ABSTRACT

PAI, VISHWESH. Effects of VANETs on Vehicle Transit Time and Average Speed in Realistic Scenarios. (Under the direction of Dr. Mihail Sichitiu).

Vehicular Ad-hoc Networks (VANETs) have recently attracted a lot of attention due to the possibility of improving safety and performance of transportation on public roads. In addition to other benefits VANETs can reduce or eliminate congestion by redirecting vehicles around traffic jams.

In this thesis, we quantify the reduction in transit time and increase in average speeds in vehicular systems by employing VANET technology. We use detailed simulations to evaluate the effects of number of vehicles on the road, penetration ratio, number of incidents and transmission range parameters on the vehicular transit time and average speed. Results show a significant increase in average speeds and a reduction in transit time in congestion scenarios caused either by traffic incidents or traffic overload.

Effects of VANETs on Vehicle Transit Time and Average Speed in Realistic Scenarios

by
Vishwesh Pai

A thesis submitted to the Graduate Faculty of
North Carolina State University
in partial fullfillment of the
requirements for the Degree of
Master of Science

Computer Engineering

Raleigh, North Carolina

2009

APPROVED BY:

Dr. Rudra Dutta

Dr. Yannis Viniotis

Dr. Mihail Sichitiu
Chair of Advisory Committee

DEDICATION

To my parents ...

BIOGRAPHY

Vishwesh Pai was born in Karwar, Karnataka, India. He earned a Bachelor of Engineering (B.E) degree in Electronics and Communication from SDM college, Dharwad in July, 2005. He worked as a Software Engineer with the 21st century network (V21) team in Infosys Technologies Limited, Bangalore. In Fall 2007, he joined North Carolina State University for graduate studies in Computer Engineering, and became a member of the Wireless and Local Area Networks (WALAN) research group. During Summer of 2008, Vishwesh worked full time as an Intern at Qualcomm Inc., in San Diego, CA in their Wireless Connectivity Software Group.

ACKNOWLEDGMENTS

My foremost thanks to my advisor, Dr. Mihail Sichitiu for his constant guidance and support over the last two years. I am indebted to him for his innumerable ideas about the research work and his help, both technical and otherwise. Without his help and guidance, this work would never have come to fruition. I thank Dr. Yannis Viniotis and Dr. Rudra Dutta for agreeing to be on my thesis committee. I thank Kishore and Mandar for their earlier contributions and suggestions to my work.

I would like to particularly thank Vineet, Rachana, Laxminarayan and Mani for several lively discussions related to my research. I would also like to thank all my present and past roomies Arjun, Kiran, Suraj, Swaroop and Phani, who have been of great support to me. I thank my friends from the Infy Gang, SDM and NC State University who played an important role in my success here. I am also very grateful to my sister, Deepa for her support, love and friendship.

Finally, I reserve my highest gratitude for my parents, family and all my alma mater for the quality education they imparted to me. I am forever indebted to my parents, to whom I dedicate this thesis.

TABLE OF CONTENTS

LIST OF TABLES

LIST OF FIGURES

Chapter 1

Introduction

1.1 Motivation

According to the U.S. National Highway Traffic Safety Administration [3], 5.97 million police-reported traffic accidents took place in the year 2006, which led to 38,588 fatalities and 1.75 million injuries. The economical loss was 230.6 billion dollars. Each day an average American spends about 2.5 hours in his vehicle, a significant percentage of this time in traffic jams and at stop lights. The statistics are similar in many other parts of the world.

A Texas Transportation Institute(TTI) [1] shows that:

- From 1982, the yearly delay per peak period traveler during rush hour, has increased from 16 to 47 hours.

- From 1982 to 2003, the number of urban areas having more than 20 hours of annual delay per peak traveler, has increased from 5 to 51 areas.

- In 2003, the total amount of delay was 3.7 billion hours, and

- Due to idling in traffic jams, 2.3 billion gallons of fuel is wasted every year.

Congestion can arise from any one of the reasons mentioned below:

- Bottleneck Points are mainly due to normal traffic demands that cause traffic congestion. This type is currently the largest source for congestion.

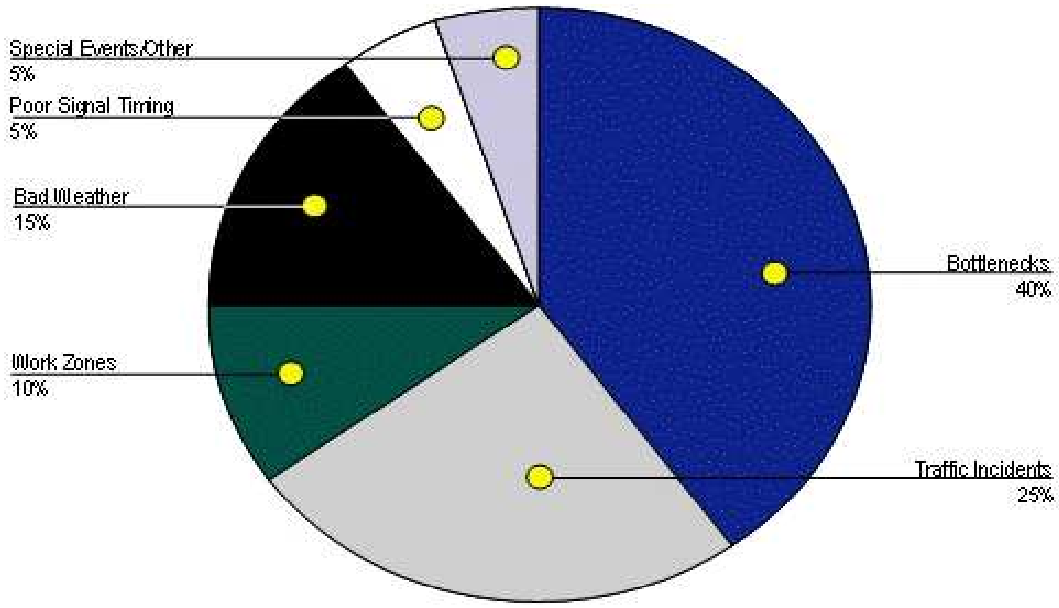

Figure 1.1: Sources of Congestion according to TTI [1]

- Traffic incidents such as vehicle crashes, debris or halts on the road.
- Work zones including road construction or maintenance activities which can more or less be decreased by planning before and giving alternate routes for traffic. Examples of maintenance activities include pothole fillings, manhole repairs, etc.
- Bad weather can also cause congestion. The severity of congestion can be reduced by informing travelers before hand.
- Poor traffic signal timing due to incorrect allocation of time slots for red and green light at a traffic signal or because of wear and tear of the lights.
- Special events like public meetings, rock concerts, demonstrations, etc. can cause a sudden increase of traffic in a certain place and can lead to major congestion for a certain period. This kind of congestion is very irregular, but measures like diversion of traffic can be implemented.

Figure 1.1 depicts the results of a national study on sources of traffic congestion. The two main reasons of congestion are, bottleneck points and traffic incidents. These account for *two-thirds* of congestion problems in 85 of the largest metropolitan areas in USA [4]. In this thesis, the focus is on these two sources of congestion namely, bottlenecks due to high traffic demand and traffic incidents from crashes.

1.2 VANETs

Vehicular Ad-Hoc Networks (VANET) is a technology that provides communications between nearby vehicles without relying on road-side network infrastructure. Every participating vehicle becomes a wireless router, allowing vehicles nearby to exchange data. VANETs primary goals are providing safety and comfort to passengers. VANETs may provide answers to questions such as: What is the wait time at the toll booth for the approaching vehicle? What is the average speed of vehicles four miles up ahead on the road? Was there an accident nearby? In all these situations, messages are sent to inform the driver to either approach the area with caution or adopt a different route to destination if such a route exists. Other problems like automatic payment for parking lots and toll collection can also be solved using VANETs. Collision warning, road sign alarms and real-time traffic updates will give the driver a comprehensive real time view of the vehicular network, thereby allowing his *navigation system* to choose the best path based on *real time* updates.

The same services can be provided by a roadside network, but ubiquitous deployment of such infrastructure is prohibitively expensive. Dedicated short-range communications (DSRC) [5], is a vehicle-to-vehicle and vehicle-to-roadside link layer and IEEE 802.11 standard group has added 802.11p [6] extensions for the same purpose. Currently, many auto manufacturers such as GM, Honda and Toyota are considering implementing the technology in their vehicles.

1.3 Contribution

In this thesis, we show the effect of both, scenario parameters (e.g., number of cars, penetration ratio, number of incidents) as well as the network parameters (e.g., transmission range, zone of relevance), on the average speed and transit time of vehicles from source to destination. Simulations are used to study the parameters that directly affect the end user experience. A vehicle's routing decision is based on the information it receives from a congestion warning message. In this thesis, we analyze how a VANET equipment improves the transit time and average speed of a vehicle journey in different city maps with life like situations.

For the simulation, Scalable Data Lookup and Replication Framework for Mobile Ad-hoc Networks (SWANS) [2] for the networking infrastructure and STreet RAndom Waypoint (STRAW) [7] a vehicular mobility model for network simulations is used. The vehicular mobility is considerably changed and improved in this thesis. At the network layer, Distributed Robust Geocast (DRG) [8] protocol is used, which efficiently propagates the message through the congested region and delivers it to all appropriate nodes (vehicles).

1.4 Thesis Organization

The rest of the thesis is organized as follows: Chapter 2 describes the related work. Chapter 3 discusses the simulation setup, the tools used, the networking stack along with geocast protocol. Chapter 3 also describes the traffic model along with parameters which affects the various scenarios (Manhattan, Raleigh downtown and I-40 highway) of an experiment. Chapter 4 summarizes the results, while Chapter 5 concludes the thesis with future work.

Chapter 2

Background

In this section an overview of current research topics pertaining to VANET technology. This is review of the VANET research in the following networking layers from bottom up.

2.1 Data Link Layer

As wireless communications are inherently broadcast, a medium access control (MAC) layer has to be implemented in practically all VANET systems. In VANET systems the fast and slow fading effects could lead to problems as both the transmitter and the receiver can move towards each other. There are several network access technologies that are being considered for deployment to enable V2V communication in VANETs. These technologies include but are not limited to: IEEE 802.11, Bluetooth and cellular networks. These technologies have their pros and cons when applied to V2V communication as they are not specifically designed for such an application. The IEEE 802.11 MAC layer, is by far the most commonly used MAC layer protocol to evaluate the performance of VANET systems. Bluetooth is a widely known standard for short range wireless data communications. Several researchers have proposed Bluetooth based V2V communication systems. The limitations of such a technology are that it cannot support a huge volume of traffic. Recently, a DSRC [5] standard with very high data rates for vehicular communications has been proposed and approved. The MAC layer of DSRC is similar to 802.11a [9].

The IEEE 802.11p [6] defines enhancements for 802.11 required to support Intelligent Transportation Systems (ITS) or VANET applications. In these systems the physical layer properties change rapidly and very short-duration communications exchanges are required. In these situations IEEE 802.11 devices can use Wireless Access in Vehicular Environments (WAVE) mode of operation. This standard provides minimum set of specifications for interoperability among wireless devices requiring to communicate in rapidly changing environments and in smaller time frames not supported by with infrastructure or ad hoc 802.11 networks. Particularly, this standards accommodates time frames that are shorter than the amount of time required to perform standard authentication and association to join a BSS (Basic Service Set). Currently there several outstanding comments yet to be resolved along with a most significant question that "will STA be able to communicate outside the scope of a BSS while that STA is still joined with a BSS?" [10]. Until these comments are not resolved the enhancements cannot be finalized for 802.11p.

2.2 Network Layer

In VANET systems, the network layer is traditionally responsible for naming the elements of the network (addressing), routing and forwarding data between sources and destinations. Here data has to be forwarded in multiple hops from a sender to one or several receivers. A few of the proposed protocols are tested on small testbeds, the vast majority, however, rely on simulations with a varying degree of detail [11, 12]. A VANET system has no physical boundaries and vehicles in a an area (street/county/state/country) can form a VANET system. Clearly, the capacity of such a large system does not scale, therefore, usually it is assumed that data is only forwarded only forwarded to vehicles within a specific target area.

The network layer in VANET can either use fixed or geographical addressing. The address mapping between the network layer and applications can be done as follows:

- If fixed addresses are used in an VANET system, a message query may flood the target area. The vehicles in the target area will reply with their fixed addresses. Then the message can be unicasted to each vehicle (or better yet, multicasted).

- If geographical addresses are used, an additional identification field may augment the geographical address, e.g., destination is a vehicle up to one mile behind and a unique

Vehicle Identification Number (VIN), such that the message is delivered to only one vehicle.

2.3 Transport Layer

In this section we will discuss the current state of research regarding the transport layer (including end-to-end quality of service (QoS) issues) and security for VANET systems. The transport layer is typically responsible for providing end-to-end services, e.g., reliability, flow control and congestion control. In comparison to the other layers, relatively few papers focus on the transport layer. Without end-to-end guarantees of QoS, many of the potential applications will not be feasible. For example, in collision warning applications, it was shown that in the absence of a congestion control mechanism, the vital information may encounter unacceptable delays. Some applications [13] may need congestion control mechanisms to avoid network overload and long delays.

Therefore, the routing protocols that have been proposed for VANET systems can be classified into three basic groups:

- Unicast routing with fixed addresses may be used by applications (e.g., on board games and file transfer).
- Unicast routing with geographical addresses may be used to increase routing efficiency in the same type of applications as in unicast with fixed addressing.
- Although, theoretically possible, multicast routing with fixed addresses would incur a huge overhead in maintaining the multicast groups. Most envisioned applications in VANET systems will require multicast routing with geographical addresses, (e.g., crash warning messages and traffic monitoring applications).

2.4 Security Layer

When the VANET systems will be extensively deployed, they in essence will become the largest open access ad hoc networks in existence. The right balance between security and privacy of this network will be of utmost importance for its long term success.

