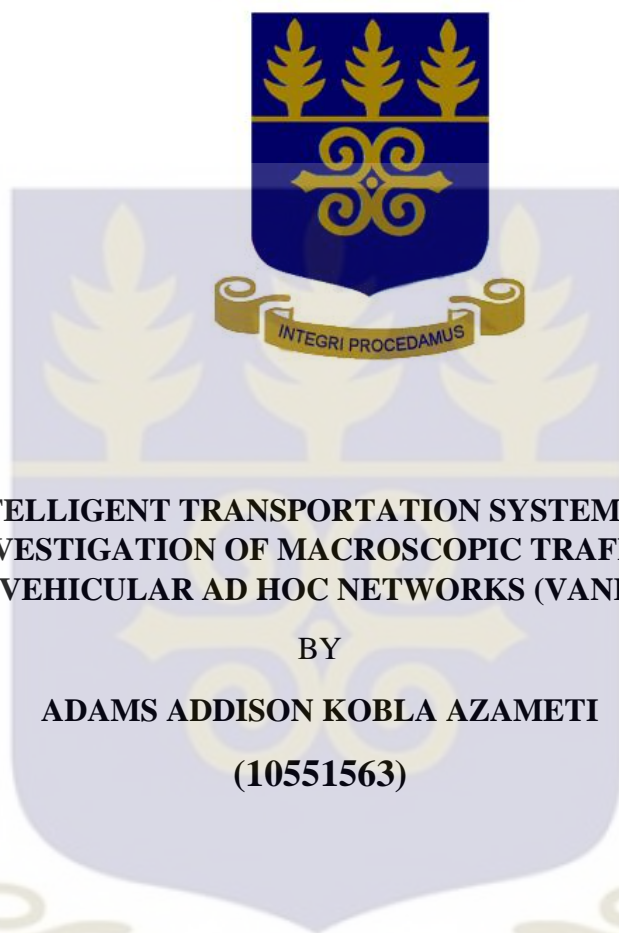


UNIVERSITY OF GHANA

COLLEGE OF BASIC AND APPLIED SCIENCES

UNIVERSITY OF GHANA - LEGON



**IMPROVING INTELLIGENT TRANSPORTATION SYSTEMS (ITS) THROUGH
ANALYTICAL INVESTIGATION OF MACROSCOPIC TRAFFIC FLOW MODEL
IN VEHICULAR AD HOC NETWORKS (VANETS)**

BY

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**THIS THESIS IS SUBMITTED TO THE UNIVERSITY OF GHANA, LEGON IN
PARTIAL FULFILLMENT OF THE REQUIREMENT FOR THE AWARD OF
MPHIL IN COMPUTER SCIENCE DEGREE**

MARCH 2018

Declaration

I wish to declare that this thesis has not been previously accepted in substance for the award of any degree. I state that this thesis is the result of my own independent investigation or work, except where otherwise stated. I hereby give consent for my thesis, if accepted, to be available for photocopying and I understand that any reference to or quotation from my thesis will receive an acknowledgement.

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I hereby certify that I have thoroughly read this thesis and, in my opinion, it is fully adequate in scope and quality, for the degree of Master of Philosophy in Computer Science.

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Abstract

In recent times, wireless communication has witnessed unprecedented growth due mainly to advances in instrumentation and computer science. Substantial research efforts have been devoted to exploring the application of Intelligent Transportation Systems (ITS) within the context of vehicular ad hoc networks (VANETs) to ensure safety and for an efficient and integrated transport network. Vehicle-to-vehicle (V2V) communication in VANETs poses many challenges. In sparse as well as in dense networks, V2V communication can result in intermittent connectivity and broadcast storm problems. Finding solutions to these challenges in an infrastructure-less vehicular ad hoc network (VANETs) with safety and non-safety applications is quite complex.

These limitations lead to the analytical investigations of the macroscopic traffic flow model to understand the effect of these spatio-temporal variations in traffic density while varying the value of the sensitivity factor for a two-vehicle interaction, λ at different time intervals during each simulation. The result from this simulation is used to develop Congestion Control Models in the congested network and Honeycomb Model in a sparsely connected network for improved performance in VANETs. The variation in the value of λ affects traffic flow in vehicles. The analytical investigation is implemented in MATLAB in which vehicular density is constant and the value of λ varies directly from 1 to 10 within the time intervals in sparse and dense network conditions. The simulation result in dense network indicates vehicular trajectories when λ increases with time.

The outcomes of this analytical investigation demonstrate that there is no need to increase λ beyond the thresholds of 12. However, further increases would increase the number of vehicles (nodes) which will result in a traffic jam. Empirical evidence suggests this range $1 \leq \lambda \leq 12$ to be used to design traffic models in dense networks. These results in principle proved that this Congestion Control Model within the four-lane networks may be considered the most appropriate model to be used in designing VANETs networks. In the work, the following design parameters were used, A: $1 \leq \lambda \leq 3$; B: $1 \leq \lambda \leq 4$ and C: $1 \leq \lambda \leq 5$. The level of services in A, B, and C, have been used to perform separate simulations in sparse networks. The simulation results also provide a framework to design sparse networks associated with frequent disconnections within the stated design parameters of A: $1 \leq \lambda \leq 3$; B: $1 \leq \lambda \leq 4$ and C: $1 \leq \lambda \leq 5$. These findings lead to the proposed Honeycomb Models in a sparsely connected network to improve the challenges in sparse network conditions.

Finally, the result from this analytical investigation provide a scientific framework and further poses greater challenges to the research communities in designing vehicular traffic flow in VANETs. This research findings, reveal the possibilities to replicate the attributes of honeybees in designing vehicular traffic flow in VANETs. This novel approach significantly improves ITS applications in VANETs V2V communication.

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This thesis would not have been made possible without the support of my supervisors. I wish to express an endless heartfelt appreciation to Dr. Ferdinand Apietu Katsriku and Dr. Jamal-Deen Abdulai for their unwavering support and constructive criticisms made to arrive at the final stage of this thesis. They have been of constant sources of inspiration, motivation, and knowledge throughout my studies in the University of Ghana. I would like also to express my deepest gratitude to Dr. Ferdinand Apietu Katsriku for his support, contributions and guidance towards the final revision of this thesis. I would like also to express my sincere gratitude to all my colleagues for their insightful criticism during seminars and presentations.

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Dedication

I wish to dedicate this thesis to the Almighty God, who is the architect and creator of every invention and ideas. God has truly helped me with all the necessary resources to come out with this novel approach to vehicular ad hoc networks (VANETs). This approach in VANETs, can provide an enhanced Intelligent Transportation Systems (ITS) which will reduce the fatalities on the road networks.

I wish also to dedicate this achievement to all my children since this will serve as a benchmark to help them climb the academic ladder with the greatest motivation and confidence.

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List of Abbreviations

3G	Third Generation
4G	Fourth Generation
C2CCC	Car-to-Car Communications Consortium
C2CC	Car-to-Car Communications
CA	Cellular Automata
CDF	Cumulative Distribution Function
PD	Probability Density
DSRC	Dedicated Short Range Communication
GPS	Global Positioning System
ISM	Industrial, Scientific, Medical
ITS	Intelligent Transportation Systems
IVC	Inter-Vehicle Communication
PHY	Physical
QoS	Quality of Service
V2V	vehicle-to-vehicle
V2R	vehicle-to-roadside
CSMA/CA	Carrier Sense Multiple Access with Collision Avoidance
IEEE	Institute of Electrical and Electronics Engineers
MAC	Medium Access Control
MANETs	Mobile Ad Hoc Networks
VANETs	Vehicular Ad Hoc Networks
Wi-Fi	Wireless Fidelity
WLAN	Wireless Local Area Networks
WiMAX	Worldwide Interoperability for Microwave Access

List of Symbols

λ = sensitivity factor of a two-vehicle interaction in the car-following model

d = distance between two vehicles

n = number of nodes

n_l = number of traffic lanes

N = number of vehicles on a highway segment

L = length of highway segments

T = observation period of spot measurements

t = time

k = traffic density

μ_s = space mean speed

$u_{i,s}$ = speed of vehicles

q = traffic flow

u_T = time-mean speed

h = headway between two consecutive vehicles

η = traffic quality of service factor

f_s = fraction of stopped vehicles

T_s = vehicle's stopped time

T_t = vehicle's average trip time

x = number of vehicles migrating to a highway

D = density measured in vehicle per mile per lane (veh/mile/lane)

V = traffic volume measured in vehicle per hour (veh/hr)

V = space mean speed measured in mile per hour (mile/hr)

Chapter 1 Introduction

1.1 Background of the study

Communication among vehicles has attracted the attention of the research communities in the world in recent times according to (Forecast, 2013; Schrank, Eisele, & Lomax, 2012). A major initiative in this direction was the European Union declaration on cooperative and ITS. As part of this initiative some research projects were investigated into the future potential of reducing road fatalities under the electronic safety initiative according to (Anda, LeBrun, Ghosal, Chuah, & Zhang, 2005; Balasubramanian, Mahajan, Venkataramani, Levine, & Zahorjan, 2008; Sheng, Mahapatra, Zhu, & Leung, 2015).

Almost simultaneously, similar initiatives were taking place in countries such as the USA and Japan (Balasubramanian et al., 2008; Lai, 2016). The Vehicle-2-Vehicle communication in the context of vehicular ad hoc networks (VANETs), can enable new applications for vehicular networks. This will create numerous opportunities for safety improvements in VANETs. The vehicle-2-vehicle communication has the potential to support drivers and allow safety applications like collision warning, complete traffic and weather information coupled with the navigation systems. However, these applications in VANETs, pose numerous challenges associated with the technology, protocol designs, security and many more. This has become an active research area that has attracted the attention of both industry and academia in the globe according to (Lai, 2016; Lu, Cheng, Zhang, Shen, & Mark, 2014; Ramadan, Al-Khedher, & Al-Kheder, 2012).

Inter-Vehicle Communication (IVC) Systems in VANETs, has attracted considerable attention from the research community and automotive industry in recent years with several automobile manufacturers planning to build communication devices into their vehicles for the purposes of safety, comfortable driving, and entertainment (Lai, 2016; Ramadan et al., 2012). Every year, more than six million crashes occur in the U.S resulting in thousands of fatalities with many more left with lifelong injuries (Shrank et al., 2012). The proposed Intelligent Transportation Systems (ITS) for VANETs, that will enable vehicle-to-vehicle and vehicle-to-infrastructure communication have the potential to prevent these collisions once developed and deployed. The successful development of this ITS applications will eventually provide a warning to drivers in vehicles concerning dangerous situation like accidents and many others.

VANETs characteristics are similar to mobile ad hoc networks that form multi-hop communications (Olaverri-Monreal, Gomes, Fernandes, Vieira, & Ferreira, 2010) with the exception that the mobile units involved are vehicles moving at high speeds. As the result of high mobility of vehicles (nodes), the network topology is highly dynamic and subject to fast changes with all the vehicles (nodes) utilizing the same channel. The resultant effect is traffic congestion in dense networks (Balasubramanian et al., 2008; Forecast, 2013; Schrank et al., 2012). The dynamic capability of VANETs, calls for a paradigm shift to new system concepts in the development of V2V communication protocols. New wireless communication standard is required to be used for message dissemination schemes capable of exchanging messages at different networks conditions will improve high-speed real-time communication to enable collision warning in ITS.

These mobilities in VANETs is usually considered as consisting of decentralized and self-organizing networks made up of high-speed moving vehicle (Schrank et al., 2012). These characteristics of VANETs is used to establish communication among vehicles and therefore indicate pervasive application for road safety (Forecast, 2013). Meanwhile, the acceptable communication mode in VANETs is usually through broadcast and these unique features of VANETs are the major challenges that impede the Intelligent Transportation Systems in VANETs. These challenges eventually render emergency traffic alert message dissemination very difficult. This is due to high mobility and fast topology changes in vehicular environments. This phenomenon in VANETs makes it very important to substantiate the position of the farthest vehicles (nodes) through different methodology according to (Lai, 2016).

To achieve this in Vehicular Ad hoc networks, it is important to use decentralized controllers that will pre-determine the exact threshold parameters variations. This will help vehicles (nodes) to dynamically decides on the exact timelines the rebroadcast message should be sent and when to discard received emergency traffic alert messages (Balasubramanian et al., 2008; Chitra & Sathya, 2013; Lai, 2016). These frequent generation of alert messages in VANETs creates the broadcast storm problems (BSPs) which are of great importance for the research community in their quest for the development of new protocols design. It is therefore imperative to design scalable applications that mitigate the broadcast storm problems and the intermittent connectivity problems in sparse Vehicular Ad Hoc Networks (VANETs), this would allow free-flow and disconnection of emergency traffic alert message (Chitra & Sathya, 2013; Lai, 2016).

1.2 Problem statement

The traffic congestion and the intermittent connectivity problems can be attributed to two main factors which may be classified as predictable and unpredictable events. The predictable events refer to the nature of the road construction (i.e. rural road, urban road, and highways) together with the number of vehicles on the road at any moment. These unpredictable events refer to weather, accident and the attitude of drivers on the road. It may however, be argued that in a fully connected world of internet of things, weather could be classified as a predictable event. When the drivers are not aware of pending congestion and traffic flow conditions ahead, it will be difficult to pre-determine the severity of the congestion but eventually add up to the situation without knowing. This phenomenon requires a lot of effort to mitigate the congestion and intermittent connectivity in VANETs. The ability of the driver to pre-determine the traffic conditions ahead on the road will aid them to take an alternate route to save time, fuel and avoid the accident and improve traffic alert information dissemination and this is the direction of this thesis.

The vehicular traffic congestion is a very difficult situation in VANETs according to (Schrank et al., 2012). Unlike the current systems such as helicopter traffic reports, which are found to be very effective. For instance, in the air, it is very easy to have a good aerial picture about the congested area within the air-space with regards to the initial point, the final point and the speed of the helicopter. However, this is not the case in VANETs. To equip drivers with accurate traffic information ahead, like the helicopter traffic reports according to (Balasubramanian et al., 2008; Chitra & Sathya, 2013; Lai, 2016), would improve V2V communication in VANETs. To mitigate this traffic congestion in VANETs, it is very important to consider these concerns:

- i. Ability to pre-determine the congestion in a timely manner.
- ii. Ability to relay this traffic information to the driver ahead before they get to the congested area.
- iii. Ability to control intelligent traffic emergency messages (ITEMs) dissemination to avoid the broadcast storm problems in VANETs
- iv. Ability to examine traffic densities within urban and highways to ascertain the exact phenomenon in VANETs.
- v. Ability to use the above information to determine various thresholds parameters to develop holistic congestion control systems in VANETs is the main objective of this study.

Above information is an important parameter necessary to satisfy any congestion control systems. The VANETs, architecture to ensure that vehicle form their own picture of congestion ahead; depend on the need to use vehicle-to-vehicle (V2V) communication or vehicle-to-infrastructure (V2I) communication. The understanding of these architectures leads, to the critical examination of the selection of suitable parameters to address the technology challenges in VANETs. To achieve these, it is important to consider the specific objectives outlined below.

1.3 Objectives of the study

1.3.1. General objective

The general objective is to conduct an analytical investigation into Intelligent Transportation Systems (ITS) through macroscopic traffic flow model under dense and sparse networks conditions.

1.3.2 Specific objectives

The specific objectives of this study are to conduct the analytical investigation in vehicular ad hoc networks.

- i. To conducts extensive performance analyses of vehicular traffic flow theory together with the tools and methods used to address the challenges confronting the selection of suitable parameters to achieve the objectives of the study.
- ii. To propose and evaluates an alternative traffic flow model to perform the analytical investigation into the macroscopic traffic flow model to ascertain spatio-temporal variations in network density in VANETs to mitigate the reachability and scalability issues.
- iii. To describes the evaluation of the macroscopic traffic model to demonstrate its importance and with evidence in dense and sparse networks conditions.
- iv. To present an interpretation of the results of the analytical investigation of the macroscopic traffic flow model in vehicular ad hoc networks to address reachability and scalability in VANETS.

1.4 Scope of the study

This thesis focused on vehicular traffic flow theory to conduct an analytical investigation into macroscopic traffic flow model, to analyse the spatio-temporal variations in dense networks and sparse networks. The results from this analytical investigation will lead to the development of congestion control model towards congestion detection and control as well as develop a Honeycomb Model to mitigate the intermittent connectivity in sparse networks. Besides, the

general findings in the research through simulation and visualization tools, which can be extended to more complex traffic models.

1.5 Justification of the proposed approach

This study is very important for the global community due to its diverse applications. In the last two decades, wireless communication technologies have witnessed unprecedented growth, due to developments in the field of instrumentation and in communication technology (Anda et al., 2005; Balasubramanian et al., 2008). Within the scope of development, substantial research efforts have been devoted to Vehicular Ad hoc Networks (VANETs) to ensure safety (Balasubramanian et al., 2008). The thesis proposes new approach to macroscopic traffic flow model to understand network variability in density. A successful implementation of the concepts proposed in this study will help provide greater safety within the transportation sector and is particularly suitable in Intelligent Transport Systems.

1.6 Organization

The rest of the study is organized as follows:

Chapter 2 of this study presents a comprehensive literature on the state-of-the-art in dense networks, sparse networks technology challenges. It also conducts an extensive performance analysis of vehicular traffic flow theory together with the tools and methods used to address each of these issues. The performance merit of wide range traffic flow models and how each affects network performance in dense and sparse networks are also discussed. The third chapter proposes and evaluates an alternative traffic flow model. The analytical investigation into macroscopic traffic flow model is also presented. Chapter 4 describes the evaluation of the

macroscopic traffic model to demonstrate its importance in dense and sparse networks scenarios. Chapter 5 present an interpretation of the results of the analytical investigation of the macroscopic model in VANETs. Finally, the last chapter of the study summarizes the results obtained in this thesis and outline possible direction of future work.

1.7 Summary of chapters

This chapter provides an account of what researchers have outlined for the development of the vehicle-to-vehicle (V2V) communication in the Vehicular Ad Hoc Networks (VANETs) in certain countries. This includes the possible projection on how fatalities on our road could be reduced once connected vehicle is developed. However, VANETs future applications in Intelligent Transportation Systems pose certain challenges with the technology, protocol designs, security and how to broadcast traffic information in a timely manner to mitigate these fatalities. Considering this, most researchers are collaborating with industries to investigate how these findings could be used to mitigate the numerous challenges. Due to the diverse application of VANETs, some automobile industries have started making plans to build communication devices in their vehicles to provide safety (i.e. prevent collision), comfortable driving and entertainment.

The main motivation of this thesis is to conduct an analytical investigation into the macroscopic traffic flow model in both dense network and sparse network conditions.

Chapter 2 Literature Review

2.1 Introduction

This section is divided into two parts to provide an in-depth literature review on the general technology challenges in VANETs protocol designs and further evaluate and discuss the main related work on performance analysis of traffic flow theory. This chapter covers the literature on the main research within the area of VANETs, with specific focus on congested networks and sparse networks conditions and the limitations associated with the technical gaps according to (Fu & Atiquzzaman, 2004; Papageorgiou, Diakaki, Dinopoulou, Kotsialos, & Wang, 2003; Wisitpongphan, Bai, Mudalige, Sadekar, & Tonguz, 2007) . The improvement of this technical gaps through the novel approach in ITS is the major direction in this thesis.

Current research advances in MANETs applications have become clear that such technology would be made appropriate for Intelligent Transportation Systems applications (Al-Sultan, Al-Doori, Al-Bayatti, & Zedan, 2014; Qian & Moayeri, 2008). VANETs applications involve onboard safety and active systems such as V2V and V2R communications. VANETs applications would also assist drivers to avoid collisions associated with dangerous road conditions. For example, the non-safety systems include the real traffic congestion, adaptive cruise control, high-speed vehicles, infotainment applications according to (H. T. Cheng, Shan, & Zhuang, 2011).

The VANETs application domain can ensure a scalable, secure and reliable Vehicular Ad Hoc Networks (VANETs). However, this challenge poses an extraordinary engineering challenge

(Liang, Li, Zhang, Wang, & Bie, 2015; Niu, Li, Liu, & Talty, 2007; Zeadally, Hunt, Chen, Irwin, & Hassan, 2012). Besides, VANETs uses several different methodologies than other ad hoc networks due to its unique characteristics according to (Harri, Filali, & Bonnet, 2009; Yousefi, Mousavi, & Fathy, 2006).

2.2 The technology challenges

Several wireless access standards being used in VANETs connectivity today and this standard provides a set of air interface protocols and certain parameters for high-speed vehicular communication using one or two several available technologies. These core technologies are:

2.2.1 Cellular technology (2G/2.5G/3G/4G/5G)

The primary advantages of 2G/2.5G technology are coverage and reliable security and 3G/4G/5G, slowly but steadily taking over with improved capacity and bandwidth which is presented (Agerholm, Jensen, & Andersen, 2015; Sheng et al., 2015). Although, several projects are implemented using cellular technology; however, due to the relatively high cost, limited bandwidth and latency make it impossible to use as the main communication tools in VANETs according to (Liu, 2011), hence the use alternative technologies.

2.2.2 IEEE 802.11p technology

IEEE, currently developing different kinds of 802.11 standards capable of supporting communication between vehicles and the roadside as well as among vehicles themselves (R. S. Cheng & Deng, 2014; Uchimura, Nasu, & Takahashi, 2010). This technology can operate at speed up to 200km/h, within a maximum communication range of 1000 meters are neatly

summarized in (N. Cheng et al., 2017; Lai, 2016; Liu, 2011). In PHY and MAC layers are based on IEEE 802.11a, with the 5.9GHz band (5.850 – 5.925 GHz within the US) based on the literature. The technology is widely used by car industry both in Europe (Car2Car CC) and the US (VSCC, VII) as presented in (Agerholm et al., 2015; Liu, 2011; Sheng et al., 2015). However, the estimated deployment cost is predicted to be relatively low due to large production volumes according to (Agerholm et al., 2015; Liu, 2011; Sheng et al., 2015).

2.2.3 Issues of spectrum

It is estimated that the period for the V2V communication system to be commercialized would last at least 20 years and within this time the spectrum availability has to be guaranteed according to (Qu, Wang, & Yang, 2010). In the US the FCC has already allocated 75MHz of spectrum at 5.9 GHz (from 5.850 to 5.925 GHz) for C2C and C2I communications according to (Cheng et al., 2017; Liu, 2011). As have been accepted by VSC and VII Consortiums, the best technology available for the communications systems using this spectrum would be a derivative of IEEE 802.11. Thus the already mentioned development of the IEEE 802.11p and ISO TC204, and also accounted for the similar approach (Cheng et al., 2017). This review is to demonstrate the variations, the suitability and the relevance of these applications in VANETs.

However, the continuous spectrum of 75 MHz in the DSRC band is not available in most countries (Agerholm et al., 2015; Sheng et al., 2015).

2.3 VANETs simulation and modelling

The road traffic has certain unique properties that cannot be easily modelled in a straightforward way, using the classical MANETs approach or testbed, as presented in (Balasubramanian et al.,

2008; Olaverri-Monreal et al., 2010; Schrank et al., 2012). Nodes move at high relative speed and the network density changes very dynamically and intermittently depending on the conditions of the roads according to (Anda et al., 2005; Olaverri-Monreal et al., 2010). This unique characteristic in VANETs need further investigation to mitigate the challenges by using appropriate simulation tools. In addition, appropriate selection of systems parameters would aid provide an alternative methodology to address VANETs challenges of ITS applications.

2.3.1 Wireless transmission and multiple access

Many technological challenges need to be tackled in the field of VANETs. These communication technologies are currently discussed to be used in car-to-car communication. Conventionally IEEE 802.11 wireless LAN (WLAN), and the dedicated short-range communication (DSRC), together with GPRS/UMTS are just some of the selected technologies to begin with.

Due to the success story in data communication in IEEE 802.11, this technology family is the most suitable to emerge as the main communication standard to be implemented in future cars, specifically in 802.11p. This is currently defined by an IEEE working group. The European Car-to-Car Communication Consortium is heavily involved in the standardization process of the IEEE 802.11p to meet automotive communication standard which is equivalent to DSRC technologies and this is currently being used in the US.

These standards use a communication frequency band of 5.9 GHz and this depends on the OFDM modulation scheme. The preferred medium access method is random access, which does not need a global scheduler. This IEEE 802.11e standard usually defines Quality of Service mechanisms for the current WLAN technology. This concept may also be used to improve

message dissemination in VANETs. For enhanced channel usage, they use the combination of IEEE 802p standard for the best result.

The WLAN-based technology has proven to be the most usable for the general task of exchanging messages between vehicles in VANETs. However, for services with specific quality or time constraints, as well as for very large networks (i.e.500 nodes), this technology may not be applied in (Anda et al., 2005). This phenomenon calls for reliable and efficient wireless transmission and multiple access technologies to provide a lasting solution in VANETs vehicle-to-vehicle communication (V2V) which is the direction in this thesis. To have a mental picture of VANETs environment, it is very important to understand the characteristics of VANETs in general.

2.4 VANETs characteristics

VANETs are entirely different from the superclass of MANETs applications, such as the mobility patterns and the constraints associated with them. These VANETs special characteristics are:

2.4.1 One-dimensional

Most research conducted in MANETs assumes that the network consists of the nodes moving freely in 2-dimensional manner (e.g. walking people) while vehicle mobility is restricted to the roads only. For instance, in the cellular networks where cell covers several square kilometres, the vehicle mobility in an urban network may be considered, 2-dimensional instead. Recent development reveals that ad hoc standards have a limited coverage area of about 1000 meters (i.e. 1km). It is obvious that vehicles along highways move in one dimension and therefore the

inter-vehicle distances are beyond the acceptable transmission range according to (M. Artimy, 2007; Jia, Lu, Wang, Zhang, & Shen, 2016). These research findings need further investigation into VANETs mobility scenarios.

2.4.2 Mobility pattern

These include many factors like road configuration, safety limits, traffic flow conditions, including physical limit seems to affects the mobility of vehicles (Jia et al., 2016; Singh & Singh, 2005). The drivers' behaviours and their interactions have advert consequences on the mobility of vehicles while in motion. These vehicles do not usually move randomly on the road rather they also follow a probabilistic set of rules to determine their mobility patterns in terms of directions, speed, acceleration or deceleration. The direction of this study is to simulate vehicle traffic flow, which is very complex tasks in the intelligent transportation systems due to VANETs characteristics in sparse and dense network scenarios.

2.4.3 Dynamic topology

The vehicular ad hoc networks may be created and re-configured in varieties of traffic situations. For example, in dense traffic conditions, vehicles may be within proximity of each other and in sparse traffic conditions in which vehicle distance may be about a few hundreds of meters away. In a typical situation in which vehicle approaching a congested traffic at about 137km/hr will change its state of proximity from 1 kilometre to 5 meters which may be approximately 26.5 seconds. In the same manner, two vehicles travelling in opposite directions at such a speed will be within about 1-kilometer range for approximately 13 seconds. In view of these characteristics, the communication protocols used in VANETs must be designed with the capabilities of

operating in a highly dynamic topology to improve ITS applications (ETSI, 2010; Forecast, 2013). To improve VANETs connectivity challenges, there is the need to understand this issue.

2.4.4 Connectivity

Current research indicates that vehicle connectivity may probably be limited to one-dimensional networks (Forecast, 2013). This consists of short-range communication networks of finite dimensions and infinite dimensions with the number of partitions at different time intervals according to (M. Artimy, 2007). This section reviews the important ITS applications in VANETs.

2.5 Intelligent Transportation Systems (ITS)

ITS applications include computers, communications, sensors, and control technologies with the capabilities to enhance the performance of the transportation systems. These systems provide travellers with accurate information to promote safety and the efficiency of the transportation systems in urban and rural areas (Torrent-Moreno et al., 2009). The Intelligent Transportation Systems (ITS) also provide essential time-critical information to systems operators in a transit vehicle, commercial vehicles, emergency as well as the security vehicles operators. These ITS applications combined users of the systems, vehicles as well as infrastructure into a comprehensive system for the enhanced exchange of information to improved better traffic management according to (Fallah, Huang, Sengupta, & Krishnan, 2011).

These applications use many exciting technologies such as cellular systems and position locating systems (Eze, Zhang, Liu, & Eze, 2016; Vinel, 2012). As the result, there has been a steady

increase in the role of electronics in vehicles for the past few decades, which inspired the creation of onboard data network to organize and coordinate the activities of different electronic units used in a vehicle to serve these functions.

The major elements of Intelligent Transportation Systems (ITS) are categorized into seven groups according to (Gubbi, Buyya, Marusic, & Palaniswami, 2013):

1. Travel demand management
2. Commercial vehicle operations
3. Travel and transportation management
4. Electronic payment
5. Emergency management
6. Public transportation operations
7. Advanced vehicle control and safety systems

To ensure better understanding and the importance of ITS in the future transportation systems. It is very important to look at the potential applications of Intelligent Transportation Systems (ITS), among the four key components of the systems. These include: the vehicle, the user, the communication systems and the infrastructure according to (Litman & Burwell, 2006; Tayyaran & Khan, 2003) are:

2.5.1 The vehicle

Intelligent Transportation Systems (ITS), the application includes fleet management, efficient enforcement of regulations, in-vehicle navigation and routing, electronic toll collection, tracking of critical cargo movements, data collection and automated control systems.

2.5.2 The user

The Intelligent Transportation Systems (ITS), offers inter-vehicle navigation, driver monitoring capabilities, route guidance and dynamic route guidance in response to changing traffic conditions.

2.5.3 The infrastructure

The Intelligent Transportation Systems (ITS), and its enabling technologies provide services such as monitoring of weather, environmental and traffic conditions. ITS, capabilities include responding to emergencies and management of both planned and unexpected events. These services include other control functions that are traditionally performed by traffic signals.

2.5.4 The communications systems

Intelligent Transportation Systems (ITS) provides the ability to exchange information between the three components in the system. This allows for the gathering of suitable data for processing into intelligence with capabilities to determine and activate appropriate command and control actions (Ferreira, Fernandes, Conceição, Viriyasitavat, & Tonguz, 2010).

