	21	463.203	22.0573		
Total	23	2743.51			

	Coefficients	*andard Err*	*t Stat*	*P-value*	*Lower 95%*	*Upper 95%*	*ower 95.0%*	*pper 95.0%*
Intercept	104.471	3.34163	31.2635	4.3E-19	97.5218	111.42	97.5218	111.42
X Variable	-2.1677	0.26607	-8.14705	6.1E-08	-2.72102	-1.61437	-2.72102	-1.61437
Dummy	-15.1566	2.07706	-2.48266	0.02157	-9.4761	-0.83715	-9.4761	-0.83715

Figure 5.21: Statistical test result for Table 5.42

The dummy-based speed-density models of dry night with light rainy night-time conditions for SS01, SS02, SS03 and SS04 are presented in equations 5.46, 5.47, 5.48 and 5.49 with their corresponding interpretations.

- $u_{LSS01} = 92.31 - 1.39k - 8.58$ $\qquad R^2 = 0.80$ $\qquad$ 5.46

equation 5.46: free-flow speed for dry condition, $u_D = 92.31km/h$, its equivalent free-flow speed for light rain condition, $u_R = 92.31 - 8.58 = 83.73km/h$

- $u_{LSS02} = 93.81 - 1.59k - 9.20$ $\qquad R^2 = 0.78$ $\qquad$ 5.47

equation 5.47: free-flow speed for dry condition, $u_D = 93.81km/h$, its equivalent free-flow speed for light rain condition, $u_R = 93.81 - 8.20 = 85.61km/h$

- $u_{LSS03} = 92.92 - 2.10k - 4.49$ $\qquad R^2 = 0.71$ $\qquad$ 5.48

equation 5.48: free-flow speed for dry condition, $u_D = 92.92km/h$, its equivalent free-flow speed for light rain condition, $u_R = 92.92 - 4.49 = 88.43km/h$

- $u_{LSS03} = 104.47 - 2.17k - 15.16$ $\qquad R^2 = 0.83$ $\qquad$ 5.49

equation 5.49: free-flow speed for dry condition, $u_D = 104.47km/h$, its equivalent free-flow speed for light rain condition, $u_R = 104.47 - 15.16 = 89.31km/h$

The model equations obtained have the expected signs of negative linear regression which by implication means that a decrease in speed results in an increase in density. The results of the statistical tests in Figures 5.18 – 5.21 showed that coefficients of determination (R^2) are greater than 0.5, thus, the models are valid and acceptable. The t-test results are greater than 2.2 suggesting that the variables are significant while F-stat values are greater than F-critical at 4.84.

The process was performed for other weather conditions of dry night with moderate rainy night-time, and heavy rainy night-time conditions. Their respective dummy-based speed-density models for all the four sites are presented as follows:

Dry night and moderate rainy night-time conditions

- $u_{MSS01} = 91.79 - 1.36k - 9.02$ $\qquad R^2 = 0.74$ $\qquad$ 5.50

equation 5.46: free-flow speed for dry condition, $u_D = 91.79km/h$, its equivalent free-flow speed for light rain condition, $u_R = 91.79 - 9.02 = 82.77km/h$

- $u_{MSS02} = 90.66 - 1.35k - 12.70$ $R^2 = 0.86$ 5.51

equation 5.47: free-flow speed for dry condition, $u_D = 90.66km/h$, its equivalent free-flow speed for light rain condition, $u_R = 90.66 - 12.70 = 77.96km/h$

- $u_{MSS03} = 91.51 - 1.97k - 8.50$ $R^2 = 0.69$ 5.52

equation 5.48: free-flow speed for dry condition, $u_D = 91.51km/h$, its equivalent free-flow speed for light rain condition, $u_R = 91.51 - 8.50 = 83.01km/h$

- $u_{MSS03} = 98.91 - 1.68k - 12.82$ $R^2 = 0.85$ 5.53

equation 5.49: free-flow speed for dry condition, $u_D = 98.81km/h$, its equivalent free-flow speed for light rain condition, $u_R = 98.91 - 12.82 = 86.09km/h$

Dry night and heavy rainy night-time conditions

- $u_{HSS01} = 90.67 - 1.28k - 7.62$ $R^2 = 0.87$ 5.54

equation 5.46: free-flow speed for dry condition, $u_D = 90.67km/h$, its equivalent free-flow speed for light rain condition, $u_R = 90.67 - 7.62 = 83.05km/h$

- $u_{HSS02} = 97.13 - 1.09k - 16.84$ $R^2 = 0.93$ 5.55

equation 5.47: free-flow speed for dry condition, $u_D = 97.13km/h$, its equivalent free-flow speed for light rain condition, $u_R = 97.13 - 16.84 = 80.29km/h$

- $u_{HSS03} = 90.66 - 1.89k - 10.22$ $R^2 = 0.80$ 5.56

equation 5.48: free-flow speed for dry condition, $u_D = 90.66km/h$, its equivalent free-flow speed for light rain condition, $u_R = 90.66 - 10.23 = 80.43km/h$

- $u_{HSS03} = 96.09 - 1.44k - 23.26$ $R^2 = 0.84$ 5.57

equation 5.49: free-flow speed for dry condition, $u_D = 96.09km/h$, its equivalent free-flow speed for light rain condition, $u_R = 96.09 - 23.26 = 72.83km/h$

With the dummy-based speed-density relationships, there is evidence of speed reduction under night-time rain influence. As driving at night is challenging, the presence of rainfall irrespective of its intensity makes it more challenging for drivers. This is due to the possible reduction in visibility under such conditions. Impaired visibility is an associated phenomenon of rainfall which forces drivers to reduce speed with a consequent increase in time spent on the road. For the reason of the increase in travel time and speed reduction, there is a possibility of consequent effect on other road characteristics such as stopping sight distance. On this basis, the implication of night-time rain on the stopping sight distance of the dark roadways will be investigated in the next chapter using the dummy-based speed-density models.

5.8 Summary

In this chapter, the functional service quality of the roadways was analysed and presented. In achieving this, a criteria table that considers both the road provider and road users' perceptions was first developed for each site using their individual traffic data. The road users' perception of good quality service delivery is based on travel time while road providers' perception of good quality service delivery is based on travel speed. The two perceptions were incorporated into the FSQ criteria table. The criteria table development was done using the empirical data of the dry daylight (peak condition) of each site. The criteria table using travel time and capacity was divided into six classes of A - F where class A is the highest quality of service of the free-flow conditions and class F is the worst quality of service with a breakdown in traffic operation. The FSQ identified class E as the threshold class where the road is at its capacity. The FSQ criteria table also prescribed the relative travel speed and other parameters for each class.

The off-peak data using flow and density of dry daylight, dry night-time and rainy night-time conditions were modelled and analysed accordingly for each site. Three rainy night conditions which are light rain, moderate rain and heavy rain were identified for assessment. The functional service quality of the four sites was assessed and compared. Based on the FSQ assessment of dry daylight (off-peak) and dry night-time conditions comparison, it was observed that the night period has an influence on the functional service delivery of the roadways though both conditions are off-peak traffic periods. The roadway functional service quality deteriorates under dry night-time condition.

The assessment of the rainy night condition further showed that rain has an impact on the functional service quality of the roadways. Rainfall led to an increase in travel time and a decrease in travel speed. With the increase in travel time, the functional service quality deteriorates as the rainfall intensity increases. However, the results showed that heavy rainfall has the most significant influence on the functional service delivery of the roadways.

By way of addition and to further substantiate the results obtained for the assessment, the speed and densities of the various conditions were related and modelled. The results confirmed speed reduction as a result of night-time rain on the roadway. This however shows that other parameters such as stopping sight distance can be affected under the night rain conditions as the service quality deteriorates. So, by implication, will night-time rain, irrespective of its intensity, have an effect on stopping sight distance? If it does, will the stopping sight distance increase or decrease? These questions are answered in chapter 6 using the dummy-based speed-density models.

CHAPTER SIX

STOPPING SIGHT DISTANCE IMPLICATION

6.1 Overview

In chapter five, the functional service quality of dark roadways was assessed using statistically fit models derived from the flow-density relationship. Also, speeds and densities were further related linearly with a dummy variable such that different sets of statistically fit dummy-based speed-density models were obtained. However, it was stated in the chapter that the dummy-based speed-density models will be used in assessing the implication of night rain on stopping sight distance of the dark roadways. Thus, the use of the obtained dummy-based speed-density models in this chapter.

Sight distance is a measure of the safe distance available for identifying, passing and/or a stopping vehicle safely. As driving, irrespective of time and condition under which it occurs, is a complex task due to interaction with the environment, night-time driving coupled with rainfall is presumed to be more tasking due to decreased visibility as a result of dark and rainy conditions. This is evident based on the result of the functional service quality assessment in the previous chapter which confirmed the first hypothesis set out earlier in chapter one. However, on the premise of the second hypothesis that 'if night rainfall on dark roadways produces functional service quality reduction, there will be a subsequent impact on stopping sight distance', therefore, this chapter sets out to investigate by implication the influence of night rain on stopping sight distance.

This chapter is thus arranged as follows: the concept of stopping sight distance is presented in section 6.2. Analysis is presented in section 6.3, while the influence of night rain is discussed in section 6.4. Section 6.5 focuses on the comparison of obtained results with previous studies. The chapter is summarised in section 6.6.

6.2 Generalised Stopping Sight Distance concept

Stopping sight distance is the distance needed by a driver to bring a car to a total or partial halt while driving, in order to avoid hitting an object ahead on the roadway. Stopping sight distance is one of the two important distances for a two-lane highway. It is an important aspect of road design for safety purposes because it is associated with good visibility which makes it a traffic safety indicator (Ben-Edigbe *et al.,* 2013). Stopping sight distance is made up of reaction distance and braking distance. Mathematically, stopping sight distance is expressed as

$$SSD_i = RD_i + BD_i \qquad 6.1$$

where SSD = stopping sight distance, RD = Reaction distance, BD = Braking distance and i = weather condition of either dry night-time (DN) or rainy night-time (RN).

6.2.1 Reaction Distance (RD)

Reaction distance is expressed as

$$RD_i = u_i t = 0.278u_i * t \qquad 6.2$$

where u = speed and t = reaction time (2.5s). Thus, reaction distance for dry night-time (DN) and rainy night-time (RN) conditions are

$$RD_{DN} = 0.278u_{fDN} * 2.5 = 0.695u_{fDN} \qquad 6.3$$

$$RD_{RN} = 0.278u_{fRN} * 2.5 = 0.695u_{fRN} \qquad 6.4$$

6.2.2 Braking Distance (BD)

Braking distance is expressed as;

$$BD_i = \frac{(uf_i)^2}{2a_i} = \frac{(0.278uf_i)^2}{2*\left|\frac{(v_1-v_2)}{(t_2-t_1)}\right|} \qquad 6.5$$

Where u = speed, i = weather condition of dry or rainy night-time condition, a = deceleration under dry and rainy night conditions respectively, $v_{1,2}$ = speed and $t_{1,2}$ = respective time of $v_{1,2}$ under dry and rainy night conditions respectively, however, note that $t = 100/v$ and the time equivalent is dependent on the speed. Thus, braking distances for dry night-time (DN) and rainy night-time (RN) conditions are expressed as;

$$BD_{DN} = \frac{\left(0.278u_{fDN}\right)^2}{2*a_{DN}} = \frac{0.5\left(0.278u_{fDN}\right)^2}{a_{DN}} \qquad 6.6$$

$$BD_{RN} = \frac{(0.278uf_{RN})^2}{2*a_{RN}} = \frac{0.5(0.278uf_{RN})^2}{a_{RN}} \qquad 6.7$$

Therefore, stopping sight distance for dry and rainy night-time conditions respectively is estimated as follows:

$$SSD_{DN} = RD_{DN} + BD_{DN} \qquad 6.8$$

$$SSD_{RN} = RD_{RN} + BD_{RN} \quad 6.9$$

Thus, equations 6.8 and 6.9 are used for the assessment of night-time rain impact on stopping sight distance. The schematic flowchart of the analysis is presented in figure 6.1 while the stopping sight distance analysis is presented in section 6.3.

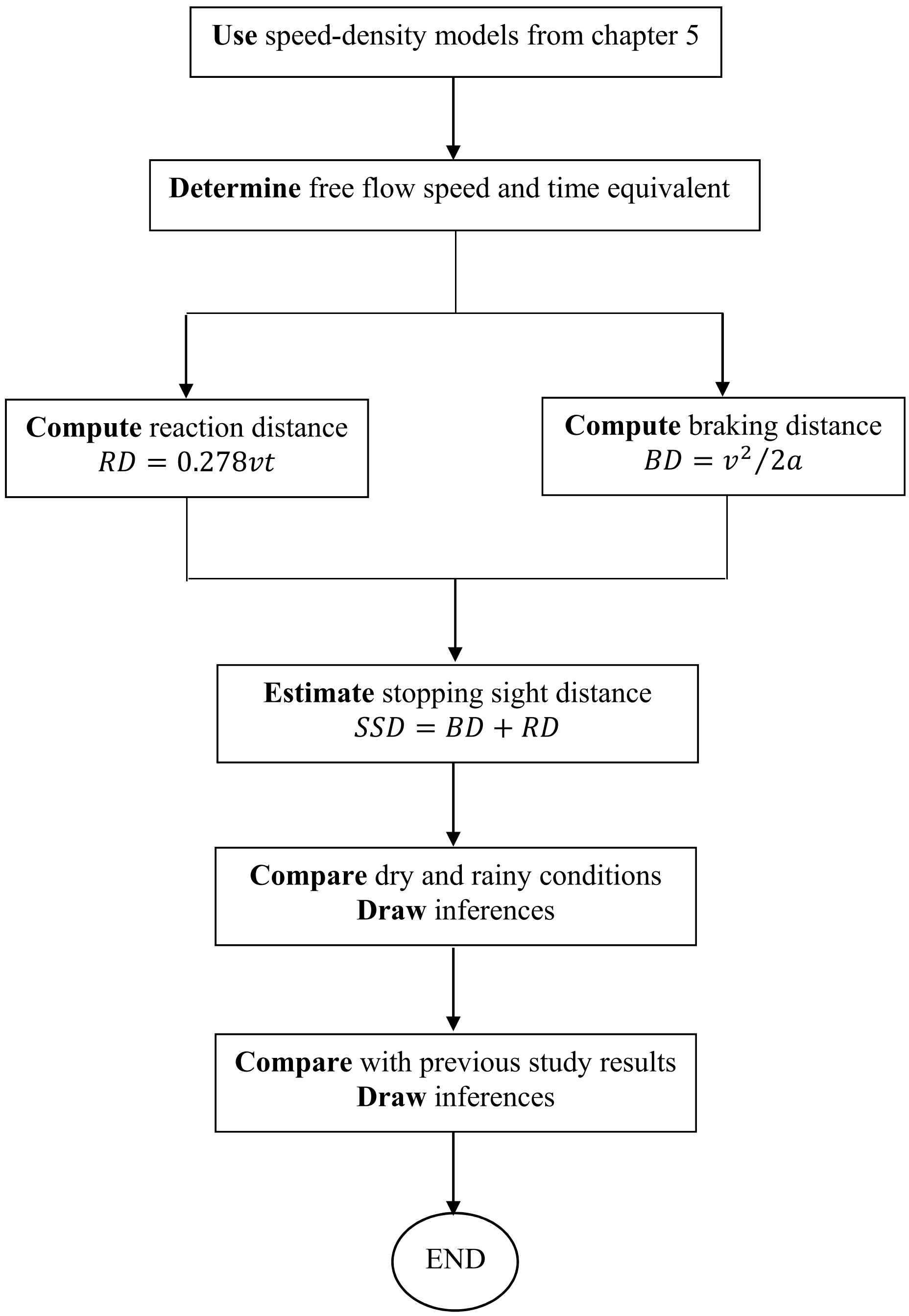


Figure 6.1: Schematic flowchart of SSD analysis

6.3 Analysis of Stopping Sight Distance

The stepwise analysis, due to its clarity and simplicity, is adopted and presented as follows:

Step 1: Recall the dummy-based speed-density relationship models presented in chapter five. Determine free flow speed for dry conditions, rainy night-time conditions and the speed differential. For example, in the light rainy night-time conditions, the four site's models are represented as equations 6.10 – 6.13

- $u_{LSS01} = 92.31 - 1.39k - 8.58 \qquad R^2 = 0.80$ 6.10

Free-flow speed for dry condition, $u_D = 92.31km/h$,
Free-flow speed differential, $u_\Delta = 8.58km/h$
Free-flow speed for light rain condition, $u_R = 92.31 - 8.58 = 83.73km/h$

- $u_{LSS02} = 93.81 - 1.59k - 8.20 \qquad R^2 = 0.78$ 6.11

Free-flow speed for dry condition, $u_D = 93.81km/h$,
Free-flow speed differential, $u_\Delta = 8.20km/h$
Free-flow speed for light rain condition, $u_R = 92.31 - 8.20 = 85.61km/h$

- $u_{LSS03} = 92.92 - 2.10k - 4.49 \qquad R^2 = 0.71$ 6.12

Free-flow speed for dry condition, $u_D = 92.92km/h$,
Free-flow speed differential, $u_\Delta = 4.49km/h$
Free-flow speed for light rain condition, $u_R = 92.92 - 4.49 = 88.43km/h$

- $u_{LSS03} = 104.47 - 2.17k - 15.16 \qquad R^2 = 0.83$ 6.13

Free-flow speed for dry condition, $u_D = 104.47km/h$,
Free-flow speed for light rain condition, $u_R = 104.47 - 15.16 = 89.31km/h$
Free-flow speed differential, $u_\Delta = 15.16km/h$

The steps were repeated for moderate and heavy rainy night-time conditions and summarised in Table 6.1

Table 6.1: Summary of Estimated Free-Flow Speeds and Speed Differential

Rainfall	SS	Model Equation	Free flow speed u_f				Speed differential
			Dry Night		Rainy Night		
			km/h	*m/s*	*km/h*	*m/s*	
LR	1	92.31 - 1.39k - 8.58	92.3	25.66	83.7	23.27	2.39
	2	93.81 - 1.59k - 8.20	93.8	26.08	85.6	23.80	2.28
	3	92.92 - 2.10k - 4.49	92.9	25.83	88.4	24.58	1.25
	4	104.5 - 2.17k - 15.2	104.5	29.05	89.3	24.83	4.23
MR	1	91.79 - 1.36k - 9.02	91.8	25.52	82.8	23.02	2.50
	2	90.66 - 1.35k - 12.7	90.7	25.21	78.0	21.68	3.53
	3	91.51 - 1.97k - 8.50	91.5	25.44	83.0	23.07	2.36
	4	98.91 - 1.68k - 12.8	98.9	27.49	86.1	23.94	3.56
HR	1	90.67 - 1.28k - 7.61	90.7	25.21	83.1	23.10	2.11
	2	97.12 - 1.09k - 16.8	97.1	26.99	80.3	22.32	4.67
	3	90.66 - 1.89k - 10.2	90.7	25.21	80.4	22.35	2.86
	4	96.09 - 1.44k - 23.3	96.1	26.72	72.8	20.24	6.48

From Table 6.1, the speed differential varies from site to site under varying night rainfall intensity. This implies that the effect of rainfall on road at night-time is not static but changes.

