A Federated Simulation Platform for the Evaluation of Connected Vehicle Applications

by

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ABSTRACT

Connected Vehicle (CV) technology is a promising advancement that has the potential to improve traffic safety and traffic efficiency, and support other Intelligent Transportation Systems (ITS) applications through facilitating vehicle-to-vehicle and vehicle-to-infrastructure communication. Since conducting a CV field test is costly, hazardous and uncontrollable, simulation becomes a preferable method for CV evaluation. Over the past decade, there have been several approaches proposed to implement a CV simulation platform; however, each approach has specific limitations. Most existing simulation platforms are not capable of supporting accurate, complex and large-scale applications. In response, this thesis proposes a new CV simulation platform, which is a federation of a commercial traffic simulator, VISSIM, and an open-source wireless network simulator, OMNeT++. This new platform supports large-scale simulations and comprehensive driving behaviors with high accuracy. Several traffic scenarios were evaluated under the dedicated short-range communication (DSRC) protocol to explore network latency issues. The findings reveal that network latency may become a significant issue when many vehicles attempts to communicate simultaneously. The research herein also evaluated advisory driving speed (ADS) in a CV environment. The results show the potential of CV technologies to solve both recurrent and non-recurrent bottleneck problems.

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LIST OF ABBREVIATIONS

AADT	Annual Average Daily Traffic
API	Application Programming Interface
CV	Connected Vehicle
CV-ADS	Connected Vehicle-based Advisory Driving Speed
DSRC	Dedicated Short Range Communication
GUI	Graphical User Interface
ITS	Intelligent Transportation Systems
LTE	Long-Term Evolution
OBE	Onboard Equipment
RSE	Roadside Equipment
SCI	Simulation Control Interface
TMC	Traffic Management Center
TTT	Total Travel Time
USDOT	US Department of Transportation
V2I	Vehicle to Infrastructure
V2V	Vehicle to Vehicle
VMS	Variable Message Sign
VSL	Variable Speed Limits
Wi-Fi	Wireless Fidelity
WiMax	Worldwide Interoperability for Microwave Access
WMD	Whitemud Drive

CHAPTER 1. INTRODUCTION

This chapter introduces Connected Vehicle (CV) technology and presents the reasons for researching CV simulation. Then, the problems within existing CV research are presented. Lastly, this chapter states the scope for this research.

1.1 Overview

Transportation systems are an indispensable component of contemporary society. With the increasing number of vehicles, transportation systems are experiencing many new challenges in both traffic safety and traffic mobility. Intelligent Transportation Systems (ITS), which aim at solving transportation problems through the use of advanced technologies, have attracted increased research attentions in recent years. Among these advancements, Connected Vehicle (CV) technologies, which include vehicle-to-vehicle (V2V) and vehicle-to-infrastructure (V2I) communications, offer unprecedented opportunities to create an information-rich environment that translates to better transportation safety, mobility and environmental performance. Through wireless communication, critical information, such as vehicle's position, speed and lane, is collected for identifying traffic accidents and traffic congestion. After analysis, suggestions are sent with enough reaction time to vehicles and their drivers. Take one potential CV application as an example: when an accident occurs, involved vehicles would broadcast the accident location to the surrounding vehicles and infrastructure, which will relay alert information to other vehicles in the network; drivers might slow down or change their routes to improve safety and mobility after receiving these messages.

With support from U.S. Department of Transportation (USDOT), a 2011 report by the American Association of State Highway and Transportation Officials (AASHTO) [1] proposed four wireless communication protocols for CV networking technologies: i) Dedicated Short Range Communications (DSRC) [2]; ii) commercial cellular service, including Long-Term Evolution (LTE); iii) Worldwide Interoperability for Microwave Access (WiMax) [3]; and iv) Wireless Fidelity (Wi-Fi). To verify the effectiveness of new applications that use these networking technologies, strict tests and evaluations under different parameter settings, configurations, conditions and scenarios are conducted. Based on the results of these experiments, lots of development and customization work is required for traffic application designs and wireless communication technology configurations to avoid design mistakes and potential challenges before field implementation. However, CV field tests are considerably complex because they require a large number of vehicles and participants (drivers and technical staff). Furthermore, dangers, especially collisions, also occur. Moreover, field tests are difficult to control and reiterate, which is problematic for finding conclusive and repeatable solutions. Given these challenges, it is better to complete CV simulation evaluations prior to conducting CV field tests.

1.2 Problem Statement and Research Motivation

1.2.1 Requirement for Simulators to Perform Integrated Evaluation

CV simulation requires the combination of both traffic and wireless network simulation; either simulator alone could not perform effective CV work. A CV application simulator should be able to simultaneously simulate wireless communication and microscopic traffic conditions. Both of the two capabilities have been provided separately by existing wireless network and traffic simulators. Wireless network simulators are used to evaluate the performance of communication protocols under different network conditions, while traffic simulators are used to assess traffic network performance in different traffic scenarios. Due to the interaction between traffic simulation and wireless network simulation, the performance of either will have a significant influence on its counterpart. Previous work shows that CV simulators focused on wireless communication tend to use professional wireless network simulators, such as Ns-2 and OMNeT++, with simplified vehicular movement models, such as the random way point model, while CV simulators focused on transportation tend to use professional traffic simulators, such as Paramics and VISSIM, with many assumptions in the wireless communication network. Take the accident information dissemination case as an example again: the former category focuses on network latency, communication range, receiving probability, etc., while the latter category focuses on traffic network performance through traffic management methods, such as speed limit and route guidance. Although the research focus is different, there is no doubt that the results from either category might be wrong or misleading due to the simulation interaction. Ignoring either side would cause a significant drop in simulation accuracy, which deduces less reliable evaluation results for CV applications. Therefore, it is necessary to build a CV simulation platform that incorporates the advantages of both traffic simulation and wireless network simulation to support CV research.

1.2.2 Unreasonable Assumption in DSRC Network Latency

In most existing transportation research, it is assumed that the DSRC network has unlimited capacity, which means that there would be no network latency. This assumption does not create negative influences when the latency is very small or the applications are insensitive to it. However, since the DSRC network does have latency in the real world, it is much better to evaluate CV applications with considerations on latency to obtain a more reliable result. For instance, if a vehicle could not receive alert messages on time, traffic safety or mobility performance might decrease; this is not reflected in a zero network latency simulation. In addition, as a result of the unlimited capacity assumption, the influence of DSRC latency in real traffic patterns is still not clear; therefore, it is necessary to address latency with various real traffic scenarios and provide useful suggestions for CV researchers to avoid application design flaws.

1.2.3 Lack of Sophisticated Traffic Mobility Application Evaluation in CV Environment

As can be seen from previous work, many studies have been done to evaluate the performance of CV safety applications. Due to the characteristics of CV technology, it could also be used to improve traffic mobility. Traffic applications, such as Variable Speed Limits (VSL) strategies, which are designed to improve traffic mobility, may significantly benefit from CV technology. However, little research has been done to evaluate these sophisticated traffic applications in a CV environment. It is necessary to research these applications and find out how CV technology could help them improve traffic mobility performance.

1.3 Research Scope

1.3.1 Design and Development of a New CV Simulation Platform

The author designed and developed a new CV simulation platform with Xiaowei Xu, a graduate research assistant from the School of Optical and Electronic Information at Huazhong University of Science and Technology in China. The platform is the federation of a commercial traffic simulator, VISSIM, and an open-source wireless network simulator, OMNeT++. Fast feedback and communication between the two simulators form this very powerful simulation platform. VISSIM is popular in both industry and research communities and supports complex transportation applications with high accuracy and a user-friendly interface. OMNeT++ is open-source and has many active communities. It also supports large-scale simulations and supplies all of the typical wireless communication protocols for CV. Therefore, the new simulation platform has the potential to support large-scale simulations, all typical CV wireless communication protocols and comprehensive driving behaviors.

1.3.2 Analysis of DSRC Network Latency and Evaluation of Advisory Driving Speed with Proposed CV Simulation Platform

This thesis analyzed DSRC network latency with various traffic scenarios. Two traffic cases were simulated with different penetration rates, packet sizes, communication frequencies and sender numbers. The results show that network latency could become a significant issue in some circumstances. These findings could be guidance for designing CV applications, especially network latency-sensitive ones. Researchers should be careful with wireless communication limitations and make CV applications better represent field conditions.

Connected Vehicle-based Advisory Driving Speed under DSRC was carefully evaluated in this thesis study, which included the implementation of various scenarios for both recurrent and non-recurrent bottleneck issues on the proposed CV simulation platform. The results prove that CV technologies can be used for solving or mitigating bottleneck issues, especially non-recurrent bottleneck issues, which cannot be solved by traditional methods. The other findings are also useful for further study or future implementation in CV-ADS.

1.4 Structure of Thesis

The remainder of this thesis is presented in five sections:

Chapter two introduces the existing research into building CV simulation platforms. The existing simulation platforms are classified into three categories: 1) separated simulators; 2) embedded simulators; and 3) federated simulators. The architecture and features of these simulators are discussed, and the reasons for developing a new CV simulation platform are illustrated.

Chapter three is the basis of this thesis. The architecture of the proposed federated CV simulation platform is illustrated in detail. The simulation process and implementation of each component is also presented.

Chapter four analyzes the DSRC network latency in different communication scenarios. Two cases are introduced in this section to show the effects of network latency. The reasons for network latency are also discussed.

Chapter five evaluates advisory driving speed in the proposed CV simulation platform. This research implements advisory driving speed in a CV environment to mitigate both recurrent and non-recurrent bottleneck issues. The results are discussed in detail.

Chapter six concludes the main work and limitations of this thesis and provides recommendations for related future research.

CHAPTER 2. LITERATURE REVIEW

The interaction between the traffic simulator and the wireless network simulator has a significant influence on CV application modeling. In a CV system, vehicles in the traffic network might change their driving behaviors as a result of receiving messages from other vehicles or infrastructure, while the receiving probability in the wireless network highly depends on the position of senders and receivers. In recent years, many studies have been conducted to develop a powerful CV simulation platform for CV application evaluation. The approaches to implement the simulation platform are classified into three categories: 1) separated approach; 2) embedded approach; and 3) federated approach. Numerous CV simulation platforms have been proposed in the last decade. The architecture, advantages and drawbacks of them are discussed in this chapter.

2.1 Separated Simulators

The separated approach focuses on using a traffic simulator or a mobility model generator, which produces mobility traces that are imported to the wireless network simulators for evaluation. For instance, the mobility simulator VanetMobiSim and the network simulator Ns-2 were used in a separated way to develop a simulation tool for the CARLINK project [4]. In this simulation tool, VanetMobiSim is responsible for generating vehicular mobility traces, and Ns-2 is responsible for network simulation. There are two advantages of this simulator:

- VanetMobiSim is an open-source tool and the mobility patterns have been validated.

- Ns-2 is a widely used network simulator that supports a wide range of protocols.

However, the drawback of this developing approach is the lack of two-way communication, which means that vehicles' behaviour could not be changed in reaction to the network events. Furthermore, VanetMobiSim is not as accurate as other pure traffic simulators. Therefore, this tool cannot effectively simulate CV applications.

2.2 Embedded Simulators

To bridge this gap, another method was developed that adopts an embedded approach, joining a scalable vehicular mobility description and network model in a single simulation tool. The embedded approach solves the one-direction communication issue in separated simulators; however, it brings some other problems at the same time.

Bononi et al. [5] developed the MoVes framework, which is a simulation tool for fine-grained parallel and distributed simulations, by modeling vehicular traffic mobility and wireless network. Mangharam et al. [6] developed GrooveNet, which is a hybrid simulation tool that supports vehicular communication between real world vehicles and simulated vehicles. GrooveNet's modular architecture contains a trip model, traffic light model, car model, infrastructure node model, mobility model and physical layer communication models. Researchers can study problems, such as network latency, communication range and penetration rate on this platform. Gorgorin et al. [7] proposed the VANET simulator, which is a discrete simulation tool composed of a microscopic simulator and a wireless communication simulator. It supports the modeling of message send, message receive and GPS-related vehicle events. The architecture enables this platform to emulate real vehicular applications. Moreover, the vehicle mobility model considers vehicle interactions, traffic rules and driver behaviors. Vuyyuru et al. [8] presented a realistic CV simulation framework, AutoMesh, which consists of a set of modules controlling all parts of a realistic simulation, including a driving simulator module, a radio propagation module, a network simulator module, a geographic database server and a Graphical User Interface (GUI) module. This simulation tool evaluates the performance of radio propagation in a realistic urban traffic environment through implementing three-dimensional maps and digital elevation models.

The biggest advantage of MoVes, GrooveNet, VANET and AutoMesh is the bi-directional communication that can be used to simulate the responses in the traffic network based on information reception. However, there are also several drawbacks of these four simulators. For example, the traffic and/or wireless network models used might need more validation before they are widely accepted by the public. Furthermore, the accuracy of models is relatively low when compared with widely used commercial or open-source simulators. As Fiore et al. [9] mentioned, the performance of wireless communication simulation is overestimated as a result of using inaccurate mobility models, while the performance of traffic network simulation is also weakened by the low accuracy of wireless network models.

To bridge these gaps, researchers embedded traffic models with validated wireless network simulators or vice versa. Arbabi et al. [10] added a well-known vehicle mobility model to a wireless network simulator, Ns-3. The vehicle mobility model consists of five classes: vehicle, obstacle, model, lane change and highway. For instance, the model classification includes the IDM (Intelligent Driver Model) car following mobility model, and the lane change classification refers to the MOBIL (Minimizing Overall Braking Induced by Lane Changes) lane change model. The highway class can use the other four classes to generate highway traffic. In this extended Ns-3, users can configure the messages to be sent, vehicles' reaction upon wireless reception and vehicles' position update. Choffnes et al. [11] embedded the STRAW (Street Random Waypoint) tool into SWANS (Scalable Wireless Ad hoc Network Simulator). STRAW is able to model complex intersection management using traffic lights and traffic signs, and SWANS is a scalable and efficient network simulator. NCTUns [12, 13] is a high-fidelity and extensible wireless network simulator and emulator, which is capable of imitating various protocols used in both wired and wireless networks. It also supports road network construction and microscopic vehicle mobility models. One problem is that NCTUns can only support a maximum of 4096 nodes in one simulation, which makes it not suitable for large-scale simulations. Khorashadi et al. [14] also extended SWANS with a Cellular Automata-based vehicular micro-simulation model to accurately simulate both vehicular mobility patterns and wireless network environments. Riemann et al. [15] simulated cooperative systems through the C2X module, which is provided by VISSIM, a commercial microscopic traffic simulator. C2X API (Application Programming Interface) allows analysts to implement CV applications in the VISSIM environment. Similar to Riemann et al., Goel et al. [16] augmented another commercial traffic simulator, PARAMICS, to interpret communication between vehicles. The last two CV simulation tools are much more user-friendly for researchers in the transportation field, because wireless communication simulators are already embedded in these mature traffic simulators. Therefore, researchers can model CV applications in a familiar developing environment. Moreover, VISSIM and PARAMICS also bring some conveniences for extending existing traffic applications to CV applications.

In summary, embedded simulation platforms improve the model accuracy and reliability, which makes them useful for CV application studies. There are no severe problems in this approach and it is possible to develop a practical platform, such as NCTUns, in this way. However, when it comes to developing a general and extensible CV simulation platform, the embedded approach is not appropriate. It is very difficult for users and developers to evolve or replace certain models, since complete knowledge of the platform development is required. Embedded CV simulation platforms do not provide much flexibility and extensibility for users—just platform developers. General users need to have a comprehensive understanding of the platform architectures before using them. Therefore, for CV simulation platforms that have an embedded traffic mobility model with a wireless network simulator, it is usually difficult to implement traffic-related applications, such as signal control or speed management, while for those simulators that have an embedded wireless communication model with a microscopic traffic simulator, it is nearly impossible to perform research on the wireless network. Taking the C2X module in VISSIM as an example, general users cannot configure the communication parameters or retrieve the network delay data.