The Intelligent Transportation Systems (ITS), projects implemented in Canada, Europe, Japan and the United States according to (Litman & Burwell, 2006), demonstrate the potential benefits of ITS applications and these are evident in all aspects of the transportation systems. The important key benefits of Intelligent Transportation Systems (ITS), technologies include improved safety, reduced congestion, and improved mobility, enhanced economic productivity, reduced impacts on the environment. However, ITS applications in VANETs are confronted with many technical challenges (Eichler, 2007; Zeadally et al., 2012). These challenges, associated

with congested networks and sparse networks in VANETs, required intensive research efforts to improve ITS applications. The improvement of ITS applications is the research direction in this thesis.

2.6 Research directions in VANETs

It is increasingly important to know from the research perspective that ITS applications are becoming very successful and researchers should endeavour to come out with new research findings to mitigate ITS challenges in these directions according to (Tayyaran & Khan, 2003; Zang, Sories, Gehlen, & Walke, 2009). These research findings need further investigation into certain technology applications in VANETs.

2.6.1 The needed technologies

The two approaches used in VANETs include Wireless Local Area Network (WLAN) technologies (i.e. IEEE 802.11) and the modification of the Third Generation (3G) cellular technologies for VANETs applications (Vinel, 2012).

2.6.1.1 IEEE 802.11

IEEE 802.11, standard outlined in (Ozer, Kahrman, Aksoy, Adiguzel, & Karadogan) indicates the Physical (PHY) and the Medium Access Control (MAC) layers of a WLAN and offers higher layers such as IEEE 802.x Local Area Network (LAN) standards. The physical layer can be either infrared or spread spectrum radio transmission. Other features support power management; the handling of the hidden nodes, license-free operation in the 2.4 GHz Industrial, Scientific, Medical (ISM) band, and data rates 1 or 2 Mbps.

IEEE 802.11 standard is usually used in PHY/MAC protocol in MANETs and VANETs because the standard's support infrastructure or ad hoc networks. There are three basic access mechanisms explained in IEEE 802.11. The first approach is the Carrier Sense Multiple Access with Collision Avoidance (CSMA/CA). The second approach is Ready-To-Send (RTS)/Clear-To-Send (CTS) handshake signals to avoid the hidden terminal problem. The third approach is the use of the mechanism to provide time-bounded services.

2.6.1.2 The Dedicated Short-Range Communication

The Dedicated Short-Range Communication (DSRC) standard reported in (Yousefi et al., 2006), provide descriptions of MAC and PHY standard specifications for wireless connectivity. This standard is mainly focused on the IEEE 802.11a, according to (Altintas et al., 2011; Wang, Song, & Han, 2013) in the 5GHz Band and which is designed for used in the high-speed vehicular environment. In fact, the PHY layer of DSRC is adapted from IEEE 802.11a PHY based on Orthogonal Frequency Division Multiplex (OFDM) technology. For instance, the MAC layer of the DSRC is very similar to the IEEE 802.11 MAC based on the CSMA/CA protocol with minor modification.

The DSRC standard utilizes the 75MHz spectrum, which is being allocated by the United States' Federal Communication Commission to provide wireless V2R or V2V communications that occur over line-of-sight distances of less than 1000 meters between the roadside units and which is mostly regarded as high-speed communications but occasionally stopped and evident in slow-moving vehicles as well as high-speed vehicles. The future expectation is that with the help of government and industry, the DSRC systems will be the first wide-scale Vehicular Ad Hoc Networks (VANETs) applications in North America.

2.6.1.3 Time Division Duplex of UMTS Terrestrial Radio Access

The Car-TALK and Fleet-Net projects have selected Terrestrial Radio Access Time Division Duplex (UMTS) with (UTRA TDD) as a suitable alternative for the air interface that can be used for their Vehicular Ad Hoc Networks (VANETs) applications according to (Altintas et al., 2011; Hadaller, Keshav, Brecht, & Agarwal, 2007). The UTRA TDD provides connection-oriented, connectionless services and control Quality of Service (QoS) through the flexible assignment of radio resources and as well as asymmetric data flows. It also includes the availability of unlicensed frequency band at 2010 – 2020 MHz in Europe, with support for high transmission range, high vehicle velocities, and high data rates of up to 2Mbps

The UTRA TDD also reserves several time slots towards high priority services. The remaining slots can be dynamically assigned and temporarily reserved by different stations of lower priority services using Reservation ALOHA (R-ALOHA) scheme. This reduced the potential collisions by reserving a small transmit capacity for a circuit-switched broadcast channel that is mainly used for signalling purposes but may be used for transmitting small amounts of user data as well.

2.6.2 MAC layer issues

VANETs are usually considered a special application of MANETs with some well-defined applications. It also includes severe operating constraints which usually result in frequent disconnection of the network coupled with fast topology changes according to (Torrent-Moreno et al., 2009). The sparseness of the nodes causes the network disconnection. This study aimed at dense network and sparse network traffic due to the challenges associated with the vehicular network ITS applications.

2.6.3 Applications

A lot of applications were proposed within Intelligent Transportation Systems (ITS) projects in recent times according to (Al-Sultan et al., 2014; Boukerche, Oliveira, Nakamura, & Loureiro, 2008). In the advent of current wireless technology research efforts from the academia and industry in mobile ad hoc and VANETs, the VANETs are seen with the capabilities of supporting these ITS applications in the future.

2.6.3.1 Safety applications

In VANETs applications, the vehicle foresee dangerous situation ahead can report it instantly to neighbouring vehicles. Sensors can recognise dangerous situation by detecting events such as the deployment of airbags due to the accident, loss of tire traction, or sudden application of brakes. The critical requirements in these applications are latency and area of coverage as reported in (Forecast, 2013; Zhang, 2006).

According to (M. M. Artimy, Robertson, & Phillips, 2005), triggers the need to introduce the concept of Zone-of-Relevance. Within this zone, a warning message is delivered to drivers to assist them to avoid dangerous situations while the vehicle outside the Zone-of-Relevance may route the message but drivers are not alerted to ensure that only the relevant messages are delivered to drivers and all the unnecessary reactions are avoided to prevent fatality on the roads.

2.6.3.2 Traffic monitoring

The use of existing capabilities of vehicles, such as Car Area Network (CAN) and GPS, VANETs act as an intelligent sensor and forms powerful traffic information systems. The

advantages of using VANETs over other infrastructure-based systems involved the rapid deployment, self-organization, and lower-cost applications.

According to (Kloiber, Strang, Spijker, & Heijenk, 2012), VANETs is composed of fixed and mobile nodes (vehicles). The vehicles are organized into clusters where they exchange beacon to maintain a neighbouring relationship. This task request is generated by the nodes or from an external network and is transmitted to immediate neighbours to monitor some relevant conditions of the roads. The forwarding tasks request may occur to propagate the requests through the network upon receiving the request; the vehicle itself samples the data from the relevant sensor. This data is then summarized and forwarded back to the originating nodes as a task response which works within certain threshold parameters.

According to (Su & Zhang, 2007; Zeadally et al., 2012), in each segment, the vehicle has the capability to monitor the locally observed traffic situation by receiving data packets concurrently with detailed information from other vehicles within the contour of the road. In their studies, a traffic situation analysis was performed in each individual vehicle and the result is transmitted through a wireless data-link to all vehicles in the local neighbourhood. This has seen a significant improvement but failed to address ITS alert message dissemination due to the fast topology changes in VANETs.

2.6.3.3 Automated highways and cooperative driving

This type of VANETs applications is primarily focused on the automation of some driving functions to increase driving safety and improve the capacity of highways. This study investigated into platoon formation and lane merge according to (Amoozadeh, Deng, Chuah,

Zhang, & Ghosal, 2015; Anda et al., 2005; Nekovee & Bogason, 2007) and obstacle avoidance and blind intersection assistance according to (Boukerche et al., 2008). This result is a serious defect that prevails during lane change at the intersection.

2.6.3.4 Entertainments

These applications ensure the delivering of multimedia content for vehicle passengers. Among the challenges in this area is the provision of QoS guarantee to locate the media content. The author (Toor, Muhlethaler, & Laouiti, 2008) assess the importance of a Car-to-Car (C2C) and Peer-to-Peer (P2P) systems for delivering media content using the cellular and VANETs applications.

2.7 An overview of VANETs applications

The vehicular ad hoc networks (VANETs) applications are seen in a broader sense as an indispensable aspect of modern life. This V2V (vehicle-to-vehicle), V2R (vehicle-to-road infrastructure) V2S (vehicle-to-sensor on-board), and V2I (vehicle-to-Internet) applications according to (Agerholm et al., 2015; Ramadan et al., 2012; Sheng et al., 2015). These applications have come to stay and will continue to evolve despite the challenges that impede the overall benefits. Irrespective of the challenges in VANETs, wireless communication capabilities are expected to continue to revolutionize the automobile industries. With the help of academia and research communities, VANETs will undoubtedly produce unprecedented results and reduced the fatalities of accidents on our roads when efficient traffic flow models are developed. The improvement of traffic flow model is the main reason for this thesis.

The new direction now would allow academia and industry to collaborate to support various applications to improve road safety such as lane change warning, cooperative merging, and collision detection. Smart and green transportation would also help applications such as traffic signal control, fleet management, and intelligent traffic scheduling and location dependent services like route optimization access. It is evident that the market of VANETs applications will grow massively according to recent global business report, that the global market is projected to reach USD 131.9 billion by 2019 according to (Forecast, 2013), due to the numerous benefits of vehicular networks in ITS applications.

The importance of VANETs applications is divided into two main driving forces of bringing together the wireless vehicular connectivity to mitigate safety alert message dissemination. The first direction is the improvement of safety and efficiency of road transportation systems. The increasing population growth correlates with the number of vehicles in urban and in large cities. This driving force accounts for traffic congestion and this led to environmental problems and economic cost. It is reported (Forecast, 2013) that the traffic congestion accounts for the cost of extra travel time and fuel consumptions in 498, United State of America, urban areas were 121 billion USD in 2011 and carbon dioxide produced during vehicular congestion was 56 billion pounds, compared to 24 billion USD and 10 billion pounds in 1982 respectively (Schrank et al., 2012). The VANETs applications are promising to mitigate traffic congestion by means of intelligent traffic controls and surveillance management according to (Anda et al., 2005). This will subsequently improve the road safety through onboard advanced traffic warning and driving assistance systems as presented (Olaverri-Monreal et al., 2010).

The second direction refers to increasing mobile data demand for vehicular users on the road. In recent times, the high demand of mobile Internet users has increased exponentially. Many people expect to have the same vehicular Internet connectivity while driving a car as compared to what they have at home and at workplaces. Vehicular Internet connectivity is expected not to meet the mobile data demands according to (Balasubramanian et al., 2008). This also support safety-related applications of online diagnosis presented in (Lai, 2016). Intelligent anti-theft tracking according to (Ramadan et al., 2012), whereby the servers resides in the Internet cloud. The VANETs Internet integrated vehicles are almost on the road with us and are projected that the percentage of the Internet integrated vehicles applications will rise from 10% to 90% by 2020 as simplified in (Lu et al., 2014). Surprisingly the US. Department of Transportation's (DOT), National Highway Traffic Safety Administration (NHTSA), recently announced that it will start taking immediate steps to enable communications between light vehicles according to (Cheng et al., 2017). Furthermore, the government has mandated the VANETs connected vehicle revolution on a fast track mission due to its important applications. The European Commission has also proposed the mandatory implementation of "eCell" system in cars beginning in 2015 by which cars may automatically establish a telephone link for emergency services in the midst of collision and congestion according to (Agerholm et al., 2015; Sheng et al., 2015). This revelation proved the importance and the relevance of this study.

VANETs connected vehicles refer to the wireless connectivity enabled vehicles that are equipped to communicate with their internal and external environments. This technology enabled vehicles presented in (Tuohy et al., 2015) This has the capabilities of supporting the interactions between V2V (vehicle-to-vehicle), V2R (vehicle-to-road infrastructure) V2S (vehicle-to-sensor on-board), and V2I (vehicle-to-Internet), as shown in Figure. 2.1. These applications are considered

as the building blocks of the emerging Internet of Vehicles (IoV). The dynamic mobile communication systems have the features of gathering, sharing, processing, computing and the release of security information. This would spearhead the evolution of the next generation of Intelligent Transportation Systems (ITS) according to (Liu, 2011). The development and deployment of the fully VANETs connected vehicles require the combination of various off-the-shelf and emerging technologies. This study focuses on the vehicular ad hoc networks (VANETs) technologies applications and presents an overview of the industrial and academic advances for establishing a comprehensive VANETs connectivity architecture. The study will also present the state-of-the-art potential challenges and identify research direction to propose the alternative solution. The literature presented in (Faezipour, Nourani, Saeed, & Addepalli, 2012; Qu et al., 2010), serve a similar goal, but with a different focus.

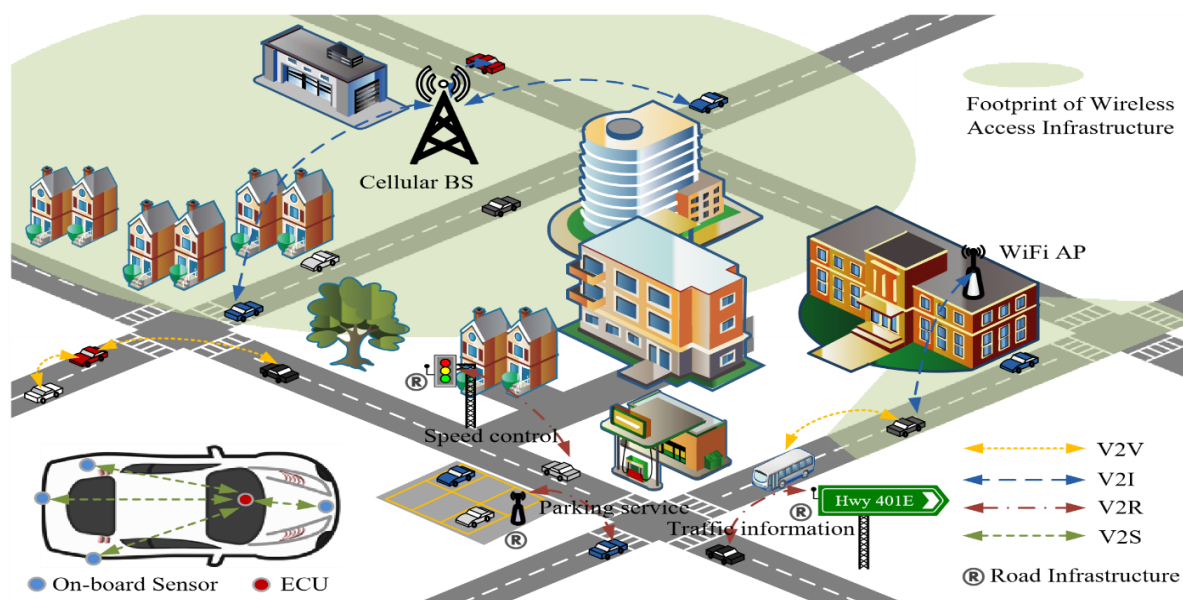


Figure 2.1 Overview of VANETs Connected Vehicles

2.8 The vehicular mobility

Many researchers are highly interested in studying sparse vehicular networks due to its importance in ITS applications in VANETs. This motivation from most researchers reflects the assumptions inherent in the inter-vehicle communication associated with sparse networks. This is seen to be more challenging due to the difficulty in maintaining connectivity. In addition, the low-density conditions offer more flexibility in setting the traffic parameters such as flow, speed, and density for analytical and simulation studies. The assumption of independent parameters is valid only in free-flow traffic. Therefore, the results of these studies cannot be used directly in dense traffic environments. This study seeks to argue that research should focus more on dense traffic and traffic jam environments due to their important significant influence on VANETs:

1. The vehicle density can contribute to rapid message dissemination according to (Torrent-Moreno et al., 2009).
2. Higher node density aggravates the contention and collision problem in the communication protocols based on shared media.
3. The traffic jams contribute to the non-homogeneous distribution of vehicles and which increases the needed transmission range to maintain connectivity.
4. The vehicle traffic may change rapidly between free-flow to congested traffic due to traffic controls, road constraints or accidents.

The focus of this thesis is to propose a novel alternative methodology to improve ITS applications associated with dense and sparse networks in VANETs. The review of research directions related to the use of vehicle mobility models and traffic simulator is provided in the next subsection.

2.8.1 The vehicle mobility models and traffic simulations

The vehicular mobility models and traffic simulators have been in development according to (Choffnes & Bustamante, 2005; Harri et al., 2009). The main reasons for these simulators are in traffic analysis, forecasting, and planning transportation networks. Due to the important applications in VANETs, the ITS initiative has generated an enormous number of vehicular traffic simulators since its inception in the United State in 1991 according to (L. Chen, Wei, & Shi, 2011; Ros, Martinez, & Ruiz, 2014). These simulators are intended to support ITS applications, but not necessarily VANETs, due to their recent introduction.

In VANETs research papers, simulation of vehicle mobility is often considered a special type of mobility model such as the RWP model with some extensions (Bettstetter, Hartenstein, & Pérez-Costa, 2004; Bettstetter, Resta, & Santi, 2003; Harri et al., 2009). These mobility models may not produce complex vehicle manoeuvres such as car-following, accelerating, decelerating under traffic jam situations. For the analysis of any complex phenomenon in view of VANETs characteristics, many studies have relied on vehicular mobility models or traffic simulators to generate vehicle movement traces to improve ITS applications. This is the major direction of this thesis.

2.8.1.1 The mobility models

Many studies in ad hoc networks often require keeping track of nodes positions at any given time and vehicular networks are no exception. In recent time, many VANETs applications depend on realistic vehicle movement patterns to obtain from traffic micro-controllers which can track the characteristics of individual vehicles including the position, speed, and direction. The early research in inter-vehicle communication relied on micro-simulators that were designed originally

for studying vehicle traffic in intelligent transportation systems. VANETs research adapts simulators to generate traces of vehicles positions at regular time interval into network simulator according to (Breslau et al., 2000; Fall & Floyd, 1996) to perform a simulation of communication protocols. In recent times, the research communities have devoted substantiate effort to the development of network traffic simulators for VANETs research according to (Harri et al., 2009; Karnadi, Mo, & Lan, 2007; Yousefi et al., 2006). Usually, these simulators have a dual focus on the communication and mobility sides of VANETs and this is considered in this thesis.

2.8.1.2 The traffic flow models

The traffic simulators are extensively used in evaluating vehicular ad hoc networks. The analytical approaches in free-flow traffic conditions are usually the preferred choice. The primary reasons for this choice are the control environments it's offered to select at least two or three parameters to establish the fundamental relationship of the traffic flow under free-flow conditions (May, 1990). This study assumes that the traffic flow and the vehicle velocity are independent under sparse network scenarios. These fundamental relationships of traffic flow are used to derive the pdf of the communication duration between vehicles and the pdf of the time between consecutive topology changes. Similar assumptions are made in (May, 1990) to derive the pdf for distance at which it is possible to establish a Multi-hop connection between two vehicles. The effective selection of time headway (i.e. the time gap between consecutive vehicles) as an input parameter can be control at the rate by which vehicles are injected to the simulation environment and the density of the vehicles. The time headway values are generated randomly from a Poisson distribution with an average value that ensures the free-flow traffic. A

uniform distribution with a minimum value that specifies the initial separation between vehicles is used. The analysis of traffic flow models is the major direction of this study in which the effect of parameters would be studied to ascertain its variations in each model. The performance analysis of traffic flow theory will be examined critically in section 2.9, to understand the merits and the demerits from several research directions.

2.8.1.3 The vehicle speed

In most cases, the desired speed is provided as an input to the simulations. The vehicle speed can be a constant value for each type of vehicles (e.g. cars and trucks) or may form a random distribution according to (Boban, Vinhoza, Ferreira, Barros, & Tonguz, 2011; Sommer, German, & Dressler, 2011). The speed distribution is chosen to correspond to real measurements from German highways, while in (Adolf, 1990; Donnell, Ni, Adolini, & Elefteriadou, 2001; May, 1990), the speed is assigned from a normal distribution and this scenario has been considered in this thesis.

One possible choice of (Khoury & Hobeika, 2007) that is usually used as a guide to set the limit on the highways (Khoury & Hobeika, 2007). The 85th percentile speed is defined as the speed 85% of drivers moving at or below. It is evident that 75% of the drivers maintain a speed within a certain range around the average speed limit. Another research finding indicates that 15% are slow drivers while the remaining 15% are driving at high speeds. According to (Adolf, 1990), the vehicle speed is sampled from a Normal distribution using the standard deviation to mark the boundaries between slow, average and high speeds. Although, the speed and time headway changes in real traffic, they are kept constant in (Alsabaan, Alasmay, Albasir, & Naik, 2013;

Haerri, Filali, & Bonnet, 2006; L. Li & Chen, 2017) and this assumption is also considered in this thesis.

In addition, the choice of the average speed varies according to the choice of the environment under considerations. In highway simulations, the average speed is set to 100-130km/hr according to (Esser & Schreckenberg, 1997; Van Arem, Van Driel, & Visser, 2006). In another development, simulations of city street grid set the average speed to 40-80km/hr either randomly according to (Ahn, Rakha, Trani, & Van Aerde, 2002) or according to the street types. The choice of speed may reflect also the posted speed limit, road conditions, and common driving habits.

2.8.1.4 The collisions

The collision in VANETs has usually assumed in some literature that a vehicle moves freely and collisions are not allowed. However, the vehicle density according to (May, 1990) is specified to create congested traffic situations and vehicles may collide if drivers fail to react in time. This finding is very necessary to evaluate the influence of the V2V and V2R communication on safety as indicated in (May, 1990).

2.8.1.5 The road topology

This may be described as a common choice of highway geometry of two or more lanes in each direction. This allows the traffic to flow in both directions which may be described as asymmetric as summarised in (Mohimani, Ashtiani, Javanmard, & Hamdi, 2009; Zeadally et al., 2012). According to (Mohimani et al., 2009; Zeadally et al., 2012), they argue that dividing the highways may be used to limit the geographic area affected by message broadcast to one traffic

direction only. According to (Jerbi, Senouci, Rasheed, & Ghamri-Doudane, 2009; Santos, Edwards, Edwards, & Seed, 2005), explained more complex geometry to be used to evaluate routing strategies and protocols in a city traffic flow environment to mitigate topology challenges in VANETs.

2.9 Performance analysis of the traffic flow theory

This section provides relevant background information to the traffic flow theory that involves the summary of the terminology as well as the parameters used to describe traffic flows is the direction in this thesis. The fundamental concepts of the traffic flow and the tools and methods available for vehicular traffic flow analysis.

The vehicular traffic flow is seen to be a complex phenomenon since they involve human activities, physical infrastructure, time and vehicular movement on the other hand. Several approaches have been adopted to investigate the problems of traffic flow according to (Adolf, 1990). This process involves the use of empirical and intuitive studies to collect traffic statistics in an event of the accident. Standard data analysis techniques are then used to determine the interrelated parameters between relevant quantities. According to (Nagel & Herrmann, 1993; Ros et al., 2014), several deterministic theories have been proposed to describe traffic dynamics at the macroscopic traffic flow model. On the other hand, the probabilities flow models and queuing theory is usually used to represent intersections or length of road to determine quantities such as delay, capacity or the average speed. To ensure a realistic result, traffic simulations are used to perform analytical analysis to simplify the traffic problems to some extent.

Vehicular traffic flow theories have been developed to define the interrelationship of quantities with respect to vehicle density, speed, and flow. These mathematical relationships among these three quantities have the tendencies to predict an abrupt change in one or two quantities. These changes usually manifest when congestion erupts by a driver.

Research indicates that several advances have emerged leading to the introduction of cellular automata (CA) models in the past. Simulation of vehicular traffic flow using CA models has exhibited characteristic as a phase transition phenomenon. Vehicular traffic flow exhibit gas or liquid states phenomenon which is in a homogeneous state.

This chapter defines the main characteristics that are used to describe traffic flow in section 2.7.1, follow by the fundamental relationship of traffic flow that relates these characteristics in section 2.8. This relationship is the fundamental basis of this thesis to perform the analytical study using macroscopic traffic flow models according to (Adolf, 1990; May, 1990; Nagel, 1996) in relation to dense and sparse networks. The section 2.8.1 explains four of the main models that are used in vehicle traffic analysis. In section 2.9, explain the concept of phase transition and the effect of parameters. Section 2.10, provides the summary of traffic simulation approaches applicable in VANETs while section 2.11, conclude the chapter.

The understanding of this model leads to methodology in chapter 3, while chapter 4 introduces concepts to improve reachability and scalability in VANETs under dense and in sparse networks scenarios.

2.9.1 Traffic flow characteristics

Road traffic stream studies is primarily focused on three characteristics of the stream. In which the flow q , measures the number of vehicles that pass an observer per unit time. The flow k , measures the number of vehicles per unit distance. The speed u , measures the distance a vehicle travels per unit time.

Although, traffic streams are usually not uniform, but vary over both space and time duration. In view of this, the quantities q , k , and μ are regarded as either an average or sample random variables. Practically, the traffic characteristics like flow, speed, and velocity are parameters used in statistical distributions but not absolute number according to (Adolf, 1990; May, 1990; Yousefi et al., 2006).

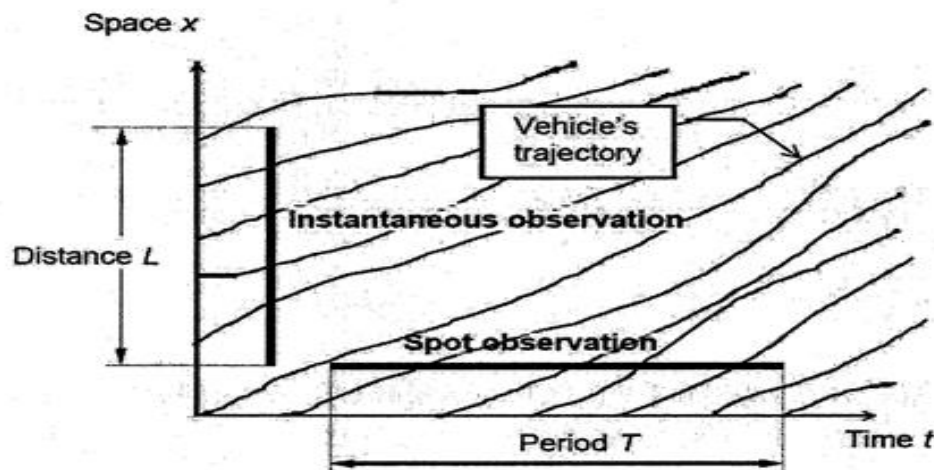


Figure 2.2 Spot and instantaneous traffic observations

The vehicular movement may be counted and measured through a specific location under observation. This observation is known as spot observation while instantaneous observation refers to the vehicle on a designated highway when the segment is counted and the speeds are measured instantly as shown in Figure 2.2. On the other hand, the instantaneous observation

occurs when the traffic density and space-mean speed are directly estimated. In addition, spot observation occurs when the traffic volume and the time-mean speed are directly estimated according to (Adolf, 1990; May, 1990; Schumacher, Priemer, & Slotke, 2009). This relationship pointed in this literature is relevant in a practical implementation of any traffic flow model in VANETs. The research findings derived from the above studies provide a theoretical background in this thesis.

In an instantaneous observation, the number of vehicles, N on highway segment in each time measurement may be changed to traffic density k :

$$k = \frac{N}{L \times n_l} \quad (2.1)$$

Where k is measured in the vehicles per kilometre per lane (veh/km/lane), L is usually the length of the segment expressed in kilometres (km), and n_l denotes the number of traffic lanes. Typically, density is measured in each direction separately based on events. The speeds of vehicles, u_i , and this measurement can be averaged to calculate the space-mean speed, μ_s :

$$u_s = \frac{1}{N} \sum_{i=1}^N u_i . \quad (2.2)$$

The spot observations render the number of vehicles passing a spot during an observation period, T . This count can be converted to traffic flow, q :

$$q = \frac{N}{T} \quad (2.3)$$

The speeds of vehicles can also be measured in a spot observation. The resultant speed, called time-mean speed, is calculated as follows:

$$u_T = \frac{1}{N} \sum_{i=1}^N u_i \quad (2.4)$$

where u_T refer to time-mean speed which is calculated based on N spot measurements, u_i is the speed of the i^{th} vehicle included under observation. The time-mean as well as space-mean speeds measured for same traffic are typically not equal since the former does not account for stopped vehicles (Adolf, 1990; May, 1990; Schumacher et al., 2009). All measurements of density and speed are based on instantaneous observation as given in (2.2) and (2.3). As a result, the average (mean) speed refers to the space-mean speed, i.e. $\mu = \mu_s$.

2.10 Fundamental relationship of traffic flow

Traffic flow is related to the headway between vehicles. The headway is defined here as the difference in arrival time between two consecutive vehicles as measured by a person standing at a fixed point on the road. If all the vehicles move at the same speed of μ , then the headway between two consecutive vehicles, h , is obtained by driving the distance, d , between these two vehicles by speed, μ , ($h = d/\mu$). If a person measures the headways and distance between consecutive vehicles under observation and calculates the average values, h and d , the

relationship between this average value will be preserved, i.e. $h=d/\mu$. Note also that $q=1/h$ and $k=1/d$ according to (Adolf, 1990; May, 1990; Schumacher et al., 2009). Thus,

$$q = u \times k \tag{2.5}$$

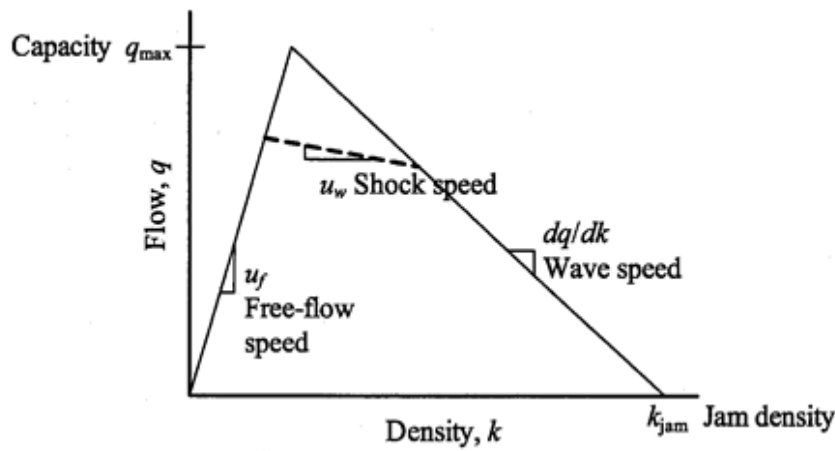


Figure 2.3 Fundamental Diagram of Road Traffic.