Step 2: Determine the time equivalent for each condition, thereafter, use the time equivalent to determine the deceleration values for the dry and rainy night-time conditions of the dark roadways using equation 6.14

$$a_i = \frac{\Delta v}{\Delta t} = \frac{(v_1 - v_2)}{(t_2 - t_1)} \qquad 6.14$$

For example, at SS01

Free flow speed for dry condition $u_{fDN} = 92.3km/h = 25.659m/s$

Free flow speed for light rainy night condition $u_{fLRN} = 83.7km/h = 23.269m/s$

Change in free flow speed $\Delta u_f = 25.659 - 23.269 = 2.391m/s$

The time equivalent for dry condition $t_{DN} = 100/25.659 = 3.897s$,

The time equivalent light rainy night condition $t_{LR} = 100/23.269 = 4.298s$,

Change in time equivalent $\Delta t = 4.298 - 3.897 = 0.400s$

Therefore, using equation 6.14, $a_{LR} = \frac{\Delta v}{\Delta t} = \frac{(v_1 - v_2)}{(t_2 - t_1)}$

$$a_{LR} = \frac{2.391}{0.400} = 5.971m/s^2$$

Thus, Table 6.2 represents the summary of the estimated deceleration values of all the sites

Table 6.2: Summary of Deceleration Rate on Dark Roadways due to Rainy Night Conditions

i	*SS*	*Model Equation*	u_{fDN} *km/h*	u_{fDN} *m/s*	*t (s)* $^{100}/_{u_{fDN}}$	u_{fRN} *km/h*	u_{fRN} *m/s*	*t (s)* $^{100}/_{u_{fDN}}$	Δu *m/s*	Δt *(s)*	*a (m/s²)*
c1	*c2*	*c3*	*c4*	*c5*	*c6*	*c7*	*c8*	*c9*	*c10 = c5 – c8*	*c11 = c9 – c6*	*c12 = c10/c11*
LR	01	92.31 - 1.39k - 8.58	92.3	25.66	3.90	83.7	23.27	4.30	2.39	0.40	5.97
	02	93.81 - 1.59k - 8.20	93.8	26.08	3.84	85.6	23.80	4.20	2.28	0.37	6.21
	03	92.92 - 2.10k - 4.49	92.9	25.83	3.87	88.4	23.46	4.26	2.36	0.39	6.06
	04	104.5 - 2.17k - 15.2	104.5	27.94	3.58	89.3	24.83	4.03	3.11	0.45	6.94
MR	01	91.79 - 1.36k - 9.02	91.8	25.52	3.92	82.8	23.02	4.34	2.50	0.43	5.87
	02	90.66 - 1.35k - 12.7	90.7	25.22	3.97	78.0	21.68	4.61	3.53	0.65	5.47
	03	91.51 - 1.97k - 8.50	91.5	25.44	3.93	83.0	23.07	4.33	2.36	0.40	5.87
	04	98.91 - 1.68k - 12.8	98.9	27.49	3.64	86.1	23.94	4.18	3.56	0.54	6.58
HR	01	90.67 - 1.28k - 7.61	90.7	25.77	3.88	83.1	23.10	4.33	2.67	0.45	5.95
	02	97.12 - 1.09k - 16.8	97.1	26.99	3.71	80.3	22.32	4.48	4.67	0.78	6.03
	03	90.66 - 1.89k - 10.2	90.7	25.22	3.97	80.4	22.35	4.47	2.86	0.51	5.64
	04	96.09 - 1.44k - 23.3	96.1	26.72	3.74	72.8	20.24	4.94	6.48	1.20	5.41
										Total	72.421
										Ave	6.035

i = intensity, SS = study site, LR = light rain, MR = moderate rain, HR = heavy rain, u_f *= free flow speed, DN = dry night, RN = rainy night, t = time, Δ = difference, a = deceleration, c = column*

From Table 6.2, the average deceleration induced by light rainfall is 6.43m/s^2, moderate rainfall 5.95m/s^2 and heavy rainfall 5.72m/s^2. The chi-square results showed that there is no significant difference in the deceleration values obtained for the three rainfall intensities, hence, it can be mentioned that the generalised average deceleration is 6.04m/s^2.

Step 3: Determine the reaction distance for both dry and rainy night-time conditions using equations 6.3 and 6.4, note that the average reaction time (*t*) of 2.5s is assumed.

Dry night and light rainy night-time conditions – SS01

$$RD_{DN} = 0.695u_{DN} = 0.695 * 92.3 = 64.1m$$

$$RD_{RN} = 0.695u_{RN} = 0.695 * 83.7 = 58.2m$$

Dry night and light rainy night-time conditions – SS02

$$RD_{DN} = 0.695u_{DN} = 0.695 * 93.8 = 65.2m$$

$$RD_{RN} = 0.695u_{RN} = 0.695 * 85.6 = 59.5m$$

Dry night and light rainy night-time conditions – SS03

$$RD_{DN} = 0.695u_{DN} = 0.695 * 92.9 = 64.6m$$

$$RD_{RN} = 0.695u_{RN} = 0.695 * 88.4 = 61.4m$$

Dry night and light rainy night-time conditions – SS04

$$RD_{DN} = 0.695u_{DN} = 0.695 * 104.5 = 72.6m$$

$$RD_{RN} = 0.695u_{RN} = 0.695 * 89.3 = 62.1m$$

The procedure was repeated for moderate rain and heavy rain conditions. The reaction distance summary for the rainy night conditions is presented in Table 6.3.

Table 6.3: Summary of Reaction Distances for All Rainy Night Conditions

Rain	SS	Model Equation	u_{fDN}	u_{fRN}	Reaction Distance (m)			
					DN	RN	Δ	Δ%
LR	01	92.31 - 1.39k - 8.58	92.3	83.7	64.1	58.2	6.0	9.3
	02	93.81 - 1.59k - 8.20	93.8	85.6	65.2	59.5	5.7	8.7
	03	92.92 - 2.10k - 4.49	92.9	88.4	64.6	61.4	3.1	4.8
	04	104.5 - 2.17k - 15.2	104.5	89.3	72.6	62.1	10.6	14.5
				Total	266.5	241.2	25.4	37.4
				Ave	66.6	60.3	6.3	9.4
MR	01	91.79 - 1.36k - 9.02	91.8	82.8	63.8	57.5	6.3	9.8
	02	90.66 - 1.35k - 12.7	90.7	78.0	63.0	54.2	8.8	14.0
	03	91.51 - 1.97k - 8.50	91.5	83.0	63.6	57.7	5.9	9.3
	04	98.91 - 1.68k - 12.8	98.9	86.1	68.7	59.8	8.9	12.9
				Total	259.2	229.3	29.9	46.0
				Ave	64.8	57.3	7.5	11.5
HR	01	90.67 - 1.28k - 7.61	90.7	83.1	63.0	57.8	5.3	8.4
	02	97.12 - 1.09k - 16.8	97.1	80.3	67.5	55.8	11.7	17.3
	03	90.66 - 1.89k - 10.2	90.7	80.4	63.0	55.9	7.2	11.4
	04	96.09 - 1.44k - 23.3	96.1	72.8	66.8	50.6	16.2	24.2
				Total	260.3	220.0	40.3	61.3
				Ave	65.1	55.0	10.1	15.3

LR = light rain, MR = moderate rain, HR = heavy rain, SS = study site, u_f = free flow speed (km/h), DN = dry night, RN = rainy night, Δ = RD difference = RN – DN, Δ% = percentage difference, ave = average

From the summary presented in Table 6.3, across the four study sites, reaction distance reduced under rainy night conditions anomalously relative to speed reduction. The change in reaction distance under the two scenarios is small. The small difference is due to driver behaviour which is already taken care of by the reaction time. Due to impaired visibility associated with night driving, it is assumed that drivers are vigilant thereby reducing their speed, and when it rains, they reduce their speed further. From the table, the average reduction in reaction distance is 9.4 percent, 11.5 percent and 15.3 percent for light rain, moderate and heavy night rain conditions respectively. The average percentage difference shows that as rainfall intensity increases, the reaction distance increases.

Step 4: Estimate braking distance for dry night and night rain conditions of the roadways using equations 6.6 and 6.7 earlier presented. The deceleration values obtained in step 2 is used respectively for each scenario as presented thus:

Dry night and light night rain conditions – SS01

$$BD_{DN} = \frac{\left(0.278u_{fDN}\right)^2}{2 * 5.97} = 0.083(0.278 * 92.3)^2 = 55.1m$$

$$BD_{LR} = \frac{\left(0.278u_{fRN}\right)^2}{2 * 5.97} = 0.083(0.278 * 83.7)^2 = 45.3m$$

Dry night and light night rain conditions – SS02

$$BD_{DN} = \frac{\left(0.278u_{fDN}\right)^2}{2 * 6.21} = 0.080(0.278 * 93.8)^2 = 54.8m$$

$$BD_{LR} = \frac{\left(0.278u_{fRN}\right)^2}{2 * 6.21} = 0.080(0.278 * 85.6)^2 = 45.6m$$

Dry night and light night rain conditions – SS03

$$BD_{DN} = \frac{\left(0.278u_{fDN}\right)^2}{2 * 6.35} = 0.079(0.278 * 92.9)^2 = 52.5m$$

$$BD_{LR} = \frac{\left(0.278u_{fRN}\right)^2}{2 * 6.35} = 0.079(0.278 * 88.4)^2 = 47.6m$$

Dry night and light night rain conditions – SS04

$$BD_{DN} = \frac{\left(0.278u_{fDN}\right)^2}{2 * 7.21} = 0.069(0.278 * 104.5)^2 = 58.5m$$

$$BD_{LR} = \frac{\left(0.278u_{fRN}\right)^2}{2 * 7.21} = 0.069(0.278 * 89.3)^2 = 42.7m$$

The process was performed for moderate and heavy night rain condition and the summary presented in Table 6.4.

Table 6.4: Summary of Braking Distances for all Rainy Night Conditions

Rain	SS	Model Equation	u_{fDN}	u_{fRN}	Braking Distance (m)			
					DN	RN	Δ	Δ%
LR	01	92.31 - 1.39k - 8.58	92.3	83.7	55.1	45.3	9.8	17.8
	02	93.81 - 1.59k - 8.20	93.8	85.6	54.8	45.6	9.2	16.7
	03	92.92 - 2.10k - 4.49	92.9	88.4	52.5	47.6	5.0	9.5
	04	104.5 - 2.17k - 15.2	104.5	89.3	58.5	42.7	15.8	27.0
				Total	221.0	181.3	39.7	70.9
				Ave	55.2	45.3	9.9	17.7
MR	01	91.79 - 1.36k - 9.02	91.8	82.8	55.4	45.1	10.3	18.6
	02	90.66 - 1.35k - 12.7	90.7	78.0	58.1	43.0	15.1	26.0
	03	91.51 - 1.97k - 8.50	91.5	83.0	55.1	45.4	9.8	17.7
	04	98.91 - 1.68k - 12.8	98.9	86.1	57.4	43.5	13.9	24.2
				Total	226.1	177.0	49.1	86.6
				Ave	56.5	44.2	12.3	21.7
HR	01	90.67 - 1.28k - 7.61	90.7	83.1	54.6	45.8	8.8	16.1
	02	97.12 - 1.09k - 16.8	97.1	80.3	60.5	41.3	19.1	31.6
	03	90.66 - 1.89k - 10.2	90.7	80.4	56.4	44.3	12.1	21.4
	04	96.09 - 1.44k - 23.3	96.1	72.8	66.0	37.9	28.1	42.6
				Total	237.4	169.4	68.1	111.7
				Ave	59.4	42.3	17.0	27.9

LR = light rain, MR = moderate rain, HR = heavy rain, SS = study site, u_f = free flow speed (km/h), DN = dry night, RN = rainy night, Δ = BD difference = DN – RN, Δ% = percentage difference, ave = average

According to Table 6.4, braking distance varies across the four selected sites for both the dry and rainy conditions considered. The estimated braking distances obtained did not follow any pattern for the two weather scenarios considered. Reduction in speed resulted in a decrease in braking distance for the rainy conditions irrespective of its intensity, though the decrease did not follow any trend in terms of rain intensity. There is a significant decrease in braking distance under rainy night conditions compared with its subsequent dry night conditions. This confirms that the negative effect of night rain on speed has a consequent effect on braking distance. The implication is such that when driving on dry pavement surface, a sufficient large distance is required in bringing a vehicle to a stop after applying the brakes, however, when driving under a rainy night condition, due to reduction in travel speed initially as a result of rainfall coupled with the absence of light, the distance needed to bring a vehicle to a halt is small. This is related to the consciousness already exhibited by the driver in terms of safety relative to driving at night on road without light. This is assumed to be in tandem with the presence of rainwater on road surface which reduces cohesion between vehicle tyre and road surface.

The average braking distance in relation to rainfall intensity reduced by 17.7 percent, 21.7 percent and 27.9 percent under light, moderate and heavy night rain respectively. By this, it means that as speed reduces due to the increase in rainfall intensity, consequently, the braking distance decreases. The estimated braking distance values for the two scenarios is presented graphically in Figure 6.2.

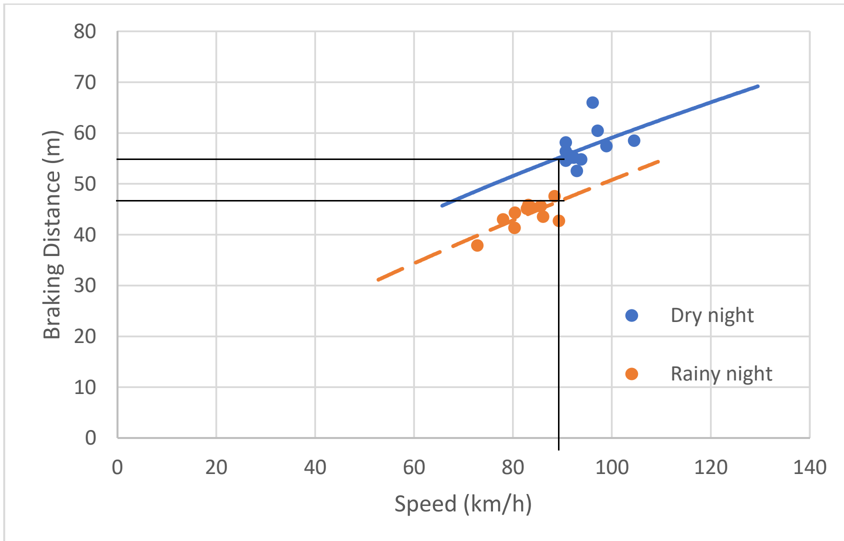


Figure 6.2: Braking distance graph for dry night and rainy night-time conditions

From the graph, there is a significant shift between the braking distances of the two scenarios. It is evident that lesser distance is required in bringing a vehicle to a halt under rainy night conditions than dry night conditions for same speed value. For example, a vehicle travelling at 90km/h will require distance of 65m for braking under dry night conditions but under rainy night conditions, the vehicle requires distance of 48m. This confirmed that rainfall at night influences braking distance of vehicles. Though the grip between the road surface and the tyres is reduced as a result of rain water on the road, the initial reduction of travel speed as induced by rainy night has taken into consideration the consequent effect on braking distance, thereby resulting in smaller distance in bringing a vehicle to a stop under the condition considered.

Step 5: Based on equations 6.8 and 6.9, estimate the stopping sight distance for dry night and rainy night conditions using the obtained results of steps 3 and 4 respectively

Dry night and light night rain conditions – SS01

$$SSD_{DN} = RD_{DN} + BD_{DN} = 0.695u_{DN} + 0.083(0.278 * u_{fDN})^2 = 64.1 + 55.1 = 119.3m$$

$$SSD_{RN} = RD_{DN} + BD_{DN} = 0.695u_{RN} + 0.083(0.278 * u_{fRN})^2 = 58.2 + 45.3 = 103.5m$$

Dry night and light night rain conditions – SS02

$$SSD_{DN} = RD_{DN} + BD_{DN} = 0.695u_{DN} + 0.080(0.278 * u_{fDN})^2 = 65.2 + 54.8 = 120.0m$$

$$SSD_{RN} = RD_{DN} + BD_{DN} = 0.695u_{RN} + 0.080(0.278 * u_{fRN})^2 = 59.5 + 45.6 = 105.1m$$

Dry night and light night rain conditions – SS03

$$SSD_{DN} = RD_{DN} + BD_{DN} = 0.695u_{DN} + 0.079(0.278 * u_{fDN})^2 = 64.6 + 52.5 = 117.1m$$

$$SSD_{RN} = RD_{DN} + BD_{DN} = 0.695u_{RN} + 0.079(0.278 * u_{fRN})^2 = 61.4 + 47.6 = 109.0m$$

Dry night and light night rain conditions – SS04

$$SSD_{DN} = RD_{DN} + BD_{DN} = 0.695u_{DN} + 0.069(0.278 * u_{fDN})^2 = 72.6 + 58.5 = 131.1m$$

$$SSD_{RN} = RD_{DN} + BD_{DN} = 0.695u_{RN} + 0.069(0.278 * u_{fRN})^2 = 62.1 + 42.7 = 104.8m$$

The process was performed for moderate and heavy rain conditions. The summary is presented as Table 6.5.

Table 6.5: Summary of Stopping Site Distances for All Rainy Night Conditions

Rain	SS	u_{fDN}	u_{fRN}	RD (m)		BD (m)		SSD (m)			
				DN	RN	DN	RN	DN	RN	Δ	Δ%
LR	01	92.3	83.7	64.1	58.2	55.1	45.3	119.3	103.5	15.8	13.2
	02	93.8	85.6	65.2	59.5	54.8	45.6	120.0	105.1	14.9	12.4
	03	92.9	88.4	64.6	61.4	52.5	47.6	117.1	109.0	8.1	6.9
	04	104.5	89.3	72.6	62.1	58.5	42.7	131.1	104.8	26.3	20.1
			Total	266.5	241.2	221.0	181.3	487.5	422.4	65.1	52.6
			Ave	66.6	60.3	55.2	45.3	121.9	105.6	16.3	13.2
MR	01	91.8	82.8	63.8	57.5	55.4	45.1	119.2	102.6	16.6	13.9
	02	90.7	78.0	63.0	54.2	58.1	43.0	121.2	97.2	24.0	19.8
	03	91.5	83.0	63.6	57.7	55.1	45.4	118.7	103.0	15.7	13.2
	04	98.9	86.1	68.7	59.8	57.4	43.5	126.2	103.4	22.8	18.1
			Total	259.2	229.3	226.1	177.0	485.3	406.3	79.0	65.0
			Ave	64.8	57.3	56.5	44.2	121.3	101.6	19.8	16.2
HR	01	90.7	83.1	63.0	57.8	54.6	45.8	117.6	103.6	14.0	11.9
	02	97.1	80.3	67.5	55.8	60.5	41.3	127.9	97.2	30.8	24.1
	03	90.7	80.4	63.0	55.9	56.4	44.3	119.4	100.2	19.2	16.1
	04	96.1	72.8	66.8	50.6	66.0	37.9	132.8	88.5	44.3	33.4
			Total	260.3	220.0	237.4	169.4	497.8	389.4	108.4	85.5
			Ave	65.1	55.0	59.4	42.3	124.4	97.3	27.1	21.4

LR = light rain, MR = moderate rain, HR = heavy rain, SS = study site, u_f *= free flow speed (km/h), DN = dry night, RN = rainy night, Δ = difference, RD = reaction distance, BD = braking distance, SSD = stopping sight distance, ave = average*

From Table 6.5, the stopping sight distance varies without any trend under both dry night and rainy night conditions across the four study sites. However, comparing the two scenarios, it was observed that stopping sight distance decreased significantly under rainy night conditions. The significant decrease in stopping sight distance under rainy night conditions is influenced by the significant change in braking distance as presented in Table 6.4 earlier. It is also evident that stopping sight distance is dependent on speed such that speed reduction due to rainfall consequently leads to a decrease in stopping sight distance. The percentage decrease in stopping sight distance in lieu of rainfall intensity is 13.2 percent, 16.2 percent and 21.4 percent for light, moderate and heavy night rain respectively. Figure 6.3 is the graphical representation of the estimated stopping sight distances for both dry and rainy night conditions.