2.3 Federated Simulators

To reap the benefits of CV technology and well-tested traffic and wireless network models, the most powerful approach is to directly federate a traffic simulator and a wireless network simulator. The traffic simulator produces traffic information and realistic mobility patterns, which are transferred to the wireless network simulator for position updating. At the same time, the wireless network simulator also provides network feedback information to the traffic simulator for vehicle reactions, which will influence traffic network performance.

Konishi et al. [17] implemented the MobiREAL simulator, which provides a new methodology to model and simulate the realistic mobility of nodes and evaluate CV applications. MobiREAL is composed of two parts: 1) the MobiREAL behavior simulator, which simulates traffic mobility; and 2) the MobiREAL network simulator, which simulates data exchange. These two parts are totally independent of one another and they exchange necessary data by a TCP channel at specific intervals. Wu et al. [18] developed a simulation platform that consist of a microscopic traffic simulator, CORSIM, and a wireless network simulator, QualNet, by a distributed simulation software package, called the Federated Simulations Development Kit. The communication between CORSIM and QualNet involves the exchange of information, including vehicle status and position. In the simulation process, vehicle position updates are transmitted from CORSIM to QualNet and mapped to mobile nodes. Lochert et al. [19] proposed a simulation environment that is composed of a microscopic traffic simulator VISSIM, a network simulator Ns-2, and an application behavior simulator (MatLab/Simulink). Similar to Lochert et al. [19], Schroth et al. [20] combined a traffic simulator, CARISMA, and a network simulator Ns-2. An application module was integrated into this CV simulation platform for application modeling. The architecture of this simulation platform could be a representative for federated simulation platforms. The developers built communication modules that take charge of the data exchange between the network simulator and the traffic simulator. Piorkowski et al. [21] proposed an open-source simulation platform, TraNS, which consists of a traffic simulator, SUMO, and a wireless network simulator, Ns-2. TraNS includes two modes: 1) a network-centric mode; and 2) an application-centric mode. In the first mode, TraNS is a one-direction simulation platform: the output obtained from Ns-2 cannot be passed back to SUMO. Therefore, this mode is not useable. In the second mode, TraNS allows the Ns-2 to control the simulation in SUMO to change driver behaviors, such as stop, change lane and change speed. Miloslavov et al. [22] integrated a transportation simulator, VISSIM, along with a modified open-source networking simulator, NCTUns, into a single synchronous system that simulates both the communication and transportation aspects of vehicular networking. Sommer et al. [23] described a bi-directionally coupled simulation framework using a road traffic simulator, SUMO, and a wireless network simulator, OMNET++. Ma et al. [24] adopted ns-2 and PARAMICS to build a simulation platform for detailed communications and traffic modeling. The internal traffic simulation can be modified by external customization with the PARAMICS API, and this platform was used for online travel-time prediction. Rondinone et al. [25] proposed the iTETRIS simulation platform, which extends SUMO and Ns-3, two widely referenced open-source platforms for simulating vehicular mobility and wireless communications.

The federated approach presents a promising way for CV simulation platform development, which could potentially solve most problems of other approaches. However, developing an effective federated simulation platform is still a challenge, as it is quite complex to couple two independent simulators directly. A loose federation may generate less accurate results and cause slow simulation speed, while a tight federation may weaken evolution ability and increase developing difficulty for users.

2.4 Conclusion

The platforms introduced above implement several interesting approaches to build CV simulation platforms. The architectures of these three different approaches are shown in Figure 1.

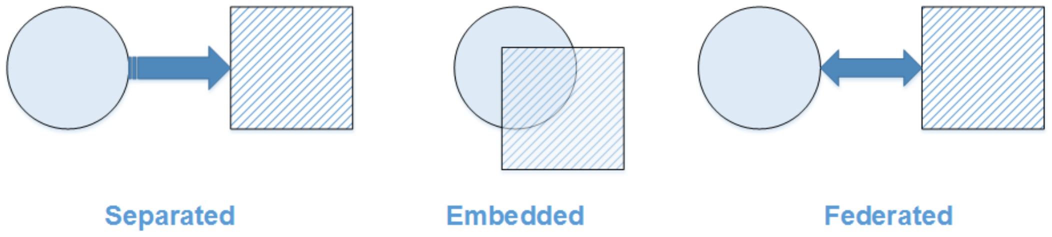


Figure 1 Architecture of Different Combination Approaches

An effective CV simulation platform needs to combine the two simulators and allow communications between them. The separated approach combines a wireless network simulator and a traffic simulator with trace files; however, the network simulator cannot transmit information to the traffic simulator, rendering the CV simulator ineffective when two-way communication is required. The embedded approach embeds a network simulator in a traffic simulator or vice versa to create a new CV simulator; however, this method was developed from scratch and lacks testing, resulting in low simulation reliability. In addition, it is quite complex for researchers to develop CV applications on embedded platforms, and the evolution capability is also very poor. The federated approach combines a network simulator and a traffic simulator directly. This method has many well-tested models to output reliable and accurate simulation results. What's more, its architecture brings an excellent developmental interface and strong evolution capability. It seems that the existing federated simulation platform could fully support CV research; however, there are still other factors that need consideration, such as comprehensive driving behavior support, various CV wireless communication protocol support and complex and large-scale CV application support. Considering all of these factors, most federated simulation platforms do not reach the requirements for CV application evaluation.

To support the CV research in our group, this thesis proposes a new CV simulation platform, which applied the federated approach to combine a commercial traffic simulator, VISSIM, and an open-source wireless network simulator, OMNeT++. The platform was designed with the purpose to match the necessary requirements in transportation research. Details of the development are presented in the next section.

CHAPTER 3. THE NEW FEDERATED CONNECTED VEHICLE SIMULATION PLATFORM

This chapter first introduces the architecture of the new federated Connected Vehicle simulation platform and follows with an illustration of the implementation of the wireless network simulator, traffic simulator, simulation control interface and external application, respectively. In addition, the simulation process is described.

3.1 Simulation Platform Architecture

The new CV simulation platform supports accurate, comprehensive and large-scale CV application simulation, including modeling onboard equipment (OBE), roadside equipment (RSE) and a traffic management centre (TMC). It should be noted that this platform does not simulate communication between RSE and TMC. In the simulation, OBE and RSE are modeled in both VISSIM and OMNeT++. For a connected vehicle, its mobility is represented as a vehicle in VISSIM, while its wireless information exchange status is handled as a node in OMNeT++. This research developed a new module, called *Simulation Control Interface* (SCI), to deal with this issue over different simulators. SCI is the core of this simulation platform. It is responsible for data exchange between VISSIM and OMNeT++, time synchronization and simulation control. The architecture of this federated CV simulation platform is illustrated in Figure 2. There are three components of the simulation platform: 1) VISSIM; 2) OMNeT++; and 3) SCI. In addition, an external application was used to emulate TMC.

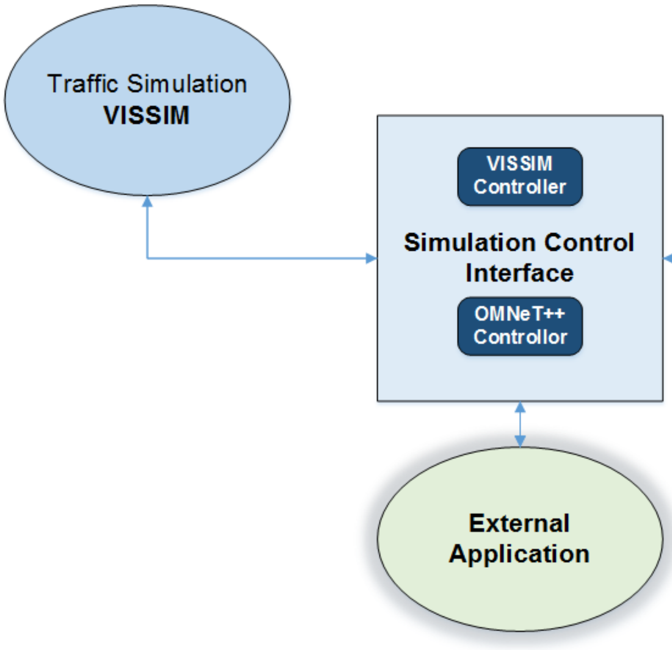


Figure 2 Simulation Platform Architecture

VISSIM [26] is a state-of-art traffic simulator that can be applied as a useful tool for analyzing various transportation problems. It can simulate the road and traffic flow in a highly accurate and visual way. VISSIM analyzes private and public transportation operations under certain constraints, like lane configuration, traffic composition, traffic signals, PT stops, etc., thus making it an effective tool for the evaluation of various alternatives based on transportation engineering practices and measures of effectiveness planning.

OMNeT++ [27] is the network simulator framework that we adopted in our platform, which was used to simulate the wireless communication between OBE and RSE. This simulator also contains an IDE (integrated development environment) derived from Eclipse, facilitating the development of network simulation applications. OMNeT++ is a public-source, component-based, discrete-event and modular simulation framework. It supports simulation of accurate and large-scale wireless transmission in different protocols, such as Wi-Fi, DSRC and LTE. It is popular in both academia and industry for its open-sourced extensibility and has built up a large user community.

SCI takes charge of the whole CV simulation. SCI is composed of two controllers: 1) a VISSIM controller; and 2) an OMNeT++ controller. Socket TCP/IP communications were implemented between these two controllers for data exchange and time synchronization.

The external application is independent of this simulation platform. Users can design their applications in it. The external application exchanges data with the VISSIM controller to control traffic and wireless network simulations.

3.2 CV Simulation Process

Due to the nature of bi-directional coupling in the co-simulation, synchronization between the traffic simulator and the wireless network simulator is a prerequisite functionality. In addition, since both VISSIM and OMNeT++ frameworks are discrete-event simulators, and both run with a unique internal simulation time step, the development of a synchronization component could be greatly simplified. The synchronization is done between each internal simulation time step, as shown in Figure 3.

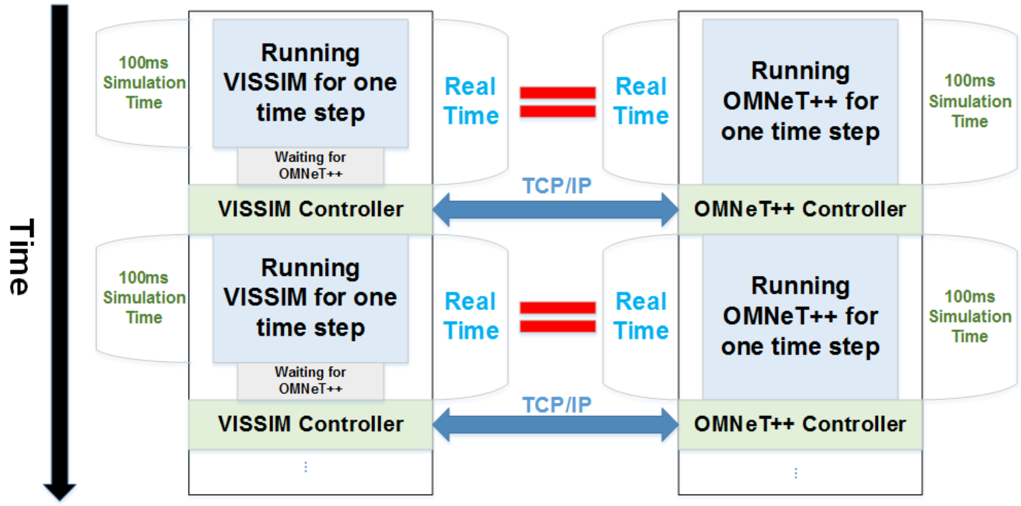


Figure 3 Sequence Diagram of Message Exchange and Synchronization

Socket TCP/IP communications were implemented to facilitate the interaction between the traffic and wireless network simulators. When the simulation begins, the VISSIM controller and OMNeT++ controller will make VISSIM and OMNeT++ run one time step based on the configuration files, respectively. The faster simulator’s controller will suspend the simulation and wait for the slower simulator to finish. When both simulators have finished one time step, the two controllers will exchange traffic and network data through established TCP/IP connections. After synchronization, the two simulators will run one-time-step simulations. The whole process is a combination of running simulations and synchronizations until the simulation time expires. As shown in Figure 3, although the real time costs for 100 milliseconds (ms) simulation are different, the two simulators always run at the same pace. The total simulation speed is determined by the slower simulator. In most simulation cases, the VISSIM simulation speed is faster than the OMNeT++ simulation speed.

The choice of a 100 ms interval as the simulation time step duration was based on a number of considerations: 1) 100 ms is the duration of one interval during which each OBE switches between the control and service channels of operation; 2) the position of a vehicle inside OMNeT++ is interpolated from the vehicle's location at the beginning and at the end of an interval; therefore, the use of a small interval, such as 100 ms ensures accuracy in the interpolated vehicular position inside the communication simulator; and 3) 100 ms is small enough to ensure that the traffic simulator and its parameter are not delayed for a long period of time and are enforced immediately after an OBE receives a message. The drawback of choosing a period as small as 100 ms is the overhead that the CV simulation platform incurs, as the two simulators often have to pause execution and synchronize to exchange information with each other.

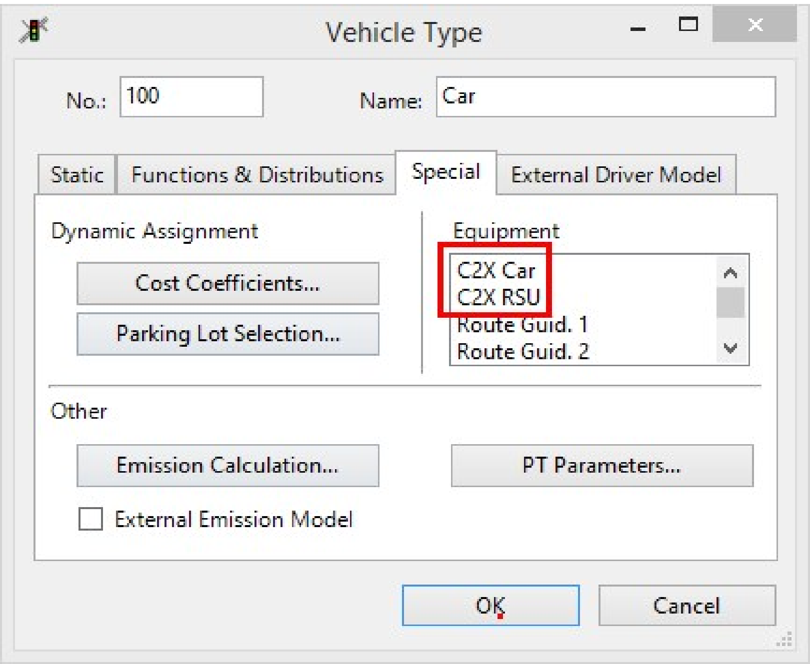
3.3 Simulation Platform Development

3.3.1 VISSIM Interface Configuration

C2X and COM modules of VISSIM have the capability to implement CV simulations, since both of them provide plenty of APIs to manage traffic parameters and driving behaviors. In this research, we chose the C2X module for the VISSIM implementation. C2X is officially released within VISSIM 5.40. All its logic is implemented within a function, named processTimestep, which can be written in Python or C++, and is called every time step to handle the data processing and operations on vehicles. However, the original C2X module has a significant deficiency: the wireless communication between OBE and RSE is implemented using the internal binary module VCOM, which users cannot modify.

In our new simulation platform, we just kept the processTimestep function and developed a new VISSIM controller, which is used to work with OMNeT++ for customizable network simulation.

The C2X module has two advantages. The first benefit is the convenience for platform development, which is brought by processTimestep function. Another benefit is the inherent GUI support for users' configuration, especially for the penetration rate. Two windows of C2X in VISSIM are displayed below.



