Development and Field Demonstration of DSRC-Based Traffic Information System for the Work Zone

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Abstract

This report describes the architecture, functionality and the field demonstration results of a newly developed DSRC based V2I work zone traffic information system with V2V assistance. The developed system can automatically acquire important work zone travel information, e.g., the travel time (TT) and the starting location of congestion (SLoC), and relay them back to the drivers approaching the congestion site. Such information can help drivers in making informed decisions on route choice and/or preparing for upcoming congestion. Previously, we designed such a system using DSRC based V2I-only communication, which could not handle longer congestion lengths and the message broadcast range was also very limited. Our current system, on the other hand, can achieve much longer broadcast range (up to a few tens of kms), and can handle much longer congestion coverage length (up to a few kms) by incorporating DSRC-based V2I communication with V2V assistance. The new system is also portable and uses only one RSU, which can acquire traffic data by engaging the vehicles traveling on the roadside whether within or outside of its direct wireless access range. From the traffic data, it estimates important traffic parameters, i.e., TT and SLoC, and periodically broadcasts them back to the vehicles approaching the congestion well before they enter the congested area. The results from the field demonstration have indicated that the new system can adapt to dynamically changing work zone traffic environment and can handle much longer congestion lengths as compared to previous system using V2I-only communication without V2V assistance.

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List of Abbreviations

ACM	A la Carte Message
BSM	Basic Safety Message
BT	Bluetooth
CTI	Communication Time Interval
DSRC	Dedicated Short Range Communication
EoMR	End of Monitoring Range
EV	Emergency Vehicles
FCC	Federal Communications Commission
FHWA	Federal Highway Administration
GCC	GNU Compiler Collection
GPS	Global Positioning System
ITI	Invite Time Interval
ITS	Intelligent Transportation systems
JSR-82	Java Application Programming Interface for Bluetooth applications
LoS	Line of Sight
OBU	On Board Unit – DSRC Radio
PATH	Partners for Advanced Transit and Highways
RSU	Road Side Unit – DSRC Radio
SAE	Society of Automotive Engineers
SLoC	Starting Location of Congestion
TT	Travel Time
TTTh	Travel Time Threshold
USDOT	United States Department of Transportation
V2I	Vehicle to Infrastructure
VII	Vehicle Infrastructure Integration

Chapter 1
Introduction

1.1 Project Background

Motor vehicle crashes are the leading cause of death among the age group of 25-34 years in the U.S. Additionally, more than 2.3 million adult drivers and passengers were treated in emergency departments in 2009 for motor vehicle related crash injuries [1]. Many of the traffic accidents can be prevented by incorporating intelligent systems to improve traffic measures and enforce traffic rules.

Intelligent Transportation Systems (ITS) program of the U.S. Department of transportation (USDOT) is focusing on the integration of vehicles and road infrastructure into intelligent systems to help manage and improve traffic safety and mobility [2]. ITS technologies have been in the focus of the government, automobile manufacturers, academia and many other groups because of the opportunity to save many lives otherwise lost in traffic accidents. One of the main research priorities of the ITS program is to facilitate wireless communication between vehicles and infrastructure so that traffic safety information data can be exchanged. To accomplish this, 5.9 GHz frequency band was allocated by the Federal Communications Commission (FCC) as the Dedicated Short Range Communication (DSRC) channel, intended to be used solely for automotive safety communication applications [3].

DSRC is a short to medium range (< 1 km), high-speed wireless communications protocol specifically designed for automotive use. It is able to minimize latency (50 ms), isolate relatively small communication zones and supports vehicle speeds up to 120 mph

[4]. DSRC frequency band consists of seven 10 MHz channels with data rates available from 3-27 Mbps as shown in Figure 1.1. First channel (172) is set aside strictly for vehicle safety, while two 10 MHz channels (174/176 and 180/182) can be combined into two 20 MHz channels with higher data rates available from 6-54 Mbps [4]. DSRC technology has been tested for its reliability, security, range and other characteristics in proof of concept tests done under the connected vehicle research program (formerly known as vehicle infrastructure integration (VII) and/or Intellidrive) [5].