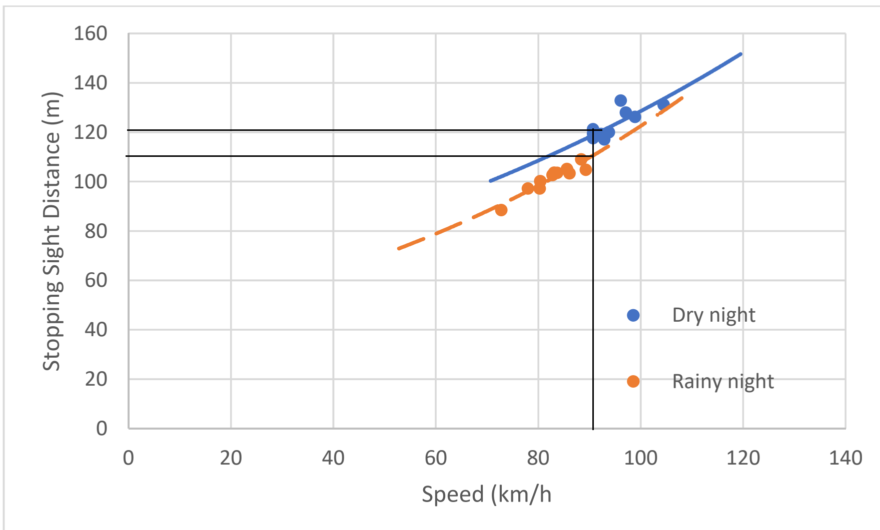


Figure 6.3: Stopping site distance graph for dry night and rainy night-time conditions

From the graph, change in stopping sight distance is significant by the difference between the positions of the trendlines for the scenarios considered. The rainy night-time trendline shifted downward away from the dry night-time trendline. Consider a vehicle traveling at 90km/h, its stopping sight distance under dry night conditions is 120m and 110m for rainy night conditions.

6.4 Influence of Rainy Night-Time on Stopping Sight Distance

The study results show that night rain has an influence on stopping sight distance. According to the results, the general average increase in reaction distance is 12.1 percent while the general braking distance decreased by 22.4 percent. However, the general average decrease in stopping sight distance due to rainy night conditions irrespective of rainfall intensity is 16.9 percent.

Based on the results obtained for stopping sight distance, it is observed that free flow speed under night rain conditions reduces irrespective of rainfall intensity. This led to a decrease in stopping sight distance under rainy night conditions in comparison with dry night condition. The decrease is a function of the negative effect of rainfall on free flow speed. However, breaking distance has a more significant impact on the stopping sight distance reduction due to rain compared to the reaction distance. It may be assumed that since visibility is impaired due to rainfall, at night, drivers are prone to reducing their speed. The reduction in speed has a consequent effect on stopping sight distance such that lesser distance is required in bringing a vehicle to a halt under rainy conditions, but their reaction is time is not affected hence the minimal influence of reaction distance on stopping sight distance reduction under rainy night conditions.

Bearing in mind that the functional service quality deteriorates significantly more under heavy night rain intensity, this trend is also followed by stopping sight distance. The decrease in stopping sight distance is more evident with heavy rain intensity as against light rain intensity. With the results obtained for the braking distance, reaction distance and stopping distance, could they be compared with results of previous studies? It may be queried. Thus, the comparison is presented in the next section.

6.5 Comparison of Previous Study and Research Study Results

The findings of this study are germane enough to be compared with past studies. Past studies were mainly carried out in a controlled environment of wetted road pavement surface, daylight conditions and presumed driver's behaviour. This study is however different from previous studies because it is carried out '*in situ*' such that there was rain occurrence at night for the period of data collection on the dark roadways without light. The environment and conditions of this study are not in any way influenced or controlled by the researcher such as to predict the outcome. The study conditions give room for behavioural differences and this further buttressed the essence of modifying passenger car equivalents. The braking distance, reaction distance and stopping sight distance results from previous studies for a wet pavement road surface are related with the results of this study.

Table 6.6 represents the reaction distance of various countries. According to the table, the countries with '*' used 2s as a reaction time while those with '**' used 2.5s as a reaction time, hence the similarity across countries with same reaction time. This study however, used 2.5s, hence, the similarity with USA and South Africa reaction distance values.

Table 6.6: Wet Pavement Reaction Distances

Speed *km/h*	Reaction Distance *(m)*									
	DNK*	FRA*	DEU*	IRL*	NLD*	CHE*	GBR*	USA**	ZAF**	Study**
50	27.8	27.8	27.8	27.8	27.8		27.8	34.8	34.8	34.8
60	33.4		33.4	33.4		33.4	33.4	41.7	41.7	41.7
70	38.9	38.9	38.9	38.9			38.9	48.7	48.7	48.7
80	44.5		44.5	44.5	44.5	44.5	44.5	55.6	55.6	55.6
90	50.0	50.0	50.0					62.6	62.6	62.6
100	55.6		55.6	55.6	55.6	55.6	55.6	69.5	69.5	69.5
110	61.2	61.2	61.2					76.5	76.5	76.5
120	66.7		66.7	66.7	66.7	66.7	66.7	83.4	83.4	83.4
130	72.3	72.3	72.3					90.4	90.4	90.4

*DNK = Denmark, FRA = France, DEU = Germany, IRL = Ireland, NLD = Netherlands, CHE = Switzerland, GBR = United Kingdom, USA = United States of America, ZAF = South Africa, * = Van Petegem et al 2014 (t = 2s), ** = AASHTO (2011) and SANRAL (t =2.5s)*

From Table 6.6, it is obvious that the difference in reaction time is comparatively small relative to speed variation. With the result obtained for the reaction distance, it is therefore imperative to ask if braking distance will follow a similar trens. Thus, the corresponding braking distance for the different speed values is presented as Table 6.7.

Table 6.7: Comparison of Wet Pavement Braking Distances

Speed *km/h*	Reaction Distance *(m)*									
	DNK*	FRA*	DEU*	IRL*	NLD*	CHE*	GBR*	USA**	ZAF**	Study**
50	26.2	22.2	26.2	42.2	32.2		43.8	28.8	32.5	16.0
60	37.6		37.6	56.6		26.6	52.4	41.3	46.7	23.0
70	51.1	46.1	51.1	81.1			68.9	56.3	63.7	31.3
80	66.5		66.5	115.5	60.5	55.5	93.5	73.4	83.1	40.9
90	84.0	80.0	84.0					93.0	105.3	51.8
100	104.4		104.4	159.4	114.4	91.4	110.6	114.7	129.9	64.0
110	125.8	133.8	125.8					138.9	157.2	77.4
120	150.3		150.3	228.3	193.3	141.3	144.7	165.2	187.1	92.1
130	175.7	207.7	175.7					193.9	219.6	108.1

*DNK = Denmark, FRA = France, DEU = Germany, IRL = Ireland, NLD = Netherlands, CHE = Switzerland, GBR = United Kingdom, USA = United States of America, ZAF = South Africa, * = Van Petegem et al 2014 (t = 2s), ** = AASHTO (2011) and SANRAL (t =2.5s)*

From table 6.7, it is evident that as speed increases, braking distance increases substantially for all the results obtained. Also, the table shows a significant difference in the obtained braking distance values. The difference in braking distance values is a function of the deceleration rate used which varies across the previous results. In this study, the average deceleration rate obtained in step 2 of section 6.3 is 6.04m/s^2, hence, it was used to calculate the braking distance for the speed values considered. Comparing the study values obtained with the previous results of other countries, the values are within the lower and upper boundary for each speed value. Table 6.7 is further presented graphically in Figure 6.4.

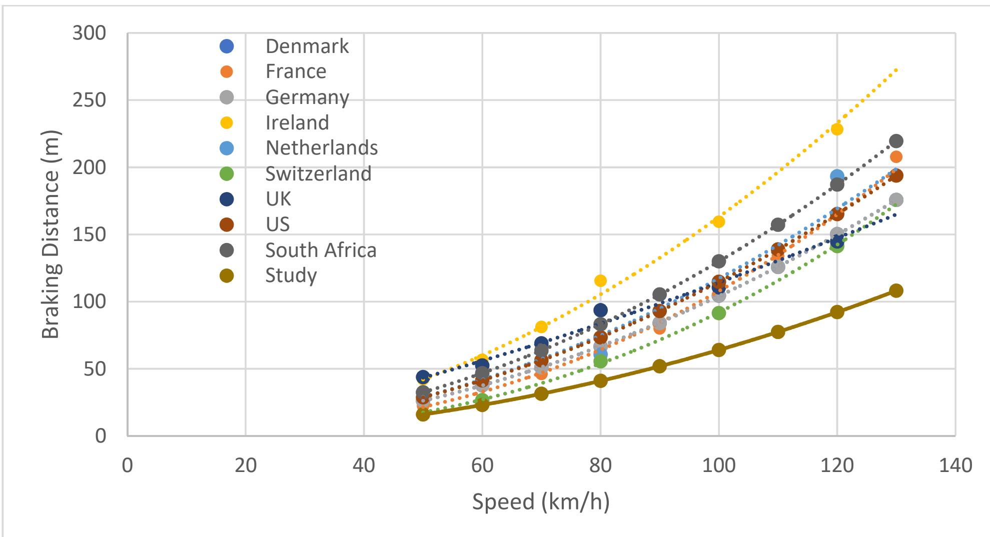


Figure 6.4: Braking distance of previous results and study result

From the graph, the obtained study result aligns with previous result values. This is evident by the trendline of the study braking distance following the trend of the previous results despite the difference in weather and environmental conditions. On this basis, the stopping sight distance for previous results and this study result is presented in Table 6.8 and Figure 6.5 respectively.

Table 6.8: Wet Pavement Stopping Sight Distances

Speed *km/h*	Reaction Distance *(m)*									
	DNK*	FRA*	DEU*	IRL*	NLD*	CHE*	GBR*	USA**	ZAF**	Study**
50	54.0	50.0	54.0	70.0	60.0		70.0	63.5	67.2	50.7
60	71.0		71.0	90.0		60.0	90.0	83.0	88.4	64.7
70	90.0	85.0	90.0	120.0			120.0	104.9	112.3	80.0
80	111.0		111.0	160.0	105.0	100.0	160.0	129.0	138.7	96.5
90	134.0	130.0	134.0					155.5	167.8	114.4
100	160.0		160.0	215.0	170.0	147.0	215.0	184.2	199.4	133.5
110	187.0	195.0	187.0					215.3	233.6	153.9
120	217.0		217.0	295.0	260.0	208.0	295.0	248.6	270.5	175.5
130	248.0	280.0	248.0					284.2	309.9	198.5

*DNK = Denmark, FRA = France, DEU = Germany, IRL = Ireland, NLD = Netherlands, CHE = Switzerland, GBR = United Kingdom, USA = United States of America, ZAF = South Africa, * = Van Petegem et al 2014 (t = 2s), ** = AASHTO (2011) and SANRAL (t =2.5s)*

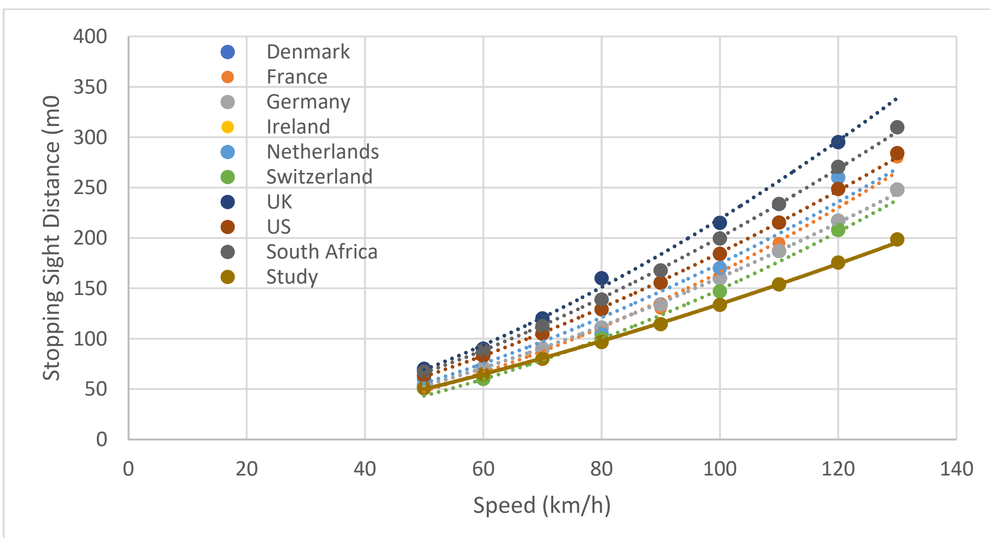


Figure 6.5: Stopping sight distance of previous results and study result

From the table and graph, the stopping sight distance of the previous results and the study result followed a similar pattern according to their trendline. For this study, the result obtained is within the lower and upper boundaries of previous results. Summarily, it may be correct to say that the difference in the computed values of braking distance, reaction distance and stopping sight distance is dependent on the environmental conditions under which the study was carried out.

6.6 Summary

This chapter focussed on the implication of night-time rain on the stopping sight distance of a two-lane road without light. Stopping sight distance was identified as the summation of braking distance and reaction distance. A dummy-based speed-density relationship was adopted in describing the behaviour of dry night and night rain conditions. The adopted models were analysed accordingly for braking distance, reaction distance and stopping sight distance. The result of the study is such that stopping sight distance is dependent on speed. Under rainy night conditions, irrespective of its intensity, a driver requires lesser distance to bring a vehicle to a halt than stopping under dry night conditions. However, as speed reduces due to increase in rainfall intensity, stopping sight distance decreases and vice-versa. The summary of the analysis is that stopping sight distance is affected by rainfall at night due to impaired visibility and reduction in speed. This could be used in setting safety measure policy(ies) on roads.

CHAPTER SEVEN

CONCLUSION

7.1 Overview

This study is based on the hypothesis that the extent of functional service quality's aberrant reduction resulting from rainfall at night on dark roadway is significant. The aim behind this exercise is to establish the extent to which functional service quality can be sustained in the presence of rainfall at night on dark roadways, and the relationship between the two variables. Rain poses a major hazard with various impacts on road and traffic performances due to its spatiotemporal nature. Probably the most obvious hazard of driving at night in the rainfall on dark roadways is decreased visibility.

Driving in the rain at night is challenging and more so if the roadway has no light. Rainfall has many characteristics which are measured in terms of quantity, frequency, distribution over an area, time of occurrence and intensity. Rainfall intensity, which is of interest to this study, is classified as light, moderate and heavy. Light rain has an intensity of less than 2.5mm/h, moderate rain with an intensity greater than or equal to 2.5mm/h but less than 10mm/h and heavy rain has an intensity greater than or equal to 10mm/h but less than 50mm/h.

Functional service quality describes the assessment of the service delivery of roadways based on both road provider (travel speed) and user (travel time) perceptions. For the purpose of assessing functional service quality, the relationship between travel time and volume/capacity ratio as well as speed/flow relationship are important. Passenger car equivalent values were used in estimating traffic flows; both the standard Nigeria values and the modified values based on empirical findings in this study.

A functional service quality criteria table was developed and used to assess the prevailing conditions. Within the purview of the study objectives, traffic on various road sections with and without rainfall at night on dark roadways were surveyed and the empirical results investigated in the light of evidence obtained from the examination of survey data. The analytical findings for dark roadways with and without rainfall at night were compared.

From the survey sites' empirical results, SS01 with 1459 vehicles has the highest recorded volume of vehicles during the one-hour daylight duration count, while SS02 recorded the lowest with 1255 vehicles. SS02 with 942 vehicles has the highest recorded volume of vehicles during the one-hour dry night-time duration count while SS03 recorded the lowest at 690 vehicles. Irrespective of rainfall intensity, SS01 and SS04 have the highest recorded volume of 934 vehicles during the one-hour rainy night-time conditions while SS03 with 543 vehicles has the lowest recorded volume during the one-hour rainy night-time rain conditions. Generally, light vehicles known as passenger cars are dominant across the four sites with an average of 82.2 percent irrespective of weather conditions. The medium vehicles accounted for 11.3 percent and heavy vehicles accounted for 6.2 percent. In all the cases, there is a substantial drop in vehicle speeds during heavy rainfall. Light vehicles constitute the highest volume of traffic both at night-time and daytime. It was observed that heavy goods vehicle, buses and coaches are the least affected by night rainfall from the three type of vehicles (passenger cars, medium vehicles, heavy goods vehicles) considered in this study and it is reasonable to suggest that an increase in the percentage of HGVs may affect the extent of functional service quality reduction. The number of rainy days was higher at SS03 and SS04 as opposed to SS01 and SS02.

Based on the synthesis of evidence obtained from the relationship between functional service quality reduction and night rainfall on dark roadways, it is correct to conclude that no lasting solution to the traffic safety challenges will be found unless that solution addresses the issue of excessively dark roadways. In summary the study has shown that:

1. Functional service quality reduction would result from night rainfall on dark roadways;
2. Night-time rainfall on dark roadways has a significant negative impact on average travel speed and travel time;
3. Heavy night rainfall on dark roadways is a significant contributor to functional service quality reduction;
4. Stopping sight distance increase resulted from night rainfall on dark roadways.

In light of the discussion thus far, the remainder of this chapter is organised into five sections. Section 7.1 summarises the major findings of the night-time rainfall on dark roadway conditions while section 7.2 summarises the major findings of functional service quality reduction analyses. Section 7.3 focuses on the synthesis of evidence obtained from average travel speed loss and travel time increase, while in section 7.4, the implication of night rainfall on aberrant stopping sight distance of dark roadways is discussed. In section 7.5 the way forward is presented.

7.2 Summary of findings based on night rainfall on dark roadways

Presently, paved road length in Nigeria is made up of 28,453km trunk A (express) and the most common two-lane highway 10,400km trunk B roads. An impact study on night-time rainfall on dark roadways was carried out at trunk B road of 7.3m carriageway with a 1.2m shoulder, 1000 – 5000 annual daily traffic, a design life of 20 years, and design speed of 80km/h on level terrain.

Rainfall intensity was classified into three categories such that light rain has an intensity less than 2.5mm/h, moderate rain has an intensity greater than 2.5mm/h but less than 10mm/h and heavy rain with an intensity greater than 10mm/h but less than 50mm/h. According to rain data obtained, rainfall distribution varies over time and day with no trend being followed. This in turn impact traffic flow operation irrespective of its intensity.