Vehicle Type

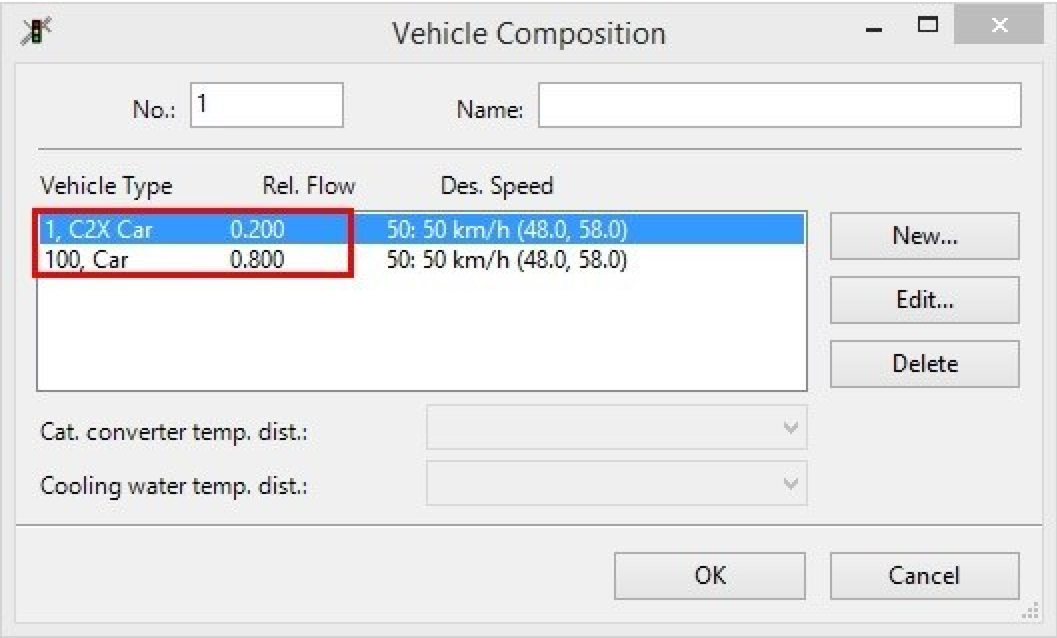
No.: 100

Name: Car

Figure 4 C2X Setting in VISSIM GUI

There are two attributes under Vehicle Type>Special>Equipment: C2X Car and C2X RSU, as shown is Figure 4. In fact, there is no difference between these two attributes, since users cannot set real-world RSE through the original C2X module (RSE was imitated by a stopped vehicle). In the new simulation platform, users only need to select the C2X Car for connected vehicles; therefore, the attributes can be obtained and set by the VISSIM controller in SCI. In addition, since the RSE locations are fixed, there is no need to simulate RSE in the traffic simulator. Therefore, RSE is modeled in SCI and simulated in the wireless network simulator.

C2X also brings a huge convenience for setting the penetration rate. Users can create a special type of connected vehicle. The composition of simulated traffic is totally decided by users. For example, in Figure 5, the traffic is composed of two types of vehicles: 1) <Car>; and 2) <C2X Car>, and the penetration rate is 20%.


Vehicle Composition

No.: 1

Name:

Vehicle Type	Rel. Flow	Des. Speed
1, C2X Car	0.200	50: 50 km/h (48.0, 58.0)
100, Car	0.800	50: 50 km/h (48.0, 58.0)

Cat. converter temp. dist.:

Cooling water temp. dist.:

Figure 5 Penetration Rate Setting

3.3.2 OMNeT++ Simulation Development

OMNeT++ model is composed of modules that communicate through message passing. The active modules in OMNeT++ are simple modules written in C++, using the simulation class library. Compound modules are composed of simple modules that could have an unlimited number of hierarchy levels. For example, the network in OMNeT++ is itself a compound module. In OMNeT++ simulation, messages can be sent either through connections that span modules or directly to other modules [28]. MiXiM is a mixed simulator combining various simulation frameworks developed for wireless and mobile simulations in OMNeT++. It provides detailed models of the wireless channel (fading, etc.), wireless connectivity, mobility models, models for obstacles and many communication protocols, especially at the medium access control level. Further, it provides a user-friendly graphical representation of wireless and mobile networks in OMNeT++, supporting debugging and defining even complex wireless scenarios [29]. Although the MiXiM project is still in development, it is a powerful tool for performance analysis of wireless networks. In the new CV simulation platform, MiXiM is used as the core for wireless network simulation.

The two important parts of OMNeT++ implementation are node management and propagation modeling. Node management is necessary for a dynamic wireless network. Here, we designed a wireless network with a fixed number of nodes. Before initialization, users need to set the number of nodes, which must be larger than the maximum number of C2X vehicles in the traffic network. All the nodes are inactive at the beginning of simulation. During the simulation process, OMNeT++ activates the necessary number of nodes, which may improve simulation efficiency. The positions and status of nodes are updated based on the traffic data from VISSIM in each cycle.

As to propagation modeling, it is often related to the communication scenarios. There are three types of communication scenarios in CV applications: 1) Vehicle-to-Infrastructure (V2I); 2) Vehicle-to-Vehicle (V2V); and 3) Vehicle-to-

Infrastructure and Vehicle-to-Vehicle (V2I&V2V). Since V2I&V2V is a hybrid scenario of V2I and V2V, we just built the first two propagation models in the OMNeT++ implementation. The model for V2I is relatively easy because there is no relay process. However, when it comes to V2V, things become much more complicated.

The vehicles that receive message packets will forward the message to other vehicles. Managing the forwarding among vehicles is the main concern in V2V. A GPS-based forwarding strategy is implemented in the new CV simulation platform.

Vehicles have four states in the V2V scenario: idle, contention, waiting, and sending. In this CV system, packets contain GPS information including sender's location and receiver's location. The sender is the vehicle or the infrastructure that sends packets, while the receiver represents the final landing place of the packet, as determined by GPS. What's more, we implemented contention packets for vehicles to compete for the opportunity to forward a received packet. Figure 6 shows area A and area B as the road sections between the sender's position and the destination's position, which are constrained by the receiver's distance from the sender. If the distance between the receiver and the original sender is less than half of the communication range, then the vehicle is in area A, otherwise the vehicle is in area B. The strategy process is shown in Algorithm 1. Four states and two timers were defined:

Idle state: All vehicles are initialized to an idle state. Once receiving a new packet, the vehicles check their distances from the sender by the location data.

According to the distance data, they will run into the contention state or waiting state.

Contention state: Vehicles in the contention state wait for a random time (from 0 to 20 microseconds). If one vehicle does not have any reception during the waiting time, it will send the contention packet to surrounding vehicles; however, if it receives a contention packet from a competitor vehicle, it will run into an idle state. If one vehicle successfully sends out the contention packet after the wait time, it will run into the sending state. Usually, only one vehicle can send the packet successfully.

Waiting state: Vehicles in the waiting state will wait for 225 microseconds. During the waiting state, if there is a reception, the vehicle will run into an idle state and process the new packet to determine its next state.

Sending state: The vehicles in the sending state will process the received packet, including changing the sender's location to its own and sending the new packet. After sending, it will run into the idle state.

The V2V model proposed above can efficiently handle information relay. As will be shown in the next chapter, network delay is a very serious issue for wireless communication; thus, it is needed to decrease unnecessary contention. In V2V scenarios, if all vehicles participate in packet relay, there will be a big network delay. However, since the packets are the same in one relay process, we just need one vehicle to forward this packet in the model we propose. This model could decrease the wireless network burden and improve transmission speed significantly.

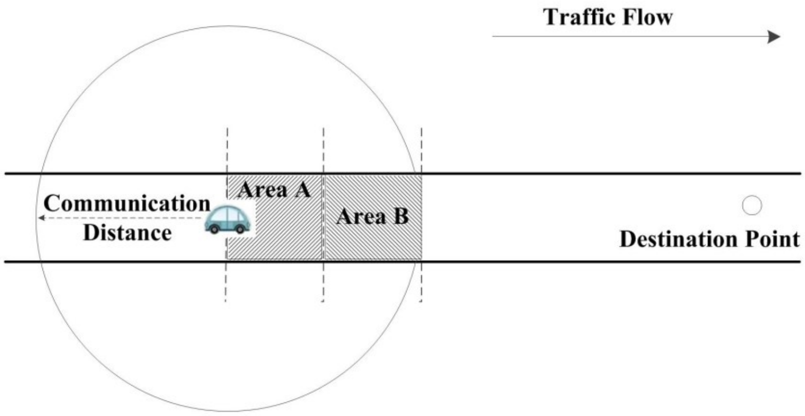


Figure 6 Area A and Area B in GPS-Based Forwarding Strategy

3.3.3 Simulation Control Interface Development

SCI is responsible for representing vehicles between the combined traffic and wireless network simulators. In addition, it defines the interfaces for data exchange with other platform parts and manages the interactions with them. SCI consists of two controllers: the VISSIM controller and the OMNeT++ controller. This section illustrated the details of the SCI development.

- ***VISSIM Controller***

The architecture of VISSIM controller is depicted in Figure 1Figure 7. The VISSIM controller has a number of responsibilities. It loads the files needed to run VISSIM and starts the simulator. Often times a VISSIM simulation starts with empty roads and needs a warm-up period, during which no communication is simulated, but instead VISSIM runs individually for a small period of time to create more realistic traffic conditions. The VISSIM controller handles the warm-up period and other issues related to the configuration of VISSIM. In addition, the VISSIM controller is responsible for extracting needed vehicular data from VISSIM's COM interface. This program collects data from both the traffic and wireless communication simulator and supplies it to any algorithms and applications that could process data, no matter whether they are implemented in the controller itself or in an external application. Finally, the VISSIM controller handles data exchange and time synchronization through the TCP/IP communication with OMNeT++. It establishes the connection, sends vehicle trajectories and processes all data coming from the OMNeT++ simulator and also translates the IDs of VISSIM vehicles to their corresponding IDs in OMNeT++.

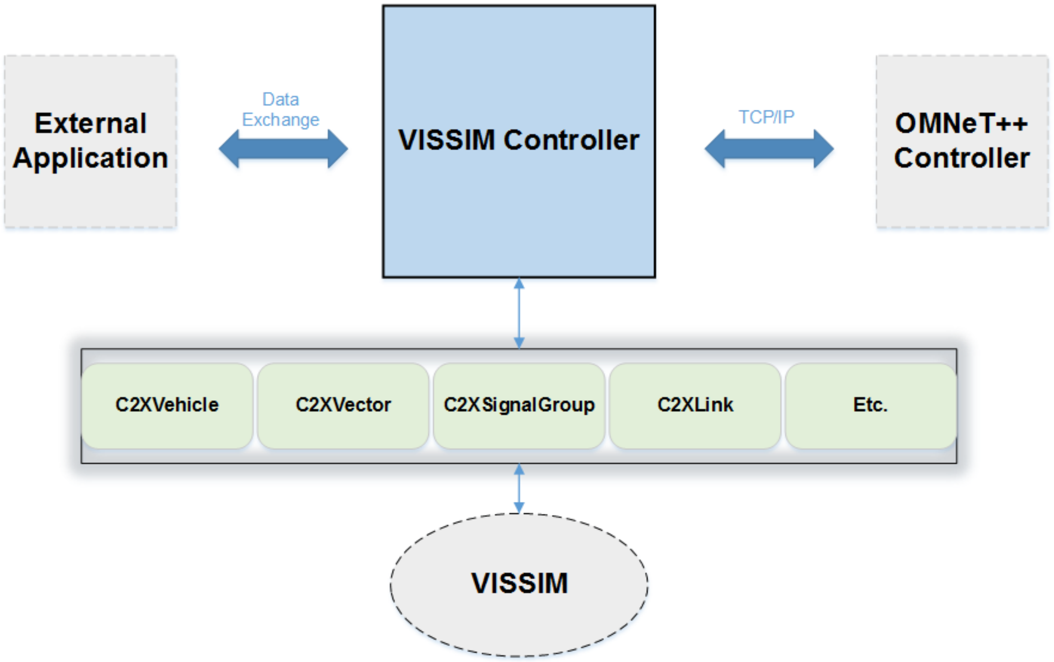


Figure 7 Architecture of VISSIM Controller

- ***OMNeT++ Controller***

The OMNET++ controller includes two parts: 1) the scheduler module (TraInterface); and 2) the MiXiM network, as shown in Figure 8.

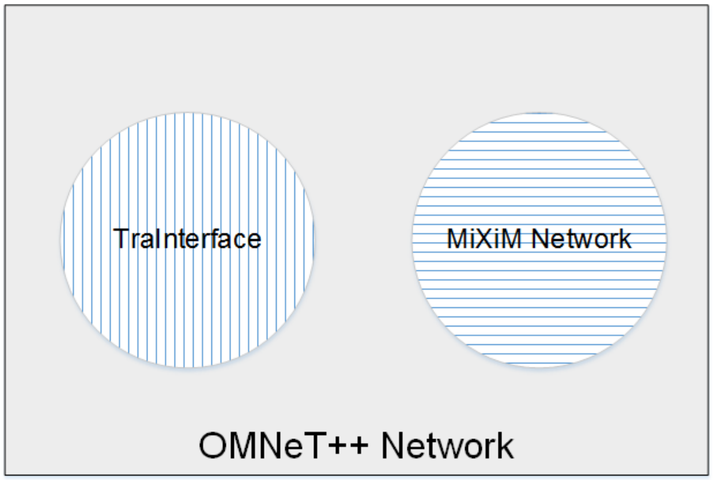


Figure 8 OMNET++ Side Program Structure

The TraInterface module is responsible for maintaining the TCP connection, updating nodes' positions with the TCP information and network message transmissions through the TCP connection. The MiXiM network is a typical MiXiM project, which was already introduced in the previous section. The TraInterface module establishes a TCP/IP connection with the VISSIM controller. In addition, the TraInterface module receives all needed data from VISSIM and update nodes' positions. After that, the TCP connection signals the MiXiM network and waits for its response. After the MiXiM network is done with its 100 ms simulation step, the TraInterface module sends the resulting message data back to the VISSIM controller.

3.4 External Application

The external application is developed by users and is an independent part of the whole CV simulation framework. It differs in different CV applications. Users can develop applications in their own ways, no matter what kind of programming language they use. The basic requirement for the external application is the ability to exchange data with the VISSIM controller. In addition, the external application should run at the same pace as the simulation platform. External applications retrieve data from VISSIM and/or the VISSIM controller, process data by their own algorithms and send the results back to the VISSIM controller for further traffic or wireless network control. To some extent, the external application can be regarded as a real-world TMC. The TMC obtains data in different ways, such as connected vehicles, loop detectors, radar, etc. The TMC processes that data and sends back directives to CV vehicles and RSE. The advantages of implementing the external application are significant. First, it provides full flexibility for application development and does not affect other parts of the platform. Second, it simplifies the process to convert existing applications to CV applications. Users do not need to implement their algorithms on the new CV simulation platform again, but rather they just need to make some minor changes in the existing applications.

CHAPTER 4. DSRC NETWORK LATENCY STUDY ON PROPOSED CV SIMULATION PLATFORM

"DSRC (Dedicated Short Range Communications) is a two-way short-to-medium-range wireless communications capability that permits very high data transmission critical in communications-based active safety applications." [30] This chapter focuses on the influence of DSRC network latency on traffic applications. Two traffic cases were modeled in the new simulation platform to test various communication scenarios and the results are analyzed in detail to show the effects.

4.1 Introduction to the DSRC Protocol and Network Latency

In the Intelligent Transportation System (ITS) Strategic Research Plan [31], 2010 – 2014, USDOT commits to the use of DSRC technologies to pro-actively improve traffic safety through V2V and V2I applications. DSRC has several advantages, which make it the most suitable short-range wireless communication technology for CV applications.

CV applications, such as CV-based intelligent traffic signal control and CV-based traffic data capturing, focus on improving the performance of traffic systems through data exchange between vehicles and infrastructure. In previous studies, it has been assumed that the communication between OBE and RSE is instantaneous within unconstrained DSRC wireless networks. This assumption becomes questionable when the market penetration rate of DSRC-equipped vehicles increases, because the DSRC networks actually have constraints and the network latency may rapidly increase and eventually become a bottleneck.

Within the range of a DSRC network, the media access control protocol of DSRC needs to coordinate multiple senders to avoid access violation. In addition, DSRC supports multiple channels and switches among channels every 50 ms, as shown in Figure 9. Given that each packet must be transmitted within one channel, some packets have to be held in the queue before being sent. With bigger data sizes, higher frequency and more OBE, it is possible to generate a long queue in the DSRC device, which leads to huge network latencies.