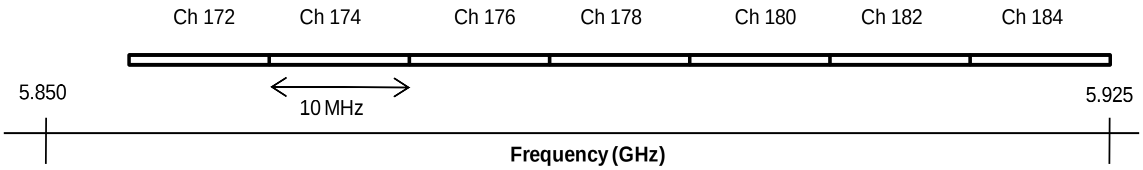

Figure 1.1 DSRC Channel Frequency Assignments.

DSRC technology is considered as one of the best near-term technologies that can support active safety and mobility of traffic on highways. Some of the benefits of DSRC technology over the other viable communication methods are given below [3, 6].

- Reliability
- Secure communication
- Fast communication speed: low latency
- Performance robustness under extreme weather conditions
- Tolerance to multi-path transmissions
- Standardized to enable interoperability

- Supports high speed exhibited by vehicles

Communication in DSRC applications can be vehicle-to-vehicle (V2V), vehicle-to-infrastructure (V2I) or a hybrid of both. V2V communication could refer to communication between only two vehicles, though it's commonly used to refer communication between multiple vehicles in a network environment.

The purpose of V2I communication applications is to receive traffic updates from multiple sources to central authority or to send traffic updates from central authority to many vehicles. Some examples of applications that benefit from V2I communication are given below [6, 7].

1. Weather and road conditions warning
2. Curve speed warning
3. Do not pass warnings
4. Electronic toll collection
5. Approaching emergency vehicle warning

The V2V communication is typically used in traffic data acquisition and dissemination systems. It allows using ad-hoc networks for the traffic scenarios which are more complex and safety critical and requires the participation of all the vehicles on the road segment. Some examples of DSRC applications that benefit from V2V communication are given below [6, 7].

1. Cooperative adaptive cruise control
2. Forward collision warning
3. Lane departure warning
4. Lane changing warning
5. Intersection collision avoidance

The work zone environment is an area of research that can benefit greatly from DSRC applications to help inform the drivers of traffic parameters about the congestion. Many of the roads carrying high traffic in USA are in need of maintenance and repair, meaning number of work zones will increase, causing lengthier delays [8]. In the work zone environment, human error is identified as the main cause of accidents [9]. If the congestion can be monitored in real time, then the drivers on the road can be informed of important traffic safety parameters such as how far they are from the starting location of congestion (SLoC), and travel time (TT) through the congestion. By knowing the distance to the SLoC, drivers can choose an alternate route when it's possible or be prepared for the sudden speed reduction when entering congestion. By knowing the TT through the congestion the driver can have a realistic understanding of when he/she will be able to exit the congestion.

Currently, to detect congestion, use of inductive loop detectors is the most common and reliable practice in the transportation industry. However while the loop detector method could be used to yield more individualized data such as the length of the car, it requires an expansive and time consuming installation process and is limited to a fixed location. On the other hand, DSRC technology has potential to overcome these limitations and possibly be used for many other safety related applications. Even though it has not been widely tested in work zone environment, the DSRC technology has the advantage of being dynamic and flexible.

1.2 Prior Art

DSRC technology is focused on providing wireless access for vehicular traffic safety communication. Before being adopted for vehicular communications, DSRC channel characteristics have been extensively tested for its suitability to handle safety messages in terms of reliability, message propagation distance, latency, security, channel congestion and other characteristics [4, 10-11]. Bai et al. studied the communication level reliability of DSRC technology in terms of packet delivery ratio and distribution of consecutive packet drops, and the application level reliability in terms of T-window metric using three vehicles having DSRC capability and GPS receivers [10]. Molisch et al. studied the IEEE 802.11p which provided the groundwork for the DSRC standard for the suitability for vehicular communication in the context of propagation aspects [11]. Similarly, message security in inter-vehicular communication is an equal concern in both the multi hopping and single V2V communication environment in case of hacking attempts. It must be noted that IEEE 1609 standard which the J2735 standard is built upon, addresses the eavesdropping, spoofing, altering and replay attacks. However IEEE 1609 does not cover attacks from vehicle originating messages yet. Research is being done to address the issue and make the communication more secure [12, 13]. The USDOT currently holds the DSRC as the only short range wireless communication that provides desired qualities for vehicular communication such as fast network acquisition time, low latency, high reliability, priority for safety applications, interoperability, security and privacy [3].