So far, general security issues have not been solved. Most papers on security present solutions for very specific problems. In [14] it is suggested that all vehicles should have electronic license plates that have the same functions as ordinary license plates while offering several advantages, e.g., chasing assistance from parked cars tracking the fugitive vehicle[15] investigates how forged position information can affect both the performance and security of VANET systems.

2.5 Applications

The applications in VANET range from public safety, traffic management and coordination to applications like traveler information and comfort. Each of these applications require a CPU, Wireless Transceiver, GPS and a Graphical User Interface(GUI).

Public safety applications are geared primarily towards avoiding accidents and loss of life. Collision warning systems have the potential to reduce the number of vehicle collisions in several scenarios. Traffic management applications are focused on improving traffic flow, thus reducing both congestion as well as accidents [16].

Platooning [17, 18], i.e., forming tight columns of vehicles closely following each other on highways, has the potential to radically increase the capacity of existing highways. High speed closed loop control is of paramount importance for this application. Passing and lane change assistance may reduce or eliminate risks during these maneuvers.

Traveler information applications provide updated local information, maps, and general messages limited in space and/or time. The main focus of comfort applications is to make travel more pleasant. This class of applications [19, 20] may be motivated by the desire of the passengers to communicate either with other vehicles or with ground based destinations, e.g., Internet hosts or the public service telephone networks (PSTN).

2.6 Projects

There are many research projects around the world which focus on VANET systems. In this section some of the prominent projects are PATH [21], CarTalk2000 [22] and a few other relevant projects are briefly discussed.

The PATH project is a collaboration between the California Department of Transportation (Caltrans), the University of California, other public and private academic institutions, and the industry. The main mission is to apply advanced technology to increase highway capacity and safety, and to reduce traffic congestion, air pollution, and energy consumption. PATH has generated a number of publications and prototypes in the area of IVC systems primarily focused on cooperative driving and vehicle platooning, for example [18, 23]. As part of the project they developed SHIFT, a fairly realistic traffic simulator that also integrates communication components, being, thus, especially suitable for the evaluation of IVC systems [24]. As part of the PATH project, a successful experiment with 8 vehicles in a platoon formation [23] was demonstrated.

The paper [25] proposes a joint model for mobility and communication in vehicle to vehicle network. This is one of first attempts to combine the two aspects in V2V networks. The paper integrates the effect of congestion in V2V networks. This model is based on an earlier model using a Enskog dense gas modeling of the traffic flow. The paper shows that the model is realistic and numerical simulations also verify the results. This application can cause oscillation waves in the traffic flow, which have so far not been recognized in literature.

CarTalk 2000 [22] was funded by the European Union within the 5th Framework program. The partners in the project were Daimler-Chrysler AG, Centro Ricerche Fiat, Robert Bosch GmbH, Siemens, Netherlands organization for applied scientific research, University of Cologne, and University of Stuttgart. An overview of the project can be found in [26]. The main objectives of the project were the development of cooperative driver assistance systems and of a self-organizing ad-hoc radio network as the basis for communication with the aim of preparing a future standard.

The E-road project [27] focuses on collaborative computing aspects required for traffic monitoring in a VANET system. The Drive-thru-Internet [28] project is experimenting with 802.11-based SRVC systems.

In Europe, there are several ongoing projects that include VANET systems. SAFESPOT [29] is an integrated research project co-funded by the European Commission Information Society Technologies among the initiatives of the 6th Framework Program. The objective of the project is to understand how intelligent vehicles and intelligent roads can cooperate to increase the road safety.

PReVENT [30] is another integrated project within the European Union. One of the objectives of this project is to contribute to the congregation and cooperation of European and national organizations and their road transport safety initiatives. One of its sub-projects is WILLWARN that is developing a communication-based system that extends the drivers horizon and intelligently warns the driver of dangerous situations ahead.

COMeSafety [31] is a recently started project that is focused on all issues related to vehicle-to-vehicle and vehicle-to-infrastructure communications as the basis for co-operative intelligent road transport systems. The Car2Car Communication Consortium [32], a non-profit organization initiated by the European vehicle manufacturers that is open for suppliers, research organizations and other partners. The main objective here is to increase road traffic safety and efficiency by means of inter-vehicle communication.

Several of these projects demonstrate vehicle-to-vehicle and roadside-to-vehicle communication on small testbeds.

2.7 Summary

It is clear that there has been substantial ground work in the area. However, there is ample scope for research on comprehensive networking and transport layer solutions that can cater to several classes of applications. Another significant aspect in this domain that needs attention is the practical evaluation of tools; this becomes important considering the difficulties in testbed evaluation. The practical evaluation of tools can be considered in analogy to what ns-2 [33] showcased in the traditional networking world.

When deployed VANET systems can facilitate several classes of applications that can make road travel safer (by avoiding many types of collisions), enhance efficiency (by decreasing travel time, avoiding traffic congestion and increasing road capacity), as well as make the driving experience more enjoyable (through locally updated information). A interesting feature of VANET systems is that they do not depend on road-side infrastructure, commonly thought to be too expensive to be ubiquitous in the near future.

This thesis uses a realistic simulator to evaluate the advantages of VANET systems. The key parameters studied here are a comparison of average speed along with transit time for vehicles with and without VANET equipment on different city scenarios. Thus, the performance of the entire VANET system is evaluated.

Chapter 3

Simulation Setup

In this chapter, we discuss the simulation setup used in this thesis. The tools used for network and vehicle traffic are discussed first and then we discuss mobility model used for vehicle movement.

3.1 Simulation Tools

3.1.1 JiST/SWANS

The JAVA-based network simulator JiST/SWANS was developed at Cornell University [2]. Java in Simulation Time (JiST) is a discrete simulation engine that runs over a standard Java virtual machine. This is done by embedding simulation time semantics at the byte-code level. In other words JiST converts a virtual machine into a simulation platform where all the Java programs can run normally. Scalable Wireless Ad hoc Network Simulator (SWANS) is a simulator that is built on top of JiST and contains software components to form complete wireless network configurations. Figure 3.1 shows some of the major components and how they interact. As shown in the figure, the whole simulation can be partitioned into several smaller ones, each with its own field and environmental parameters.

3.1.2 STRAW

The STreet RAndom Waypoint (STRAW) [7], is a vehicular mobility model which was implemented on JiST/SWANS. STRAW uses map data for real cities from the Topologically Integrated Geographic Encoding and Referencing (TIGER) [34] system available

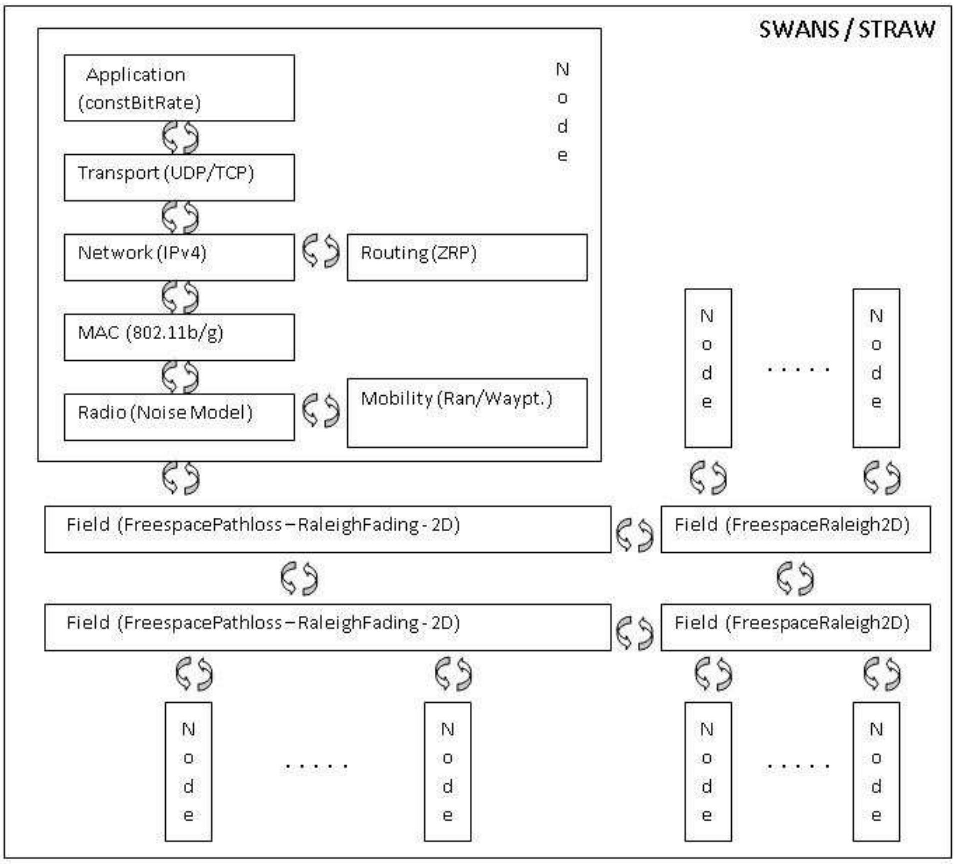

Figure 3.1: SWANS Basic Components Model [2]

from the US Census Bureau Geography. STRAW uses a car-following model (described in 3.4.3) for defining mobility of vehicles within a road segment. Vehicles encounter stop signs or traffic signals depending on the class of the road as defined in TIGER files; the timings of traffic signals are also controlled based on the road class. An admission control mechanism, based on the room on the next road segment, is used to model mobility at an intersection. The vehicle route planning can be done by specifying an origin-destination pair, or vehicles can move randomly by selecting a random direction at an intersection. The TIGER files and mobility model used in this work are discussed in detail in Section 3.4.

3.2 Networking Stack

The physical layer components are responsible for modeling signal propagation between radios and node mobility. Radios transmit packets and other radios receive the packets, if they are within the range of the transmission. A freespace pathloss model [35] and a Rayleigh fading model [36] is used for the simulations.

The MAC layer issues of vehicle-to-vehicle communication are not considered in detail and it is assumed that an efficient network access technology is used. The IEEE 802.11b implementation of SWANS is used at the MAC layer. The SAN implementation includes the complete DCF functionality, with retransmission, NAV and backoffs.

The VANET system uses the Distributed Robust Geocast Routing (DRG) [8] protocol at the network layer described in Section 3.4.4. The UDP transport protocol, is used in all simulations.

3.3 Additional Software

This section briefly discusses the applications used for the simulation. The applications developed helped in visualizing the vehicles on the maps and automate simulations.

3.3.1 Straw Visualizer

To be able to verify the simulation environment the SimulationViewer was developed [7]. The main purpose of the viewer is to display the map and movement of cars, see Figure 3.2. The simulation viewer has 4 main components:

- Map section pane: this section of the visualizer shows all the road segments and the vehicles. The cars with radio are colored white and others are colored gray. Whenever there is a crash, the car is highlighted in red.
- General information pane: this section displays debugging information about the events such as crashes.
- Routing Information pane: this window constantly displays the cars that have sent/received the crash warning or traffic information packets within Zone of Relevance (ZOR).

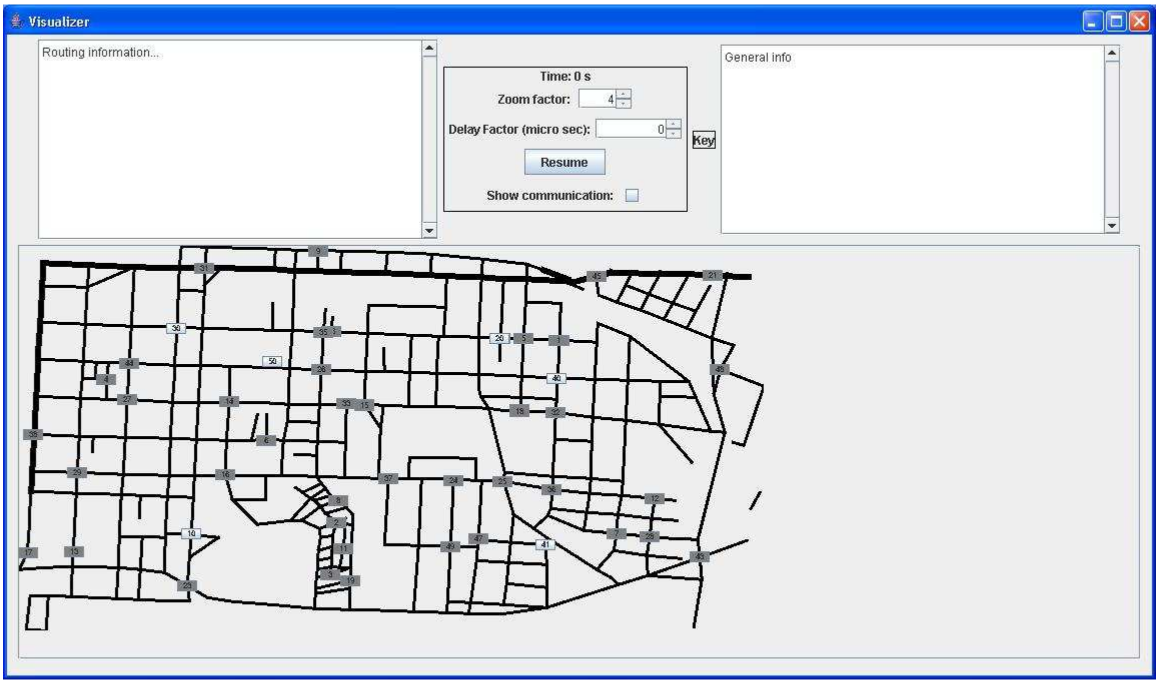

Figure 3.2: Straw Visualizer showing Raleigh downtown area, cars with VANET equipment(white) and cars without VANET equipment(gray)

- Control key pane: consists of buttons like pause, current simulation time and zoom factor that helps in controlling and tracking the simulation.

To speed up the debugging process, the visualization can be started in playback mode. In this mode, the car movements can be seen quickly using rewind/forward buttons along with current state of every node. This is made possible by storing information (map scenario, vehicle positions, packet data, etc.) in an XML file. During playback, the XML file is read and nodes are shown on map to the corresponding x,y coordinates.