This thesis work modeled different traffic scenarios to research the tendencies of DSRC network latency. The details of these scenarios are introduced in the following sections.

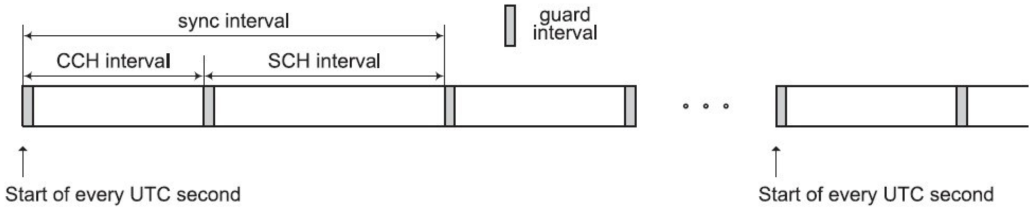


Figure 9 Control Channel (CCH)/Service Channel (SCH) Timing [32]

4.2 VISSIM-Based Connected Vehicle Communication Cases

Two CV cases were evaluated to research the network latency in real-world traffic systems. In both cases, it was assumed that the buffer size of DSRC devices was unlimited. The details of these two cases are introduced below.

4.2.1 Ideal Case

The ideal case was a simulation of V2V or V2I communication scenarios without too much consideration of traffic patterns. A small segment of the traffic network, including one unit of RSE, a one-direction road with two lanes and several connected vehicles, were modeled in the proposed simulation platform. Although the traffic pattern is very simple, the vehicles on the road still follow the VISSIM mobility models, such as the car-following model, the lane-changing model, etc. The discovering range of both RSE and OBE were set at approximately one kilometer (km), the same as most DSRC equipment in the market. Vehicles were capable of communicating with RSE and other vehicles within range. As shown in Figure 10, the RSE covers approximately 1,600 meters on the road actually. Since the desired speed was set to 40 km/h in the simulation, it took each vehicle approximately 140 seconds to drive through the RSE coverage area. In the process, network latency data in the first 100-second period were collected by the RSE. In addition, the bandwidth of the physical layer in the DSRC equipment was set at 18 Mbps (megabit per second). All connected vehicles broadcast data at certain frequencies and the packet size was assumed to be unchanged in one scenario.

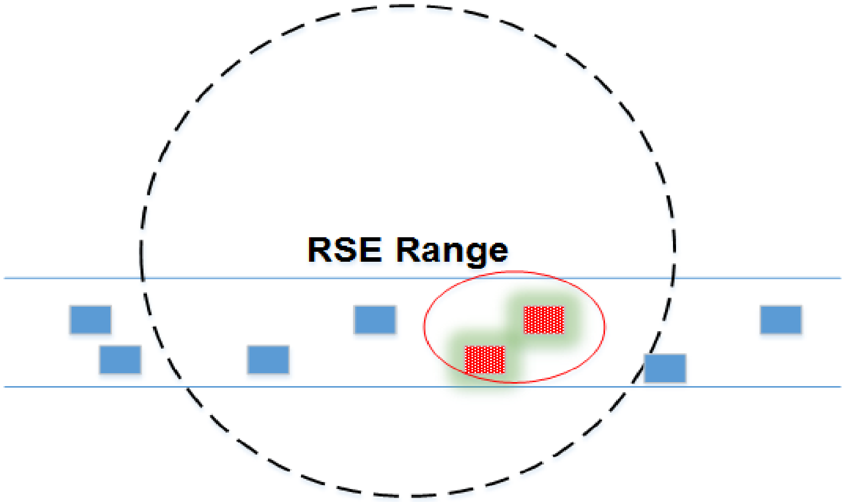


Figure 10 Ideal CV Case

In this case study, three factors were considered relevant to network latency:

- Number of senders within communication range;
- Data size (Data were composed by one or more WAVE Short Messages); and
- Transmitting frequencies;

The bandwidth determines the sending rates of data packets. The data size, number of CVs and transmitting frequency determine the number of data packets that could be sent within one channel interval. For one-sender scenarios, we selected one random vehicle that would broadcast messages at the given frequency when driving in the RSE coverage segment. In two- or three-senders scenarios, we selected vehicles close to each other, and repeated the same broadcast. Each scenario was repeated 10 times to generate more reliable results. The simulation scenarios of the ideal case are listed in Table 1.

Table 1 Simulation Scenarios of the Ideal Case

Sender Numbers	Data Size	Frequency
1, 2, 3	10KB,50KB,75KB	1Hz, 5Hz, 10Hz

4.2.2 Urban Traffic Case

In addition to the ideal case, an urban traffic network was developed to research the effects of DSRC network latency. This research modeled a typical four-approach signalized intersection with one RSE placed right beside the intersection. The traffic volume on each approach was set at 400 vehicles per hour per lane, which represents a moderate traffic condition. This intersection is shown in Figure 11. The communication range was set the same as the ideal case, while the bandwidth was set at 6 Mbps. Connected vehicles communicated with each other or the RSE, and we collected network latency data from just the RSE in this case. Connected vehicles broadcast messages when entering the range of RSE. No management or control methods were implemented. If the delay was too big, such as more than 10 or 20 seconds, the sender vehicle may have driven out of the intersection when the RSE received the message. Since the network latency often increases with time, RSE will stop collecting data if the latency is larger than 20 seconds in the simulation. For each simulation scenario, VISSIM was run 30 minutes first without any CV communications to ensure appropriate travel demand was loaded into the traffic networks; network latency data was not collected until 10 minutes after the connected vehicles begin to transmit data—

this was done to warm up the wireless network in OMNeT++. From the preliminary results, it can be observed that there were in total 200 ~ 300 vehicles within the scope of RSE most of the time.

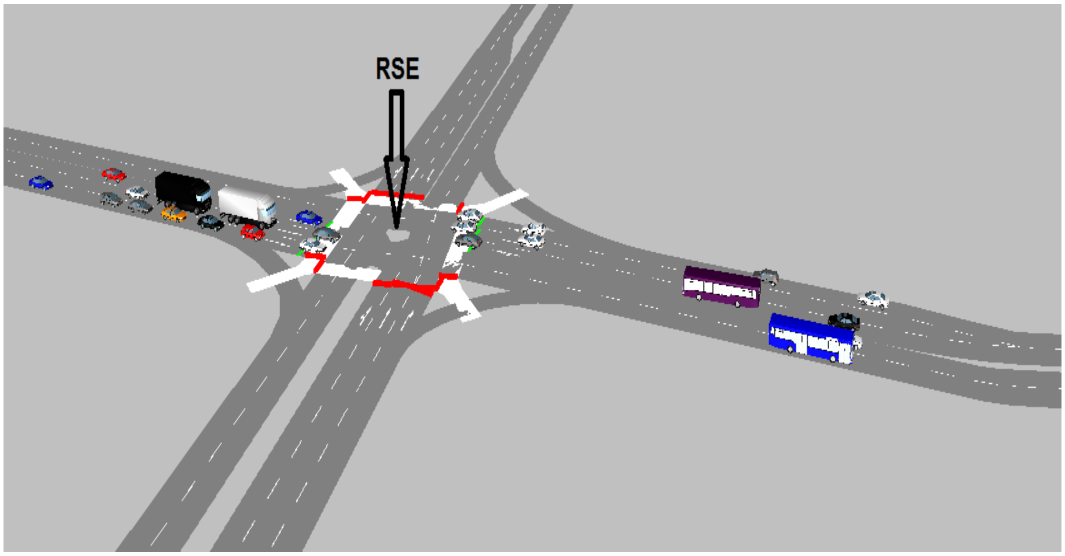


Figure 11 Urban Traffic Case

In this case study, three factors were considered relevant to network latency:

- Connected vehicle penetration rate;
- Data size; and
- Transmitting frequencies;

Each scenario was also repeated 10 times. The configurations of the urban traffic scenarios are listed in Table 2.

Table 2 Simulation Scenarios of the Urban Traffic Case

Penetration Rate	Data Size	Frequency
10%, 30%, 50%	1KB, 10KB	1Hz, 5Hz, 10Hz

4.3 Results and Discussions

4.3.1 Ideal Case Analysis

100-second simulation data were collected for each scenario. For one-sender scenarios, the network latency only depends on the data size. As shown in Figure 12, the network latency was constant for the given data size. Even for the most critical scenarios (75 KB (Kilobyte) data size & 10 Hz Frequency), the latencies still remained the same. If the data size was smaller than the limit, they could be sent within one channel interval. If the data size exceeded the limit, they will never be received.

Figure 13 through Figure 15 shows the network latencies from connected vehicles to RSE and other vehicles in multi-sender scenarios. The results show that frequency, data size and sender number significantly influence DSRC network latency. If the wireless communication workload was over the capacity of the communication network, huge network latency was inevitable. There are two tendencies of network latency, as shown in Figure 13 to Figure 15. The latency pattern mainly depends on the network load, which is determined by frequency, data size and sender number in this case. If the workload is within the capacity, there will be a stable latency tendency. As can be seen from the figures, the stable latencies still have some fluctuation, which is different from the one-sender scenarios. This is caused by the contention between senders. Since senders cannot transmit information simultaneously, there must be a sending sequence, which leads to the wavy latency lines. In this situation, almost all of the vehicles could send messages out in a one-channel interval. Even though a short packet queue may be generated, it would be discharged soon. Therefore, the overall delay remains at a lower level, such as less than 0.5 seconds. This kind of network latency is what we expect in the CV environment, because it will not cause problems for most CV applications.

On the contrary, the other latency pattern could be a serious issue. When the workload was higher than the capacity, the network latency increased, since the queue would become longer and longer. This delay could reach more than 40 seconds (75 KB data size & 10 Hz Frequency & 2 or 3 senders), which is not acceptable. Although DSRC network latency is not the focus for transportation researchers, we still need to consider this when designing CV applications. Inappropriate design might cause huge network latencies, which might make applications useless in real-world implementation. The basic idea is realizing the required traffic management or control at the lowest expense to the wireless communication network. CV researchers should always remember that the capacity of the wireless network is limited. If network delay might affect the traffic performance, researchers should not make assumptions on this factor. Take a highway overpass as an example: it is quite possible that there will be hundreds of vehicles in a small area, as the roads are overlapped. Even with small data size and low frequency, the network latency could still be very large because of the critical contention situation.