Traffic flows and vehicle speeds drop significantly, while density increases on road sections during night rainfall. During dry nights, speed distribution fluctuates suggesting that drivers are not constrained by night-time rainfall, hence, they can choose their speed. Whereas during night rainfall speed distribution is almost flat suggesting that drivers are constrained by night-time rainfall conditions. Generally, passenger cars are dominant at the four surveyed sites with an average of 82.2 percent, medium vehicles accounted for 11.3 percent and heavy vehicles 6.2 percent. In all the cases, there is a substantial drop in vehicle speeds during heavy rainfall due to vehicle composition.

From the study, it was observed that rainfall amounts at SS03 and SS04 are higher than the rainfall amounts obtained at SS01 and SS02. Interestingly, even though the rainfall amounts at site SS03 and SS04 are higher than those obtained at SS001 and SS002 that has not translated into a functional service quality reduction. Site SS02 had the worst functional service quality deterioration being D. At SS02, it is evident that as rainfall intensity increases, free-flow speed decreases while travel time increases. So, it is correct to assert that night rainfall on dark roadways has aberrant functional service quality mainly because rainfall intensity does not cause proportional reduction in functional service quality.

7.3 Summary of findings based on functional service quality reduction

The novelty in the study is such that with the criteria table, either the road provider or the road users' perception of functional service quality can be assessed. This study incorporated travel speed and travel time as service measures for assessing functional service quality. Functional service quality reduction was assessed using the criteria table developed for each site.

The criteria table was based on travel time as the proxy for road user perception of functional service quality and travel speed as the proxy for road provider perception of functional service quality. The criteria table was divided into six classes using alphabets A to F. Class A represents the best service quality in which traffic performance is without any hassle while class F is the worst service quality where traffic performance is at its worst on the road. Class E is the capacity class in which road performance is at its maximum before breaking down to class F. However, class D is the threshold class which serves as a warning for management and control purposes. Results of the functional service quality aberrant reduction analysis can best be summed up as an increase in travel time relative to a decrease in travel speed.

The functional service quality criteria table was developed using standard Nigeria passenger car equivalent (PCE) values: Light vehicles, (LV) = 1; Medium vehicles, (MV) = 3 and heavy goods vehicle, (HV) = 3 units. Nigeria passenger car equivalent (PCE) values were modified for night rainfall travel on dark roadways, the modified PCE values are PC = 1; MV = 1.15 and HV = 1.34 units.

Generally, the modified PCE values gave lower functional service quality reduction because the modified PCE values were smaller and took account of the prevailing dark roadway and traffic conditions. Nevertheless, modification of the PCE values did not affect the outcome of the study as functional service quality aberrant reduction resulted from night rainfall on dark roadways. Since PCE values are central to functional service quality calculation, it follows that the problem of passenger car equivalency values cannot however be ignored. On the one hand, it shows the potential of commercial vehicles gaining control of the road by exploiting the presence of night rainfall on dark roadways. On the other hand, it exposes the weakness of passenger cars as a mode of transport during night rainfall on dark roadways.

7.4 Synthesis of evidence obtained from average travel speed and travel time

In this study, travel speed and travel time were obtained and used as service measures in assessing road functional service quality. The obtained travel speed and travel time were used in setting the FSQ criteria table in which travel speed is for the road providers' perception and travel time is for the road users' perception of quality service delivery. Travel time over a roadway length is used as the proxy for road users' perception of quality. In the travel speed/density model, linear regression was used while applying the least square method to determine the correlation between the parameters under dry and night rainfall conditions. By applying the least squares, assumptions were made among others that the explanatory variables were truly endogenous; that there was one-way causation between the dependent variable and the explanatory variables. Each slope coefficient was tested for usefulness in estimating the extent of night rainfall on dark roadways. The slope coefficient with the strongest indicator by way of the t-statistic value was compared separately with the extent of functional service reduction.

Based on the result of the findings, travel speed reduction was evident across the four sites under night rainfall conditions, though the reduction is anomalous. Similarly, travel time increased under night rainfall conditions due to a reduction in the travel speed. However, it is to be noted that the travel time increase did not follow any trend, but the increase is more evident and significant under heavy rain intensity. This may be attributed to poor visibility associated with rainfall irrespective of its intensity. The changes in travel speed and travel time are more evident at SS02 and SS03 than SS01 and SS04. The anomaly in travel time increase and travel speed aberrant behaviour may be attributed to differences in traffic composition and driver behaviour.

According to the study results, the average travel time increase is 0.16min (27.1 percent) for dark roadways under night rainfall conditions, irrespective of its intensity. The increase in travel time is a result of speed reduction which reduced averagely by 20.9km/hr (18.7 percent) under rainfall conditions. Based on the synthesis of evidence from the average travel time and average travel speed differentials, it is correct to state that night rain irrespective of its intensity affects the functional service quality of dark roadways.

7.5 Synthesis of evidence from night rainfall on dark roadways' implication for stopping sight distance (SSD)

Bearing in mind that rainfall triggers speed reduction with a subsequent increase in travel time, it is necessary to investigate the influence of night rain on stopping sight distance of dark roadways without light. Although not considered a major part of the study, the possible implication of night rainfall on stopping sight distance of dark roadways was reviewed. Stopping sight distance is dependent on various factor in which speed is a common parameter for both breaking distance and reaction distance. The coefficient of friction varies for different road surfaces under varying prevailing conditions. Jones and Childers (2001) reported 0.7 and 0.4 for dry surface and wet surfaces respectively. It is rather unclear whether the wet road is under rainfall or dry weather conditions, nevertheless, it contained enough reasoning to substantiate the admission of 0.7 for dry and 0.4 for wet road surfaces. What is clear from the postulations is that the friction factors for wet and dry road surfaces have different values. It was self-evident at survey sites based on observation that vehicle road surface grip performance during rainfall on dark roadways forced motorists to travel at a reduced speed. Since stopping sight distance is an impact study implication there is no need to build new friction factors.

Given the synthesis of evidence from night rainfall on dark roadway conditions, it is correct to argue that both vehicle speed and the coefficient of friction were significant enough to cause changes in stopping sight distance. The result of the findings showed that reaction distance increased while both braking distance and stopping sight distance decreased under night-time rainfall conditions, irrespective of rainfall intensity. The reaction distance increased averagely by 12 percent while braking distance decreased by 22.4 percent. However, the decrease in braking distance is more significant compared to its equivalent reaction distance. The change in braking distance resulted in a significant change in stopping sight distance. The stopping sight distance of dark roadways decreased averagely by 16.9 percent due to night-time rainfall. Based on this synthesis of evidence from night-time rainfall on dark roadways' implication for stopping sight distance, the hypothesis that night rain irrespective of its intensity will have a significant effect on stopping sight distance is correct.

7.6 The way forward

The study shows that significant functional service quality reduction will result from night rainfall on dark roadways and concludes that the estimated functional service quality values are correct. It has long been clear that the problem of the road system in Nigeria is not one of engineering but policies and management. This implies that the development of effective road policy will be the way forward. There has been a systematic neglect of roads in Nigeria, to the extent that the physical condition of virtually every category of road is poor and, in some cases, extremely poor. It is conceded that the task of managing a road system effectively is not without maintenance difficulties and other challenges. Notwithstanding, whether it is poor maintenance or the lack of it that is responsible for widespread dark roadways, night rainfall will trigger functional service quality deterioration and heighten the risk of traffic accidents. It can be argued that the vicious circle of dark roads derives largely from the prevalence of an uncoordinated road management system and defective road policy.

Road management will require good planning for effectiveness and efficiency, and good planning depends on relevant, timely and accurate data. In Nigeria, the approach to road management at the moment can best be described as intuitive and short-term focused. The national road database is still partial, manual, ineffective and incomplete, and it can be extremely difficult if not impossible at times to locate reliable, updated and comprehensive documents on the road system. Keep in mind that the absence of road data would make accurate quantification, evaluation and planning decisions become questionable, short-termed and crisis-oriented. The longer the problem of dark roadways remains unresolved, the greater will be the degree of road users' security concerns, especially when it rains at night.

This study gave an insight into some of the problems associated with the road system in Nigeria. At the time of survey, there was no evidence of a road capacity manual at any level of government. Barely sufficient information on road geometry and pavement conditions was available from the Federal Ministry of Works and the Nigerian Building and Road Research Institute (NBRRI); there is very little information concerning highway capacity in relation to road, traffic and control conditions. This in itself would make the road system in Nigeria very difficult to manage.

Currently little is known about driver behaviour under rainfall conditions and it would be useful if research could be undertaken in this area. In particular, there is a need to investigate comprehensively in the car-following models. There is further concern about the problem of vehicle passing manoeuvres and drivers' lane discipline.

In Nigeria where local capability to manage the road system is limited, assistance is generally needed, as a successful outcome will require a fusion of foreign technology, investments and local inputs. The process will generally involve new learning at a small price when compared to the costs of ignorance, primitive technology and outdated management techniques. This study believes that of far greater value is an understanding and experience of a systematic approach to road transportation conditions' problem-solving than the potential availability of particular technology and problem-solving approach. While it is recognised that technology must be appropriate to the specific needs of a particular country, it can be argued that the depth of understanding and experience of systematic, objective approach to maintenance is more relevant and readily transferable than individual items of technology. One reason among many others is the lack of quality information database for a more robust decision- making process.

At the moment, the Nigeria road system needs policy provision to promote road management learning and improve road maintenance performance. Despite all the investments in road building, road rehabilitation and expansion programmes; road transportation in Nigeria has remained poor, because once roads are constructed; they are often laid to waste. It is asserted that a departure from the prevalent 'use to breakdown' culture is the way forward and the cornerstone for any meaningful road policy.

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APPENDIX I

Publications, Conferences and Training

Re: 2016 Transportation Planning and Safety Course

Confer <awconfer@vsnl.com>

Tue 2016-09-13 10:01 PM

To: Opeyemi Makinde (216073398) <216073398@stuukznac.onmicrosoft.com>;

Dear Opeyemi Makinde,

The International Course on Transport Planning and Traffic Safety will be held at the Indian Institute of Technology Delhi (India) from 1st – 7th December, 2016.

The Review and Finance Committee met this week and is happy to make the following offer to you :

1. You are offered a place in the International Symposium on Transportation Planning and Safety being held at IIT Delhi from 1st – 7th December, 2016.

2. Your registration fee of US$. 850 will be paid on your behalf by the Department of Transportation Research and Injury Prevention Programme or TRIPP at IIT Delhi.

3. We have reserved a basic twin sharing accommodation for you at Guest House near to the IIT Delhi campus from 1st – 7th December, 2016. You will be sharing the room with another Female participant.

4. The Department of Transportation Research and Injury Prevention Programme or TRIPP at IIT Delhi is happy to offer you upto INR. 49,000/- towards your travel. Kindly bring copies of your travels document with you. You will be reimbursed by a cheque made in your name.

Kindly confirm your participation by/before the 20th of September. In case we do not hear from you, we will offer the place to another participant.

Thanking you,

Kind regards
Peter
TRIPP Course

Diya Walia / Peter Tennent
D-1, Kalindi Colony
New Delhi - 110065
T: 91-11-2691 9377, 2684 9399
F: 91-11-2684 8343
awconfer@vsnl.com

THIS IS TO CERTIFY THAT

Opeyemi Oluyemisi Makinde

has participated in the

INTERNATIONAL COURSE

on

TRANSPORTATION PLANNING AND SAFETY

01 - 07 December, 2016

This course was designed to bring together professionals working in the area of transportation planning, safety promotion, biomechanics of impact and vehicle crashworthiness to acquaint them with the state-of-the-art information in the field. The contents of the course were especially focussed to give a global perspective to the road safety problem. The participants have been exposed to

- The latest findings and methodologies for prevention of traffic accidents and injuries
- The policies and methods which have been shown to be successful or have not worked in the past
- Strategies for starting local programmes in road safety

Geetam Tiwari
I I T Delhi, India

Sudipto Mukherjee
I I T Delhi, India

SUPPORTED BY

Transportation Research & Injury Prevention Programme,
Indian Institute of Technology Delhi;
Volvo Research & Educational Foundations, Sweden
Ministry of Urban Development, Govt. of India;
Ministry of Road Transport & Highways, Govt. of India ;
TATA Trusts; Independent Council of Road Safety International (ICoRSI);
Shakti Sustainable Energy Foundation
World Health Organisation (SEARO)

FW: CSCE 2018: Paper Status

Johnnie Ben-Edigbe
Mon 2018/04/23 12:50 AM
To: Opeyemi Makinde (216073398) <216073398@stuukznac.onmicrosoft.com>

From: 12th International Transportation Specialty Conference <noreply@xcdsystem.com>
Sent: 23 April 2018 14:28
To: Johnnie Ben-Edigbe <Ben-Edigbe@ukzn.ac.za>
Subject: CSCE 2018: Paper Status

Paper Reference No: TR3

Paper Title: Effect of Rainy Darkness Intensity at Two-Lane Highway on Travel Time Differentials

Dear Johnnie Ben-Edigbe,

Thank you for submitting the above-referenced paper to the 2018 CSCE Annual Conference to be held in Fredericton June 13 -16.

Members of the Technical Committee have received the reviewers' comments and we are pleased to inform you that your paper (or case study) has been accepted for oral presentation and inclusion in the Conference Proceedings. **Acceptance is conditional on adequately addressing the reviewers' comments and implementing any editorial and/or formatting changes.**

For your Final Paper (or Case Study) Submission please ensure that any comments below are reviewed and addressed.

- your paper (or case study) fully meets the formatting requirements and templates provided on the conference website.
- your paper does NOT EXCEED **10 pages** in length, or that your case study does NOT EXCEED **4 pages** in length.
- your paper (or case study) is submitted as a **.docx file** (NOT a pdf file).
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Note from specialty chair: Given the conference theme is about "building tomorrow's society", I suggest you make edits that highlight how this work is necessary for building tomorrow's society and how it could also have relevance for transportation in Canada as well.

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1. Grammar needs work (for eg. they use the term "rainy darkness" to describe rainy conditions that occur when it is dark). 2. There are equations and figures inserted in the paper that add little/no value. 3. Unclear why they didn't contrast their findings against daylight. 4. Unclear how the results would be used in any practical sense. 5. Concluding that "rainy darkness has a significant effect on travel time" is not particularly profound. This is CSCE....how might these findings be replicated for snow?? 6. p2: what is "colour vision"? 7. Section 3: were pavement markings present?? (important) 8. Figure 1 is useless 9. Figures 1-4 should be combined on a single plot and presented as Figure 5. 10. References to HCM2000 are outdated.

CSCE – Paper_TR3_0221052620 This research paper presented travel time differentials prompted by rainy darkness on Two-Lane Highway. Field data collected based on the selected sites in Nigeria during the rainy season. This is a promising study and the results include important variables such as the travel time increase relative to speed decrease during rainy darkness, thus suggesting that

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EFFECT OF RAINY DARKNESS INTENSITY AT TWO-LANE HIGHWAY ON TRAVEL TIME DIFFERENTIALS

Makinde, Opeyemi Oluyemisi[1,3] and Ben-Edigbe, Johnnie[2]
[1] University of KwaZulu-Natal, South Africa
[2] University of KwaZulu-Natal, South Africa
[3] 216073398@stu.ukzn.ac.za

Abstract: In this paper travel time differentials prompted by rainy darkness on Two-Lane Highway were investigated. The investigation raises the issue of night travel on roads without lights. Even though drivers react to rainfall and darkness simultaneously, studies have not been carried out insufficiently. Hence the paper wants to provoke debate on this issue. Based on the hypothesis that rainy darkness irrespective of intensity will cause travel time increase, with and without rainy darkness studies were carried out at three selected sites in Nigeria during the rainy season (June-August). Traffic and rainfall data were collected continuously for eight weeks. Rainfall intensity was classified according to the conventional rate of precipitation: Light rain — when the precipitation rate is < 2.5 mm (0.098 in) per hour. Moderate rain — when the precipitation rate is between 2.5 mm (0.098 in) - 7.6 mm (0.30 in) or 10 mm (0.39 in) per hour. Collated data on which the study was based were analyzed. Travel times for with and without rainy darkness were estimated and compared. Results show that there is speed reduction of 4.1% due to light rain effect, 8.6% and 14.8% due to moderate and heavy rain effect respectively. Further, travel time increase relative to speed decrease during rainy darkness, thus suggesting that motorists reduce vehicle speed when it is dark and rainy irrespective of intensity. The paper concluded that rainy darkness has a significant effect on travel time.

1 Introduction

The highway is an important element of transportation because it connects all other forms of transportation. Traffic flows on the highway are expected to be safe, efficient, give good driving comfort and with minimum delay. Vehicle performance on highway depends on the road geometry, traffic volume, traffic composition and weather condition like fog, snow, wind, darkness and rainfall. These weather conditions can be mild and could be harsh depending on the intensity of rain and fog, wind speed and their duration. Harsh weather condition can bring about total traffic flow disruption on the highway. The weather impacts on traffic flows affect delays, safety, travel demand, and road accident (FHWA, 2008 and Cools *et al.* 2010). Weather impact on traffic flow may increase accident, delay, speed reduction and traffic flow contraction (Alhassan and Ben-Edigbe, 2014). Rainfall disrupts traffic flow by reducing driver's visibility, thereby leading to speed reduction, and increase in headways (Ben-Edigbe, 2010). Other studies by Chung et al, (2005) and Mukhlas et al (2016) showed that increase in rainfall intensity causes speed and capacity decrease and increase in travel time. Under darkness condition where there is no road lightning, there is poor or no illumination, drivers are dependent on the performance of their vehicle headlights. This condition affects the driver's visibility because of deterioration in colour vision which could lead to a reduction in sight distance. If rainfall is thrown in the mix, then driving conditions deteriorate even further. Rainy darkness depicts rainfall and darkness conditions. When driving under rainy darkness, the driver will be subjected to the combined effect of rainfall and darkness. This might

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EFFECTS OF NIGHT-TIME RAINFALL ON TRAVEL TIME AT TWO-LANE HIGHWAY WITHOUT STREET LIGHTS

Makinde, Opeyemi Oluyemisi[1] and Ben-Edigbe, Johnnie[2]
[1] University of KwaZulu-Natal, South Africa
[2] University of KwaZulu-Natal, South Africa
[2] corresponding author Email: ben-edigbe@ukzn.ac.za

Abstract: Travel time is a function of speed. It is perhaps the most pertinent road link information for road users. In this paper the effects of night-time rainy conditions on travel time at Two-Lane Highway without road lights were investigated. The impact studies were carried out at three selected sites in Nigeria. Survey data for night time rain and dry weather conditions were collected. Traffic and rainfall data were collected continuously for eight weeks, then collated and analysed. Night time rainy conditions were classified as: light rain — when the precipitation rate is < 2.5 mm (0.098 in) per hour; moderate rain — when the precipitation rate is between 2.5 mm (0.098 in) and 10 mm (0.39 in) per hour; heavy rain when precipitation is between 10mm (0.39in) and 50mm (1.97in) per hour. Violent rainy conditions — when the precipitation rate is > 50 mm (1.97 in) per hour were excluded in the studies. Results show an average speed reduction of about 4.1% due to a light rainfall, 8.6% due to moderate rainfall and 14.8% due to heavy rainfall. Consequently, the average travel times increase by 0.8min due to a light rainfall, by 3.2min due to moderate rainfall and by 6.3min due to heavy rainfall. The paper concluded that night-time rainy conditions have significant effects on travel time at the two-lane highway without road lights and the impact of heavy rainfall is very significant

Keywords: travel time; travel speed; traffic volume; rainfall; darkness;

1 Introduction

Street lighting provides a number of important benefits. It can be used to promote security in urban areas and to increase the quality of life by artificially extending the hours in which it is light so that activity can take place. Street lighting also improves safety for drivers, riders, and pedestrians. major advantages of street lighting include prevention of accidents and increase in safety according to Rea *et all* (2009). Studies have shown that darkness results in a large number of crashes and fatalities, especially those involving pedestrians; pedestrian fatalities are 3 to 6.75 times more likely in the dark than in daylight according to Sullivan, J.M., and Flannigan, M.J, (1999). However, street lightings in Nigeria are historic relics.Driver performances at night time on roads without street lights are very challenging especially during raniny conditions. The rainy conditions can be mild or harsh. Harsh weather condition can bring about total traffic flow disruption on the highway. Wet weather affects traffic flows, cause delays, reduce traffic safety, and increase the probability of road accidents (FHWA, 2008 and Cools *et al.* 2010, Alhassan and Ben-Edigbe,

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Night-Time Rainfall Effect on Road Service and Travel Time Loss: A Case Study of Roadway without Light

Makinde, O, O[1] and Ben-Edigbe, J[2]

Department of Civil Engineering
University of KwaZulu-Natal, Durban, South Africa.
[2]Corresponding author

Abstract

On roads without lights, the effect of night time rainfall on the functional quality of service is investigated in this paper. Functional level or quality of service (FQS) is taken as a qualitative measure of the operating conditions of a roadway where travel time and travel speed are used as key performance indicators. Travel time is used as proxy for road service users' quality perception and travel speed used as a proxy for road service provider's perception of service quality. Travel time in conjunction with travel speed and traffic flow were used to develop a novel six-class functional quality of service criteria table where Class A is the best and Class F is the worst. 24hr continuous traffic volume, vehicle speed, vehicle type and rainfall intensity data were collected for eight weeks at four selected 2-lane interstate roadways without light in Nigeria. Results show that an average travel time increase and corresponding travel speed decrease under light, moderate and heavy rainfall. Heavy rainfall caused the highest travel time increase of 9%. Whilst moderate rainfall accounted for 6% increase in travel time and light rainfall accounted for 4% travel time increase, FQS dropped from Class B to Class C during night rainfall on roadways without light. The paper concluded that rainfall has negative effect on the functional quality of service. The findings could be used in a variety of ways in traffic management to predict travel time under rainy conditions and prescribe speed limits accordingly.