3.3.2 Simulation Management

This application creates investigations, input XML files, links map files and then runs simulations in batch mode shown in Figure 3.3. All simulation data is stored in an MySQL database and is logically organized into investigations, simulations and runs. An investigation specifies the settings for the simulation. A simulation is defined as one step in an investigation and thus has exactly the same values as the other simulations except

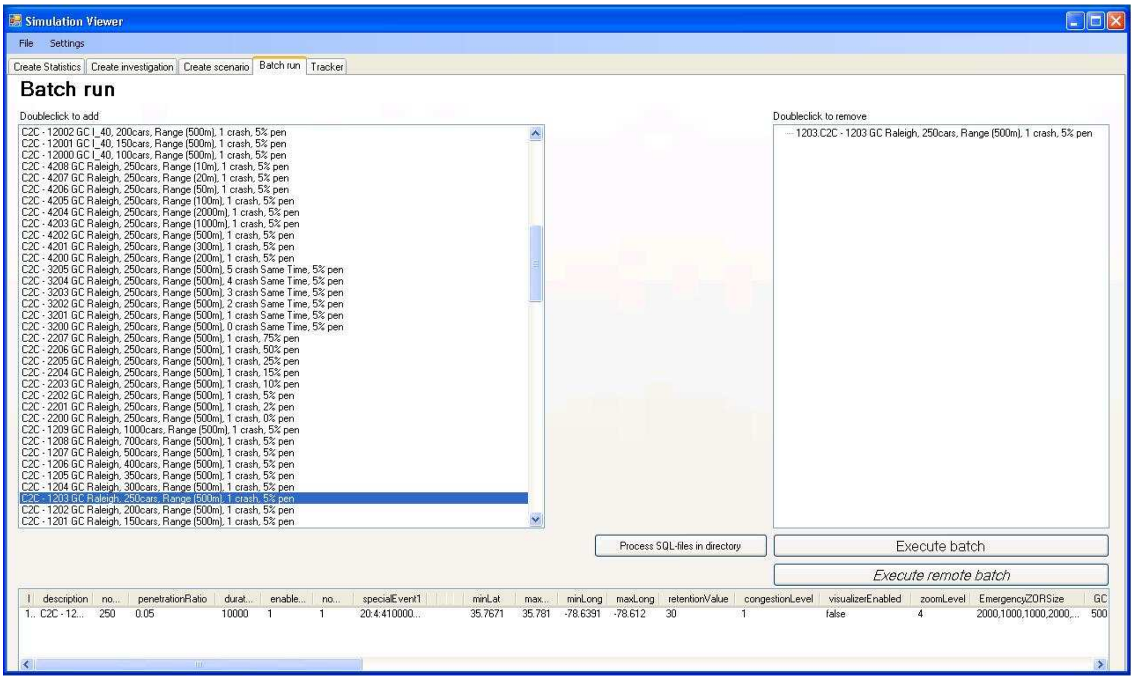

Figure 3.3: Simulation Batch Run

for the varying field (e.g., no of nodes, transmission range). Each simulation is run for the specified number of times and results are stored in the database. The varying field is the same for every run in a simulation. The only field which changes is the seed that is randomly selected by the application. The application has several panels:

- Create statistics panel simplifies the process of generating statistics for the investigations, simulations and runs. It retrieves all relevant data from the database and creates a text file that will be used by Matlab.

- Create investigation panel is used for specifying all settings for the simulation and defines the variable to be varied. If no variable is chosen to be varied there will only be one simulation. All investigations are saved in the database. situations. A text file that SWANS will read and use is generated with the necessary information.

- Batch run panel lists all the investigations in the database. By choosing one or more investigations all of them can be added to the batch queue and then run. The number of actual runs is therefore the number of simulations multiplied by number of runs for each investigation.

3.4 Simulation Model

3.4.1 Introduction

The format of the street map data from the U.S. Census [34] is explained followed by discussion on generation of mobility scenario using this data.

3.4.2 Tiger Files

The United States Census Bureau [34] provides detailed street maps for the entire United States, based on the Bureau's TIGER (Topologically Integrated Geographic Encoding and Referencing) database. These maps, in the form of TIGER/Line files, contain selected geographic and cartographic information, and are freely available to the public. These files are typically used to provide the digital map base for Geographic Information Systems or mapping software.

TIGER/Line file are organized according to United States counties. There can be up to 17 data files for each county, each file representing a different data type; some counties do not require all of the 17 data types. Within these files, we use one type of data, the Complete Chain Basic Data Record, and specifically those which correspond to different kinds of roads. The following essential information is present for each road:

- Road identifier - a unique identifier for the road.
- Road type - this can be one of several types, such as highways and unseparated city streets, etc. However, the type of road does not identify whether the road is a one-way road or not. All road are assumed to be bidirectional.
- Start longitude and latitude - the longitude/latitude of the starting intersection for this segment of the road. If a road does not start at an intersection but starts at a dead end, the longitude/latitude of the dead end is given.
- End longitude and latitude - the longitude/latitude of the ending intersection for the road segment.

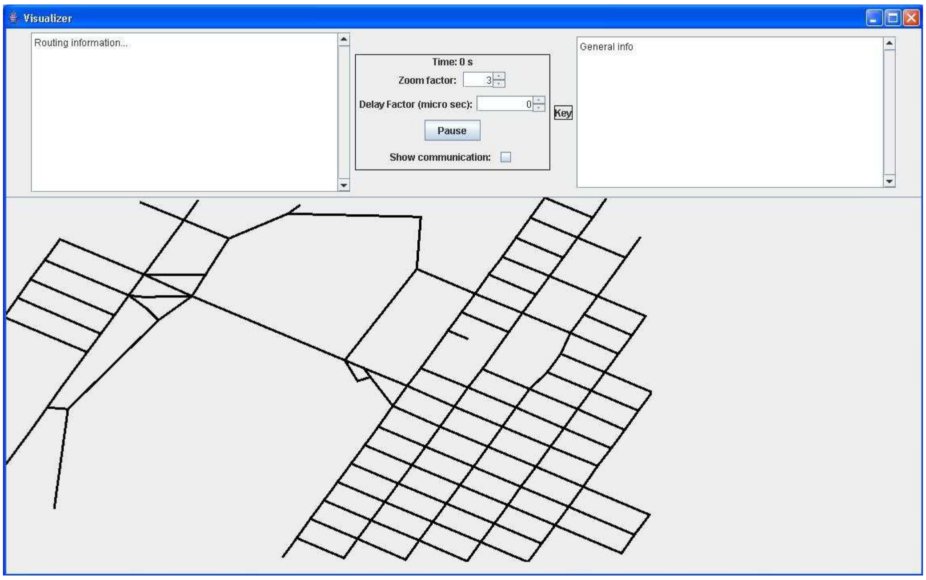

Figure 3.4: Manhattan map used in our simulation

The TIGER/Line database also contains supplementary files that describe the latitude and longitude of intermediate points in on a road so that the curvature of the road can be approximated by a piecewise linear curve. However, we currently model each road segment as a straight line between its starting and the ending intersection.

Figures 3.4, 3.5 and 3.6 show the Manhattan downtown, the Raleigh downtown and I-40 highway maps which is used in our simulations.

3.4.3 Mobility Model

Each node starts at a random point on a random road segment in the network and moves towards a another random point on a random destination street. The standard A* [37] shortest path routing algorithm is used to calculate the route from source to destination. The motion of the node is then constrained along this shortest route to the destination. Since, in addition to the speed limit on the road represented by an edge, the weight of an edge in this shortest path computation also changes with the number of vehicles on that road, the weight of an edge changes dynamically, and thus the actual route taken between a source and destination can change depending upon the load on the roads. Once a vehicle reaches its destination, it chooses another random destination, and repeats this process.

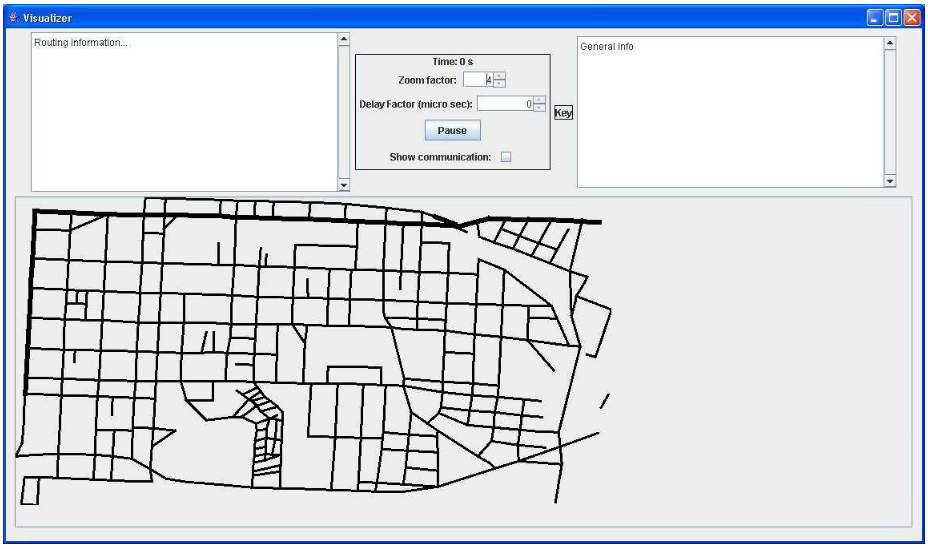

Figure 3.5: Raleigh downtown map used in our simulation

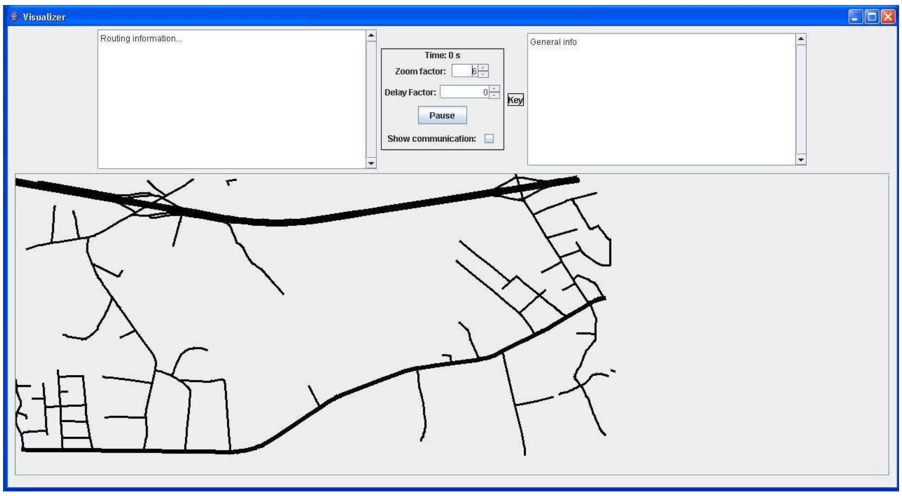

Figure 3.6: I-40 highway map used in our simulation, connecting Conover and Claremont in Catawba County, North Carolina

We assume the speed limit for each road based on the type of road as indicated in the TIGER/Line files. Each vehicle is assigned a speed randomly chosen from the range plus or minus 20% of the speed limit.

3.4.4 DRG Protocol

We use the Distributed Robust Geocast [8] for message transmission between nodes (vehicles). Whenever a node receives a packet, it first examines the geocast header. The packet is discarded if it doesn't belong to either the ZOR or the ZOF. If the message is in ZOR and received for the first time, then it is stored in a unique message buffer. This is message is then scheduled for retransmission after a backoff time and the persistence timer is started. The backoff time is calculated based on distance, collision avoidance and priority parameters.

Since VANETs are prone to frequent but temporary fragmentation, a retransmission mechanism is provided to improve reliability. This is done by periodic retransmission of the message until a new relay transmits the message, which is treated as an implicit acknowledgment by the previous relay. If an implicit acknowledgment is received before the scheduled transmission time, the transmission is canceled.

The message is regularly retransmitted at maximum backoff time, and the retransmissions are counted. When the number of retransmissions reach the maximum retransmissions, the retransmission counter is reset and the next retransmission is scheduled after a long backoff time. Each received packet's message ID is recorded along with the sender's VIN and position in a recent message buffer. This buffer is used to determine when a message is acknowledged. Once a message has been acknowledged, it is marked as such in the unique message buffer, and future receptions of the message are ignored. At the expiration of the persistence timer, a node just transmits the message once, without expecting an acknowledgment. A message is discarded if it's time-to-live has expired, any scheduled transmissions are canceled and the message details are dropped from the unique and recent message buffers.

3.4.5 ZOR and ZOF

The zone of relevance (ZOR) [38] is defined relatively based on the originator, having left, right, front and back parameters and is set in meters. The shape is therefore a rectangular, but can if needed to accommodate other shapes. A ZOR also has deviation which defines how much a car can deviate from the originators current position. All nodes within the ZOR plus the allowed deviation are expected recipients of the packet.

The zone of forwarding (ZOF) [38] is defined as ZOR plus an additional length on both sides. This makes ZOF larger than ZOR. A node can also be considered to be in the ZOF while being in the area of ZOR if the car is not within the allowed deviation, for example a car going the opposite direction.

In our simulations, the ZOR is rectangular of a certain length and width specified in table 4.1. The minimum length of ZOR, should be the safe braking distance for vehicles at the maximum allowed speed, while the minimum width, should cover all the lanes on the road moving in the direction of the road incident. For the simulations a deviation of 180 degrees is allowed, i.e., all the vehicles within the area specified by length and width are part of the ZOR, regardless of their direction. The ZOF is defined by adding 15 meters to the bounds of ZOR.

3.4.6 VIN

One of the most significant modification we had to make was to modify various modules of SWANS to work with the geographical addressing. For implementing geocast, the IPv4 header includes the geographic address of destination, i.e., the zone of relevance. Instead of an IP address, the nodes are identified with a vehicle identification number (VIN). The VIN of the source vehicle along with the packet sequence number uniquely identifies a geocast packet at the receiver end. The header of geocast packets includes the ZOR, the source VIN and the sender position. We assume that each node knows its position through a GPS device.