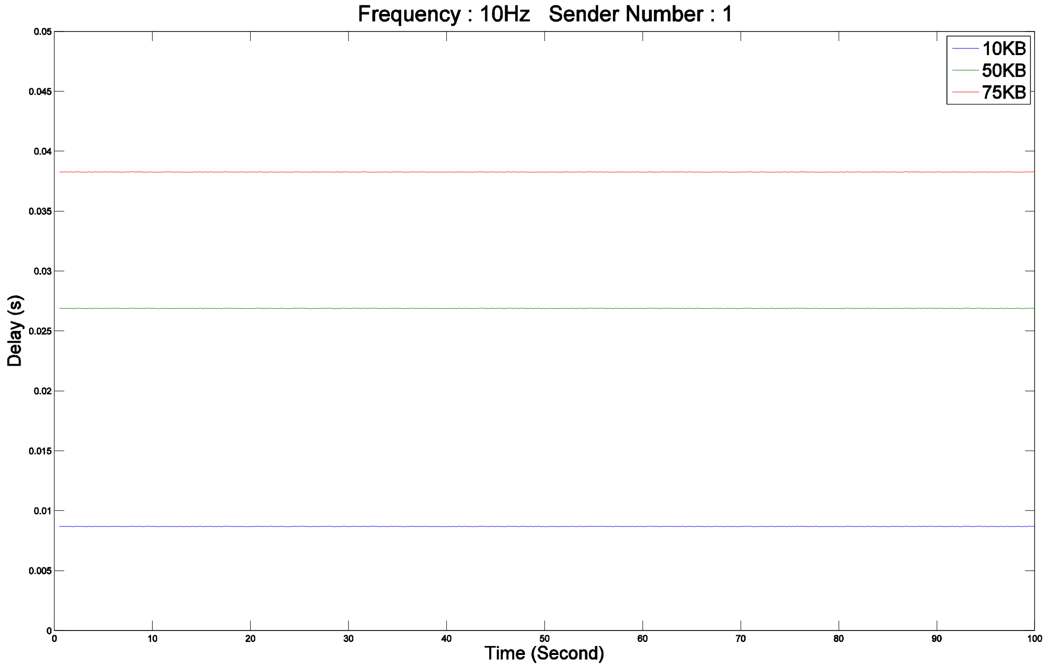


Figure 12 Network Latency with 10 Hz and 1 Sender

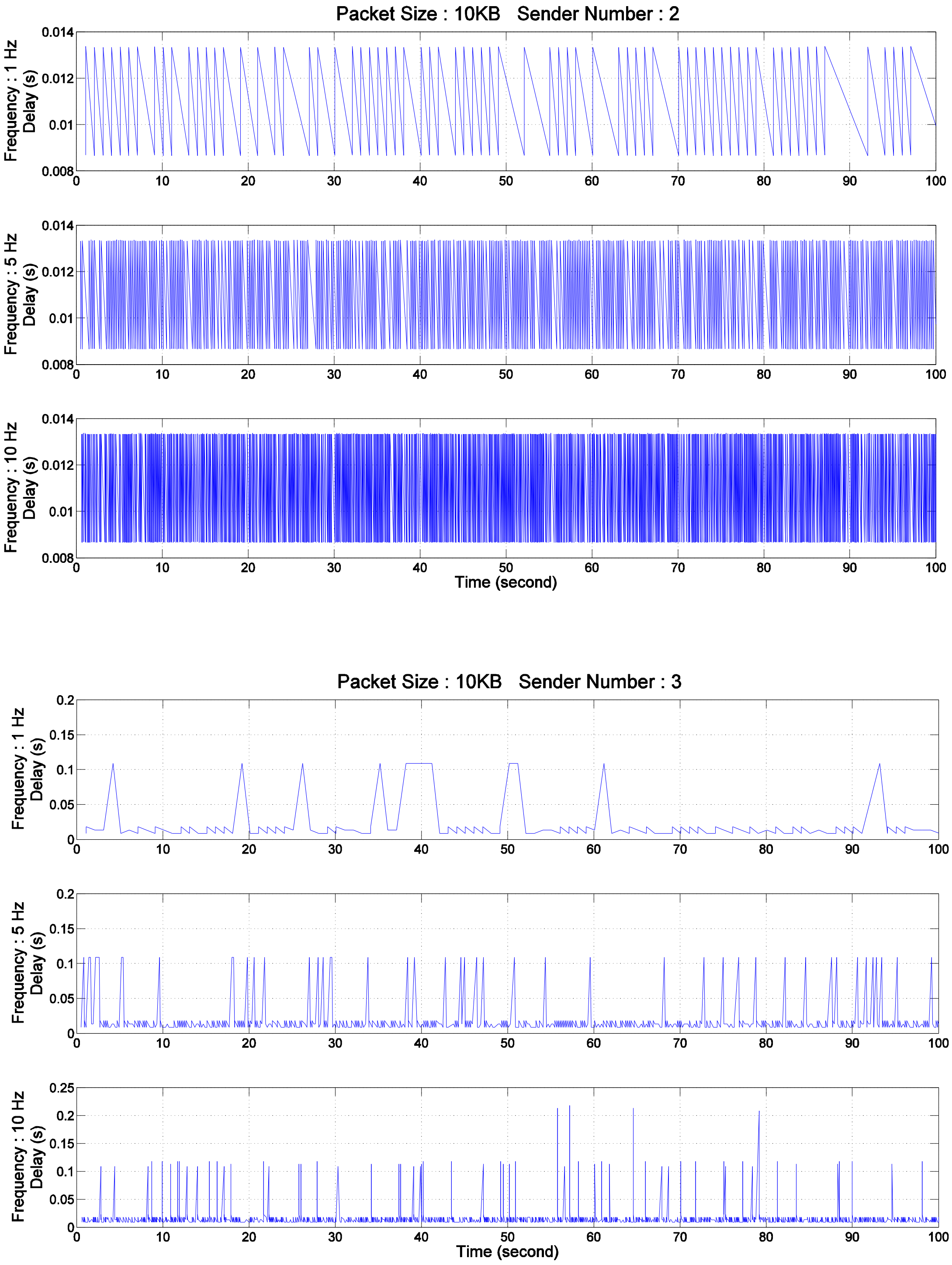


Figure 13 Network Latency with 10 KB Packet Size

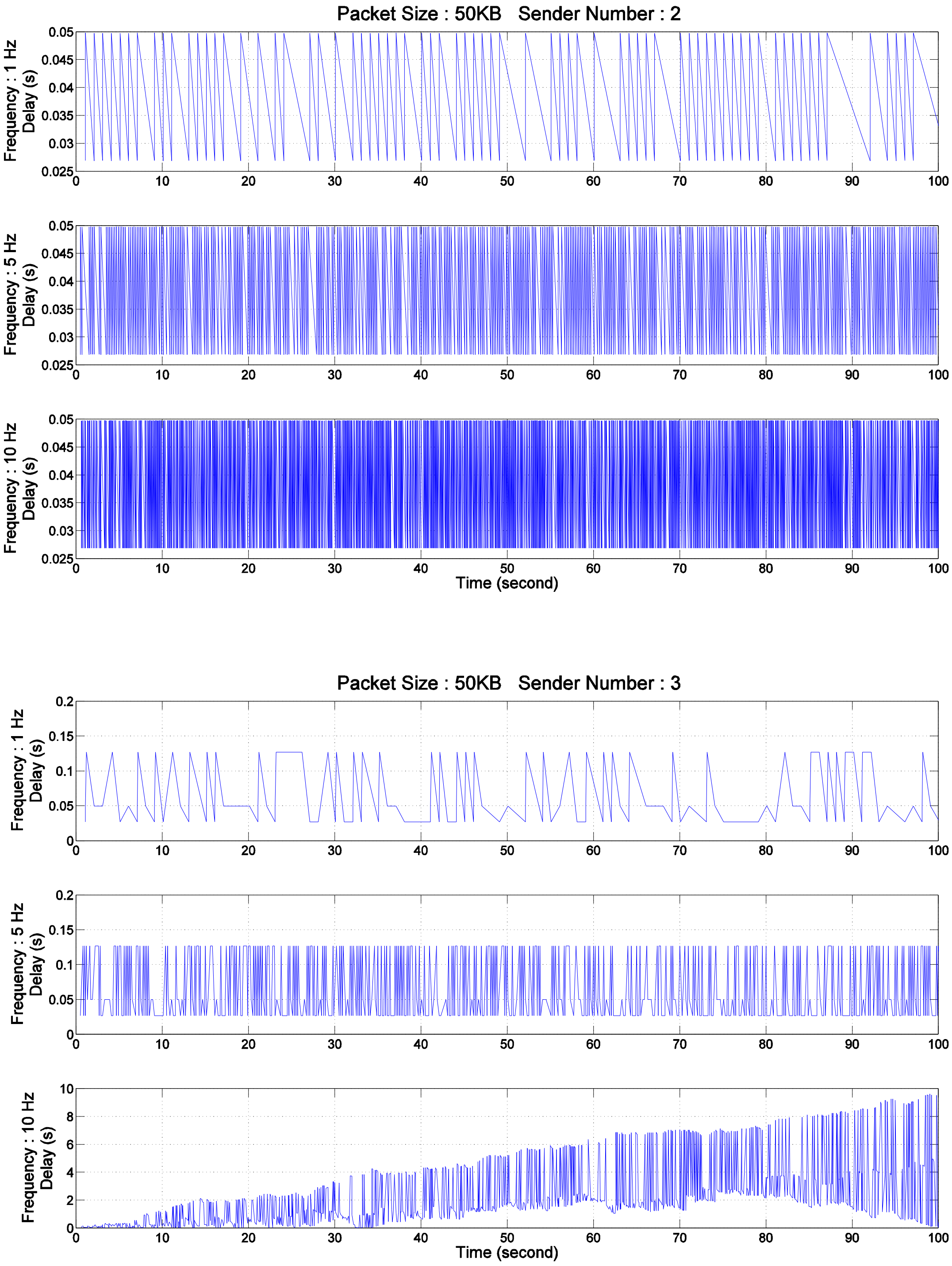


Figure 14 Network Latency with 50 KB Packet Size

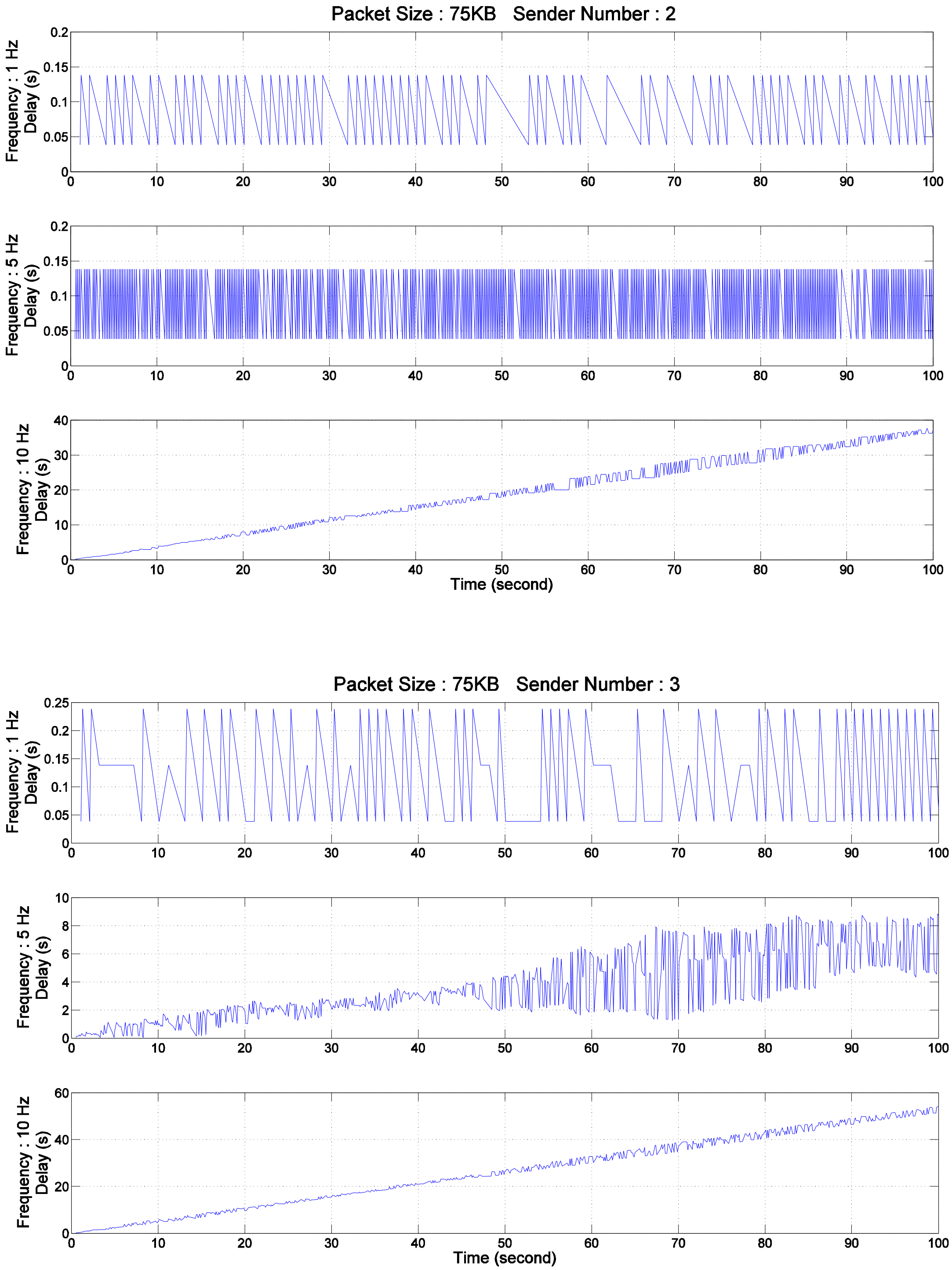


Figure 15 Network Latency with 75 KB Packet Size

4.3.2 Urban Traffic Case Analysis

100-second simulation data were also collected for each scenario in the urban traffic case. The results show that the average network latency increased with the penetration rate. Since the CV penetration rate is the same as the sender number, the control factors are totally the same in both cases. Therefore, it is reasonable that the urban traffic case presents similar latency tendencies as the ideal case. The results demonstrate that the DSRC network latency issue also exists in realistic traffic patterns, and this problem could become very serious as the penetration rate rises. Take 10 KB packet size and 5 Hz frequency as an example: with a 10% penetration rate, the average network latency is approximately 0.1 seconds, and the highest latency is lower than 0.6 seconds; with a 30% penetration rate, the average network latency is 2 seconds, which is 20 times higher than the 10% penetration rate, and the highest latency is near 7 seconds; with a 50% penetration rate, the average network latency is approximately 3 seconds, and the highest latency is near 11 seconds.

It is also quite obvious that these data have too much fluctuation when compared to the ideal case. The reason is that there are much more senders in this case that generate a very severe contention situation. What’s more, since this research set 20 seconds as threshold for network latency in the urban traffic situation, scenarios with a higher penetration rate will reach the threshold earlier.

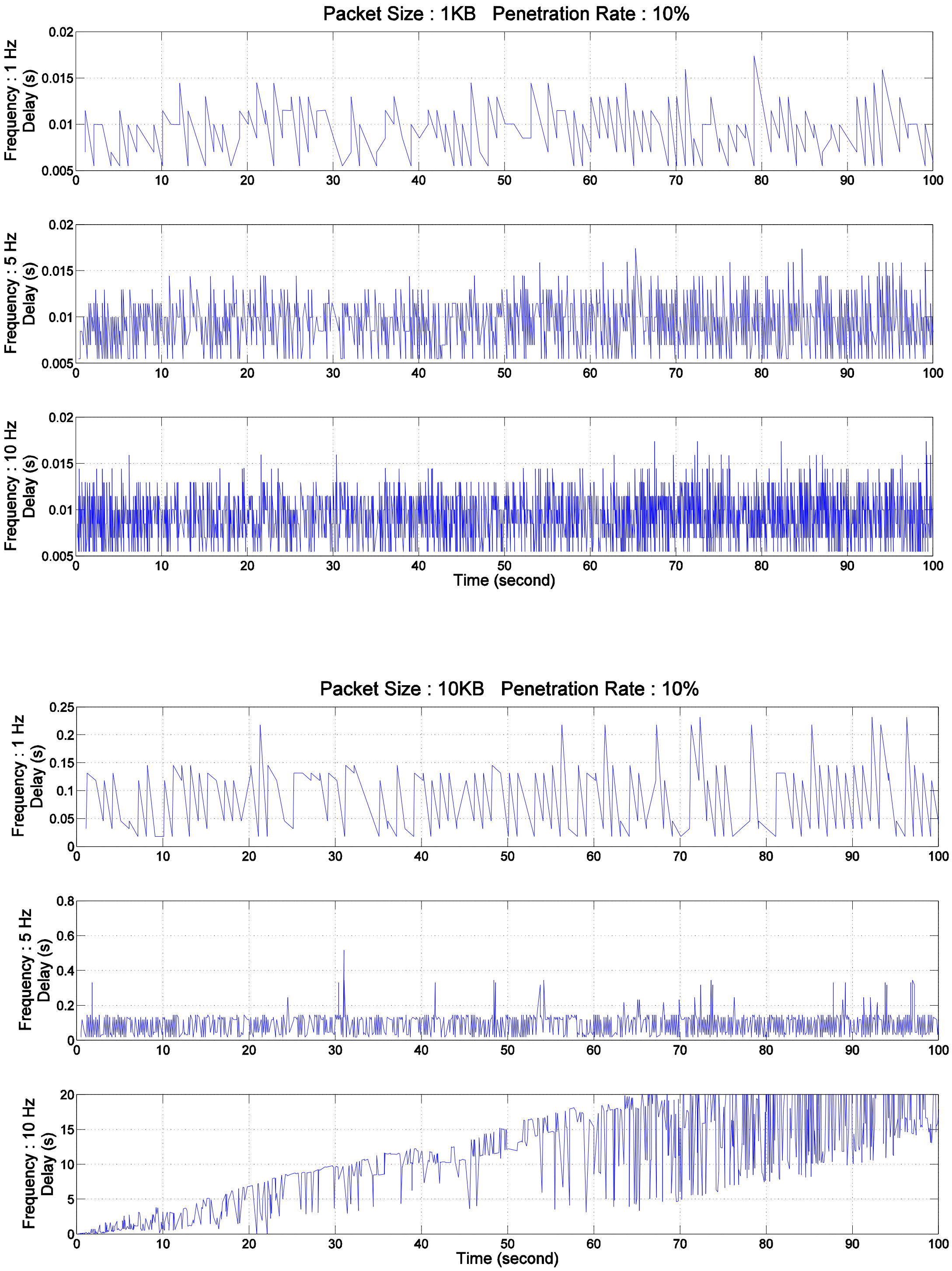
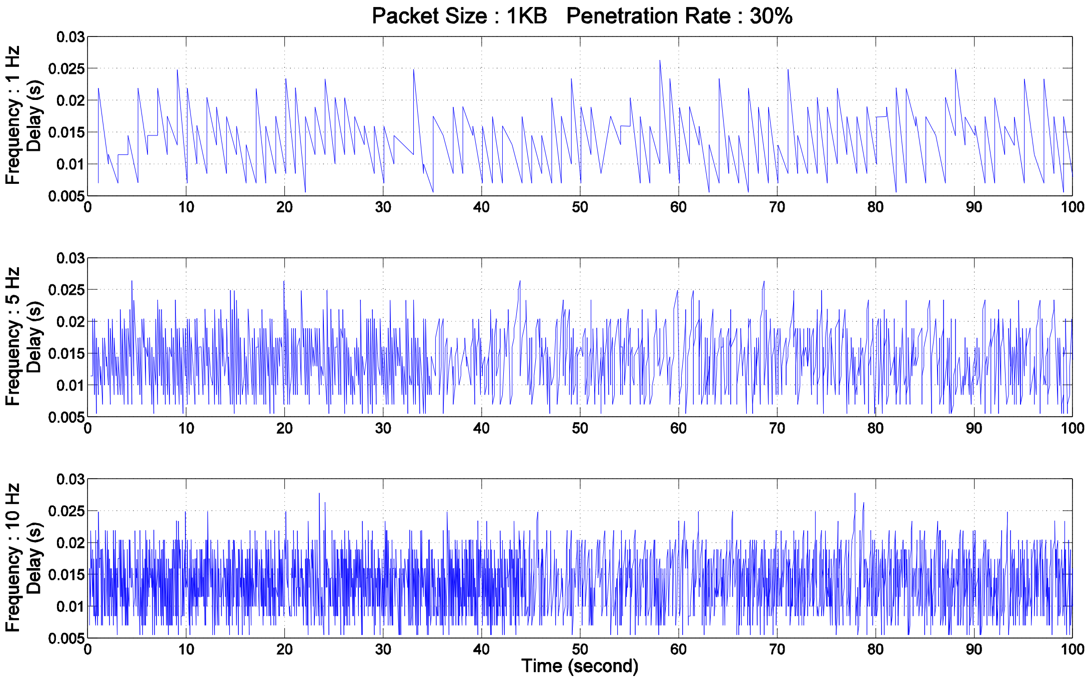