Keywords: Night-time, rainfall, level of service, travel time, speed, traffic flow

1. Introduction

Road pavements are intended to sustain structural vehicular load as well as functional traffic flow over time. It can be argued that structural as well as functional quality of service are arguable the key performance indicators. Functional level or quality of service (FQS) is a measurement of overall traffic performance of service. Over the years, measuring quality of service has become a critical area of interest to highway practitioners for design and management purposes. Highway Capacity Manual 2010 level of service (LOS) is often used to assess the quality of service. LOS is an effective measure of a travel speed no doubt, but it is one dimensional. Moreover, HCM-LOS is quiet on estimation of criteria table parameters. In this paper, functional quality of service is presented a measure based on service perception of road users and providers.

List of notation

T	Travel time over roadway length
t_f	Travel time at free-flow speed
x	degree of saturation ($\frac{v}{Q}$)
v	demand traffic volume,
Q	traffic capacity
ρ	ratio of free-flow to speed at capacity
β	abrupt drop of curve from the free-flow speed
q	Flow
u	speed
u_Q	speed at capacity
k	density
u_f	free-flow speed
k_Q	density at capacity

The criteria table parameter estimation methods are presented and discussed. Travel time is used as proxy for road users' service perception and travel speed retained as proxy for road providers' perception of service. There is no previous study on the effect of night time rainfall on functional quality of service (FQS) on roads without lights. Many studies have shown that speed reduction, capacity loss, travel time increase amongst others would result from driving under rainy conditions (Chung et al., 2006; Mashros and Ben-Edigbe, 2013; Ben-Edigbe, 2014; Wang and Luo, 2016; Zhang et al., 2017). Xu et al. (2013) considered rainfall occurrences as a source of uncertainty capable of affecting traffic regarding safety and operation. According to Alhassan and Ben-Edigbe, (2011), rainy conditions are amongst the causes of traffic instabilities and other traffic-related problems on highways. The studies were carried out on road traffic performances under daylight and rainy conditions or night time on roads with light. Road lights are important safety feature for drivers where visibility is essential. Driving in the rain at night poses seriously challenges. It is made even more difficult by the consequence of specular reflection and the absence of road light. Often, there is no legal requirement to provide street lighting in high income countries, yet the provision of road lights is near total. Lights are not switched off on busy roadways with high traffic

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Effect of Night-Time Rain on Travel Speed at Two-Lane Highway without Lights

MAKINDE, Oluyemisi[a], BEN-EDIGBE, Johnnie[b]*

[a]Department of Civil Engineering, School of Engineering, University of KwaZulu-Natal, 4001 South Africa
[b]Department of Civil Engineering, School of Engineering, University of KwaZulu-Natal, 4001 South Africa

Abstract

Speed is one of the parameters used for performance measure of traffic. It is affected by weather changes. This paper investigates the effect of night-time rainfall on travel speed on two-lane highway without lights. Traffic and rainfall data were collected at four different sites in Nigeria for a period of eight weeks. The data were sorted into dry and rainy night-time, filtered and analysed. The use of flow-density relationship gives a better understanding of travel speed within traffic stream operation. The result of the study shows significant change in travel speed between the dry and rainy night-time conditions. The average travel speed reduction was observed to be 3.4%, 6.8% and 10.2% for light, moderate and heavy rain at night-time respectively. This confirms that travel speed reduces under night-time rainfall irrespective of its intensity.

Keywords: Travel speed; free-flow speed; night-time rain; percentile

1. Introduction

Weather conditions and its impacts have been of primary concern to highway and traffic engineers in achieving a smooth, safe and reliable traffic operation. Changes in weather condition has been known to disrupt smooth traffic operations. The disruptions could result in delay, accident, safety implications, speed reduction, congestion and other hazardous driving conditions (FHWA, 2008 and Cools et al. 2010). Over the years, studies have recognised various

* Corresponding author. Tel.: +27 031 260 2005
E-mail address: ben-edigbe@ukzn.ac.za

EFFECT OF NIGHT-TIME RAIN ON TRAVEL SPEED AT TWO-LANE HIGHWAYS WITHOUT LIGHT

Opeyemi Oluyemisi MAKINDE* and Johnnie BEN-EDIGBE**
*, **Department of Civil Engineering, University of KwaZulu-Natal, 4001 South Africa
* [illegible]@stu.ukzn.ac.za, **ben-edigbe@ukzn.ac.za

Introduction

Speed is one of the parameters used for performance measure of traffic. Travel speed is the average speed of a traffic stream over an average time of vehicles moving in the stream. Travel speed is important for assessing traffic operations on roadway. Rain as a weather condition is of concern to highway and traffic engineers due to its impacts on traffic in achieving a smooth, safe and reliable roadway operations. The impacts of weather generally lead to disruption in smooth traffic operations which results in delay, accident, safety implications, speed reduction, congestion and other hazardous conditions.

Driving in the rain is harder than driving in fair weather while driving in rain at night on a roadway without street light is generally harder and of greater risk. Rain affects driving in terms of tyre-pavement friction and visibility. Driving under rainy conditions, drivers may reduce their travel speed because of poor visibility. As speed is use as a measure of traffic performance, it is therefore necessary to study it under rainy condition at night.

Aim

The study aimed at investigating the effect of rainfall on travel speed at a two-lane highway at night.

Hypothesis

On a two-lane highway, travel speed reduces under night time rain irrespective of its intensity as shown in figure 1. UD denotes speed under dry weather and UR denotes speed under rainfall conditions.

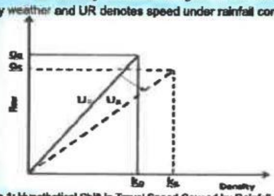

Fig 1: Hypothetical Shift in Travel Speed Caused by Rainfall at Night

Methodology

- Traffic and rata were collected simultaneously for eight weeks on four selected roadways in Nigeria
- Rain data was sorted into different intensities of light, moderate and heavy using World Meteorological Organisation classification system
- Traffic data was collected using Automatic Traffic Counter (ATC)
- Night time considered is 7pm – 11pm
- Data sorted into dry night time and rainy night time for each site

Analysis

Stepwise analysis adopted for the study

Step 1: Speed-percentile differential due to rain determined as shown in figure 2 and result presented as table 1

Step 2: Traffic volume converted to flow using passenger car equivalent values

Step 3: Flow and density related to establish flow-density models based in form of $q = -ak^k + bk - c$

Step 4: Capacity and speed at capacity estimated

All results are presented as table 2 and 3

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Results

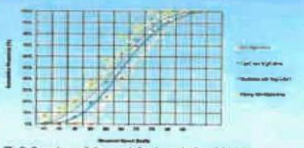

Fig 2: Speed-cumulative graph for dry and rainy night-time

Table 1: Summary of Speed percentile

Site	Weather condition	85%	Δ	50%	Δ	15%	Δ
1	Dry (Night-time)	[illegible]	-	[illegible]	-	[illegible]	-
	Light rain (Night-time)	[illegible]	[illegible]	[illegible]	[illegible]	[illegible]	[illegible]
	Moderate rain (Night-time)	[illegible]	[illegible]	[illegible]	[illegible]	[illegible]	[illegible]
	Heavy rain (Night-time)	[illegible]	[illegible]	[illegible]	[illegible]	[illegible]	[illegible]
2	Dry (Night-time)	[illegible]	-	[illegible]	-	[illegible]	-
	Light rain (Night-time)	[illegible]	[illegible]	[illegible]	[illegible]	[illegible]	[illegible]
	Moderate rain (Night-time)	[illegible]	[illegible]	[illegible]	[illegible]	[illegible]	[illegible]
	Heavy rain (Night-time)	[illegible]	[illegible]	[illegible]	[illegible]	[illegible]	[illegible]
3	Dry (Night-time)	[illegible]	-	[illegible]	-	[illegible]	-
	Light rain (Night-time)	[illegible]	[illegible]	[illegible]	[illegible]	[illegible]	[illegible]
	Moderate rain (Night-time)	[illegible]	[illegible]	[illegible]	[illegible]	[illegible]	[illegible]
	Heavy rain (Night-time)	[illegible]	[illegible]	[illegible]	[illegible]	[illegible]	[illegible]
4	Dry (Night-time)	[illegible]	-	[illegible]	-	[illegible]	-
	Light rain (Night-time)	[illegible]	[illegible]	[illegible]	[illegible]	[illegible]	[illegible]
	Moderate rain (Night-time)	[illegible]	[illegible]	[illegible]	[illegible]	[illegible]	[illegible]
	Heavy rain (Night-time)	[illegible]	[illegible]	[illegible]	[illegible]	[illegible]	[illegible]

Table 2: Summary of travel speed at dry and rainy night-time

Site	Weather condition	Model Equation	u_f (km/h)	Δu_f (%)	u_o (km/h)	Δu_o (%)	u_t (km/h)	Δu_t	Δu_t (%)
1	Dry	$-1.012k^2 + 69.76k - 0.949$	70		35		58		
	LR	$-0.992k^2 + 67.53k - 4.404$	67	-4.3	34	-2.9	57	-1	-1.7
	MR	$-1.031k^2 + 66.35k - 1.226$	66	-5.7	33	-5.7	56	-2	-3.4
	HR	$-1.032k^2 + 65.92k - 1.877$	66	-6.2	33	-5.7	55	-3	-5.2
2	Dry	$-0.975k^2 + 66.17k - 2.66$	66		33		56		
	LR	$-0.989k^2 + 63.38k - 1.177$	63	-4.5	32	-3.0	53	-2	-3.6
	MR	$-0.919k^2 + 60.62k - 0.333$	61	-7.6	30	-9.0	50	-5	-9.1
	HR	$-1.023k^2 + 62.09k - 1.726$	62	-6.1	31	-6.1	54	-1	-1.8
3	Dry	$-1.024k^2 + 75.17k - 1.809$	76		38		63		
	LR	$-1.099k^2 + 70.58k - 6.886$	71	-6.3	35	-7.9	59	-4	-6.3
	MR	$-1.088k^2 + 69.61k - 1.176$	70	-6.7	35	-7.9	58	-5	-7.9
	HR	$-0.969k^2 + 63.65k - 0.269$	64	-14.7	32	-15.8	46	-17	-26.9
4	Dry	$-0.942k^2 + 69.52k - 0.579$	70		35		58		
	LR	$-0.996k^2 + 69.76k - 2.341$	70	0	35	0	58	0	0
	MR	$-1.029k^2 + 66.54k - 4.645$	66	-5.7	33	-5.7	56	-2	-3.4
	HR	$-1.097k^2 + 67.54k - 6.488$	67	-4.3	34	-2.9	56	-2	-3.4

LR = light rain, MR = moderate rain, HR = heavy rain, u_f = free-flow speed, u_o = speed at capacity, u_t = travel speed, Δu = speed change

Table 3: Average speed summary for all sites

Weather condition	u_f (km/h)	Δu_f (%)	u_o (km/h)	Δu_o (%)	u_t (km/h)	Δu_t (%)
Dry night-time	70		35		59	
Light rain (night-time)	68	-2.9	34	-2.9	57	-3.4
Moderate rain (night-time)	66	-5.7	33	-5.7	55	-6.8
Heavy rain (night-time)	65	-7.1	33	-5.7	53	-10.2

Discussion

- There is clear evidence that rain at night-time irrespective if its intensity has effect on travel speed
- Speed reduction is associated with impaired visibility as a result of the rain
- The speed percentile graph showed a backward shift in the s-shaped curve thereby indicating speed reduction due to rain irrespective of its intensity
- Using flow-density relationship, speed-reduction was evident across the four study sites though with no particular trend
- Both free-flow speed and speed at capacity reduced anomalously under rainy conditions
- Heavy rain influences traffic more than moderate and light rain i.e as rain intensity increases, visibility becomes more impaired and speed reduces more

Conclusion

- *Study results show a significant effect of rainfall on travel speed*
- *Travel speed decreases with increase in rainfall at night-time on road with light*
- *Speed reduction is more significant with heavy rain*
- *Hypothesis earlier stated is valid*
- *Flow-density relationship gives proper understanding of travel speed*

Acknowledgements

The authors would like to express their appreciation to the University of KwaZulu-Natal for funding the impact study. Also, we appreciate the Federal University of Technology, Akure-Nigeria for the use of their WASCAL rainfall information for validation of collected rainfall data

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Submission Title: Effect of Night-time Rainfall on Traffic Stream Deterioration of Roads without Light

Dear Dr. Johnnie Ben-Edigbe,

I am pleased to inform you that your article entitled "Effect of Night-time Rainfall on Traffic Stream Deterioration of Roads without Light" has been accepted for publication in "The Open Transportation Journal" after independent peer review.

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We have reached a decision regarding your submission to "The Open Transportation Journal". The manuscript has been reviewed by the editorial board members of the journal and independent experts in the field. Based on the reviewers comments, I am delighted to inform you that the manuscript is now accepted for publication in the journal. On behalf of the Editorial Board, I would like to thank for your contribution and hope that you will consider this journal for future manuscripts.

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We wish to thank you for submission of the manuscript to "The Open Transportation Journal" and look forward to a continued collaboration in the future.

Again, I sincerely thank you for submission of the manuscript in The Open Transportation Journal.

Our decision is to: Accept Submission

With warm regards,

Ambreen Irshad
Senior Editor
Bentham Open
ambreen@benthamopen.net

The Open Transportation Journal
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Alessandro Laviano
[Sapienza - University of Rome, Italy]

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Effect of Night-time Rainfall on Traffic Stream Deterioration of Roads without Light

O.O. Makinde, J.E Ben-Edigbe
Department of Civil Engineering. University of KwaZulu-Natal, Durban South Africa

Abstract

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This paper fills an important gap in the on-going road lighting debate by investigating traffic stream deterioration during night-time rainfall.

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The study carried out an investigation into the impact of night-time rainfall on traffic stream deterioration of two-lane roadways without lighting

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In the rainfall impact studies, traffic volume, speed, vehicle type and headway data were collected at selected road segments in Akure, Nigeria. All surveyed roadways were within rain gauge catchment area of about 1km. Rainfall intensity was divided into three groups (light, moderate, and heavy). Dry weather data were used as a control parameter.

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Stepwise data analysis approach used for the ease of explanation and clarity. All model equations were tested for statistical fitness and deemed satisfactory for further analysis.

Conclusion:

Based on the results and findings, it is correct to conclude that the effect of night-time rainfall on traffic stream deterioration of roadways without lighting is significant. It is also correct to assert that rainfall will affect night-time traffic stream performance on roads without lighting.

Keywords: Traffic flow, Night-time, Rainfall, Delay, Capacity.

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RESEARCH ARTICLE

Effect of Night-time Rainfall on Traffic Stream Deterioration of Roads without Light

O.O. Makinde and J.E Ben-Edigbe*

Department of Civil Engineering, University of KwaZulu-Natal, Durban, South Africa

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Data Analysis:

Stepwise data analysis is used for the ease of explanation and clarity. All model equations were tested for statistical fitness and deemed satisfactory for further analysis.

Results:

From the result, it is observed that rainfall intensityinfluences traffic flow at night-time.

Conclusion:

Based on the results and findings, it is correct to conclude that the effect of night-time rainfall on traffic stream deterioration of roadways without lighting is significant. It is also correct to assert that rainfall affect night-time traffic stream performance on roads without lighting.

Keywords: Traffic flow, Night-time, Rainfall, Delay, Capacity, Traffic Stream.

