Connected Vehicle Technology: User and System Performance Characteristics

Osama Abdulmonaem Thabet Osman
Louisiana State University and Agricultural and Mechanical College

Follow this and additional works at: https://digitalcommons.lsu.edu/gradschool_dissertations

Part of the Civil and Environmental Engineering Commons

Recommended Citation
https://digitalcommons.lsu.edu/gradschool_dissertations/1064

This Dissertation is brought to you for free and open access by the Graduate School at LSU Digital Commons. It has been accepted for inclusion in LSU Doctoral Dissertations by an authorized graduate school editor of LSU Digital Commons. For more information, please contact gradetd@lsu.edu.
CONNECTED VEHICLE TECHNOLOGY: USER AND SYSTEM PERFORMANCE CHARACTERISTICS

A Dissertation
Submitted to the Graduate Faculty of the
Louisiana State University and
Agricultural and Mechanical College
in partial fulfillment of the
requirements for the degree of
Doctor of Philosophy

in

The Department of Civil and Environmental Engineering

by
Osama A. Osman
B.S., Cairo University, 2006
M.S., Cairo University, 2010
December 2015
To my father,

Abdulmonaem Thabet Osman

May His Soul Rests in Peace in the Heaven
ACKNOWLEDGMENTS

Before any acknowledgments, I would not be writing this dissertation with three publications in prestigious journals and four presentations in very prestigious conferences without the great help and guidance of my advisor, Dr. Sherif Ishak. Dr. Ishak has been always directing me to the right track, not only in my professional career, but also to build a new understanding, open minded, and accepting personality. I will be always indebted to him for all the help and guidance he has been always and still providing me.

Special and very warm thanks to my father Abulmoneam Thabet, who I miss all the time, for all what he did for me to be here writing this dissertation. I will never forget his great support in every stage of my life, especially the moral support he provided me in one of my worst health breakdowns one year before he passed away in 2013.

Very special thanks to my mother Hanadi Ahmed for all her care and prayers. I could not go through a lot of hardships in my life without her prayers that were to give me great confidence that the better will always come.

Many thanks to my wife Jailan Khorsheed for her understanding to the nature of my work as a research assistant. She has been always of great support to me whenever I needed the support, even if I did not ask for it.

Without the support of everyone I mentioned, or even forgot to mention, I would not have been able to see the light at the end of the tunnel when it gets dark in my life. Your existence in my life gave it a meaning. I will always be grateful to God for making you part of my life, without you standing by my side I would not have found the joy in this long yet worthy journey of life.
# TABLE OF CONTENTS

ACKNOWLEDGMENTS .................................................................................................................. iii

LIST OF TABLES .......................................................................................................................... vi

LIST OF FIGURES ...................................................................................................................... vii

ABSTRACT .................................................................................................................................. ix

1. INTRODUCTION .................................................................................................................. 1
   1.1 Overview ......................................................................................................................... 1
   1.2 Society of Automotive Engineers (SAE) J2735 Standard .............................................. 2
   1.3 Research Motivation ....................................................................................................... 4
   1.4 Research Objectives ........................................................................................................ 5
   1.5 Dissertation Outline ........................................................................................................ 6

2. LITERATURE REVIEW ....................................................................................................... 9
   2.1 General Overview of Connected vehicles Technology .................................................. 9
   2.2 Security and Privacy in VANETs ................................................................................. 23
   2.3 Performance Controlling Factors in Connected Vehicles Environments ..................... 25
   2.4 Measures of Effectiveness in Connected vehicles Environments ................................ 29

3. DEVELOPMENT OF CONNECTIVITY ROBUSTNESS MODEL .................................. 35
   3.1 Introduction ................................................................................................................... 35
   3.2 CONnectivity ROBustness (CONROB) Model ............................................................ 36
   3.3 Verification of CONROB ............................................................................................. 47
   3.4 Simulation Results and Analysis .................................................................................. 49

4. TRAFFIC CONDITIONS PREDICTION IN TERMS OF NETWORK CONNECTIVITY ROBUSTNESS .................................................................................................................................. 55
   4.1 Introduction ................................................................................................................... 55
   4.2 Simulation Runs ............................................................................................................ 57
   4.3 Results and Analysis ............................................................................................... 59

5. ROAD-SIDE UNITS DEPLOYMENT ................................................................................ 70
   5.1 Introduction ................................................................................................................... 70
   5.2 Literature Review ......................................................................................................... 72
   5.3 Optimization of RSUs’ Locations ............................................................................... 74
   5.4 Numerical Analysis ..................................................................................................... 76

6. INDIVIDUAL USER PERFORMANCE CHARACTERISTICS ........................................ 83
   6.1 Introduction ................................................................................................................... 83
   6.2 Literature Review ......................................................................................................... 84
   6.3 Methodology ................................................................................................................. 88
   6.4 Results and Discussion ............................................................................................... 100
LIST OF TABLES

Table 3.1: Multiple Regression Analysis Results ................................................................. 54

Table 4.1: Regression Analysis Results (TTEE vs. Connectivity Robustness) ................. 68

Table 4.2: Regression Analysis Results (Standard deviation of TTEE vs. Connectivity
Robustness) ..................................................................................................................... 68

Table 5.1: GA Algorithm Parameters ............................................................................... 77
# LIST OF FIGURES

<table>
<thead>
<tr>
<th>Figure</th>
<th>Description</th>
<th>Page</th>
</tr>
</thead>
<tbody>
<tr>
<td>2.1</td>
<td>Process of Propagation with a Transmission Range L</td>
<td>20</td>
</tr>
<tr>
<td>2.2</td>
<td>Two Possible Cases Relative to the Transmission Range According to Road Separation</td>
<td>20</td>
</tr>
<tr>
<td>3.1</td>
<td>Illustration of CONnectivity ROBustness (CONROB) Model</td>
<td>40</td>
</tr>
<tr>
<td>3.2</td>
<td>Total Connectivity Robustness Calculation for Cluster n</td>
<td>45</td>
</tr>
<tr>
<td>3.3</td>
<td>Study road network</td>
<td>47</td>
</tr>
<tr>
<td>3.4</td>
<td>Clustering and Robustness Calculation Algorithm</td>
<td>50</td>
</tr>
<tr>
<td>3.5</td>
<td>Effect of Traffic Density and Market Penetration on the Connectivity Robustness</td>
<td>53</td>
</tr>
<tr>
<td>4.1</td>
<td>Actual Market Penetration in the Road Network</td>
<td>61</td>
</tr>
<tr>
<td>4.2</td>
<td>Percentage of Links Covered by Connected Vehicles for 154 veh/sq-mile Traffic Density</td>
<td>62</td>
</tr>
<tr>
<td>4.3</td>
<td>Percentage of Links Covered by Connected Vehicles for 236 veh/sq-mile Traffic Density</td>
<td>62</td>
</tr>
<tr>
<td>4.4</td>
<td>Percentage of Links Covered by Connected Vehicles for 333 veh/sq-mile Traffic Density</td>
<td>63</td>
</tr>
<tr>
<td>4.5</td>
<td>Percentage of Links Covered by Connected Vehicles for 481 veh/sq-mile Traffic Density</td>
<td>63</td>
</tr>
<tr>
<td>4.6</td>
<td>Travel Time Estimation Error (TTEE)</td>
<td>64</td>
</tr>
<tr>
<td>4.7</td>
<td>Connectivity Robustness and Travel Time Estimation Error</td>
<td>66</td>
</tr>
<tr>
<td>4.8</td>
<td>Travel Time Estimation Reliability</td>
<td>67</td>
</tr>
<tr>
<td>5.1</td>
<td>GA algorithm for optimal RSU Deployment</td>
<td>76</td>
</tr>
<tr>
<td>5.2</td>
<td>Fitness Values for the Different RSU Scenarios</td>
<td>78</td>
</tr>
<tr>
<td>5.3</td>
<td>Number of Equipped Vehicle Clusters</td>
<td>80</td>
</tr>
<tr>
<td>5.4</td>
<td>Average Percentage Area Covered by Each Cluster</td>
<td>81</td>
</tr>
<tr>
<td>5.5</td>
<td>Connectivity Robustness Results</td>
<td>82</td>
</tr>
</tbody>
</table>
Figure 6.1: LSU Driving Simulator ................................................................. 90
Figure 6.2: Distribution of Controller Information Needs Survey ....................... 92
Figure 6.3: Location of the Information Display ................................................. 94
Figure 6.4: Alert Messages Logic in C++ ......................................................... 95
Figure 6.5: Alert Messages Display ............................................................... 96
Figure 6.6: TTC Profile Plot for Drivers with and without Alert Messages .......... 101
ABSTRACT

The emerging connected vehicle (CV) technology plays a promising role in providing more operable and safer transportation environments. Yet, many questions remain unanswered as to how various user and system characteristics of CV-enabled networks can shape the successful implementation of the technology to maximize the return on investment. This research attempts to capture the effect of multiple factors such as traffic density, market penetration, and transmission range on the communication stability and overall network performance by developing a new CONnectivity ROBustness (CONROB) model. The model was tested with data collected from microscopic simulation of a 195 sq-mile traffic network and showed a potential to capture the effect of such factors on the communication stability in CV environments.

The information exchanged among CVs can also be used to estimate traffic conditions in real time by invoking the probe vehicle feature of CV technology. Since factors affecting the connectivity robustness also have an impact on the performance of traffic condition estimation models, a direct relationship between connectivity robustness and traffic condition estimation performance was established. Simulation results show that the CONROB model can be used as a tool to predict the accuracy of the estimated traffic conditions (e.g. travel times), as well as the reliability of such estimates, given specific system characteristics.

The optimal deployment of road-side units (RSUs) is another important factor that affects the communication stability and the traffic conditions estimates and reliability. Thus, an optimization approach was developed to identify the optimal RSUs locations with the objective function of maximizing the connectivity robustness. Simulation results for the developed approach show that CONROB model can help identify the optimal RSUs locations. This shows the importance of CONROB model as a planning tool for CV environments.
For the individual user performance characteristics, a preliminary driving simulator test bed for
CV technology was developed and tested on thirty licensed drivers. Forward collision warning
messages were delivered to drivers when predefined time-to-collision values take place. The
findings show improved reaction times of drivers when receiving the warning messages which
lend credence to the safety benefits of the CV technology.
1. INTRODUCTION

1.1 Overview

Recently, the development of a fully connected transportation network has received special attention from researchers, federal and state government agencies, and public and private stakeholders. The concept of connected vehicle relies on vehicle-to-vehicle (V2V) and vehicle-to-infrastructure (V2I) communication technologies, which require a robust platform to allow for not only creativity and interoperability, but also the ability to interact with the complex human behavior. In a connected vehicle environment, each vehicle acts as a sender, receiver, and router to broadcast information to the vehicular network or transportation agency. In other words, messages of different types (safety, operational, or others) are exchanged between the vehicles in the network through the V2V application, and between the vehicles and the infrastructure through the V2I application. This information transmission requires a highly efficient and dynamic broadcasting protocol that guarantees a high level of connectivity between the network elements (vehicles and infrastructure). Because of that, many studies have been conducted with the goal of developing an efficient protocol that can cope with the highly dynamic vehicular environment. The most common developed protocol is the Society of Automotive Engineers (SAE) J2735 standard. This protocol deals with the Dedicated Short Range Communication (DSRC) technology that proved to be very effective for similar application to the connected vehicle technology applications. The DSRC is communication channels that provide short-range to medium-range communication with a frequency band of 5.9 GHz. This DSRC band was approved in 2006 to support a vast variety of applications.
1.2 Society of Automotive Engineers (SAE) J2735 Standard

The Society of Automotive Engineers (SAE) J2735 standard is the data dictionary that provides useful information to understand the data frames, data elements, and message sets transmitted by the DSRC. In connected vehicle environments, two main components are dealt with in the information exchange process between vehicles and each other as well as between vehicles and the infrastructure: the On-Board Units (OBUs) and the Road-Side Units (RSUs). The OBUs are data units the vehicles are equipped with to collect data on the vehicle’s activity in the road network. The data collected and stored on the OBU of a vehicle include vehicle latitude, longitude, elevation, speed, brake status, wipers status, vehicle heading, yaw rate, lateral acceleration, longitudinal acceleration, vertical acceleration, among others. These data are collected in the form of data snapshots and stored on the OBU up to a predefined number of snapshots that represents the OBU capacity, or in other words the buffer size. The RSUs, on the other hand, represent the infrastructure component in the connected vehicle V2I application.

The data exchange process between a vehicles and an RSU takes place when the vehicle falls into the communication range of the RSU. In other words, the collected data snapshots on a vehicle’s OBU is transmitted to an RSU when the vehicle falls into the communication range of that RSU. As a vehicle transmits the collected snapshots to an RSU, the OBU is cleared for another turn of data snapshots collection. The collected snapshots from different vehicles in the network go through a data processing and analysis process at the Traffic Management Centers (TMCs) and/or control units in order to monitor the road network performance. Accordingly, decisions are made at the TMC and disseminated through the RSUs to the vehicles in their communication range. The disseminated information may include weather, safety, and routing choice information, among others. This data and information exchange process is performed according to the SAE J2735
protocol using the Dedicated Short Range Communication (DSRC) technology that allows up to 3280 ft (1000 meters) communication range.

1.2.1 Data Snapshots in the SAE-J2735 Protocol

The SAE-J2735 standard allows snapshots collection on a vehicle’s OBU with three distinctive types: periodic snapshots, starts-and-stops snapshots, and event-triggered snapshots. Periodic snapshots represent the vehicle moving in normal conditions. These snapshots are collected at predefined time intervals according to the vehicle speed. In order to have a reasonable representation to the vehicle movement, the time interval of the data snapshots decreases as the vehicle speed decreases. Specifically, the SAE-J2735 standard allows periodic snapshots to be collected every 20 seconds when the vehicle speed is higher than 60 mph (on rural roads), every 4 seconds when the vehicle speed is below 20 mph (on urban roads), and at a linearly interpolated time intervals when the vehicle speed is between 20 and 60 mph. An exception is made for the periodic snapshots when the vehicle speed is zero. In such case, no periodic snapshots are collected; instead, a zero vehicle speed is captured by the starts-and-stops snapshots. Starts-and-stops snapshots are designed to describe the vehicle state when it stops and starts moving again. When a vehicle stops (speed = 0 mph) for five seconds, a stop snapshot is collected. Another stop snapshot is also collected when the vehicle remains stopped for 15 seconds. Then, when the vehicle starts moving with a speed exceeding 10 mph, a start snapshot is collected. Event-triggered snapshots are collected when a changes in the vehicle status elements takes place. Examples of that are traction control changes from off to on and air-bags activation. These snapshots help identifying hazards and situations with safety concerns.
1.2.2 Data Types in Connected Vehicle Environments

The collected snapshots in the SAE-J2735 standard represent two main data types: Probe Data Messages (PDMs) and Basic Safety Messages (BSMs). The information provided in the PDMs only include vehicle locations and speeds. Whereas, the BSMs include, in addition to the vehicle speeds and locations, braking state, emergency braking instances, and acceleration and deceleration values. In some instances, especially at the signalized intersections, when an equipped vehicle is approaching a traffic signal with an installed RSU, the Signal Phase and Timing (SPaT) data are sent to the vehicle to inform the driver about the signal status and timing. This data type allows the driver to make a decision on whether to slow down or speed up according to the remaining green and/or red times and the vehicle’s location relative to the intersection.

1.3 Research Motivation

According to the National Highway Traffic and Safety Administration (NHTSA), connected vehicle technology has the potential to reduce crashes by unimpaired drivers by around 80%. The national statistics show that annual vehicle crashes claim the lives of more than 32,000 and result in 2.3 million Emergency Room visits leading to a loss of 240 billion dollars each year. As such, successful implementation of connected vehicles’ applications will have substantial economic benefits. Moreover, connected vehicle technology has tremendous operational benefits in terms of reducing travel times and delays for the traveling public, as well as environmental impact in terms of reduced vehicle emissions and fuel consumption. The deployment of such technology offers an opportunity for economic development by targeting improvements in the areas of traffic operation, safety, and environmental impacts. Nevertheless, before implementation of such technology, researchers have to first answer several questions on how effective the applications will be and what benefits can be realized prior to implementation, what infrastructure is needed,
what minimum market penetration is required, and what technological specifications should be adopted, in order to address some of the system-wide performance characteristics. In addition, in order to address the individual user performance characteristics of the connected vehicles technology, researchers need to answer questions on how can people benefit from the technology, what are the people needs, what are the expected drawbacks that can result from a distracted driver with a massive in-vehicle amount of information and how could this be dealt with, among others.

Connected vehicle research relies on the use of test beds to address the potential problems associated with the development and deployment of V2V and V2I technologies. Connected vehicle test beds are physical and/or simulation-based platforms that are designed to test the connected vehicle applications. Test beds for connected vehicle research can also be used for testing real time data capture and management systems, as well as testing the integration and interoperability of the equipped vehicles with the technology, mobile devices, and highway infrastructure. Along with the physical platforms for test beds, simulation-based test beds can also be harnessed to achieve similar goals.

1.4 Research Objectives

As discussed in the previous section on the research motivations, there are many questions on the system and user levels that need to be answered before implementing the connected vehicle technology. As such, this doctoral dissertation addresses some of the system wide and individual user performance characteristics of connected vehicles technology. The following objectives will be addressed.

1- Develop a mathematical model for quantifying the robustness of connected vehicle environments (transportation networks with equipped vehicles and infrastructure that enable both V2V and V2I applications of connected vehicle technology) under varying
traffic conditions, market penetration, and transmission range;

2- Test the sensitivity of the developed model to the traffic density, market penetration, and transmission range;

3- Establish a relationship between the developed model and the reliability of the traffic conditions estimates obtained using the connected vehicle data;

4- Investigate the use of the developed model as a performance measure to optimally deploy the RSUs using Genetic Algorithms (GA) optimization tool;

5- Conduct a survey about the type of information people expect and need to have in their cars;

6- Design a test bed for connected vehicle environments in the driving simulator, using the survey results;

7- Measure the potential changes in the driving behavior resulting from the technology using the designed test bed.

It is anticipated that the research findings will provide evidence on the operational and safety benefits of the connected vehicle technology.

This research is implemented over different stages according to the research objectives. As such, the research methodology is broken down and discussed in each of the following chapters according to its research problem. Moreover, the research motivation is elaborated in each chapter based on the objectives achieved in that chapter.

1.5 Dissertation Outline

Chapter 1 of this dissertation presents an introduction about connected vehicle technology, the challenges researchers are trying to overcome, the different components of the technology, and the
communication protocol used in the technology. This chapter also discusses the overall motivation for this research as well as the research objectives.

Chapter 2 introduces a comprehensive literature review about the connected vehicle technology and all its aspects such as, the communication protocols, the different components, the different factors affecting the performance of the technology, and the performance measures used to assess the technology among others.

The remainder of the dissertation is organized according to the objectives of the research. In other words, each of the following chapters complements the preceding one in a hierarchical organization so as to achieve the research objectives.

Chapter 3 introduces a mathematical discussion of developing a connectivity robustness performance metric for connected vehicle environments. In addition, this chapter presents the verification of the developed model using microscopic simulation.

Chapter 4 complements the connectivity robustness model development process by introducing a method to interpret the values resulting from the developed model. In other words, this chapter presents establishing relationships between the connectivity robustness measure and the estimated travel time using the Probe Data Messages (PDMs) collected by the connected vehicles.

Chapter 5 discusses the significance of the connectivity robustness model as a performance measure that can be used as a planning tool for connected vehicle environments. A Genetic Algorithm (GA) approach is developed for the Road Side Units (RSUs) deployment plans with the objective function of maximizing the network connectivity robustness.
Chapter 6 discusses an experimental approach using the driving simulator to investigate the benefits of the connected technology in the context of the drivers’ safety. The developed connected vehicle test bed, the experimental design, and the performed experiments are discussed.

Chapter 7 provides a summary for the research effort and the conclusions of the research.
2. LITERATURE REVIEW

2.1 General Overview of Connected vehicles Technology

Connected vehicle (CV) rely on Vehicle-to-Vehicle (V2V) and Vehicle-to-Infrastructure (V2I) communication technologies. The technological component of CV requires a robust platform that allows for not only creativity and interoperability, but also the ability to interact with complex human behavior. This has become a cutting-edge area of research for more advanced and low cost intelligent transportation systems (ITS). Inter-vehicle communication (IVC) has the potential to link vehicles, transportation infrastructure, and personal mobile devices in a safe and interoperable wireless network, turning the road network into the so called vehicle ad hoc network (VANET), to approach challenging transportation areas such as safety, mobility and environment [1]. In a CV environment, each vehicle acts as a sender, receiver, and router to broadcast information to the vehicular network or transportation agency, which then uses the information to ensure safety and smooth operation of traffic [2]. Most of the currently available traffic information systems still rely on a centralized communication model, where the collected traffic data are sent to a central processing unit before being distributed back to the drivers. This is not only inefficient, mostly because of the delay of information receiving, processing and sending, but also costly because of the high infrastructure cost [3]. This has given rise to an increasing interest in computing and wireless communication in surface transportation systems; an emerging trend is to equip vehicles with computing and communication capabilities. Seven channels in the 5.9GHz band for dedicated short range communication (DSRC) have been allocated and regulated by the U.S. Federal Communications Commissions (FCC) to support the V2V applications [4].
In contrast to the conventional centralized traffic information systems, the V2V systems support the development of a decentralized VANET system. Vehicles in a VANET send and receive messages directly between each other through wireless communication and indirectly with vehicles beyond the transmission range via intermediate ones. Although estimating connectivity a priori is important to help guide specifications of appropriate communication devices, technical problems such as routing protocols, network capacity and message delivery latency are fundamental technology problems in IVC systems [5], and that is yet to be tackled. An ideal IVC system is defined as the connectivity between all CV on the road network with 100% coverage of the road network and a minimal probability of failure. Two groups of factors determine such connectivity: (1) those related to the traffic stream, such as traffic flow (density) and market penetration; and (2) others related to the technology itself such as the transmission range, interference caused by infrastructure, and channel information. Generally, larger transmission range with higher traffic density and higher market penetration allow more vehicles to be connected and information to propagate further on road networks.