In the current phase of this project, the focus is on the V2V communication taking place in a highly dynamic and mobile environment. In safety critical applications using V2V communication, ad-hoc networks are needed to be established for obtaining comprehensive traffic data with minimal delays. The ad-hoc networks need to be adapted for the V2V communication because of its unique rapidly changing topology and fragmented nature among other qualities [14]. Lim et al. studied the multi hopping aspect, and proposed a protocol to improve the critical issues affected by multi hopping such as data transmission delay, packet overload, and network connectivity [15]. Similarly Palazzo et al. suggested a protocol that focused in fast multi-hopping of messages, able to adjust the communication parameters to better handle messages intended for different purposes [16]. In the work done by Rezaei, a new dissemination scheme is proposed, where the ad-hoc network to be used by each message is defined dependent on traffic density for more effective propagation of the message [17].

A significant amount of research effort has gone into researching message relay protocols to evaluate the suitability of DSRC technology to being adopted for vehicular communication [18-20]. Jiang et al. examined critical operations of DSRC technology such as channel congestion control, concurrent multi-channel operation, and maintaining broadcast performance and designed a set of protocols addressing the possible issues that could affect the communication reliability [18]. Xu et al. designed several variants of a DSRC based V2V communication protocol for safety messaging and measured the performance of the protocols using reception reliability and channel usage for various simulated traffic flow conditions [19]. A secure message protocol has been developed by Qian et al. aimed at dissuading possible abuse and having an efficient medium access control for the purpose of safe and timely dissemination of safety messages [20].

Once the viability of using DSRC technology for vehicular communication was thoroughly evaluated through extensive research, the focus of research shifted to proof of concept for DSRC applications [21]. Yang et al. outlined a V2V communication protocol for cooperative collision warning system and discussed some of the challenges that need to be faced [22]. Hsu et al. verified a vehicle collision avoidance warning system where the algorithm converted location updates provided by nearby GPS receivers integrated with DSRC units into relative position of neighboring vehicles and displaying that to the driver [23]. USDOT's Cooperative Intersection Collision Avoidance Systems (CICAS) project aims to make driving safer by helping the drivers to maneuver through the traffic intersections safely and at the same time warning them of any likely violations of traffic control devices [24]. Crabtree et al. developed an algorithm for incident detection on a rural freeway, which monitored for traffic disturbances by finding travel times [25]. Another application similar to the research area of this project, focused on using DSRC technology to warn motorists of imminent changes to their operating environments, such as approaching of an emergency vehicle or an upcoming work zone [8]. In displaying the

DSRC messages to the end user, the Partners for advanced transit and Highways (PATH) program has developed a cell phone application that takes advantage of GPS to estimate the arrival time so the user can determine if using mass transit system is advantageous. Another project by the PATH program is millennium mobile project which anonymously surveys those cell phones which consented to run the application to gather real time traffic data to estimate traffic parameters [26].

In ITS research concerning work zone environment, many non-DSRC systems have been already implemented. Federal Highway Administration (FHWA) conducted studies to analyze the traffic flow after such systems have been implemented at work zone sites to quantify the benefits in terms of reducing demand and congestion through active traffic diversion in the work zone [27]. Other FHWA studies found ITS technologies, used at four different states work zone sites, helped reduce crashes, delays and cost while construction was taking place [28]. A system that uses ITS technologies to monitor traffic flow and provide delay and routing information to drivers was implemented during the project redesigning the Big I interstate-interstate interchange and proved beneficial [29]. Similarly an automated traffic information system was used to collect and disseminate real time traveler information to motorists via portable message signs in the highway reconstruction of I-55 interstate, which resulted in reduced congestion and improved safety [30]. Another instance of ITS technologies being used at work zone is during widening of the highway SR 68, where a traffic system was installed to monitor the vehicles and calculate the travel time through the work zone and monitor it for irregularities [31]. ITS technologies were also used to implement a dynamic lane merge system at I-94 interstate to help smoothen the traffic flow and reduce aggressive driving by cautioning drivers. This system resulted in a decrease in aggressive maneuvers and a reduced average peak period travel time [32]. Lastly, a speed advisory system was developed that monitors the work zone and suggests alternative routes if the speed of the monitored vehicles falls below a specified value and was tested at a work zone site in I-680 interstate [33]. In many of these non-DSRC traffic information systems, traffic flow is monitored for congestion through cameras and other sensors and once congestion is detected, detours are recommended via message boards and signs on the roadside [29-31]. The congestion on roads can grow very quickly especially during rush hours which highlights the need for a monitoring system with quick update times for travel time and congestion lengths [34, 35].