Equation (2.5) is called the Fundamental Traffic Flow Relationship. For the comprehensive derivation of this relationship according to (Adolf, 1990; May, 1990; Nagel, 1996). All the bivariate relationships among the variable in (2.5) are studied in the literature. Some of the approaches starts with mathematical models while others are mainly empirical according to (Adolf, 1990; May, 1990; Nagel, 1996). The bivariate relationship between traffic flow and density considered useful is the Fundamental Diagram of Road Traffic. The q-k relationship can be deduced intuitively in (Adolf, 1990; May, 1990; Nagel, 1996). The flow must be zero when density is zero. The flow also falls to zero when density is at maximum (vehicles are stationary in a traffic jam). For values of density between these limits, flow must rise to at least one maximum. The experimental data seem to confirm this argument, but there is some conflicting

evidence regarding the exact shape of the curve. Previous studies assumed the curve to take a parabolic shape (Adolf, 1990; Nagel & Herrmann, 1993). Furthermore, empirical data such as those reported in (Burstedde, Klauck, Schadschneider, & Zittartz, 2001; Kerner, Klenov, & Wolf, 2002; Nagel & Schreckenberg, 1992), and simulations using CA models (Kerner et al., 2002), including the simulations produced in Chapter 3, show that the fundamental diagram may take the so-called reverse λ shape. The latter shape is an extension of Figure 2.3 and will be described in more detail in section 2.5.

Figure 2.3 shows that vehicle density has a maximum value denoted k_{jam} , the density of a traffic jam density is regarded as the reciprocal of the average length a vehicle occupies in a traffic jam. The maximum value of flow is denoted q_{max} . The maximum flow is also known as the ‘capacity’ of the road.

The left branch of the fundamental diagram describes free-flow traffic. Vehicles in this traffic condition move free from interference from other vehicles. The average free-flow speed of vehicles, u_f , is the ratio of flow to density. Figure 2.3 suggests that the free-flow speed remains constant as density increases up to a point where the increase in vehicle density starts to influence drivers and force them to reduce speed. Beyond this point, the vehicle speed is dependent on the density and this assumption has been studied in this thesis under dense network scenario.

The right branch of the fundamental diagram describes a congested traffic condition whereby q decrease with increasing k . The slope of this branch represents the speed of the traffic jam wave propagating backward relative to the direction of traffic, dq/dk according to (Adolf, 1990). Given

the previous discussion, it is possible to define the following terms to be used in the remainder of the thesis.

Definition 3.1 congested traffic is a vehicle traffic condition in which drivers cannot maintain the desired vehicle speed due to the close presence of other neighbouring vehicles. The speed in this traffic is influenced by the surrounding vehicles. Vehicles in congested traffic may experience stop-go movement patterns due to traffic jams.

Definition 3.2 free-flow traffic is a vehicle traffic condition in which drivers can maintain a virtually constant speed. The constant speed is determined by factors such as vehicle engine capability and traffic laws but it is not dependent on the speed of, or the distance to other vehicles.

Definition 3.3 traffic jam refers to several vehicles blocking one another in a queue so that they cannot move.

2.10.1 Traffic flow models

Traffic flow characteristics such as volume, density, and speed do not vary independently from each other. This fundamental relation of traffic flow (2.5) combines these three characteristics altogether but give room to determine one quantity when the other two are known. In addition, another equation is needed to calculate the two unknown flow characteristics from the known values.

There is no single theory that can explain all the complexities of traffic flow. Instead, there are several models that try to explain the relationships between traffic parameters. The oldest among these models are the macroscopic model (i.e. is the direction of this thesis) and based on the

fluid-dynamic theory, based on the assumption of a delayed adaptation of velocity. Research papers in physics journal (Chowdhury, Santen, & Schadschneider, 2000; Helbing & Tilch, 1998) model traffic as a system of interacting vehicles. These traffic models are more successful in describing physical phenomena such as the phase transition. One CA model of the macroscopic model will be used extensively in this thesis as an analytical tool to derive various relationships in Chapter 4 through to Chapter 5. The macroscopic models will be introduced briefly in Section 2.5 and in more detail in Chapter 3.

Unlike, other traffic models, the macroscopic model does not describe all aspects of vehicle traffic. The following subsections include an overview of three main traffic models. Each one of these models describes some aspect of vehicles traffic that will be employed in later chapters. The phenomenon of these models is interrelated in many ways possible. In Chapter 4 a relationship between the car-following model and the macroscopic model will be investigated. These relationships will be established in Chapter 5 to allow vehicles to estimate their local density without relying on infrastructure to exchange information with other cars.

2.10.1.1 Macroscopic (continuum) traffic models

Highway traffic can be visualized as a stream or a continuum fluid. Because of this analogy, traffic is often associated with fluid flow and treated similarly as a one-dimensional compressible fluid. The theory can also describe traffic flow along a multi-lane highway. This section will introduce the basics of this theory in (Hoogendoorn & Bovy, 2001). This section is the primary focus in this thesis with a similar model in (May, 1990), would be used extensively in chapter 4 and these results will be discussed in chapter 4 and chapter 5 with their models.

The continuum theory of traffic flow is based on two relations. The first is the law of conservation of vehicles and the other is an assumed relation between the flow and density according to (Adolf, 1990; Hoogendoorn & Bovy, 2001). In one-dimensional flow consider that measurements of the flow, q , are taken at two points, $x=a$ and $x=b$, a short distance apart, assuming there are neither entrances nor exits between these points. Then the change in the number of cars results from cars crossing at $x=a$ and $x=b$ only. This is expressed as follows (Waters & Laker, 1980):

$$\frac{\partial k}{\partial t} + \frac{\partial q}{\partial x} = 0 \quad (2.6)$$

This equation states that if, at a specific location, the flow coming in from the left is less than the flow going out to the right, then density must decrease at that location over some time, t . On the other hand, the density must increase if the incoming flow is greater than the outgoing flow. An additional equation or assumption is needed to solve (2.6). One possible option is to state speed as a function of density, $u=u(k)$, which is a clear reasonable assumption, but it is only valid in dense traffic scenario. It follows from this assumption that drivers vary their speed according to the density (i.e. as density increases hence the speed must decrease to maintain safe headway). Then q is assumed to be a function of density only, $q=ku(k)$. It should be noted that $u(k)$ can be any function (see section 2.8.3). Then, (2.6) can be written as

$$\frac{\partial k}{\partial t} + \frac{\partial q}{\partial x} = 0 \quad (2.7)$$

Where $dq/dk = u(k) + ku'(k) = 0$.

The solution of (2.7) has suggested that the density k is constant along a family of curves known as characteristics or waves. A wave represents a change in flow and the density along the roadway. The speed of the wave is c , a constant representing the slope of the flow as a function of density is evaluated at a constant density. According to (Adolf, 1990; Hoogendoorn & Bovy, 2001), the value of c is negative when the road is beyond a critical density and it represents the traffic wave velocity propagating backward (see Figure 2.3).

A shockwave is created when two characteristic lines intersect. The shock represents a mathematical discontinuity in q - k , or u - k elevations. Physically, a shockwave is an interface between congested and free-flow traffic. It is created where vehicles slow down or accelerate rapidly. The shock wave can travel forward or backward (the end of growing queue moves backward while the end of a dense column of vehicles behind a truck can move forward). The speed of the shock wave, u_w , is given in (Hoogendoorn & Bovy, 2001; Meshkov, 1969):

$$u_w = \frac{q_d - q_u}{k_d - k_u} \quad (2.8)$$

Where k_d , q_d and k_u , q_u represent downstream and upstream traffic parameter, respectively. In Figure 2.3, the shockwave speed is represented by the slope of the dotted line connecting the two traffic conditions (free-flow and congested traffic).

2.10.1.2 Car-following models

The car-following models depend on a single-lane dense traffic environment with no overtaking. These models assume that each driver reacts in certain specific fashion to a stimulus from the vehicles ahead or behind. In general, road conditions do not affect interactions between vehicles. A different approach is useful for low densities where interaction between vehicles disappears. The basic equation of the car-following model is found in (Adolf, 1990; Hoogendoorn & Bovy, 2001), Response = Sensitivity x Stimulus. This response is taken as the acceleration of the following vehicle. It has been established also that the stimulus is the relative speed between the following vehicle and the lead vehicle within a certain range. One example of the stimulus-response equation of the car-following model according to (Adolf, 1990; Hoogendoorn & Bovy, 2001; Saltelli & Annoni, 2010) (Kleijnen, 2005; May, 1990):

$$\frac{d^2 x_i(t + \tau)}{dt^2} = \lambda \left(\frac{dx_i(t)}{dt} - \frac{dx_{i-1}(t)}{dt} \right) \quad (2.9)$$

Where x_i is the position of the i_{th} vehicle, τ is the driver's reaction time and λ , refer to as the sensitivity of the interaction, which is considered proportional to the headway between the two consecutive vehicles. The sensitivity may take the value of one of the several functions (Adolf, 1990; Hoogendoorn & Bovy, 2001) and (Kleijnen, 2005; Saltelli & Annoni, 2010). This sensitivity factor λ , is used as a function of several input variables (i.e. thus increasing the value of λ from 1 to 10) to examine the effects of the macroscopic traffic flow model under dense and sparse networks scenario is investigated in this thesis.

Equation (2.9) and similar equations (Adolf, 1990; Kleijnen, 2005; Saltelli & Annoni, 2010) are used to derive the speed-density and the flow-density relationships for single steady-state traffic flow. In the linear case, λ is assumed to be constant and the equation (2.9) is integrated to derive the velocity-density relationship according to (Adolf, 1990; May, 1990).

$$u = \lambda \left(\frac{1}{k} - \frac{1}{k_{jam}} \right) \quad (2.10)$$

This consist of a linear car following model specifies an acceleration response which is completely independent of the inter-vehicle distance. When taking the following distance into account, the linear model can be modified by assuming that λ is inversely proportional to the following distance according to (Adolf, 1990; Kleijnen, 2005; Saltelli & Annoni, 2010).

Equation (2.10), which was proposed by Pipes in 1953 according to (Shercliff, 1953), has an undesirable feature. In this case, the speed tends to be unrealistically high near low densities. The recent event for the observations of freeway traffic and simplifications in traffic modelling led to the modification of the equation (2.10) according to (Adolf, 1990).

$$u = \min \left[u_{max}, q_{max} \left(\frac{1}{k} - \frac{1}{k_{jam}} \right) \right] \quad (2.11)$$

Where the speed cannot exceed a maximum value of u_{max} .

Figure 2.4 shows the speed-density relationship of (2.11). The flow can be obtained by substituting (2.11) into the fundamental relationship in (2.5).

$$q = \min \left[u_{max}k, q_{max} \left(1 - \frac{k}{k_{jam}} \right) \right] \quad (2.12)$$

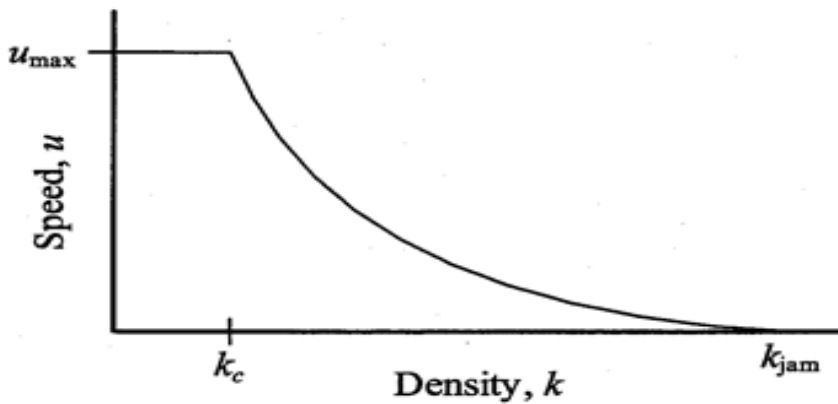


Figure 2.4 The speed-density relationship (Pipes Equation).

Equation (2.12) is represented by the q - k relationship of Figure 2.3. This equation is quite useful for understanding the effects of driver behaviour under traffic conditions. Another possible observation is that drivers tend to slow down when density increases. Similar observation is that when the capacity is reached at a density value. If density increases beyond certain critical value, k_c , the loss in flow caused by the speed decrease exceeds the gain caused by the density increase and the flow drops. The capacity is determined by the headway drivers maintain between vehicles. Drivers select spacing perceived as safe for the speed that persists in the capacity conditions.

Throughout this thesis, the relationships between speed-density and flow-density are assumed to follow equations (2.1) and (2.3), respectively. The traffic simulations produced in Chapter 3, results in relationships that are like those shown in figure 2.3 and figure 2.4 (with some modifications that will be clarified in Chapter 4). The reason for this similarity is that the macroscopic model belongs to the same class of the car-following models as the Pipes model, which assumes a linear relation between speed and the distance between vehicles. Moreover, in Section 3.2.1 the value of the sensitivity factor, λ , will be varied from 1 to 10 during simulations. Later, in Section 3.2.1 the value of λ will be derived analytically with the macroscopic traffic flow model in dense networks and sparse networks. Both results will be used in Chapter 4 and Chapter 5 to estimate the local vehicle density variations.

2.10.1.3 Two-fluid models

Two-fluid theory on traffic flow was proposed by Herman and Prigogine according to (Herman & Prigogine, 1979), to measure the level of quality of traffic service in an urban street network. This model applies to congested traffic in the right branch of the q-k relationship. The vehicles in this traffic stream are divided into two classes known as running and stopped vehicles. In addition, those in the later classes include vehicle stopped in the traffic stream due to traffic control signals and signs, blocking vehicles, normal congestion, but exclude those that are outside the traffic stream (e.g., parked cars). The model is based on two assumptions and this is reported in (Herman & Prigogine, 1979):

1. The average running speed within certain street network is proportional to the fraction of vehicles that are moving and
2. The fractional stop time within a test vehicle circulating within a network is equal to the

average fraction of the vehicles that stopped during the same period.

This first assumption of the two-fluid theory usually relates to the average speed of the moving (running) vehicle, u_r , to the fraction of moving vehicles, f_r , in this sequence:

$$u_r = u_{max} f_r^\eta \quad (2.13)$$

Where u_{max} is usually the average maximum running speed and η is an indicator of the quality of traffic service in the networks.

This average vehicle speed can be defined as $u = u_r f_r$, and $f_r + f_s = 1$, where f_s is the fraction of the stopped vehicles. Therefore, (2.13) can be rewritten as,

$$u = u_{max} (1 - f_s)^{\eta+1} \quad (2.14)$$

Second assumption of the two-fluid model that relates to the fraction of time when a test vehicle is circulating a network is stopped during a trip time to the average fraction of vehicles stopped during the same time, or

$$f_s = \frac{T_s}{T_t} \quad (2.15)$$

Where T_s is the stopping time and T_t is the trip time.

The relation has been proven analytically in (Ichoua, Gendreau, & Potvin, 2003; Jenelius & Koutsopoulos, 2013), and represented the principle embedded in the model, (i.e., that the network conditions can be represented by a single vehicle appropriately sampling the network).

The parameter, η , is considered a measure of the resistance of the network to degraded operation with increased demand. Higher values of η indicate the networks that degrade faster as demand increases. Field studies and simulations show that values of two-simulations, show that $\eta=0$ when vehicles are moving according to the macroscopic model.

The two-fluid theory is similarly significant to this thesis because it shows that a single vehicle may predict the surrounding traffic condition, more specifically the fraction of vehicles stopped in the transportation network, based on the vehicle's own movement (and stopping) pattern. This similar result in the macroscopic traffic flow model will be used in Chapter 5 in combination with results from traffic models to derive a relationship that allows a vehicle to estimate the local density by varying the value of λ from 1 to 10. This investigation would help to address the objectives of this study with regards to ITS applications in VANETs. The outcomes of this study would significantly improve on the congested networks and spares networks conditions in VANETs.

2.10.1.4 Cellular automata (CA) models

Quite recently, there has been much interest in studying traffic flow problems within the context of CA models. This cellular automaton is dynamic models in which space, time, and state are discrete. The discrete space consists of a grid of cells where each one can be in one of a finite number of possible states. These states of the cells in grid are updated according to a local rule.

That is, the state of a cell at the next time step depends only on its own current state, as well as the current states of its nearby neighbour. This CA approach follows the macroscopic traffic flow model where the value of λ increases. All the cells in the grid are updated in parallel, so that the state of the entire grid advances in discrete time steps. The details of the system, including lane changing, complex turns and intersection configurations are fully represented and each driver is given a destination and a preferred path accordingly.

Compared with the other traffic flow models, the CA models are conceptually simpler, and can be readily implemented on computers. These models capture the complexity of the nonlinear character of the problem and provide clear physical pictures. For example, CA models show the existence of a transition between a free-flow phase and a congested phase in the vehicle traffic as the car density is varied and this is investigated in this thesis (see Chapter 4 and Chapter 5). A well-known CA model according to (Adolf, 1990; Hoogendoorn & Bovy, 2001), will be discussed in detail in Chapter 4 in the context of macroscopic traffic flow model.

2.11 Phase transition and order parameters

The behaviour of the vehicles in a traffic jam can be described by this example in (Sugiyama et al., 2008). Consider a situation when a constraint causing a traffic jam has just been cleared. Assume there is a queue of five vehicles of zero speed creating a small traffic jam. In the first-time step, only the lead vehicle can move. The second step, the second vehicle may start, and so on. In the meantime, it can happen that other vehicles join the queue at the upstream end. Given the right conditions (fewer vehicles joining at the upstream end than leaving at the downstream end), this results in a cluster of vehicles of zero speed moving against the traffic direction and so

on. The vehicle composition of this cluster is constantly changing from the perspective of an observer. This represents the wave phenomenon's that have been described by the theory of kinematic wave's equation (2.6).

It is believed that the scenario described above may occur without necessarily in the presence of obvious constraints but mainly due to fluctuation (noise) in driving speed. These fluctuations may usually be caused by bumps, curves, lapses of attention due to different engine capabilities. The amount and types of congestion induced by erratic drivers depend on how much the leading vehicle car's speed fluctuates. Moderate fluctuations of an erratically driven car can trigger a train of density waves, which moves upstream like shock waves. As the average speed decreases, isolated moving clusters may grow quickly into a nearby continuous jam in (Sugiyama et al., 2008). This type of traffic jam has been studied extensively using traffic simulation models (Ichoua et al., 2003; Kerner, 2000a, 2000b). The phase transition phenomenon occurs in composite systems and is being described an emergent feature because it is observable at the macroscopic level but not in the microscopic level according to (Adolf, 1990; Sugiyama et al., 2008). The research findings reported as the phase transition (see Figure 2.5) is theoretically improved in this thesis using the macroscopic traffic flow model and have been discussed extensively in Chapter 4 and Chapter 5 respectively.

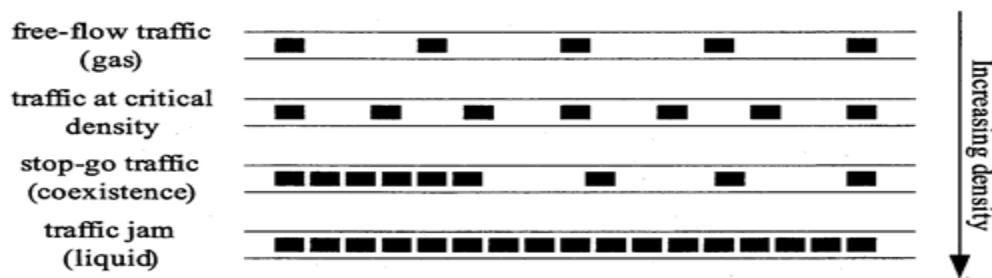


Figure 2.5 Phase Transition

The breaking down of vehicle traffic into jams has properties like phase transition in physical matter. Given the gas-liquid analogy of Figure 2.4, traffic has two phases and can be in one of the three states. Free-flow traffic will correspond to the gas phase, jammed traffic will correspond to the liquid phase and traffic characteristics by stop-go waves will correspond to the coexistence of liquid and gas. A transition between the two phases occurs at a critical point according to (Fisher, Fisher, & Huse, 1991). An alternative point of view divides traffic into three phases where the free-flow and jammed phases are separated by a synchronized flow phase, and there is two critical points that separate the three phases (see Figure 2.5). This phenomenon is like the congestion control model developed in this thesis (see Figure 4.11, Figure 4.12 and Figure 4.13) as explained in chapter 5.

Figure 2.6 reflects the speed-density relationship that results from traffic conditions similar to ones shown in Figure 2.5 according to (Sugiyama et al., 2008). The left branch (OA) of the relationship represents free-flow traffic at densities below k_1 .

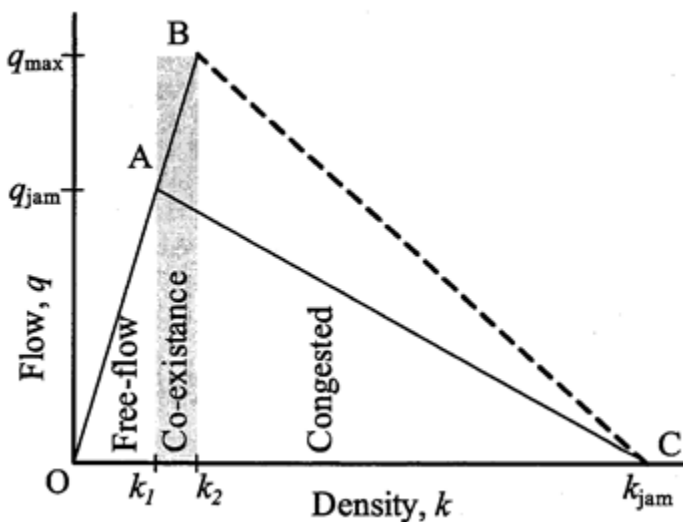


Figure 2.6 A reverse λ shape fundamental diagram showing free-flow, congested, and mixed state traffic conditions

When the densities are above k_2 , traffic becomes congested and hindered by traffic jams. This q - k relationship of the congested traffic is represented by the right branch (AC). Empirical evidence indicated in (Adolf, 1990; Sugiyama et al., 2008) and traffic simulation suggest that traffic would also be in a coexistence phase. At densities between k_1 and k_2 , drivers may accept shorter headways between vehicles. Thus, achieving the maximum flow q_m , at the critical density, k_2 . High fluctuations of speed in this traffic phase. The dashed line (BC) shows the relationship between the reverse λ shape and the triangular shape of the fundamental diagram shown in Figure 3.3.

Although the traffic models described in section 2.5 predict the occurrence of traffic jams and shock waves, they do not show the breakdown of traffic into three states. The speed-density relationship in Figure 2.6 can be generated in MATLAB model, by the choice of appropriate parameters (Adolf, 1990; Fall & Floyd, 1996; Martinez, Toh, Cano, Calafate, & Manzoni, 2011), which will be discussed in details in Chapter 3

The phase transitions are classified, in physics into first and second order. The first order transitions are discontinuous. The system changes its state from one phase to the other in a spontaneous way such that there is an obvious interface between phases at a critical point. The second order transitions are continuous. There is a gradual change from one phase to another such that there is no distinct phase at a critical point.

Phase transitions describe system going between a disordered state and an ordered state. Order is a macro feature that is characterized by an order parameter, which is a macroscopic variable that

describes variations between macro-states. The order parameter takes a finite value in the ordered state and zeroes in the disordered state as investigated in this thesis (see Chapter 4).

The previous example of the road scenario indicates vehicles in a traffic jam are not permanently stopped, instead of driver's experience a repeated stop-go sequence. An external observer monitoring the traffic (say from a helicopter) will notice that there is a fraction of vehicles whose speed is zero at any given moment. This fraction can be considered an order parameter characterizing the traffic flow according to (Claffy, Braun, & Polyzos, 1995; Cuesta, Martínez, Molera, & Sánchez, 1993; Zhao, Lai, Park, & Ye, 2005). In the free-flow state of traffic, all vehicles are moving and the order parameter is zero (the system is disordered). In traffic jams, the order parameter is nonzero (the system is ordered state).

The order parameter concept described here is not different from the fraction of stopped vehicles that was used in (2.14) to determine the average speed. The same concept will be used to analyse spares network as describe in Chapter 5 to distinguish between free-flow and congested conditions.

2.12 Traffic simulation models

Traffic simulation models are effective tools for analysing complex problems that cannot be described easily in analytical terms because of the complex, simultaneous interactions of many system components. These traffic simulation models can be used for a wide range of applications according to (Al-Sultan et al., 2014). Almost all traffic simulation models describe dynamic systems where time is usually the basic independent variable. Continuous simulation models describe how each element of system change its state continuously over time in response to

continuous stimuli. Discrete simulation models represent real-world systems (that are either continuous or discrete) by updating their states abruptly at any given point in time.

Generally, we have two types of discrete models: discrete time models and discrete event models. The discrete time models segment time into a sequence of time intervals. Within each interval, the simulation model computes the activities which change the states of selected system elements. Discrete event models are effective and economical when the system states change infrequently. However, for any systems that experience a continuous change in state, such as vehicle traffic environment and where the model objectives require very detailed descriptions, then the discrete time model is the better choice due to the frequent change of the system states and this phenomenon applies to VANETs applications due to its fast topology changes.

Simulation models are usually classified according to the level of detail with which they represent the systems to be studied according to (Al-Sultan et al., 2014):

2.12.1 The microscopic model

This describes both the systems entities and their interactions at a high level of detail. For instance, a decision to change lane are determined for each individual vehicle by considering the distance to its current leader, then its presumed leader and follower in the target lane. The duration of the lane-change manoeuvre can be calculated.

2.12.2 The mesoscopic model

This generally represents most entities at a high level of detail but describes their activities and interactions at a much lower level of detail than the microscopic model. In this model, the lane-change decision could be based on relative lane densities than detailed vehicle interactions.

2.12.3 The macroscopic model

This describes entities with their activities as well as their interactions at a low level of detail. For instance, a traffic stream may usually be represented by scalar values of flow, density, and speed. Lane changes in this model may not be represented at all in this context. Instead, the model ensures that the traffic stream is appropriately allocated to each lane which is the main direction of this study. This macroscopic model has been investigated in the context of a congested network and sparse network scenario to improve ITS in VANETs applications.

Microscopic models are known to be costly to develop, execute (i.e. carry-out) and to maintain, relative to the other models but they possess the potential to be more accurate and precise. Macroscopic models may be less accurate in their representation of the real-world system but they are appropriate when the intended results are not sensitive to details, when the scale of application is too big to be accommodated by microscopic models or when resources are limited.

Another classification addresses the processes represented by the model as either deterministic or stochastic. Deterministic models define all entities and their interactions by the exact relationships (mathematical, statistical or logical). Stochastic models usually have processes that include probability functions. A car-following model, for example can be formulated either by a deterministic or stochastic relationship by defining the driver's reaction time as a constant value or as a random variable, respectively.

The suitable simulation model to be used in this thesis is the macroscopic models and this will be discussed in detail in Chapter 3. MATLAB, is the traffic simulator to simulate the models in both dense and sparse networks scenarios.

2.13 Summary and conclusions

In this chapter, the characteristics of VANETs has discussed along with the features of MANETs implementation since VANETs is a subset of MANETs. This is done with emphasizes on the physical layer and the MAC layer with regards to VANETs Characteristics in general. Further discusses challenges associated with Intelligent Transportation Systems and vehicular mobility. The study also focused on the overview of VANETs applications such as V2I connectivity and V2R connectivity and finally narrow down to the research directions in VANETs to improve safety alert information dissemination in a timely fashion under sparse and dense networks environments.

This chapter presented a general overview of the state-of-the-art wireless solutions to vehicle-to-sensor, vehicle-to-vehicle, vehicle-to-internet and vehicle-to-road infrastructure connectivity in VANETs. The study discussed the potential challenges and identified the space for future improvement. The biggest challenge for efficient and robust wireless connections in VANETs is to combat the harsh communication environment inside and/or outside the vehicle. In addition, significant research and development efforts are required to deal with the following issues.

- i. Inter-vehicle systems have a stringent requirement on latency and reliability for traffic alert message dissemination in VANETs. The architecture such as V2I and V2R lead to a high cost and thereby impede the development of connected vehicles VANETs.
- ii. A novel solution to provide V2X communication in VANETs with low cost is the direction of this study. In view of the above information, the best alternative methodology is the vehicle to vehicle (V2V) communication which is the most cost-effective approach once suitable solutions is developed.

This chapter recognizes the challenges that impede the intelligent transportation systems in VANETs and provide background information on the existing approaches and the need to use the macroscopic traffic flow model to perform analytical investigation under dense and sparse networks to fix the gap investigated in the literature.

The next section examines the performance analysis of vehicular traffic flow theory. This covers a wide range of existing traffic flow model developed to ascertain their merits and demerits with regards to vehicular ad hoc networks (VANETs). In this context, certain important factors that inhibit vehicular traffic flow is the parameters used in developing VANETs Models. These parameters include flow, speed and density, to perform simulation on the node mobility, and the sensitivity factor called λ . The choice of a model depends upon how well the parameters have been selected. It is important to know which parameter should be made constant (i.e. fixed) and which should be made varied (i.e. varying) for a model.