The relevant literature on CV technology can be divided into two main categories: one focuses on simulation-based research and the other focuses on analytical studies [4]. Previous studies include networks in one and two dimensions [[6]; [7]; [8]; [9]], and networks where the number of nodes can be finite or infinite (number of vehicles is limited or unlimited) [[4]; [10]]. The focus of most studies is mainly on the expected propagation distance, probability of communication and the critical transmission range. In most instances, it is assumed that communication nodes (vehicles) follow a Poisson distribution on a line or a plane. This means that their locations are independent of each other, and their density is uniformly random at any location. This is not valid for a traffic stream due to interactions between vehicles. Vehicle position depends on car-following
and lane-changing rules and density changes along the roadway due to driver behavior and network geometry [5]. Considering this problem, an analytical model was developed in which positions of vehicles were known through observations, traffic simulators or traffic theories [5].

2.1.1 Vehicle Ad hoc Network (VANET)

Vehicle ad hoc networks (VANETs) turn vehicles into wireless nodes, allowing vehicles in a specific range of each other to communicate and send and receive information, which creates a wireless network of wide range on road networks. Road side units are also used in VANETs in order to fill the gaps between vehicles that a leaving vehicle can create in order to guarantee as continuous communication as possible. For communication to occur between vehicles and road side units in VANETs, vehicles must be equipped with an on-board unit that enables short-range wireless ad hoc networks to be formed. In addition, vehicles must also be fitted with hardware that permits detailed position information to be established such as using Global Positioning System (GPS) device. However, fixed road side units, which are connected to the backbone network, must be in place to facilitate communication. The number and distribution of roadside units is dependent on the communication protocol that is to be used including those located throughout the whole road network, those only at intersections, and those only at region borders. Because of this, it would be unrealistic to require that vehicles continuously have wireless access to road side units.

Possible communication configurations in intelligent transportation systems include vehicle-to-vehicle (V2V), vehicle-to-infrastructure (V2I), and routing-based communications. These types of communications rely on very accurate and up-to-date information about the surrounding environment. Also, they require the use of accurate positioning systems and smart communication
protocols for information exchanging. These protocols must guarantee fast and reliable delivery of information to all vehicles in the vicinity.

It is believed that VANETs have grown out of the need to support the increasing wireless products that can now be used in vehicles [11]. These products include remote keyless entry devices, personal digital assistants, laptops and mobile telephones. As mobile wireless devices and networks become increasingly important, the demand for V2V and V2I Communication will continue to grow [11]. VANETs can be utilized for a broad range of safety, operational, and environmental applications allowing for value added services such as vehicle safety, automated toll payment, traffic management, enhanced navigation, location-based services such as finding the closest fuel station, restaurant or travel lodge and entertainment applications such as providing access to the Internet [3]. In other words, VANETs have the ability to provide drivers with attractive services in two relevant areas:

1. Comfort applications in which drivers’ comfort and traffic mobility are aimed to be improved. This includes traffic information system, weather information, gas station or restaurant location and price information, and interactive communication such as internet access or music download.

2. Safety applications which aim to increase driver safety by exchanging safety information such as emergency warnings, lane-changing assistance information, intersection coordination, traffic sign/signal violation warning, and road-condition warning information. The latter category of applications depends mostly on vehicle-to-vehicle communication because of the strict delay requirements [12]. Safety messages can be categorized into two main types: event driven and periodic. Event driven messages are released as a result of an unsafe situation such as car crash and approaching other vehicles at high speed. On the other hand, periodic
messages (or called beaconing) are also treated as preventive messages in terms of safety and they can be used by non-safety applications such as traffic monitoring. Beacon messages include the state of the sending vehicle in terms of its position, direction, speed, and other information, as well as aggregated information about the state of the neighboring vehicles [13].

In VANETs, as it is clear from the previous discussion, there are two types of communications: V2V communication and V2I communication. Each type has its own characteristics and challenges. In V2I the information transmission is done via single hop broadcast between the roadside unit and all the equipped vehicles that fall in the communication range of that unit. On the other hand, in V2V networks, communication is achieved via multi-hop multicast/broadcast to transmit traffic information over single and/or multiple hops to groups of receiving vehicles. According to Wu et al. [22][8], V2V networks have certain unique characteristics:

1. Predictable high mobility: Vehicles travel on roads at high speeds, this makes their mobility rather regular and predictable, especially with their spatially constrained and limited movement by traffic regulations.

2. Dynamic: The connections between vehicles is changeable because of their high mobility. In addition, because of the obstacles on roads, the wireless communication between vehicles on different roads can be limited except near intersections.

3. Potentially large scale: Because of the communication that can occur between all vehicles, especially at high market penetration, V2V networks can extend to cover an entire road network.

4. Partitioned network: Because high market penetrations are not guaranteed, vehicles on even 1-D networks can be partitioned. Vehicles in one partition can communicate, whereas, there is no direct connection between different partitions.
5. Uncertain network reliability: Vehicles in V2V networks are not totally reliable, as they can fail in different unforeseen ways.

6. Instrumentation capabilities: In vehicle instrumentation requires significant computing, communication, and sensing capabilities. This is not a problem in V2V networks as operating vehicles can afford the required power to handle these requirements.

2.1.2 Message Dissemination, Relay, and Delay

As discussed in the previous section, there are three main types of messages to be disseminated in a VANET with three different levels of priority: event driven safety messages, beaconing safety messages, and comfort messages, and they are prioritized in a decreasing order. Each type has different characteristics and hence a different priority in the broadcasting and dissemination technique [13].

In a VANET hybrid wireless network, when a vehicle moves out of the wireless coverage area of a base station (infrastructure), the vehicle is located in the coverage gap between two adjacent base stations, it will identify and use its neighboring vehicles (if any) as relays to access the roadside infrastructure. As such, for the information to be transmitted between two nodes (vehicle-to-vehicle or vehicle-to-infrastructure) over a specific information path, the information may be transmitted directly between the two nodes or indirectly by relaying via intermediate nodes (i.e. direct access or via hops). As the number of intermediate nodes increase, the delay of information transmission increases so that the information path may be already lost because of the high mobility of nodes. Therefore, many studies tried to study and address this relay and delay issue.

A specific study addressing the relay and delay issue is work done by Blaszczyszyn et al. [14] where they propose an opportunistic routing protocol to be used in broadcast-oriented traffic. The main purpose was to satisfy the limited time constrains and high delivery ratio required by VANET
safety applications because of the multiple relays via movable nodes. The opportunistic broadcast in VANET (OB-VAN) protocol uses a slightly modified 802.11 DCF MAC protocol that enables selecting the best relay amongst the nodes that have received the safety information packet correctly. Simulation results using ns-2 (a communication and networking simulator) prove the ability of the OB-VAN to significantly decrease the delay of packet broadcasting compared to the Simple Flooding Scheme. The results also prove the robustness of the proposed protocol to random errors and that it works efficiently in networks with high traffic densities.

Nzouonta et al. [15] present a class of routing protocols called road-based using vehicular traffic (RBVT). The new protocols influence real time traffic information in order to create road-based paths that consist of successive road intersections that are connected with high probability. RBVT uses geographical forwarding which allows using any node on a road segment between two consecutive intersections to transfer information packets between them, reducing the sensitivity of the information path to individual node movements. The authors designed and implemented two RBVT protocols: a reactive protocol RBVT-R and a proactive protocol RBVT-P and compared them to the other protocols used in mobile ad hoc networks (MANETs) and vehicle ad hoc networks (VANETs). Simulation delivery ratio and average delay results show that the proposed two protocols outperform the existing protocols. More specifically, the RBVT-R gives 40% increase in the delivery ratio compared to the other protocols. Whereas, the RBVT-P give 80% decrease in the average delay of information delivery compared to the other protocols.

Cardote et al. [16] developed a model for the duration of the connectivity periods and the number of relay nodes in each cluster of communicating vehicles. This was conducted considering the transmission of information through a series of relays. To validate their model, the authors used traffic information collected from interstate I-80 by Berkeley Highway Labs (2 from the paper
itself). The results show that the developed model is able to provide key information about the connectivity patterns in a VANET that can help determine the required optimization level of VANET protocols. This can help dealing with the time limitations of VANETs.

In order to overcome the unstable environments in vehicular networks resulting from the high mobility of nodes, Yang and Chih Lo [17] proposed a new efficient street-based broadcast scheme for disseminating and announcing emergency messages in VANETs. The proposed scheme has the ability to disseminate messages along chains of relay nodes without any support of digital maps. The verification experiments results show that the proposed scheme have high delivery ratio, low broadcast overhead, as well as low end-to-end delay. To make their scheme more efficient especially in low density environments, the authors designed the smart relay mechanism that enables vehicles to receive the emergency messages and in an intelligent way relay them to other vehicles. The designed smart relay mechanism is able accomplish high delivery ratio but at some delay time cost, which makes this smart scheme appropriate for sub-emergency message warning.

Delay-tolerant network (DTN) architectures have recently been proposed as a means to enable efficient routing of messages in VANETs, which are characterized by alternating periods of connectivity and disconnection. This solution adopts a model that exploits opportunistic connectivity between vehicles moving in opposing directions to achieve greedy data forwarding [18]. In the absence of connectivity, messages are cached in a vehicle’s memory and travel at the vehicle’s speed. When connectivity is restored, messages are forwarded multi-hop at radio speed, which is typically at least an order of magnitude larger than the vehicle speed [8]. Agarwal et al. [19] developed an analytical model to characterize the average propagation speed of messages over a long distance in a DTN formed over moving vehicles. Through the course of
the analysis, they determined how radio and network parameters, such as the radio range, speed of vehicles, and traffic density in both directions, influence the average message propagation speed. Their study describe that, for a highway model, vehicle traffic density on the roadway is a time-varying quantity. Road traffic statistics and time-series snapshots of vehicular traffic have demonstrated that vehicles tend to travel in clusters on the roadway [[20]; [21]]. The clusters tend to be separated by some distance. Thus, in networking terms, the network is partitioned (the network is composed of disconnected subnets that are partitioned from each other). However, the network topology changes as vehicles travel in opposing directions. Subnets come in intermittent contact with other subnets. Thus, subnets connect and disconnect frequently, leading to time-varying partitioning and a lack of end-to-end connectivity in the network. Once connectivity is achieved, the messages are able to propagate multi-hop over connected relay nodes in either one direction or the other until the next partition is encountered.

Agarwal et al. derived an upper bound, lower bound, and an approximation on the average message propagation speed. Their analysis revealed that the critical threshold of the phase transition depends only on the traffic density in each direction and on the radio range. Thus, through their analysis, they identified the regimes of densities where the delay-tolerant architecture is able to provide significant gains in messaging performance. It was shown that the messaging performance predominantly lies in between two extremes. For sufficiently high traffic density, the network behaves as if it is fully connected and the maximum speed of messaging is achieved. On the other hand, for low traffic density, the network is mostly partitioned, and no gains from delay-tolerant architecture are achievable. These results imply that DTN-based VANET architectures prove most useful at medium traffic densities (20 vehicles/km) and higher [[19]; [20][19]].
2.1.3 Spatial Propagation of Information in VANETs

The relay and delay issue discussed in the previous section sheds the light on how fast and how far can information propagate along a specific road using only V2V communications. The specific V2V network characteristics mentioned before make them significantly different from any other ad hoc network. The End-to-End (E2E) delay due to network partitioning is one of the greatest limitations of V2V networks. Several studies assumed that networks were always connected, thus the E2E delay is calculated by the number of hops and the queuing delay in each hop. However, V2V networks are partitioned networks and the probability of E2E connectivity decreases with distance [21]. It has been reported that vehicle motion can contribute to overcome E2E delay [22]. Thus, Wu et al. [8] studied how vehicle mobility patterns impact information propagation. Although they addressed the problem mainly in the context of V2V networks, their results are also applicable when studying information propagation beyond fixed infrastructure. Their findings include one-way and two-way vehicle traffic scenarios. For a one-way traffic the study reported that a larger relative speed between vehicles leads to quicker “catch-ups”, which represents higher message propagation speed. These models involve dynamics of vehicle traffic like vehicles moving along roads and the fact that slower vehicles are overtaken by faster vehicles. They stated that, in sparse networks, information propagation is approximated as solely depending on vehicle movement. In dense networks, however, information propagation is modeled as a renewal reward process. These models could be used for data dissemination in the way that they can help in selecting the path with lowest delay.

In several studies found in the literature, it is assumed that communication nodes follow a Poisson distribution on a line or a plane. That means that their locations are independent of each other, and their density is uniformly random at any location. This is not valid for a traffic stream
due to interactions between vehicles. Vehicle position depends on car-following and lane-changing rules, and density changes along the roadway due to driver behavior and of network geometry. Facing this issue, Jin and Recker [5] proposed an analytical model to describe multi-hop connectivity in which positions of vehicles were known through observations, traffic simulators or traffic theories. Although the model assumes instantaneous information propagation (a condition that applies for high market penetration), it shows that the distribution patterns of vehicles on road can significantly affect the performance of IVC networks for both uniform and not-uniform traffic conditions. Also, the model is more general than models that assume spatial Poisson distribution of communication nodes and can incorporate fidelity factors like “failure” at each hop. In addition, the model can be extended to calculate the distance between consecutive roadside stations for V2I communications as a supplement of the V2V system.

The information propagation process holds a key for other research such as communication protocol development, routing algorithms, mobile ad hoc grid network computing, all being important to VANET. Although studies on single road propagation have appeared successful in deriving analytical results and gaining insights [5], the ultimate goal is information propagation that is applicable to the general network. The last study [5] is just an example of an extensive literature on information propagation on a single road, but the extension of study into a network of two or more roads is significant. Usually places with dense traffic network and congestion are where inter-vehicle communication is most important. However, a network with two or more roads has challenges to the applicability of results from the single road case and the complexity of network with multiple roads is immense. The complexity in modeling lays on the interaction between the two roads: information could possibly take a detour through the other road because the headway of the next consecutive vehicle is larger than the transmission range of the vehicles.
on the same road, but shorter than the distance between the two parallel roads (Figure 2.1). Wang et al. [23] identified a Bernoulli process to approximate the process of propagation under those circumstances. With that process, they were able to characterize the stochastic (randomly determined) propagation distance in terms of its mean and variance.

![Figure 2.1: Process of Propagation with a Transmission Range L](image1.png)

Two main cases were studied and \( d = \sqrt{(3/2)} L \) was the critical point separating Case I and Case II, where \( d \) was the road separation and \( L \) is the transmission rage as shown in Figure 2.2.

![Figure 2.2: Two Possible Cases Relative to the Transmission Range According to Road Separation](image2.png)

The developed formulas proposed for Case I were robust and accurate for Poisson vehicle distribution especially when the higher density between the two roads was located on R2. The
proposed formulas for Case II where not as accurate as those in Case I, especially when road separation distance was too large [[7]; [24]; [26]]. In a further study, Wang et al. identified a Markov Chain approach that equivalently determines the propagation distance and exact models were proposed.

The great majority of the analytical models focus on propagation distances rather than on propagation time lags. Consequently, they underestimate the potential of V2V communication since the recency (how recent) of information rather than a predicted propagation distance is likely more critical for many applications. Information may still be able to further propagate at the end of the predicted propagation distance due to changes in the traffic composition as time evolves. However, depending on the time lag, the information may or may not remain useful. Moreover, most analytical models in the literature focus on the one-dimensional propagation problem and network effects are not considered [[4]; [23]; [27]]. Ng and Waller presented a network level model to describe the information propagation in VANETs. Upper and lower bounds were developed for the time of information propagation between two nodes in the network (upper and lower bounds on the time lag between any origin-destination pair are obtained by finding the shortest paths in the appropriately defined network). The study stated that the upper bounds did not vary as a function of the penetration rate (as it was expected). Furthermore, they were higher with increased demand levels due to more congestion on the roads. For very low penetration rates, the lower the demand level, the smaller the lower bound was. Thus, for sufficiently low penetration rates (in this case lower than 3%) more traffic on the road does not necessarily promote the fast propagation of information. In other words, the addition of equipped vehicles potentially increases the propagation distances, but due to the lower vehicle speeds, the overall effect might be a worsening of the system performance in terms of time lags. On the other hand, when
penetration rates are sufficiently high (greater or equal than 3%), higher traffic densities could potentially lead to faster information propagation at the network level [4].

A major limitation of the above-mentioned works is that they rely on a simplistic model of radio wave propagation, where vehicles communicate to each other if and only if their separation distance is smaller than a given value (transmission range). In addition, the analysis assumes that all the vehicles in the network have the same transmission range and the effect of randomness present in the radio communication channel is not considered for the analysis.

Chandrasekharan and Anchar [1], from a queuing theoretic perspective, analyzed the connectivity characteristics of a one-dimensional VANET taking into account the effect of channel fading making the transmission range of every vehicle a random variable. Three fading models were considered for the analysis: Rayleigh, Rician, and Weibull. By assuming vehicle speed to be a random variable (with truncated Gaussian probability distribution), the authors presented the dependence of vehicle speed statistics (mean ($\mu_v$) and standard deviation ($\sigma_v$)) and average vehicle density ($\rho_{av}$) on the connectivity characteristics such as connectivity distance and platoon size (number of vehicles in a connected spatial cluster).

It was found that shadow fading (vehicle behind an obstruction experiencing a significant reduction in signal power) standard deviation had positive impact on both connectivity distance and platoon size, improving the connectivity performance of VANETs. It was also observed that both $\mu_v$ and $\sigma_v$ had a significant impact on them. For a fixed $\mu_v$, the $\rho_{av}$ increased as the $\sigma_v$, which improved connectivity distance and platoon size. On the other hand, for a given value of $\sigma_v$, $\rho_{av}$ decreased as $\mu_v$ increased, resulting in degradation of connectivity distance and platoon size.

In V2V communication, due to the relatively low elevation of the antennas on the communicating vehicles, it is reasonable to expect that other vehicles will act as obstacles to the
signal, often affecting propagation even more than static obstacles like buildings or hills, especially in the case of an open road. Not modeling the vehicles as obstacles may lead to unrealistic assumptions about the physical layer and have significant implications on the behavior of the upper layers of the protocol.

Boban et al. [24] proposed a model that accounts for vehicles as three-dimensional obstacles and considers their impact on the line-of-sight (LOS) obstruction, received signal power, and packet reception rate. Vehicles speed, locations and dimensions were obtained from two real world highway data sets via stereoscopic aerial photography and the antenna was assumed to be located on top of the vehicles in the middle of the roof. For both highways (dense and sparse), it was clear that the impact of other vehicles as obstacles should not be neglected. Even for vehicles that are relatively close to each other (100 m), there is a non-negligible 15% probability that the vehicles will not have LOS while communicating and those LOS conditions will remain largely unchanged for at least a couple of seconds. In addition, the obstructing vehicles decreased the received signal power and that received power was highly variable even for relatively short distances between communicating vehicles. These results suggest that the effect of vehicles as obstacles cannot be neglected even in the case of relatively sparse vehicular networks.

2.2 Security and Privacy in VANETs

In VANETs there are two main issues that need to be addressed in their design: security, and privacy. The notion of security (trust) among different agents is an important issue among others that may arise in VANETs, as there might be some fake messages that can disrupt the traffic or create dangerous (life threatening) situations [[25]; [26]]. The goal of incorporating trust is to give incentives for these agents to behave honestly and to discourage self-interested behavior. Modeling trustworthiness of agents in VANETs presents some unique challenges. First of all, on
a typical highway (average speed of 60 mph) the time to react to an imminent situation is very critical; therefore, it is very important for the agents to be able to verify/trust incoming information very quickly. Second, the number of agents can become very large creating network congestion. Also, information about road condition is rapidly changing in VANET environments (a road might be congested 5 min ago, but now it is in free flow state) making it hard to detect if the agent spreading such information is malicious or not [26].

Since trusting in the data received from another vehicle agents in VANETS can potentially become a question of life and death, Minhas et al. [26], developed a framework that models the trustworthiness of the agents of other vehicles in order to receive the most effective information. The model incorporates trust based on role, experience, priority and majority and it is able to restrict the number of reports received. Based on the model, the authors reported that average speed of vehicles is reduced when malicious nodes (vehicles reporting congestion when there is none) are added to the network. However, it increases when the trust models are added and increases even more when authority agents, which are considered to be trustworthy, are added to the network. There has been significant effort in the same context to address that trustworthiness issue [e.g. [26]; [27]; [29][28]; [29]; [30]; [31]; [32]].