1.3 Project Objective

The goal of this project is to design, implement and demonstrate a V2V assisted V2I System using DSRC technology that is able to acquire traffic data, calculate important traffic safety parameters e.g. SLoC and TT at a work zone environment, and broadcast these parameters to the nearby drivers. The DSRC units in the vehicles approaching the congestion zone are able to calculate their distance to the SLoC. From the knowledge of distance to the SLoC drivers can know when to expect the sudden speed reduction, and by knowing the TT, drivers are able to evaluate the pros and cons of using alternate routes to reach their destination.

This newly designed system is an improvement on previously demonstrated V2I-only communication system, which could only cover a limited congestion length and a small broadcast coverage range [36]. Whereas in a practical road scenario, congestion length could grow up to few kms and message broadcast range is desired to be more than 10 kms. A longer broadcast coverage range means that the drivers approaching the congestion zone have more time to react to the congestion information and are able to make route choices that are otherwise not possible. By incorporating V2V communication we are able to meet the above requirements of extending the communication range, making the new system more suitable to handle complex traffic congestion scenarios. The system is designed to be both portable and secure. A field demonstration of the system was conducted at work zone environment to test the system reliability and adaptability to varying congestion scenarios found in real world setting.

1.4 Report Organization

The first chapter is the introduction, where project background, prior literature and project objectives are presented and explained. The second chapter covers the system architecture and functionality, giving the reader an understanding of the hardware and software of the system and its operability. In the third chapter, an overview of the V2V communication protocols and its detailed design is described. The fourth chapter is on field demonstration which describes the results and discussion pertaining to the system evaluation and findings in the field test. Finally the fifth chapter contains the conclusion and recommendations for the future work. Following the main body of the report are the references and the appendices.

Chapter 2
System Architecture and Functionality

2.1 System Architecture

A DSRC-based V2I-only traffic information system was developed and then extended with V2V assistance with the goal to acquire real time traffic data, and then use it to generate and broadcast useful travel safety information to inform and warn the drivers on the road. In this system the DSRC roadside unit (RSU) is installed near roadside at the work zone site and it engages vehicles on the road with DSRC onboard unit (OBU) to acquire traffic data such as TT and SLoC. Previous V2I-only traffic information system acquired TT and SLoC information from vehicles passing through the work zone and communicated these two parameters back to the vehicles in its range. The major limitation of that system was that the RSU's direct wireless access range (~1km) determined both the congestion coverage length and safety message broadcast range. That means that both the message broadcast range and congestion coverage length were in the order of 1 km. However, in practical road conditions, the congestion caused by work zone, accident or rush hour can typically grow beyond 1 km which the previous system would not be able to handle. Also to utilize the traffic information system fully, the drivers should receive the traffic safety messages well before approaching the congestion so they have more time and options to react and take alternative decisions regarding the travel route. The V2V assisted V2I traffic information system was developed to address the above limitations of the previously developed V2I-only traffic information system. In the new system using V2V communication assistance, the message broadcast range and congestion coverage range can be scaled to be much longer than 1 km.