3.4.7 Lane Changing model

The original version of STRAW that we used only has a car following model without lane changing behavior, on a multi-lane road a vehicle would slow down or stop

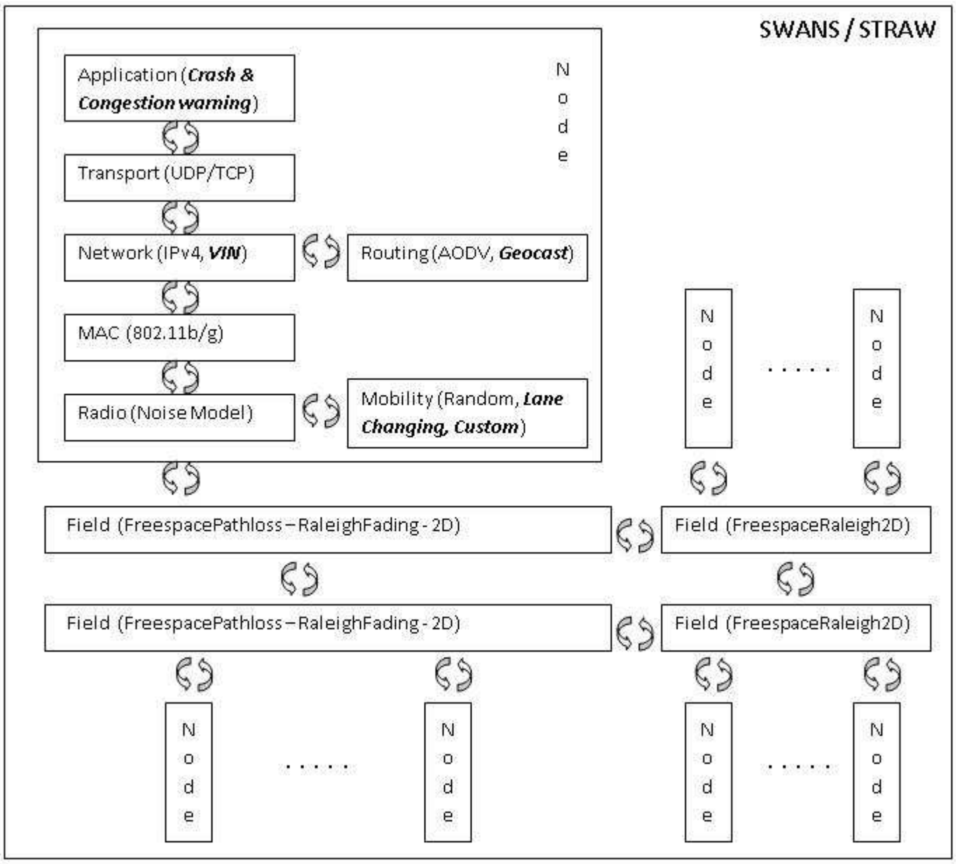

Figure 3.7: SWANS Modified Components Model [2]

if the vehicle in front does so, even when there would be empty adjacent lanes. This causes an unrealistic mobility pattern for multi-lane roads. Hence we have implemented a lane changing behavior based on a model proposed in [39]. The model, minimizes overall breaking declarations induced by lane changes and proposes that a vehicle changes lanes when the potential new target lane is more attractive, i.e., the incentive criterion is satisfied, and the change can be performed safely.

3.4.8 Congestion Warning messages

We use congestion warning messages for reducing congestion on roads caused by incidents or traffic overload. A congestion warning application periodically sends a geocast message with the node's geographic information (location, current speed and maximum speed). On receiving a congestion warning message from another car, the application updates the corresponding information in its traffic monitoring table. Using this table, the node generates a map with the estimated or known positions of other nodes. Thus, using the application, a node can get a picture of other vehicles in the region and their distribution.

Originally, in STRAW, the drivers do not react as a function of the information received from the other drivers. In our system, a driver that receives an congestion warning message changes the lane if possible, or re-routes if it has a chance, i.e., if an appropriate exit exists.

We evaluate the performance in a given scenario where the ZOR is a rectangle with the source node at the center of the rectangle. The nodes are placed on the map randomly, and each node generates a congestion information packet every 10 seconds.

3.4.9 A* Routing Algorithm

A* [37] is an efficient graph search algorithm that finds the least cost path from a given initial node to one goal node. It resembles Dijkstras algorithm [40] for finding the shortest path and also Breadth-first search (BFS) [41] which uses a heuristic to guide itself for finding routes. A* combines information that Dijkstras algorithm uses (favoring vertices that are close to the starting point) with information that BFS uses (favoring vertices that are close to the goal). For every iteration, it examines the vertex n that has the lowest f(n) = g(n) + h(n), where g(n) represents the cost of the path from the starting point to any vertex n, and h(n) represents the heuristic estimated cost from vertex n to the goal node.

Like all informed search algorithms, it first searches the routes that appear to lead towards the goal. What sets A* apart from a greedy best-first search is that it also takes the distance already traveled into account (the heuristic is the cost from the start, and not simply the local cost from the previously expanded node). The cost of each node (road segment) varies and hence the overall cost from the start.

3.4.10 Weight Calculation

Cars with VANET equipment maintain a table comprising of all road segments along with their weights/costs. These weights are accompanied by a time stamp. The weight of each path is increased or decreased based on the information from other vehicles in a VANET system. Whenever a vehicle receives a congestion warning message it updates this table with a new weight.

The information packet contains a copy of senders table with corresponding weights and timestamps. The receiver compares this table with its own and updates its table fields with the most recent time stamp information.

The weight field is the ratio of current speed to the maximum speed for a car on a road segment. The maximum possible speed is not equal to the speed limit of the road segment. Each vehicle is assigned a speed randomly chosen from the range ± 20 percentage of speed limit. Once assigned, the maximum speed for that vehicle remains unchanged throughout simulation. This random factor is assigned to all vehicles based on normal distribution. The range ± 20% is chosen based on statistics collected on driver's behavior.

The weight of each road segments varies depending on traffic congestion and is calculated every 20 seconds. For a particular road segment if the car does not receive any traffic update for a span of 20 seconds, the weight is decreased implying an easing of the congestion. This feature ensures that the weight of any road segment is not set unnecessarily to a very high value for a long time. The weight is updated immediately after the car receives an message from a vehicle and the timer is reset.

The calculated weights of all road segments is used by the A* routing algorithm for calculating cost from start for each of the routes. This method ensures the current route is shortest and more time sensitive.

The road segment information is only available to the cars that have the VANET system. Therefore the cars with VANET equipment have better routes to destination than the cars without the equipment. Also the cars have better travel times and higher average speeds since they avoid congested road segments.

3.4.11 Collisions and Queue Buildups

A traffic collision occurs when a vehicle on road collides with another vehicle or any other obstacle on the road. It can also be due to break down of a vehicle due to internal problems. The collision can be due to any one or combination of reasons like driver behavior, road design or vehicle design. In this thesis, we consider one or more vehicle incidents due to any one of the above reasons. The crashed vehicle is colored red in the visualizer for the

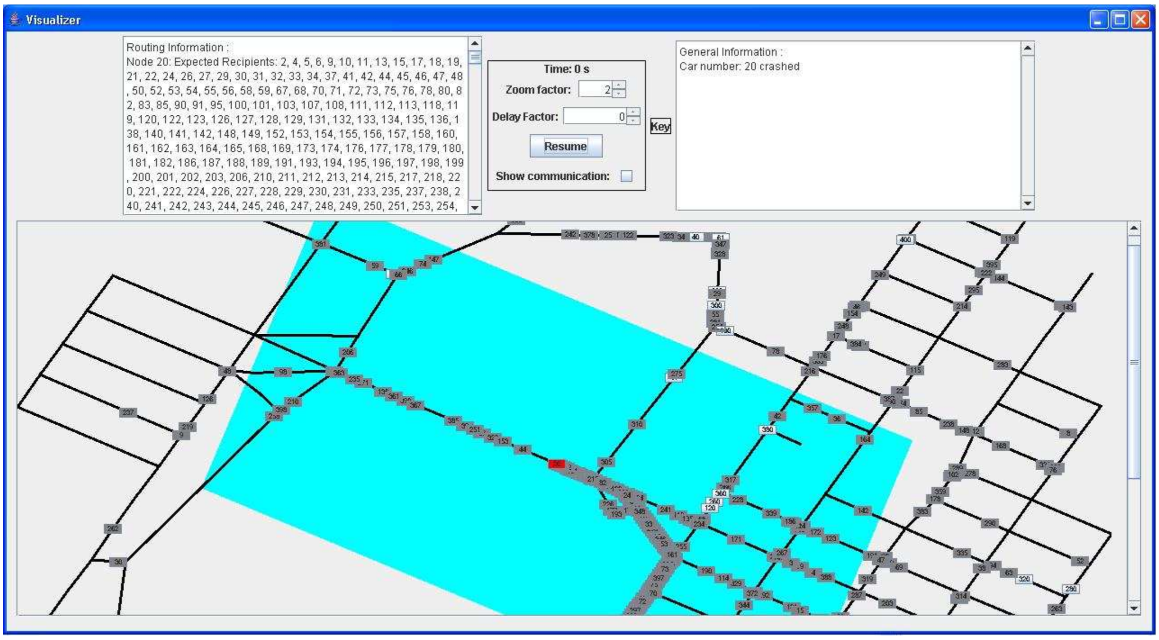

Figure 3.8: Collisions and Queue Buildups as seen on Manhattan map. The map has one incident(red car) on the connecting(critical) road and traffic pile up behind it which extends to adjacent road segments. The green rectangular region specifies the ZOR region

purpose of identification.

The traffic collision results in congestion on the road segment for that particular lane resulting in a queue buildup. This scenario is shown in Figure 3.8. The vehicles go around the collision if there is alternate lane available as discussed in Section 3.4.7. If not the vehicle slows down and waits behind the broken vehicle. This results in others vehicles behind this vehicle to slow down and wait. After 30 seconds, the vehicles immediately close to the accident perform a u-turn and leave the road segment. Also the *cars without VANET equipment* hold the information regarding the crashed road segment in its routing table for 30 seconds. This value is chosen such that the car reroutes to destination through a different road, thus avoiding the car from rerouting to the crashed road segment again. The figure shows a situation where the crashed vehicle results in congestion on a critical road segment.

A collision on one road segment results in slowly down of traffic on adjacent road segments. The intensity of the congestion depends on the density of the vehicle in that particular area. In the simulations all the scenarios are explored by varying densities with crashes on random road segments.

3.4.12 Gridlock

The simulation results in gridlock with an increase in density of vehicles near a traffic incident. Gridlock happens due to inability of vehicles to move at road intersections. Gridlock occurs in a grid network situation where intersections are blocked, thus preventing cars from backing up to an upstream intersection or moving forward through the intersection. The term gridlock is used for describing high traffic congestion scenario with a traffic jam, with or without a blocked grid system.

Usually gridlock is caused by traffic heading in one direction blocking cross traffic at an intersection. In many jurisdictions, drivers are prohibited from entering an intersection at a green light if there is no room for them to clear the intersection. If drivers follow this rule of the road, gridlock will be prevented and traffic will only be slow in the direction that is actually congested. One method of reducing gridlock is to aggressively enforce penalties for vehicles that block intersections. Drivers who *block the box* can be subjected to a violation that comes with a penalty.

In the simulation gridlocks are avoided by not allowing vehicles to proceed in the intersections when the driver sees the congested road segment ahead. The cars with VANET system have this information before they arrive the intersection and can take decisions in advance as opposed to cars without the system. This allows the drivers with the VANET system to reroute to a different road segment, if the time to destination is smaller.

3.4.13 Traffic Load Balancing

Load balancing of vehicles on roads is similar to network load balancing. In this scenario due to congestion on one of the routes the traffic takes an alternate path, this results an increase of traffic on the alternate path. The situation can be resolved by rerouting traffic through other alternate routes whenever possible.

In our VANET system, whenever there is a crash on a road segment or heavy congestion the cars with VANET equipment reroute to alternate routes. This results in increase of load on the alternate path.

In the simulation, the cars with VANET system constantly exchange messages with other peers. The messages are sent even in case of a minor congestion. Hence the information of congestion on other roads is constantly available. Congestion occurs whenever there is increase in traffic on a particular path, resulting in increase of cost for that route. Hence, the traffic is distributed among other routes whenever more than one alternate route is available.

Chapter 4

Results and Parameter Analysis

In this chapter, we evaluate the effect of various parameters that affect the average speed of cars and transit time to reach destinations in using Distributed Robust Geocast (DRG) protocol on different scenarios (Manhattan downtown, Raleigh downtown, I-40 highway). The simulation models used for network and vehicle traffic simulation are discussed in third chapter. The default values of some of the parameters are selected for a typical scenario and a single parameter is varied at a time to see the effects on the average speed and transit time. We first show how the average speed and transit time parameters are calculated along with the values of the default parameters. The four parameters namely number of cars, penetration ratio, number of traffic incidents and transmission range are explained and compared in detail for each of the scenarios.

4.1 Average Speed and Transit Time Calculation

Average speed and transit time are very important indicators of performance for traffic facilities and networks. In this thesis we evaluate the change in average speed and transit time while varying parameters like number of vehicles, penetration ratio, number of traffic incidents and transmission range.

The average speed is the total distance traveled divided the time taken to travel that distance by a particular car. For a simulation the average speed is the average of the average speeds for each car with and without VANET equipment.

The transit time is the time taken by a car to go from its source to the destination.

The destination is chosen randomly from the available road segments in the given map. Once it reaches destination another random destination is chosen and the car reroutes to the new destination. This process continues until the end of the simulation time. The transit time for a car is the average of all the transit times for the car into consideration till the end of the simulation. The destinations are chosen randomly for all vehicles. Finally the transit time for a simulation is the average of transit times of cars with and without VANET equipment.