Privacy is also an important issue in VANETs that needs to be addressed in the early design stages. The information transmission should be done anonymously in order to make vehicle tracking by untrusted parties impossible. Failure in addressing this issue in VANET design may lead to life threatening situations should be avoided. Therefore, there has been too many studies that addressed that issue through coming up with broadcasting techniques that can preserve privacy [e.g. [33]; [34]; [35]; [36]; [37]; [38]].
The privacy issue was also accounted for in the SAE-J2735 standard by introducing the Probe Segment Number (PSN). Each OBU of a vehicle in the network is assigned an identification number, referred to as PSN. This number is dynamically changing every 120 seconds or 3280 ft whichever is achieved last. This allows a transmitted set of snapshots not to have the same PSN, and hence tracing a specific vehicle is impossible which maintains the vehicle’s privacy.

2.3 Performance Controlling Factors in Connected Vehicles Environments

The performance of connected vehicles environments is controlled by two main groups of factors: (1) factors related to the traffic stream, such as traffic flow (density) and market penetration; and (2) factors related to the technology itself such as the transmission range and signal strength, and channel information. In the following sections some of the studies that addresses these factors are summarized.

2.3.1 Traffic Density

Traffic density is one of the very important controlling factors that can determine how efficient the communication between vehicles (relay nodes) in VANETs. Traffic density determines the number of relay nodes, whether the VANET is partitioned or not, and if it is partitioned, the size of each partition. There are three different traffic regimes that determine the operational characteristics of VANETs: dense traffic, sparse traffic, and regular traffic regime. Studying the characteristics of each regime is very important as it determines the efficient broadcast protocol that can deal with all regimes.

In dense traffic conditions, the most serious problem is what is so called the broadcast storm problem [3]. This is caused by the excessive number of broadcasts for the same safety message by several consecutive vehicles. In such scenario there is a possibility of losing some important
safety messages because of the high level of contention and collisions at the shared wireless medium \([38]; [39]\). In that context, there have been several attempts to solve and mitigate the broadcast storm problem by proposing new broadcasting techniques \([e.g. \[1\]; \[7\]; \[8\]; \[39\]; \[40\]\].

In sparse traffic conditions, on the other hand, it might become so difficult for a broadcasted message from some vehicle to be transmitted to other vehicles. In this case the target vehicles might be out of the transmission range of the source vehicle so that the multi-hop relaying becomes unlikely to happen in such traffic condition. This is even worse when there are no vehicles on the opposite direction in the road so that broadcasting becomes a very challenging task \([39\]. Several studies tried to address this problem through coming up with broadcasting techniques that can deal with that problem \([e.g. \[7\]; \[8\]; \[13\]; \[41\]; \[42\]; \[44\]\].

In any of the previous two regimes, the predominant traffic condition is either the dense traffic condition or the sparse traffic condition. This makes the broadcasting task easier as it will be via the broadcasting scheme that can work with the predominant traffic condition. In regular (mixed) traffic regimes, some vehicles may be in a part of the road experiencing sparse regimes while other vehicles may be in a part of the road experiencing dense traffic condition. More so, short term topology change is always taking place in road networks with regular conditions. More specifically, one vehicle may be moving in a sparse condition and later it becomes moving in a dense condition. In such mixed case, the traffic condition is detected and then the suitable broadcasting scheme is used \([38]; [39]\).

2.3.2 Market Penetration

Feasibility of a cooperative VANET system requires certain number of vehicles equipped with a communication device (market penetration). This is required in order to complete the end-to-end information broadcasting over the different relay nodes in the network. This way, traffic
management and entertainment applications can be deployed safely. According to the USDOT, there were around 240 million registered vehicles in the U.S. in 2006, while the annual nationwide vehicle production is around 16 million vehicles. Assuming an ideal case that all the new vehicle production is DSRC-equipped vehicles, the initial application of the technology will be with around 7% market penetration. This means that to reach 100% market penetration, it will take around 15 years after the first application of the technology. In such situation, the designed broadcasting mechanism in VANETs should be able to handle the various levels of market penetrations properly. In that context, many studies tried to address the broadcasting issue at different market penetration scenarios. Most of the studies agreed on that the performance of VANET systems at low penetration could be critical. However, considering the numerous challenges of ad hoc networking where nodes and traffic patterns are arbitrarily located, the vehicle (node) movements are somewhat predictable in VANETs. This leads to increasing the connectivity and reducing the critical penetration requirements. Despite some studies were able to come up with broadcasting mechanisms that can deal with low penetration levels without the need for any infrastructure, the infrastructure is still considered a support for backbone connectivity assisting VANETs as it can significantly reduce the critical penetration needs required to satisfy the connectivity requirements of safety and management applications.

2.3.3 Transmission Range

Transmission range is one of the most important factors that determine the efficiency of the communication in VANETs. It, on par with the traffic density and market penetration, determines if the network is partitioned (clustered) or not. A vehicle’s transmission range is determined by the transmission power of the wireless channel in the equipped vehicle, which in turns determines
the topology of the communication network. The topology of any ad hoc wireless network, which is the set of the communication pairs of nodes require information packets transmission, depends upon two sets of factors: (1) uncontrollable factors, such as nodes mobility, weather condition, interference, and noise; (2) controllable factors, such as transmission power and antenna direction [54]. Therefore, one of the main issues in ad hoc networks is the power management.

For more details about the topology, in dense vehicular environments, the transmission coming out of vehicles could be disrupted by each other creating a high competition between vehicles for the radio transmission resources and reducing the average of radio capacity per vehicle [13]; [25]). It was reported that as the density goes up to the jam density, the interference between the transmissions coming out of the different vehicles can cause a reduction in the reliable transmission range that may go up to 90% [55]; [58]). For the sparse vehicular environments, vehicles are highly likely to be isolated and form isolated clusters [13]; [25]; [26]). In order to deal with the different scenarios that result in different topologies, the key factor is the transmission power.

According to the vehicular scenario, the transmission power is selected in order to have a reasonable transmission range that covers a specific area within which the number of neighboring vehicles is kept between a maximum and minimum thresholds that result in an optimum topology [56]. In that context also, there have been significant effort to address the power management issue [e.g. 0; [54]; [57]; [58]; [59]; [60]]. The main objective of most of these studies was to select the transmission power, and in turns the transmission range, that covers a specific number of nodes within a predetermined threshold in order to result in an optimum topology. Most of these studies were based on 100% market penetration scenario, some other studies were based
on removing redundant nodes, while other studies were based on high penetration rates scenarios in order to reach the optimum topology.

The selected transmission range according to the vehicular scenario is a ratio of the maximum transmission of the equipped vehicle. The maximum transmission range, also called the practical transmission range, is determined based upon surrounding conditions to the vehicle. This can be calculated according to (2.1) [61].

\[ R = T_r \cdot (1 - \epsilon); \quad 0 < \epsilon \leq 1 \]  

Where \( T_r \) is the absolute maximum transmission range of the wireless channel and the parameter \( \epsilon \) refers to the wireless channel fading conditions at the vehicle position. This simplified equation reflects the practical transmission range according to the surrounding conditions to the vehicle that can affect the maximum transmission range \( T_r \) of that vehicle. The value of \( \epsilon \) change according to the area type (downtown or suburbs). In downtown areas, for instance, the high rise buildings, industries, and other installations, will interfere with the wireless signals of the vehicles. In such case, the value of \( \epsilon \) will be high so that the practical transmission range might be far less than the maximum value. On the other hand, in the suburbs, the obstacles are fewer and hence the interference with the wireless signals is much less resulting in a small value of \( \epsilon \). In such case the value of the practical transmission range is very close to the maximum value [61].

2.4 Measures of Effectiveness in Connected vehicles Environments

Vehicular Ad-hoc networks are a rapidly emerging, promising, challenging, and self-organized communication technology that is taking place in the near future. It is aiming at using the moving vehicles as a basis for safety and comfort information transmission in order to have a highly operable and safe transportation environment. In VANETs, the information transmission is taking
place between nodes (vehicles) with high mobility and also limited degrees of freedom that is
determined by the transportation network and the surrounding vehicles. Therefore, a highly
efficient and dynamic broadcasting protocol that guarantees a high connectivity is required.
Because of that, many studies were conducted to come up with an efficient protocol that can cope
with the highly dynamic vehicular environment. Yet, a proper performance metric is required to
assess the performance of VANETs. In that context, there has been a significant effort to come up
with some performance metrics for VANETs [e.g. [3]; [6]; [59]; [60]; [61]; [62]; 0; [64]; [65]].
These studies are concerned about the connectivity probability, the healing time after a
connectivity failure, the delay in message delivery, or the traffic delay time or other traffic metrics.
In the following, a summary of some of these studies is discussed.

Panichpapiboon and Pattara-atikom [6] presented a theoretical framework for analyzing the
number of vehicles required for distributing the traffic information in a self-organizing vehicular
network. Their analysis allowed them to determine the critical transmission range for a particular
connectivity level. One and two-way street scenarios were considered while considering the
important physical factors, such as fading, propagation path loss, transmit power, and transmission
data rate.

From the network layer perspective in one way streets, network connectivity depends on the
transmission range of each vehicle and the penetration rate. According to that, the authors
developed an equation that describes the relationship among the three important design parameters,
which are the connectivity probability (P_c), transmission range (\( z \)), and node spatial density (\( \rho \),
penetration rate)

\[ P_c = \prod_{i=1}^{N-1} Pr\{X_i \leq z\} = (1 - e^{-pz})^{N-1} \quad (2.2) \]
Where $X_i$ is the distance between consecutive vehicles and $N$ is the total number of equipped vehicles. For a given transmission range, the connectivity probability increases as the penetration rate increases. In other words, the higher the number of equipped vehicles on the road segment, the higher the chance of having a connected network.

Using this model, the critical transmission range for a specific connectivity probability can be determined for the design purposes as in (2.3).

$$z_c = -\frac{1}{\rho} \ln \left( 1 - P_c^{\frac{1}{N-1}} \right)$$  \hspace{1cm} (2.3)

Connectivity probability on the one-way street of less than 1 means that it is possible that the network may have more than one cluster. In other words, instead of having a single connected cluster in the network, there might be some broken links, which are links with length greater than the transmission range, splitting the network into multiple clusters. However, it is possible to take advantage of the vehicles on the opposite lane, in two-way streets, by a forwarding strategy usually referred to as store–carry–forward routing. The connectivity probability in the two-way street scenario with store–carry–forward routing can be written as in (2.4).

$$P_{c,2-way} = \sum_{j=0}^{N-1} P_{cl|j}(j) \cdot P_j(j)$$  \hspace{1cm} (2.4)

Where,

- $P_{cl|j}(j) = (1 - P_{nf})^j$, $j = 0, 1, 2 ..., N - 1$ is the Connectivity Probability that there are $J$ broken links,
- $P_{nf} = plk(0) = e^{-2z\rho_o}$ is the Probability that a broken link is not fixable,
- $P_b = Pr[X_i > z] = e^{-\rho z}$ is the Probability that a link is broken, and
- $P_j(j) = \binom{N - 1}{j} p_b^j (1 - p_b)^{N-1-j}$ is the Probability that $J$ of them will be broken.
The authors also described the connectivity from the physical layer perspective where characteristics of the wireless channel and other factors such as transmit power, transmission rate and propagation path loss are taken into consideration. This analytical framework is meaningful in designing and developing a self-organizing distributed traffic information system. It provides a deep understanding about the relationship among various system parameters and suggests how to appropriately select each of them.

Basics from traffic theory have been also applied to IVC systems. Yousefi et al. [66] studied the three macroscopic parameters that describe the state of a road (speed, density, and flow) analytically describing the connectivity of VANETs operating in the free-flow regime. To have a better understanding of the connectivity in VANETs, the authors investigated the connectivity by numerically evaluating the model proposed. The connectivity problem was studied in low-density traffic, which corresponds to the free-flow state. In the free-flow state, the traffic flow is usually considered to be below 1000 veh/h/lane for freeways and below 500 veh/h/lane for other roads. Moreover, although the proposed transmission range for the DSRC standard is 1000 m, the range used was 800 m and the traffic flow values below 1000 veh/h. Furthermore, it was assumed that the vehicles’ speed was normally distributed, which also holds in the free-flow state. Based on the model, the study suggests that when the transmission range increases, the expected value of the connectivity distance increase. When the transmission range is sufficiently large (greater than 500 m), even if the transmission range slightly increases, the expected values of the platoon size and connectivity distance noticeably increase and larger platoon sizes and larger connectivity distances are more probable. In addition, the study states that when the traffic flow increases, the tail probability of the connectivity distance and the average connectivity distance increase. For sufficiently large traffic flows (greater than 600 veh/h), the expected values of the platoon size and
connectivity distance are noticeably improved by increasing the traffic flow and larger platoon sizes and connectivity distances are more likely to be observed. However, the study concluded that, for a fixed traffic flow and vehicles’ transmission range the expected value of the connectivity distance decreases if the velocity increases [3].

Spanos and Murray [67] developed the geometric connectivity robustness model to measure the connectivity robustness between CV in terms of their freedom of movement relative to each other. The geometric connectivity robustness model measures the freedom vehicles can move relative to each other and maintain the two way communication. The model calculates what is so called path robustness \( P(i, j, k, \ldots) \) for each vehicle (i), where i is directly connected to j and j is directly connected to k and so forth. It considers one path at a time, starting from a vehicle (i), along which information is being transmitted, and then for each two successive vehicles along this path, the freedom of vehicles to move relative to each other is calculated by

\[
P(i, j) = \min_{j \in N_C(i)} \{r_i, r_j\} - d_{ij} \tag{2.5}
\]

Where \( r_i \) and \( r_j \) are the transmission ranges for vehicles i and j, \( d_{ij} \) is the distance between the two vehicles, and \( N_C \) is the communication network (i.e. the direct communications between vehicles). The minimum over the transmission ranges is to guarantee two-way communication between the two vehicles.

The freedom of movement is then calculated for each pair of vehicles along the selected path. In the end, the path robustness is calculated as the minimum difference along that path using

\[
P(i, j, k, \ldots) = \min_{N_C(i)} \left\{ \min_{j \in N_C(i)} \{r_i, r_j\} - d_{ij}, \min_{k \in N_C(i)} \{r_j, r_k\} - d_{jk} \right\} \tag{2.6}
\]
This is repeated for all possible paths starting from vehicle i. The geometric connectivity robustness is then calculated for vehicle i by

$$R_i(i) = \frac{1}{2} \min_{j \in N_i(i)} \max_{k \in N_C(i)} P(i, j, k)$$  \hspace{1cm} (2.7)

Where $R_i(i)$ is the geometric connectivity robustness for vehicle (i) and $N_i$ is the information network (i.e. all information transmission paths direct or indirect with hops). The maximum over the communication network is to guarantee the existence of communication along at least one path. That is to account for the possibility of the $P(i, j, k, \ldots)$ value to be negative if there is a partial communication along a specific path. The minimum taken over the information network is to identify whether vehicle i is connected and can transmit information to all other CV in the network. $R_i(i)$ is obtained by dividing the path robustness by two in order to split the available freedom of movement equally between the two vehicles. The connectivity exists between all vehicles if $R_i(i)$ is positive; the larger the value of $R_i(i)$, the more robust the connectivity.
3. DEVELOPMENT OF CONNECTIVITY ROBUSTNESS MODEL*

3.1 Introduction

Connected vehicle (CV) is an emerging technology that gained the attention of many researchers over the past few years. The promising features of such technology are expected to provide a safer and highly operable transportation environment. Nevertheless, many technology-related and operational issues are being investigated in order to gain the expected benefits of the CV technology. One of the issues being investigated is studying the impact of the different factors that can affect the performance of connected vehicle environments (a transportation network with connected vehicles). Two groups of factors determine such connectivity: (1) those related to the traffic stream, such as traffic flow (density) and market penetration; and (2) others related to the technology itself such as the transmission range, interference caused by infrastructure, and channel information.

There have been many attempts to come up with a performance measure that can explain the effect of each of the aforementioned factors on the CV technology’s system wide performance characteristics. However, there is no clear measure of the robustness and stability of a CV environment that accounts for the combined effect of such factors. Thus, this chapter presents a mathematical model that gives an indicator to the robustness and stability of the connectivity between CV on large scale road networks. This model accounts for more than one controlling factor affecting the connectivity in CV environments.

3.2 CONnectivity ROBustness (CONROB) Model

CONROB combines Newton’s law of universal gravitation and the Geometric Connectivity Robustness model, previously developed by Spanos and Murray [67]. Connectivity robustness is considered a measure for the stability of existing communications between connected vehicles as well as the potential of the disconnected vehicles to reconnect again and cover a significant area of the road network. In the next section, the geometric connectivity robustness model is presented to point out the reason for developing the CONROB model, then the derivation of CONROB model is discussed.

3.2.1 Geometric Connectivity Robustness Model

The geometric connectivity robustness model measures the freedom vehicles have to move relative to each other without losing the two way communication between one another. The model calculates what is so called path robustness $P_{i,j,k,...}$ for each vehicle (i), where i is directly connected to j and j is directly connected to k and so forth. It considers one path at a time, starting from a vehicle (i), along which information is being transmitted, and then for each two successive vehicles along this path, the freedom of vehicles to move relative to each other is calculated by

$$P_{i,j} = \min_{j \in N_C(i)} \{r_i, r_j\} - d_{ij} \quad (3.1)$$

Where $r_i$ and $r_j$ are the transmission ranges for vehicles i and j, $d_{ij}$ is the distance between the two vehicles, and $N_C$ is the communication network (i.e. the direct communications between vehicles). The minimum over the transmission ranges is to guarantee two-way communication between the two vehicles.

The freedom of movement is then calculated for each pair of vehicles along the selected path. Then, the path robustness is calculated as the minimum difference along that path using
\[ P_{i,j,k,\ldots} = \min_{N_c(i)} \left\{ \min_{j \in N_c(i)} \{ r_i, r_j \} - d_{ij}, \min_{k \in N_c(i)} \{ r_j, r_k \} - d_{jk} \right\} \] (3.2)

The minimum of the differences in (3.2) is obtained to detect any one way communication or disconnection between at least two vehicles along the selected path. This is repeated for all possible paths starting from vehicle \( i \) to all other vehicles. The geometric connectivity robustness is then calculated for vehicle \( i \) by

\[ R_i(i) = \frac{1}{2} \min_{j \in N_i(i)} \max_{k \in N_c(i)} P(i, j, k) \] (3.3)

Where \( R_i(i) \) is the geometric connectivity robustness for vehicle \( i \) and \( N_i \) is the information network (i.e. all information transmission paths direct or indirect with hops). The maximum taken over the communication network is used to detect the existence of communication along at least one path. This is because a negative \( P_{i,j,k,\ldots} \) value means all paths have either partial or no communication. The minimum is taken over the information network to identify whether vehicle \( i \) is connected and can transmit information to all other CV in the network. As shown in (3.3), \( R_i(i) \) is obtained by dividing the path robustness by two in order to split the available freedom of movement equally between each two vehicles. In this model, the connectivity exists between all vehicles if \( R_i(i) \) is positive. More so, larger values of \( R_i(i) \) imply higher connectivity robustness.

The connectivity robustness defined in (3.3) is measured in distance units such that large distance implies more freedom for the vehicles to move without losing the connectivity, and hence higher connectivity robustness. This model accounts for the transmission range and the spatial distribution of vehicles relative to each other in the network. However, the model in its present form does not account for critical factors such as market penetration, traffic density, and the spatial propagation of the wireless signal over the road network. Therefore, the CONROB model is
developed to account for those factors in order to give a reliable and more representative measure of the connectivity robustness. The proposed model is presented in the next section.

3.2.2 CONROB Model

The ideal condition in a CV environment is realized when information about the entire road network can be transmitted between all vehicles. This occurs when all CV occupying the network are connected to each other such that the entire area of the road network is covered. Unfortunately, this is impractical since the market penetration for CV is expected to be far less than 100%. Also, it is highly unlikely that the spatial distribution of CV in the road network will ensure full connectivity at all times. Therefore, given the expected limited spatial distribution of CV and the low market penetration, communication between CV will likely be limited to groups or clusters of vehicles. These clusters are formed based on the relative spatial distribution of CV, the market penetration, the transmission range, and the number of vehicles per square kilometres (traffic density) determined by traffic demand.

For a road network with clusters of CV, connectivity between vehicles is expected to become more robust as clusters get closer to each other and merge into fewer clusters resulting in larger area of the network to be covered. Ideally, maximum robustness is achieved when all clusters merge into one cluster with enough CV to cover the entire road network area. This case minimizes the probability of connectivity failure, which is affected by a set of controlling factors such as the ratio of CV in the network (market penetration), the traffic density, the relative spatial distribution of CV, and the spatial propagation of the wireless network.

According to Newton’s law of universal gravitation, any two objects experience an attraction force that is directly proportional to the mass of each object and inversely proportional to the distance between them [68]. The force is estimated by
\[
F = \frac{G M_1 M_2}{d^2}
\]  
(3.4)

Where \(M_1\) and \(M_2\) are the masses of the two objects, \(d\) is the distance between them, and \(G\) is the universal gravitation constant.