Figure 16 Network Latency with 10% Penetration Rate


Packet Size : 1KB Penetration Rate : 30%

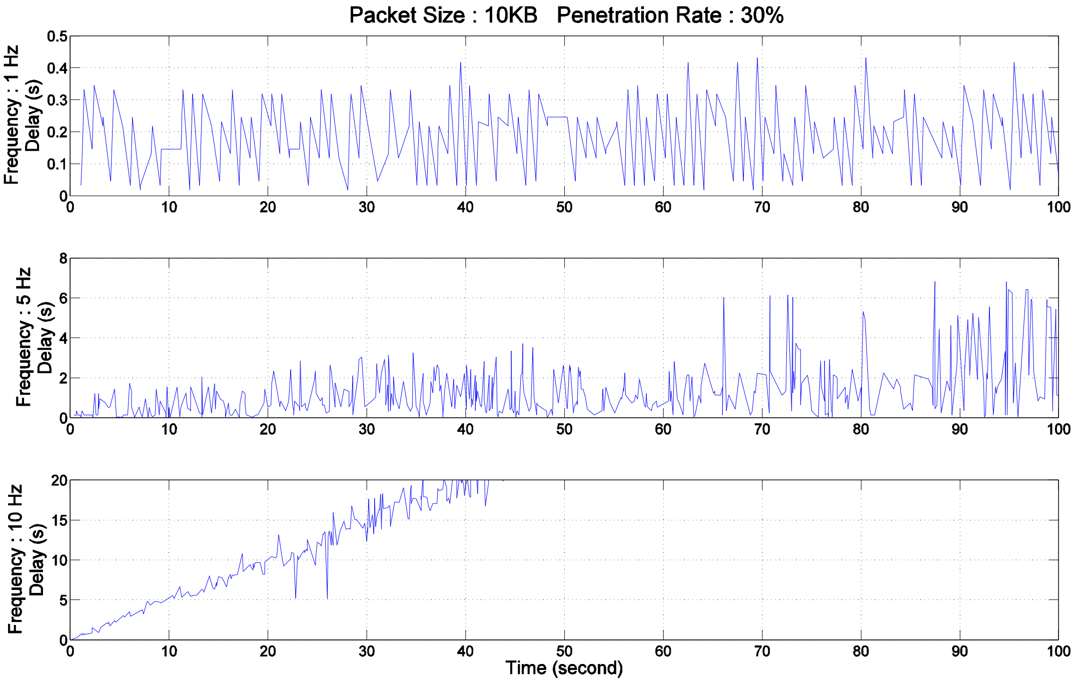

Packet Size : 10KB Penetration Rate : 30%

Figure 17 Network Latency with 30% Penetration Rate

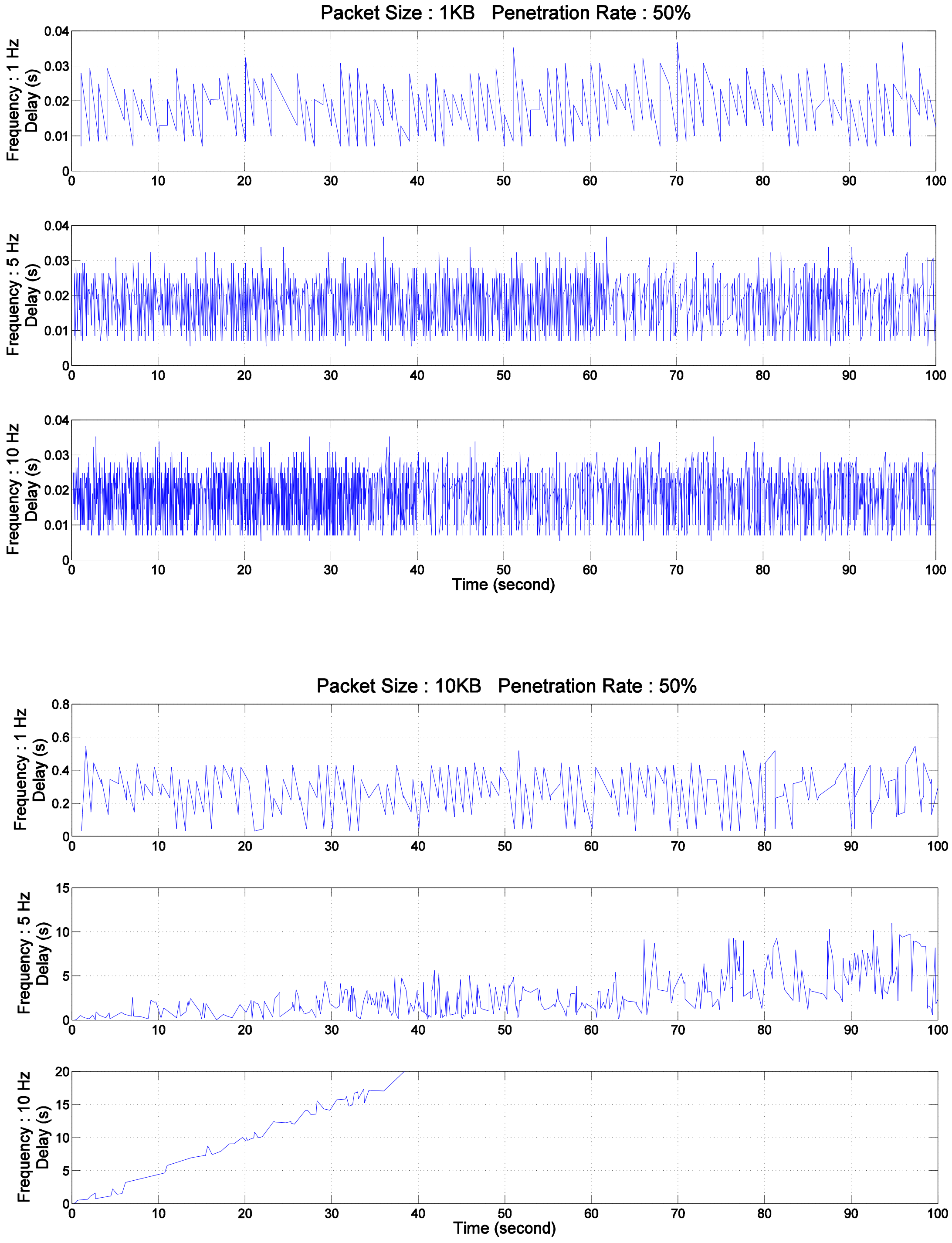


Figure 18 Network Latency with 50% Penetration Rate

CHAPTER 5. ADVISORY DRIVING SPEED STUDY ON PROPOSED CV SIMULAITON PLATFORM

In this chapter, Connected Vehicle-based advisory driving speed (CV-ADS) is proposed with a feature comparison between CV technology and variable message signs (VMS). To evaluate the performance of CV-ADS, the methodologies behind control strategies, communication scenarios, compliance rates of drivers and penetration rates of connected vehicles are carefully discussed. Both recurrent and non-recurrent bottlenecks were implemented with CV-ADS in the CV simulation platform. The results are analyzed in detail to show the performance of CV technologies.

5.1 Introduction to CV-ADS

Several studies on ADS have been conducted in Europe and the U.S. The results indicate that ADS improves both safety and mobility [33-35]. This thesis implements a CV-ADS application, which means that the ADS information is transmitted via wireless communications, rather than variable message signs (VMS). The benefits of CV-ADS are presented in three aspects.

5.1.1 Flexible Deployment Location

In traditional ADS messages are given by VMS and the locations of these signs are usually fixed. In CV-ADS, these messages are sent and received via wireless communications. Since the wireless communication ranges can be very large, RSE can be flexibly deployed.

5.1.2 High Resistance to External Factors

Through VMS, ADS information is captured when the sign is in the view distance of drivers. However, some external factors, such as large vehicles, snowy and other extreme conditions, might influence the view distance. In CV-ADS, there is no such disturbance. It is also more convenient for drivers to receive information wirelessly. OBE could notify drivers in a more comfortable and efficient way than VMS.

5.1.3 Convenient Control Management

CV-ADS also brings benefits to traffic operators. The control segment is fixed after setting signs in VMS. It is be a great amount of work when operators need to make changes. Although the location of RSE also might be fixed, the vast communication range of DSRC could cover a much bigger road segment when compared to the visibility of drivers. In addition, the packets could be customized to fit the requirements. Therefore, operators have more convenient control management. Furthermore, CV technology is one of the countermeasures for solving non-recurrent bottleneck problems. Connected vehicles or RSE could broadcast messages to improve traffic performance at any position using CV technology. For instance, connected vehicles involved in a collision could broadcast messages to upstream vehicles for traffic control.

5.2 ADS Control Model

Since congestion on the study corridor is caused by active bottlenecks, the aim of ADS is to obtain maximum active bottleneck flow. Therefore, the strategy of ADS is to control the bottleneck feeding flow by recommending speed based on an understanding of capacity flow at bottlenecks. The advisory speed was calculated by the model from Md. Hadiuzzaman et al. [36], who made three modifications to the basic METANET model [37]. As shown in Figure 19, a freeway section was divided into *M* links with on- and off- ramps:

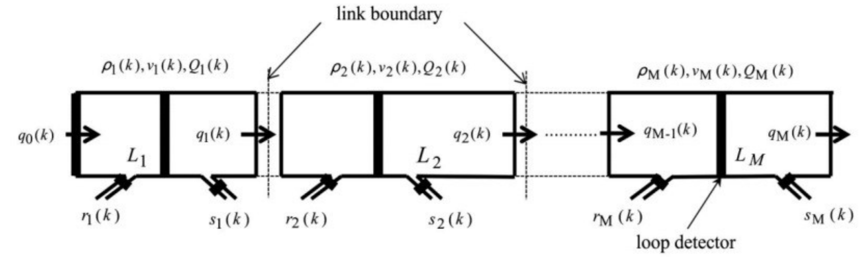


Figure 19 Freeway Section [36]

In the basic METANET model, the evolution of traffic flow, density and speed are:

$$q_i(k)=\rho_i(k)v_i(k) \tag{1}$$

$$\rho_i(k+1)=\rho_i(k)+\frac{T}{L_i\lambda_i}\left[\lambda_{i-1}q_{i-1}(k)-\lambda_i q_i(k)+r_i(k)-s_i(k)\right] \tag{2}$$

$$\begin{aligned} v_i(k+1)&=v_i(k)+\frac{T}{\tau}\left\{V_{e,i}\left[\rho_i(k)\right]-v_i(k)\right\} \\ &+\frac{T}{L_i}v_i(k)\left[v_{i-1}(k)-v_i(k)\right]-\frac{1}{\tau}\left[\frac{T\upsilon}{L_i}\frac{\rho_{i+1}(k)-\rho_i(k)}{\rho_i(k)+\kappa}\right] \end{aligned} \tag{3}$$

$$V_{e,i}\left(\rho_i(k)\right)=v_{free,i}\exp[-0.5\left(\frac{\rho_i(k)}{\rho_{c,i}}\right)^2] \tag{4}$$

Where,

$q_i(k)$ = traffic flow for link *i* at time step *k*,
$\rho_i(k)$ = density for link *i* at time step *k*,
$v_i(k)$ = space-mean speed for link *i* at time step *k*,
λ_i = number of lanes in link *i*
L_i = length of link *i,*
τ, κ, υ = global model parameters,
$v_{free,i}$ = free-flow speed,
$\rho_{c,i}$ = critical density of link *i*,

Based on the basic model, Md. Hadiuzzaman et.al made several modifications: 1) the nonlinear FD was replaced by the linear ADS control variable; 2) practical constraints were introduced to Eq. (1) to represent density dynamics. Therefore, Eq. (1) and Eq. (3) were replaced by Eq. (5) and Eq. (6):

$$q_i(k) = \min\left\{v_i(k)\rho_i(k), Q_{max,i+1}, w_i\left[\rho_{Jam,i+1} - \rho_{i+1}(k)\right]\right\} \tag{5}$$

$$\begin{aligned} v_i(k+1) &= v_i(k) + \frac{T}{\tau}\left\{u_i(k) - v_i(k)\right\} \\ &+ \frac{T}{L_i} v_i(k)\left[v_{i-1}(k) - v_i(k)\right] - \frac{1}{\tau}\left[\frac{T\upsilon}{L_i}\frac{\rho_{i+1}(k) - \rho_i(k)}{\rho_i(k) + \kappa}\right] \end{aligned} \tag{6}$$

(Eq. (6) is used for speed dynamics of links with ADS control. For the no control case, Eq. (3) was still applied.); and 3) capacity drop was introduced to represent active bottlenecks in the FD. For the active bottleneck segment, when the density at the bottleneck was over the critical density, the discharge flow was represented by:

$$Q_b^{'} = (1-\theta)Q_b \tag{7}$$

So, Eq. (5) in this condition is represented by:

$$q_i(k) = min\{v_i(k)\rho_i\left(k\right), Q_b^{'}, w_{bottleneck}[\rho_{Jam,bottleneck} - \rho_{bottleneck}\left(k\right)]\} \tag{8}$$

The average flow for link *i* at link *k* is:

$$Q_i\left(k\right) = \rho_i\left(k\right) v_i\left(k\right) \tag{9}$$

Based on this modified model, the objective is minimizing the weighted summation of total travel time (TTT) and throughput. This is better than just focusing on TTT or throughput because the former will reduce flow and the latter will maintain high density. The constraints in this model are related to safety, driver acceptance and traffic flow characteristics, which makes the model more reasonable. In Md. Hadiuzzaman's model, advisory speed was calculated by the model predictive control (MPC) approach.

5.3 Connected Vehicle System Modeling and Experiment Design

5.3.1 Road Network Modeling

The studied freeway corridor, shown in Figure 20, is a westbound 11-km section (between 122 Street and 159 Street) of an urban freeway, Whitemud Drive (WMD), in Edmonton, Canada. There are six interchanges and a static posted speed limit of 80 km/h on this corridor. The directional average annual daily traffic (AADT) is approximately 100,000 vehicles. Traffic information, including speed, volume and occupancy, can be obtained by loop detectors, which are instrumented in the test bed. Traffic density is estimated from the fundamental relation of traffic variables. Due to high traffic demand coupled with several active bottlenecks, this freeway experiences heavy congestion during the morning and afternoon commute peak hours [36]. This road network was modeled in VISSIM and all of the parameters were calibrated.

5.3.2 RSE and Connected Vehicle Modeling

Since the experiment included both recurrent and non-recurrent bottleneck simulations, this research developed two CV models for these two cases. Recurrent bottleneck congestion happens recurrently at a certain time and location, while non-recurrent bottleneck could happen at arbitrary time and place. The recurrent bottleneck was modeled in the same way as in Md. Hadiuzzaman et.al [36]. However, all of the ADS-related messages are broadcasted by wireless communication, which is different from VMS in Md. Hadiuzzaman et.al [36]. The validity of the CV simulation can be demonstrated through comparing the traffic network performance with VMS. As to non-recurrent bottleneck simulation, all VMS for existing bottlenecks in the model were removed, and an accident was modeled in a random place.

Two units of RSE were implemented for the two bottlenecks in the recurrent scenarios. As shown in Figure 20, one unit of RSE was located near 122 St NW, and the other unit was located near 53 Ave. Both were placed upstream of the bottlenecks within one communication distance of DSRC devices. Therefore, in V2I scenarios, the upstream connected vehicles could receive packets two DSRC device communication distances from the bottlenecks at most. The two RSE units periodically broadcasted packets with ADS for the control segments. In this experiment, we selected 1 Hz as the broadcasting frequency, the reason being that the maximum speed on the road is 80 km/h (22.2 m/s), thus vehicles can drive at most 25 meters (m) in one second, which is far less than the receiving distance of CV communication. Furthermore, low frequency would bring fewer burdens on the whole wireless communication network. The loop detectors on ramps and on the mainline were implemented to collect data for ADS calculation. The calculation algorithm updated ADS every minute. The RSE would track this update and broadcast the latest ADS packets in their own schedule. In the recurrent bottleneck case, several factors were considered relevant to traffic network performance:

- Connected vehicle penetration rate;
- Driver compliance rate; and
- Message propagation scenario;

The detailed simulation configurations are listed in Table 3.