4.2 Simulation Parameters

The simulation parameters are shown in table 4.1. In the simulations the average speed and transit time are measured as a function of the number of nodes, penetration ratio, number of vehicle incidents and transmission range. By choosing to vary the number of nodes on the map we induce an increase in the density of vehicles, which can result in higher congestion. Similarly, with increase in the number of road incidents the vehicles might face more congestion and possibly will reroute to destinations using longer routes. By varying the penetration ratio we can evaluate the effects on traffic congestion with increase in percent of cars having the VANET equipment. Others parameters which can varied are the ZOR, simulation time, packet transmission frequency, wait time behind an accident, etc. The extent of the dissemination of the congestion warning message is more dependent on the transmission range than on the size of the ZOR; therefore we choose to vary the transmission range rather than the size of the ZOR. The dissemination within the ZOR is rather fast and not sensitive to the message transmission period.

Although it may seem that the results would be very sensitive to the amount of time a vehicle waits behind a stopped car or a single lane road before it makes a u-turn, in reality the average wait-time penalty of all cars is not greatly affected as the backlog of cars to the nearest intersection is constant regardless of how long each car waits in the backlog. In the average results we consider, the total amount of time wasted by all cars in the backlog is constant regardless of how many vehicles go through the backlog and the rate of backlog clearance as long as the street remains completely backlogged during the entire incident period.

Due to the complex vehicular and network modeling, each simulation takes approximately 25 minutes of real time. This precludes a large amount of simulations for all

Table 4.1: Simulation Parameters Values; the default value is shown in parenthesis

Parameter	Value
Simulation Duration	5000s (1hour 22 minutes)
Pathloss	Freespace
Signal Fading	Rayleigh
Congestion Warning ZOR size	[2000 m, 1000 m, 1000 m, 2000 m]
Car Placement	Random
Map	(Manhattan, Raleigh, I-40)
Number of Nodes	100, 200, (250), 300, 350, 400, 500, 700
Penetration Ratio	0%, 2%, (5%), 10%, 15%, 25%, 50%, 75%
Number of Incidents	0, (1), 2, 3, 4
Transmission Range	200m, 300m, (500m), 1000m, 2000m

points in this thesis; in all graphs we perform 15 simulations, i.e., not sufficient for tight confidence intervals; however, in figures 4.1 and 4.3 we demonstrate that relatively tight 95% confidence intervals are possible by repeating 100 times the simulation for 500 vehicles.

4.3 Manhattan Scenario

The Manhattan scenario (Figure 3.4) has two bridges connecting two important areas of the city.

In Figure 4.1 shows the average speed as a function of number of nodes with no traffic incidents. Initially the difference between the average speeds of cars with and without VANET equipment is negligible. At about 300 vehicles, the congestion increases on roads due to traffic overload on roads. After this point there is congestion and the cars with VANET equipment have a advantage. With one crash (Figure 4.2), the advantage can be observed initially due to congestion created by the incident on the road segment. After around 300 nodes this difference average speed increases because now there is also congestion from traffic overload. In both these graphs, the overall average speed reduces as number of nodes increase due to increase in traffic density on roads.

In Figure 4.3, the transit times are similar until the traffic load on roads increases and after that there is slight reduction in transit time for cars with VANET equipment. In Figure 4.4, there is a considerable reduction in transit times during a crash. For more than 400 vehicles, the transit times for cars without VANET equipment increase significantly due to heavy traffic load and large queue build ups on roads. The cars with VANET equipment reroute through congested roads and reach destinations fast. This gain is clearly visible in gradual increase of transit times for cars with VANET equipment.

By analyzing trends in graphs with no crashes and the one with a crash there is a clear reduction of time to reach a destination. In effect, cars with VANET equipment have a significant improvements in average speed and transit time during congestion.

In Figure 4.5 the penetration ratio i.e. the percentage of cars having VANET equipment is increased from 2% to 75%. Initially at very low penetration ratios of around 2%, only a few cars have the VANET equipment and only they have a advantage over other cars. Also there is less traffic on roads, as many cars without VANET equipment are part of queue build on the road with incident (crashed car). With a higher penetration ratio, there is a gain, but is smaller than for lower penetration ratios, as there are many cars with VANET equipment. In Figure 4.6, there is a reduction in transit time for crash with VANET equipment.

In Figure 4.7, the number of incidents i.e., simultaneous breakdown of vehicles on the roads, is varied. The average speed of vehicles with VANET equipment increases with more incidents on roads while it decreases for cars without equipment. Whenever a car with VANET equipment receives congestion warning message, it will reroute using a alternate road if available. This results in traveling larger distances and in turn higher transit times. These transit times are however, smaller than those of cars without the VANET system. The transit times are shown in Figure 4.8.

Figures 4.9 and 4.10 show average speed and transit times as a function of the transmission range of congestion warning messages with one traffic incident. The average speed of cars with a VANET system is higher and almost constant because the cars with VANET equipment will travel with almost the same speed with or without the congestion warning packet. But there is noticeable decrease in the transit time with increase in transmission range. This indicates that the cars with VANET equipment can take better decisions early and reroute to destinations quicker than the cars without VANET equipment.

In the Manhattan scenario, cars with VANET equipment achieve average speeds which are 1.5 - 2.5 times the average speeds for cars without VANET equipment and around 60% reduction in transit times during peak congestion. A significant result is the fact that benefits of VANETs can be observed even at penetration ratios of 2%. This means that

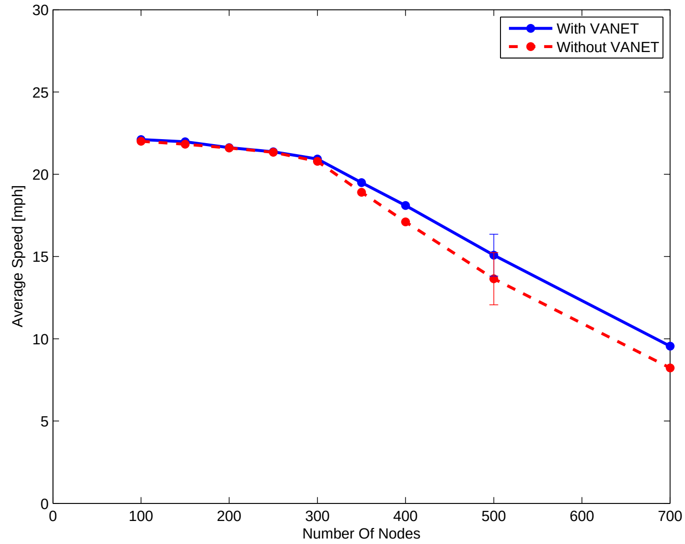

Figure 4.1: Average speed as a function of the number of nodes in the Manhattan scenario with no traffic incidents having 100 simulations for 500 vehicles

even small investments in VANETs can translate into large benefits. With the increase in incidents on different roads, cars with VANET equipment will be redirected on available routes. These will not be the shortest paths to the destination. This is observed in the form of insignificant decrease in transit times even with significant increase in the average speed.

4.4 Raleigh Downtown Scenario

The Raleigh downtown scenario (Figure 3.5) has a grid with many alternate routes unlike Manhattan scenario where there is only one alternate route.

Figures 4.11 and 4.12, show trends similar in average speeds compared to Manhattan scenario in Section 4.3. In Raleigh scenario, the congestion on road without any crash is observed at around 500 nodes on map compared to 300 nodes in Manhattan scenario. The Raleigh map is more grid like and devoid of any particular critical road as in case of Manhattan map. So it takes a higher number of nodes to create congestion on Raleigh map compared to Manhattan. The transit times of vehicles is shown in Figures 4.13 and 4.14 with trends similar to Manhattan map.

Figures 4.15 and 4.16 show improvements in average speeds and transit times

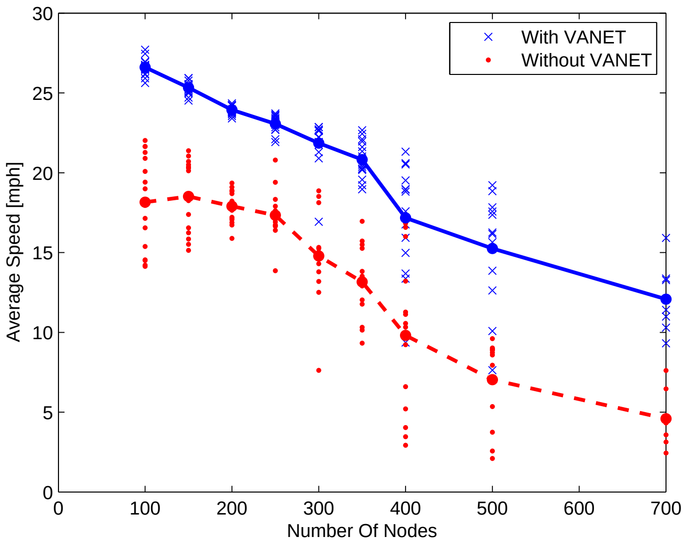

Figure 4.2: Average speed as a function of the number of nodes in the Manhattan scenario with one traffic incident

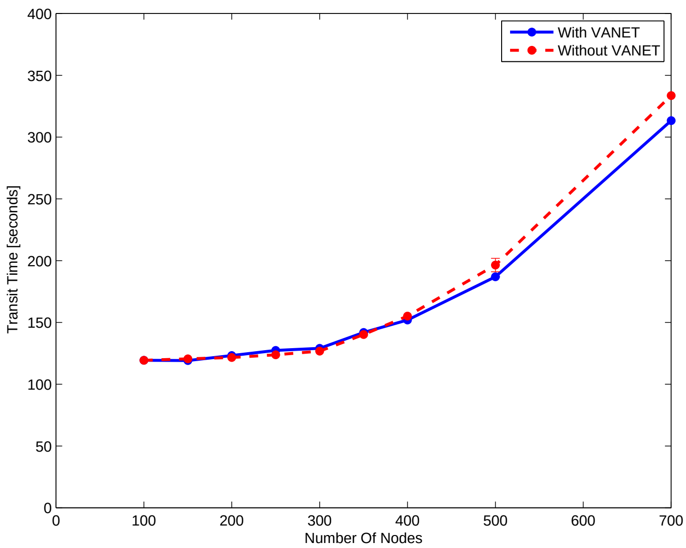

Figure 4.3: Transit time as a function of the number of nodes in the Manhattan scenario with no traffic incidents having 100 simulations for 500 vehicles

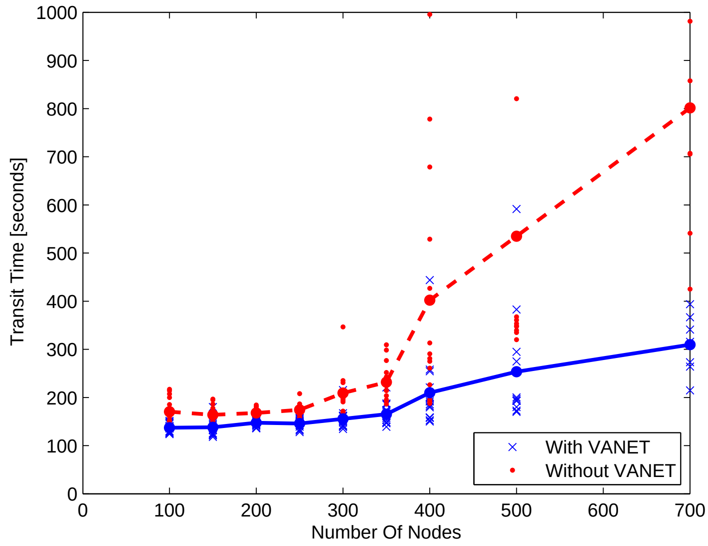

Figure 4.4: Transit time as a function of the number of nodes in the Manhattan scenario with one traffic incident

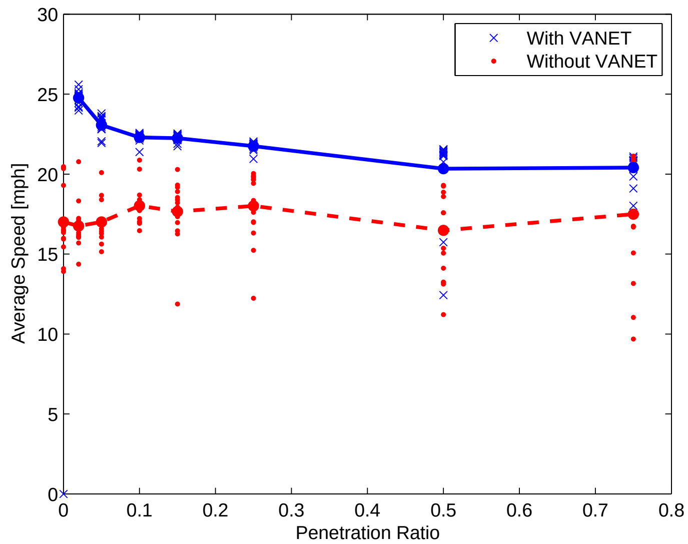

Figure 4.5: Average speed as a function of the penetration ratio in the Manhattan scenario with one traffic incident

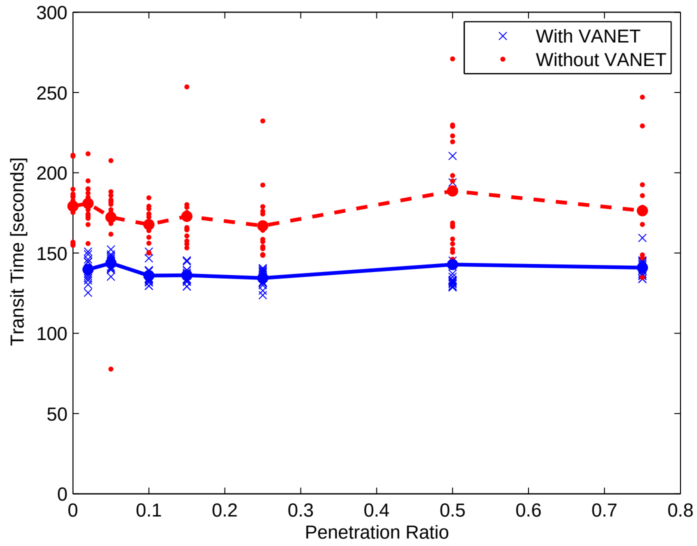

Figure 4.6: Transit time as a function of the penetration ratio in the Manhattan scenario with one traffic incident