Article History	Received: February 04, 2019	Revised: April 04, 2019	Accepted: May 25, 2019

1. INTRODUCTION

Nigeria is faced with the problem of insufficient electricity supply to the extent that roadways are without road lights. Driving on such a road at night is challenging as a result of impaired visibility. Nigeria is still saddled with poor provision of road system that often, dark roads are traffic stream optimization constraints at night. Nigeria roads are classified as: Trunk A federal, Trunk B state and Trunk C local with majority of the roads in poor conditions. Given that the roads promote social development and foster economic growth, the tests of optimising traffic stream characteristics would call for roads irrespective of classification to have functional lights and the road surface. According to the report of Ayeni & Oni (2012) and Nzoiwu *et al.* (2017) [1, 2] road accidents increase during the wet season in Nigeria, therefore, it may be correct to assume that roadways without light may be death traps at night when it rains. Generally, it has been shown in previous studies that driving under rainy conditions has an impact on traffic flow, speed, travel time and capacity. How-ever, previous studies focused on roads with lighting consi-dered rainfall occurrences as a source of uncertainty capable of affecting traffic regarding safety and operation [3 - 5]. Note that

* Address correspondence to this author at the Department of Civil Engineering, University of KwaZulu-Natal, Durban South Africa;
Email: ben-edigbe@ukzn.ac.za

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APPENDIX II

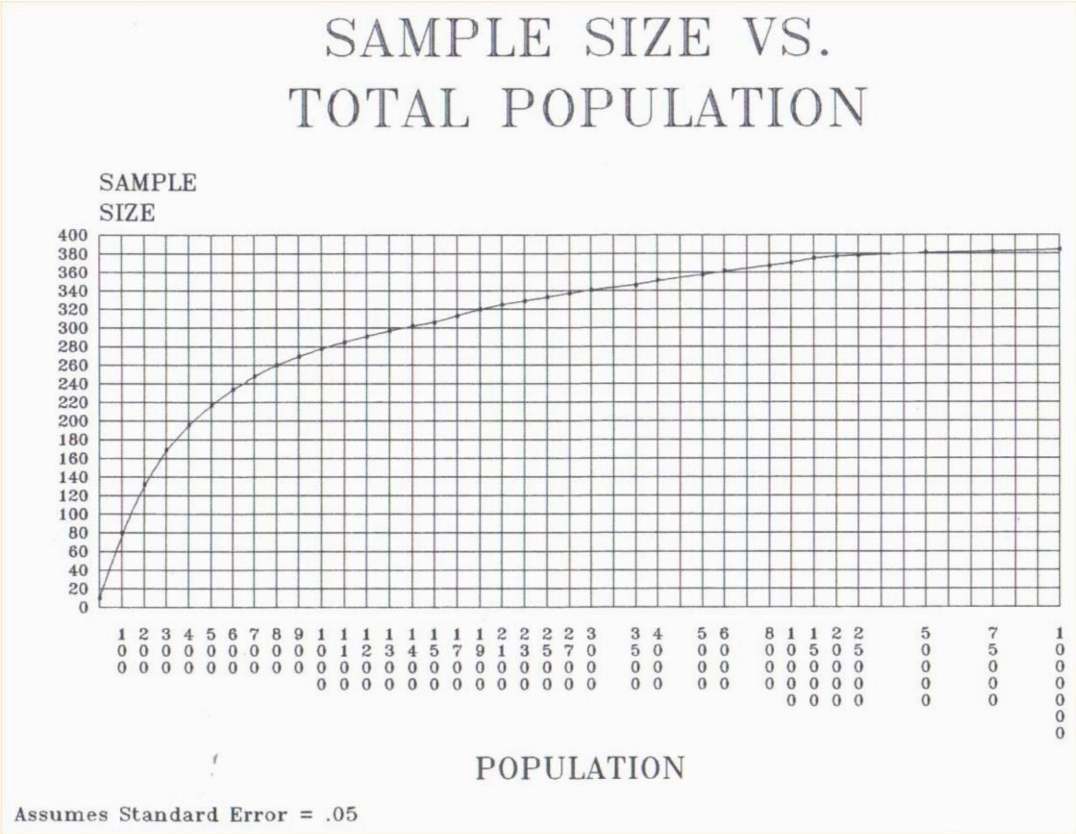
Statistical tables and chart

Table for Determining Sample Size from a Given Population

N	*S*	*N*	*S*	*N*	*S*
10	10	220	140	1200	291
15	14	230	144	1300	297
20	19	240	148	1400	302
25	24	250	152	1500	306
30	28	260	155	1600	310
35	32	270	159	1700	313
40	36	280	162	1800	317
45	40	290	165	1900	320
50	44	300	169	2000	322
55	48	320	175	2200	327
60	52	340	181	2400	331
65	56	360	186	2600	335
70	59	380	191	2800	338
75	63	400	196	3000	341
80	66	420	201	3500	346
85	70	440	205	4000	351
90	73	460	210	4500	354
95	76	480	214	5000	357
100	80	500	217	6000	361
110	86	550	226	7000	364
120	92	600	234	8000	367
130	97	650	242	9000	368
140	103	700	248	10000	370
150	108	750	254	15000	375
160	113	800	260	20000	377
170	118	850	265	30000	379
180	123	900	269	40000	380
190	127	950	274	50000	381
200	132	1000	278	75000	382
210	136	1100	285	1000000	384

Note. - *N* is population size. *S* is sample size.

Source: Krejcie, R.V. and Morgan, D. W. (1970). Determining sample size for research activities, Educational and Psychological Measurement, 30, 607-610



Source: Krejcie, R.V. and Morgan, D. W. (1970). Determining sample size for research activities, Educational and Psychological Measurement, 30, 607-610

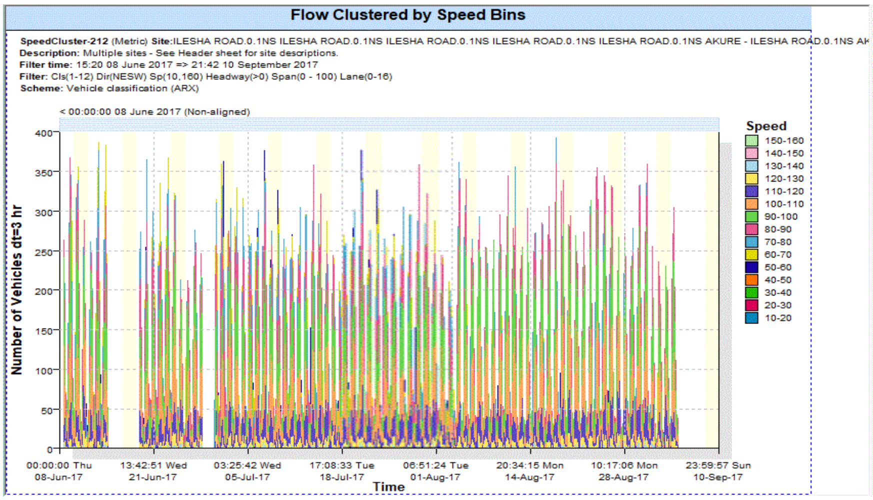
Chi-square Distribution Table

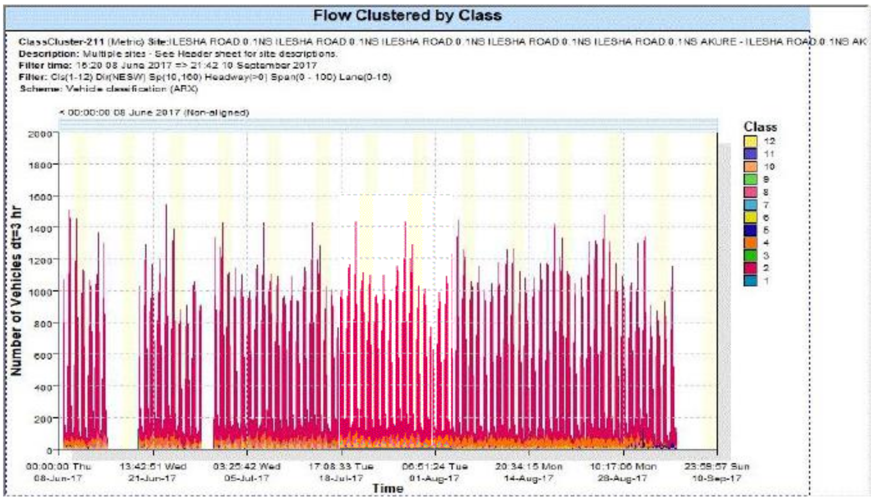
d.f.	.995	.99	.975	.95	.9	.1	.05	.025	.01
1	0.00	0.00	0.00	0.00	0.02	2.71	3.84	5.02	6.63
2	0.01	0.02	0.05	0.10	0.21	4.61	5.99	7.38	9.21
3	0.07	0.11	0.22	0.35	0.58	6.25	7.81	9.35	11.34
4	0.21	0.30	0.48	0.71	1.06	7.78	9.49	11.14	13.28
5	0.41	0.55	0.83	1.15	1.61	9.24	11.07	12.83	15.09
6	0.68	0.87	1.24	1.64	2.20	10.64	12.59	14.45	16.81
7	0.99	1.24	1.69	2.17	2.83	12.02	14.07	16.01	18.48
8	1.34	1.65	2.18	2.73	3.49	13.36	15.51	17.53	20.09
9	1.73	2.09	2.70	3.33	4.17	14.68	16.92	19.02	21.67
10	2.16	2.56	3.25	3.94	4.87	15.99	18.31	20.48	23.21
11	2.60	3.05	3.82	4.57	5.58	17.28	19.68	21.92	24.72
12	3.07	3.57	4.40	5.23	6.30	18.55	21.03	23.34	26.22
13	3.57	4.11	5.01	5.89	7.04	19.81	22.36	24.74	27.69
14	4.07	4.66	5.63	6.57	7.79	21.06	23.68	26.12	29.14
15	4.60	5.23	6.26	7.26	8.55	22.31	25.00	27.49	30.58
16	5.14	5.81	6.91	7.96	9.31	23.54	26.30	28.85	32.00
17	5.70	6.41	7.56	8.67	10.09	24.77	27.59	30.19	33.41
18	6.26	7.01	8.23	9.39	10.86	25.99	28.87	31.53	34.81
19	6.84	7.63	8.91	10.12	11.65	27.20	30.14	32.85	36.19
20	7.43	8.26	9.59	10.85	12.44	28.41	31.41	34.17	37.57
22	8.64	9.54	10.98	12.34	14.04	30.81	33.92	36.78	40.29
24	9.89	10.86	12.40	13.85	15.66	33.20	36.42	39.36	42.98
26	11.16	12.20	13.84	15.38	17.29	35.56	38.89	41.92	45.64
28	12.46	13.56	15.31	16.93	18.94	37.92	41.34	44.46	48.28
30	13.79	14.95	16.79	18.49	20.60	40.26	43.77	46.98	50.89
32	15.13	16.36	18.29	20.07	22.27	42.58	46.19	49.48	53.49
34	16.50	17.79	19.81	21.66	23.95	44.90	48.60	51.97	56.06
38	19.29	20.69	22.88	24.88	27.34	49.51	53.38	56.90	61.16
42	22.14	23.65	26.00	28.14	30.77	54.09	58.12	61.78	66.21
46	25.04	26.66	29.16	31.44	34.22	58.64	62.83	66.62	71.20
50	27.99	29.71	32.36	34.76	37.69	63.17	67.50	71.42	76.15
55	31.73	33.57	36.40	38.96	42.06	68.80	73.31	77.38	82.29
60	35.53	37.48	40.48	43.19	46.46	74.40	79.08	83.30	88.38
65	39.38	41.44	44.60	47.45	50.88	79.97	84.82	89.18	94.42
70	43.28	45.44	48.76	51.74	55.33	85.53	90.53	95.02	100.43
75	47.21	49.48	52.94	56.05	59.79	91.06	96.22	100.84	106.39
80	51.17	53.54	57.15	60.39	64.28	96.58	101.88	106.63	112.33
85	55.17	57.63	61.39	64.75	68.78	102.08	107.52	112.39	118.24
90	59.20	61.75	65.65	69.13	73.29	107.57	113.15	118.14	124.12
95	63.25	65.90	69.92	73.52	77.82	113.04	118.75	123.86	129.97
100	67.33	70.06	74.22	77.93	82.36	118.50	124.34	129.56	135.81

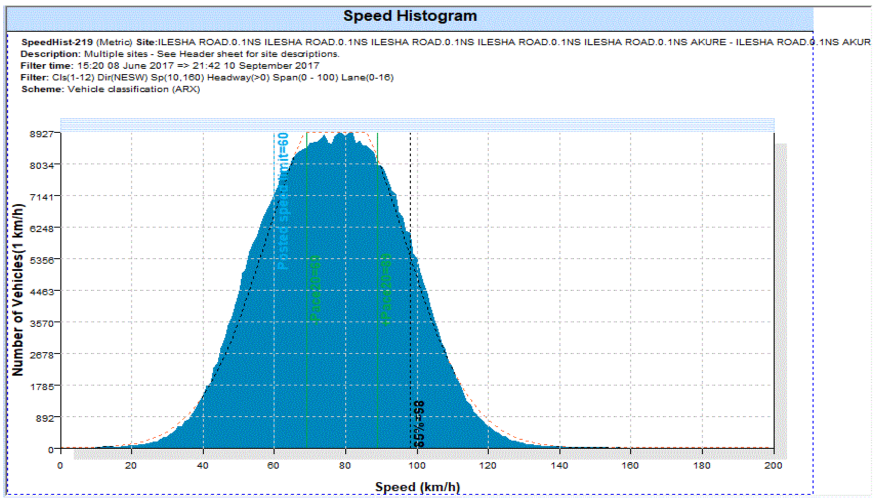
APPENDIX III

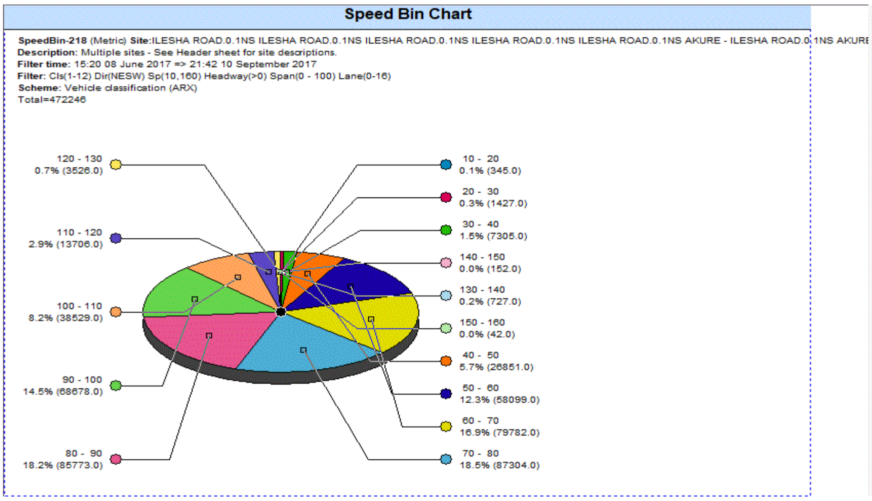
Other Traffic Survey Information from the ATC

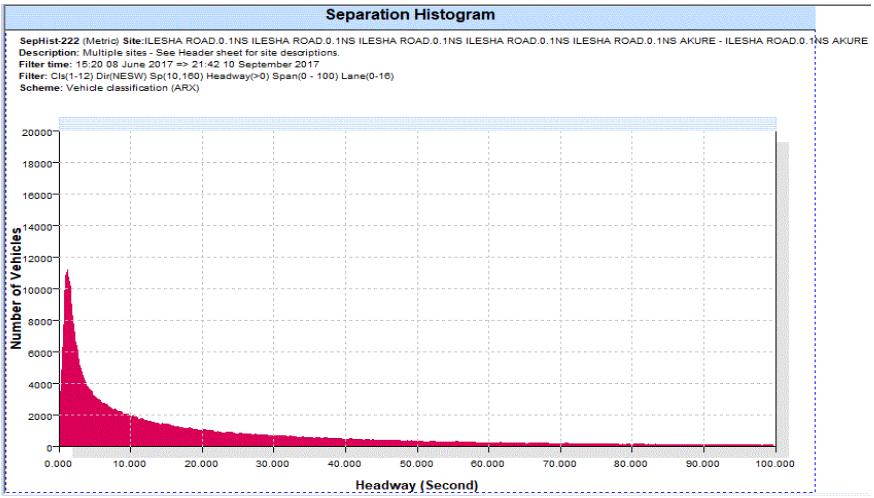
SS01: Akure - Ilesha Highway

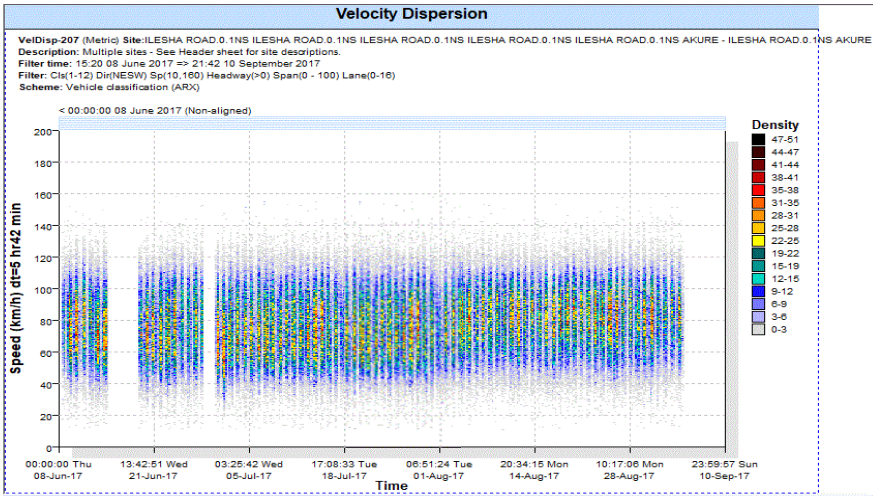




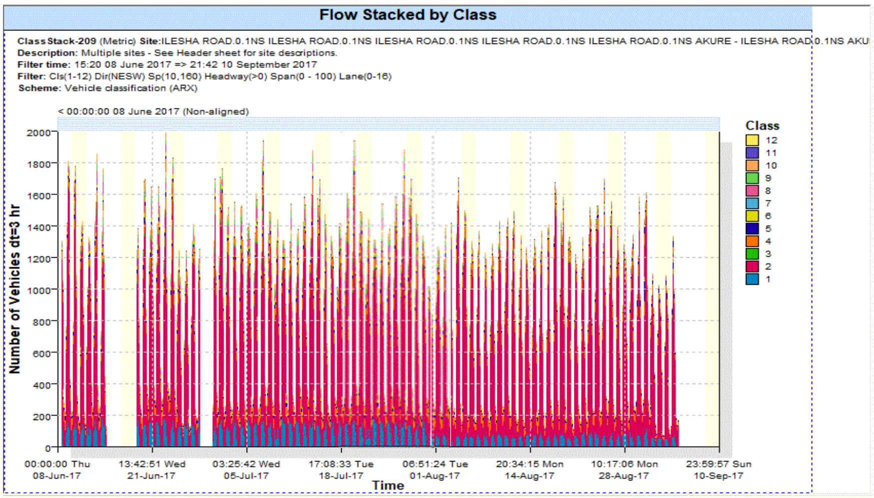


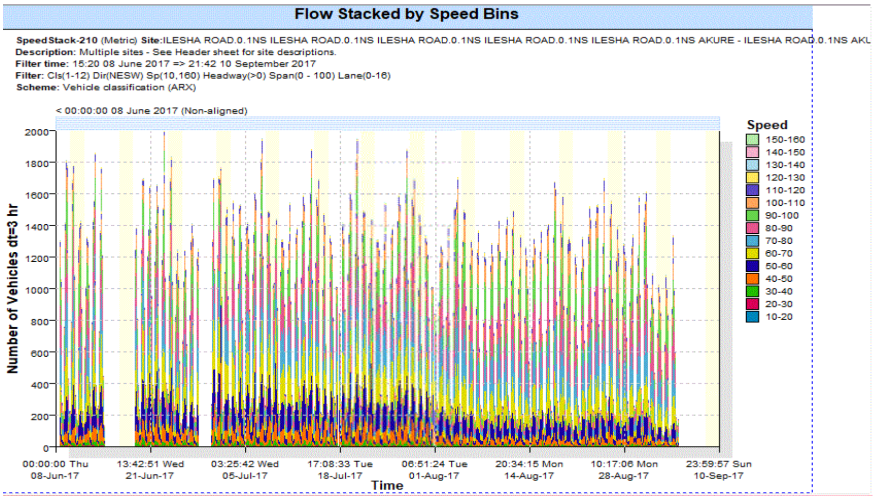

Speed Bin Chart
SpeedBin-218 (Metric) Site:ILESHA ROAD.0.1NS ILESHA ROAD.0.1NS ILESHA ROAD.0.1NS ILESHA ROAD.0.1NS ILESHA ROAD.0.1NS AKURE - ILESHA ROAD.0.1NS AKURE
Description: Multiple sites - See Header sheet for site descriptions.
Filter time: 15:20 08 June 2017 => 21:42 10 September 2017
Filter: Cls(1-12) Dir(NESW) Sp(10,160) Headway(>0) Span(0 - 100) Lane(0-16)
Scheme: Vehicle classification (ARX)
Total=472246
120 - 130
0.7% (3526.0)
110 - 120
2.9% (13706.0)
100 - 110
8.2% (38529.0)
90 - 100
14.5% (68678.0)
80 - 90
18.2% (85773.0)
10 - 20
0.1% (345.0)
20 - 30
0.3% (1427.0)
30 - 40
1.5% (7305.0)
140 - 150
0.0% (152.0)
130 - 140
0.2% (727.0)
150 - 160
0.0% (42.0)
40 - 50
5.7% (26851.0)
50 - 60
12.3% (58099.0)
60 - 70
16.9% (79782.0)
70 - 80
18.5% (87304.0)