2.1.1 System Setup

When installing the units in the field, the RSU is installed nearby the road at a height that gives a clear line of sight with vehicles travelling on the road, so the DSRC radio communication isn’t blocked by nearby vehicles at times. Once powered up, the RSU seeks to acquire traffic safety data from OBU’s travelling on the congested road towards it. The OBU’s on the other hand are installed on the top of vehicle whenever possible to give a clear LoS with RSU. The RSU is placed in the work zone site near the road so that the reach of its wireless access range; *End of Monitoring Range* (EoMR) falls just beyond the work zone’s ending location of congestion (ELoC) which is fixed and known, as shown in Figure 2.1. The RSU’s role in the system is to acquire the TT and SLoC information from the travel data updates of the selected OBU passing through the work zone and then disseminate the same to all the OBU’s travelling on the road. To acquire travel data updates, the RSU will engage the OBUs travelling towards the work zone prior to entering the starting location of congestion (SLoC) so that congestion behavior can be accurately and completely estimated. Once an OBU that is engaged in communication with the RSU passes through the congestion, RSU will continue to gather speed, location and time information from it and once it is passed beyond the ELoC, it will calculate the TT and SLoC and update the values in the broadcasted message. When the work zone site is longer, the SLoC can occur more than 1 km away from the RSU, and the RSU and OBU's are unable to directly communicate using V2I communication. However with the V2V communication assistance, the message from the RSU can be relayed to much farther distances via intermediate OBUs, and it can receive messages from OBUs located well beyond the RSU's communication range in the same manner. When a remote OBU that was engaged for communication through V2V communication travels through the congestion region, it will keep sending its current speed, location and time information to the RSU through intermediate OBUs until it arrives near RSU. At that stage, the intermediate OBUs will not be needed to communicate with RSU. Once the OBU passes the EoMR, the OBU will stop sending travel data and the RSU will calculate the SLoC and TT. These updated values of SLoC and TT will replace the previous values of the safety message which is periodically being broadcasted by the RSU to inform all the vehicles in the monitored work zone range.

When the RSU selects an OBU to receive travel data updates the selection should be made well before the vehicle carrying the OBU enters the congestion region. The area before the congestion region where OBUs are allowed to start engaging in communication with the RSU is termed as the *Desired Region* as shown in Figure 2.1. In the previously designed V2I-only system [36], the *Desired Region* was at the extreme end of the RSU range, where vehicles were selected before the congestion occurs. In the current V2V assisted V2I communication system the SLoC can vary over a distance measured in kms. The option of simply picking a far enough *Desired Region* is too simplistic a solution as it will result in non-useful data collection and cause bandwidth congestion. The better solution is to have multiple *Desired Regions* stored in the RSU, which will look at the current SLoC and decide the most suitable *Desired Region* before the congestion takes place. The system monitors the congestion growth and adapts itself, by selecting a closer or a farther away desired region depending on the SLoC.

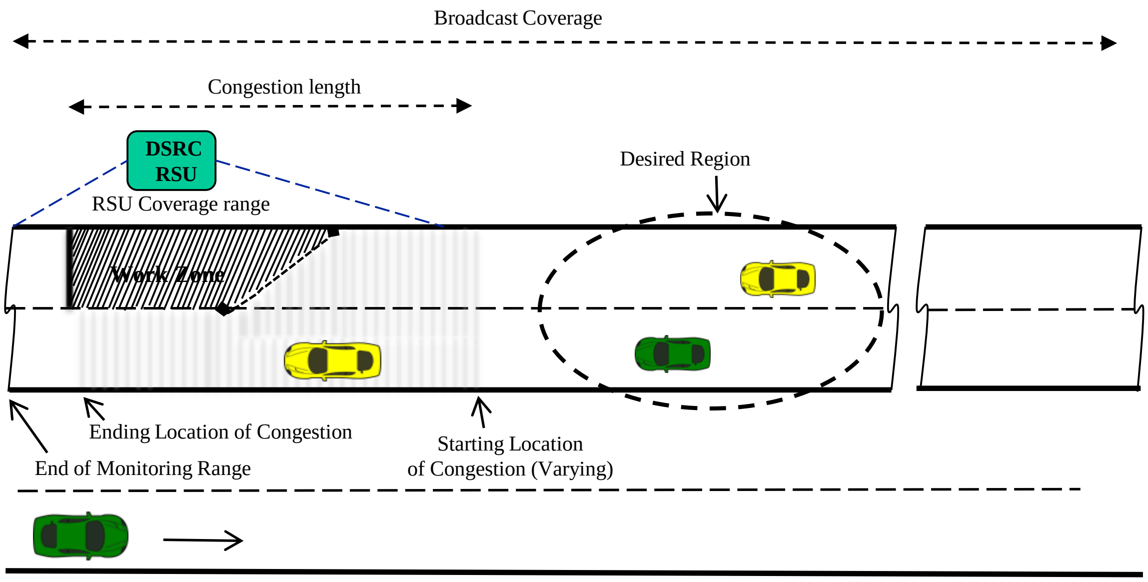

Figure 2.1 Conceptual Diagram Showing the *Desired Region* and the Coverage Range of V2V Assisted V2I Traffic Information System.