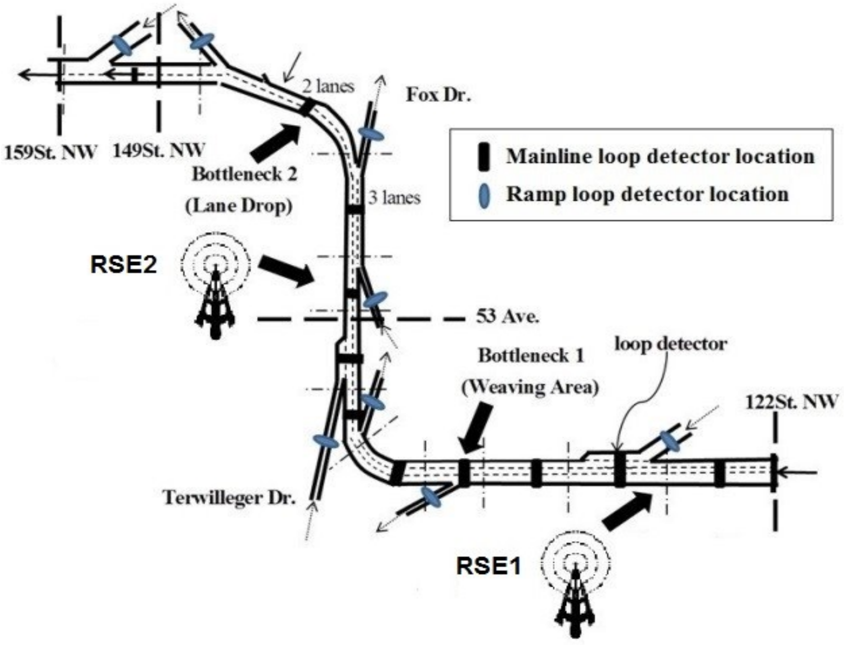


Figure 20 Studied Freeway Corridor

Table 3 Recurrent Bottleneck Simulation Scenarios

Penetration Rate	Compliance Rate	Propagation scenario
25%, 50%, 75%, 100%	20%, 45%, 100%	V2I, V2I&V2V

In the non-recurrent bottleneck simulation, an accident was emulated in a random location, as shown in Figure 21. This accident closed one lane, which caused a lane drop bottleneck. The accident vehicle would periodically broadcast ADS messages to other connected vehicles upstream. The other ADS settings were the same as the recurrent bottleneck simulation. The accident began at the 30-minute mark of simulation and lasted for 20 minutes. In this case, the compliance rate was set at 100% and the focus was the penetration rate.

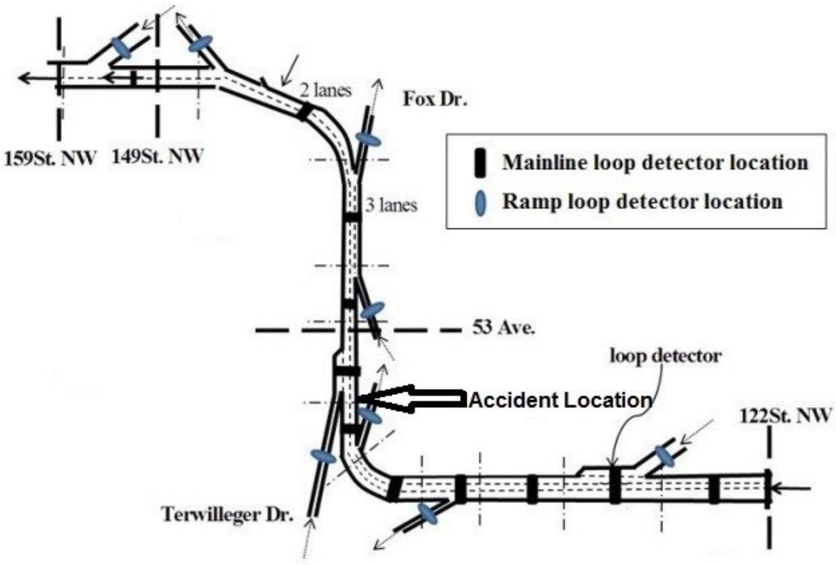


Figure 21 Non-recurrent Bottleneck Simulation

The specific DSRC configurations are shown in Table 4.

Table 4 DSRC Configurations

Application layer	ADS packet size	64B
	Contention packet size	32B
Media Access Control (MAC) layer	Channel number	2
	Switching mode	CCH(50ms), SCH(50ms)
Physical layer	Transmission power	3mW
	Communication distance	352m
	Receiving sensitivity	-94dBm
	Thermal noise	-110dBm
	Data rate	18Mbps

5.3.3 Simulation Process

This research implemented the ADS calculation algorithm in the external application. Since the ADS information was updated every minute, offline files were applied to exchange data between the external application and the SCI. The external application directly extracted loop detector data from VISSIM by COM. After calculation, the advisory speed information was sent to the SCI for further processing. SCI would send commands to OMNeT++ for wireless communication simulation and change the speed of relevant vehicles in VISSIM according to the reception data. The whole process is shown in Figure 22.

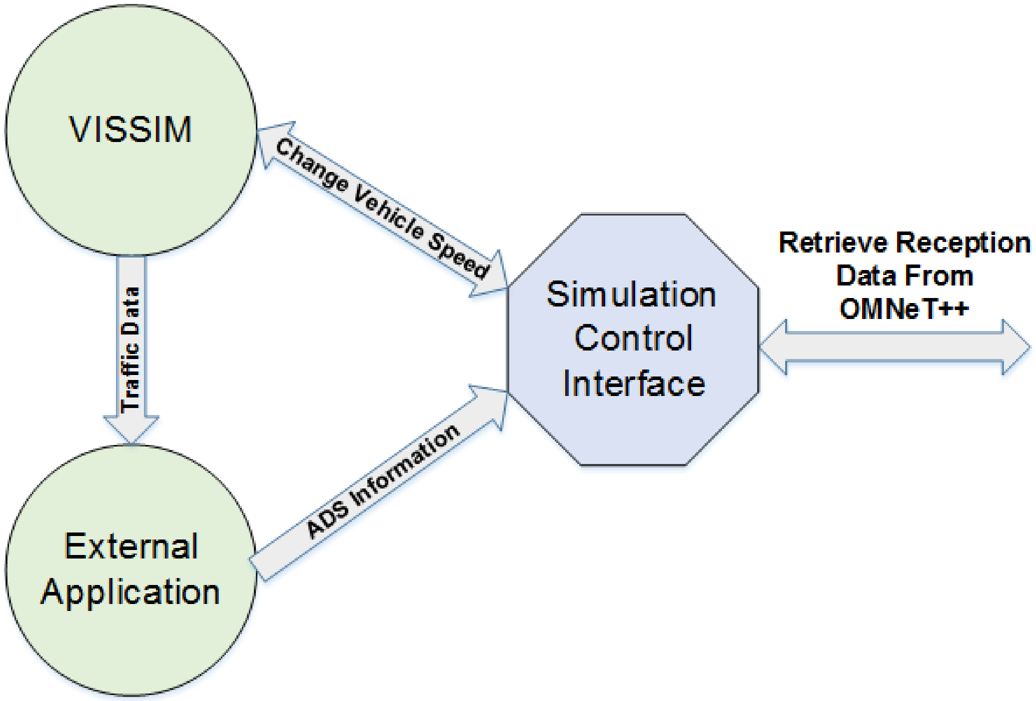


Figure 22 CV-ADS Simulation Process

5.4 Results and Discussions

5.4.1 Comparison Between CV-ADS and VMS

One purpose of this CV traffic management case was to evaluate the effectiveness of CV technology. This research compared the traffic performance between CV-ADS and VMS. The MoEs (Measure of Effectiveness) were accumulative total travel time (TTT), throughput and overall performance. The overall performance was the weighted summation of TTT and throughput [36], and it is given by the equation below:

$$OverallPerformance = \alpha \times TotalTravelTime + \beta \times Throughput \qquad (10)$$

The improvement is given by the Eq. (11):

$$\text{Improvement} = \left| \frac{NoControlValue - ControlValue}{NoControlValue} \right| \times 100\% \qquad (11)$$

NoControlValue is the value in the no control scenarios, and it is regarded as the benchmark for traffic performance. In the simulation, each scenario was repeated 10 times with 10 different VISSIM seeds to achieve a reasonable result, and average values are used for results analysis.

CV-ADS was implemented in both V2I and V2I&V2V propagation scenarios with 100% OBE penetration rate. Three compliance rates were introduced in the experiments. As shown in Figure 23 and Figure 24, there are some minor improvement differences between CV-ADS and VMS in both TTT and throughput improvements. When it comes to the overall performance, which was decided by the weighted summation of TTT and throughput, CV-ADS and VMS presented almost the same results as can be observed in Figure 25. The overall performance improvement of CV-ADS and VMS are well-matched with different compliance rates. As the compliance rate decreased, the traffic performances of both CV-ADS and VMS also decreased, showing the same tendency. These results prove that this new simulation platform could generate reasonable output for CV applications.

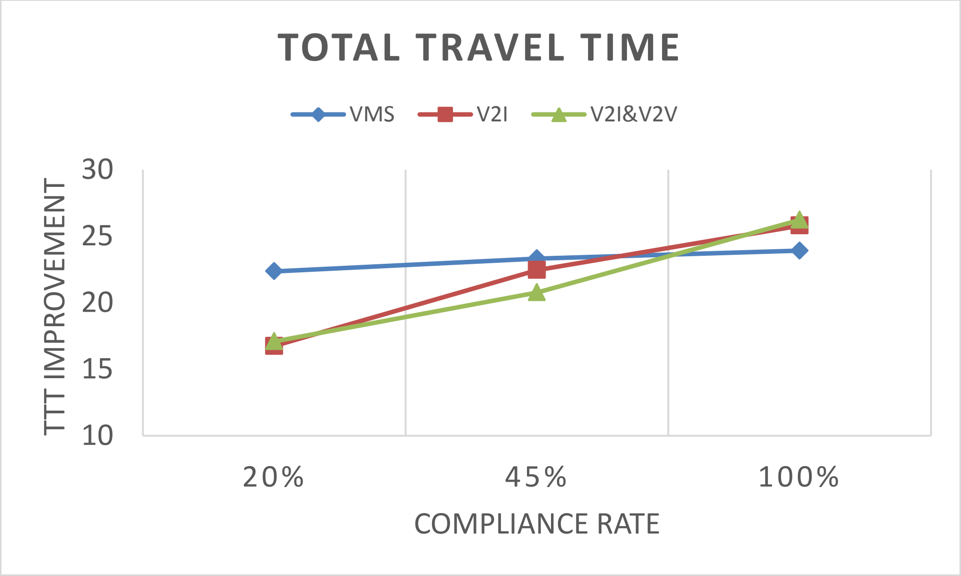


Figure 23 TTT Improvement of CV-ADS (V2I and V2I&V2V) and VMS

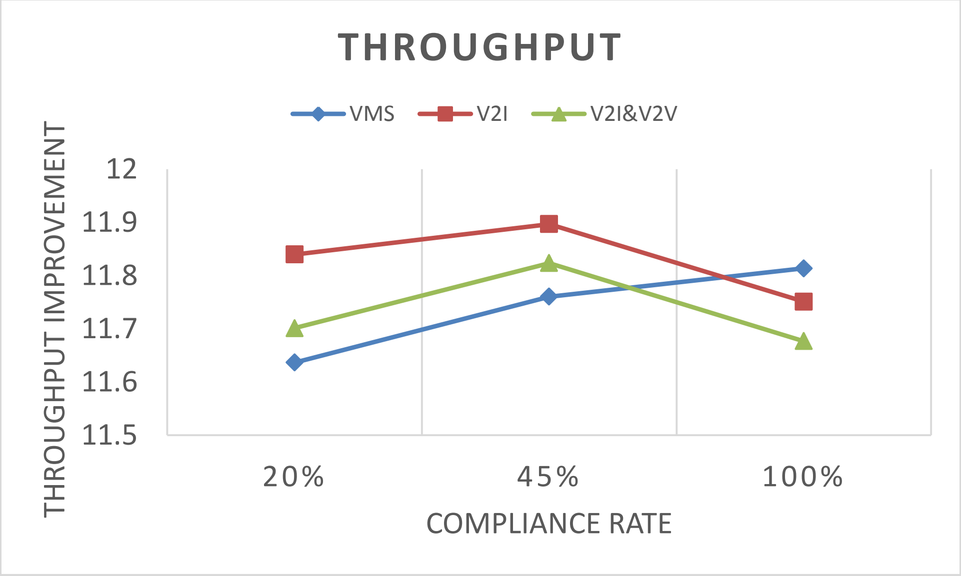


Figure 24 Throughput Improvement of CV-ADS (V2I and V2I&V2V) and VMS

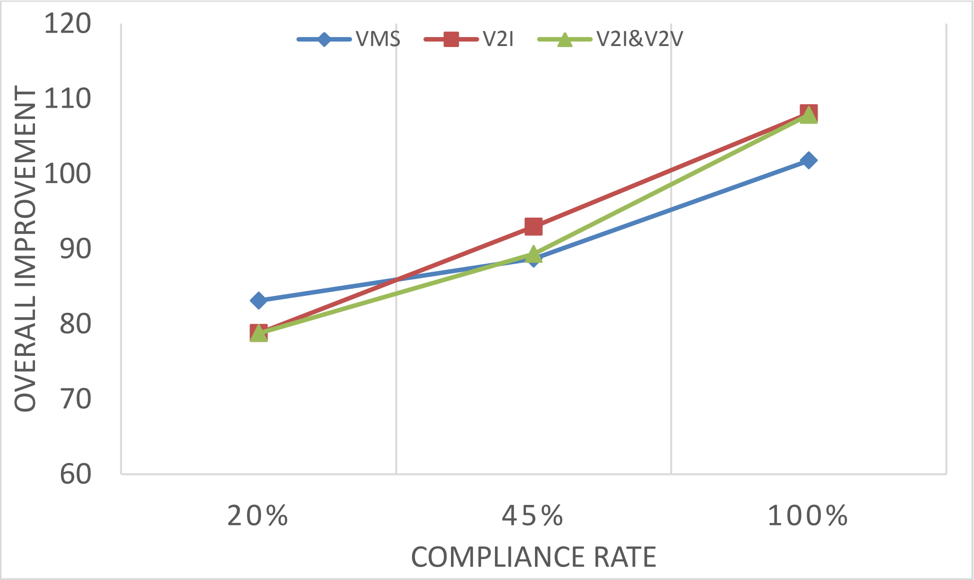


Figure 25 Overall Improvement of CV-ADS (V2I and V2I&V2V) and VMS

5.4.2 Influences of Penetration Rate and Compliance Rate

This research also studied the influence of penetration and compliance rates in CV-ADS. Four penetration rates and three compliance rates were selected for simulation. It is difficult to find out some tendencies in both TTT and throughput improvements as shown in Figure 26 and Figure 27. However, the overall performance improvements are quite straightforward as can be observed in Figure 28. As the penetration rate dropped from 100% to 25%, the change rate of all compliance rates decreased with a relatively small slope. The figure also indicates that CV-ADS could have an effective control even when the penetration rate is just 25%. This is useful for the future implementation of CV technologies, since the penetration rate would be relatively low in the early stages of CV field implementation. In addition, when the compliance rate was lower than 100%, there was a big gap between V2I and V2I&V2V propagation models, indicating V2I could bring better performances. It can be also observed that compliance rate has a much bigger influence than penetration rate on traffic performance. For future CV application evaluation, more work should be done to research the drivers' compliance rate as well as the CV penetration rate.