Similarly, CV clusters can be treated as objects experiencing an attraction force between each other that tries to merge them into one cluster (see Figure 3.1). This force can be assumed to represent the connectivity robustness measure \((R)\) between pairs of clusters. As two clusters move closer to each other, the likelihood that they will merge into one cluster increases, which increases the connectivity robustness. Accordingly, the connectivity robustness \(R\) between any pair of clusters \(n\) and \(m\) can be defined by

\[
R = \frac{C M_n M_m}{d_{n,m}^2}
\]  
(3.5)

The parameter \(d_{n,m}\) is a surrogate measure for the resistance clusters \(n\) and \(m\) have to overcome in order to merge in one more robust cluster. This resistance decreases as the distance between the two clusters decreases and as the transmission range of vehicles in both clusters increases. Based on that, \(d_{n,m}\) is measured as the ratio between the minimum distance \(d_{i,j}\) separating two vehicles \(i\) (in cluster \(n\)) and \(j\) (in cluster \(m\)) to the minimum transmission range of both vehicles \((r_i\) and \(r_j\)) to ensure two-way communication between them. This distance is mathematically calculated by

\[
d_{n,m} = \frac{\min_{i \in N_n \& j \in N_m} d_{i,j}}{\min_{i \in N_n \& j \in N_m} \{r_i, r_j\}} + 1
\]  
(3.6)

Where \(N_n\) and \(N_m\) are the number of CV within clusters \(n\) and \(m\), respectively. This is the distance vehicles in one cluster have to travel toward the vehicles in the other cluster in order for
the two clusters to merge into one, which is more likely to happen as the transmission range increases for the same distance $d_{i,j}$. Adding 1 in (3.6) ensures that $d_{n,m} \geq 1$, and, consequently, sets the boundaries of the connectivity robustness to be $0 \leq R \leq 1$.

Figure 3.1: Illustration of CONnectivity ROBustness (CONROB) Model

The larger the number of clusters, the more deviated the case is from the ideal, and the lower is the connectivity robustness. To account for this, the factor $C$ is used as an adjustment factor and as an indicator for the weakness or strength of connectivity between CV in the network area. It is measured by the inverse of the total number of clusters $N_K$ in the network area, where the subscript $K$ refers to the cluster number. In other words, as the number of clusters increases, for the same number of vehicles in the network, these vehicles become distributed between more disconnected clusters, and hence more areas in the network may lose connectivity, resulting in a decrease in the overall connectivity robustness. Mathematically, $C$ can be expressed by

$$C = \frac{1}{N_K}$$  \hspace{1cm} (3.7)
$M_n$ and $M_m$ are surrogate measures for the masses of the two clusters. The cluster mass, $M$, is determined by the local connectivity robustness within the cluster and its contribution to the connectivity robustness between that cluster and any other cluster in the network. Hence, the mass $M_n$ for a cluster $n$ is measured by

$$M_n = \frac{LR_n}{\min\{r_i\}} \cdot \left(\frac{N_n}{N_T}\right)^{0.5} \cdot \left(\frac{a_n}{A}\right)^{0.5} \quad (3.8)$$

Where $LR_n$ is the local robustness of cluster $n$, $N_n$ is the number of CV in cluster $n$, $N_T$ is the total number of vehicles in the network, $a_n$ is the connectivity area coverage by the CV in cluster $n$, and $A$ is the total surface area of the network. The ratios $N_n/N_T$, which is determined by the market penetration in the network and represents the market penetration when all vehicles in the network are communicating in one cluster, and $a_n/A$, which represents the spatial propagation of the wireless signal in cluster $n$ relative to the total area of the network, account for the contribution of the local robustness value to the connectivity robustness between cluster $n$ and any other cluster. This in turns represents the contribution of cluster $n$ to the connectivity robustness in the entire network. For one cluster that covers a small area or has a small number of CV in a large scale network, these two ratios may give very small values that result in significantly small connectivity robustness values; therefore, in order to get reasonable connectivity robustness values, the square root of each ratio is used. As these two ratios increase, the effect of the local robustness on the connectivity robustness over the entire network increases. This effect is maximum when the values of $N_n/N_T$ and $a_n/A$ reach 1, in which case this cluster contains all vehicles in the network, at 100% market penetration, and the spatial propagation of the wireless signal extends to cover the entire network area, providing 100% connectivity area coverage.
The local robustness in the CONROB model is derived from the geometric connectivity robustness model defined in (3.3). In this model, the concept of using the minimum difference over the communication network to obtain the freedom of movements vehicles have, might not be representative of the connectivity robustness among all vehicles, as there might be a case in which that minimum difference happens only once between two vehicles in the network while all other vehicles have larger freedom of movement. To overcome this limitation, the average of the differences between the minimum transmission range of each two directly connected vehicles and the distance separating them is used to represent the spatial distribution of all vehicles relative to one other, as shown in (3.9).

\[
LR_n = \frac{1}{2} \sum_{i=1}^{N} \sum_{j=i+1}^{N} \frac{\min_{i,j\in N_n} \{r_i, r_j\} - d_{ij}}{N_n}
\]  
(3.9)

Based on the previous discussion and by plugging the different parameters in the CONROB model, the connectivity robustness between two clusters \(n\) and \(m\) in a road network is determined by

\[
R_{n,m} = \frac{1}{N_K \left( \frac{LR_n}{m_{\min} \{r_i\}} \left( \frac{N_n}{NT} \right)^{0.5} \left( \frac{a_n}{A} \right)^{0.5} \right) \left( \frac{LR_m}{m_{\min} \{r_j\}} \left( \frac{N_m}{NT} \right)^{0.5} \left( \frac{a_m}{A} \right)^{0.5} \right)} \left( \frac{m_{\min} \{d_{i,j}\}}{\min_{i\in N_n, j\in N_m} \{r_i, r_j\} + 1} \right)^2
\]  
(3.10)

3.2.3 Properties of CONROB

CONROB model is a dimensionless measure that has two extreme cases that take place at zero and 100% market penetration values. The first extreme case, zero market penetration means no connectivity in the network and hence a zero connectivity robustness value. The second extreme case occurs when the market penetration value is 100% provided that the traffic density and spatial distribution of the vehicles allow 100% connectivity area coverage (the entire road network area
covered by the wireless communication). In this case, vehicles are all connected to form one cluster that has a good communication stability between vehicles. In order to calculate the connectivity robustness for the latter one cluster case, knowing that CONROB model requires having two clusters to be used, this one cluster is virtually treated as two clusters with a zero separating distance. Thus, the robustness for that cluster is measured by

\[
R_{n,n} = \frac{1}{N_K} \left( \frac{LR_n}{\min\{r_l\}} \left( \frac{N_n}{N_T} \right)^{0.5} \left( \frac{a_n}{A} \right)^{0.5} \right) \left( \frac{LR_n}{\min\{r_l\}} \left( \frac{N_n}{N_T} \right)^{0.5} \left( \frac{a_n}{A} \right)^{0.5} \right)
\]

(3.11)

Hence, this equation can be formulated as

\[
R_{n,n} = \frac{1}{N_K} \left( \frac{LR_n}{\min\{r_l\}} \left( \frac{N_n}{N_T} \right)^{0.5} \left( \frac{a_n}{A} \right)^{0.5} \right)^2
\]

(3.12)

In this case, one cluster that has all vehicles in the network with 100% market penetration, the ratio \( N_n/N_T \) becomes 1. In addition, the 100% connectivity area coverage condition in the road network required for this extreme case makes the ratio \( a_n/A \) also 1. More so, the value of \( 1/N_C \) is 1 as the number of clusters \( N_C \) is 1. In this case, when the market penetration reaches 100%, the distances between vehicles keep decreasing as the traffic density on the roads in the network increases, until jam density is, theoretically, reached everywhere in the network. In such an extreme case the distances between vehicles is the minimum headway distances that is not likely to change much in a short period of time. In other words, changes in distances between vehicles will be minor so that it will not affect the local connectivity robustness value \( LR_n \). Therefore, the local robustness and the unity of the one cluster, in this extreme case, will be controlled by the
minimum communication range in the road network; hence, $R_{1,n}$ will be calculated as $0.5[\min(r_{1,n})]$. Accordingly, the connectivity robustness formula will be as in (3.13).

$$R_{n,n} = \left( \frac{0.5 \cdot \min[r_i]}{\min[r_i]} \right)^2$$

(3.13)

This yields a robustness value of 0.25. To set the boundaries of the model between 0 and 1, the original mathematical model is multiplied by 4 to yield

$$R_{n,m} = \frac{4}{N_{K}(t)} \left( \frac{L_{R_n}(t) \cdot \left( \frac{N_n(t)}{N_T(t)} \right)^{0.5} \cdot \left( \frac{a_n(t)}{A} \right)^{0.5}}{\min[r_i]} \right) \left( \frac{L_{R_m}(t) \cdot \left( \frac{N_m(t)}{N_T(t)} \right)^{0.5} \cdot \left( \frac{a_m(t)}{A} \right)^{0.5}}{\min[r_i]} \right)^2$$

(3.14)

The connectivity robustness of 1 is when the ideal connectivity between CV in the road network is achieved, which took place in the latter extreme case. However, that extreme case is just a special case of the ideal connectivity that only requires all CV in the road network to be connected in one cluster with 100% connectivity area coverage. This can occur when the traffic is operated with reasonably high market penetration and reasonable traffic density. This means that robustness value of 1 is just an extreme value for the ideal connectivity condition. However, the ideal robustness is a range of values at different levels of traffic density provided that the suitable market penetration is taking place.

The robustness measured by the CONROB model is time dependent since all the parameters in the model are subject to change with time (time dependent) thus the model is modified to

$$R_{n,m}(t) = \frac{4}{N_{K}(t)} \left( \frac{L_{R_n}(t) \cdot \left( \frac{N_n(t)}{N_T(t)} \right)^{0.5} \cdot \left( \frac{a_n(t)}{A} \right)^{0.5}}{\min[r_i]} \right) \left( \frac{L_{R_m}(t) \cdot \left( \frac{N_m(t)}{N_T(t)} \right)^{0.5} \cdot \left( \frac{a_m(t)}{A} \right)^{0.5}}{\min[r_i]} \right)^2$$

(3.15)
In order to calculate the connectivity robustness in a road network that has clusters of CV, the robustness is calculated for all possible pairs of clusters in the road network. Then, a single value for the robustness, called network robustness $R_{\text{network}}$, is calculated as follows:

1- For each cluster $n$, the robustness $R_{n,m}(t)$ is calculated with each of the other clusters $m$; $m \in [1, N_C(t)]$. See Figure 3.2.

2- The total robustness $R_n(t)$ for cluster $n$ is calculated then, as shown in Figure 3.2, as the average of all $R_{n,m}(t)$, which can also be expressed by

$$R_n(t) = \frac{1}{{N_K(t) - 1}} \sum_{m=1}^{N_K(t) - 1} \frac{4}{N_K(t)} \left( \frac{LR_n(t)}{m_{[r_i(t)]} N_T(t)} \right)^{0.5} \left( \frac{\alpha_n(t)}{A} \right)^{0.5} \left( \frac{LR_m(t)}{m_{[r_i(t)]} N_T(t)} \right)^{0.5} \left( \frac{\alpha_m(t)}{A} \right)^{0.5}
$$

$$= \frac{1}{{N_K(t) - 1}} \sum_{m=1}^{N_K(t) - 1} \left( \frac{m_{[r_i(t)]} d_{ij}(t)}{\min_{i \in N_N, j \in N_m} |r_i(t) - r_j(t)| + 1} \right)^2
$$

(3.16)

Figure 3.2: Total Connectivity Robustness Calculation for Cluster n
3- This is repeated for all other clusters, then, the network robustness $R_{\text{network}}(t)$ is calculated as the average value of all $R_n(t)$’s as

$$R_{\text{network}}(t) = \frac{1}{N_K(t)} \cdot \sum_{n=1}^{N_K(t)} R_n(t)$$ (3.17)

Because the network robustness is time dependent, it is calculated at different pre-specified time steps ($t$), determined based on the required accuracy of calculation, over a pre-specified time duration ($T$) over which the connectivity robustness is required to be calculated. In other words, the connectivity robustness is defined as a distribution over time that is represented by the average robustness value over the total time ($T$) which is referred to as the overall connectivity robustness ($R_{\text{overall}}$), and is calculated by.

$$R_{\text{overall}} = \frac{1}{T} \sum_{t=0}^{T} R_{\text{network}}(t)$$ (3.18)

It is worth pointing out that the procedure used for robustness calculation over time in the CONROB model accounts for the dynamic clustering of vehicles in road networks as well as the LET and RET, which measure the decrease in the probability of connectivity [69]. This can be referred to as the stability of connectivity between vehicles. In other words, calculating the connectivity robustness at different time steps accounts for the change in the distribution of vehicles in the network, and hence accounts for the change in vehicles’ clustering at each time step and consequently the communication links and routes that expire and/or form between vehicles over time. This, in addition to the model derivation and properties discussion, shows that CONROB can serve as a viable planning tool for CV/AV environments in large scale road networks.
3.3 Verification of CONROB

In this section CONROB model is verified in order to show that it gives reasonable and reliable results that conform to the proved effect of each factor on connectivity as in the literature. The sensitivity of CONROB is measured against traffic density, market penetration, and transmission range. In order to achieve that, the model was applied to results of VISSIM simulation runs on the road network shown in Figure 3.3.

Figure 3.3: Study Road Network

The study road network is 195 square-miles of Washington County Oregon road network to the west of Portland city. This network was obtained from PTV Company, the developers of VISSIM software, who collected the traffic volumes and speeds data, built, and calibrated the network. This network has two freeways of 10 and 22 miles length intersecting at a grade separation. It also
has 111 intersections out of which 66 intersections are signalized with actuated signal heads, and 22 ramp meters.

In order to verify CONROB model and test its ability to capture the effect of traffic density, market penetration, and transmission range on the connectivity, a total of 45 different scenarios generated from five levels of traffic density, three levels of market penetration, and three levels of transmission range (5 traffic densities X 3 market penetration values X 3 transmission range values) were conducted, each scenario was simulated once. In order to overcome the randomness effect in each simulation run, the output was obtained over 36 time steps of 100 seconds each, starting from the second 1800 to the second 5400 in order to have 30 minutes warm-up period, then, the network robustness is calculated for each time step.

The traffic volumes in the network links, provided by PTV, were multiplied by a factor of 0.8, 0.9, 1, 1.1, and 1.2, in order to generate five different flow scenarios and the corresponding five different traffic densities per sq-mile of the network. For the market penetration, three values of 5%, 15%, and 25% were considered and assumed to be consistent on all the network links in the beginning of each simulation run. For the transmission range, three different values of 250, 500, and 1000 ft were considered. The chosen transmission range values are based upon the average values of the wireless communication fading error in urban areas [70], and are assumed to be fixed in each simulation scenario.

It is worth mentioning that the main objective of using VISSIM is to obtain a realistic dynamic distribution (X, Y, and Z coordinates) of the vehicles on a large scale network that has freeways, arterials, ramp meters, and traffic signals. Moreover, as the main objective is to develop and verify CONROB model, and because the accuracy is not an issue at this stage, the 100 seconds time steps were arbitrarily selected.
3.4 Simulation Results and Analysis

Simulation runs for 45 different scenarios were conducted to verify and test the sensitivity of the proposed CONROB model. Five traffic volume values were tested, each value was translated into a number of vehicles per square kilometres based on the results of the simulation runs [234, 267, 304, 347, and 402 vehicles per square miles, respectively]. Using the main output files from VISSIM that have the X, Y, and Z coordinates of the vehicles for each time step in each simulation run, the CV in the road network were clustered then all connectivity robustness values were calculated (robustness for each two clusters at each time step, network robustness at each time step, and overall robustness). This was done using a MATLAB algorithm shown in Figure 3.4 that is executed using the following set of pseudo codes:

1- At time step \( t \), develop a distance matrix for all CV on the network by computing distances between all possible pairs of CV \( d_{ij} \) using

\[
d_{ij}(t) = \sqrt{(z_j(t) - z_i(t))^2 + (y_j(t) - y_i(t))^2 + (x_j(t) - x_i(t))^2} \]

\( \forall i \in N(t), j \in N(t), i \neq j \) \hspace{1cm} (3.19)

Where, \( x_i(t) \), \( y_i(t) \), and \( z_i(t) \) are the coordinates of vehicle \( i \) and \( N(t) \) is the number of vehicles in the road network area at time step \( t \).

2- Construct a binary matrix for the direct connectivity \( \beta_{ij}(t) \) between all pairs of CV, where direct connectivity exists when the distance \( d_{ij} \) is less than the transmission range \( r \) that is considered fixed for the simulation scenario:

\[
\beta_{ij}(t) = \begin{cases} 
1 & \text{if } d_{ij}(t) \leq r \\
0 & \text{if } Otherwise
\end{cases}
\]

\( \forall i \in N(t) \& j \in N(t), i \neq j \) \hspace{1cm} (3.20)
3- If vehicle i has not been assigned to a cluster, set $C_i(t) = 0$, where $C_i(t)$ is the cluster number at time step $t$.

![Figure 3.4: Clustering and Robustness Calculation Algorithm](image-url)
4- For each vehicle $i$, construct a vector $J$ for all vehicles $j$ that are directly connected to $i$.

5- For each vehicle $i \in N(t)$, assign a cluster number $C_i(t)$ using:

$$C_i(t) = \begin{cases} C_i(t) & \text{if } C_i(t) > 0 \\ C_j(t) & \text{if } C_j(t) > 0 \forall j \in J \\ C_i(t) + 1 & \text{if } C_i(t) = 0 \text{ and } C_j(t) = 0 \forall j \in J \\ \end{cases} \quad (3.21)$$

Where, $C_j(t)$ is the cluster number of any vehicle in the vector $J$.

6- For all vehicles $j$’s connected to $i$, give them the same cluster number as $i$ using:

$$C_j(t) = C_i(t) \quad (3.22)$$

Repeat 5 and 6 until all CV are assigned a cluster number.

7- For each cluster, do a pairwise analysis with all other clusters in order to find out if there is any vehicle $i$ in cluster $C_n$ connected to another vehicle $j$ in cluster $C_m$. If this is true, then cluster $C_m$ is merged into cluster $C_n$, and all vehicles in cluster $C_m$ are assigned to cluster $C_n$. This is mathematically expressed by:

$$C_j|_{C_m} = \begin{cases} C_i|_{C_n} & \text{if } \beta_{ij}(t)|_{C_n,C_m} = 1 \\ C_j|_{C_m} & \text{if } \beta_{ij}(t)|_{C_n,C_m} = 0 \forall i \in N(t)|_{C_n} \& j \in N(t)|_{C_m} \end{cases} \quad (3.23)$$

Then get the number of clusters $N_C(t)$ at time step $t$.

8- Keep executing 7 until the number of clusters $N_C(t)$ is fixed

9- For each cluster, calculate connectivity robustness with all other clusters

10- Calculate the network robustness

11- Go to time step $t + \Delta t$. If the new time step is within the simulation period ($T$), repeat 1 to 11.

12- Calculate overall robustness
Simulation results are shown in Figure 3.5 for the relationship between the relative traffic density, calculated as the ratio between the actual number of vehicles per square mile of the network and the jam density on the entire area of the road network (3070 vehicles per sq-miles for a jam density of 200 vehicles/mile/lane, according to the highway capacity manual), and the robustness, raised to an arbitrary exponent of 0.1 in order to show the differences between the curves at each market penetration, for the tested market penetrations.

The results show that for some cases with different traffic density and market penetration values, the number of connected vehicles is almost the same; yet the CONROB value is different. For instance, the number of connected vehicles for the 144 veh/mile density with 25% penetration is approximately the same as for 248 veh/mile density with 15% penetration; however, the CONROB value is significantly different. This could be explained by considering vehicles distribution on the network at each case. For the first case, vehicles are freely moving allowing a better distribution on the network and hence better coverage and higher connectivity robustness value, especially with higher transmission range values. Whereas, for the second case vehicles are not moving as free as in the first case, which means that vehicles may not be distributed on the network properly and clustered in specific locations giving a bad coverage that does not change much with time, because of the relatively lower speeds of the vehicles, and hence a low connectivity robustness value.

The results also clearly indicate that the overall robustness increases as the relative traffic density and market penetration increase given the same transmission range. Similarly, the overall connectivity robustness increases as the relative traffic density and transmission range increase for the same market penetration. More so, the connectivity robustness becomes more sensitive to the relative traffic density at higher values of transmission range and market penetration. Overall, this
indicates that the CONROB model can capture the effect of market penetration, transmission range, and traffic density on the connectivity robustness as in the literature.

Figure 3.5: Effect of Traffic Density and Market Penetration on the Connectivity Robustness
To measure the statistical significance of the connectivity robustness to the relative traffic density, transmission range, and market penetration, multiple regression analysis was performed on the simulation results as shown in Table 3.1. The adjusted R-square value for the multiple regression model, which accounts for relative traffic density, market penetration, transmission range, and the interaction between them, is 95% with a p-value < 0.0001. This shows that the regression model is significant at 0.05 significance level, and so are the p-values for each variable in the regression model.