The vehicle traffic is characterized by three parameters: flow, density and speed. Although, there is a simple, 'fundamental relationship' that relates the three parameters show a bivariate relationship. This relationship among them has been the subject of intensive research for the past decades. The flow-density relationship is called the Fundamental Diagram of Road Traffic (see Figure 2.6) and it shows that traffic flow increases as the density increases until it reaches a maximum value, known as road capacity, then the flow starts to decline until it reaches zero at maximum density, called jam density. The density at which flow reaches capacity separate free-flow traffic from congested traffic in which vehicle speed is influenced by vehicle density.

Several theories are proposed to define the relationship between traffic parameters and explain these observations. However, no single theory provides a comprehensive relationship between

traffic parameters in VANETs. The focus of this thesis is to conduct the analytical investigation into this bivariate relationship in traffic flow and density as the parameter λ increases with time and this has been investigated in this thesis.

Similarities between traffic flow and fluid gave rise to continuum models, which discuss the relationship between traffic flow and density. The models determine the speed of traffic waves caused by congestions as bottlenecks. The models also explain discontinuities in the flow-density relationship because of shock waves which occur due to abrupt changes in speed. A car-following model provides a relationship between vehicles' speed and density based on stimulus-response models. These models apply to single-lane, congested traffic, but not to light traffic where vehicles tend to move freely unaffected by other vehicles. Two-fluid theory predicts the relationship between the trip time of a test and the average speed of vehicles on the road. The previous models predict that vehicle traffic remains in free-flow state until density reaches a certain point and beyond which sufficiently large fluctuations will cause traffic jams.

Complexities of vehicle traffic prevent the use of mathematical models in solving all but simple problems. Studies, that involve complex traffic scenarios must resort to traffic simulations and this is the direction of the thesis. Traffic simulators are classified according to the details in mimicking real-world traffic in microscopic, mesoscopic and macroscopic. Microscopic traffic simulators, micro-simulators, are highly accurate because they reproduce detailed interactions between vehicles. The CA models are used to build micro-simulators, due to their easy adaptation by computer systems

In MANETs, analytical studies of connectivity in one-dimension usually assume that nodes are dispersed according to a uniform (or Poisson) distribution to derive a relationship between

connectivity and node density. On several occasions, the assumption of uniform distribution is extended to vehicular networks due to their one-dimensional nature. While this assumption may be valid for traffic in homogenous states such as in free-flow traffic, it cannot be used to describe non-homogenous traffic in the congested traffic that exhibit stop-go traffic wave and traffic jams. The latter case is important considering that phase transition may occur anywhere there is a constant or bottleneck in traffic or even because of high fluctuations in driving behaviour. These challenges have been addressed with the novel approach in this thesis using the macroscopic traffic flow model at varied nodes densities and perform various simulations in chapter 3.

The primary objective of this investigation is to identify and outline the performance limitations of this vehicular traffic flow models to propose a novel alternative methodology to address these limitations in ITS applications in VANETs. Chapters 3, proposes an efficient methodology to overcome these limitations.

Chapter 3 Methodology

3.1 Introduction

As has been indicated in Chapter 2, several approaches have been adopted to investigate the problems of traffic flow according to (Adolf, 1990; Kerner, 2000b; Korkmaz, Ekici, & Özgüner, 2010; May, 1990). However, some of these challenges remain and therefore require an intensive research to improve ITS applications. Chapter 2 serve as a framework to understand the challenges to help perform an analytical investigation using the macroscopic traffic flow model established in (May, 1990). To ensure a realistic result, traffic simulations are used to perform analytical analysis to simplify the traffic problems. There is no single theory that can explain all the complexities of traffic flow. Instead, there are several models that try to explain the relationships between traffic parameters but these challenges still lingered on and require further research effort. The direction of this thesis is to investigate these challenges associated with traffic flow to mitigate congestion and sparsely connected networks to improve ITS in VANETs.

In this Chapter, a macroscopic traffic model in (May, 1990) is used to the carry-out analytical investigation to improve congestion control in dense networks and connectivity problems in sparse networks. This investigation is done through simulation by making certain parameters constant while varying other parameters to model the traffic flow phenomenon for a realistic result. Although, several traffic flow models were developed in the past, this model is the first to be investigated in this context to improve reachability and scalability.

The next chapter is organized as follows: Section 3.2 describes the proposed macroscopic traffic flow model adopted in (Adolf, 1990; Daganzo, 2011) to perform the analytical investigation in this thesis. Section 3.3 analyses the factors to be considered in the selection of parameters for the model. Section 3.4 explains the step used to perform simulations in this thesis. Finally, Section 3.5 outlines the density for traffic flow conditions and system parameters while section 3.6 concludes the chapter.

3.2 Macroscopic traffic flow characteristics

The traffic flow represents the traffic density associated with the transportation system and the interaction between these densities determines the operational performance of the system. It is important to know the flow rates, their spatio-temporal variations and the nature of the traffic stream. The measurement of traffic has many uses in planning, designing and the operations of highways facilities

The flow rate (volume) is the important macroscopic flow characteristics and is defined as the number of vehicles passing a point in each period and usually expressed as an hourly flow rate.

3.2.1 The macroscopic traffic flow models

The vehicles under low traffic density and their interaction between vehicles are very low and therefore experiences free traffic flow movement. This free flow condition results in realistic independent movement among vehicles without any restriction on the roads but in a dense network the traffic situation is stop-and-go movement. The computational model developed in (Adolf, 1990; Daganzo, 2011; Kerner, 2000b; May, 1990), indicates that the arrival process of vehicles has a highway density. This can be modelled as a Poisson process with an arrival rate λ .

Therefore, the probability that n vehicles arriving in a time t can be computed using the equations shown in (3.1) and (3.3).

$$P(X = n) = \frac{(x\lambda t)^n}{n!} e^{-\lambda t x} \quad (3.1)$$

λ , represents vehicles migrating to a highway in a time interval x . The time headway distribution is described in (Adolf, 1990; Cowan, 1975), as an exponential distribution of this parameter $\left(\frac{1}{\lambda_t}\right)$ with the probability density function (PDF) $f_T(t) = \lambda_t e^{-\lambda_t t}, t \geq 0$. The PDF allows the time headway to be zero and this gives it the highest relative likelihood of occurrence which is not possible to be zero by the set conditions. For a realistic result to be achieved, it is important to increment the minimum allowable time headway. This PDF is given by

$$f_T(t) = \begin{cases} \lambda_t e^{-\lambda_t(t-\tau)}, & t \geq \tau \\ 0, & t < \tau \end{cases} \quad (3.2)$$

$$D = \frac{V}{v} \quad (3.3)$$

where V in equation (3.3) is the traffic volume measured in the vehicle per hour (veh/hr) and D , density is measured in the vehicle per mile per lane in (veh/mile/lane),

and v represents the space mean speed in mph. The traffic flow conditions corresponding to each density level are classified in Table 3.1. in (May, 1990)

3.3 Parameter selection for new traffic flow models

Vehicular mobility models and traffic simulators have become popular for use in VANETs studies according to (Greenshields, Channing, & Miller, 1935). The main reasons for these simulators are for traffic analysis, forecasting and planning transportation networks. Due to the important applications in VANETs, the ITS initiative has generated an enormous number of vehicular traffic simulators since its inception in the United State in 1991 according to (Boxill & Yu, 2000). These simulators are intended to support ITS applications, but not necessarily VANETs due to their recent introduction.

In VANETs research papers, simulation for vehicle movement is usually considered a special type mobility model according to (Tian, Hahner, Becker, Stepanov, & Rothermel, 2002; Tian, Han, & Rothermel, 2003). These mobility models cannot produce complex vehicle manoeuvres while car-following, decelerating, and accelerating, during traffic jam situations. For the analysis of any complex phenomenon like VANETs, many studies have relied on vehicular mobility models to generate vehicle movement traces.

3.3.1 The mobility models

Many studies in ad hoc networks often require keeping track of node positions at any given time and vehicular networks are no exception. In recent time, many VANETs applications depend on

realistic vehicle movement patterns and this can be obtained from traffic micro-controllers which can track the characteristics of individual vehicles including the position, speed and direction.

The early research in inter-vehicle communication relied on micro-simulators that were designed for the purpose of investigating vehicle traffic flow in transportation systems according to (Eze et al., 2016). VANETs research adapts simulator to generate traces of vehicles position at regular time interval into network simulator such as ns-2, ns-3, MATLAB according to (Eze et al., 2016; Härrri, Filali, Bonnet, & Fiore, 2006; Hartenstein & Laberteaux, 2008; Naumov, Baumann, & Gross, 2006; Zeadally et al., 2012) to perform simulation of communication protocols. In recent times, researchers have devoted substantiate effort to the development of network traffic simulators for VANETs research investigated in (Eze et al., 2016; Härrri et al., 2006). Usually, these simulators have a dual focus on the communication and mobility of VANETs.

3.3.2 The traffic flow models

The traffic simulators are extensively used in evaluating vehicular ad hoc networks. The analytical approaches in free-flow traffic conditions are usually the preferred choice. The primary reason for this choice is the control environments it offers, ability to select at least two or three parameters to establish the fundamental relationship of the traffic flow. Under free-flow conditions, according to (Harri et al., 2009; Michael Rudack, Meincke, Jobmann, & Lott, 2003; M Rudack, Meincke, & Lott, 2002; Weil, Wootton, & Garcia-Ortiz, 1998), it is assumed that the traffic flow and the vehicle velocity are independent. This fundamental relationship of traffic flow is used to derive probability density function (pdf) of the communication duration between vehicles and the pdf of the time between consecutive topology changes. Similar assumptions are made in (Ebner & Rohling, 2001) to derive the pdf for distance at which to establish a multi-hop

connection between two vehicles. The effective selection of time headway (i.e. the time gap between consecutive vehicles) as an input parameter control both the rate by which vehicles are injected to the simulation environment and the density of the vehicles. According to (Adachi, Morita, Fujimura, Takatori, & Hasegawa, 2002), the time headway values are generated randomly from a Poisson distribution with an average value that ensures the free-flow traffic. A uniform distribution with a minimum value that specifies the initial separation between vehicles is used in (Ebner & Rohling, 2001).

3.3.3 The vehicle speed

In most cases, the desired speed is provided as an input to the simulations. The vehicle speed can be a constant value for each type of vehicles (e.g. cars and trucks) or may be sampled from a random distribution. In (Füßler, Mauve, Hartenstein, Käsemann, & Vollmer, 2002), the speed distribution is chosen to correspond to real measurements from German highways, while in (Korkmaz et al., 2010; Korkmaz, Ekici, Özgüner, & Özgüner, 2004), the speed is assigned from a normal distribution and this is the direction of this thesis.

One possible choice of random vehicle speed is based on the theory of the “85th percentile speed” that is usually used as a guide to set limit on the highways as reported in (Haglund, 2001; Johnson & Pawar, 2005; Milazzo II, Roupail, Hummer, & Allen, 1999; Setting & Limits, 1998). The 85th percentile speed is defined as the speed 85% of drivers moving at or below. It is evident that 75% of the drivers maintain speed within a certain range around the average speed limit. Another research finding indicates that 15% are slow drivers while the remaining 15% are driving at high speeds. According to (Z. D. Chen, Kung, & Vlah, 2001; M Rudack et al., 2002), vehicle speed is sampled from a Normal distribution using the standard deviation to mark the

boundaries between slow, average and high speeds. Although, the speed and time headway changes in real traffic, they are kept constant in (Cowan, 1975; Duan, Li, & Salvendy, 2013; Kanagaraj, Asaithambi, Kumar, Srinivasan, & Sivanandan, 2013; Naus et al., 2008).

Furthermore, the choice of the average speed varies according to the choice of the environment under considerations. For instance, in highway simulations environment the average speed is set to 100-130km/hr according to (Füßler et al., 2002; Michael Rudack et al., 2003). Similarly, the simulations of city street grid set the average speed to 40-80km/hr either randomly according to (Korkmaz et al., 2004) or according to the street types (Mangharam, 2008). The choice of speed may reflect also the posted speed limit, road conditions and common driving habits.

3.3.4 The collisions

The collision in VANETs has usually assumed in some literature that vehicles move freely and collisions are not allowed. However, the vehicle density according to (Adachi et al., 2002) is specified to create congested traffic situations and vehicles may collide if drivers fail to react in time. This finding is very necessary to evaluate the influence of the V2V and V2R communication on safety according to (Adachi et al., 2002).

3.3.5 The road topology

This may be described as a common choice of highway geometry of two or more lanes in each direction. This allows the traffic to flow in both directions may be described as asymmetric as indicated in (Michael Rudack et al., 2003) . According to (Al-Sultan et al., 2014), they argue that dividing the highways may be used to limit the geographic area affected by message

broadcast to one traffic direction. According to (Choffnes & Bustamante, 2005; Lochert et al., 2003; Mangharam, 2008), explained more complex geometry to be used to evaluate routing strategies and protocols in a city traffic flow environment.

3.3.6 The vehicular mobility in sparse networks

Many researchers are highly interested in studying sparse vehicular networks due to its importance in ITS applications in VANETs. This motivation from most researchers reflects the assumptions inherent in the inter-vehicle communication in sparse networks as more challenging due to the difficulty in maintaining connectivity. In addition, the low-density conditions offer more flexibility in setting the traffic parameters such as flow, speed and density for analytical and simulation studies. The assumption of independent parameter is valid only in free-flow traffic. Therefore, the results of these studies cannot be used directly in dense traffic environments. This study seeks to argue that research should focus more on dense traffic and traffic jam environments due to their important significant influence on VANETs, since:

- i. The vehicle density can contribute to rapid message dissemination (Ferreira et al., 2010; Härrri et al., 2006; Raya, Aziz, & Hubaux, 2006; Tonguz, Wisitpongphan, Bait, Mudaliget, & Sadekart, 2007) .
- ii. Higher node density aggravates the contention and collision problem in the communication protocols based on shared media.
- iii. The traffic jams contribute to certain non-homogeneous distribution of vehicles and therefore increasing the range of transmission needed to maintain connectivity.

- iv. The vehicle traffic may change rapidly between free-flow in congested traffic as the result of the traffic controls, road constraints or accidents.

The research directions related to the use of vehicle mobility models and traffic simulator in this thesis is provided in the next section.

3.4 Steps in developing the simulation models

The first step is the problem identification and how to formulate the objectives explicitly with alternative analytical techniques to evaluate the subsequent steps. At this stage, a lot of questions need to be answered well for the problem to be solved. What are the desired inputs to arrive at the outputs? What is the boundary, timelines and limitation of the problem? Are the parameters needed to be modelled individually? In this context, when the question is answered successfully then the next step needs to continue. The steps are based on (see Figure 3.1).

The second step need to answer the question explicitly: Is simulation the appropriate analytical techniques for the problem? Several more questions need to be addressed such as: How could the problem be solved without simulation? Why is simulation a better solution to the problem? Are the needed resources available to perform the experiment? Can the problem really be solved? In this thesis simulation is the best choice to carry-out the macroscopic traffic model according to (Eze et al., 2016; Härrri et al., 2006; Hartenstein & Laberteaux, 2008; Naumov et al., 2006; Zeadally et al., 2012). One major reason for selecting MATLAB in this thesis is to perform simulation on the macroscopic traffic flow models, due to easy-to-use environment in which problems and solutions are expressed in familiar mathematical notation. Besides, MATLAB is

one of the network simulators that have a significant number of users in both academia and industry.

The third step is the formulation of the problem. This is done by developing a flowchart of the model beginning with an input, process and an output variable with emphasize on an input and an output requirement. This thesis is to perform the analytical investigation to gain understanding of the macroscopic traffic flow model. The input requirements include design elements, traffic demand pattern, operational rules and control conditions.

The fourth steps are the formulation of the macroscopic traffic model. This is done by developing an intermediate flowchart to understand the logic behind the model. This stage is iterative in nature until the desired model is accomplished.

The fifth step consists of estimation all the required parameters in the model. To accomplish this, some of the parameters need to be deterministic while other need to probabilistic (stochastic). The deterministic parameters may be constant for all situations and may take on one of a set of constant values depending on the problem at hand or this may vary over the range of continuous manner when necessary. The probabilistic parameters require the variations of variables to meet the set objectives.

The six stages explain the evaluation of the current state of the models. In this process judgment and decisions are required by adding, changing and deleting variables in the model. This stage is done until the desired solution to the problem is achieved before the process can continue to the next stage to formulate the computer code using MATLAB to perform various simulations to ascertain the desire solution through validation of codes.

3.4.1 Flowchart for the simulation models

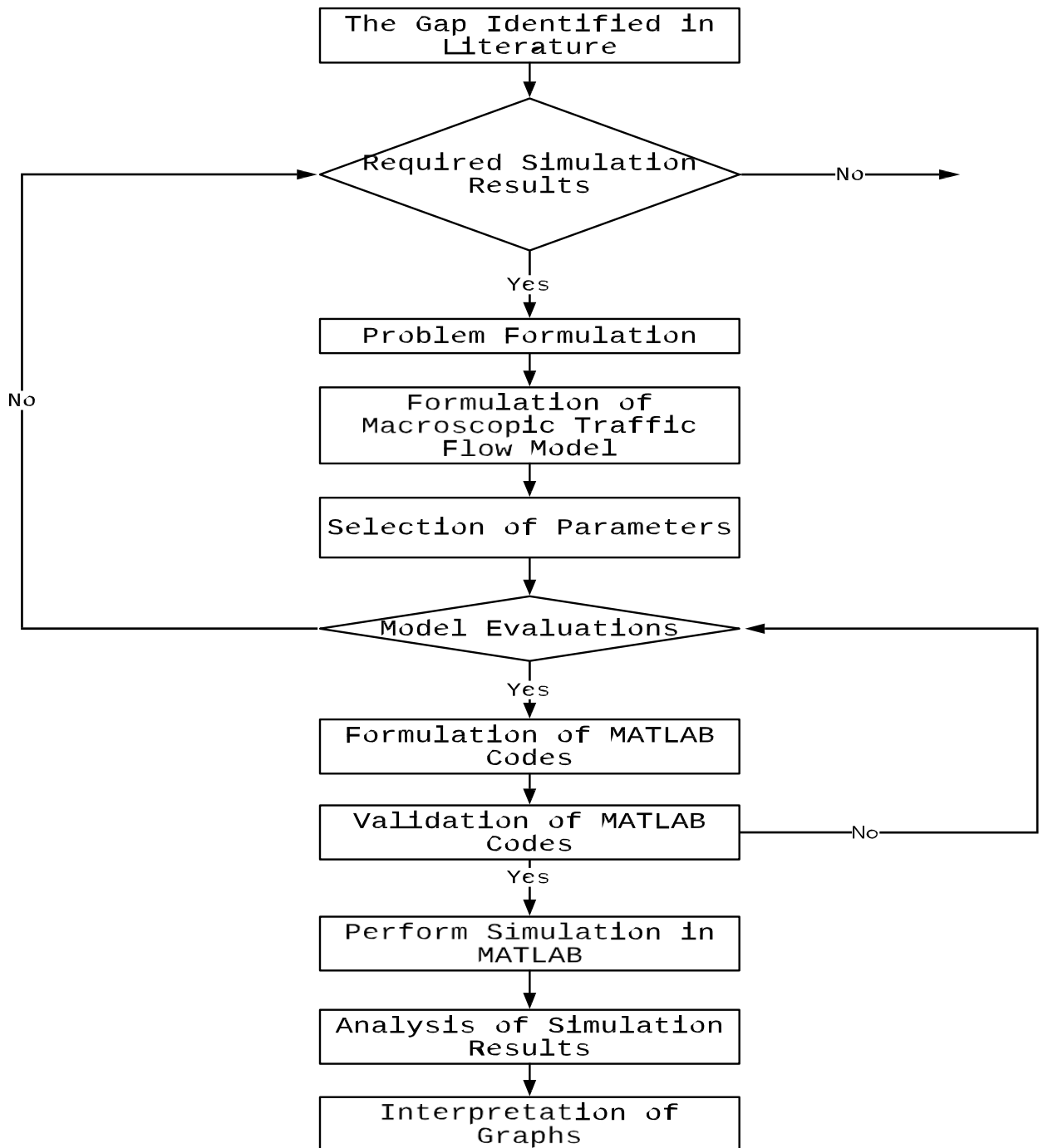


Figure 3.1 Flowchart showing steps used to develop the simulation model

3.5 The traffic flow state for different densities and level of services

These traffic flow parameters were generally used to investigate traffic flow in civil engineering according to (May, 1990). This table is used to investigate the flow conditions of uncongested flow conditions and the congested flow conditions using the level of services with regards to the densities (see Table 3.1).

Density (Veh/Mile/Lan	Level of Service	Flow Conditions	
0-12	A	Free-flow operations	Uncongested flow conditions
12-20	B	Reasonable free-flow operations	
20-30	C	Stable operations	
30-42	D	Borders on unstable operations	
42-67	E	Extremely unstable flow operations	Near-capacity flow conditions
67-100	F	Forced or breakdown operations	Congested flow conditions
>100		Incident situation operations	

Table 3.1 Traffic flow state for different densities

Level of service	Flow condition	v/c limit	Service Volume(veh/hr)	Speed (mph)	Density (veh/mile/lane)
A	Free	0.35	700	60	12
B	Stable	0.54	1100	57	20
C	Stable	0.77	1550	54	30
D	High Density	0.93	1850	46	40
E	Near Capacity	1.00	2000	30	67
F	Breakdown	Unstable	Unstable	<30	>67

Table 3.2 Levels of service for freeway under ideal conditions and 70mpr design speed

3.5.1 System parameters for dense networks simulations

This study modifies the known civil engineering traffic flow models in Four-Lane Mobility in VANETs within a congested network. This study demonstrates how the network behaves under varying traffic densities which involve 10Miles veh/mile/lane to 100 vehicles per each lane (veh/mile/lane) within 36Miles road section to investigate network behaviour within four lanes analytically.

To really understand the interactions among two vehicles in terms of traffic flow density. This study seeks to vary the value of λ from 1 to 10 against 30 veh/mile /lane to investigate the network behaves under the various λ in a congested network as shown (see Table 3.3).

Item Number	Parameters	Descriptions
1	Platform	MATLAB
2	Speed of Vehicles	60km/hr
3	No. of Vehicles on the Road	1800
4	Type of Road (Capacity)	Highways, Urban, Semi-Urban
5	Number of Lanes in Each Direction	4
6	Average Percentage of Vehicles	30%
7	Expected Threshold Changes	15%
8	Speed Limit	36 mile/hr

Table 3.3 Dense Networks System Parameters

3.5.2 System parameters for sparse networks simulations

This explains the traffic flow models in Four-Lane Mobility in VANETs within a sparse network. This study demonstrates how the network behaves under varying traffic densities which

involve 10Miles veh/mile/lane to 30 vehicles per each lane (veh/mile/lane) within 60Miles road section to investigate network behaviour with four lanes analytically.

This explains the interactions among two vehicles in terms of traffic flow density. This study seeks to vary the value of λ from 1 to 10 against 30 veh/mile /lane to investigate the network behaves under the various λ in a sparse network as shown in (see Table 3.4).

Item Number	Parameters	Descriptions
1	Platform	MATLAB
2	Speed of Vehicles	54 - 60m/hr
3	No. of Vehicles on the Road	700 -1550
4	Type of Road (Capacity)	Highways, Urban, Semi-Urban
5	Number of Lanes in Each Direction	4
6	Average Percentage of Vehicles	15%
7	Expected Threshold Changes	10%
8	Speed Limit	60 mile/hr

Table 3.4 Sparse Networks System Parameters

3.6 Conclusions

This chapter used a well-known macroscopic traffic flow model developed in (May, 1990) and presented a novel approach to model traffic flow in vehicular ad hoc networks (VANETs) through simulation. This approach utilizes the challenges in traffic flow models to improve reachability and scalability through analytical investigation to mitigate congestion in dense networks and mitigate the challenges associated with sparsely connected networks under four-lane road network (i.e. off-peak and peak periods).

This study performs several simulations with the macroscopic traffic flow models to investigate the spatio-temporal variations in the dense network and sparse network associated in VANETs. The analytical investigation and performance analysis have been conducted under different traffic densities. In the first place, the study outlines the simulation set-up with rigor in a flowchart to examine each step iteratively until the model is fully developed (see Figure 3.1). In the second place, the impact of traffic density on the performance of the traffic flow model is assessed by varying the number of vehicles (nodes) under fixed traffic flow conditions (see Table 3.1). In the third place, the sensitivity factor of two-vehicle interaction in the car-following model λ , is varied from 1 to 10 under dense network and sparse network conditions to assess the performance of the traffic flow model to measure reachability and scalability. In the fourth place, the simulation results were assessed to developed congestion control model in a dense network and Honeycomb model in sparsely connected networks to be used to mitigate congestion in the dense network and sparsely connected network to improve (ITS) in VANETs.

Chapter 4 Improving VANETs congestion in dense networks & intermittent connectivity in sparse networks

4.1 Introduction

Due to inter-vehicle communication, vehicle speed, driver behaviour and connectivity have become a very important performance indicator in VANETs. The challenges associated with regards to reliable connectivity, fast communication among transmitting and the receiving nodes have become an important research challenge in recent times. Two nodes are connected if they can establish a reliable communication between each node either through a single hop or multiple hops. In recent times, several research studies have investigated into VANETs connectivity problems both in sparse and dense networks according to (L. Li & Chen, 2017; Reis, Sargento, & Tonguz, 2011). Connectivity in VANETs is primarily depended on the inter-vehicle time headway being the time interval between the lead vehicles and the successive vehicles on the road.

The time headway depends on vehicle speed, traffic flow, driver behaviour and so on. Under normal traffic flow condition, three states of classification are associated with vehicular mobility: free flow, synchronized flow, and wide moving jam according to (Daganzo, 2011; Nagel & Herrmann, 1993). During free flow state, traffic density is low and vehicles on the road have the tendency to move at a high speed. This is associated with intermittent connectivity since some of the vehicles move out of the acceptable transmission range in VANETs. During the synchronized state, traffic flow reaches its maximum and the vehicles in different lanes travel with a synchronized speed where stop-and-go movement of vehicles may occur steadily. In

synchronized and wide moving jam occur under a congested traffic flow (Adolf, 1990; May, 1990; Nagel & Herrmann, 1993), where vehicles experience heavy congestions due to a high density of vehicles on the roads. In vehicular traffic flow condition, there exists a correlation between traffic flow and traffic density during a free flow condition and up to critical density. In congested traffic flow, the headway is very low and vehicles are within the connected transmission range.

The rest of the chapters are organized as follows. Section 4.2 describes the performance metrics in dense networks and performs the analytical investigation to simulate the macroscopic traffic flow model in detail. Section 4.3 proposed a congestion control model based on the simulation results in dense networks. Section 4.4 presents how to improve connectivity in sparse networks through analytical investigation. Section 4.5 proposed a Honeycomb Model in sparsely connected networks to improve connectivity. Finally, section 4.6 concludes this chapter.

4.2 Performance metrics under dense network conditions

This λ , is an important parameter used to model the behaviour and the interaction of vehicles at different traffic densities. The study used 0veh/mile/lane to 100veh/mile/lane and varies the λ from 1 to 10 to investigate the effects of λ on the interaction of vehicles within the four-lane according to (Azameti, Katsriku, Chong, & Abdulai, 2018)

4.2.1 The four-lane traffic flow under dense network conditions when $\lambda = 1$

The network behaviour with respect to the lane changes is shown in the figure below. If $\lambda = 1$, the traffic flow trajectories within the four-lane exhibits exponential distribution where lane 1: has the

least congestion with less priority in terms of packet reception. The next less priority occurs in lane 2 but has an increased number of vehicles than in lane 1. Lane 3, experiences a high number of vehicles while lane 4 shows a higher number of vehicles and therefore receives the highest priority reception rate to control the congestion. Lane 3, is the second higher lane with the next higher priority reception rate when lane 4, is reduced to the acceptable threshold as shown in Figure 4.1a and 4.1b. The effect also indicates the correlation between traffic density and speed (see Figure 2.4) and (see Figure 2.5), showing the fundamental diagram on free flow, congested and mixed state traffic conditions as explicitly indicated in chapter 2. These relationships are the results in this thesis and have been explained in this section as the value of the λ increases. These effects are further explained under vehicle trajectories when the value of λ increases the density also increases.