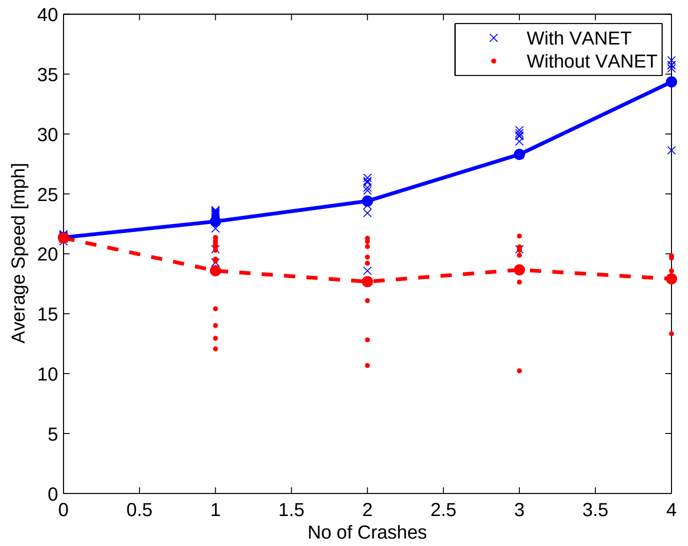

Figure 4.7: Average speed as a function of the number of incidents in the Manhattan scenario

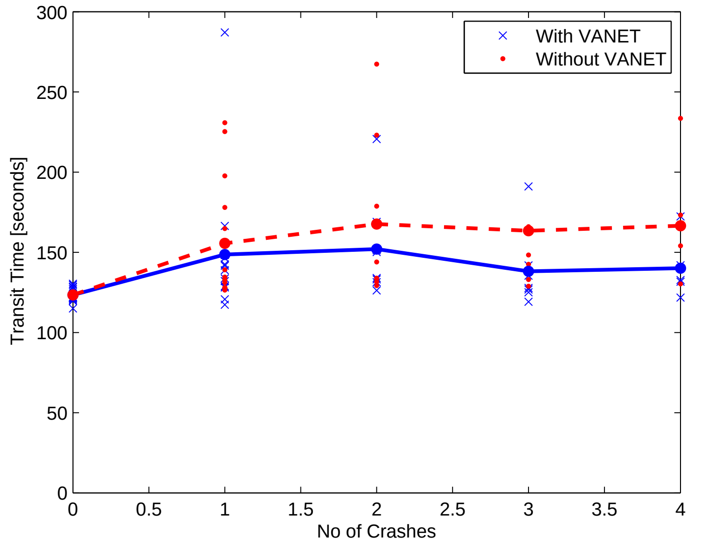

Figure 4.8: Transit time as a function of the number of incidents in the Manhattan scenario

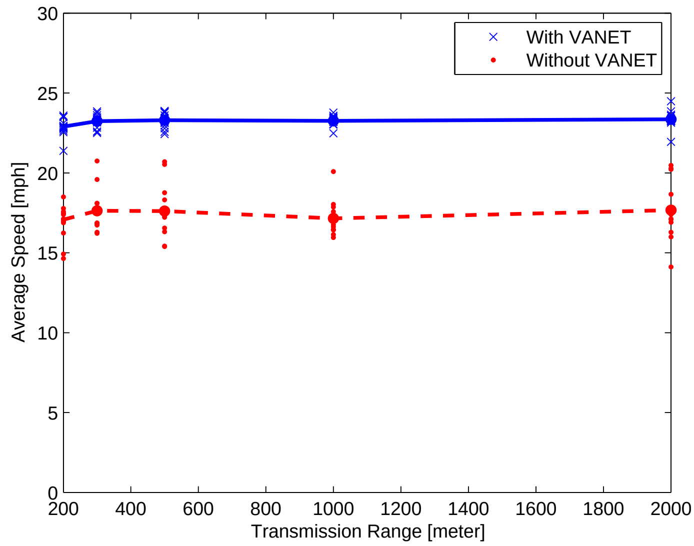

Figure 4.9: Average speed as a function of the transmission range in the Manhattan scenario with one traffic incident

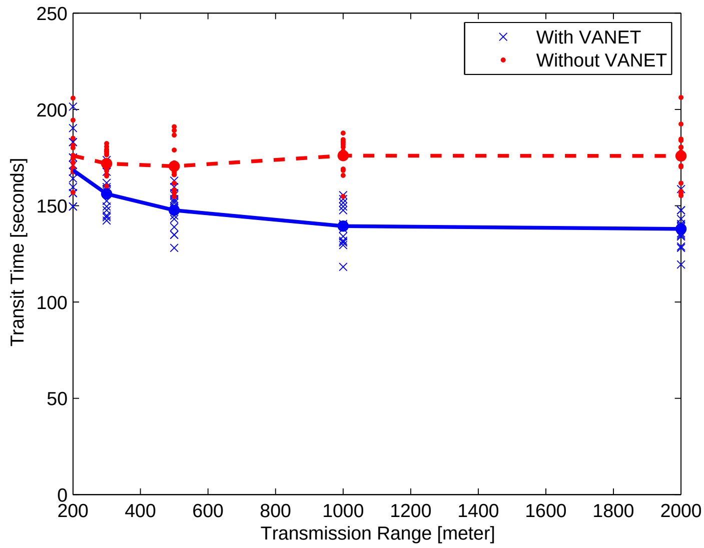

Figure 4.10: Transit time as a function of the transmission range in the Manhattan scenario with one traffic incident

similar to Manhattan scenario.

Figures 4.17 and 4.18 show average speeds and transit times during incidents on road which is similar to Manhattan scenario trends.

Figures 4.19 and 4.20 show average speeds and transit times which is similar to Manhattan scenario trends.

In the Raleigh scenario, the improvement in average speeds is about 1.15 - 1.25 times the average speeds for cars without VANET equipment and around 20% reduction in transit times during high congestion. The Manhattan scenario shows higher improvements because the road on which the crash is simulated is a critical path. All the cars in the Manhattan scenario travel this road unlike the Raleigh Scenario, which has a grid structure, and all roads are equally important. Thus the scenario is major factor in determining the percentage improvements due to VANETs.

4.5 I-40 Highway Scenario

The I-40 highway scenario (Figure 3.6) has I-40 and a connecting highway (with multiple lanes) between cities.

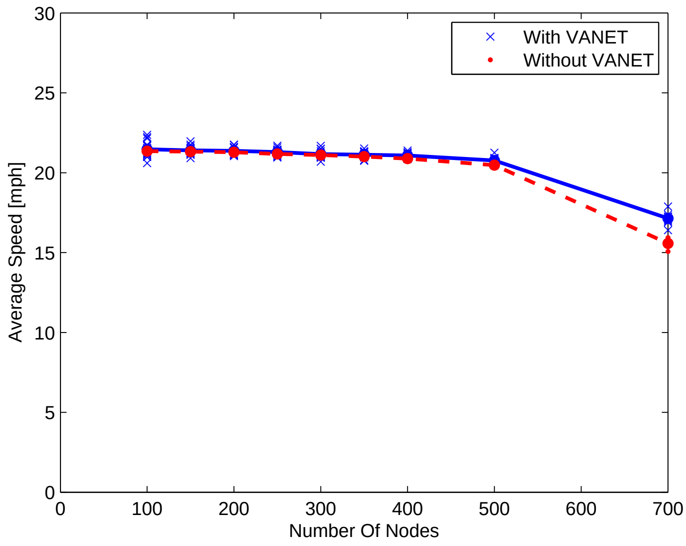

Figure 4.11: Average speed as a function of the number of nodes in the Raleigh scenario with no traffic incidents

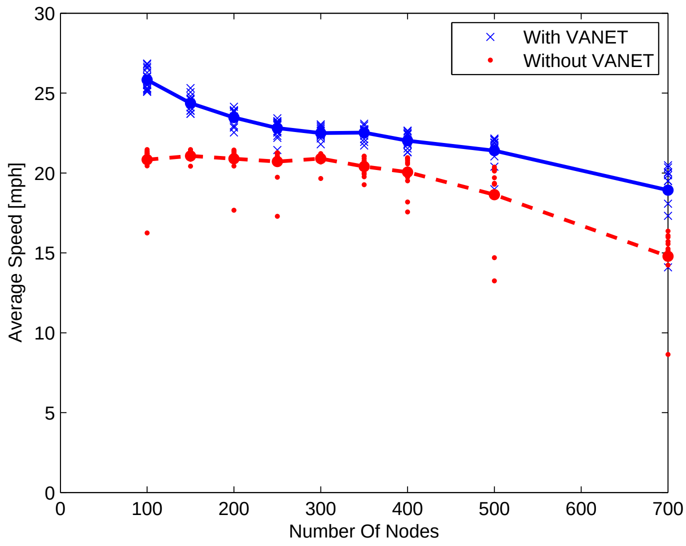

Figure 4.12: Average speed as a function of the number of nodes in the Raleigh scenario with one traffic incident

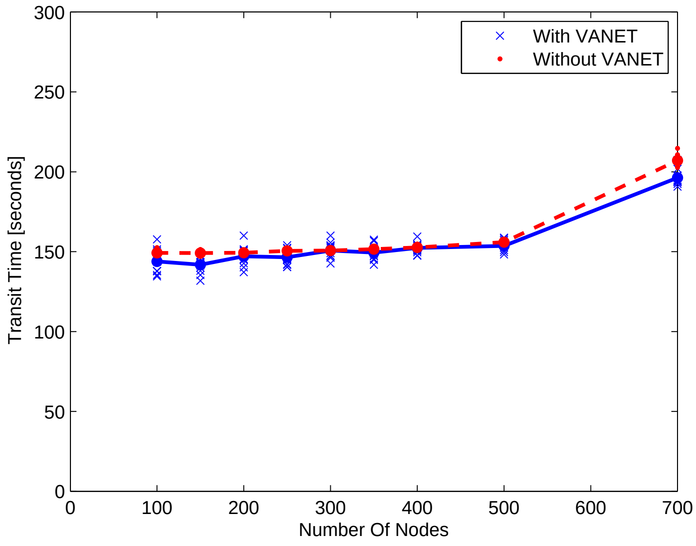

Figure 4.13: Transit time as a function of the number of nodes in the Raleigh scenario with no traffic incidents

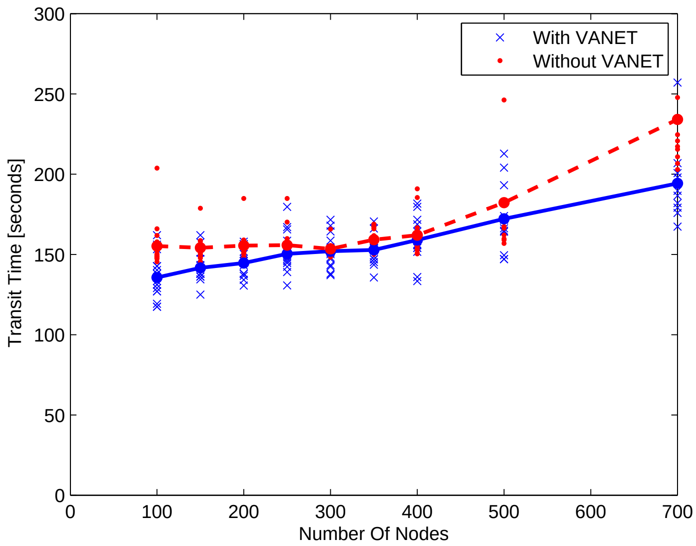

Figure 4.14: Transit time as a function of the number of nodes in the Raleigh scenario with one traffic incident

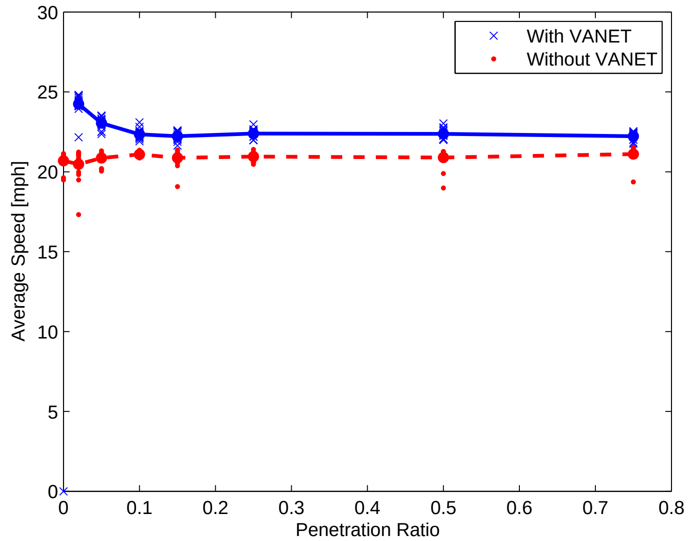

Figure 4.15: Average speed as a function of the penetration ratio in the Raleigh scenario with one traffic incident

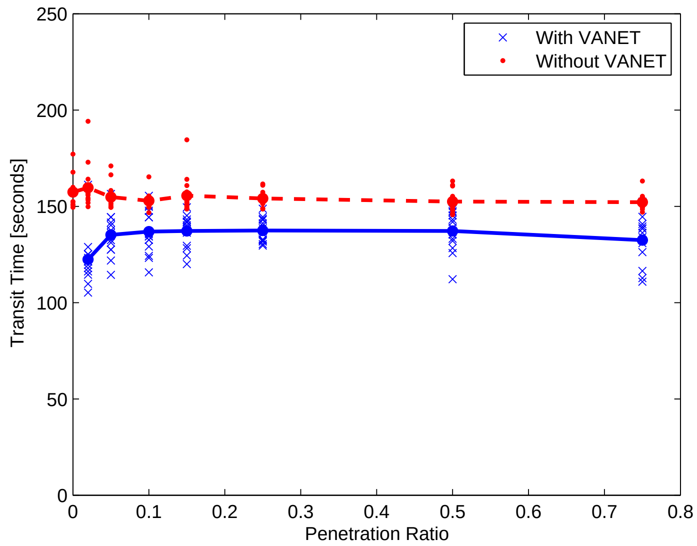

Figure 4.16: Transit time as a function of the penetration ratio in the Raleigh scenario with one traffic incident