Table 3.1: Multiple Regression Analysis Results

<table>
<thead>
<tr>
<th>Analysis of Variance</th>
<th></th>
<th></th>
<th>F Value</th>
<th>Pr &gt; F</th>
</tr>
</thead>
<tbody>
<tr>
<td>Source</td>
<td>DF</td>
<td>Sum of Squares</td>
<td>Mean Square</td>
<td></td>
</tr>
<tr>
<td>Model</td>
<td>4</td>
<td>10.264</td>
<td>2.566</td>
<td>7734.95</td>
</tr>
<tr>
<td>Error</td>
<td>1615</td>
<td>0.536</td>
<td>0.0003</td>
<td></td>
</tr>
<tr>
<td>Corrected Total</td>
<td>1619</td>
<td>10.8</td>
<td></td>
<td></td>
</tr>
<tr>
<td>Root MSE</td>
<td>0.018</td>
<td>R-Square</td>
<td>0.950</td>
<td></td>
</tr>
<tr>
<td>Dependent Mean</td>
<td>0.15</td>
<td>Adj R-Sq</td>
<td>0.950</td>
<td></td>
</tr>
<tr>
<td>Coeff. Var.</td>
<td>12.143</td>
<td></td>
<td></td>
<td></td>
</tr>
</tbody>
</table>

| Parameter Estimates |                      |                      | t-value | Pr > |t| |
|---------------------|----------------------|----------------------|---------|------|---|
| Variable            | DF | Parameter Estimate | Standard Error |       |     |
| Intercept           | 1  | 0.0335             | 0.00183       | 18.33  | <.0001 |
| Traffic Density     | 1  | 7.6755             | 0.10239       | 74.96  | <.0001 |
| Market Penetration (Pen) | 1  | -0.00154           | 0.00004089    | -37.55 | <.0001 |
| Transmission Range (TR) | 1  | 0.0001107          | 0.0000058     | 19.07  | <.0001 |
| Density*Pen*TR      | 1  | 0.00029765         | 0.00001616    | 18.42  | <.0001 |
4. TRAFFIC CONDITIONS PREDICTION IN TERMS OF NETWORK CONNECTIVITY ROBUSTNESS

4.1 Introduction

The network level connectivity robustness (CONROB) metric measures the stability of existing communications between connected vehicles as well as the potential of the disconnected vehicles to reconnect and gain a significant spatial propagation over the road network. The model provided evidence to be able to capture the effect of the different factors on the connectivity between vehicles, which suggests it has potential as a viable tool to assess the performance of connected vehicle environments. CONROB model also suggested it can be used as an indicator for the robustness and stability of communication in CV environments.

CV technology offers a probe vehicle feature that can be used to estimate vehicular traffic measures of effectiveness (MOEs) such as queue length, speed, and travel time. Several studies investigated the probe vehicle feature of the CV technology. For instance, Comert and Cetin [71] studied the effect of market penetration on the estimation accuracy of queue lengths. In their study, the authors were able to identify the queue length using only the location information of the last equipped vehicle in the queue. Arogate et al. [72] presented estimation methods for different traffic MOEs at arterial as well as intersection level such as average speed, acceleration noise, and queue length. The authors tested their estimation methods at undersaturated and saturated traffic conditions and determined the required market penetration for accurate estimation of the MOE’s. They concluded that for saturated traffic conditions, the required market penetration for accurate estimate of the different MOE’s is less than that is required for the undersaturated conditions. More specifically, they concluded that higher accuracy can be obtained in oversaturated traffic conditions even at the early stages of CV deployment where the market penetration is low.
The equipped vehicles in CV environments collect data in the form of data snapshots that provide information about the vehicle state such as the vehicle coordinates and speed. The data snapshots are collected and stored on the vehicle’s OBU. These snapshots are then transmitted to the first RSU the vehicle passes by through the V2I application of the CV technology. The data snapshots are collected according to the Society of Automotive Engineers (SAE) J2735 standard. The SAE-J2735 standard allows snapshots collection on a vehicle’s OBU at predefined time intervals according to the vehicle speed. In order to have a reasonable representation to the vehicle movement, the snapshots collection time interval decreases as the vehicle speed decreases. In other words, the SAE-J2735 standard allows periodic snapshots to be collected every 20 seconds as the vehicle speed is higher than 60 mph, every 4 seconds as the vehicle speed is below 20 mph, and at a linearly interpolated time intervals when the vehicle speed is between 20 and 60 mph.

While the SAE-J2735 standard is the basic data snapshots collection protocol proposed for the CV technology, there were some attempts to come up with a more effective protocol. For instance, Chen et al. [92] presented a new protocol called R² protocol for collecting probe data in CV environments. The protocol is based upon collecting a vehicle snapshot when a significant change in the vehicle speed happens. Two data sets obtained from a CV simulation test bed and a real world test bed in Michigan were used to evaluate the R² protocol. The proposed protocol was compared to three existing protocols (Fixed 2 second, Fixed 4 second, and SAE J2735 protocols). The results show that the R² protocol outperforms the other three protocols in terms of the error measure in the collected data with fewer snapshots than those required for the other three protocols.

The probe vehicle feature of the CV technology enables real-time data collection which in turn enables real-time traffic conditions estimation. The past research showed that the accuracy of the estimated traffic conditions is affected by many factors such as the transmission range, market
penetration, and the traffic density. Since these factors also affect the communication stability, this suggests that relationships between the connectivity robustness and the traffic conditions estimation accuracy could be developed. Thus, this chapter investigates the relationships between the connectivity robustness model and the traffic conditions prediction models. More specifically, the travel time estimation accuracy as well as estimation reliability are investigated in terms of the communication stability.

4.2 Simulation Runs

The accuracy of the estimated traffic information by the connected-vehicle collected data is totally dependent on the factors affecting the connectivity robustness such as transmission range, market penetration, traffic density, spatial distribution of vehicles and spatial propagation of the vehicles. This suggests the existence of a relationship between the connectivity robustness and the accuracy of the transmitted traffic information. As such, a relationship between the connectivity robustness and the accuracy of the estimated travel time information in CV environments is investigated. More specifically, two relationships are investigated: the connectivity robustness with the travel time estimation error and the connectivity robustness with the standard deviation of the travel time estimation error. The standard deviation is used as a measure for the reliability of the travel time estimation.

The aforementioned relationships are investigated using simulation results of, a total of 10 simulation runs for each of 12 different scenarios (4 traffic density values X 4 market penetration values) obtained from the 195 sq-miles network in Figure 3.3. The traffic volumes in the network links, provided by PTV, were multiplied by a factor of 0.5, 0.75, 1, and 1.25, in order to generate four different flow scenarios. Each flow value was translated into a traffic density normalized by the network area (a number of vehicles per sq-miles) based on the results of the simulation runs.
(154, 236, 333, and 481 vehicles per sq-miles). These values were selected in order to have reasonably free flowing traffic. For the market penetration, three values of 5%, 15%, 25%, and 50% were considered and assumed to be consistent on all the network links in the beginning of each simulation run. The simulation runs were performed considering dynamic transmission range to account for the randomness effect resulting from the surrounding obstacles. The actual transmission range is calculated, according to [58], as a ratio of the maximum transmission range of the wireless channel as in (4.1).

\[ R = T_r \cdot (1 - \epsilon); \quad 0 < \epsilon \leq 1 \]  

(4.1)

Where \( T_r \) is the maximum transmission range of the wireless channel, and the parameter \( \epsilon \) refers to the wireless channel fading conditions at the vehicle position. This simplified equation reflects the practical (R) transmission range that is determined based upon the surrounding conditions to the vehicle. This is determined using the parameter \( \epsilon \) which changes according to the area type (downtown or suburbs). In downtown areas, for instance, the high rise buildings, industries, and other installations, interfere with the wireless signals of the vehicles. In such case, the value of \( \epsilon \) will be high so that the practical transmission range becomes less than the maximum value. On the other hand, in the suburbs, the obstacles are fewer in their numbers and lower in their heights, and hence the interference with the wireless signals is much less, resulting in a small value of \( \epsilon \). In such case the value of the practical transmission range is very close to the maximum value [58].

In order to apply this dynamic transmission range equation in the simulation, the selected network is divided into four zones with almost similar characteristics in each zone. For each zone, an arbitrary range is selected for the fading error according to the prevailing conditions. Then, based on these arbitrary ranges and a maximum transmission range value of 3000 ft, the actual
transmission range for each 10ft×10ft area block is calculated. This is performed using a MATLAB code executed for each simulation time step.

For the travel time estimations, a number of RSUs, each with a 492 ft transmission range, are placed across the entire road networks. The number and locations of the RSUs are determined using MATLAB based on a proposed deployment plan that suggests every RSU to cover an area of the network determined by a radius of 1200 ft. Based on this deployment plan, 46 RSU are placed at 46 intersections distributed uniformly (with uniform separating distances between one another) over the road network. PDMs are then collected by the CVs for each simulation time step according to the SAE-J2735 protocol. This was performed using the open access Trajectory Conversion Algorithm (TCA) software that integrates VISSIM-C2X feature with Python programming interface.

4.3 Results and Analysis

Using the speed information provided by the collected data snapshots, the travel time (TT) information is estimated according to equation 4.2 for each of 193 links with different lengths. The selected links are distributed over the network area to give a reasonable representation about the traffic conditions in the entire network. On the other hand, the speed data provided by all vehicles in VISSIM output on each of the selected links are used to calculate the ground truth TT information. The TT as well as the connectivity robustness are calculated over 12 time steps for each simulation run.

\[
TTE_{l,t} = \frac{L_l}{\sum_{s=1}^{S(t)} \sum_{n=1}^{N(t)} \alpha_{s,t} \beta_{s} (v_{s,n,t} p_{n,l,s,t}) / \sum_{s=1}^{S(t)} \sum_{n=1}^{N(t)} \alpha_{s,t} \beta_{s} p_{n,l,s,t}}
\]  

(4.2)

Where \(TTE_{l,t}\) is the estimated TT for link \(l\) at time step \(t\), \(L_l\) is the length of link \(l\), \(v_{s,n,t}\) is the speed information of CV \(n\) obtained from snapshot \(s\) at time step \(t\), \(\alpha_{s,t}\) is a binary factor (0 or 1)
that determines whether a snapshot is transmitted to an RSU at time step $t$ or not, $\beta_s$ is a binary factor that determines whether a snapshot is collected on the OBU at time step $t$, $p_{n,l,s,t}$ is a binary factor that determines if a snapshot represents the vehicle state while it is on link $l$, $N(t)$ is the total number of CVs in the network at time step $t$, and $S(t)$ is the total number of snapshots transmitted to the RSUs at time step $t$. For a snapshot to be considered in the TT estimation equation, it needs to be collected on the link of interest and transmitted to a RSU within the time step of interest.

The absolute percentage TT estimation error (TTEE) is then calculated as an average value for the 193 links over the simulation time period $T$, as in equation 4.3.

$$TTEE = \frac{1}{T} \times \sum_{t=1}^{T} \frac{1}{L} \sum_{l=1}^{L} \left[ \frac{TTE_{l,t} - TTG_{l,t}}{TTG_{l,t}} \right] \times 100$$  \hspace{1cm} (4.3)

Where, $TTG_{l,t}$ is the ground truth TT for link $l$ at time step $t$ and $L$ is the total number of links. In order to measure the reliability of the TT estimations, the standard deviation in the estimation error is also calculated. The connectivity robustness is also calculated for the different simulation scenarios using CONROB model. Two relationships are then established between the connectivity robustness calculated using CONROB model and the aforementioned measures.

4.3.1 Travel Time Estimation Error (TTEE)

The accuracy of the travel time estimates is totally dependent on the available PDMs from the network which is controlled by the number of CVs in the network. As the market penetration increases, more CVs should be available in the network which can help improve the accuracy of the travel time estimates. For a pre-specified market penetration in the network, due to the vehicles’ distribution, route choice decisions, and vehicle arrivals, every link in the network may have a number of CVs that is either lower than or higher than the design market penetration. As such, the average market penetration in the network becomes less than the design value, as shown
in Figure 4.1. The figure shows that the actual market penetration in the network changes between 71% and 77% of the design market penetration. The figure also shows that the actual market penetration becomes closer to the design value at higher traffic density values.

![Figure 4.1: Actual Market Penetration in the Road Network](image)

The actual market penetration in the network is, as mentioned earlier, determined by the vehicles’ distribution over the road links in the network. Some links may have very low number of CVs or even no CVs, as illustrated in Figure 4.2 for a traffic density of 154 veh/sq-mile. The figure shows that the percentage of links in the network that are travelled-over by mixed traffic with CVs increases at higher market penetration values. As the market penetration increases, more CVs are distributed over the network which reduces the percentage of links with no CVs. More so, at higher market penetrations, the vehicles’ distribution over the network becomes more stable which results in reducing the variance of the percentage of links travelled-over by CVs, as shown in the figure. This discussion applies to the different traffic density scenarios as shown in Figure 4.3, Figure 4.4, and Figure 4.5.
Figure 4.2: Percentage of Links Covered by Connected Vehicles for 154 veh/sq-mile Traffic Density

Figure 4.3: Percentage of Links Covered by Connected Vehicles for 236 veh/sq-mile Traffic Density
The previous discussion shows that higher market penetrations can provide better network coverage with the CVs. As the number of CVs in the network increases, the number of road links travelled-over by CVs increases. Thereby, larger number of PDMs can be collected that can cover...
larger areas of the road network and provide a better representation to the traffic conditions in the network. This is illustrated by the TTEE values in Figure 4.6. The figure shows that, at higher market penetrations, more accurate travel time estimates could be obtained. The figure also shows that the accuracy of the travel time estimates deteriorates with the higher traffic densities, especially for market penetration values up to 25%. Whereas, as the market penetration increases to 50%, an infliction point takes place on the TTEE curve. The accuracy of the travel time estimates improves as the traffic density increases up to that infliction point, then the accuracy deteriorates as the traffic density increases beyond the infliction point.

![Figure 4.6: Travel Time Estimation Error (TTEE)](image)

The results in Figure 4.6 suggest that nevertheless the number of CVs increases for the higher traffic densities, higher market penetrations are yet required to obtain accurate travel time estimates. This can be related to the variability and the randomness of traffic. As the traffic density in the network increases, the vehicles’ distribution in the network changes randomly (only restricted by the network geometry and the enforced traffic rules). This may exasperate the variability of the traffic conditions over the network which could lead to unreliable travel time
estimates. In order to overcome such variability, higher market penetrations are required to allow more comprehensive data to be collected which can help better estimate the traffic conditions in the network.

4.3.2 TTEE vs. Connectivity Robustness

The discussion in the previous section shows that the TTEE depends on the traffic density, market penetration, and the distribution of the CV in the network. These factors also determine the network connectivity robustness and stability, as discussed in chapter 3. This indicates that the TTEE and the connectivity robustness could be correlated. Thus, this correlation is investigated in this section. Then, if such a correlation exists, a relationship between the TTEE and the connectivity robustness is investigated.

Figure 4.7-a illustrates the change in the connectivity robustness as the market penetration and the traffic density change. For market penetration values up to 25%, the network have low connectivity robustness values that do not change significantly over the traffic density. This suggests that the available number of CVs is not enough to reach a network coverage that can achieve higher connectivity robustness values. As the market penetration increases to 50%, the network coverage improves which results in a significant increase in the connectivity robustness. In such a case, an infliction point is clear in the trend of the connectivity robustness over the traffic density. The connectivity robustness changes significantly up to a 333 veh/sq-mile density value. As the traffic density increases beyond that value, the change in the connectivity robustness is not as significant. These results indicate that, for the higher traffic density scenarios, higher market penetrations are required to achieve significant improvements in the connectivity robustness. This behaviour is consistent with the TTEE results in Figure 4.7-b which is discussed in the previous section.
Figure 4.7: Connectivity Robustness and Travel Time Estimation Error

Similar results are found for the standard deviation of the TTEE as a measure of the estimation reliability. Figure 4.8 shows that, for market penetration values up to 25%, no clear trend can be captured for the reliability of the TTEE. This may be related to the high variability in the traffic conditions. This variability, as discussed in the previous section, requires higher market
penetration values to be overcome. This occurs as the market penetration increases to 50% as shown in the figure. In such a case, the standard deviation of the TTEE decreases significantly as the traffic density increases up to 333 veh/sq-mile (the inflection point in Figure 4.7-a). As the traffic density increases beyond that value, the standard deviation does not decrease as significant. This behaviour is consistent with the connectivity robustness trend in Figure 4.7-a.

The previous discussion shows that the accuracy and the reliability of the travel time estimates are correlated with the connectivity robustness. In order to further investigate this, regression analysis is performed between the connectivity robustness and the TTEE as well as between the connectivity robustness and the standard deviation of the TTEE. Table 4.1 shows that the adjusted $R^2$ value for the regression model between the TTEE as the dependent variable and the logarithm of the connectivity robustness as the independent variable is 98% with p-value less than 0.0001. Similarly, Table 4.2 shows that the adjusted $R^2$ value for the model between the standard deviation of the TTEE and the logarithm of the connectivity robustness is 88% with p-value less than 0.0001.
This implies that both the TTEE and the standard deviation of the TTEE are significantly sensitive to the connectivity robustness in the road network at 0.05 level of significance.

Table 4.1: Regression Analysis Results (TTEE vs. Connectivity Robustness)

<table>
<thead>
<tr>
<th>Source</th>
<th>DF</th>
<th>Sum of Squares</th>
<th>Mean Square</th>
<th>F Value</th>
<th>Pr &gt; F</th>
</tr>
</thead>
<tbody>
<tr>
<td>Model</td>
<td>1</td>
<td>162.883</td>
<td>162.883</td>
<td>799.22</td>
<td>&lt;.0001</td>
</tr>
<tr>
<td>Error</td>
<td>14</td>
<td>2.853</td>
<td>0.204</td>
<td></td>
<td></td>
</tr>
<tr>
<td>Corrected Total</td>
<td>15</td>
<td>165.736</td>
<td></td>
<td></td>
<td></td>
</tr>
</tbody>
</table>

Root MSE    | 1.953 | 0.885 |
Dependent Mean | -17.177 | 0.876 |
Coeff. Var. | -11.371 | 0.876 |

| Variable              | DF | Parameter Estimate | Standard Error | t-value | Pr > |t| |
|-----------------------|----|--------------------|----------------|---------|------|
| Intercept             | 1  | -4.003             | 0.179          | -22.336 | <.0001 |
| Log (Robustness)      | 1  | 0.229              | 0.008          | 28.270  | <.0001 |

Table 4.2: Regression Analysis Results (Standard deviation of TTEE vs. Connectivity Robustness)

<table>
<thead>
<tr>
<th>Source</th>
<th>DF</th>
<th>Sum of Squares</th>
<th>Mean Square</th>
<th>F Value</th>
<th>Pr &gt; F</th>
</tr>
</thead>
<tbody>
<tr>
<td>Model</td>
<td>1</td>
<td>1628.177</td>
<td>1628.177</td>
<td>107.22</td>
<td>&lt;.0001</td>
</tr>
<tr>
<td>Error</td>
<td>14</td>
<td>212.602</td>
<td>15.186</td>
<td></td>
<td></td>
</tr>
<tr>
<td>Corrected Total</td>
<td>15</td>
<td>1840.779</td>
<td></td>
<td></td>
<td></td>
</tr>
</tbody>
</table>

Root MSE    | 3.897 | 0.885 |
Dependent Mean | 34.340 | 0.876 |
Coeff. Var. | 11.348 | 0.876 |

| Variable               | DF | Parameter Estimate | Standard Error | t-value | Pr > |t| |
|------------------------|----|--------------------|----------------|---------|------|
| Intercept              | 1  | 9.458              | 2.593          | 3.65    | 0.0026 |
| Log (Robustness)       | 1  | -3.134             | 0.303          | -10.35  | <.0001 |
The developed regression models in Table 4.1 and Table 4.2 show that as the connectivity robustness increases, the TTEE and the standard deviation of the TTEE decrease. This indicates that more stable and robust communication in the vehicular network allows more representative data to the traffic conditions in the network to be collected, and hence allows more accurate and reliable travel time estimates to be obtained.
5. ROAD-SIDE UNITS DEPLOYMENT

5.1 Introduction

The CV technology is a rapidly emerging, promising, challenging, and self-organized technology that is taking place in the very near future. It aims at using safety and operation information from moving vehicles in the network in order to have a highly operable and safe transportation environment. In environments with this technology, the information transmission takes place between vehicles with high mobility and limited degrees of freedom, as determined by the transportation network and the surrounding vehicles. Therefore, a highly efficient and dynamic broadcasting protocol that guarantees a high connectivity is required. In that context, many studies were conducted to develop an efficient protocol that can cope with the highly dynamic vehicular environment. Moreover, a proper performance metric is required to assess the performance of the technology. In that context, there has been a significant effort to develop some performance metrics for its performance. Some of these studies are concerned about the connectivity probability, the healing time after a connectivity failure, the delay in message delivery, or the vehicular traffic delay time or other vehicular traffic metrics.

Vehicle-to-Vehicle (V2V) and Vehicle-to-Infrastructure (V2I) communication technologies are the two main components of a CV environment. The management of such environments requires a robust platform that allows proper interaction between the vehicles in the road network and the traffic management centers (TMCs). For this to happen, V2I is the main key through which information is exchanged between vehicles in the network and the TMCs. The collected snapshots on a vehicle’s OBU are transmitted to the closest RSU the vehicle falls into its transmission range, which represents the V2I application. Based on the collected data snapshots, decisions could be made and disseminated to the closest vehicles in the RSU transmission range in what is so called
I2V, and then through the V2V application vehicles that received the information can transmit it to the other vehicles in the network. When vehicles are not reachable by the RSU or by other vehicles that received the information from the RSUs, delays in the transmission of the information will occur. This is very critical especially in safety applications; therefore, the required interaction between vehicles in the network and the TMCs should be guaranteed in a timely manner.