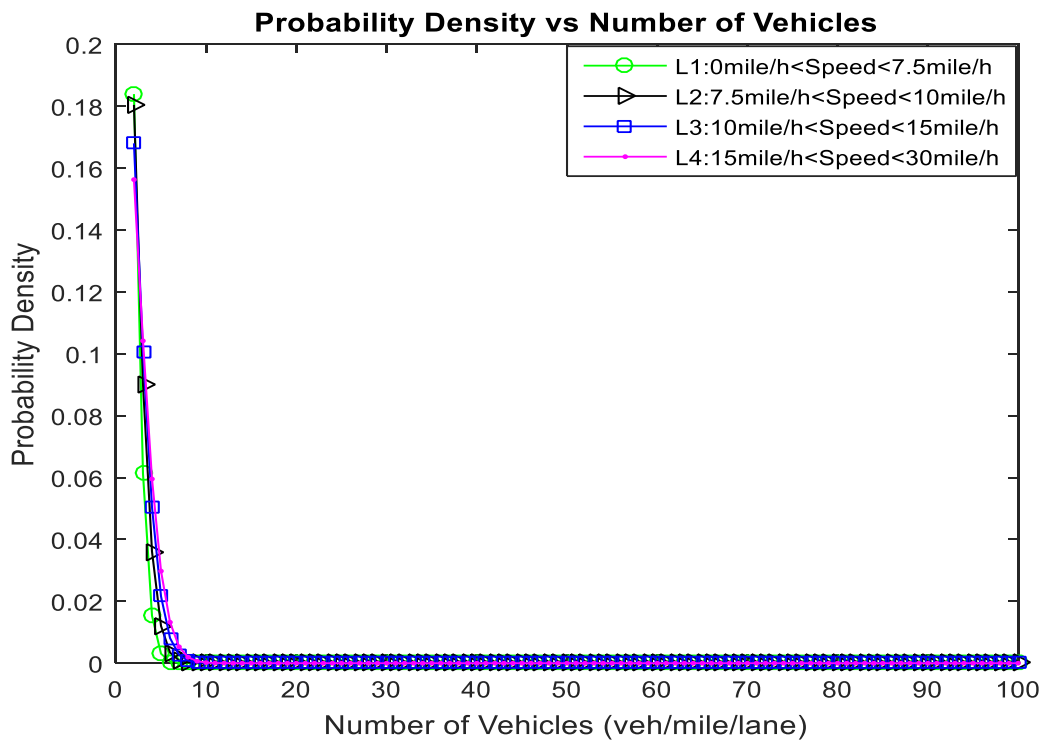


Figure 4.1a the effect of traffic flow when $\lambda = 1$

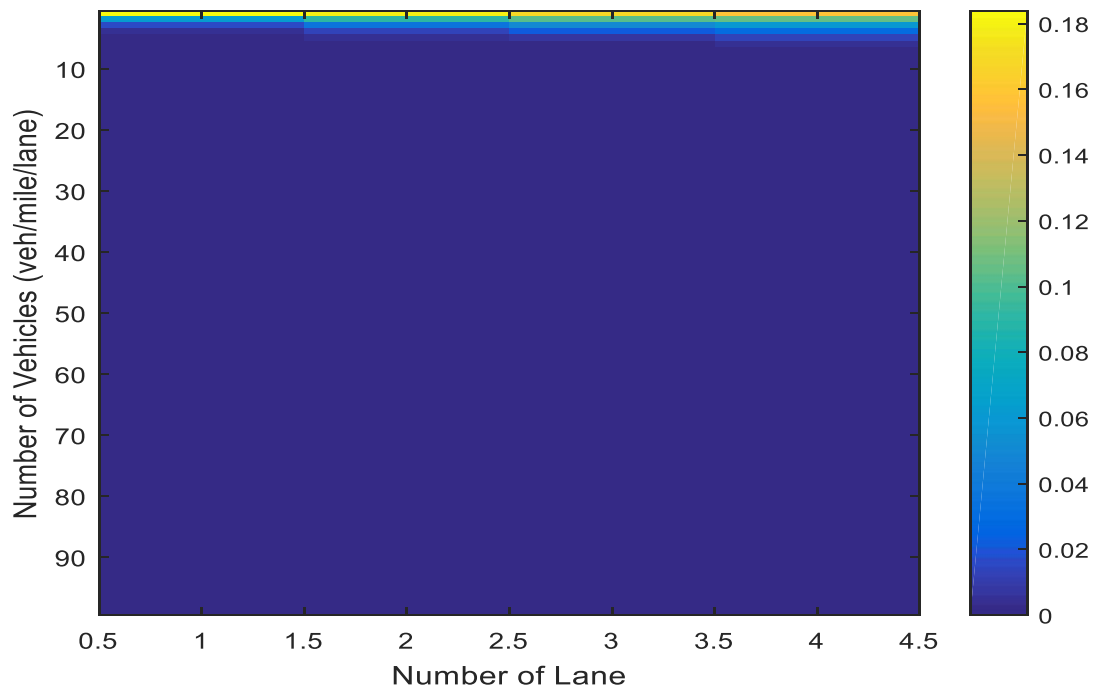


Figure 4.1b Vehicle trajectories in each lane

4.2.2 The four-lane traffic flow under dense network conditions when $\lambda = 2$

$\lambda = 2$, the traffic flow within the lanes also indicate an exponential distribution at lane 1 and lane 2 and therefore have the least priority while lane 2 having a fewer number of vehicles than in lane 1. Lane 3 and lane 4 begin to show the partial normal distribution in Figure 4.2a and 4.2b. Lane 4, has the highest priority in terms of packet reception and lane 3 has the next higher priority after lane 4 has successfully received the needed reception. It also explains the relationship between traffic density and speed.

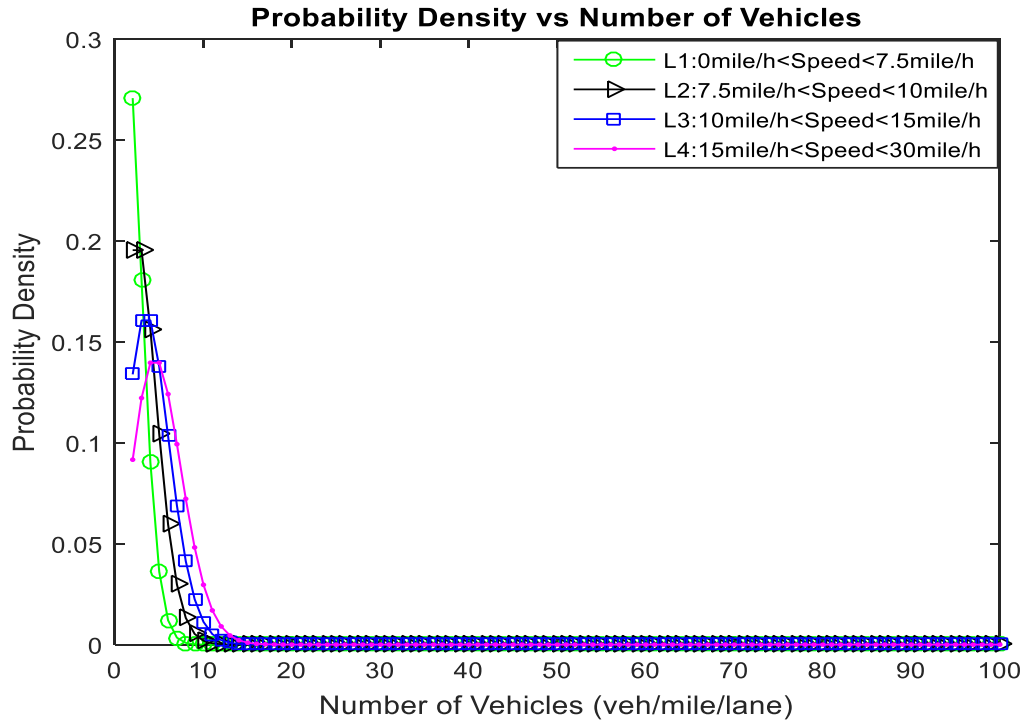


Figure 4.2a The effect of traffic flow when $\lambda = 2$

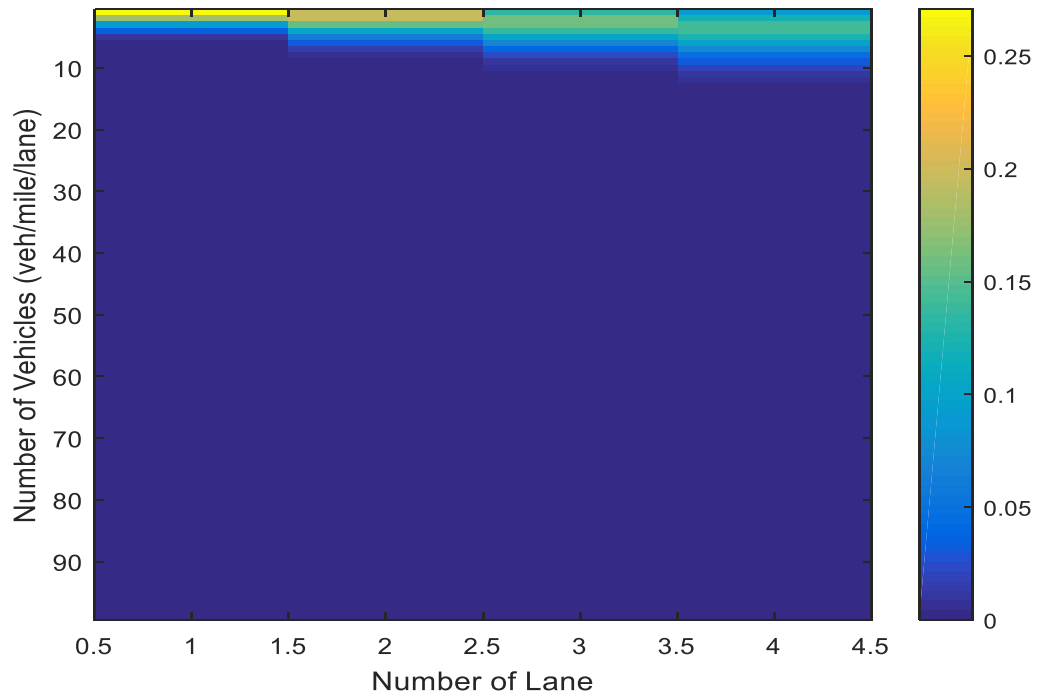


Figure 4.2b Vehicle trajectories in each lane

4.2.3 The four-lane traffic flow under dense network conditions when $\lambda = 3$

Again, if $\lambda = 3$, the traffic flow within the four-lane shows an exponential distribution at lane 1 and indicates a partial normal distribution from lane 3 and lane 4 in Figure 4.3a and 4.3b. Since lane 3 and lane 4 with partial normal distribution indicate that there is an increased number of vehicles but lane 4 having the highest number of vehicles than in lane 3. Therefore, lane 4 is congested with the highest priority reception rate and the next priority is lane 3. When $\lambda = 3$ shows the initial threshold in which lanes continue to experience an increased number of vehicles anytime the value of λ is increased.

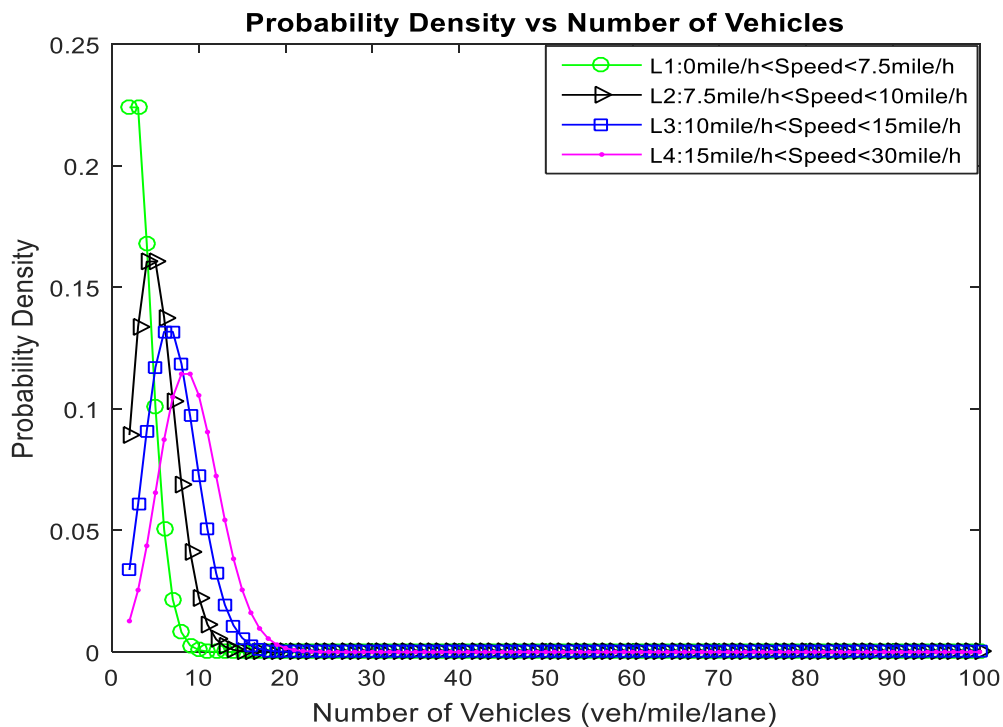


Figure 4.3a The effect of traffic flow when $\lambda = 3$

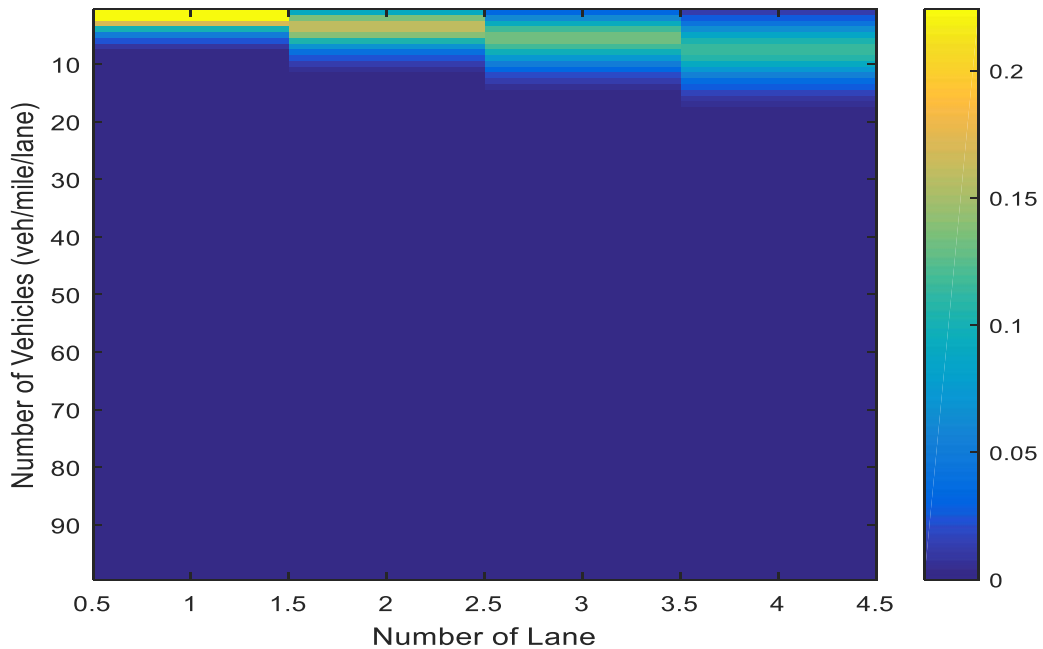


Figure 4.3b Vehicle trajectories in each lane

4.2.4 The four-lane traffic flow under dense network conditions when $\lambda = 4$

When $\lambda = 4$, the traffic flow shows a complete normal distribution at lane 3 and lane 4 with an increased number of vehicles as indicated in Figure 4.4a and 4.4b. At this stage, lane 3 and lane 4 are congested but lane 4 has the highest number of vehicles and therefore need to receive the highest priority of reception rate before lane 3. Lane 1, is still the least but with an increased number of vehicles once the value λ , increases. Lane 1, has high mobility than in lane 2 since the number of vehicles in lane 2 is higher than in lane 1. Therefore, lane 1 has the highest mobility rate.

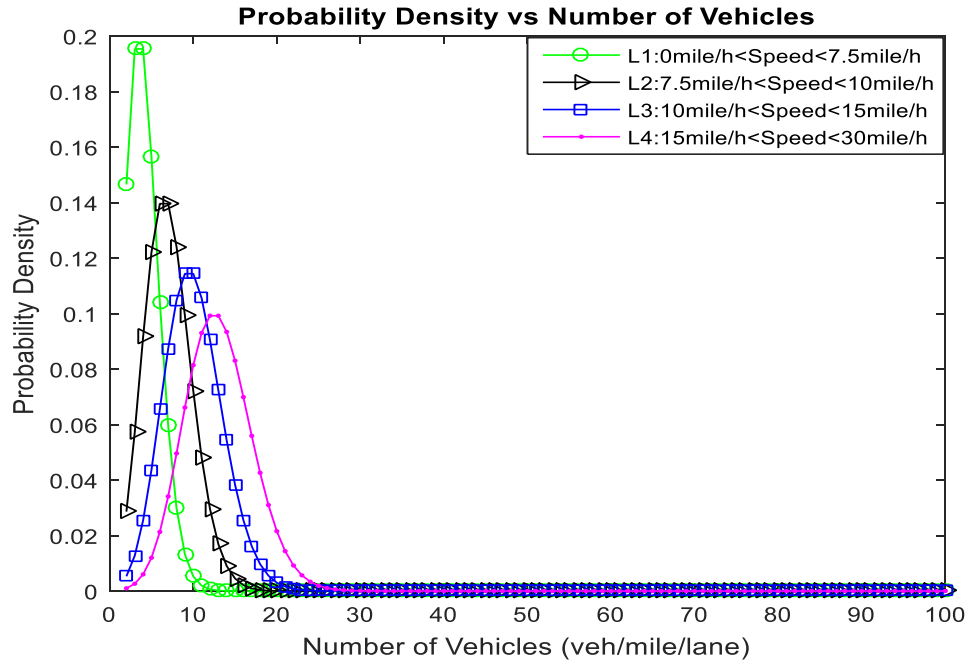


Figure 4.4a The effect of traffic flow when $\lambda = 4$

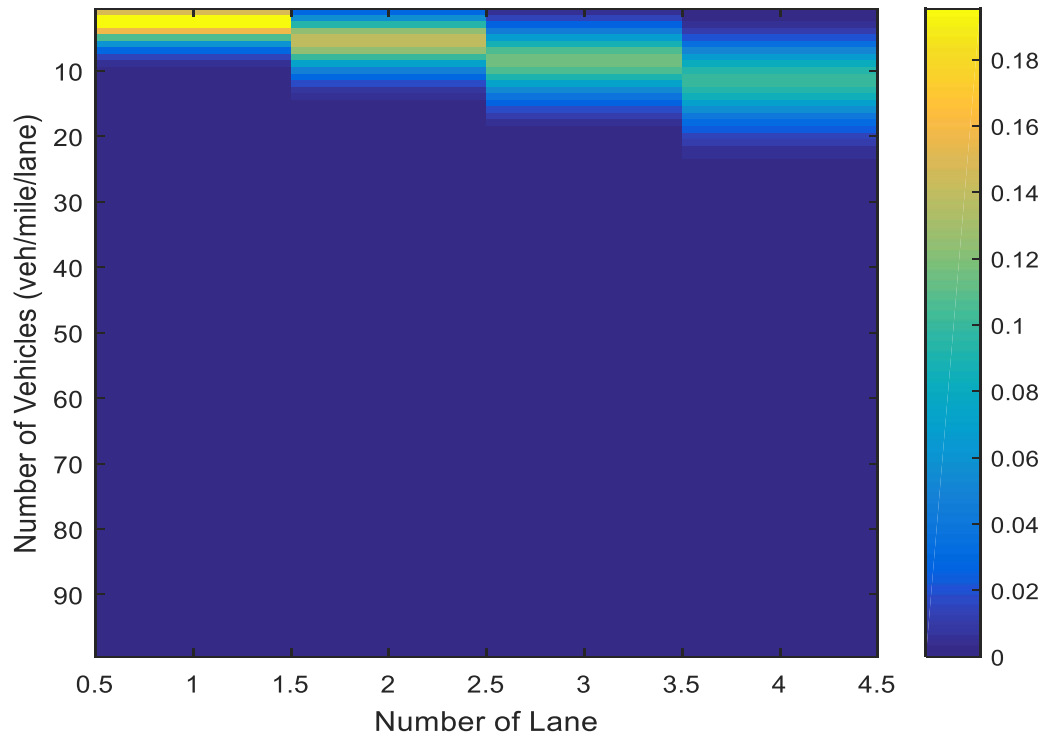


Figure 4.4b Vehicle trajectories in each lane

4.2.5 The four-lane traffic flow under dense network conditions when $\lambda = 5$

Subsequently, when $\lambda = 5$, the traffic flow exhibits a complete normal distribution at lane 2, lane 3 and lane 4. Lane 1, has the least number of vehicles and therefore has the highest mobility rate than in lane 2. Lane 3 and lane 4 still have the highest number of vehicles, since both lanes become congested with lane 4 having the highest number of vehicles indicating a high priority in terms of packet reception and move subsequently to lane 3. This phenomenon also demonstrates the relationship between traffic density and speed as shown in figure 4.5a and 4.5b.

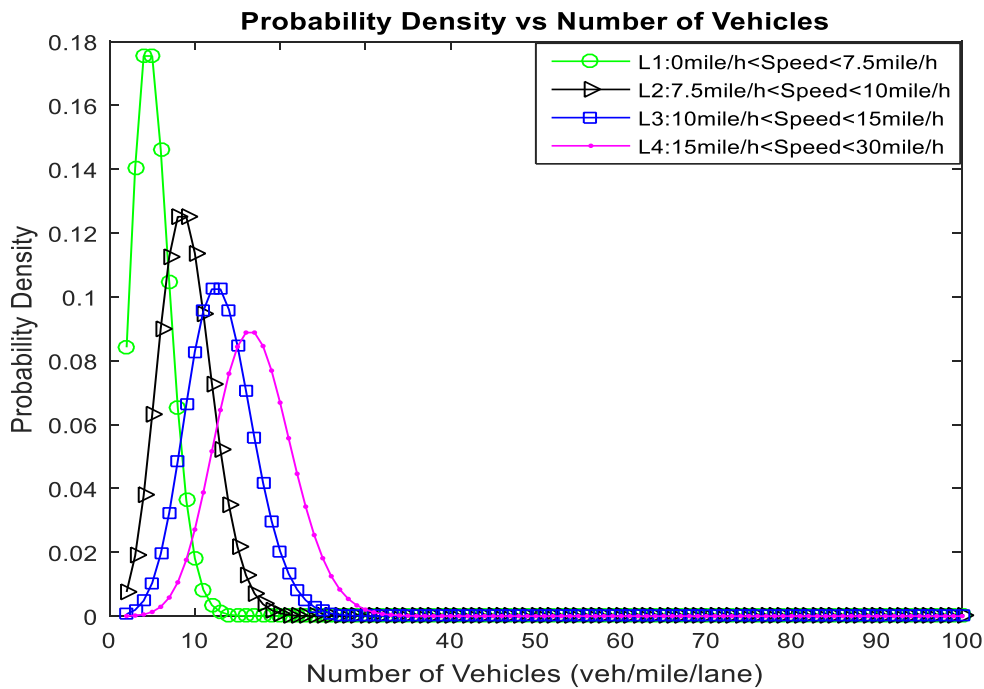


Figure 4.5a The effect of traffic flow when $\lambda = 5$

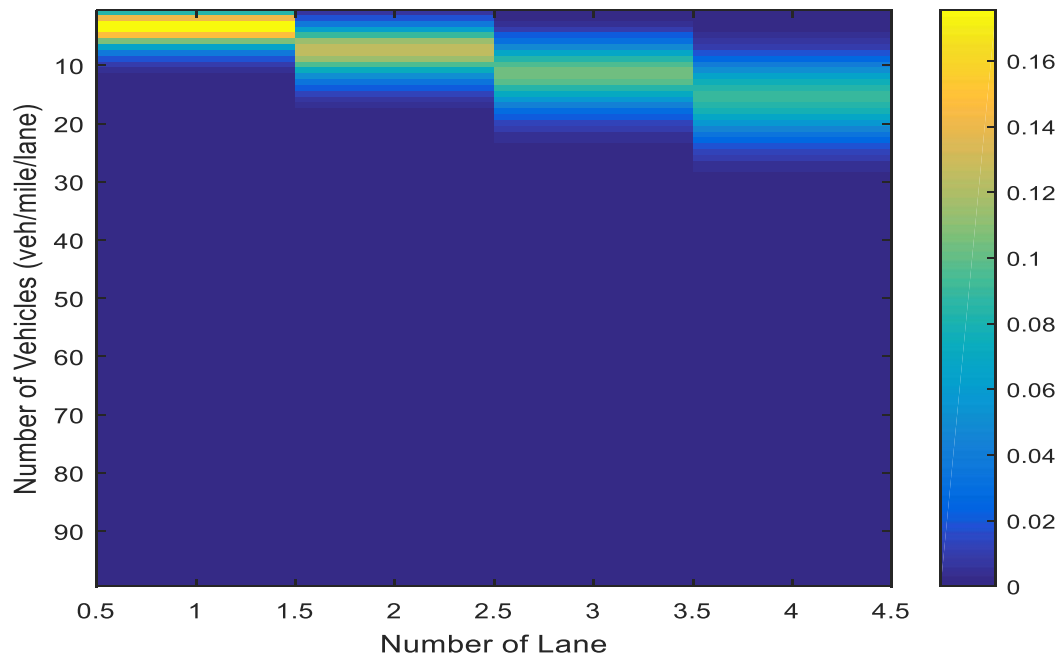


Figure 4.5b Vehicle trajectories in each lane

4.2.6 The four-lane traffic flow under dense network conditions when $\lambda = 6$

In addition, when $\lambda = 6$, the traffic flow also shows a complete normal distribution at lane 2, lane 3 and lane 4. At this stage lane, 3 and lane 4 have an increased number of vehicles and therefore congested but lane 4 is congested than lane 3. Lane 4, seems to experience higher congestion than lane 3. Lane 1, still has the least number of vehicles with a reasonable amount of mobility rate than in lane 2, lane 3 and lane 4. Therefore, establishes a relationship between density and speed in figure 4.6a and 4.6b.

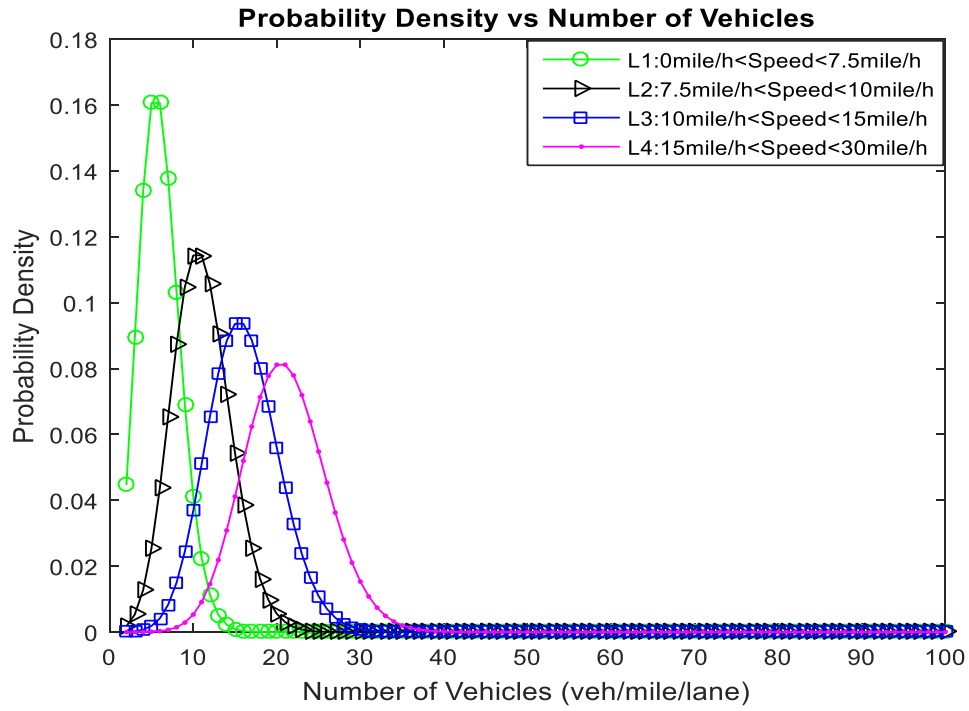


Figure 4.6a The effect of traffic flow when $\lambda = 6$

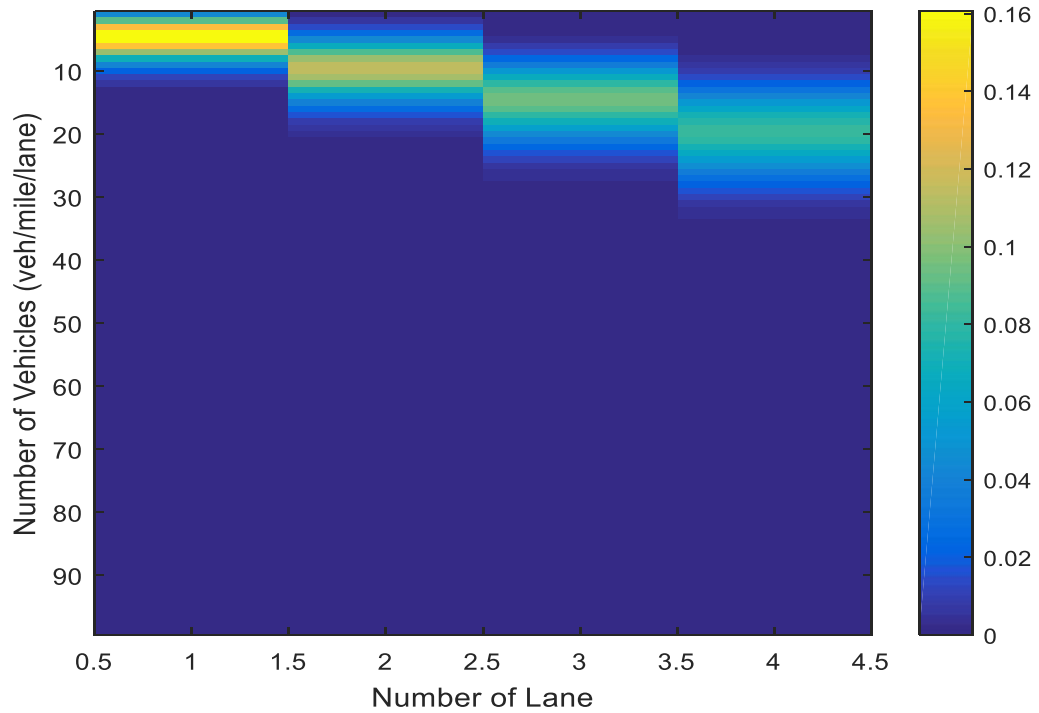


Figure 4.6b Vehicle trajectories in each lane

4.2.7 The four-lane traffic flow under dense network conditions when $\lambda = 7$

If $\lambda = 7$, the traffic flow shows a complete normal distribution at lane 2, lane 3 and lane 4. Lane 4 has the highest priority in terms of packet reception and move subsequently to next lane 3. At this instance, is worth to note that anytime the value of λ increases then all the four-lane also seen an appreciable increase indicating a direct proportion in each lane. This shows a correlation between traffic density and speed as shown in figure 4.7a and 4.7b.