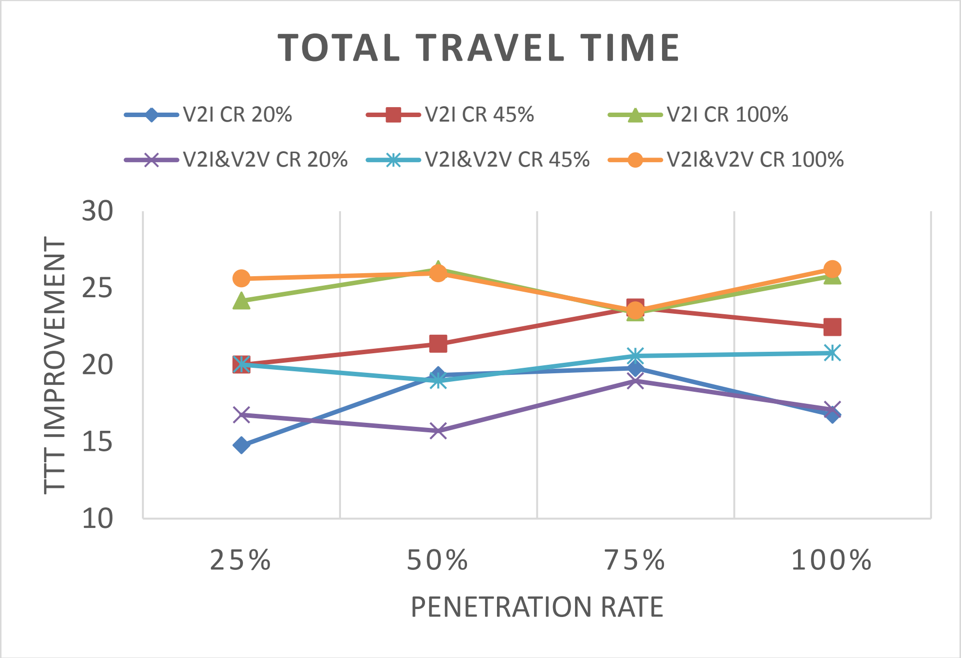


Figure 26 TTT Improvement of CV-ADS with Different Penetration Rates and Compliance Rates

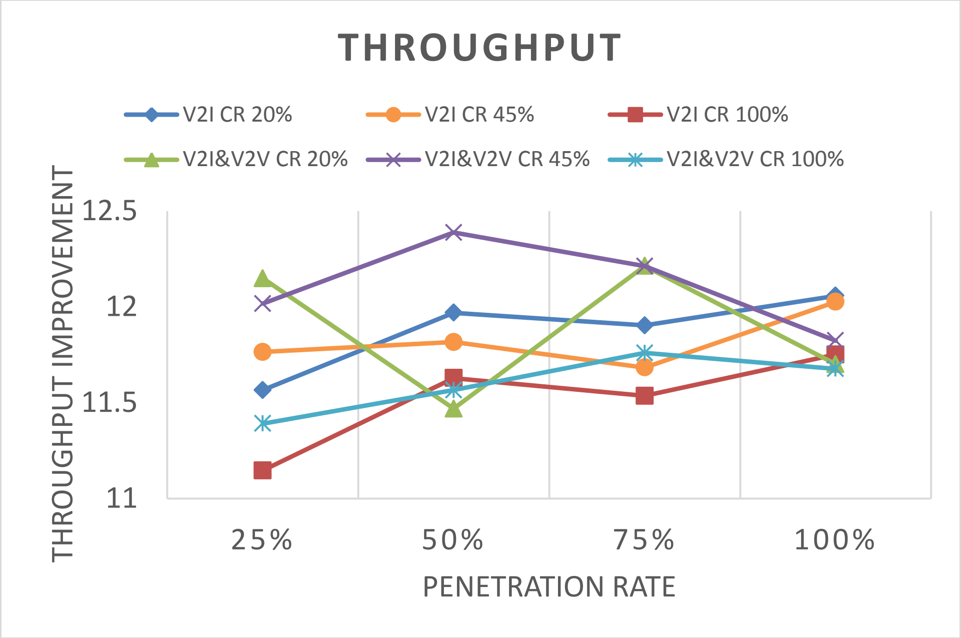


Figure 27 Throughput Improvement of CV-ADS with Different Penetration Rates and Compliance Rates

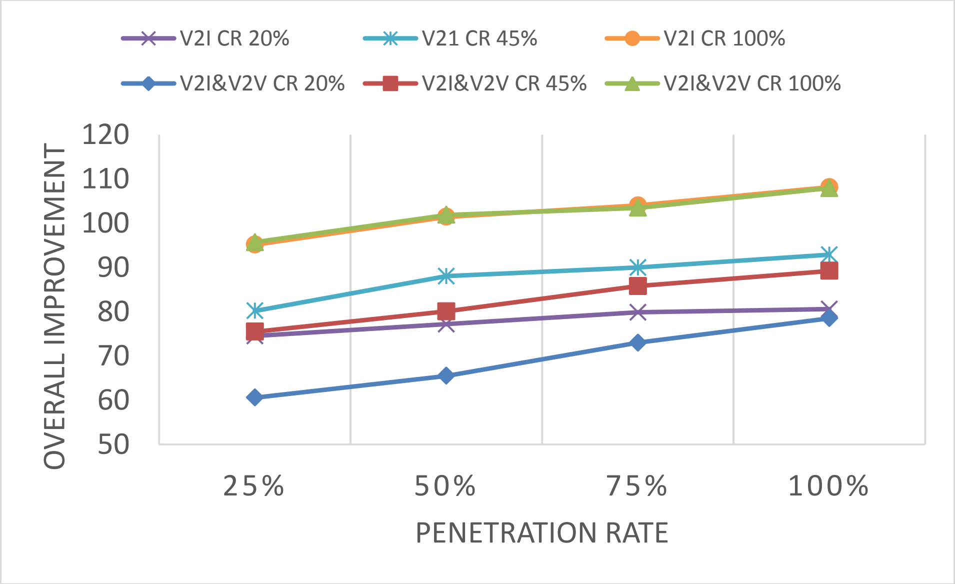


Figure 28 Overall Improvement of CV-ADS with Different Penetration Rates and Compliance Rates

5.4.3 Transmission Distance of V2I and V2I&V2V

The transmission distance of V2I and V2I&V2V was also compared in this research. The penetration rates of V2I and V2I&V2V were simulated at 100%. Network latency and the receiving distance data were collected from both propagation models. In V2I&V2V, the destination's position was 1600 meters upstream of the RSE.

As shown in Figure 29 and Figure 30, each vehicle's delay and receiving distance was plotted as a point. If a vehicle received packets in the upstream of the RSE, the distance was positive, otherwise it was negative. For V2I scenarios, since the RSE is the only equipment that broadcasted packets, the network delays were discrete. For V2I&V2V scenarios, as both RSE and OBE could broadcast packets, the distribution of delays is more uniform. For both V2I and V2I&V2V scenarios, most of the vehicles received packets upstream of the RSE.

The average delay of V2I&V2V is a just little higher than the average delay of V2I, but the average receiving distance of V2I&V2V is about 2.5 times longer than the average receiving distance of V2I, which means that V2I&V2V could control a much larger area with the DSRC communication range. Although V2I&V2V does not have any difference from V2I in this particular CV-ADS application, it might be more powerful for other applications, such as lane-drop warning, with its long transmission distance characteristic.

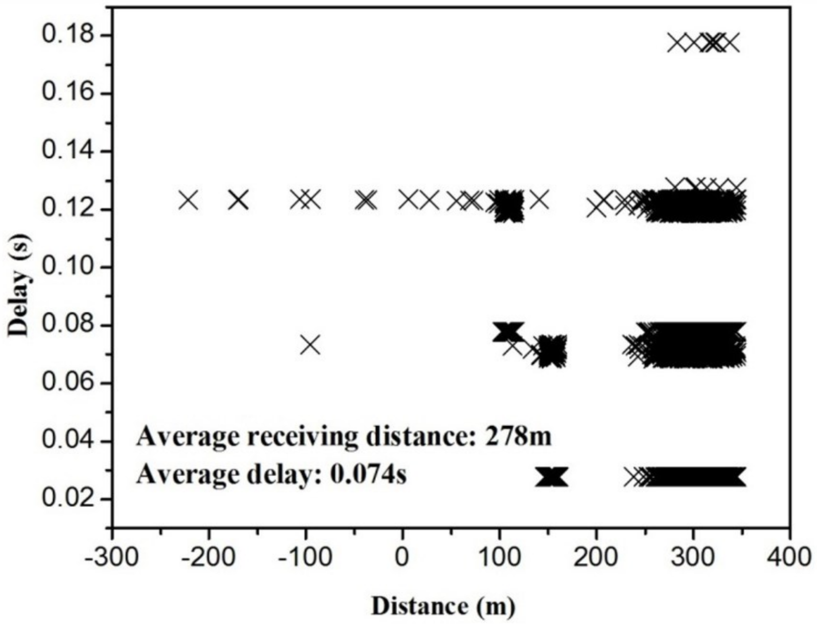


Figure 29 Transmission Distance in V2I scenarios

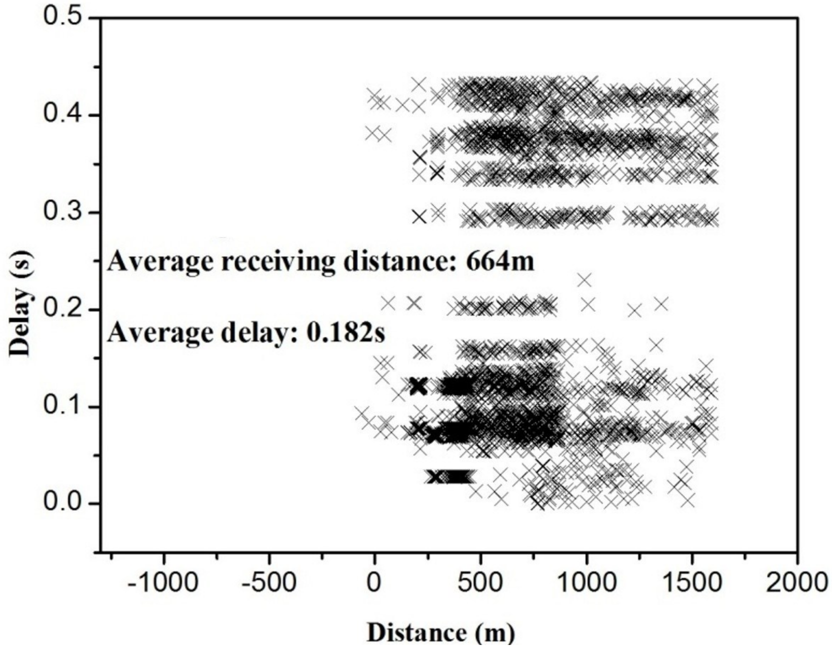


Figure 30 Transmission Distance in V2I&V2V Scenarios

5.4.4 Non-recurrent Bottleneck Analysis

The non-recurrent bottleneck problem was simulated with six different penetration rates. The overall improvement during the accident time was used to evaluate the performance of CV-ADS control. As shown in Figure 31, the improvement value increased as the penetration rate rose. Since a bigger improvement value means a shorter travel time and/or a higher throughput, the results show that a higher penetration rate brings a better performance. Furthermore, since non-recurrent bottlenecks can happen anywhere at any time, it is quite difficult to control these bottlenecks by VMS or other traditional ways. This shows the potential of using CV-ADS to solve these problems.

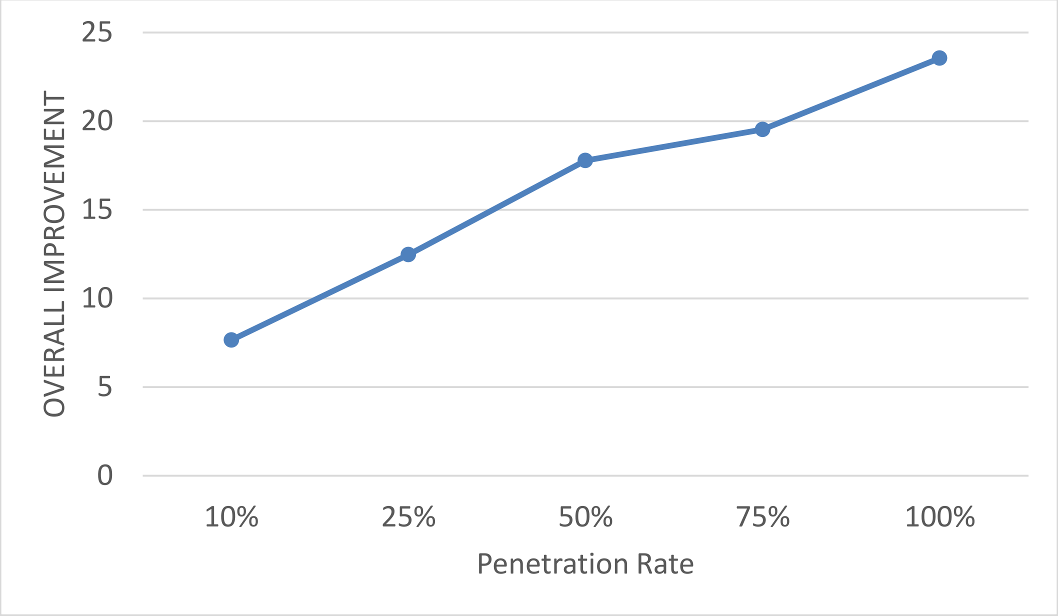


Figure 31 Overall Improvement in Non-Recurrent Bottleneck Scenarios

CHAPTER 6. CONCLUSION AND RECOMMENDATIONS

This chapter presents the major work of this study. The limitations of this research work are also summarized in this section. From the preliminary CV application evaluation study, some directions and recommendations are presented for future research.

6.1 Conclusion

6.1.1 Research Summary

ITS could be the key to a safer, greener and more efficient transportation system, while CV technology is a promising way to achieve this goal. Since controllable and repeatable field trials for CV are too expensive and sophisticated, simulation becomes a better preliminary evaluation method. This thesis presents a new federated CV simulation platform that overcomes some of the problems in existing simulators. The research combined a traffic simulator, VISSIM, and a network simulator, OMNeT++ to build a CV simulation platform that supports validated traffic and network models, large-scale simulation, comprehensive driver behaviours and all CV wireless communication protocols, including DSRC, WiMax, Wi-Fi and LTE. This platform is a very powerful tool for CV application evaluation.

DSRC network latencies in real traffic patterns were also studied in this thesis. Since most previous work in transportation research assumed zero network latency in the CV evaluation, this thesis determined the influence of network latency on transportation applications and modeled a simple road and a signalized intersection in the proposed CV platform. The results show that DSRC network latency could be a serious issue in some scenarios. CV researchers should be careful in CV application design, especially for network latency-sensitive applications.

A preliminary evaluation of CV-ADS implementation was also conducted in this platform. This research made several meaningful conclusions that can be useful for further research. First, CV-ADS (both V2I and V2I&V2V) obtain almost the same results as VMS, which indicates the effectiveness of both CV technology and the proposed CV simulation platform. Second, a lower penetration rate like 25% could still provide relatively good control results in the CV-ADS application. This shows that the future implementation does not require a high penetration rate for effectiveness. Third, the driver compliance rate also had a significant effect on CV application performance. This issue should be treated seriously in future evaluations. In addition, since the CV-ADS application is not sensitive to the receiving distance, there is not much difference between V2I and V2I&V2V with a 100% penetration rate; however, there may be an obvious difference for many other CV applications.

6.1.2 Research Limitations

This research has two limitations. First, since the simulation control interface was developed based on the C2X module in VISSIM for a better performance, the evolution capability is limited. Second, the influence of network latency on traffic performance needs more research. This thesis indicates the possibility of huge network latency in real traffic network; however, the exact impacts on specific applications are still unknown.

6.2 Future Work and Recommendations

Future research in CV simulation platform includes several directions:

- First, CV researchers could evaluate DSRC network latency for various real-world traffic applications. It is better to know the feasibility of converting existing traffic applications to CV applications before field implementation.
- Second, a lot of work can be done in CV-ADS. For example, researchers could try to improve the lane-drop bottleneck capacity by implementing an intelligent merging system. The characteristics of CV technology give us plenty of benefits to improve traffic safety and mobility.
- Third, a comprehensive comparison between the performance of V2I and V2V is needed. It is necessary to capture the influences on traffic performance of different propagation models for future implementation.
- Fourth, different wireless communication protocols, such as LTE, Wi-Fi and WiMax, need to be implemented to make comparisons with DSRC.
- Lastly, it is better to separate SCI from the C2X module if it is needed to replace the traffic simulator. However, this work is not too urgent, since VISSIM provides excellent traffic simulation results.

The ensuing challenges in the CV field are attractive to researchers, and lots of work can be done to achieve a better transportation system.

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