Unfortunately, because of the dynamic nature of traffic, the aforementioned interaction between TMCs and vehicles may not be easily achieved at all times. The reason is that a chosen RSU location may not be connected to most of the CVs especially at low penetration rates. Therefore, an optimal location for a RSUs should be identified. This is defined as a location that guarantees proper communication between RSUs and as many vehicles as possible in the network. More so, the RSUs should also be deployed where vehicles are able to communicate with each other (clusters of vehicles able to communicate) most of the time. This is to connect the different clusters and merge them which could help in exchanging the information with the lowest delay possible.

In order to determine the optimal locations, an optimization tool, such as Genetic Algorithm (GA) could be used. More importantly, vehicles’ clusters, their sizes, locations, and distances from each other should be identified. In that context, a performance measure that deals with all these parameters is required to serve as the reference for the RSU locations optimization.

The network level connectivity robustness model measures the stability of existing communications between connected vehicles, as well as the potential of the disconnected vehicles to re-connect with information transmitted with better ability for information to propagate over significant distances in the road network. CONROB metric accounts for the geometric characteristics of the road network in addition to vehicular traffic related factors as well as wireless communication related factors.
CONROB model was introduced as a planning tool for connected/automated vehicle environments. Thus, this chapter investigates using Genetic Algorithm (GA) for RSUs deployment using the connectivity robustness as a performance measure.

5.2 Literature Review

Traffic performance measures estimations in connected/automated vehicle environments is a critical issue that is of significant interest for researchers and officials. These measures are the key elements in traffic monitoring and decision making process by TMC. Several studies were conducted in estimating traffic measures of effectiveness (MOE’s) such as queue length, travel speeds, and travel times. For instance, Comert and Cetin [71] studied the effect of market penetration on the accuracy of queue lengths estimations. In their study, the authors were able to identify the queue length using only the location information of the last equipped vehicle in the queue. Arogate et al. [72] presented estimation methods for different traffic MOE’s at arterial as well as intersection level such as average speed, acceleration noise, and queue length. The authors tested their estimation methods at undersaturated and saturated traffic conditions and determined the required market penetration for accurate estimation of the MOE’s. They concluded that for saturated traffic conditions, the required market penetration for accurate estimate of the different MOE’s is less than that is required for the undersaturated conditions. More clearly, they concluded that higher accuracy can be obtained in oversaturated traffic conditions even at the early stages of connected vehicle deployment. The common factor in these studies was the accuracy of the obtained estimates, which is determined by the amount of data available and how much it covers of the traffic situations in the road network. The main factors affecting the accuracy are the effective communication range, penetration rate, snapshots resolution, buffer size of the On-Board Units (OBUs), and number of active RSUs.
For a RSU to be active, its location should be optimized in order to be able to serve collecting reliable data from vehicles and send information back to them. In that context, Kainfar and Edara [92] proposed a methodology to determine the optimal locations of the RSU’s for better travel time estimations in V2I environments. They developed a simulation test bed for Boise, Idaho, in VISSIM traffic simulation software. In conjunction with the simulation test bed, the authors implemented a GA-based solution method to determine the optimal location of the RSU’s with travel time estimation accuracy serving as part the fitness function. According to the values obtained for a hybrid performance measure, the network coverage index, which combines the error in the estimated travel time and the number of links that have the travel time information available, improved with higher penetration rates and longer travel time estimation periods.

RSUs are very significant also in dissipating important information to vehicles in order to manage traffic in the network. For instance, I2V was investigated for eco-speed applications in which signal timing information are required to be sent to the vehicles for optimal eco-speeding decisions [75]. More so, optimal lane selection was investigated for improved mobility [76]. In that study, information was required from the vehicles using V2I application, and based on that, optimal lanes are selected and sent to vehicles through I2V application.

In summary, past research shows critical issues related to data collection, traffic performance measures, and traffic management in the CV environments. Some of these issues can be addressed with RSUs, which have to be deployed throughout the transportation network to collect data on traffic conditions. The collected data can then be used to determine traffic performance measures that influence decisions such as rerouting, signal timing optimization, and speed choice. This traffic management process requires communication to take place between RSUs and most of the equipped vehicles in the network to achieve reasonable coverage. Therefore, RSU deployment
needs to be optimized to expand communication among vehicles (clusters of vehicles based on vicinity). In other words, RSUs location optimization needs to account for the size of vehicle clusters that is represented by the number of vehicles in each cluster and the network area covered. In addition, the location optimization should account for larger clusters locations and the separating distances between clusters. Connectivity robustness is a performance measure developed specifically for CV environments that accounts for the aforementioned factors. This chapter hence investigates the application of Genetic Algorithm (GA) for location optimization of Road Side Units (RSUs) by maximizing the connectivity robustness.

5.3 Optimization of RSUs’ Locations

The optimization problem is solved in the study using Genetic Algorithm (GA). GA is a search process that was invented in the 1970s by John Holland to mimic the process of natural selection. It is a search tool that looks for optimal combination of solutions. GA is an optimization approach that can solve multi-dimensional optimization problems. GA also performs a search process in large spaces to find the global optima. The advantages GA tool offers are capable of solving the problem of this study. In large network areas with low CV market penetration rates, GA can find the optimal RSUs locations where equipped vehicles are located in large numbers and communicating over significant areas in the road network.

The search process in the GA depends on finding the fittest elements in large populations. For a population of chromosomes constructed by a set of genes, the fittest chromosomes are selected to reproduce through the crossover and mutation process and create new generations of chromosomes. Using this biological analogy, the methodology for RSU deployment is as shown in Figure 5.1. First of all, for a given number of RSUs (N), which represents the chromosome size, a population of size (P) of chromosomes is randomly generated with different RSUs arrangements.
over the entire number of intersections and access points (I) in the road network. Through the
crossover process, with a crossover rate ($p_c$), and mutation process, with a mutation rate ($p_m$), new
population of chromosomes is generated. In each new population, a selected number of elite
chromosomes ($n_e$), RSUs arrangement with highest fitness values, are selected. This is repeated
over the total number of generations ($G$).

First of all, for a given number of RSUs ($N$), which represents the chromosome size, a
population of size ($P$) of chromosomes is randomly generated with different RSUs arrangements
over the entire number of intersections and access points (I) in the road network. Through the
crossover process, with a crossover rate ($p_c$), and mutation process, with a mutation rate ($p_m$), new
population of chromosomes is generated. In each new population, a selected number of elite
chromosomes ($n_e$), RSUs arrangement with highest fitness values, are selected. This is repeated
over the total number of generations ($G$).

The fitness of a RSUs arrangement is determined based on the number of clusters the RSUs can
communicate with, as in 5.1. The higher the number of clusters the RSUs can communicate with
and merge, the fittest that arrangement will be. The fitness is calculated over time so that to
guarantee that a RSU is active most of the time.

$$f_{c,g} = \sum_{t=1}^{T} \sum_{n=1}^{N} \beta_n(t)$$

(5.1)

Where, $f_{c,g}$ is the fitness of RSU arrangement $c$ in generation $g$, $\beta_n(t)$ is the number of vehicle
clusters RSU number $n$ is connected with at time step $t$, and $T$ is the total time interval over which
the RSU arrangement should be optimized. This time interval could be the peak hours in a road
network over which the information exchange between vehicles and the TMC is more critical.
5.4 Numerical Analysis

5.4.1 Simulation Runs

The study area chosen for the numerical analysis is the 195 sq-miles in Figure 3.3. A total of 10 simulation runs were conducted with different penetration rates (5%, 15%, 25%, and 50%) to
obtain the connected and regular vehicle trajectories over 3600 seconds. A warm up period of 1800 seconds was taken into consideration. The vehicle trajectories were then used in MATLAB for connected vehicle clustering and connectivity robustness calculation, using the effective transmission range value of 1000 ft, also used as the base case for the case of no RSUs. The GA algorithm was also coded in MATLAB and the clustered connected vehicles served as its input for four RSUs scenarios (42, 58, 68, and 111 RSUs). The fitness of each RSU arrangement was calculated for the different market penetrations over the simulation period with 5 minutes time step in order to find the optimal arrangement over 616 intersections and access points in the study road network. The parameters used in the GA algorithm are detailed in Table 5.1. For each RSU scenario, the connectivity robustness was calculated twice: once for a uniformly distributed arrangement, and the other for the optimized arrangement. The results are discussed in the following section.

Table 5.1: GA Algorithm Parameters

<table>
<thead>
<tr>
<th>Parameter</th>
<th>Value</th>
<th>Parameter</th>
<th>Value</th>
<th>Parameter</th>
<th>Value</th>
</tr>
</thead>
<tbody>
<tr>
<td>P</td>
<td>30</td>
<td>nₑ</td>
<td>4</td>
<td>pₘ</td>
<td>0.07</td>
</tr>
<tr>
<td>G</td>
<td>400</td>
<td>pₓ</td>
<td>0.7</td>
<td>R*</td>
<td>1000</td>
</tr>
</tbody>
</table>

* RSU Transmission Range (ft)

5.4.2 Results and Analysis

Fitness function sample results are depicted in Figure 5.2. The figure shows that the fitness of each RSU scenario increases over the generations. This means that, for a specific number of RSUs, as the locations are optimized, more vehicle clusters are connected and merged into fewer clusters with larger area coverages. The figure also shows that there is almost no change in the fitness
values after 300 generations, which means that an optimal solution has been reached. Moreover, the figure shows that increasing the number of the RSUs improves the fitness values.

![Fitness Values for the Different RSU Scenarios](image)

**Figure 5.2: Fitness Values for the Different RSU Scenarios**

Since the fitness of the RSUs’ arrangements is determined based on the number of clusters the RSUs can communicate with, the performance of the developed approach is analyzed in terms of the change in vehicle clustering (number of clusters and area covered by each cluster) and the associated connectivity robustness. The analysis is performed comparatively between three cases: (1) no RSUs, (2) RSUs uniformly deployed (equally spaced over the network), and (3) RSUs optimally deployed.

Figure 5.3 illustrates the change in the number of clusters for the different deployment scenarios. The figure shows that the number of clusters decreased as the RSUs are deployed. For 15% penetration rate, the number of clusters decreased from 118 to 112 once 42 RSUs are optimally deployed, and decreased more significantly to 102 clusters once 111 RSUs are optimally deployed. On the other hand, for 50% penetration rate, the number of clusters did not change
significantly. It was reduced from 22 to 21 clusters once 42 RSUs are optimally deployed, and to 19 clusters once 111 RSUs are optimally deployed. These reductions are more significant than the uniform RSUs’ deployment case as shown in the figure. In addition, the difference in the number of clusters between the optimal and the uniform deployment scenarios becomes more significant as the number of RSUs increases. This indicates that optimal RSUs’ deployment is able to improve vehicle clustering more significantly compared to uniform deployment.

The reductions achieved in the number of clusters mean that the RSUs were able to merge clusters together which increases the area coverage. As such, an overall increase in the average area covered by each cluster is achieved which becomes more significant as the RSUs are optimally deployed, as shown in Figure 5.4. The figure shows that the increase in the area coverage becomes more significant with higher penetration rates. This is related to the original number of vehicle clusters in the network when no RSUs are deployed. For higher penetration rates, vehicles are originally clustered in few groups, when no RSUs are deployed (22 clusters as in Figure 5.4-d). In addition, each cluster in such a high penetration scenario covers a significantly large area. In this case, RSUs deployment increases the average area coverage significantly as clusters merge. On the other hand, for low penetration rates, vehicles are grouped in considerably larger number of clusters (162 clusters as in Figure 5.4-a). Furthermore, the area covered by each cluster in this case is significantly small. Clusters in such an environment could be spaced apart according to the distribution of the vehicles in the network and the network geometry. Thus, as the RSUs are deployed, some clusters may merge while many others remain disconnected. This may result in slight increase in the average area coverage of each cluster. Nevertheless, in such low penetration scenario, the number of clusters merged by an RSU is more than that in the higher penetration-rate case, which is considered a relatively more significant improvement, as shown in Figure 5.3.
The improvements achieved in the vehicle clustering are also reflected in the communication stability and robustness as shown in Figure 5.5. It is clear that for the different penetration rates, equally spaced RSUs increase the connectivity robustness, but the improvement in robustness values is more significant when the RSUs are optimally deployed. The improvement in robustness also increases as the number of RSUs increases for the different penetration rates. Changing RSUs deployment from uniform to optimal increases the connectivity robustness by 15 to 20%, 22 to 54%, 11 to 34 %, and 1 to 46 %, for penetration rates 5%, 15%, 25%, and 50%, respectively. This is clear in Figure 5.5-a for 5% penetration rate, b for 15% penetration rate, c for 25% penetration rate, and d for 50% penetration rate.
Overall, the uniform-deployment results show that as the number of RSUs increases the change in the number of clusters and the average area covered is not as significant as the optimal deployment case. Moreover, considering the uniform deployment as a base case, the optimal deployment results show that the change in the number of clusters, area covered by each cluster, and hence the connectivity robustness increases significantly as more RSUs are deployed. The results also show that for lower penetration rates the gain obtained by optimizing RSUs locations is higher compared to higher penetration rates. This is clear in the percentage increase in the connectivity robustness. As the number of RSUs increases the connectivity robustness increases by 34% to 127%, for 15% penetration rate; whereas, the increase in the robustness is from 3% to 83% for penetration rate of 50%.
Figure 5.5: Connectivity Robustness Results
6. INDIVIDUAL USER PERFORMANCE CHARACTERISTICS*

6.1 Introduction

Test beds for connected vehicle research can be used for testing real time data capture and management systems, as well as testing the integration and interoperability of the CVs, mobile devices, and highway infrastructure. Along with the physical platforms for test beds, driving simulator test beds can also be harnessed to achieve similar goals. More specifically, driving simulators are a high fidelity human-in-the-loop simulation platform that has a great potential to serve as a connected vehicles test bed.

The ability of driving simulation technology to interact with the complex human behavior is of great interest. However, to fully investigate the benefits of CVs using this technology, the use of test beds is required. The use of a driving simulator test bed for connected vehicles allows for a controlled environment to test real-time data capture and the integration and operability of connected vehicle.

Traffic accidents in the U.S. have declined over the last two decades but continue to cost the country billions of U.S. dollars each year. Intersection collisions alone account for about 50% of the total number of annual accidents [77]. A study of the characteristics of these accidents showed that 75% of intersection accidents resulted from driver error including driver inattention, faulty perception and vision impaired/obstruction. There has been significant effort to overcome this problem over the past few years and it is viewed that connected vehicle technology may offer a very promising means to reduce, and maybe totally overcome, the driver error factor in intersection

collisions [78]. Part of this can be achieved through providing a properly designed system of collision warning messages to drivers at the right time that will allow drivers a suitable reaction time to overcome any potential collision. However, this is not always the case especially with the complex driving behavior that differs within any driver population based on factors such as, mood, age, and gender among others. These factors affect the way people drive in terms of the headway, speed, and perceived risk that is translated into the minimum time to collision value. Driver aggressiveness is the main attribute that captures the different driving styles of people, therefore two levels of aggressiveness were tested for this study.

From this perspective, a preliminary driving simulator test bed was developed in the driving simulator laboratory at Louisiana State University (LSU) so as to allow a lead vehicle to communicate warning messages to the simulator vehicle (CV technology) within the virtual environment. A pilot study was then undertaken with a group of aggressive and non-aggressive drivers to assess which group could most benefit from this technology when approaching intersection stop lines. It was anticipated that a successful driving simulator test bed may impact on the driving behavior of the aggressive drivers, and thereby reduce the number of potential collisions at intersections.

6.2 Literature Review

Over the past few years there has been targeted significant research effort in CV technology in order to address operational, safety and environmental related issues. In addition, some studies have focused on the drivers’ behavior and response to the existence of the technology and how they handle the information load in their vehicle. It has been determined that providing too much information in the form of multiple warning and/or information in multiple displays may
overwhelm and distract the driver. In fact, too much information being presented affect the drivers’ reaction times and may lead to inappropriate responses in emergency situations [77].

The human information processing capability is limited and may involve errors sometimes [79]. Humans process information using three key components: memory, attention, and decision making. Further, the human memory consists of three subsystems that each have their own limitations as to the information they can receive: sensory storage, working memory, and long-term memory. The first memory subsystem is sensory storage, and this type of memory is based entirely on stimuli. When a stimulus is present, the human memory creates a sensory storage that will last until it has been replaced by another stimulus of similar function. However, as a way to separate different stimuli, humans have four different modes of sensory storage: auditory, visual, tactual, and olfactory. This allows humans to retain various stimuli. The problem with sensory storage is that it is only for short amounts of time [80] because the purpose of sensory storage is to retain the information long enough to pass it along to working memory [79]. Working memory uses a coding system to determine the type of information it receives i.e. visual, phonetic, or semantic [[80]; [81]]. This type of coding allows the working memory to determine which type of information it received from the sensory storage, and then process that information. However, Yang and Fricker note that “one of the most noticeable limitations of working memory is that it has a very limited capacity. The maximum number of items that can be held in working memory is 7±2 ‘chunks’.” [79]. This is an interesting observation because the findings suggest that if information can be pieced together into meaningful chunks then working memory space can be maximized. As new information enters the working memory, it is held temporarily until it is encoded and stored permanently in the long-term memory. The information stored in the long-term memory can be retrieved either by recall, if the entire stored information has to be retrieved,
or recognition, if it is only to find out whether or not a specific piece of information is stored in the long-term memory [82].

With the rapid advances in the transportation system, such as the Advanced Traveler Information Systems (ATIS) and the in-vehicle information systems (IVIS), drivers are prone to have divided attention between the driving and the information processing tasks. In that context, Yang and Fricker [79] conducted an experiment to determine the amount of information that is considered to be too much for a driver to process, and to determine which way of conveyance is most effective. They used a driving simulator to simulate familiar and unfamiliar areas to the subjects. The responses when given twelve different information combinations for both familiar and unfamiliar areas were evaluated. Their findings showed that when a driver is in a familiar area, the need for a visual display (e.g. a map) is not necessary due to the fact that a driver will rely on their prior knowledge of the area. The opposite is observed when the driver is in an unfamiliar area. They also found that a visual display was more effective when accompanied with an auditory message that alerted drivers.

Lloyd et al. [78] studied the most effective means to convey potential collision information at intersections. They began by analyzing the occurrence of collisions at intersections using the National Automotive Sampling System (NASS) crash data, and found that together, driver inattention (28.7%), faulty perception (33.9%), and vision impaired/obstructed (11.1%), accounted for nearly 75% of intersection crashes. This shows that a majority of crashes are caused by a lapse in judgment in some manner. In their study, the authors analyzed different means for conveying the potential collision information and found two types of warning systems that could benefit a large group of people in the most effective manner: heads-up-display (HUD) and haptic cueing. The main finding of this study was that using a combination of these technologies can be the most
effective way because drivers could be stimulated with a haptic cue, and then alerted to the situation approaching so that a proper reaction could be performed. However, the warnings have to be simple and short as lengthy and complex messages could rather prove distracting and reduce safety.

In another study, Lloyd et al. [83] explored when and how to present warning messages of a stop when approaching signalized intersections in order for drivers to optimally perform safe reactions. The authors analyzed drivers’ behavior data and focused on four main parameters: throttle lift-off, brake application, steering, and turn signal activation. In their analysis, the authors found that the optimal time to alert drivers when to stop was 15 seconds before reaching the intersection. They also suggested that alerts should be such that they should benefit all drivers, not require specific directional orientation, be compatible with drivers’ response, and have a viable integration with other Collision Avoidance Systems (CAS) and Driver Assistance Systems (DAS). Based on these characteristics, the authors analyzed the effectiveness of both visual and auditory messages. For the auditory messages, the results showed that a tone alert would not benefit all drivers especially drivers with a hearing disability; whereas, a voice command was found to potentially cause a driver to experience attention overload. For the visual messages, HUD was found to be effective but could potentially lead to distraction and compromise safety if not located in a forward view position.

Fitch et al. [84] tested the Connected-Vehicle Collision Avoidance System (CAS) applications using a Wizard-of-Oz technique. The main objective of the study was to test whether to present multiple crash alerts in multiple conflict scenario, or present only one alert to the first conflict and suppress the subsequent alerts. The results of study suggest that presenting multiple unique auditory alerts in a multiple conflict scenario was appropriate to most of the drivers provided. This
supports the first part of earlier studies [[85]; [86]] that state that multiple alerts in multiple conflicts can provide drivers with the appropriate guidance to conduct the appropriate avoidance maneuvers. However, the results conflicted with the second part of the studies which states that any alerts presented after the first alert could confuse and distract the drivers. Therefore, Fitch et al. [84] concluded that their results need to be investigated further.

Jeong et al. [87] conducted a simulation study to evaluate the proposed Inter-vehicle Safety Warning Information System (ISWS) aimed at improving drivers’ attentiveness through providing warning alerts about potential hazards in a connected vehicle environment. They used a crash prone location in the Korean freeway system to collect data about drivers’ behavior in different situations and then transformed into a VISSIM simulation model. The results showed that with a 100% market penetration, the number of rear-end conflicts was reduced by around 84% under level of service D. However, for free flowing conditions, the ISWS did not show any significant impact on drivers’ safety as the conditions are already stable.