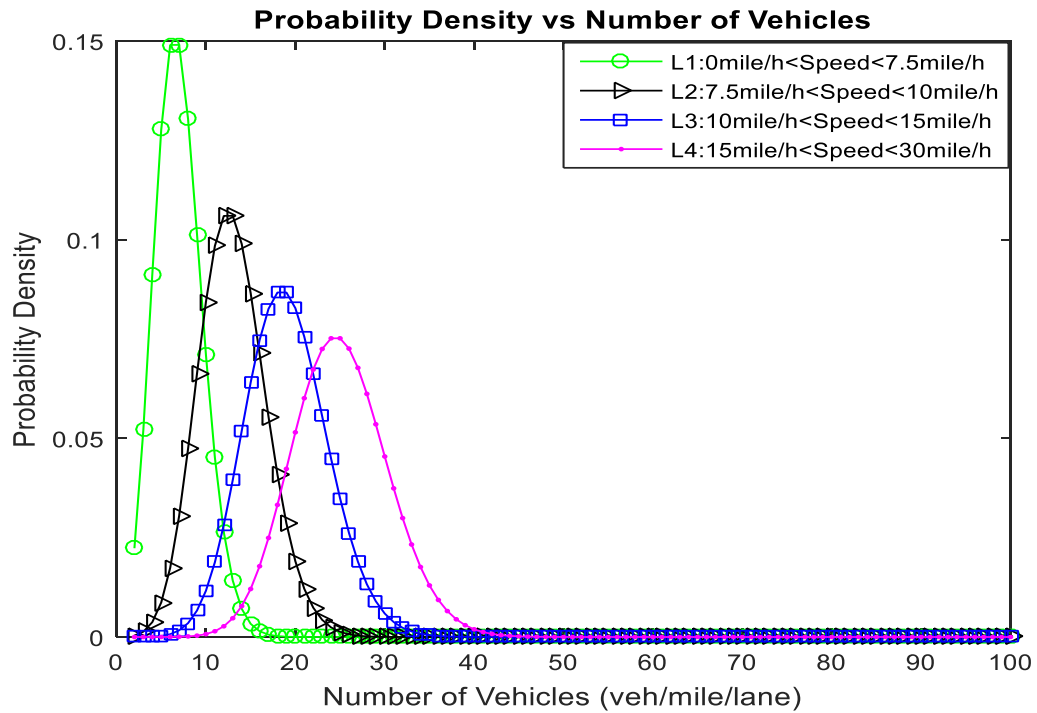


Figure 4.7a The effect of traffic flow when $\lambda = 7$

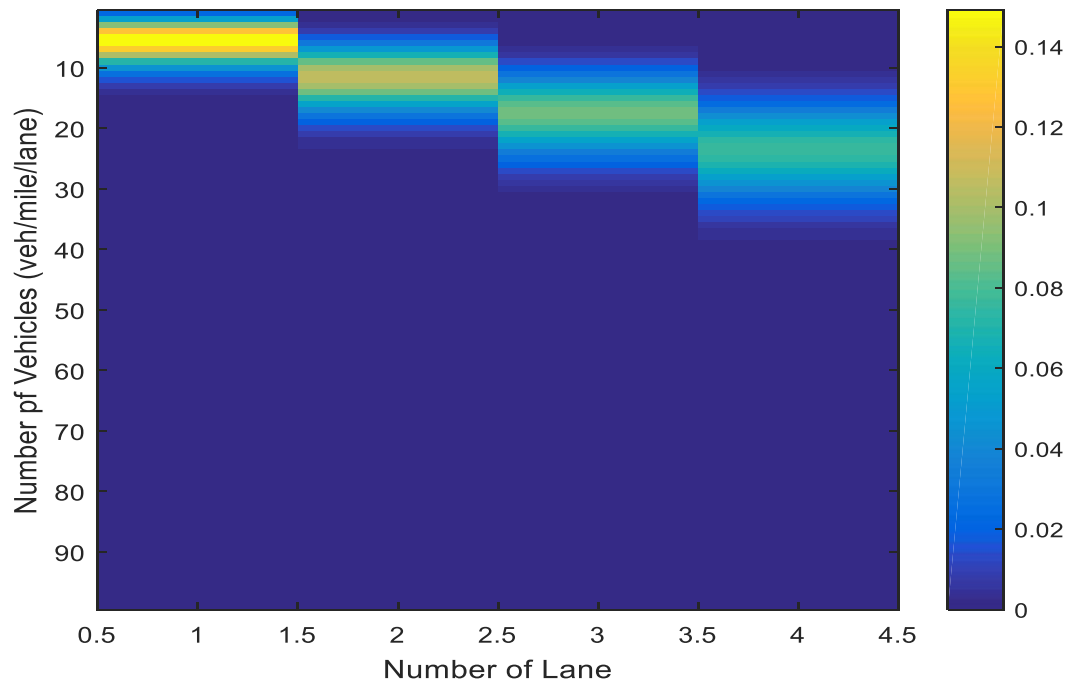


Figure 4.7b Vehicle trajectories in each lane

4.2.8 The four-lane traffic flow under dense network conditions when $\lambda = 8, 9$ and 10

When $\lambda = 8, 9$ and 10 , the traffic flow shows a complete normal distribution for the entire four-lane. Lane 4 has the highest priority in terms of packet reception and move subsequently to next lane 3 but with an increased number of vehicles. This trend shows that once all the lanes assumed a complete normal distribution it would correlate with an increased number of vehicles but with lane 3 and lane 4 term a congested network. In this instance, lane 4 has the highest packet reception next to lane 3, lane 2 and lane 1 in that order of magnitude in terms of traffic density as shown in figure 4.8a 5.8b, 4.9a and 4.9b and 4.10a and 4.10b. In these cases, the graph shows a definite relationship between density and speed.

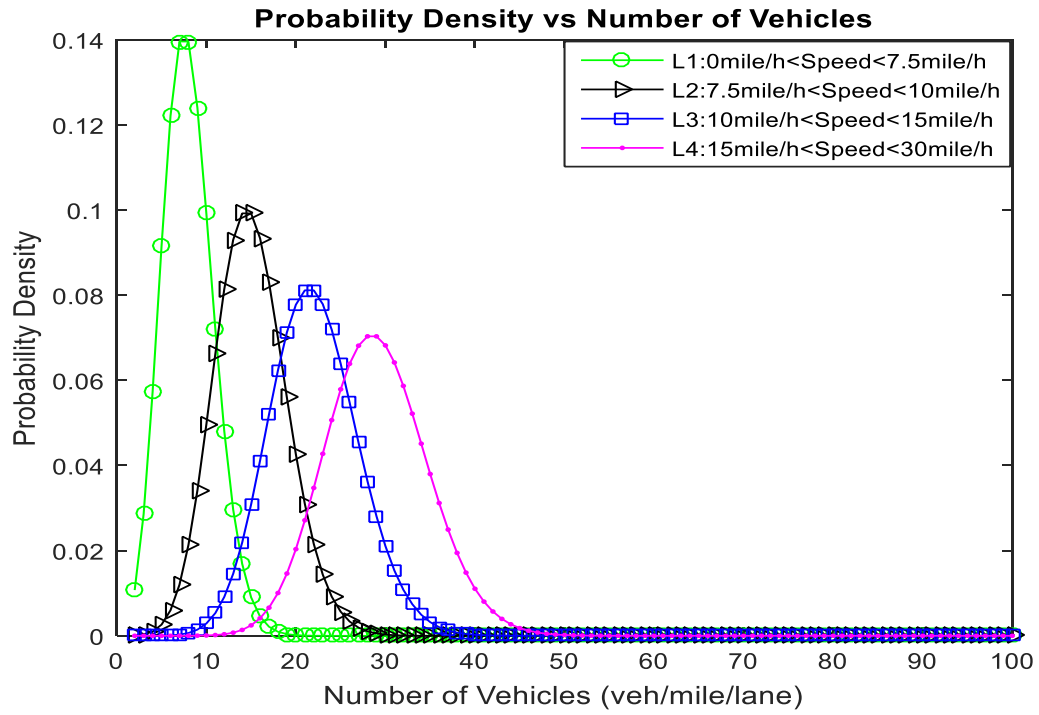


Figure 4.8a The effect of traffic flow when $\lambda = 8$

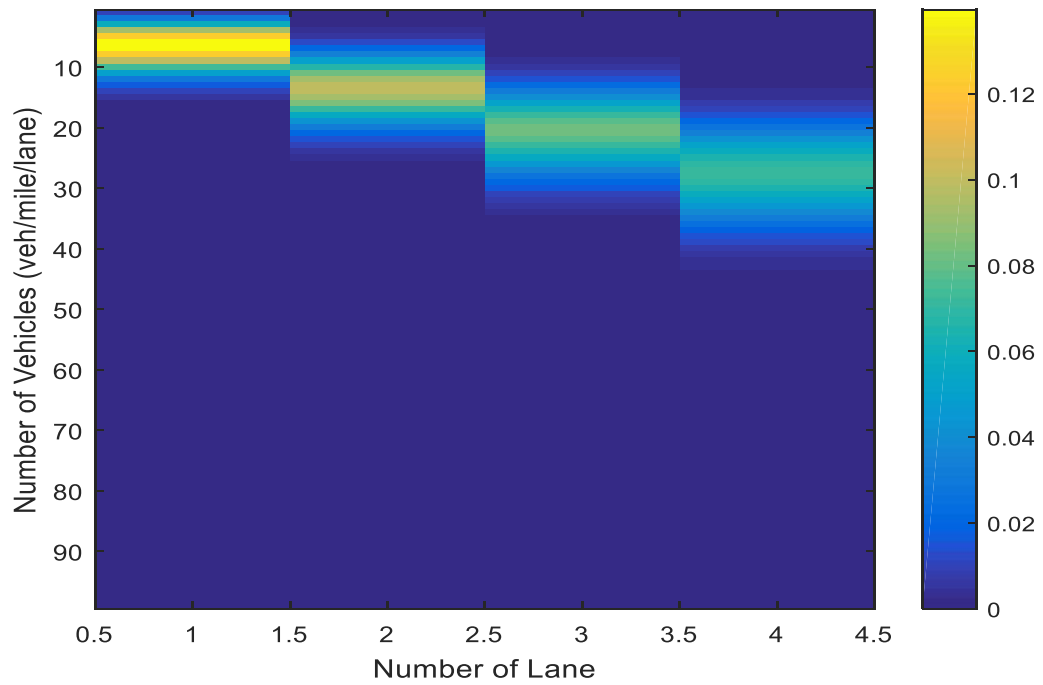


Figure 4.8b Vehicle trajectories in each lane

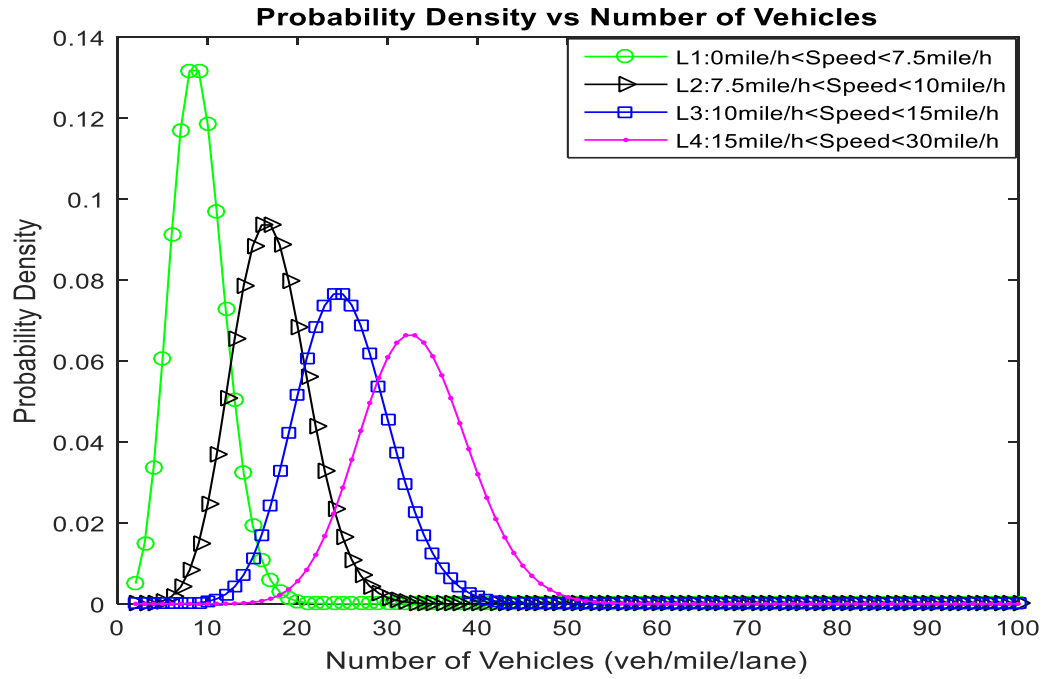


Figure 4.9a The effect of traffic flow when $\lambda = 9$

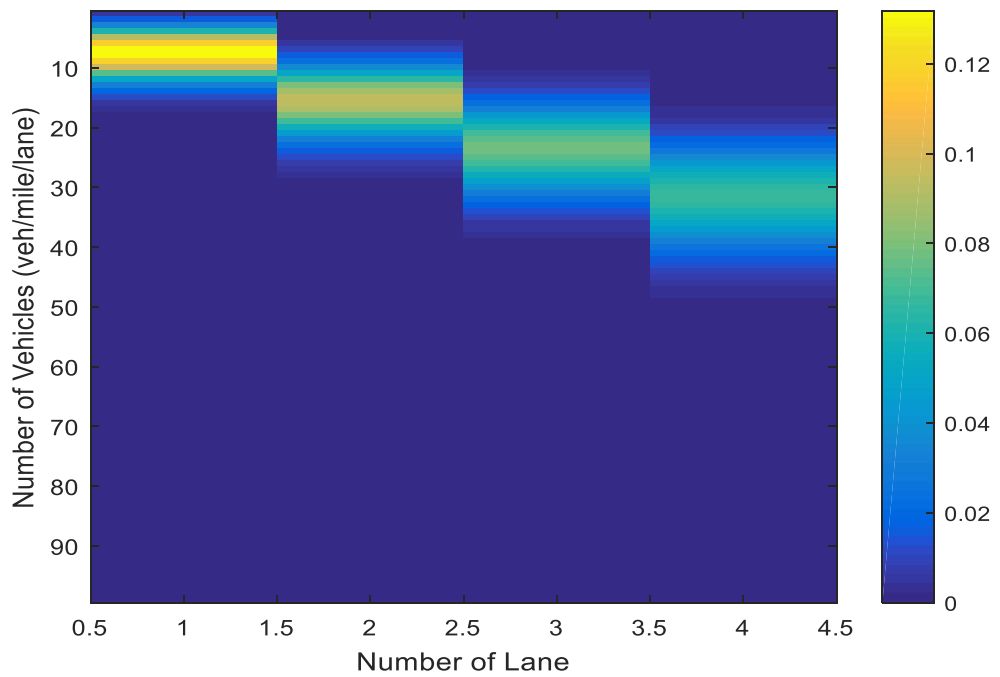


Figure 4.9b Vehicle trajectories in each lane

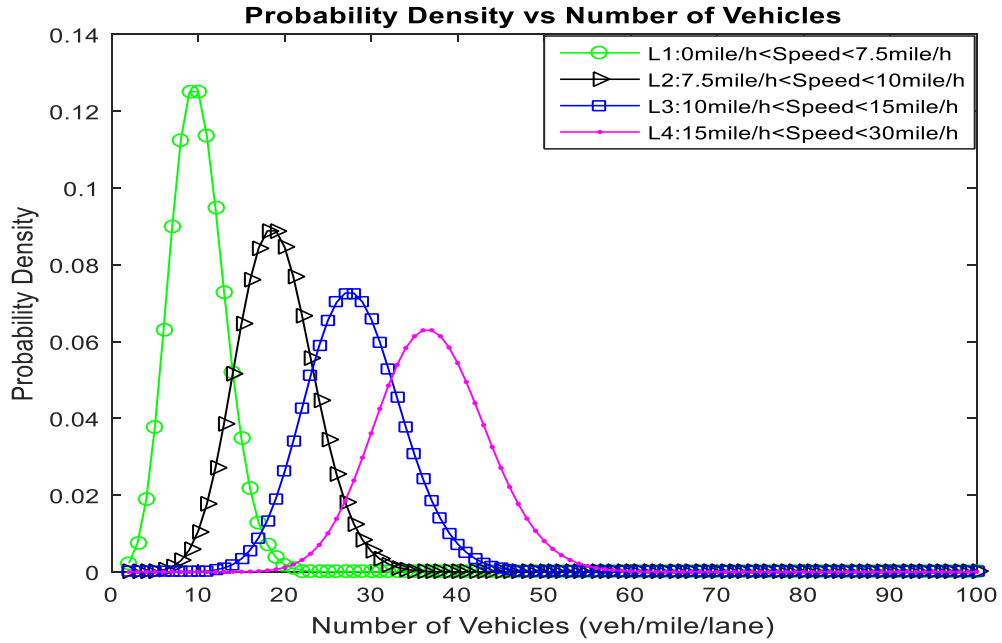


Figure 4.10a The effect of traffic flow when $\lambda = 10$

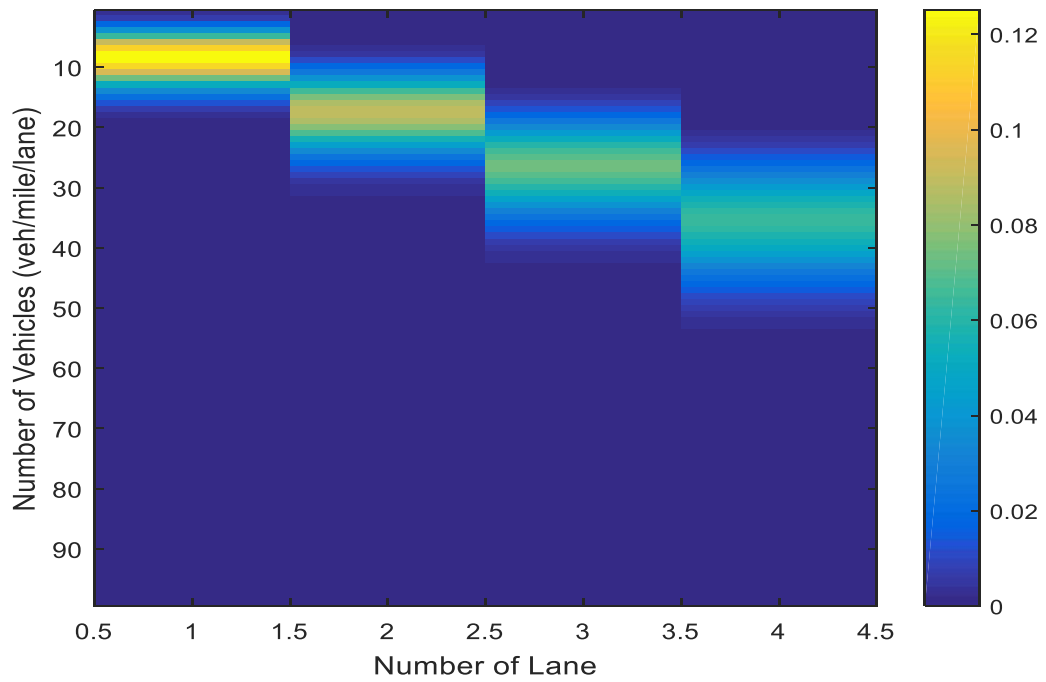


Figure 4.10b Vehicle trajectories in each lane

4.3 The congestion control models using four-lane networks

This study used Four-Lane Mobility in VANETs, within a congested network which is similar (see Figure 2.5) with increased traffic density as the value of λ from 1 to 10. These effects are shown in (see Figure 4.11 and Figure 4.12) in this thesis and the combined effects of the congestion control model (see Figure 4.13) which is like Phase transition (see Figure 2.5), showing the level of transitions on each lane according to (Adolf, 1990; Sugiyama et al., 2008). This transition is demonstrated in the congestion control models with the effects of the value of parameter λ (Figure 4.11, 4.12 and figure 4.13) as outlined below.

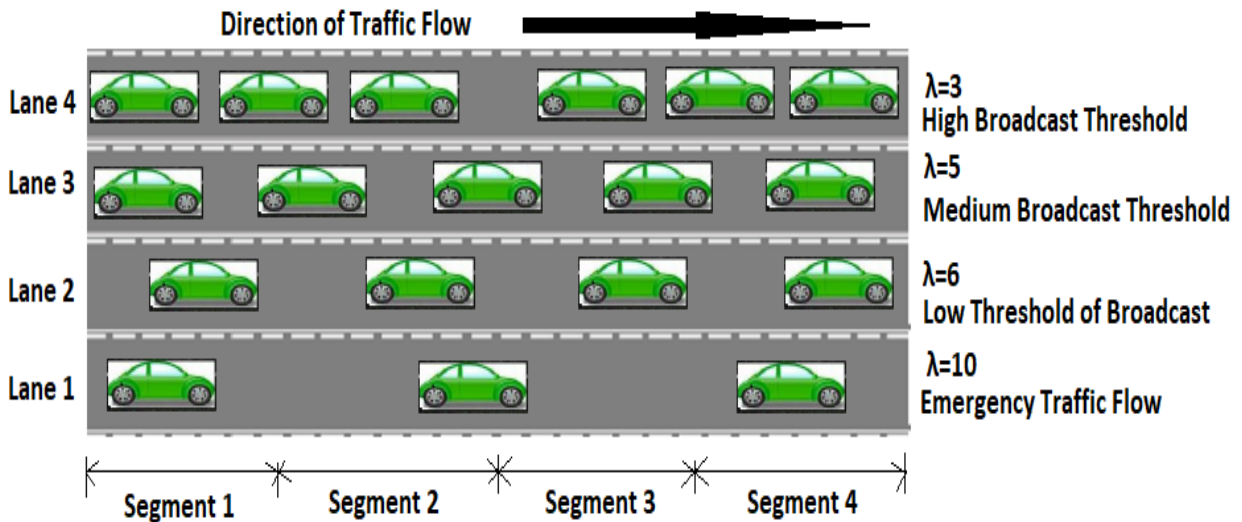


Figure 4.11 Four-Lane at the right side of the road showing the direction and movement of vehicle

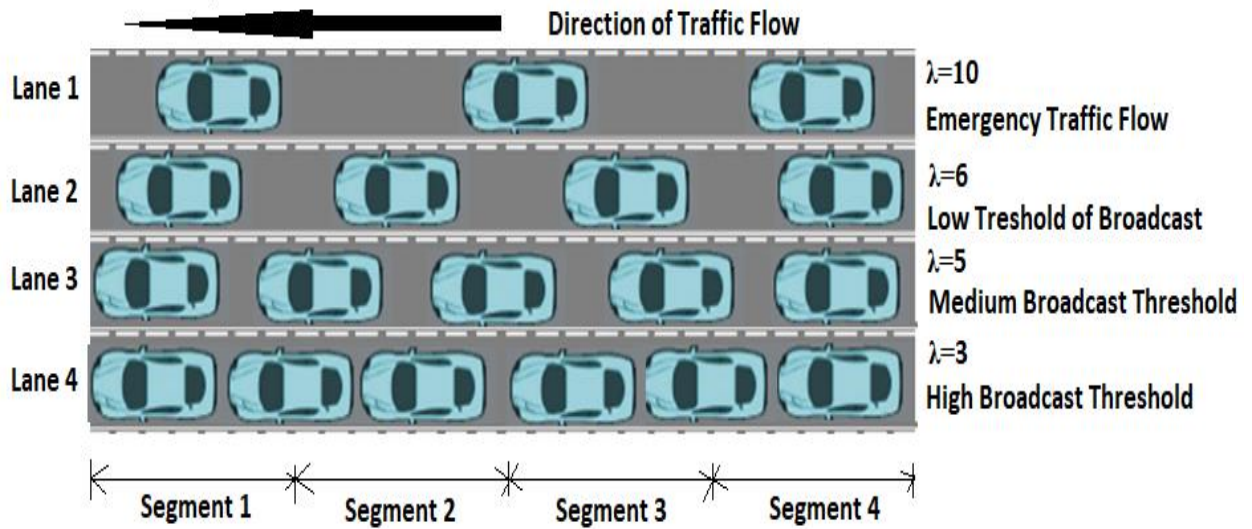


Figure 4.12 Four-Lane at the left side of the road showing the opposite direction and movement of vehicles

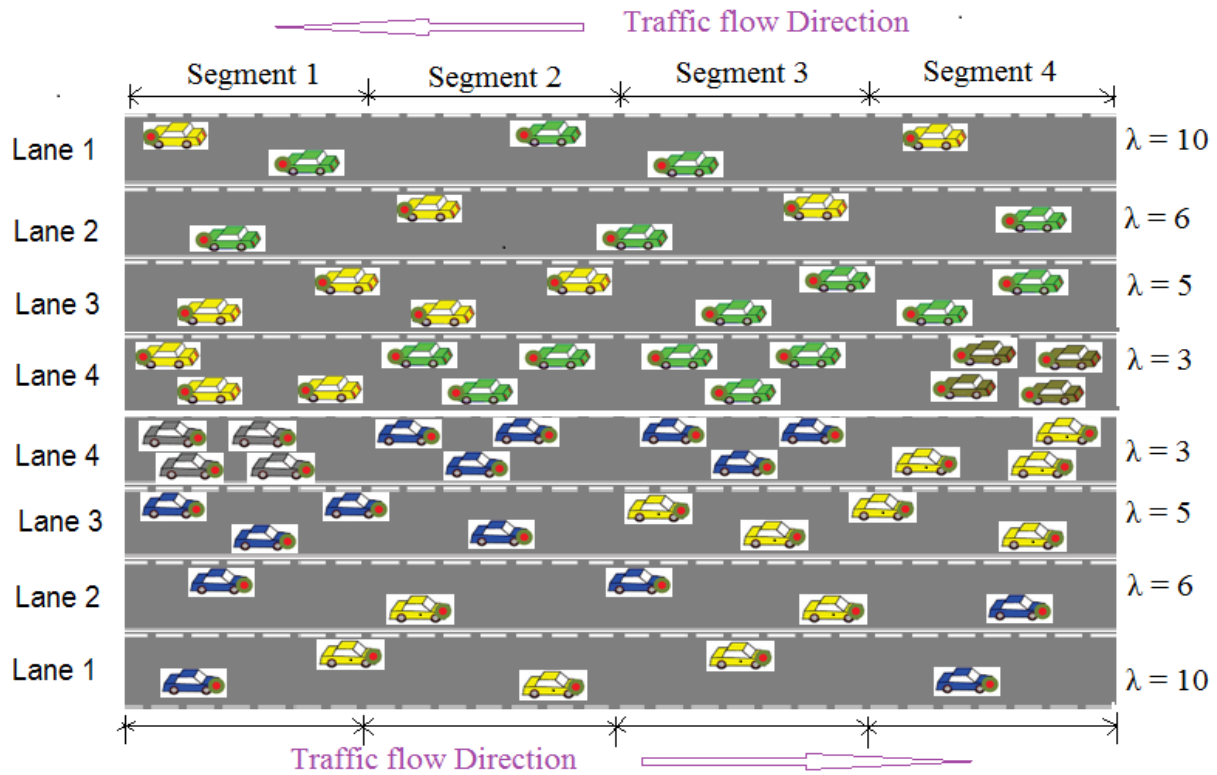


Figure 4.13 Two-way Congestion Control Model showing different threshold of λ

4.4 Improving connectivity in sparse networks

This thesis analyse the connectivity challenges in sparse networks under free-flow condition according to (May, 1990) and other related studies challenges have been discussed in chapter 2 extensively. Chapter 3 discussed how the challenges are addressed to improve VANETs problems in sparse network and dense networks.

In free flow condition, extensive studies have been reported concerning the connectivity challenges of mobile ad-hoc networks in different context in (Kloiber et al., 2012). The connectivity of mobile ad-hoc networks primarily depends on the pattern of mobility and the channel conditions. In most studies, on ad-hoc networks were investigated with predefined node placement and static transmission range to examine the network phenomenon associated with connectivity. This phenomenon is then analysed according to the node density, speed, transmission range etc.

According to (Adolf, 1990; Bettstetter et al., 2004) the connectivity probability density of one dimensional network is analysed with uniform node distribution and is extended to multiple dimensions to find the bounds of connectivity through extensive simulation. The authors (Kleijnen, 2005; Ros et al., 2014), derived a critical range of nodes for connectivity with probability of one and considered as infinity. This type of node distribution is not applicable in vehicular network due to high dynamic fast topology changes. However, vehicular movement of nodes are considered in (Zeadally et al., 2012). In (Adolf, 1990; May, 1990), the author relies on some road statistics and numerical solution for the connectivity distance, platoon size derived based on queuing theoretical views. According to author (Adolf, 1990; Schumacher et al., 2009), real road scenario is created through simulation to determine the minimum transmission

range to arrive at full network connectivity and the effect of vehicle density on the transmission range is investigated in thesis.

According to (Choffnes & Bustamante, 2005), the enhancement of connectivity is done by considering both direct connectivity from a source node as well as the indirect connectivity through multi hop forwarding to ensure the available connectivity. According to (May, 1990) (Adolf, 1990) , the link lifetime from the PDF of relative velocity of consecutive vehicles and PDF of vehicle headway distance were derived. The link lifetime corresponding to multi-hop connectivity in two-lane road with opposing vehicle direction is also analysed. The rest of the chapter is organized as follows: Section 4.2 describes in detail the simulation outcome associated with sparse networks. Section 4.3 analyse the connectivity problems associated with sparse network in detail. Finally, section 4.4 concludes the chapter.