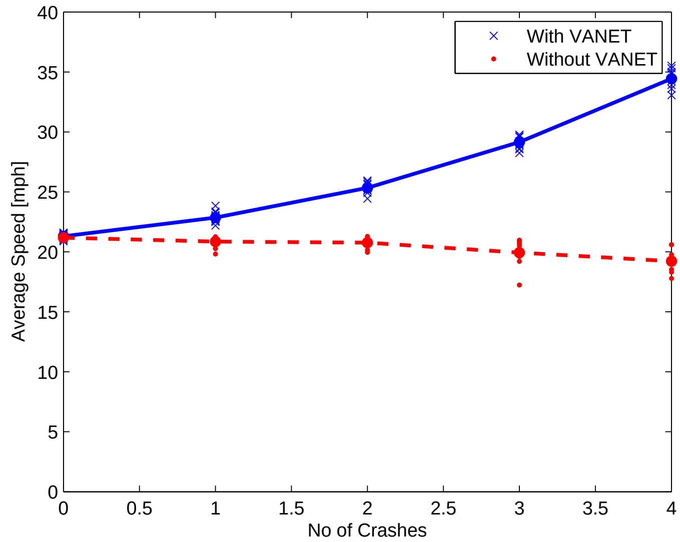

Figure 4.17: Average speed as a function of the number of incidents in the Raleigh scenario

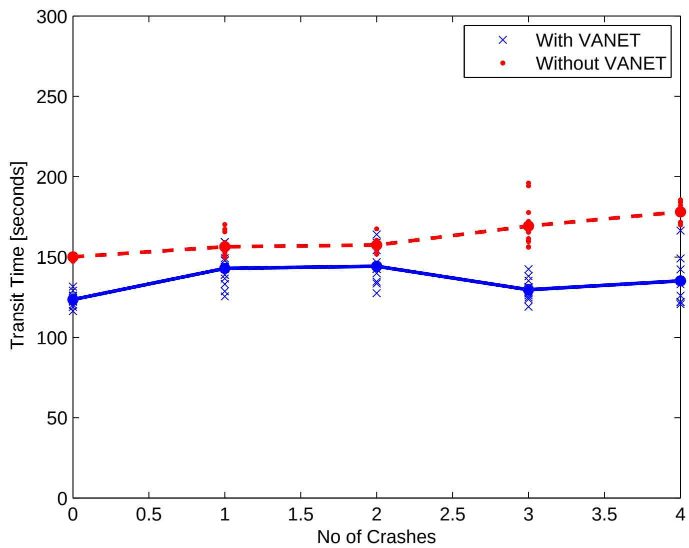

Figure 4.18: Transit time as a function of the number of incidents in the Raleigh scenario

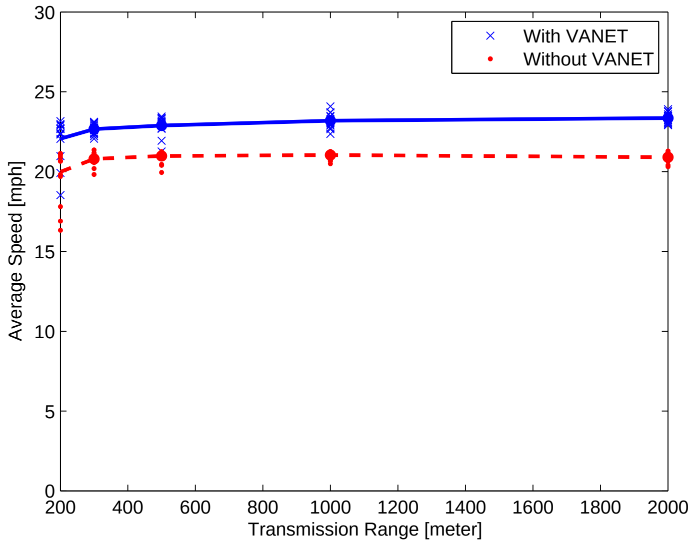

Figure 4.19: Average speed as a function of the transmission range in the Raleigh scenario with one traffic incident

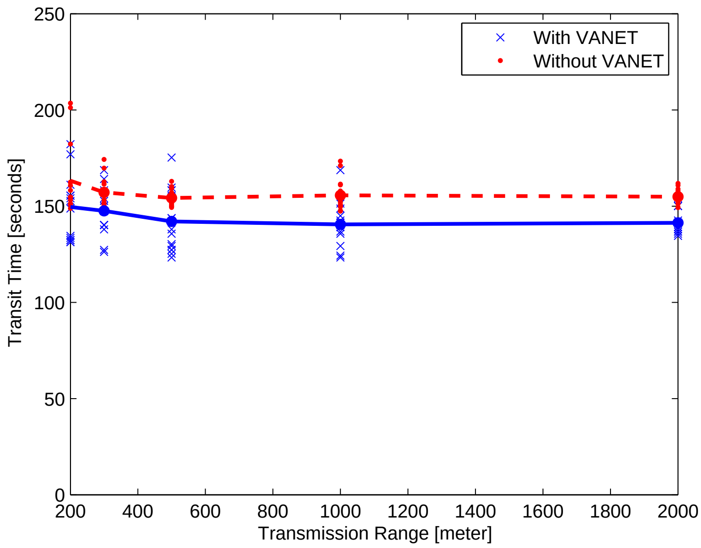

Figure 4.20: Transit time as a function of the transmission range in the Raleigh scenario with one traffic incident

Figures 4.21 and 4.22, show trends similar in average speeds compared to Raleigh scenario 4.4. In I-40 Scenario, there is no congestion on road because of traffic overload as in Raleigh and Manhattan scenarios. In this scenario there are 2 highways (critical roads), I-40 and US-70 both having multiple lanes which connect Conover to Claremont, NC. The incident is on US-70 highway over one of its lanes. This results in congestion as in Manhattan scenario but the cars change lane here or reroute to I-40 highway based on the intensity of congestion. The transit times of vehicles is shown in Figures 4.23 and 4.24 with trends similar to Raleigh scenario.

Figures 4.25 and 4.26 show improvements in average speeds and transit times similar to Manhattan and Raleigh scenario.

Figures 4.27 and 4.28 show average speeds and transit times during incidents on road which is similar to Manhattan and Raleigh scenario trends.

Figures 4.29 and 4.30 show average speeds and transit times which is similar to Manhattan and Raleigh scenario trends.

In the I-40 scenario, the improvement in the average speeds are about 1.45 - 1.8 times the average speeds for cars without VANET equipment and around 15% reduction in transit times. The I-40 scenario shows lower improvements compared to Manhattan scenario as there are multiple lanes on each road while the incident only blocks a single lane.

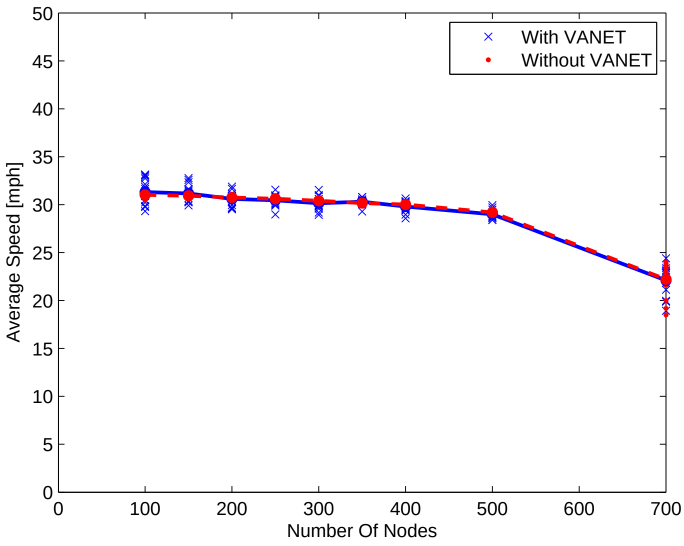

Figure 4.21: Average speed as a function of the number of nodes in the I-40 scenario with no traffic incidents

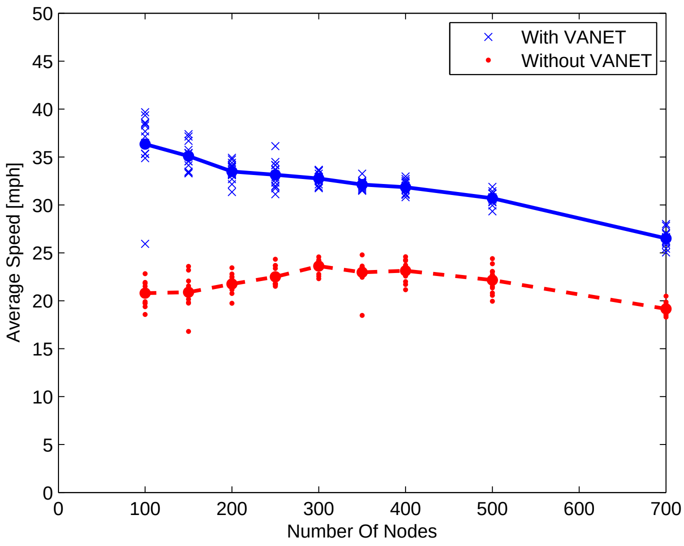

Figure 4.22: Average speed as a function of the number of nodes in the I-40 scenario with one traffic incident

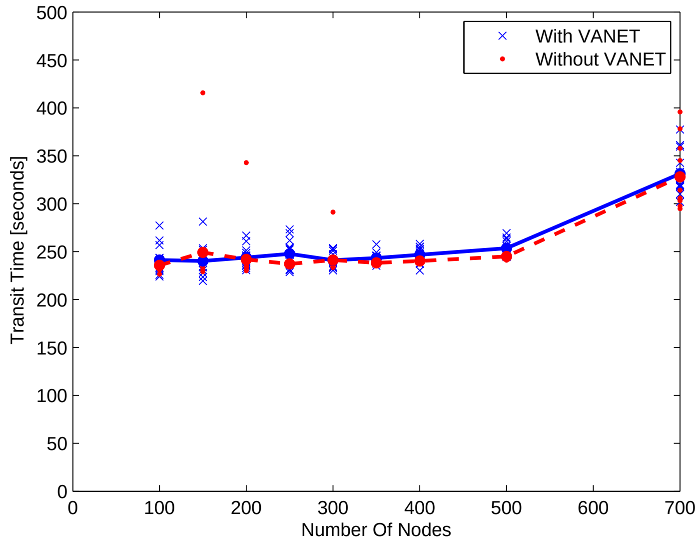

Figure 4.23: Transit time as a function of the number of nodes in the I-40 scenario with no traffic incidents

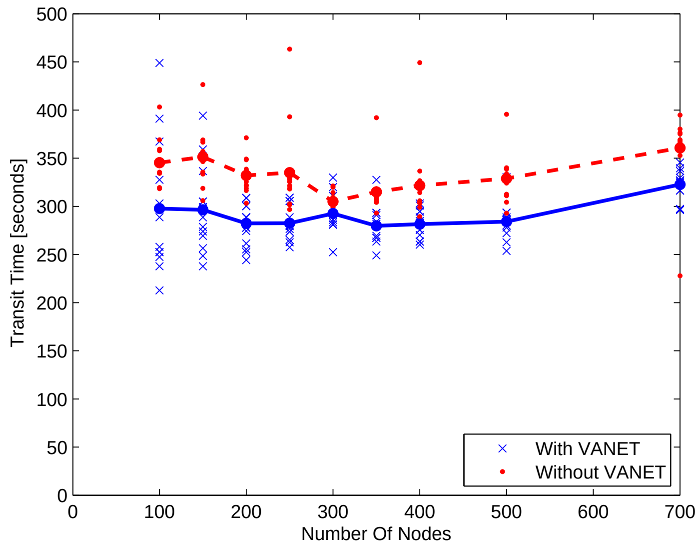

Figure 4.24: Transit time as a function of the number of nodes in the I-40 scenario with one traffic incident

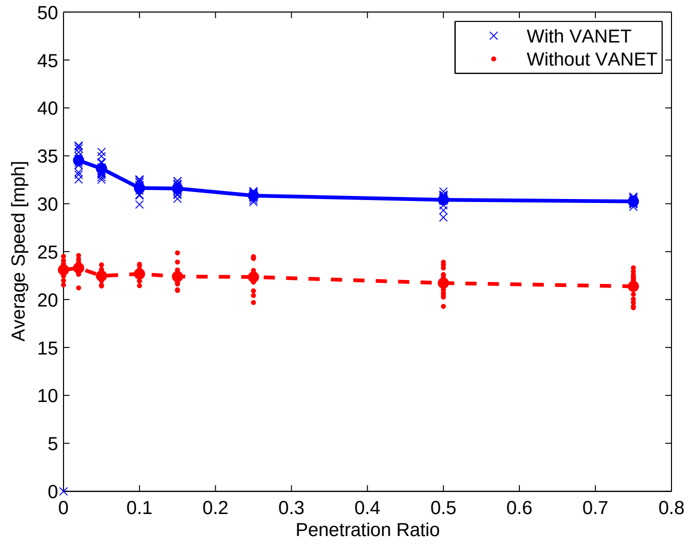

Figure 4.25: Average speed as a function of the penetration ratio in the I-40 scenario with one traffic incident