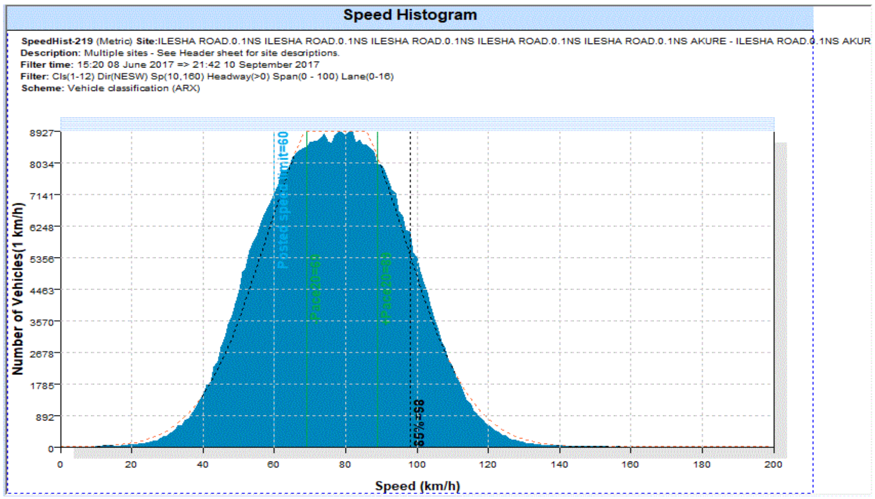

Separation Histogram
SepHist-222 (Metric) Site:ILESHA ROAD.0.1NS ILESHA ROAD.0.1NS ILESHA ROAD.0.1NS ILESHA ROAD.0.1NS ILESHA ROAD.0.1NS AKURE - ILESHA ROAD.0.1NS AKURE
Description: Multiple sites - See Header sheet for site descriptions.
Filter time: 15:20 08 June 2017 => 21:42 10 September 2017
Filter: Cls(1-12) Dir(NESW) Sp(10,160) Headway(>0) Span(0 - 100) Lane(0-16)
Scheme: Vehicle classification (ARX)
Number of Vehicles
20000
18000
16000
14000
12000
10000
8000
6000
4000
2000
0
0.000
10.000
20.000
30.000
40.000
50.000
60.000
70.000
80.000
90.000
100.000
Headway (Second)

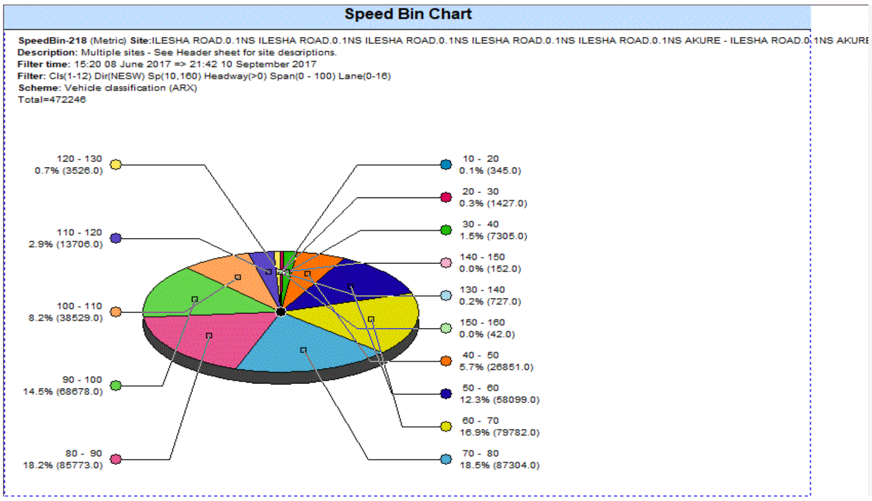

Velocity Dispersion
VelDisp-207 (Metric) Site:ILESHA ROAD.0.1NS ILESHA ROAD.0.1NS ILESHA ROAD.0.1NS ILESHA ROAD.0.1NS ILESHA ROAD.0.1NS AKURE - ILESHA ROAD.0.1NS AKURE
Description: Multiple sites - See Header sheet for site descriptions.
Filter time: 15:20 08 June 2017 => 21:42 10 September 2017
Filter: Cls(1-12) Dir(NESW) Sp(10,160) Headway(>0) Span(0 - 100) Lane(0-16)
Scheme: Vehicle classification (ARX)
< 00:00:00 08 June 2017 (Non-aligned)
Speed (km/h) dt=5 hr42 min
200
180
160
140
120
100
80
60
40
20
0
00:00:00 Thu 08-Jun-17
13:42:51 Wed 21-Jun-17
03:25:42 Wed 05-Jul-17
17:08:33 Tue 18-Jul-17
06:51:24 Tue 01-Aug-17
20:34:15 Mon 14-Aug-17
10:17:06 Mon 28-Aug-17
23:59:57 Sun 10-Sep-17
Time
Density
47-51
44-47
41-44
38-41
35-38
31-35
28-31
25-28
22-25
19-22
15-19
12-15
9-12
6-9
3-6
0-3

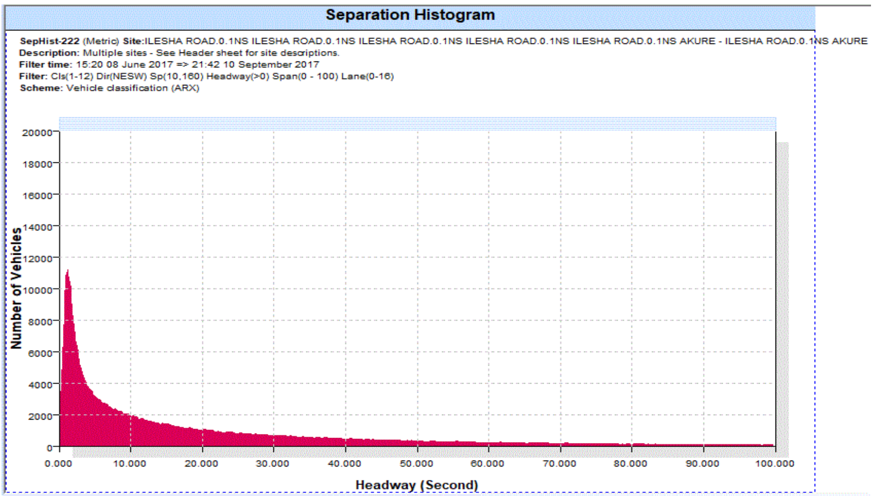
SS02: Ilesha - Akure Highway

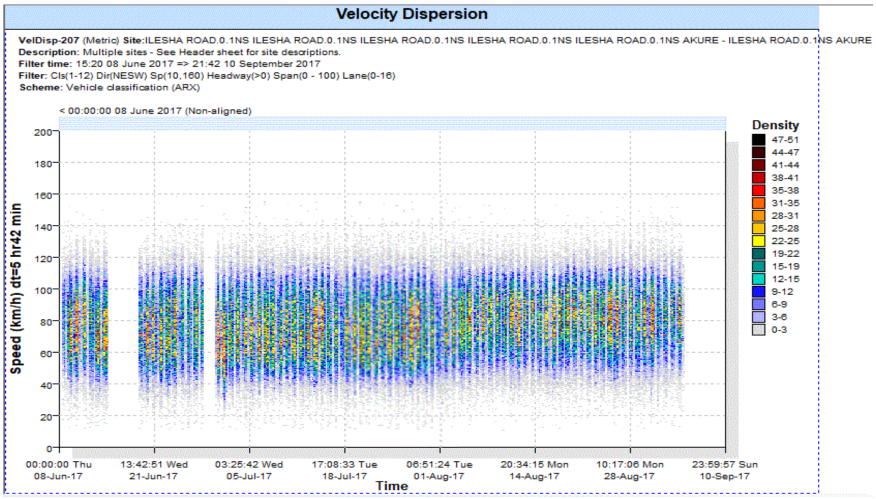







Speed Bin Chart
SpeedBin-218 (Metric) Site:ILESHA ROAD.0.1NS ILESHA ROAD.0.1NS ILESHA ROAD.0.1NS ILESHA ROAD.0.1NS ILESHA ROAD.0.1NS AKURE - ILESHA ROAD.0.1NS AKURE
Description: Multiple sites - See Header sheet for site descriptions.
Filter time: 15:20 08 June 2017 => 21:42 10 September 2017
Filter: Cls(1-12) Dir(NESW) Sp(10,160) Headway(>0) Span(0 - 100) Lane(0-16)
Scheme: Vehicle classification (ARX)
Total=472246
120 - 130 0.7% (3526.0)
110 - 120 2.9% (13706.0)
100 - 110 8.2% (38529.0)
90 - 100 14.5% (68678.0)
80 - 90 18.2% (85773.0)
10 - 20 0.1% (345.0)
20 - 30 0.3% (1427.0)
30 - 40 1.5% (7305.0)
140 - 150 0.0% (152.0)
130 - 140 0.2% (727.0)
150 - 160 0.0% (42.0)
40 - 50 5.7% (26851.0)
50 - 60 12.3% (58099.0)
60 - 70 16.9% (79782.0)
70 - 80 18.5% (87304.0)


Separation Histogram
SepHist-222 (Metric) Site:ILESHA ROAD.0.1NS ILESHA ROAD.0.1NS ILESHA ROAD.0.1NS ILESHA ROAD.0.1NS ILESHA ROAD.0.1NS AKURE - ILESHA ROAD.0.1NS AKURE
Description: Multiple sites - See Header sheet for site descriptions.
Filter time: 15:20 08 June 2017 => 21:42 10 September 2017
Filter: Cls(1-12) Dir(NESW) Sp(10,160) Headway(>0) Span(0 - 100) Lane(0-16)
Scheme: Vehicle classification (ARX)
Number of Vehicles
20000
18000
16000
14000
12000
10000
8000
6000
4000
2000
0
0.000
10.000
20.000
30.000
40.000
50.000
60.000
70.000
80.000
90.000
100.000
Headway (Second)


Velocity Dispersion
VelDisp-207 (Metric) Site:ILESHA ROAD.0.1NS ILESHA ROAD.0.1NS ILESHA ROAD.0.1NS ILESHA ROAD.0.1NS ILESHA ROAD.0.1NS AKURE - ILESHA ROAD.0.1NS AKURE
Description: Multiple sites - See Header sheet for site descriptions.
Filter time: 15:20 08 June 2017 => 21:42 10 September 2017
Filter: Cls(1-12) Dir(NESW) Sp(10,160) Headway(>0) Span(0 - 100) Lane(0-16)
Scheme: Vehicle classification (ARX)
< 00:00:00 08 June 2017 (Non-aligned)
Speed (km/h) dt=5 hr42 min
200
180
160
140
120
100
80
60
40
20
0
00:00:00 Thu 08-Jun-17
13:42:51 Wed 21-Jun-17
03:25:42 Wed 05-Jul-17
17:08:33 Tue 18-Jul-17
06:51:24 Tue 01-Aug-17
20:34:15 Mon 14-Aug-17
10:17:06 Mon 28-Aug-17
23:59:57 Sun 10-Sep-17
Time
Density
47-51
44-47
41-44
38-41
35-38
31-35
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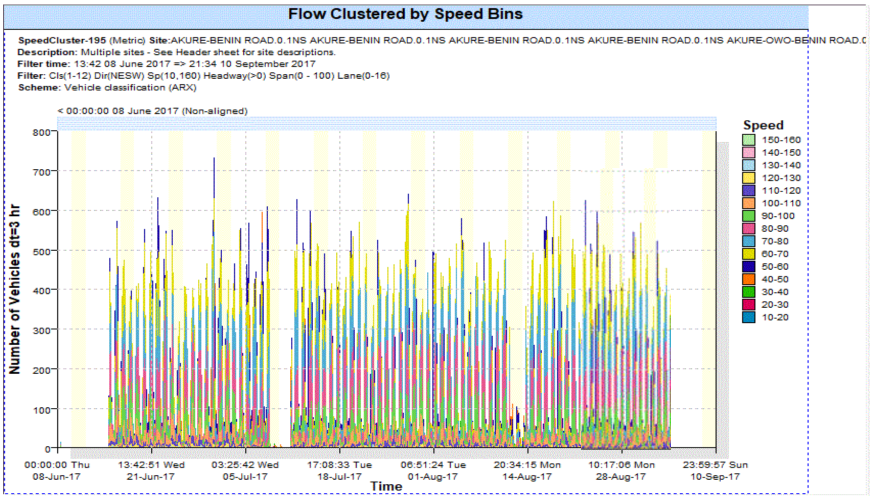
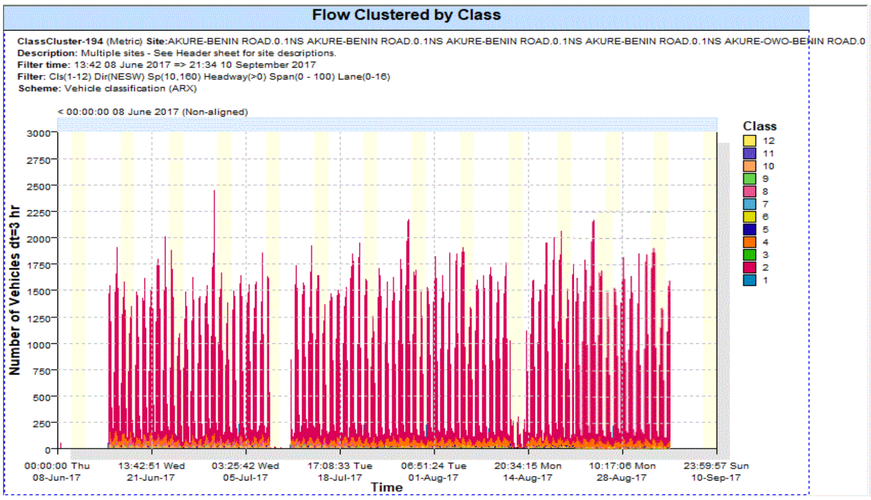
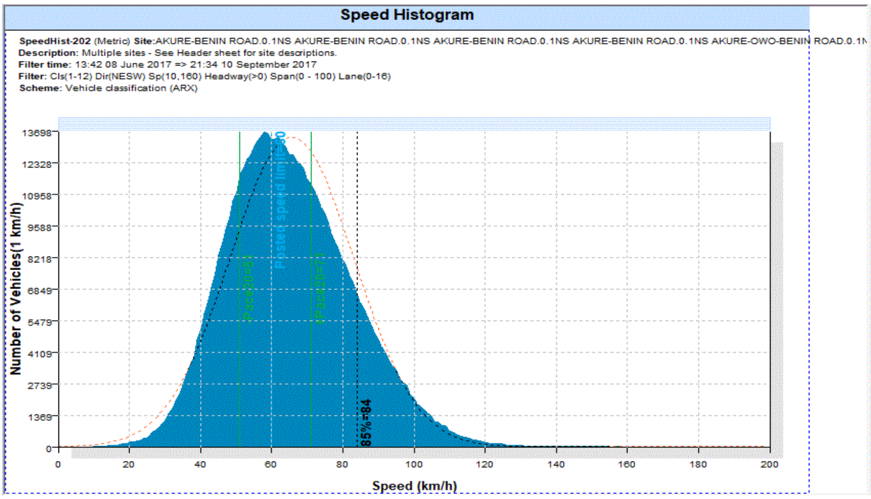
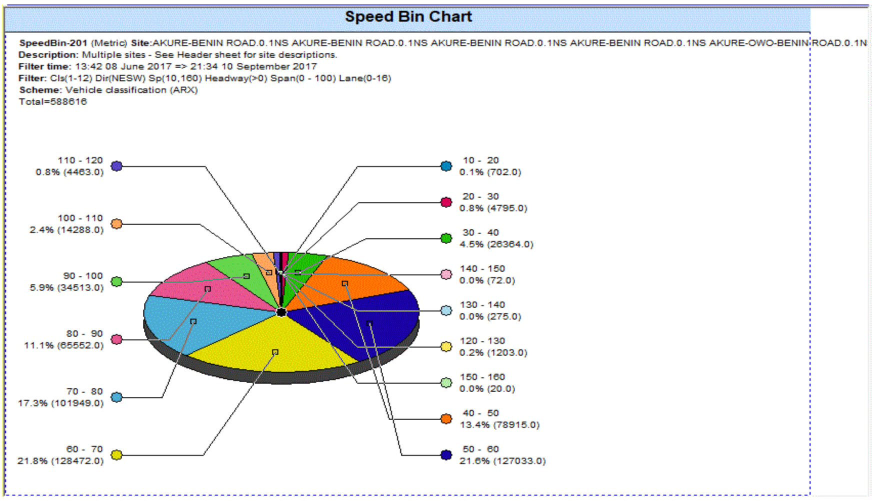
0-3