4.4.1 Performance metrics in sparse network conditions

In lane 1,2,3 and 4, when $\lambda=1, 2, 3, 4$ and 8; the smaller standard deviation than the mean indicates that certain number of the vehicles on the roads are closed or clustered around the mean value. This indicates reasonable distribution among few numbers of vehicle on the road, with respect to high speed and distances. This separates vehicles beyond the acceptable transmission range (i.e. 1000m). The vehicle connectivity range for effective communication, When $\lambda=1$; lane 1: 79.5%.; lane 2: 79.9%; lane 3: 81.1% and lane 4: 82.3%, when $\lambda=2$; lane 1: 70.8%.; lane 2: 78.4%; lane 3: 81.9% and lane 4: 83.9%, when $\lambda=3$; lane 1: 75.5%.; lane 2: 81.8%; lane 3: 84.7% and lane 4: 86.5%, when $\lambda=4$; lane 1: 78.4%.; lane 2: 83.9%; lane 3: 86.5% and lane 4: 87.9% and finally when $\lambda=8$; lane 1: 83.9%.; lane 2: 87.9%; lane 3: 89.8% and lane 4: 90.9%. When $\lambda=1$: all the four lanes, shows an exponential distribution when $\lambda=2$: lane 1 and 2, show an

exponential distribution while lane 3 and 4 begin to show normal distribution but skewed to the right. When $\lambda=3$ in lane 1, shows an exponential distribution while lane 2,3 and 4 indicate a normal distribution but skewed to the right at varying degree of skewness. When $\lambda=4$: lane 1, shows an exponential distribution, in lane 2, 3 and 4; indicates a normal distribution but skewed to the right at varying degree of skewness.

In lane 1,2 and 3, when $\lambda=5$, the smaller standard deviation than the mean indicates that certain number of the vehicles on the roads are closed or clustered around the mean value. This indicates fair distribution among few numbers of vehicle on the road, with respect to high speed and distances. In lane 4; the vehicles are spread-out at varying degree when the standard deviation is greater than the mean value. On the other hand, vehicles in lane 4; are much further away from each other due to fewer vehicles on the road with very high speed and high distances within each neighbour. The vehicles in lane 1, 2 and 3, are at reasonable distances from each vehicle but beyond the acceptable transmission range (i.e. 1000m). The vehicle connectivity range for effective communication, When $\lambda=5$, lane 1: 80.3%; lane 2: 85.4%; lane 3: 97.3% and lane 4: 88.0%. When $\lambda=5$: lane 1 begin to show a normal distribution but skewed to the right while lane 2, indicates a normal distribution but also skewed to right. Lane 3 and 4, indicate a complete normal distribution but lane 3 slightly skewed to right while lane 4 also slightly skewed to left.

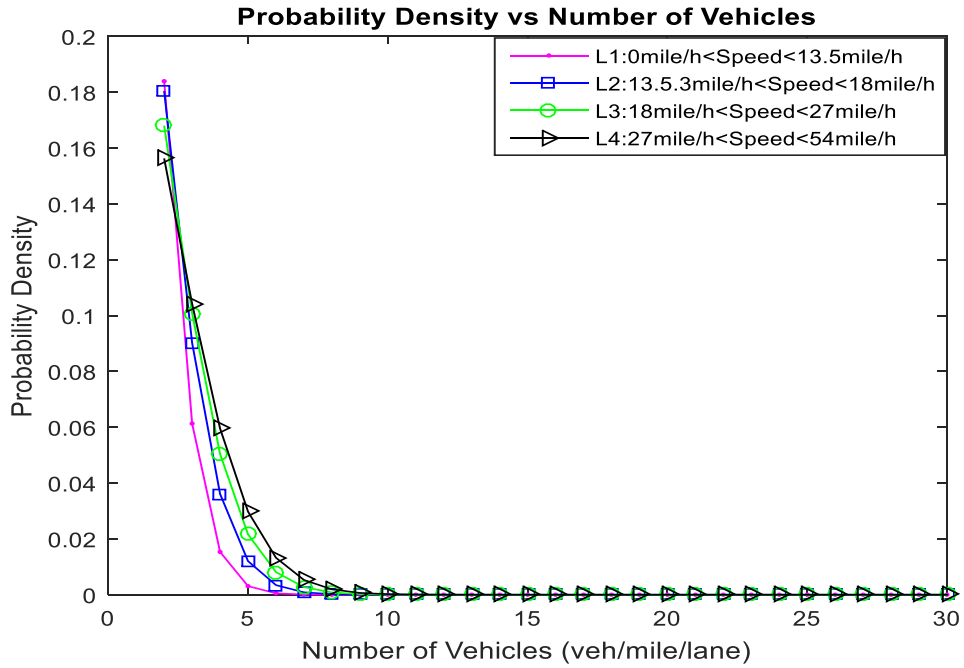


Figure 4.14 The effect of traffic flow when $\lambda = 1$

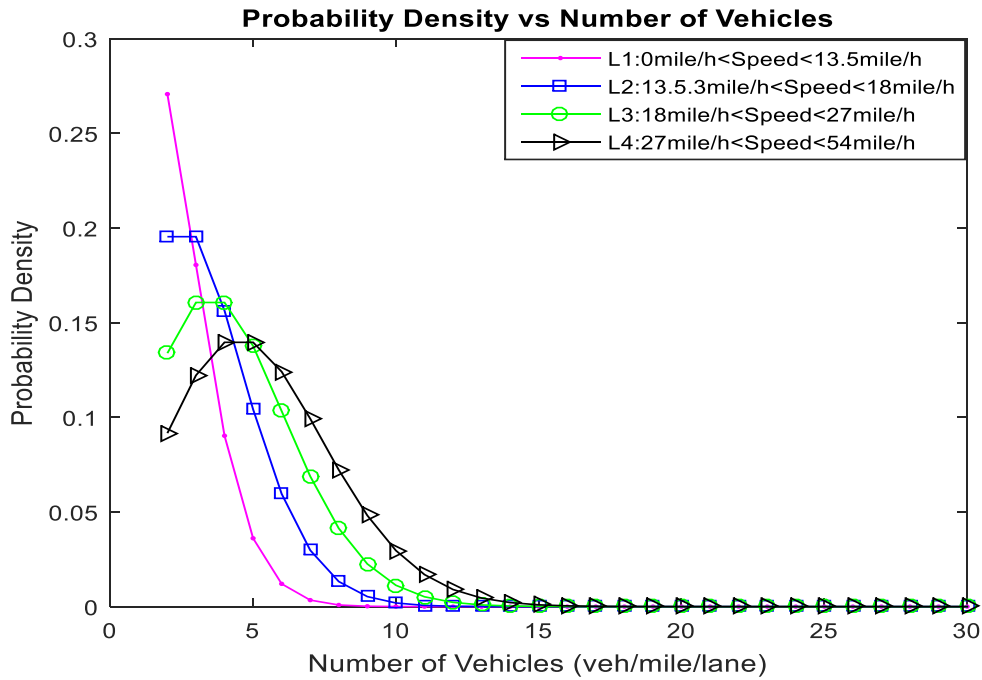


Figure 4.15 The effect of traffic flow when $\lambda = 2$

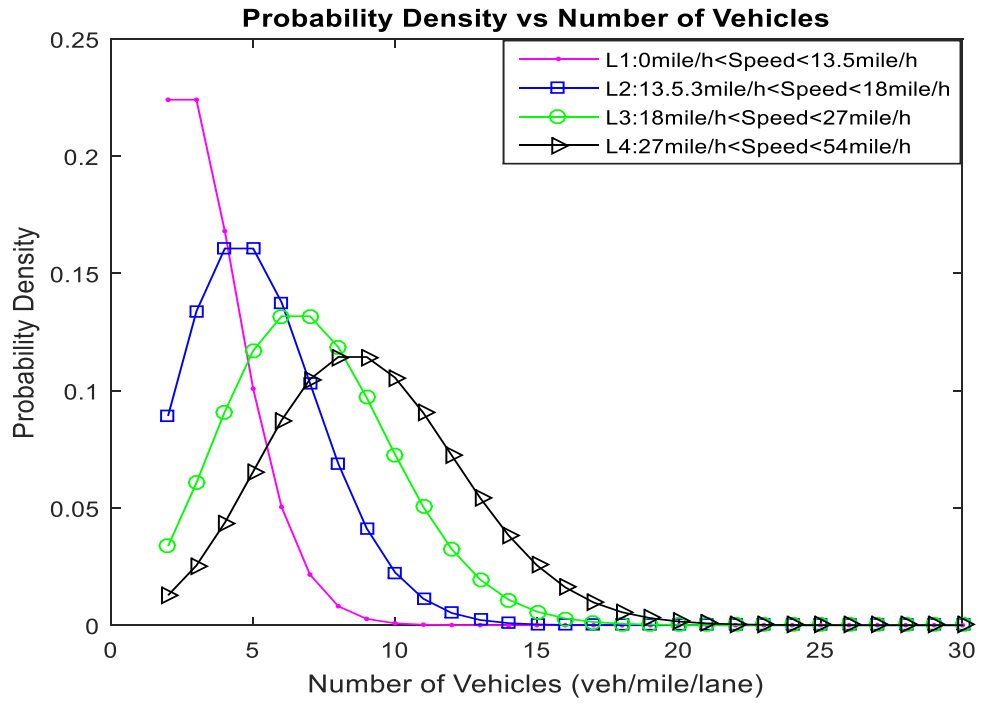


Figure 4.16 The effect of traffic flow when $\lambda = 3$

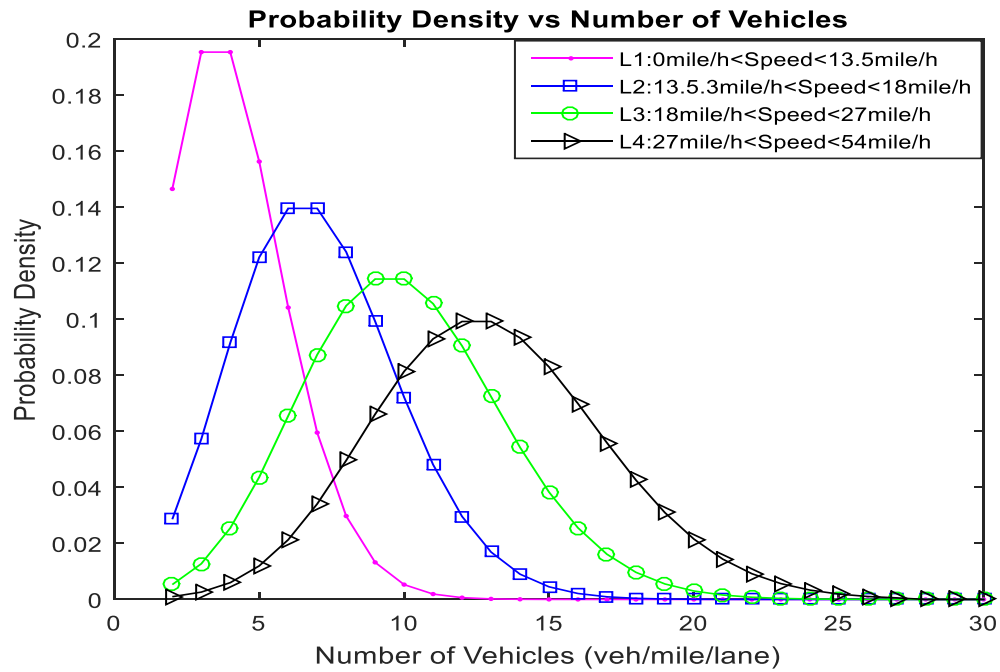


Figure 4.17 The effect of traffic flow when $\lambda = 4$

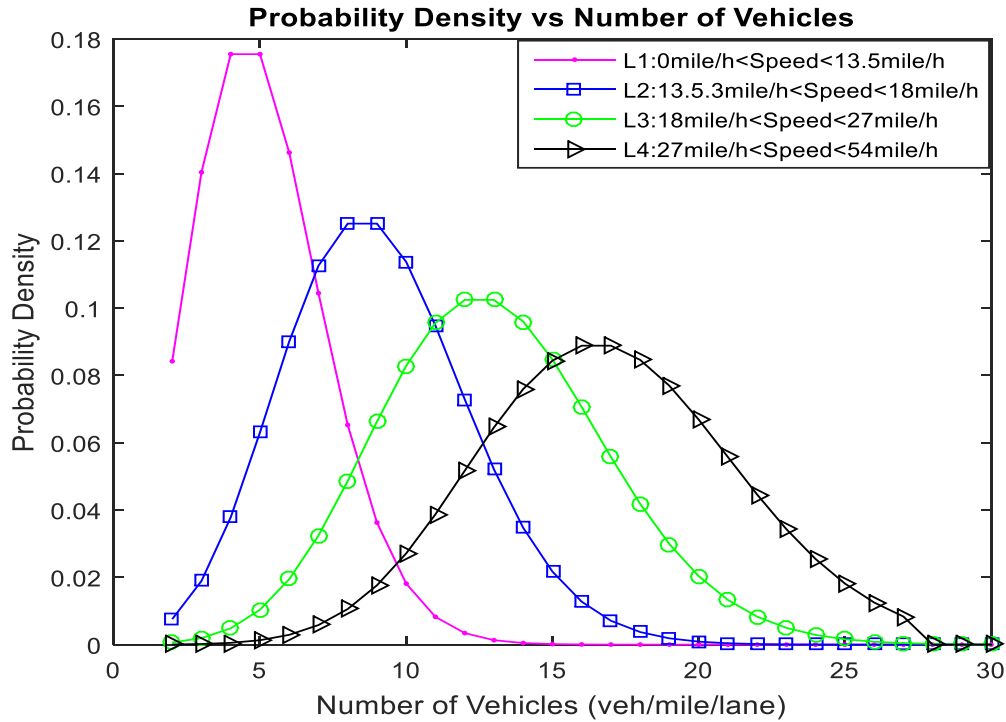


Figure 4.18 The effect of traffic flow when $\lambda = 5$

4.5 The proposed Honeycomb Models under sparse network conditions

This study introduces a Honeycomb Model (HCM) to improve sparsely connected network using the idea on how honeybees form honeycomb and in search of food. This idea is based on the orientation of the wagging dance of the honeybees. This study has found out that the angle of rotation precisely matches the angle between the feeding station and the hive (honeycomb). This clue demonstrates how the bees can share information about the location of food. The honey bee form clusters and one cluster of A and B may accurately share important information by communicating among the two clusters. This phenomenon can be replicated in VANETs traffic information dissemination in sparsely connected networks to enable vehicles to share traffic information in a cluster within the acceptable transmission range.

This idea follows a macroscopic traffic flow model which is often used in civil engineering to describe the traffic aggregation behaviour of traffic flow on the road for both free-flow and congested traffic conditions. This level is very important for deciding the traffic flow state coupled with density disruptions according to (M. Artimy, 2007; Mohimani et al., 2009). This proposed model is shown in Figure 4.19, 4.20 and 4.21, 4.22 and the complete Honeycomb Model is shown in Figure 4.23.

Angle 1 at the feeding station

Angle 2 at the Hive

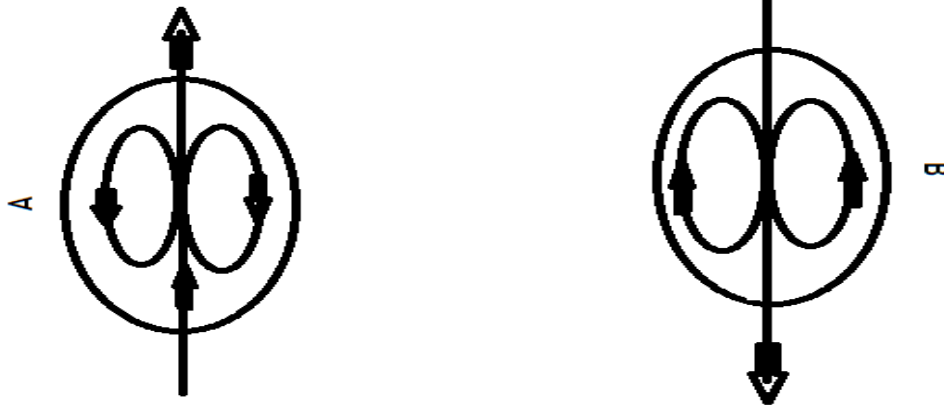


Figure 4.19 Showing the rotation of the two clusters based on the wagging dance of the Honeybees in A and B

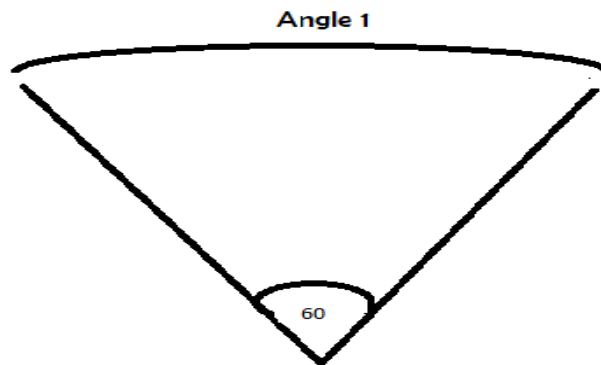


Figure 4.20 Showing the angle 1 at the feeding station

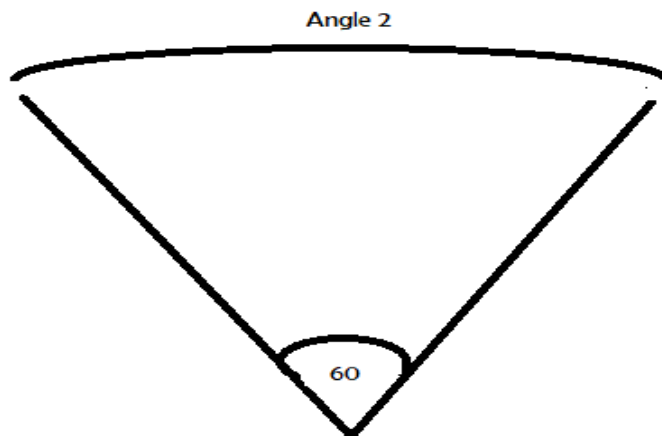


Figure 4.21 Showing the angle 2 at the bee hive

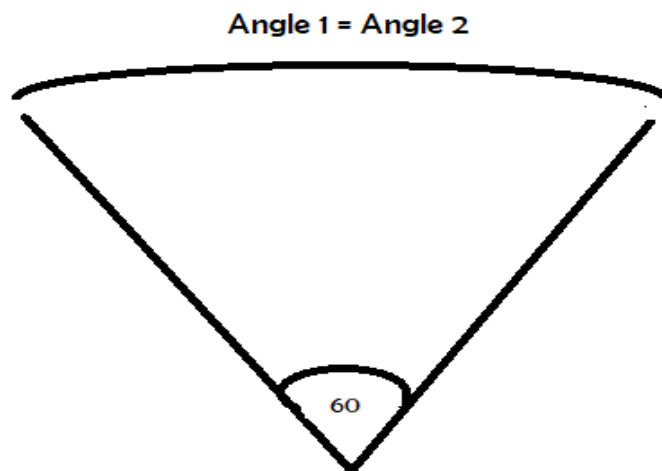


Figure 4.22 Showing how the angle of rotation matches the angle between the feeding stations and the bee hive.

4.5.1 The Honeycomb Model (HCM)

The traffic flow models developed in (May, 1990) are summarized into subsection for simplicity. The result in (Adolf, 1990; Mohimani et al., 2009), show that the traffic flow characteristics depends to a large extent on the traffic flow conditions on the roads and this is usually based on

the condition imposed by the level of interaction between the vehicles on the roads. For instance, under a low traffic density, the interaction between the vehicles is negligible. Similarly, the vehicles moving independently enjoy the maximum level of services in A or B as indicated in Table 3.1. When the traffic density increases, it corresponds with the interaction between vehicles increase and this eliminates the free flow conditions. For instance, when the traffic density approaches the road capacity, the interaction that exists between vehicles further increases. This subsequently, further eliminates randomness in the vehicle movement. These occurrences lead to the steady movement with deterministic traffic characteristic values proceeded by the car following models.

Both circles represent cluster P and Q. Cluster P is where the source vehicle, segment vehicle and the neighbour vehicle are located while the destination vehicle is in cluster Q. Cluster P contains two right-angled triangles: namely angle ASC and angle BSC. Angle ASC is the source vehicle while angle BSC is the destination vehicle. The angle formed in ASC is the same as the angle formed in BSC. Therefore, $\text{angle ASC} = \text{angle BSC}$ (see Figure 4.19, Figure 4.20 and Figure 4.21) for these assumptions. The angle $\text{ASC} = \text{angle BSC}$ is explained in the Model (see Figure 4.23) to replicate the attributes of Honeybees and how this phenomenon is implemented in VANETs to mitigate the sparse network problem.

The source vehicle within cluster P has two directions to transmit messages to the destination vehicle in cluster Q. The angle at which to transmit messages within cluster P to cluster Q is 180° , since the angle of rotation from cluster P matches cluster Q precisely. Each triangle within cluster P behaves differently when transmitting messages to the destination vehicles.

In this model, any vehicle that has the least distance will serve as the cluster head to communicate with destination vehicles within the acceptable transmission range R .

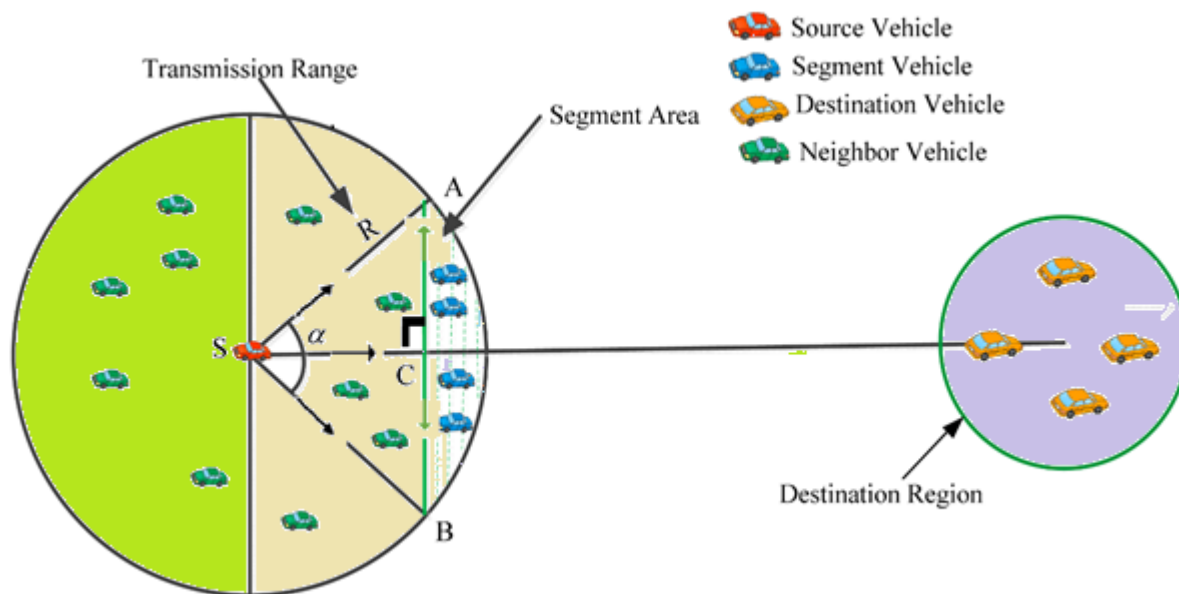


Figure 4.23 Proposed Honeycomb Models (HCM)

4.6 Conclusions

This chapter has suggested a new congestion control model in dense networks and Honeycomb Model in sparsely connected networks based on the macroscopic analytical investigations through simulations. The simulations result of the analytical investigations in dense networks and sparse networks were represented graphically to demonstrate the performance analysis under traffic density while varying the value of λ . The simulation result reveals the vehicle trajectories as the value of λ increases with time. The outcome of this study indicates that there is no need increasing the value of λ beyond 12, since further increases would only increase the number of vehicles leading to traffic jam. In principle, it is very important to use $1 \leq \lambda \leq 12$ in designing

traffic models in VANETs. The analytical result proved that the Congestion Control Model for the four-lane may be the most appropriate model to be adopted and use in designing VANETs networks. The analytical investigation also provides a model to mitigate the frequent disconnections in sparse vehicular networks (VANETs). This model provides a scientific basis in designing vehicular networks for different level of services. For service A: $1 \leq \lambda \leq 3$; B: $1 \leq \lambda \leq 4$ and C: $1 \leq \lambda \leq 5$, the study proposed a Honeycomb Models in sparsely connected model to mitigate the challenges in sparse networks. The first model is the congestion control model that has been used to describe four-lane road networks and indicate the various thresholds with respect to the value of λ . The second model is the Honeycomb model in sparsely connected networks based on the science behind how honey bees move from the feeding station to the hive. These models were developed to help VANETs researchers to develop scalable algorithm to enhance traffic alert message dissemination in VANETs.

Chapter 5 Evaluation of the simulation results

5.1 Introduction

In Chapter 2, the Cellular Automata (CA) model was discussed in the context of macroscopic traffic flow model as the discrete model. In this approach, parameter such as density, speed and traffic flow were investigated in which the level of service in (Adolf, 1990; May, 1990; Rickert, Nagel, Schreckenberg, & Latour, 1996), were selected based on traffic flow conditions under congested and free-flow scenario to ascertain the spatio temporal variations. Chapter 3, adopted the macroscopic traffic flow model according to (May, 1990), using the novel approach in this thesis to perform simulation in MATLAB and proposed a congestion control model along with the Honeycomb Model to mitigate ITS problems in VANETs for enhanced future applications. Chapter 4 demonstrates the performance of the adopted macroscopic traffic flow model and used equations (3.1) and (3.3) to perform simulation in terms of density, speed and traffic flow.

This chapter evaluates the result of the simulations in dense and sparse networks as reported in chapter 3 while chapter 4 conduct an experiment through simulation to address the specific objectives of this thesis and briefly show the results graphically.

The rest of the chapter is organized as follows: Section 5.2 describes in detail the result associated with dense network traffic flow. Section 5.3 also describes in detail the result concerning the sparse network and demonstrates the percentage link intermittent connectivity in

each lane with respect to the acceptable transmission range. Finally, section 5.4 concludes the chapter.

5.2 Result obtained under dense network traffic flow

This evaluation is based on the simulation using MATLAB and depends on the node's density of each lane. This demonstrates the spatio temporal variations in vehicular trajectories with respect to the node density. The nodes in each lane indicate the vehicular (nodes) trajectories as the value of λ increases (see Figure 4.1b, 4.2b, 4.3b, 4.4b, 4.5b, 4.6b, 4.7b, 4.8b, 4.9b and 4.10b).

5.2.1 Network reachability

Figure 4.1a, 4.1b shows the average packet penetration distance as a function of λ . The faster the packet delivery the more efficient the Congestion Control Model (CCM). The model is considered efficient if it can send a message to the target destination within an acceptable time frame. Under an ideal condition, it is expected as the time increases, the packet penetration distance also increases up to the end of the Region of Interest (ROI). In contrast, if there is no vehicle (node) within the transmission range at the time of broadcast, then the disconnected vehicle moves out of (ROI) (i.e.1000 m). In this case, lane 1, lane 2 has seen a few vehicles than in lane 3 and lane 4. Therefore, lane 3 and lane 4 experiences reasonable penetration distance while lane 1 and lane 2 are within (ROI). The results are like Figure 4.2a and 4.2b but the average packet penetration distance is better as the value of λ increases the faster the packet delivery until the normal distribution occurs.

Similarly, Figure 4.3a, 4.3b shows the average packet penetration distance as a function of λ , when lane 3 and lane 4 have seen normal distribution around nodes 10 (veh/mile/lane) and

therefore experiences faster packet delivery and more efficient as indicated in the Congestion Control Model (CCM). As the value of λ increases the model is considered efficient since it can send a message to the target destination within an acceptable time frame. Lane 1 and lane 2 also seen fewer packet penetration under an ideal condition as the time increases, the packet penetration distance also increases up to the end of the Region of Interest (ROI). In the same way, figure 4.4a and 4.4b have seen a complete normal distribution indicating how the vehicles spread across the road when the value of λ increases with time. The complete normal distribution between 5 nodes and 15 nodes indicate faster packet delivery than in lane 1. As the value of λ increases the model is considered efficient since it can send a message to the target destination within an acceptable time frame than in lane 1.

In addition, Figure 4.5a and 4.5b are like Figure 4.4a and 4.4b, have also seen a complete normal distribution indicating how the vehicles spread across the road as the value of λ increases with time. The complete normal distribution between 8 nodes and 20 nodes indicate faster packet delivery than in lane 1. As the value of λ increases the model is considered efficient since the target destination is within an acceptable time frame than in lane 1. In Figure, 4.6a and 4.6b have seen an increased node between 10 and 26 nodes as the value of λ increases with time than in lane 1. The packet penetration distance as a function of λ is greatly enhanced since lane 2, lane 3 and lane 4 have seen increased packet penetration rate under the normal distribution while lane 1 experiences fewer packet penetration rate.

Figure 4.7a and 4.7b have also seen an improvement over Figure 4.6a and 4.6b, since almost all the lanes nearly assumed a normal distribution. In this case, the nodes are distributed between 10 and 35 nodes within lane 2, lane 3 and lane 4 as the value of λ increases with time than in lane 1.

This is evident when the packet penetration distance is expressed as a function of λ and therefore have increased packet penetration rate in lane 2, lane 3 and lane 4 while lane 1 experiences an average packet penetration rate with increased nodes.

Similarly, Figure 4.8a and 4.8b, have seen an increased in nodes distribution between 10 and 40 nodes and lane 2, lane 3 and lane 4 have also demonstrated a complete normal distribution than lane 1 as the λ increases. Lane 2, lane 3 and lane 4 have experienced high packet penetration rate as a function of λ .

5.2.2 Network scalability

Figure 4.9a and 4.9b, almost assumed a complete normal distribution in all the lanes with nodes density between 10 and 50 nodes as the λ increases with time. In this case, network scalability emerges as the nodes density increases and the average network overhead for a single broadcast is observed in each vehicle (node) with respect to each lane. This network overhead seems to scale very well in lane 2, lane 3 and lane 4; especially in heavy traffic conditions in which broadcast storm is likely to occur. The result from the analytical investigation indicates that the amount of overhead is about four times less than in lane 2 and lane 1 and therefore no broadcast storm occurred.