6.3 Methodology

In this chapter, the main focus is to design a message alert system, based on time-to-collision between two vehicles, in a driving simulator environment and analyzing the driving performance of a sample of aggressive and non-aggressive drivers to determine if there were any safety benefits to either group of drivers.

6.3.1 Design of Connected Vehicle Test-bed

The following subsections present detailed discussion of aspects of the driving simulator test bed.
6.3.1.1 Driving Simulator Features

The driving simulator at Louisiana State University (LSU), shown in Figure 6.1, consists of a full-sized passenger car modeled after a Ford Focus automobile, and combines with a series of cameras, projectors and screens to provide a high fidelity virtual environment. The simulator has an audio software and hardware plus real time one degree of freedom motion in the forward-backward direction so that participants can drive with engine sound, tire sound and noise from the vehicle. The driving process almost mirrors the realistic driving task of an actual vehicle. Participants have to put the car in motion, use mirrors for better visual awareness, and react to other vehicles in traffic.

Two computers control the simulation, one screens the image that is being captured by the cameras, and two more are used for data analysis. The simulator is able to gather sensing data such as vehicle speed but has not been programmed to collect any data on the ambient traffic. Also, digital cameras installed within the vehicle, are linked to the application software, SimObserver, to collect video that is time-referenced with the sensing data. Its flexible scenario creation interface and customizable highway system design tools allow for the driving scenarios to be changed based on weather conditions, roadway surfaces and environments, and also allows for other options to be added by the application software SimVista. The dynamics of the simulator itself can be modified by the application software SimCreator; a graphical simulation and modeling system. In addition to those programs, there exist the JavaScript files, scripted vehicle activity in C/C++ code components, and can be used to call up functions during the simulation to either control aspects of SimCreator or the SimVista. For this study, the JavaScript files were scripted to allow collection of sensing data for the lead vehicle in addition to that of the simulator. One negative side effect of the simulator is motion sickness, and therefore, some researchers discourage
the use of the simulator by participants that suffer from balance disorders such as vertigo and dizziness.

Figure 6.1: LSU Driving Simulator

6.3.1.2 Connected Vehicle Test Bed Information Survey

The purpose of this survey is to have a clear idea about the drivers’ information requirements that can help them drive in a safer and more operable environment. The survey is intended to
address the information requirements in different driving situations. It is also anticipated to address the best way for information presentation that can decrease the information processing time by the drivers. As such, a questionnaire with 18 questions was designed on “SurveyMonkey” website, as shown in Appendix A, and sent out to LSU civil engineering graduate and undergraduate students. The responses of 79 participants to each question are analyzed and presented in the following section.

The participants were asked about their acceptance to the technology. The 79 participants expressed their need to have the connected vehicle technology which indicates the importance of the different applications the technology may offer. Then, the participants’ need to specific technology applications was investigated. As such, the participants were asked about their need to the signal timing as an important information while approaching a traffic signal. With a 100% response rate, 82.3% of the participants showed their need to have this piece of information in their cars. Based on the participants’ responses, the remaining green time information was found to be more important than the remaining red time information.

While approaching an intersection, some drivers may become confused about whether the lane they are occupying is the right lane for their planned movement. This may lead to improper lane changing behavior at the intersection which could cause unnecessary delays. As such, when the participants were asked about their need to the lane use information (whether a lane is assigned to left turn lane only, right turn lane only … etc.), 81% showed their need to that piece of information while they are approaching an intersection.

Drivers’ inattentiveness is a critical issue that could result in traffic violations and lead to traffic accidents in many cases. Unless the distracted drivers receive alerts, they may run a red traffic light, run a stop sign at an intersection, or speed up to beyond the speed limit. These warning alerts
are one of the connected vehicle applications. As such, the participants were asked about the signs they usually do not notice and need to have information about while they are driving. The participants’ responses, as shown in Figure 6.2, indicated that they need to receive alert messages about all the signs they were asked about but with different ratings. The participants rated the importance of all the sings with ratings higher than 3 out of 5. They also proposed to receive information about other signs such as, exit ramps, work zones, and no turn on red signs.

![Figure 6.2: Distribution of Controller Information Needs Survey](image)

In addition to the drivers’ inattentiveness, short sight distances at the intersections is one of the factors that could cause traffic accidents. Vehicles traveling on two intersecting roads may run into one another if they do not have enough time to stop, which could result from either driver’s inattentiveness or short sight distance. In such a conflicting-movement scenario, an alert message about a right-angle vehicle coming from an intersecting road can help to reduce the crash risk at intersections. Thereby, the participants were asked about the importance of such warning alerts. Unsurprisingly, 75% of the participants showed their need to these alerts, which indicated the importance of these messages as a safety application of the connected vehicle technology.
The warning alerts about another critical conflicting movement that take place on the interstates was investigated. The participants were asked about the importance of receiving information on the safety of a merging maneuver they are planning to perform while they are entering the interstates. Their answers showed that 77% out of 77 respondents need such information, indicating that most of the drivers may need assistance to perform the merging maneuvers on the interstates.

In addition to safety, connected vehicle technology is aiming at improving the operational characteristics of the transportation networks. One of the operational applications of the technology is the incident-ahead information. Drivers should receive information about the incident locations which could help them make the right decision (re-routing, slowing down … etc.) at the right time. As such, the participants were asked about the importance of such incident-ahead information. All the participants found this information to be very critical for them, not only to improve the mobility but also, because of the associated safety benefits.

Regarding their ability to process and react to the relayed information, the participants were asked about the amount of information they can handle at a time. Most of the participants expressed their ability to process multiple pieces of information at the same time, with 87% of them thought that two to three pieces of information as the maximum amount they can handle at a time. They also thought that more than 3 pieces of information could represent an overload that might result in unsafe driving environment.

The drivers of the equipped vehicles with the connected vehicle technology should receive the information on a display in their cars. This information could be presented in the form of images, text, auditory alerts, or combination of two or more of the previous forms. In order to investigate the optimal form to relay the information to the drivers, the participants were asked about their
ability to process the aforementioned forms. Their responses showed that 80% of the participants found the images to be the easiest form that they can process. Whereas 50% found the auditory alerts to be the second best form, and a low percentage of 33% found the text as a good way for presenting the information. These results are very reasonable as people are better in processing images and audio alerts more than the text, especially while driving at high speeds which can minimize the drivers’ distraction.

In addition to the form in which the information could be relayed to the drivers, the in-vehicle location where this information should be relayed could contribute to the drivers’ distraction. As such, the participants were asked to choose the best out of three locations where the relayed information should be presented. The three locations are shown in Figure 6.3. The participants’ responses showed that 42% preferred location one, 34% thought that location two is the best, and only 24% found that location three is better to relay the information. These results agreed with a previous study [88] that suggested that most of the drivers comply with the messages displayed at that location one. The study also identified that location to be the safest for drivers to mount off-the-shelf GPS devices so as to minimize the drivers’ distraction.

![Figure 6.3: Location of the Information Display](image-url)
6.3.1.3 Design of Alert Message System

The alerts were designed as visual text messages that warned the driver of imminent potential crash with the lead vehicle. The alert messages were designed using the C++ interface of the simulator according to the logic shown in Figure 6.4.

![Flowchart showing the logic of alert messages](image-url)

Figure 6.4: Alert Messages Logic in C++
Based on Yang and Fliker’s study [79], it was decided to omit auditory warnings because drivers were allowed to become familiar with the scenario surroundings before the actual test. The first of two visual warning messages was projected onto the driver’s screen in a yellow font as “SLOW DOWN” when the driver’s minimum time-to-collision (TTC) was down to 3 seconds. This is shown in Figure 6.5-a.

(a) At 3 seconds threshold

(b) At 1.5 seconds threshold

Figure 6.5: Alert Messages Display
The second visual warning message, displayed in red font, read “SLOW DOWN- POTENTIAL CRASH” when the TTC further dropped to 1.5 seconds, the minimum TTC required for drivers to safely react [89]. This is shown in Figure 6.5-b. The generation of these alert messages were programmed using the JavaScript files associated with the driving scenario. For the message size to be readable, a 7” frame that mirrors a HUD was projected onto the middle of the windshield. Three participants were asked to assess the readability of the projected message inside the frame and the text size was edited until the three drivers agreed that it was clear and readable within the 7” frame. This made the test-bed very close to simulate a connected vehicle HUD.

6.3.2 Participants

Thirty participants aged between 18 and 58 years of age (mean = 27.3, standard deviation = 8.17), and consisting of five females and twenty-five males were recruited from the Louisiana State University’s community of students and staff. They were all of good general health, and were active drivers with a valid driver’s license. They were recruited using flyers on university bulletin boards and in accordance with the university’s Institutional Review Board’s (IRB) standards. No financial incentive or course credit was offered so all subjects participated out of their own interest. To be able to classify them into aggressive and non-aggressive drivers, participants were asked to complete the Larson Driver’s Stress Profile (LDSP) questionnaire [90] but were not informed of the criteria so as to not influence the scoring of their driving behavior. The LDSP, shown in Appendix B, was developed by psychiatrist Dr. John Larson for the AAA foundation for Traffic Safety and is a 40-question Likert scale instrument, grouped into four sub-groups of 10 questions each: Anger, Impatience, Competition, and Punishing Behaviors. Participants scored each question on a 0-3 scale (0 = never; 1 = sometimes; 2 = often; 3 = always). Scores were then summed up and participants with a summed score less than or equal to 21 were
classified as non-aggressive drivers, while those with greater scores were classified as aggressive drivers. This criteria was selected based on previous studies by Blanchard et al. [91] and Loretta et al. [92]. Consequently, there were 20 non-aggressive and 10 aggressive drivers from the subject pool. The validity of the LDSP questionnaire for determining aggressive and non-aggressive drivers has been thoroughly analyzed by Blanchard et al. [91] who found the instrument to be “sound, reliable, and valid scale for use with aggressive driving”.

6.3.3 Experiment Design and Procedure

The experiment was designed as a pre-post-test study with all thirty participants required to drive the simulator with and without the alert message system within the developed test bed scenario. The test route consisted of a divided four lane road within urban settings with corresponding road furniture. It had a solid double yellow line down the center, solid white lines on the outside edges, dashed white lines separating the two lanes that go in each direction, and on a flat grade with a posted speed limit of 35 mph. Drives with alert messages resulted in the warning messages being generated as described under ‘Design of Alert Message System’, while drives without the alert messages did not produce any warning messages.

Upon arrival at the driving simulator lab, participants were briefed on the experiment and asked to review the university’s IRB approved consent sheet before signing it. This was then followed by completing the LDSP questionnaire. Participants were then asked to draw a card to determine the order of their drives (with or without alert messages). The drives were randomly determined in order to nullify any learning effect. Each participant was then allowed to practice with the driving simulator until such time that they became familiar with the controls and its operation. The actual test then followed with participants being asked to drive as they would normally on their
way to work or college but to always stay in the right-lane, avoid changing lanes or overtaking, and maintain a consistent following distance that they considered as safe.

6.3.4 Data Collection and Analysis

Data was collected for only when the vehicles were within 20 seconds of approaching an intersection stop line due to earlier studies [83] suggesting 15 seconds as the minimum time required for drivers to react to warning messages at stop lines. Each participant’s velocity ($v$), lead vehicle’s velocity ($v_l$), and headway distance ($D_h$) between the participant’s vehicle and the lead vehicle for both drives were collected at 60 Hz frequency through the proprietary software of the driving simulator. The time-to-collision for each participant ($TTC_i$), defined as the time in seconds for the participant’s vehicle (of length $l$) to make contact with the lead vehicle, was calculated for each drive and for all the observations as follows:

$$TTC_i = \frac{D_h - l}{v - v_l}$$  \hspace{1cm} (6.1)

For each participant, the mean value of $TTC_i$ was then computed for each drive so that the final data consisted of one row of data for each participant containing four columns: participant ID; mean $TTC$ for the drive with alert messages; mean $TTC$ for the drive without alert messages; and the difference in means between the $TTC$s for the two drives. The data were then organized into two separate groups based on aggressive and non-aggressive drivers and analyzed separately.

Because the same participant carried out both drives, the samples were treated as dependent and subjected to a dependent t-test in ANOVA to find whether there were any differences in the driving behavior of the subjects as they were exposed to the alert messages. The paired sample test was appropriate as it did not impose an equal variance assumption on the two drives, and exclusively allots any difference between the mean $TTC$s for the two drives to the presence of the
alert messages. Prior to the t-test, the data was checked for violation of the normality assumption. All statistical analysis were undertaken using SAS Enterprise Guide 4.3.

6.4 Results and Discussion

A formal test of the normality assumption was performed for the difference in means between the TTCs for the two drives for all participants. The result (Shapiro-Wilk’s statistic = 0.9478, p = 0.1479) was not significant at 0.05 level of significance, and hence, the normality assumption was not rejected. This is a required assumption of the t-test for dependent samples.

The t-test for dependent samples was performed separately for the aggressive and non-aggressive drivers. The null and alternative hypotheses tested in each case were:

H₀: There is no significant difference between the mean TTC observed without and with alert messages.

H₁: There is a significant difference between the mean TTC observed without and with alert messages.

For non-aggressive drivers, the result [t (19) = -0.32, p = 0.7561] suggests that the null hypothesis cannot be rejected at a 5% level of significance. On the other hand, for aggressive drivers, the result [t (9) = 2.58, p = 0.0297] suggests that the null hypothesis can be rejected at the 5% level of significance, leading to the conclusion that the display of alert messages caused a significant difference in the driving behavior of aggressive drivers. Furthermore, Figure 6.6 shows the profile plots for the two groups of drivers: TTC values for the drives with and without alert messages.
Figure 6.6: TTC Profile Plot for Drivers with and without Alert Messages

The profile plot for the non-aggressive drivers suggests that while the difference between the drives with and without alert messages was not significant, the mean TTC for the drives with alert messages was slightly lower than the drives without alert messages. This means that for drives
without alert messages, the non-aggressive drivers drove with slightly more caution than they would normally do. Upon analysing their video data, it was obvious that a few of them tended to drive closer to the lead vehicle during the drive with the alert messages. When interviewed, they expressed that they knew they would be prompted by the alert messages when they were too close to the lead vehicle and that influence their driving behaviour.
7. SUMMARY AND CONCLUSIONS

7.1 Summary

The emerging connected vehicle technology is expected to improve transportation network operation and safety. In a connected vehicle environment, the information exchange between vehicles and between vehicles and the infrastructures will provide users with real-time awareness of the prevailing traffic conditions in the transportation network. This will improve traffic monitoring and management systems, and will lead to a better decision making process by drivers and transportation officials in a timely manner. The promising aspects of the connected vehicle technology are yet to be fully investigated in order to answer different questions on the system wide performance characteristics such as how effective the applications will be and what benefits can be realized prior to implementation; what infrastructure is needed; what minimum market penetration is required; and what technological specifications should be adopted, in order to address some of the system wide performance characteristics. In order to address the individual user performance characteristics of the connected vehicles technology, researchers need to answer questions on how people can benefit from the technology; what the people needs are; if there are safety benefits or drawbacks resulting from the use of the technology, among others.

The main objective of this research is to study the system wide and individual user performance characteristics of connected vehicle technology. For the system wide performance characteristics, a mathematical model was developed to measure the robustness and stability of the wireless communications between vehicles in connected vehicle environments. This model is referred to as the CONnectivity ROBustness (CONROB) model. CONROB model accounts for the traffic density in the network, the transmission range of the wireless channels in the equipped vehicles, the spatial distribution of the vehicles in the network, the spatial propagation of the wireless signal
over the network, and the market penetration. The connectivity robustness model was verified using a computer simulation test bed developed in VISSIM microsimulation software.

Connected vehicle technology provides a probe vehicle feature that allows collection of data. These data can help estimating traffic conditions in a transportation network. The accuracy of estimates is determined by quality of the collected data, which is impacted by different factors such as the market penetration, traffic density, and transmission range. These factors also affect the communication stability in the connected vehicle environments, and subsequently, this analogy offered the ability to apply CONROB model in predicting traffic conditions in the network. This was investigated using results obtained from the computer simulation model.

Road-Side Units (RSUs) in connected vehicle environments represent a vital component that creates a link between equipped vehicles in the network and Transportation Management Centers (TMCs). RSUs transmit traffic data collected by connected vehicles to the TMCs. Using the collected data, traffic conditions in the network are estimated and decisions, such as route choice, are made by the TMCs and relayed back to vehicles in the network through the RSUs.

The accuracy and reliability of the obtained estimates are affected by the RSUs locations. The optimal deployment of the RSUs is also an important factor that affects the communication stability in the network. Their optimal locations are identified as locations whereat connected vehicle clusters can be merged into larger ones that cover larger areas of the network. Thus, a GA-based optimization approach was developed to identify the optimal RSUs deployment plan with the objective function to maximize the network connectivity robustness.

The system wide characteristics were studied using a computer simulation model developed in VISSIM microsimulation platform. A 195 sq-miles road network in Washington County Oregon to the west of Portland city was coded in VISSIM and simulated for different market
penetration and traffic density values. Different MATLAB codes were developed to calculate the connectivity robustness over different time steps, estimate the traffic conditions in the network, and identify the optimal RSUs locations.

For the individual user performance characteristics, the human-in-the-loop LSU driving simulation platform was used to develop a connected vehicle test bed in order to study the impact of technology on the drivers’ behavior. Using the time-to-collision information, warning messages were disseminated to the drivers on a heads up display on the simulators’ screen. Two main types of messages were delivered: a yellow warning message showing “Slow Down” when the time-to-collision is less than 3 seconds, and a red warning message showing “Slow Down- Potential Crash” when the time-to-collision is less than 1.5 seconds. The 1.5-second threshold is based on previous studies that suggested this value as the minimum time-to-collision at which drivers start braking. The 3-second threshold, on the other hand, is assumed to allow enough time for the drivers to react before being in a potential crash situation (TTC < 1.5 seconds). A group of 30 licensed drivers were recruited for testing two different scenarios: the first scenario represents a regular vehicle when no warning messages are expected to be shown, and the second scenario represents an equipped vehicle that gives warning messages when a potential near crash situation is present (1.5 seconds TTC) or about to be present (3 seconds TTC). The vehicle trajectory data were collected for the two scenarios and grouped based on the aggressiveness of the drivers into two groups: one represents the conservative drivers and the other represents the aggressive drivers. The aggressiveness of the drivers was determined based on a designed questionnaire. Comparative statistical analysis was then performed to determine whether the connected vehicle technology is effective in reducing the crash risk and hence improving the drivers’ safety. The following sections present the main conclusions of the research based on the performed analysis of results.
7.2 Conclusions

7.2.1 Connectivity Robustness (CONROB) Model

The simulation results showed that the overall robustness increases as the market penetration increases, given the same transmission range, and relative traffic density. Similarly, the overall connectivity robustness increases as the relative traffic density increases for the same market penetration. More so, the connectivity robustness becomes more sensitive to the relative traffic density at higher values of transmission range and market penetration. The reason for this is that at higher market penetrations and as the traffic density increases the number of CV on the network increases which gives a better chance for better communication between vehicles, especially at higher transmission range values at which the area coverage is higher.

In order to measure the significance of the connectivity robustness against the parameters in the model, multiple regression analysis was performed on the simulation results. The results showed that the effect of relative traffic density, transmission range, and market penetration is significant at 95% confidence level, thereby supporting the simulation results as well as the significance of the tested variables in CONROB model.

It is clear that the simulation and statistical results conform to the effect and significance of the traffic density, transmission range, and market penetration in the literature. This proves the validity of CONROB model to be used as an indicator for the robustness and stability of communication in connected vehicle environments.

7.2.2 Predicting Estimation Accuracy of Traffic Conditions

The simulation results showed that the accuracy of the travel time estimates deteriorated with the higher traffic densities, especially for market penetration values up to 25%. Whereas, as the
market penetration increased to 50%, the accuracy improved over the different traffic density scenarios, except for the very high density values where the accuracy slightly deteriorated. Similarly, the reliability of the travel time estimates did not show a clear trend for market penetration values up to 25%. As the market penetration increased to 50%, the travel time estimates became more reliable for the different traffic density scenarios.

The connectivity robustness results showed similar performance to that of the travel time estimates. For market penetration values up to 25%, the network had low connectivity robustness values that did not change significantly as the traffic density increased. As the market penetration increased to 50%, the network connectivity robustness improved significantly.

The results showed that the travel time estimation accuracy and reliability are correlated with the network connectivity robustness. To further investigate this, regression analysis was performed between the connectivity robustness and the travel time estimation accuracy as well as between the connectivity robustness and the reliability of the travel time estimates. The results showed that the adjusted R² value for the regression model between the accuracy of travel time estimates as the dependent variable and the logarithm of connectivity robustness as the independent variable is 98% with a p-value less than 0.0001. Similarly, the adjusted R² value for the model between the estimates reliability and the logarithm of connectivity robustness is 88% with a p-value less than 0.0001. The resulting regression models can be used to predict the accuracy and the reliability of travel time estimates in transportation networks with specific connectivity robustness values, which supports the connectivity robustness model as a viable planning tool for connected vehicle environments.
7.2.3 Optimization of RSUs Deployment

The performance of the optimization approach was compared to the performance of the uniform deployment (equally spaced over the network) of RSUs for four scenarios: 42, 58, 68, and 111 RSUs. The results show that the GA approach was able to deploy the RSUs at locations whereat vehicles are moving in large numbers for the same market penetration rate. Finding these locations helped connecting more vehicles together which enabled covering larger areas over the road network. As a result, optimizing the RSUs significantly increased the connectivity robustness in the network. For the uniform deployment case, the improvement in the robustness was not as significant. The results also showed that by changing the RSUs deployment plan from uniform to optimal the gain in the connectivity robustness is more significant for the lower market penetration rates. As the number of RSUs increased, the connectivity robustness increased significantly, especially for the optimal deployment. This means that more vehicles became connected and larger network areas were covered, which means that more representative data about larger areas of the network can be obtained. This can help better estimate the traffic conditions in the network, and hence help achieve more efficient traffic management.