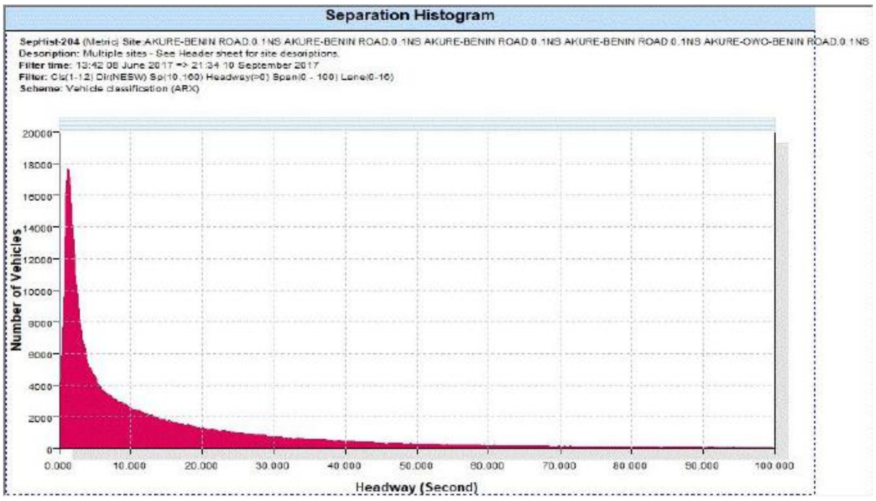
SS03: Akure - Benin Highway

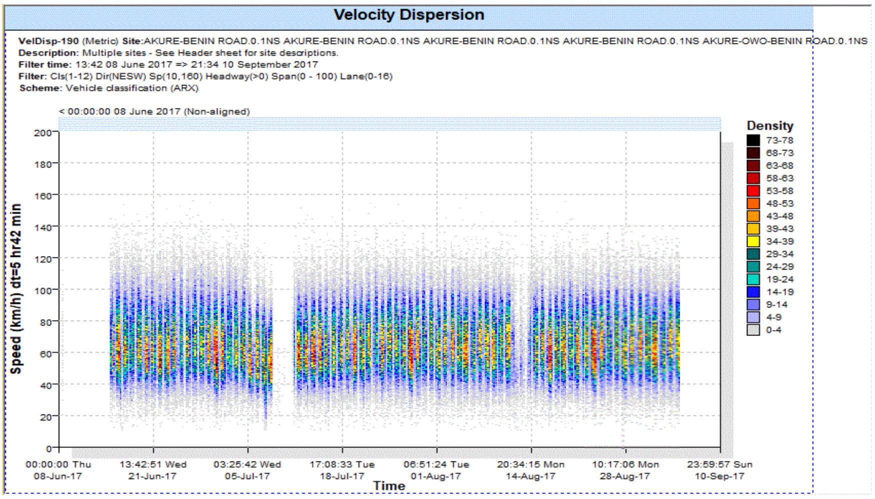




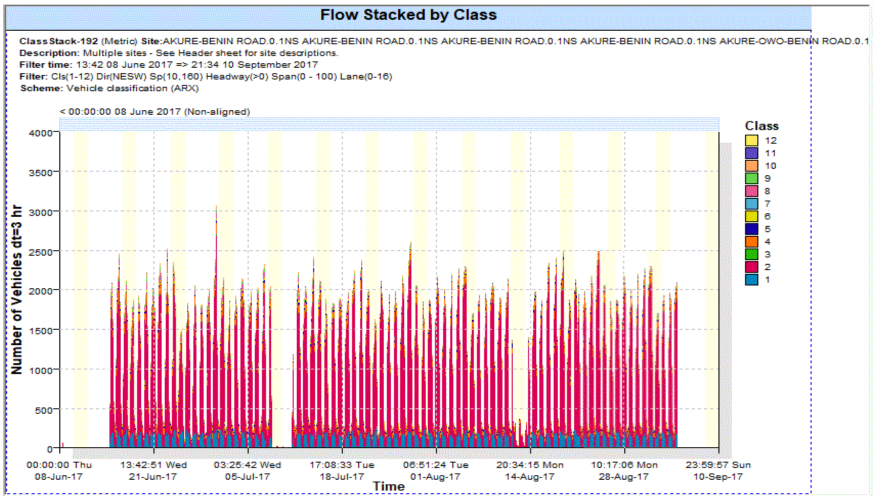


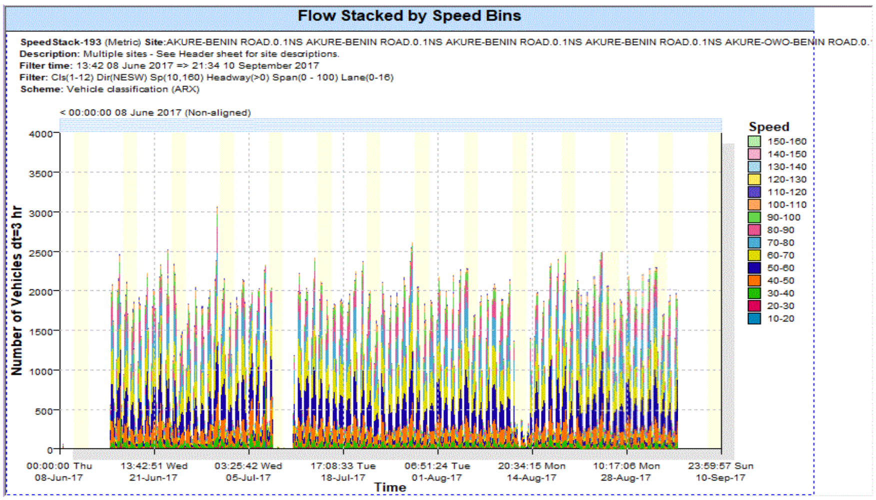

Speed Bin Chart
SpeedBin-201 (Metric) Site:AKURE-BENIN ROAD.0.1NS AKURE-BENIN ROAD.0.1NS AKURE-BENIN ROAD.0.1NS AKURE-BENIN ROAD.0.1NS AKURE-OWO-BENIN ROAD.0.1N
Description: Multiple sites - See Header sheet for site descriptions.
Filter time: 13:42 08 June 2017 => 21:34 10 September 2017
Filter: Cls(1-12) Dir(NESW) Sp(10,160) Headway(>0) Span(0 - 100) Lane(0-16)
Scheme: Vehicle classification (ARX)
Total=588616
110 - 120 0.8% (4463.0)
100 - 110 2.4% (14288.0)
90 - 100 5.9% (34513.0)
80 - 90 11.1% (65552.0)
70 - 80 17.3% (101949.0)
60 - 70 21.8% (128472.0)
10 - 20 0.1% (702.0)
20 - 30 0.8% (4795.0)
30 - 40 4.5% (26364.0)
140 - 150 0.0% (72.0)
130 - 140 0.0% (275.0)
120 - 130 0.2% (1203.0)
150 - 160 0.0% (20.0)
40 - 50 13.4% (78915.0)
50 - 60 21.6% (127033.0)

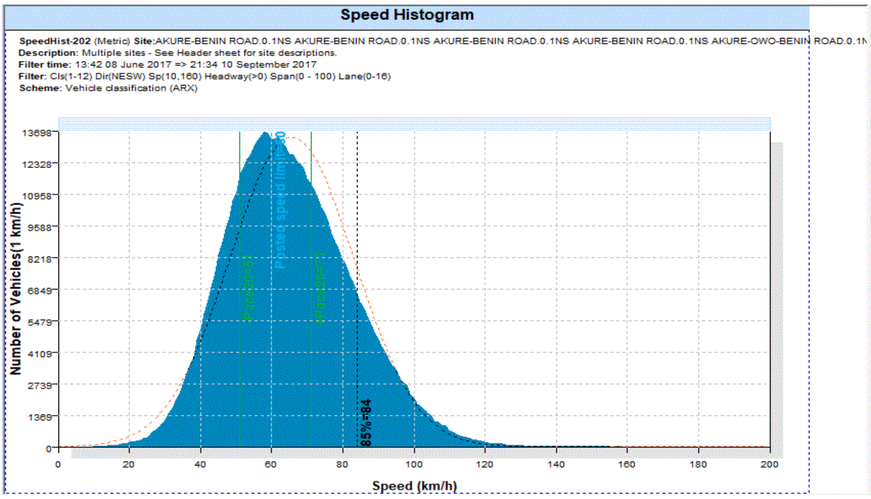

Separation Histogram
SepHist-204 (Metric) Site:AKURE-BENIN ROAD.0.1NS AKURE-BENIN ROAD.0.1NS AKURE-BENIN ROAD.0.1NS AKURE-BENIN ROAD.0.1NS AKURE-OWO-BENIN ROAD.0.1NS
Description: Multiple sites - See Header sheet for site descriptions.
Filter time: 13:42 08 June 2017 => 21:34 10 September 2017
Filter: Cls(1-12) Dir(NESW) Sp(10,160) Headway(>0) Span(0 - 100) Lane(0-16)
Scheme: Vehicle classification (ARX)
Number of Vehicles
20000
18000
16000
14000
12000
10000
8000
6000
4000
2000
0
0.000
10.000
20.000
30.000
40.000
50.000
60.000
70.000
80.000
90.000
100.000
Headway (Second)

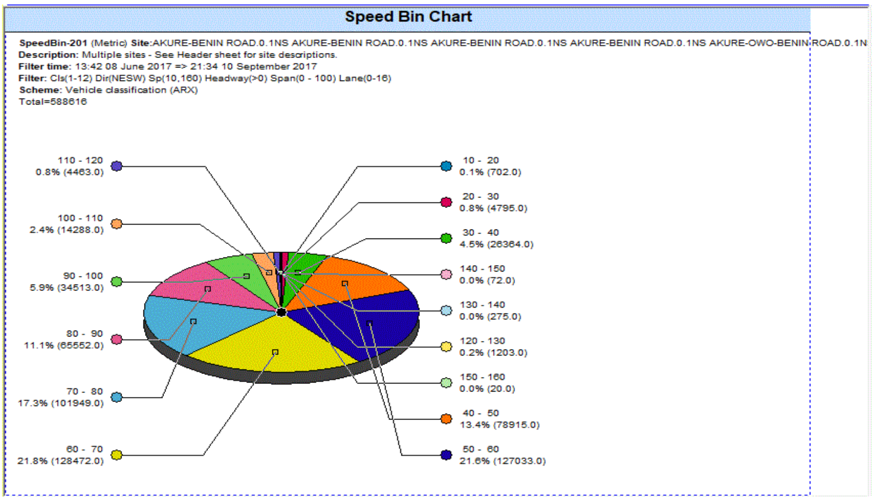

Velocity Dispersion
VelDisp-190 (Metric) Site:AKURE-BENIN ROAD.0.1NS AKURE-BENIN ROAD.0.1NS AKURE-BENIN ROAD.0.1NS AKURE-BENIN ROAD.0.1NS AKURE-OWO-BENIN ROAD.0.1NS
Description: Multiple sites - See Header sheet for site descriptions.
Filter time: 13:42 08 June 2017 => 21:34 10 September 2017
Filter: Cls(1-12) Dir(NESW) Sp(10,160) Headway(>0) Span(0 - 100) Lane(0-16)
Scheme: Vehicle classification (ARX)
< 00:00:00 08 June 2017 (Non-aligned)
Speed (km/h) dt=5 hr42 min
200
180
160
140
120
100
80
60
40
20
0
00:00:00 Thu 08-Jun-17
13:42:51 Wed 21-Jun-17
03:25:42 Wed 05-Jul-17
17:08:33 Tue 18-Jul-17
06:51:24 Tue 01-Aug-17
20:34:15 Mon 14-Aug-17
10:17:06 Mon 28-Aug-17
23:59:57 Sun 10-Sep-17
Time
Density
73-78
68-73
63-68
58-63
53-58
48-53
43-48
39-43
34-39
29-34
24-29
19-24
14-19
9-14
4-9
0-4

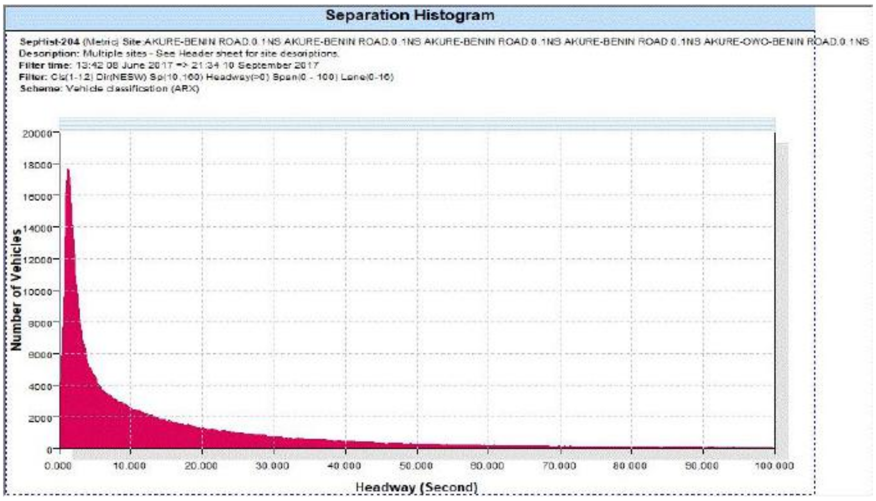
SS04: Benin - Akure Highway








Speed Bin Chart
SpeedBin-201 (Metric) Site:AKURE-BENIN ROAD.0.1NS AKURE-BENIN ROAD.0.1NS AKURE-BENIN ROAD.0.1NS AKURE-BENIN ROAD.0.1NS AKURE-OWO-BENIN ROAD.0.1N
Description: Multiple sites - See Header sheet for site descriptions.
Filter time: 13:42 08 June 2017 => 21:34 10 September 2017
Filter: Cls(1-12) Dir(NESW) Sp(10,160) Headway(>0) Span(0 - 100) Lane(0-16)
Scheme: Vehicle classification (ARX)
Total=588616
110 - 120
0.8% (4463.0)
100 - 110
2.4% (14288.0)
90 - 100
5.9% (34513.0)
80 - 90
11.1% (65552.0)
70 - 80
17.3% (101949.0)
60 - 70
21.8% (128472.0)
10 - 20
0.1% (702.0)
20 - 30
0.8% (4795.0)
30 - 40
4.5% (26364.0)
140 - 150
0.0% (72.0)
130 - 140
0.0% (275.0)
120 - 130
0.2% (1203.0)
150 - 160
0.0% (20.0)
40 - 50
13.4% (78915.0)
50 - 60
21.6% (127033.0)


Separation Histogram
SepHist-204 (Metric) Site:AKURE-BENIN ROAD.0.1NS AKURE-BENIN ROAD.0.1NS AKURE-BENIN ROAD.0.1NS AKURE-BENIN ROAD.0.1NS AKURE-OWO-BENIN ROAD.0.1NS
Description: Multiple sites - See Header sheet for site descriptions.
Filter time: 13:42 08 June 2017 => 21:34 10 September 2017
Filter: Cls(1-12) Dir(NESW) Sp(10,160) Headway(>0) Span(0 - 100) Lane(0-16)
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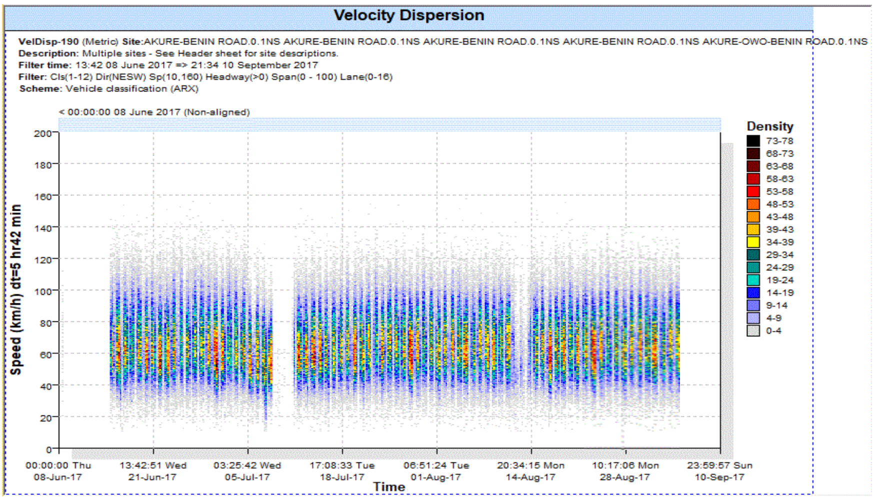
2000
0
0.000
10.000
20.000
30.000
40.000
50.000
60.000
70.000
80.000
90.000
100.000
Headway (Second)


Velocity Dispersion
VelDisp-190 (Metric) Site:AKURE-BENIN ROAD.0.1NS AKURE-BENIN ROAD.0.1NS AKURE-BENIN ROAD.0.1NS AKURE-BENIN ROAD.0.1NS AKURE-OWO-BENIN ROAD.0.1NS
Description: Multiple sites - See Header sheet for site descriptions.
Filter time: 13:42 08 June 2017 => 21:34 10 September 2017
Filter: Cls(1-12) Dir(NESW) Sp(10,160) Headway(>0) Span(0 - 100) Lane(0-16)
Scheme: Vehicle classification (ARX)
< 00:00:00 08 June 2017 (Non-aligned)
Speed (km/h) dt=5 hr42 min
200
180
160
140
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60
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20
0
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13:42:51 Wed 21-Jun-17
03:25:42 Wed 05-Jul-17
17:08:33 Tue 18-Jul-17
06:51:24 Tue 01-Aug-17
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10:17:06 Mon 28-Aug-17
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Time
Density
73-78
68-73
63-68
58-63
53-58
48-53
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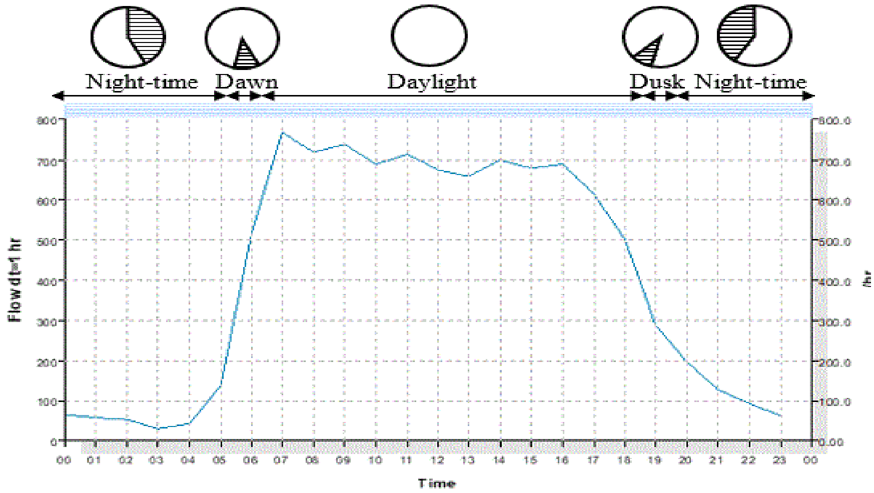
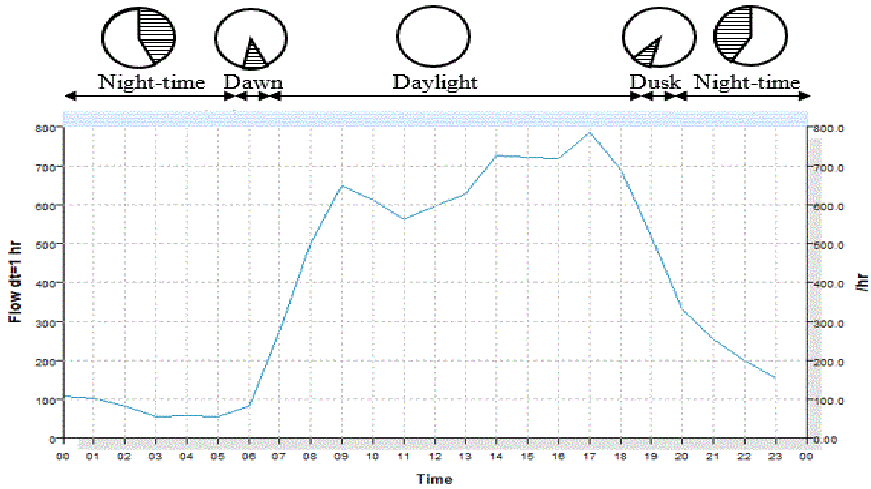
14-19
9-14
4-9
0-4



A typical one-day (24 hour) traffic flow on a 2-lane rural highway



A typical one-day (24 hour) traffic flow on a 2-lane rural highway

Researcher with her team during the installation of the ATC

Installation team at work alongside security personnel

Installed pneumatic tubes across the road section

Installed pneumatic tubes across the road section

Secured ATC in a metal box along the road

Explaining and demonstration of ATC installation for the team