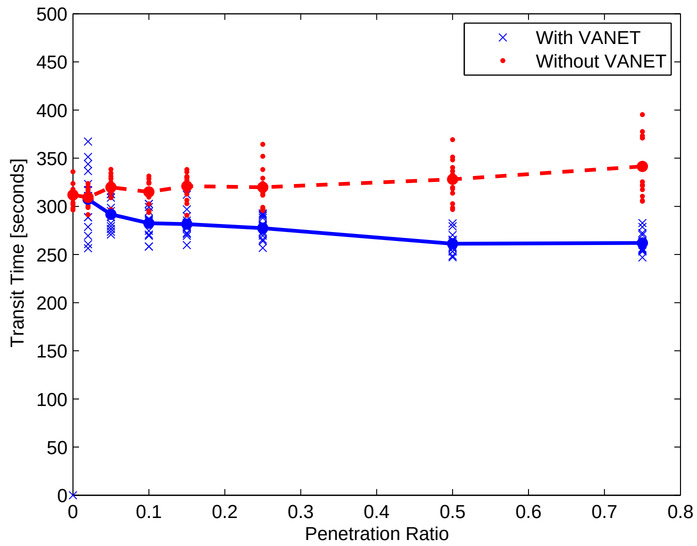

Figure 4.26: Transit time as a function of the penetration ratio in the I-40 scenario with one traffic incident

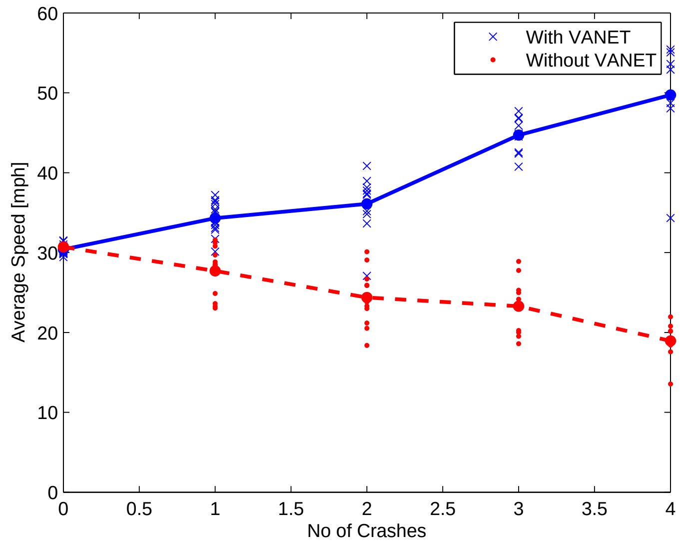

Figure 4.27: Average speed as a function of the number of incidents in the I-40 scenario

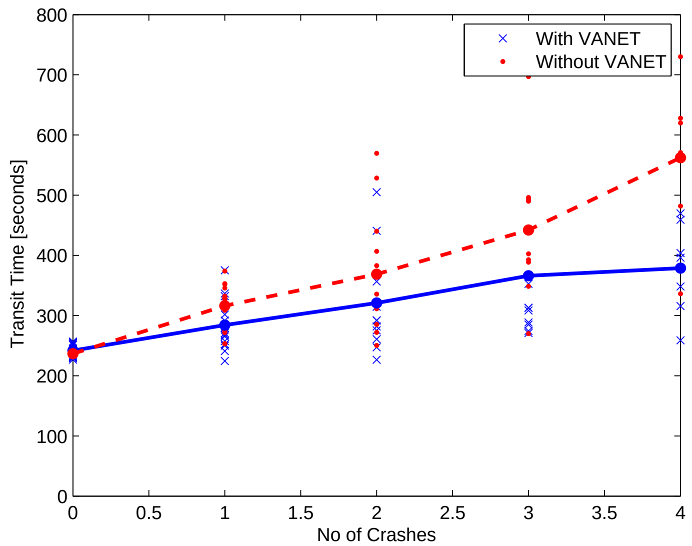

Figure 4.28: Transit time as a function of the number of incidents in the I-40 scenario

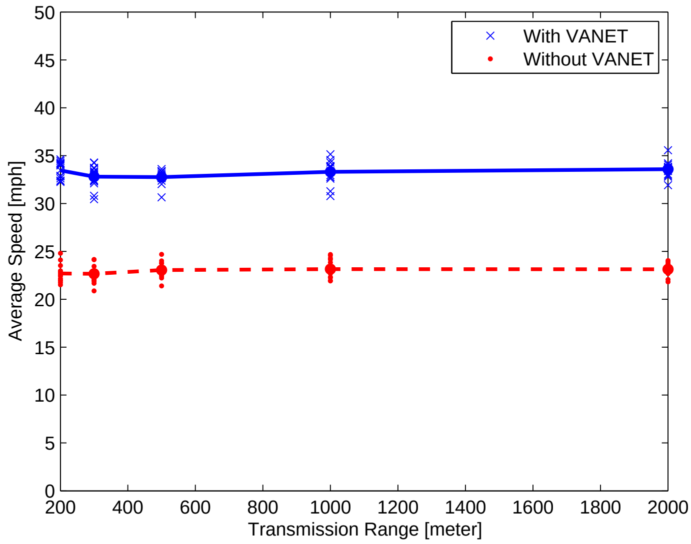

Figure 4.29: Average speed as a function of the transmission range in the I-40 scenario with one traffic incident

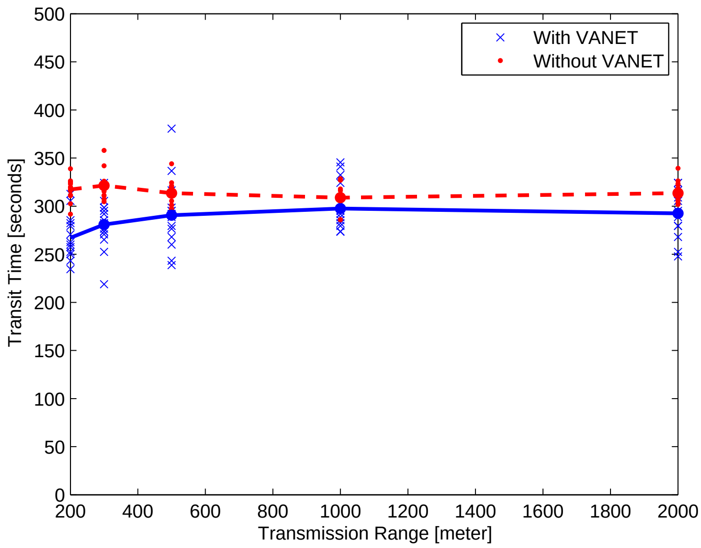

Figure 4.30: Transit time as a function of the transmission range in the I-40 scenario with one traffic incident

Chapter 5

Conclusion

In this thesis we have successfully implemented the simulation environment for simulating realistic scenarios, with cars reacting to congestion by taking alternate routes, crashing, avoiding queue buildings, clearing gridlocks and balancing traffic on alternate routes during traffic congestions.

In these scenarios, the VANET system identifies intersections and areas which often cause problems in the real world. The results in our tests show that cars with VANET equipment have significant advantages on the overall average speed and transit time as compared with cars having no VANET equipment. We have shown the advantage on 3 different scenarios (Manhattan downtown, Raleigh downtown and I-40) each having one or more alternate routes. The system requires at least one alternate route to realize the advantages of having a VANET equipment. However, we have not been able to extend our simulation environment for investigating the advantages of VANET system for collision avoidance on these scenarios. Using the collision avoidance application, cars with VANET equipment will be able to avoid collisions at intersections, vehicles moving towards each other or at rail road crossings.

We have shown that cars with VANET equipment reroute to destinations using alternate routes during congestion. This results in better average speeds and transit times in all the scenarios.

Bibliography

[1] Texas transportation institute. http://www.tti.tamu.edu.

[2] Java in Simulation Time and Scalable Wireless Ad hoc Network Simulator. http://jist.ece.cornell.edu/.

[3] National highway traffic safety administration. http://www.nhtsa.dot.gov/.

[4] Federal highway administration. http://www.fhwa.dot.gov.

[5] Standard specification for telecomunications and information exchange between roadside and vehicle systems - 5GHz band dedicated short range communications (DSRC) medium access control (MAC) and physical layer (PHY), 2003.

[6] Standard Specification for Telecommunications and Information Exchange Between Roadside and Vehicle Systems - 5.9 GHz Band Wireless Access in Vehicular Environments (WAVE) / Dedicated Short Range Communications (DSRC) Medium Access Control (MAC) and Physical Layer (PHY) Specifications. http://www.astm.org/Standards/E2213.htm.

[7] STreet RAndom Waypoint - vehicular mobility model for network simulations. http://www.aqualab.cs.northwestern.edu/projects/STRAW/.

[8] Harshvardhan P. Joshi. Distributed Robust Geocast:A Multicast Protocol for Inter-Vehicle Communication. Master's thesis, Department of Electrical and Computer Engineering, NCSU, 2006.

[9] IEEE 802.11a standard. http://standards.ieee.org/getieee802/download/802.11a-1999.pdf.

[10] IEEE 802.11p update. http://grouper.ieee.org/groups/802/11/Reports/tgp update.htm.

[11] Hao Wu, Mahesh Palekar, Richard Fujimoto, Randall Guensler, Michael Hunter, Jaesup Lee, and Joonho Ko. An empirical study of short range communications for vehicles. In *Proceedings of the Second ACM International Workshop on Vehicular Ad Hoc Networks*, Cologne, Germany, 2005.

[12] Fay Wah Hui and Prasant Mohapatra. Experimental Characterization of Multi-Hop Communications in Vehicular Ad-Hoc Network. In *Proceedings of the Second ACM International Workshop on Vehicular Ad Hoc Networks*, Cologne, Germany, 2005.

[13] X. Yang, J. Liu, F. Zhao, and N.H. Vaidya. A Vehicle to Vehicle Communication Protocol for Cooperative Collision Warning. In *Proc of the First Annual International Conference on Mobile and Ubiquitous Systems: Networking and Services*, pages 1–14, 2004.

[14] J.P. Hubaux, S. Capkun, and J. Luo. The Security and Privacy of Smart Vehicles. *IEEE Security & Privacy Magazine*, 2:49–55, 2004.

[15] T. Leinmuller, E. Schoch, and F. Kargl. Position verification approaches for Vehicular Ad Hoc Networks. *IEEE Wireless Communications*, 13:16–21, 2006.

[16] L. Wischhof, A. Ebner, and H. Rohling. Information Dissemination in Self-Organizing Intervehicle Networks. *IEEE Transactions on Intelligent Transportation Systems*, 6(1):90–101, 2005.

[17] L. Li and F.Y. Wang. Cooperative Driving at Blind Crossings Using Intervehicle Communication. *IEEE Transactions on Vehicular Technology*, 55:1712–1724, 2006.

[18] S.E. Shladover, C.A. Desoer, J.K. Hedrick, M. Tomizuka, J. Walrand, W.Zhang, D.H. McMahon, H. Peng, S. Sheikholeslam, and N. McKeown. Automatic Vehicle Control Developments in the PATH Program. *IEEE Transactions on Vehicular Technology*, 40(1):114–130, 1991.

[19] H. Wu, R. Fujimoto, R. Guensler, and M. Hunter. MDDV: A Mobility-Centric Data

Dissemination Algorithm for Vehicular Networks. In *Proc. of the first ACM workshop on Vehicular ad hoc networks*, pages 47–56, 2004.

[20] A.C. Brown, E.J. Cullen, J. Wu, M. Brackstone, D.J. Gunton, and M. McDonald. Vehicle to Vehicle Communication Outage and its Impact on Convoy Driving. In *Proc. of the IEEE Intelligent Vehicle Symposium*, pages 528–533, 2000.

[21] PATH web site. http://www.path.berkeley.edu.

[22] CarTalk 2000 web site. http://www.cartalk2000.net.

[23] R. Rajamani and S.E. Shladover. An experimental comparative study of autonomous and co-operative vehicle-follower control systems. *Transportation Research Part C*, 9:15–31, 2001.

[24] SHIFT home page. http://path.berkeley.edu/SHIFT/.

[25] Rudra Dutta Pritesh Patwa. Joint Modeling of Mobility and Communication in a V2V Network for Congestion Amelioration. *ICCCN*, 2007.

[26] D. Reichardt, M. Miglietta, L. Moretti, P. Morsink, and W. Schulz. CarTalk 2000: Safe and Comfortable Driving Based Upon Inter-Vehicle-Communication. In *Proc. of the IEEE Intelligent Vehicle Symposium*, pages 545–550, 2002.

[27] T. Nadeem, S. Dashtinezhad, C. Liao, and Liviu Iftode. TrafficView: Traffic Data Dissemination using Car-to-Car Communication. *ACM Mobile Computing and Communications Review*, 8(3):6–19, 2004.

[28] The Drive-thru Internet Project. http://www.drive-thru-internet.org/index.html.

[29] SAFESPOT homepage. http://www.safespot-eu.org.

[30] PReVENT homepage. http://www.prevent-ip.org.

[31] COMeSafety homepage. http://www.comesafety.org.

[32] Car2Car Communication Consortium. http://www.car-to-car.org.

[33] The Network Simulator - ns-2. http://www.isi.edu/nsnam/ns/.

[34] Topologically Integrated Geographic Encoding and Referencing system. http://www.census.gov/geo/www/tiger/.

[35] Theodore Rappaport. Freespace Pathloss. In *Wireless Communications (2nd edition), Prentice Hall Professional Technical*, 2001.

[36] John G. Proakis. Rayleigh Fading. In *Digital Communications (3rd edition), McGraw-Hill Book Co*, page 767768, 1995.

[37] Peter E. Hart, Nils J. Nilsson and Bertram Raphael. Correction to "A Formal Basis for the Heuristic Determination of Minimum Cost Paths". *ACM*, 37:28–29, 1972.

[38] Y. Ko and N.H Vaidya. Flooding-Based Geocasting Protocols for Mobile Ad Hoc Networks. *Mobile Networks and Applications*, 7(6):471–480, 2002.

[39] M. Treiber A. Kesting and D. Helbing. Game-theoretic approach to lane-changing in microscopic traffic models. *Transp. Res. B.*, 2006.

[40] Ronald L. Rivest Thomas H. Cormen, Charles E. Leiserson and Clifford Stein. Dijkstra's algorithm. In *Introduction to Algorithms, Second Edition, MIT Press and McGraw-Hill*, pages 595–601, 2001.

[41] Donald E. Knuth. Breadth-first search. In *The Art Of Computer Programming Vol 1. 3rd ed., Boston: Addison-Wesley*, 1997.