Overall, the performance of the proposed approach in the tested large scale network area showed that the road-side units’ deployment-optimization can still be achieved, especially with the network-level connectivity robustness performance metric. This supports the importance of CONROB model as a viable planning tool for connected vehicle environments.

7.2.4 Individual User Performance Characteristics

Upon carrying out a t-test for dependent samples for each group of drivers, the results showed that the non-aggressive drivers did not significantly change their driving behavior when exposed to the alert messages. On the other hand, aggressive drivers significantly changed their driving
performance by slowing down more at intersections and increasing their time-to-collision. It was also observed that aggressive drivers activated more alerts than the non-aggressive drivers, implying the alert message system was successful in altering their driving style. These findings show that connected vehicle technology has the potential to improve drivers’ safety if the warning alerts are properly designed to be delivered in a time manner. It is acknowledged that the sample size used in this research is a limitation; however, this is an exploratory research for the benefits of the connected vehicle technology on drivers’ safety.

7.3 Future Research

The study of the system wide and individual user performance characteristics supports the high potential of the emerging connected vehicle technology to provide an operable and safe transportation network. Yet, more research can be done to strengthen the practice-readiness of some of the research findings.

While the proposed connectivity robustness model proved to be a viable planning tool for connected vehicle environments, the associated travel time prediction models need further work to be done. The prediction models can be tested for more scenarios with higher traffic density and market penetration values as well as for different network configurations. This will make the travel time models able to deal with all the possible scenarios for connected vehicle environments, which also makes the models ready as reliable travel time prediction tools.

The successful development of the designed preliminary driving simulator test bed in this research means future sensitivity tests can be undertaken to ascertain the optimal moment to prompt the activation of the alert messages. The addition of audio prompts to the current visual alert system can also be explored and a larger sample size can be utilized to analyze demographic effects of such technology. In addition, other driving characteristics such as speed, acceleration
and time headways could be analyzed before and after the alert message in order to investigate potential adaptation effects in driving behavior. Furthermore, the preliminary test bed can be enhanced to allow more vehicles to communicate within the generated network of the driving simulator environment, and further benefits of the V2V technology explored.
REFERENCES


115


## APPENDIX A: LARSON DRIVER’S STRESS PROFILE (LDSP) QUESTIONNAIRE

### Are YOU an Aggressive Driver?

Take the Driver Stress Profile to Measure Your Hostility on the Road.

LARSON DRIVER’S STRESS TEST HAS BEEN REPRINTED WITH PERMISSION FROM AAA FOUNDATION AND DR. JOHN LARSON

### HOW DO YOU RATE?

<table>
<thead>
<tr>
<th>Anger</th>
<th>Competing</th>
</tr>
</thead>
<tbody>
<tr>
<td>Never (0)</td>
<td>Compete on the road.</td>
</tr>
<tr>
<td>Sometimes (1)</td>
<td>Compete with yourself.</td>
</tr>
<tr>
<td>Often (2)</td>
<td>Compete with other drivers.</td>
</tr>
<tr>
<td>Always (3)</td>
<td>Challenge other drivers.</td>
</tr>
<tr>
<td>Total</td>
<td>Race other drivers.</td>
</tr>
</tbody>
</table>

### ANGER
- Get angry at drivers.
- Get angry at fast drivers.
- Get angry at slow drivers.
- Get angry when cut off.
- Get angry at malfunctioning stoplights.
- Get angry at traffic jams.
- Spouse or friends tell you to calm down.
- Get angry at tailgaters.
- Get angry at your passengers.
- Get angry when multilane highway narrows.

### IMPATIENCE
- Impatient waiting for passengers to get in.
- So impatient, won't let car engine warm up.
- Impatient at stoplights.
- Impatient waiting in lines (car wash, bank).
- Impatient waiting for parking space.
- As passenger, impatient with driver.
- Impatient when car ahead slows down.
- Impatient if behind schedule on a trip.
- Impatient driving in far right, slow lane.

### PUNISHING
- Do you "punish" bad drivers?
- Complain to passengers about other drivers.
- Curse at other drivers.
- Make obscene gestures.
- Block cars trying to pass.
- Block cars trying to change lanes.
- Ride another car's tail.
- Brake suddenly to punish tailgater.
- Use high beams to punish bad driver.
- Seek personal encounter with bad driver.

### IMPATIENCE
- Total

### PUNISHING
- Total

---

[Complete contest ballot on opposite side]
ANGER
In certain circumstances, you may feel like you lose self-esteem or status by giving in and allowing a demanding driver to get his/her way. If the driver continues in the attempt to pass or cut you off, a dangerous situation may occur. Anger results when this type of behavior persists, escalates or if the other driver succeeds.
You will be much happier if you learn to enjoy your journey instead of letting yourself grow angry over petty road behavior. Be relaxed, listen to some soothing music or have a nice conversation with your passengers. When you think of driving, whether it is to work every day or on your vacation, don’t think of it as wasted time. Instead, relax and think of driving as worthwhile and pleasurable.
Plan ahead and allow yourself plenty of time to drive comfortably to your destination. This will allow you to deal with unforeseen situations like traffic jams that may set you back. Remember that if you are looking for drivers to yell at and cars to cut off, you will find them.

KEY REMINDERS TO CONTROL YOUR ANGER
• If another driver cuts you off or races by, program your response to be “Be my guest.”
• Instead of making good time, make time good!
• If you’re tempted to retaliate against another driver, think: “Would I want to fly in an airplane whose pilot was acting like this?”
• Instead of judging the other driver, try to imagine why he or she is driving that way.

IMPATIENCE
When you begin to feel your blood boil, give the other drivers the benefit of the doubt and treat them how you would like to be treated. This will make for a more pleasant driving experience.
If you approach driving with an attitude of willingness to cooperate and accommodate other drivers, you will be a much safer driver.
If you think another car is driving too slowly and you are unable to pass, pull back and allow more space, not less. That way, if the car does something unexpected you will have time to get out of the way. If you attempt to pressure the driver in front of you by following as closely as possible, an accident is much more probable.

KEY REMINDERS TO IMPROVE YOUR PATIENCE
• Don’t get mad at people who go the speed limit. It’s the law, and everyone should follow it.
• Allow at least a two-second space between your car and the car ahead.
• When growing impatient with a driver, act as if he or she is a guest in your home.

COMPETING
There are plenty of times and many other places to partake in games, but on the road is not one of them. For too many motorists on the road today, driving has become a contest.
The most important actions you can take to avoid aggressive and competitive driving take place inside your head. Change your approach to driving to make your trips more enjoyable. If you insist on playing a game, see how nice you can be to other drivers.
When you begin to speed and pass other drivers on the highway because of a game only you are playing, ask yourself, “Is this worth dying for?” Highways are too dangerous for games.

KEY REMINDERS TO FORGET BEING COMPETITIVE
• The more you speed, the less you experience your surroundings.
• Enjoy the ride with your companions. If you race and compete you may actually upset yourself and your passengers.
• Instead of thinking that winning is everything, start to think that making it to your destination safely is the only thing that matters.
• Allow more time for your trips. You’ll be amazed at how much more relaxed you will be when you have a few extra minutes.

PUNISHING
It is rarely helpful to other drivers, yourself and least of all your passengers, for you to assume the responsibility of punishing other motorists. This is a job that should be left to the police. Attempting to take things into your own hands is likely to inflame the situation and put you and your passengers at risk.
Change your attitude toward other drivers’ aggressive driving habits. Keep in mind that they are likely not motivated by personal intention to harm, threaten, or endanger you. They may be inattentive, forgetful, extremely fatigued or have bad driving habits.
Punishment, coming from someone who really has no authority in the matter, is not perceived as punishment by the other driver. Instead, they will perceive it as “sticking your nose in their business.”

KEY REMINDERS TO STEER CLEAR OF PUNISHING
• Punishing other drivers will only aggravate them more.
• If you believe another driver is attempting to start a fight, immediately get help. Do not get out of your car and do not go home.
• Being annoyed at other drivers’ bad driving habits can only happen if you let it. You can’t control other drivers. You can only control your reaction to them.
• If you notice an aggressive driver, pull over safely and take down as much information as you can including details of the situation and vehicle information. Then call the local non emergency police service number to report this information.

Once you have completed and filled out this entry form, cut and place in a bullet box located in one of the centerpieces.

1. Based on your driver stress profile what is one habit you need to work on?
2. Identify one driving habit that you have that shows courtesy to other drivers.

Name ___________________________ Phone ___________________________
Master # ___________________________
APPENDIX B: TEST BED SURVEY QUESTIONS

Can Cars Talk in the Future?

Are you willing to drive in an environment where cars are able to talk to each other? In the near future, cars will be able to send and receive information about traffic conditions. Vehicles can communicate with each other as well as with the infrastructure and this information can be brought to you. This technology could transform the nation’s surface transportation safety, mobility, and environmental performance.

The Department of Civil Engineering at I.S.U has been working on ways to design this technology, in the I.S.U Driving Simulator. This five minutes survey will help us answer the questions of whether you as a driver would benefit from receiving information to your vehicle, what type of information, and what would be the best way to present it to you. More information can be seen in the following videos, http://youtu.be/T8Rg5530-8 & http://youtu.be/ajlMgDZMRU

* 1. If information about traffic conditions, traffic incidents, hazards, congestion, and potential detour routes ahead of you are presented to you on a display in your vehicle would that benefit you?

  ○ Yes
  ○ No
### Can Cars Talk in the Future?

**2.** If you are approaching a signalized intersection, would you think it is beneficial to get information about the traffic light timing in your car?
- [ ] Yes
- [ ] No

**3.** If yes, choose the applicable answers

<table>
<thead>
<tr>
<th>Least Important</th>
<th>Most Important</th>
<th>N/A</th>
</tr>
</thead>
<tbody>
<tr>
<td>Amount of Remaining Green Time</td>
<td></td>
<td></td>
</tr>
<tr>
<td>Amount of Remaining Yellow Time</td>
<td></td>
<td></td>
</tr>
<tr>
<td>Amount of Remaining Red Time</td>
<td></td>
<td></td>
</tr>
</tbody>
</table>

**4.** Would you want to get information about whether the lane you occupy is a right turn lane ONLY, left turn lane Only, or shared lane presented on a screen in your car?
- [ ] Yes
- [ ] No

**5.** Please rank how important the lane usage information is to you, with 1 being least important and 5 being very important
- [ ] 1
- [ ] 2
- [ ] 3
- [ ] 4
- [ ] 5
Can Cars Talk in the Future?

*6. While you are on the roadway, which of the following signs do you feel would be beneficial to be displayed as a warning message in your vehicle?

<table>
<thead>
<tr>
<th>Sign</th>
<th>Least Important</th>
<th>Most Important</th>
<th>N/A</th>
</tr>
</thead>
<tbody>
<tr>
<td>Stop Sign</td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>Yield Sign</td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>Merging Zone</td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>Speed Limit</td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>School Zone</td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>Right Turn OK</td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>Other</td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>Other (please specify)</td>
<td></td>
<td></td>
<td></td>
</tr>
</tbody>
</table>

*7. While approaching an intersection, do you think it is beneficial to get warning messages on a display in your car telling you whether it is safe to cross or not?

- Yes
- No

*8. Please rank how important you feel the conflicting vehicle warning information is, with 1 being least important and 5 being most important

1  2  3  4  5

*9. Would you like to get information displayed on a screen in your car about whether a pedestrian is about to cross the street, displayed as a warning message in your vehicle?

- Yes
- No
<table>
<thead>
<tr>
<th>Question</th>
<th>Options</th>
</tr>
</thead>
<tbody>
<tr>
<td>*10. Please rank how important the crossing pedestrian information is to you, with 1 being least important and 5 being most important.</td>
<td>1, 2, 3, 4, 5</td>
</tr>
<tr>
<td>*11. At an interstate, would you find it beneficial to know whether it is safe to merge at the end of on-ramps presented on a display in your car?</td>
<td>Yes, No</td>
</tr>
<tr>
<td>*12. Please rank how important the on-ramp safe merging information is to you, with 1 being least important and 5 being most important.</td>
<td>1, 2, 3, 4, 5</td>
</tr>
<tr>
<td>*13. Would you find it beneficial to receive and display in your vehicle, any information about a traffic incident ahead of you, and to know potential detour routes?</td>
<td>Yes, No</td>
</tr>
</tbody>
</table>
Can Cars Talk in the Future?

14. Please rank how important the incident information is to you, with 1 being least important and 5 being most important
   - [ ] 1
   - [ ] 2
   - [ ] 3
   - [ ] 4
   - [ ] 5

15. Based on your previous answers, do you think you are able to react to more than one piece of information at the same time?
   - [ ] Yes
   - [ ] No

16. How much information? (Specify how many pieces of information)
   [ ]
Can Cars Talk in the Future?

Shown are four potential display locations in your vehicle.

* 17. Which location from the above image is preferred?
   - 1
   - 2
   - 3

* 18. How would you like information to be given to you?
   - [ ] Images
   - [ ] Numbers
   - [ ] Audio Alerts

The Department of Civil Engineering at LSU would like to thank you for participating in our survey. If you would like to participate in experiments with the LSU Driving Simulator to test new technology, please put your contact information in the comment box below. Thank You.
Can Cars Talk in the Future?

19. Email Address

20. Phone Number

We would like to thank you for participating in our survey. Please feel free to comment below about the technology.

21. Comments
APPENDIX C: WRITTEN APPROVALS FOR PUBLISHED WORK

C-1- Approval to use a paper titled “A network level connectivity robustness measure for connected vehicle environments” in Chapter 3

From: Osama Osman
Sent: Tuesday, October 27, 2015 1:02 PM
To: permissionshelpdesk@elsevier.com
Subject: Written approval to include published work in a doctoral dissertation

Sir/Madam,

I am Osama Osman, a doctoral student at Louisiana State University and the first author on the paper titled “A network level connectivity robustness measure for connected vehicle environments” that was published in the Journal of Transportation Research Part C with the DOI: 10.1016/j.trc.2015.01.023. I am writing this email to request a written approval to include this paper in my dissertation that could be viewable on the college website. I would appreciate your prompt response as my dissertation has to be submitted to the graduate school within a week.

From: Permissions Helpdesk <permissionshelpdesk@elsevier.com>
Sent: Tuesday, October 27, 2015 1:04 PM
To: Osama Osman
Subject: RE: Written approval to include published work in a doctoral dissertation

Dear Osama:

As an Elsevier journal author, you retain the right to include the article in a thesis or dissertation (provided that this is not to be published commercially) whether in part or in toto; see [http://www.elsevier.com/about/company-information/policies/copyright#Author%20Rights](http://www.elsevier.com/about/company-information/policies/copyright#Author%20Rights) for more information. As this is a retained right, no written permission is necessary provided that proper acknowledgement is given.

This extends to the online version of your dissertation and would include any version of the article including the final published version provided that it is not available as an individual download but only embedded within the dissertation itself.

If the article would be available as an individual download, only the preprint or (subject to the journal-specific embargo date) accepted manuscript version, but not the final published version, may be made available; see [http://www.elsevier.com/journal-authors/sharing-your-article](http://www.elsevier.com/journal-authors/sharing-your-article) for more information. The embargo date for Transportation Research Part C is 36 months from final publication; see [http://www.elsevier.com/__data/assets/pdf_file/0018/121293/external-embargo-list.pdf](http://www.elsevier.com/__data/assets/pdf_file/0018/121293/external-embargo-list.pdf)

If I may be of further assistance, please let me know.

Best of luck with your dissertation and best regards,

Hop

Hop Wechsler
Permissions Helpdesk Manager
Elsevier
1600 John F. Kennedy Boulevard
Suite 1800
Philadelphia, PA 19103-2899
Tel: +1-215-239-3520
Mobile: +1-215-900-5674
Fax: +1-215-239-3805
E-mail: h.wechsler@elsevier.com
Contact the Permissions Helpdesk: [+1-800-523-4069 x 3808 permissionshelpdesk@elsevier.com](tel:+1-800-523-4069)
C-2- Approval to use a paper titled “Impact of Time-to-Collision Information on Driving Behavior in Connected Vehicle Environments Using A driving Simulator Test Bed” in Chapter 6

发件人: Osama Osman <othabel1@lsu.edu>
发送时间: 2015年10月27日 星期二
收件人: "jtle@ejournal.net" <jtle@ejournal.net>
抄送: Sherif S Ishak <sishak@lsu.edu>
主题: Written approval to include published work in a doctoral dissertation

Sir/Madam,

I am Osama Osman, a doctoral student at Louisiana State University and the first author on the paper titled “Impact of Time-to-Collision Information on Driving Behavior in Connected Vehicle Environments Using A driving Simulator Test Bed” that was published in your prestigious journal with the DOI: 10.12720/jtle.3.1.18-24. I am writing this email to request a written approval to include this paper in my dissertation that could be viewable on the college website. I would appreciate your prompt response as my dissertation has to be submitted to the graduate school within a week.

From: Jtle <jtle@ejournal.net>
Sent: Thursday, October 29, 2015 9:40 PM
To: Osama Osman
Subject: Re:Written approval to include published work in a doctoral dissertation

Dear sir,

You have our permission to include this paper in your dissertation on the condition that where this paper has been orginally published could be referred to.

Best regards

Shira.W.Lu
APPENDIX D: IRB FORM FOR HUMAN SUBJECT EXPERIMENTS

ACTION ON PROTOCOL CONTINUATION REQUEST

TO:       Sherif Ishak
          Civil Engineering

FROM:     Dennis Landin
          Chair, Institutional Review Board

DATE:     May 8, 2015

RE:       IRB# 3505

TITLE:    Safety Assessment of Connected Vehicles Technology using a Driving Simulator

New Protocol/Modification/Continuation:  Continuation

Review type:  Full ___ Expedited X ___ Review date: 5/8/2015

Risk Factor:  Minimal ___ X ___ Uncertain ________ Greater Than Minimal ______

Approved X ___ Disapproved ______

Approval Date: 5/8/2015  Approval Expiration Date: 5/7/2016

Re-review frequency: (annual unless otherwise stated)

Number of subjects approved: __30__

LSU Proposal Number (if applicable):

Protocol Matches Scope of Work in Grant proposal: (if applicable) ___

By: Dennis Landin, Chairman

PRINCIPAL INVESTIGATOR: PLEASE READ THE FOLLOWING –
Continuing approval is CONDITIONAL on:
1. Adherence to the approved protocol, familiarity with, and adherence to the ethical standards of the Belmont Report, and LSU's Assurance of Compliance with DHHS regulations for the protection of human subjects*
2. Prior approval of a change in protocol, including revision of the consent documents or an increase in the number of subjects over that approved.
3. Obtaining renewed approval (or submittal of a termination report), prior to the approval expiration date, upon request by the IRB office (irrespective of when the project actually begins): notification of project termination.
4. Retention of documentation of informed consent and study records for at least 3 years after the study ends.
5. Continuing attention to the physical and psychological well-being and informed consent of the individual participants, including notification of new information that might affect consent.
6. A prompt report to the IRB of any adverse event affecting a participant potentially arising from the study.
8. SPECIAL NOTE:
   *All investigators and support staff have access to copies of the Belmont Report, LSU’s Assurance with DHHS, DHHS (45 CFR 46) and FDA regulations governing use of human subjects, and other relevant documents in print in this office or on our World Wide Web site at http://www.lsu.edu/irb

131
VITA

Osama Abdulmonaem Osman was born in Benghazi, Libya, in 1984. He received his B.S. degree in civil engineering from Cairo University, Egypt, in 2006. In 2010, Osama received the M.S. degree in transportation engineering from Cairo University, Egypt. He is currently pursuing his PhD degree in transportation engineering at Louisiana State University, Louisiana, USA.

From 2006 to 2010, he worked as a Teaching and Research Assistant at the Civil Engineering Department at Cairo University in Egypt. During the same time, Osama was also working as a laboratory engineer with the Highway, Traffic, and Airport Engineering Laboratory, and he was also working as a Traffic Engineer for a Consultancy Company that was doing projects in the Middle East and Africa. Since 2011, he has been a Research Assistant at the Louisiana State University. His research interests include operation and optimization of connected vehicles environments, drivers’ behavior in connected vehicles environments, traffic operation and management, and traffic modeling.

Mr. Osman is a member of the Golden Key International Honors Society, student member of the Institute of Transportation Engineers, American Society of Civil Engineering, and Gulf Region Intelligent Transportation Society. He is also an active reviewer for the Journal of Transportation Research Record, the Canadian Journal of Civil Engineering, Journal of Advanced Transportation, and the IEEE Transactions on Intelligent Transportation Systems. He is the beneficiary of the Troy H. Middleton Graduate Scholarship.