Similarly, Figure 4.10a and 4.10b depicted a complete normal distribution within all the lanes. The nodes are distributed between 10 and 55 nodes as the value of λ increases to 10. This phenomenon shows the average network overhead for a single broadcast as observed by each vehicle (node) within lanes. This network overhead seems to scale very well as the value of λ increases with time; especially in heavy traffic conditions in which broadcast storm is likely to

occur. The result from the analytical investigation also indicates that the amount of overhead is about four times less than in lane 2 and lane 1.

This network overhead seems to scale very well; especially in heavy traffic conditions in which broadcast storm is likely to occur. The result from the analytical investigation indicates that the amount of overhead is about four times less than in lane 2 and lane 1. In this scenario, further increases in the value of λ beyond 10 would result in a jam situation where reachability will suffer. Therefore, in designing traffic flow models it is advisable to use $1 \leq \lambda \leq 12$ to avoid a traffic jam.

In conclusion, the analytical investigation of the macroscopic traffic flow model presents the performance in terms of reachability and scalability within the congested network in highways scenario under multiple traffic conditions. The Four-lane Congestion Control Model is developed to mitigate the extreme conditions of heavy traffic. This phenomenon, during simulation, was evident according to the network behaviour under lane 1, lane 2, lane 3 and lane 4.

5.3 Result obtained under sparse network traffic flow

The result in (Adolf, 1990; Daganzo, 2011; Kloiber et al., 2012; May, 1990), show that the traffic flow characteristics depends to a large extent on the traffic flow conditions on the roads and this is usually based on the condition imposed by the level of interaction between the vehicles on the roads. For instance, under a low traffic density, the interaction between the vehicles is negligible.

Similarly, the vehicles moving independently enjoy the maximum level of services in A or B as indicated in Table 3.1. When the traffic density increases, it corresponds to the interaction

between vehicles and this eliminates the free flow conditions. For instance, when the traffic density approaches the road capacity, the interaction that exists between vehicles further increases. This subsequently, eliminates randomness in the vehicle movement. These occurrences lead to the steady movement with deterministic traffic characteristic values proceeded by the car following models.

As described in chapter 2 and chapter 3, the simulation consists of a traffic flow model. The mobility pattern generated among the four-lane using the traffic model to describe in Chapter 3. This mobility pattern is used under sparsely connected networks to perform each simulation under different densities scenario to gain deep insight into network performance metrics such as reachability and scalability. The simulation parameter used are presented in Chapter 3, where vehicle density of (0 – 30 veh/mile/lane) are also selected for sparsely connected networks to perform various simulation while varying the value of λ from 1 to 10 at a different time interval.

When the simulation result indicates non-normal distribution, it may lead to drop and peaks in graph demonstrating unexpected increases in packet penetration rate when the density is reduced. On the other hand, when the simulation results also indicate normal distribution, this may lead to dense traffic in the graph with expected increases in the packet penetration rate. To mitigate the challenges in sparsely connected networks where packet penetration rate is reduced due to low traffic density, a Honeycomb model is developed with respect to the simulation results under sparse networks. This result indicates the percentage disconnection within each lane and with regards to the level of service volume as shown below:

5.3.1 Totally disconnected nodes (vehicles)

A vehicle operating in a sparse traffic condition is regarded as totally disconnected nodes if it has no neighbour in the message forwarding direction and is not connected to any node in the opposite direction. The simulation result, reveals the traffic situation in a typical disconnected network. To mitigate these challenges, a Honeycomb model is proposed to improve the packet penetration rate.

5.3.2 Partially sparsely connected nodes (Vehicles)

A vehicle is operating in a sparse traffic condition if it is the last node in a cluster. Furthermore, a vehicle in this regime is said to be in a sparsely connected neighbourhood if there exists at least one neighbour in the opposite direction as indicated in the Figure below

In Figure 4.14, 4.15 and 4.16 with lane 1,2,3 and 4, when $\lambda=1, 2, 3$ and 4; this explains that the number of vehicles on the roads are closed or clustered. This indicates reasonable distribution among few numbers of a vehicle on the road, with respect to high speed and distances. This separate vehicle beyond the acceptable transmission range (i.e. 1000m) and therefore experiences low packet penetration rate with respect to the lanes. The vehicle connectivity range for effective communication. When $\lambda=1$; lane 1: 79.5%.; lane 2: 79.9%; lane 3: 81.1% and lane 4: 82.3%, when $\lambda=2$; lane 1: 70.8%.; lane 2: 78.4%; lane 3: 81.9% and lane 4: 83.9%, when $\lambda=3$; lane 1: 75.5%.; lane 2: 81.8%; lane 3: 84.7% and lane 4: 86.5%, finally when $\lambda=4$; lane 1: 78.4%.; lane 2: 83.9%; lane 3: 86.5% and lane 4: 87.9% and When $\lambda=1$: all the four lanes, shows an exponential distribution when $\lambda=2$: lane 1 and 2, show an exponential distribution while lane 3 and 4 begin to show normal distribution but skewed to the right. When $\lambda=3$ in lane 1, shows an exponential distribution while lane 2,3 and 4 indicate a normal distribution but skewed to the

right at varying degree of skewness. When $\lambda=4$: lane 1, shows an exponential distribution, in lane 2, 3 and 4; also indicates a normal distribution but skewed to the right at varying degree of skewness.

In lane 1,2 and 3, when $\lambda=5$, this indicates that a certain number of vehicles on the roads are closed or clustered. This indicates fair distribution among few numbers of the vehicle on the road, with respect to high speed and distances. In lane 4; the vehicles spread-out at varying degree.

On the other hand, vehicles in lane 4; are much further away from each other due to fewer vehicles on the road moving at a very high speed and high distances within each neighbour. The vehicles on the road moving at a very high speed and high distances within each neighbour. The vehicles in lane 1, 2 and 3, are at reasonable distances from each vehicle but beyond the acceptable transmission range (i.e. 1000m). The vehicle connectivity range for effective communication. In Figure 4.17, when $\lambda=5$, lane 1: 80.3%; lane 2: 85.4%; lane 3: 97.3% and lane 4: 88.0%. When $\lambda=5$: lane 1 begin to show a normal distribution but skewed to the right while lane 2, indicates a normal distribution but also skewed to right. Lane 3 and 4, indicate a complete normal distribution but lane 3 slightly skewed to right while lane 4 also slightly skewed to left explains the variations in node density. These intermittent percentage disconnections of nodes (vehicles) show the severity in the sparse network with regards to information dissemination. The model ensures that the nodes are cluster using Honeycomb model to mitigate the frequent disconnection associated with the sparse network in VANETs.

5.4 Conclusions

This chapter presented a new macroscopic traffic flow model and run various simulations under dense network and sparse network to ascertain traffic flow variability in VANETs. This model is implemented in MATLAB.

The performance of the macroscopic traffic flow model is measured in terms of these performance metrics: reachability and scalability. Performance analysis has been done using various system parameters for dense networks (See Table 3.3) and for sparse networks (See Table 3.4). In the first place, the impact of the network density concerning the performance of the macroscopic traffic flow model is assessed by varying the number of nodes placed in a fixed level of service (See Table 3.1). In the second place, the impact of varying the value of λ as a function of average packet penetration distance. Finally, the performance analysis of the macroscopic traffic flow model has been conducted under varying node densities by varying the value of the nodes in the network.

The simulation results of the performance analysis demonstrate that the performance of the four-lane road of the macroscopic traffic flow model in terms of scalability as the value of λ increases. It performs well in the dense network than in sparse network. The simulation results of the second performance analysis also indicate that the performance of the four-lane road macroscopic traffic model in terms of reachability is achieved by varying the value of λ to ensure the connectivity of nodes to determine the packet penetration rate within dense and sparse network and the acceptable threshold in which the nodes reaches its destination under both scenarios. The results in dense networks have seen high packet penetration rate than in sparse network.

Finally, in the dense network the simulation result reveals the vehicle trajectories as the value of λ increases with time. The performance analysis indicates that there is no need for increasing the value of λ beyond 12 since further increases would only increase the number of vehicles leading to the traffic jam. It is very important to use $1 \leq \lambda \leq 12$ in designing traffic models in VANETs to achieve good reachability and scalability. In the sparse network, the performance analysis provides the basis to mitigate the frequent disconnections in sparse vehicular networks (VANETs). This range provides the basis in designing vehicular networks for the different level of services. For service A: $1 \leq \lambda \leq 3$; B: $1 \leq \lambda \leq 4$ and C: $1 \leq \lambda \leq 5$ to improve reachability and scalability.

Chapter 6 Conclusions and Future Directions

6.1 Introduction

Vehicular Ad Hoc Networks (VANETs) have attracted the attention of academia and industry recently according to (Dressler, Kargl, Ott, Tonguz, & Wischhof, 2011; Hartenstein & Laberteaux, 2009). Due to current advances in Intelligent Transportation Systems (ITS) applications cannot be overemphasized. This research effort cut across international boundaries due to its important applications to improve vehicular ad hoc networks (VANETs) according to (Hartenstein & Laberteaux, 2009). Although the nodes in VANETs have similar characteristics of MANETs, they present certain unique challenges inherent in dense networks and sparse networks due to the wireless communication medium and the distribution functions of their medium access mechanism (Bianchi, 2000; Bianchi, Fratta, & Oliveri, 1996). This result in frequent topology changes in vehicular mobility pattern (Fiore, Harri, Filali, & Bonnet, 2007; Zeadally et al., 2012). In view of the important (ITS) applications in VANETs, a lot of research efforts have been devoted to finding immediate solutions to these challenges according to (Hartenstein & Laberteaux, 2009).

The provision of congestions control models and sparsely connected models would improve information dissemination in ITS applications in VANETs. When this is achieved, it will greatly mitigate the frequent topology changes, and improve reachability and scalability being the most significant challenges in VANETs according to (F. Li & Wang, 2007). To accomplish this, quite several traffic flow models have been proposed as indicated in (Choffnes & Bustamante, 2005; Hoogendoorn & Bovy, 2001; Kerner et al., 2002). In these articles, the models have been

grouped into congestion control models and sparsely connected model. The models developed for both congestion control model and sparsely connected model are considered not to be scalable and reachable because of the excessive overhead and intermittent connectivity associated with traffic alert message disseminations under critical life-changing situations.

To mitigate these challenges in VANETs, several traffic flow models were proposed according to (Adolf, 1990; Hoogendoorn & Bovy, 2001; May, 1990). However, no single traffic flow models have improved these limitations and therefore require a new methodology to mitigate the challenges for an improved VANETs application in general. This, therefore requires a paradigm shift and system concepts approach for enhanced collaboration across the globe to mitigate the challenges.

6.2 Summary of the results

- i. Figure 4.1a, 4.1b shows the average packet penetration distance as a function of λ . The faster the packet delivery the more efficient the Congestion Control Model (CCM). The model is considered efficient if it can send the message to the target destination within an acceptable time frame. Under an ideal condition, it is expected as the time increases, the packet penetration distance also increases up to the end of the Region of Interest (ROI). In contrast, if there is no vehicle (node) within the transmission range at the time of broadcast, then the disconnected vehicle moves out of ROI (1000 m). In this case, lane 1, lane 2 has seen a few vehicles than in lane 3 and lane 4. Therefore, lane 3 and lane 4 experiences reasonable penetration distance while lane 1 and lane 2 are within (ROI). These results are seen in Figure 4.2a and 4.2b but the average packet penetration distance

is better as the value of λ increases the faster the packet delivery until the normal distribution occurs.

- ii. Similarly, Figure 4.3a, 4.3b shows the average packet penetration distance as a function of λ , when lane 3 and lane 4 have seen normal distribution around nodes 10 (veh/mile/lane) and therefore experiences faster packet delivery and more efficient as indicated on the Congestion Control Model (CCM). As the value of λ increases the model is considered efficient since it can send the message to the target destination within an acceptable time frame. Lane 1 and lane 2 also seen fewer packet penetration under an ideal condition as the time increases, the packet penetration distance also increases up to the end of the Region of Interest (ROI). In the same way, Figure 4.4a and 4.4b have seen a complete normal distribution indicating how the vehicles spread across the road when the value of λ increases with time. The complete normal distribution between 5 nodes and 15 nodes indicate faster packet delivery than in lane 1. As the value of λ increases the model is considered efficient since it can send the message to the target destination within an acceptable time frame than in lane 1.
- iii. In addition, Figure 4.5a and 4.5b are like Figure 4.4a and 4.4b have also seen a complete normal distribution indicating how the vehicles are spread across the road as the value of λ increases with time. The complete normal distribution between 8 nodes and 20 nodes indicate faster packet delivery than in lane 1. As the value of λ increases the model is considered efficient since the target destination is within an acceptable time frame than in lane 1. In Figure 4.6a and 4.6b, have seen an increased node between 10 and 26 nodes as the value of λ increases with time than in lane 1. The packet penetration distance as a function of λ is greatly enhanced since lane 2, lane 3 and lane 4 have seen increased

packet penetration rate under the normal distribution while lane 1 experiences fewer packet penetration rate.

- iv. Figure 4.7a and 4.7b have also seen an improvement over Figure 4.6a and 4.6b since almost all the lanes nearly assumed a normal distribution. In this case, the nodes are distributed between 10 and 35 nodes within lane 2, lane 3 and lane 4 as the value of λ increases with time than in lane 1. This is evident when the packet penetration distance is expressed as a function of λ and therefore have increased packet penetration rate in lane 2, lane 3 and lane 4 while lane 1 experiences an average packet penetration rate with increased nodes.
- v. Similarly, Figure 4.8a and 4.8b have seen an increased in nodes distribution between 10 and 40 nodes and lane 2, lane 3 and lane 4 have also demonstrated a complete normal distribution than lane 1 as the value of λ increases. Lane 2, lane 3 and lane 4 have experienced high packet penetration rate as a function of λ .
- vi. In Figure 4.9a and 4.9b, almost assumed a complete normal distribution in all the lanes with nodes density between 10 and 50 nodes as the value of λ increases with time. In this case, network scalability emerges as the nodes density increases where the average network overhead for a single broadcast is observed by each vehicle (node) with respect to each lane. This network overhead seems to scale very well in lane 2, lane 3 and lane 4, especially in heavy traffic conditions in which broadcast storm is likely to occur. The result from the analytical investigation indicates that the amount of overhead is about four times less than in lane 2 and lane 1 and therefore no broadcast storm occurred.
- vii. Similarly, Figure 4.10a and 4.10b depicted a complete normal distribution within all the lanes. The nodes are distributed between 10 and 55 nodes as the value of λ increases to

10. This phenomenon shows the average network overhead for a single broadcast as observed by each vehicle (node) within lanes. This network overhead seems to scale very well as the value of λ increases with time; especially in heavy traffic conditions in which broadcast storm is likely to occur. The result from the analytical investigation also indicates that the amount of overhead is also about four times less than in lane 2 and lane 1.
- viii. In the sparse network, Figure 4.14, 4.15 and 4.16 with lane 1,2,3 and 4, when $\lambda=1$, 2, 3 and 4; indicates that a certain number of the vehicles on the roads are closed or clustered. This indicates reasonable distribution among few numbers of a vehicle on the road, with respect to high speed and distances. This separate vehicle beyond the acceptable transmission range (i.e. 1000m) and therefore experiences low packet penetration rate within a certain lane. The vehicle connectivity range for effective communication is affected due to the position of the vehicles on the road.
- ix. This network overhead seems to scale very well; especially in heavy traffic conditions in which broadcast storm is likely to occur. The result from the analytical investigation indicates that the amount of overhead is subsequently about four times less than in lane 2 and lane 1. In this scenario, further increases in the value of λ beyond 10 would result in a jam situation where reachability will suffer. Therefore, in designing traffic flow models it is advisable to use $1 \leq \lambda \leq 12$ in designing traffic models in VANETs to improve ITS applications.
- x. The performance of the macroscopic traffic flow model is measured in terms of these performance metrics: reachability and scalability. Performance analysis has been done using various system parameters. In the first place, the impact of the network density on

performance of the macroscopic traffic flow model is assessed by varying the number of nodes placed in a fixed level of service in Table 3.1. In the second place, the impact of varying the value of λ as a function of average packet penetration distance. Finally, the performance analysis of the macroscopic traffic flow model has been conducted under varying node mobility by varying the maximum node speed in the network.

- xi. In conclusion, the analytical investigation of the macroscopic traffic flow model presents the performance in terms of reliability and scalability within the congested network on highways under multiple traffic conditions. The Four-lane Congestion Control Model is developed to mitigate the extreme conditions of heavy traffic. This phenomenon during simulation was evident according to the network behaviour under lane 1, lane 2, lane 3 and lane 4.
- xii. The simulation results of the performance analysis demonstrate that the performance of the four-lane road of the macroscopic traffic flow model in terms of scalability as the value of λ increases. It performs well in the dense network than in sparse network.
- xiii. The simulation results of the second performance analysis also indicate that the performance of the four-lane road macroscopic traffic model in terms of reachability is achieved by varying the value of λ to ensure the connectivity of nodes to determine the packet penetration rate within dense and sparse network and the acceptable threshold in which the nodes reaches its destination under both scenarios. The results in dense networks have seen high packet penetration rate than in sparse network.
- xiv. Finally, in the dense network, the simulation result reveals the vehicle trajectories as the value of λ increases with time. The performance analysis indicates that there is no need for increasing the value of λ beyond 12 since further increases would only increase

the number of vehicles leading to a traffic jam. It is very important to use $1 \leq \lambda \leq 12$ in designing traffic models in VANETs to achieve good reachability and scalability. In the sparse network, the performance analysis provides the basis to mitigate the frequent disconnections in sparse vehicular networks (VANETs). This provides basis for in designing vehicular networks for a different level of services. For service A: $1 \leq \lambda \leq 3$; B: $1 \leq \lambda \leq 4$ and C: $1 \leq \lambda \leq 5$ to improve reachability and scalability.

6.3. Conclusions and Future Work

This thesis has revealed very interesting challenges that require further investigation have emerged to promote further research in the future.

One important novel articles in congestion control model have been published from this thesis according to (Azameti et al., 2018). This research article has been widely read, indicating the novel contributions that would be used by both academia and industry for the development of new protocols and ITS applications in VANETs. These are clearly outlined below:

- i. This thesis has performed an analytical investigation into macroscopic traffic flow model to gain deep insight into the traffic density to ascertain the spatio-temporal variation as the value of λ increases under dense network and sparse network according to (May, 1990)
- ii. This study used traffic flow models (Civil Engineering) and concentrated on the macroscopic model stated in (May, 1990) and has presented a scalable solution to a congestion control in highly populated city environment. This proposed approach is a Congestion Control model designed for a four-lane road network. The lanes are numbered from 1 to 4 and in either direction (see Figure 4.14a).

- iii. The simulation in MATLAB provides a practical implementation of V2V and V2R Communication where each lane shows the vehicle trajectories and the lane with the highest congestion and the spatial variation in the successive lanes. Therefore, vehicular movements are not entirely random but also sequential and depend largely on the drivers' perception and the interactions with other road users. This Congestion Control Model (CCM) would help in designing vehicular traffic flow. Therefore, there is no need for increasing the value of λ beyond this range $1 \leq \lambda \leq 12$ in congested networks.
- iv. This study provides a fast, reliable and scalable model to congestion control. Although there exist many interventions to provide a lasting solution to congestion problem in VANETs, this proposed Congestion Control Model (CCM) provides an alternative methodology and framework for the research community to develop a lasting protocol for safety alert message dissemination in VANETs for ITS applications.
- v. Finally, the research findings reveal the possibilities to replicate the attributes of honeybees in designing vehicular traffic flow in VANETs. This novel approach would significantly improve ITS applications in VANETs V2V communication and therefore requires further investigation in VANETs protocol design.

Appendix

Appendix A: Publications

A Publications during the MPhil course

Adams A.K. Azameti et al. “The Effect of Congestion Control Model on Congested Traffic Flow in Vehicular Ad Hoc Networks (VANETs)” EAI Endorsed Transactions on Mobile Communications and Applications, vol.3. no.10, March 2018.doi={10.4108/eai.22-3-2018.154371}, <http://eudl.eu/doi/10.4108/eai.22-3-2018.154371>

Appendix B: Performance analysis under sparse network conditions and the value of λ

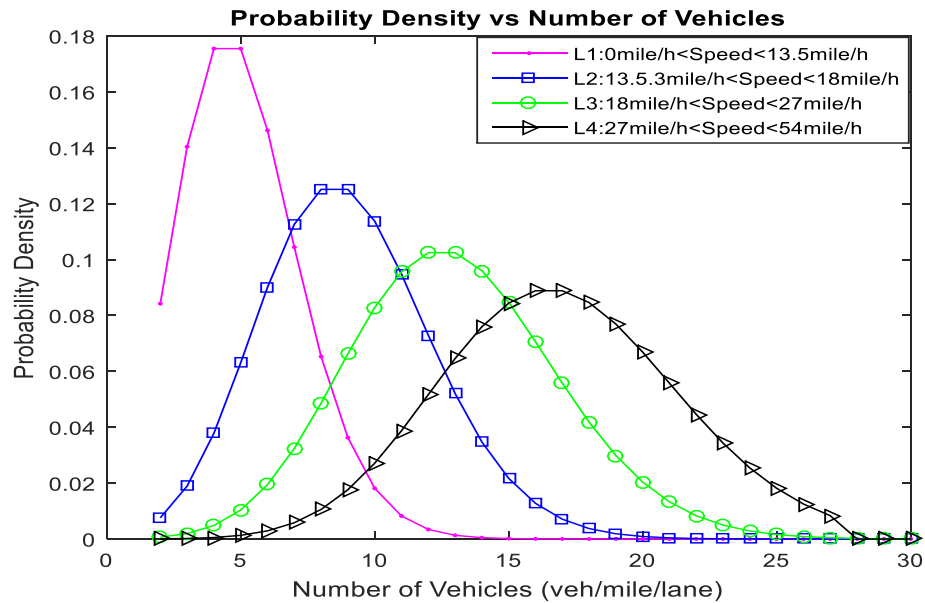


Figure B.1 The effect of traffic flow when $\lambda = 6$

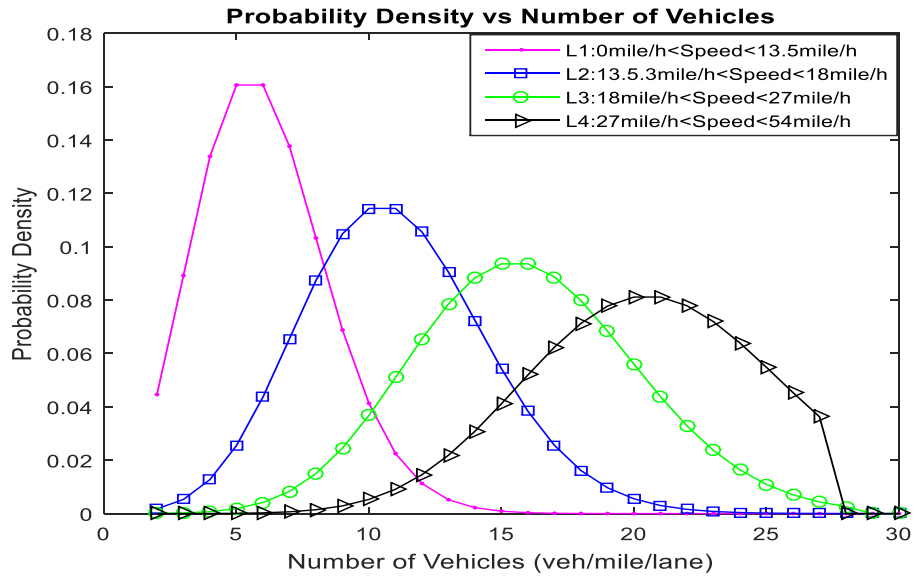


Figure B.2 The effect of traffic flow when $\lambda = 7$

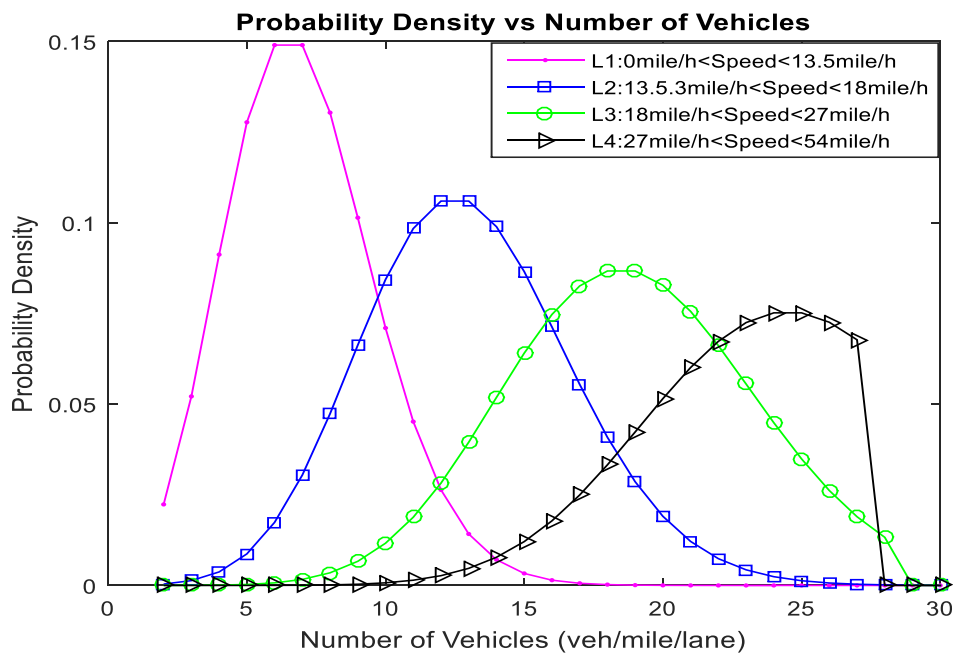


Figure B.3 The effect of traffic flow when $\lambda = 8$

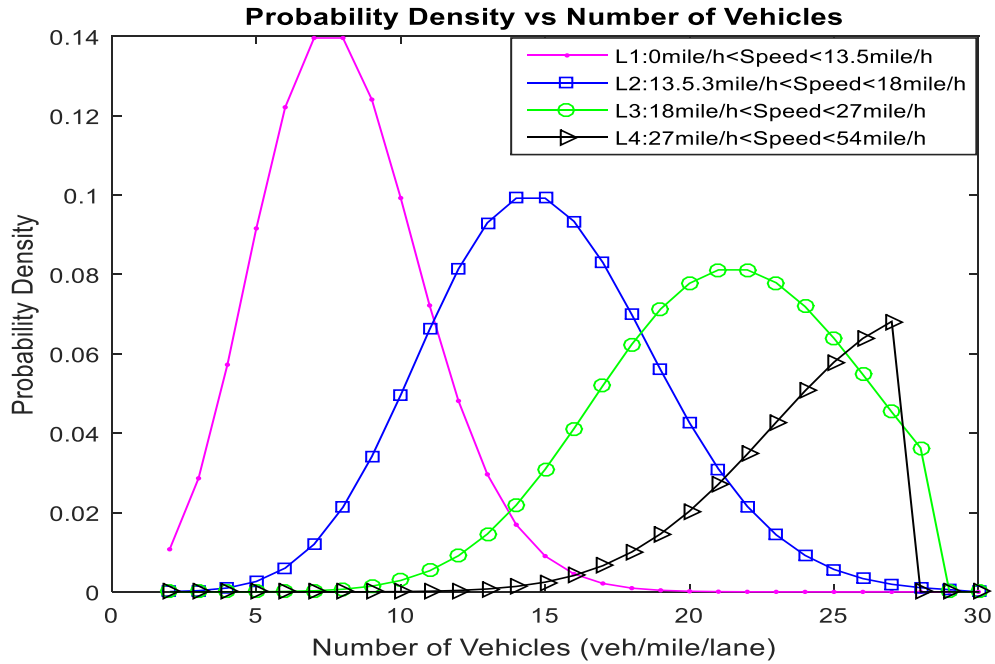


Figure B.4 The effect of traffic flow when $\lambda = 9$

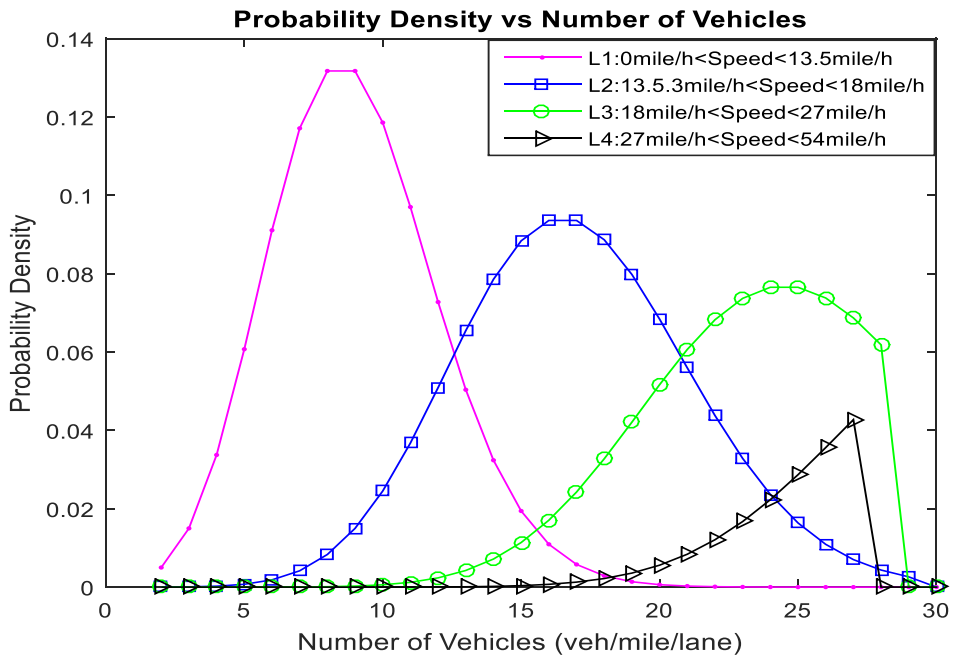


Figure B.5 The effect of traffic flow when $\lambda = 10$

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