The developed system is desired to be portable and capable of adapting itself to the traffic congestion conditions quickly. The OBUs once installed in the vehicles need to be able to work without the prior knowledge of the road. For this purpose the software in the OBU was designed such that it is independent of the road location and doesn’t require any prior knowledge of the road parameters to function. On the other hand the software in the RSU needs to be adapted to the road location by a set of initializing parameters before it can function. Table 2.1 lists such initializing parameters for the RSU. Some of the parameters are road specific parameters e.g., road width and the designated speed limit etc., while other parameters such as the ELoC, road direction and angular region half width etc., need to be set according to the work zone scenario.

Table 2.1 RSU Input Parameters

RSU Parameter	**Units**	**Description and Usage**
Nominal Speed Limit	MPH	The maximum speed permissible on the road. It is used to set thresholds in estimating SLoC
Road Direction	Degrees	An angle describing the road direction at *Desired Region*, relative to North, increasing in clockwise direction. It is used for the *Direction Check* in the OBU to filter out vehicles going in other directions to the congestion on the same or other roads.
Ending Location of Congestion (ELoC)	Longitude, Latitude	This is the location where the work zone or congestion ends and the lanes are opened up again. It is used for the ELoC check in the OBU to disengage OBU from V2I communication with the RSU.
Angular Region Direction	Degrees	The average direction of heading of the Angular Region measured from the main focal point in degrees relative to the North. It is used in the *Angular Region Check.*

Angular Region half-width Angle	Degrees	The half angle of the width of the Angular Region. It is used in the *Angular Region Check.*
Angular Region Focal Point	Longitude, Latitude	The GPS location of the main focal point of Angular Region. It is used in the *Angular Region Check* and *Back Propagation Check.*
Reference Angle Initial Value	Degrees	The value to be used for the *Reference Angle Check*, by the receiving OBUs. It is an angle relative to North, increasing in clockwise direction.
Road Width	Feet	This is the road width for one direction of travel. This is used for location check for the vehicles approaching to the work zone to participate in the V2I communication.
Road name and descriptive direction	100 characters maximum	This is an easily understood name for the road and descriptive direction which is broadcasted along with the TT and SLoC by the RSU for drivers to know whether a message pertains to them.

The OBU hardware contains DSRC radio communication capability as well as global positioning system (GPS) technology as compared to RSU which only needs to have DSRC radio communication capability. The GPS capability in OBU is needed so that the current location of the vehicle can be known. Please note that in the newly developed system, RSU communicates with OBUs and OBUs communicate with each other without knowing or keeping any identity information of any OBU to maintain privacy.

Once the RSU chooses an OBU within the *Desired Region* to communicate with, it will send the road and work zone parameters to the OBU so it can adapt the OBU program to the desired settings while it sends travel data to the RSU. Once the OBU travels past the ELoC, the OBU indicates the event to the RSU, so the communication session ends. At this point the OBU reverts back to listening for new RSU communications for acquiring data.

2.1.2 User Interface

The User Interface is composed of three components, the Microcontroller, Bluetooth Radio Module and the mobile phone. The OBU passes the safety messages to the Microcontroller through its serial port connection so that microcontroller can in turn send that message to the mobile phone via Bluetooth Radio Module so that the driver can be informed of road conditions.

The microcontroller monitors for the paired Bluetooth cell phone once the initial pairing has been made and automatically establishes the connection when in range. The microcontroller is able to receive the incoming DSRC traffic safety messages through a RS232 serial connection to the DSRC OBU. After messages are read from serial input buffer, they are stored in the memory of the microcontroller for transmission to the Bluetooth radio module through another RS232 serial connection.

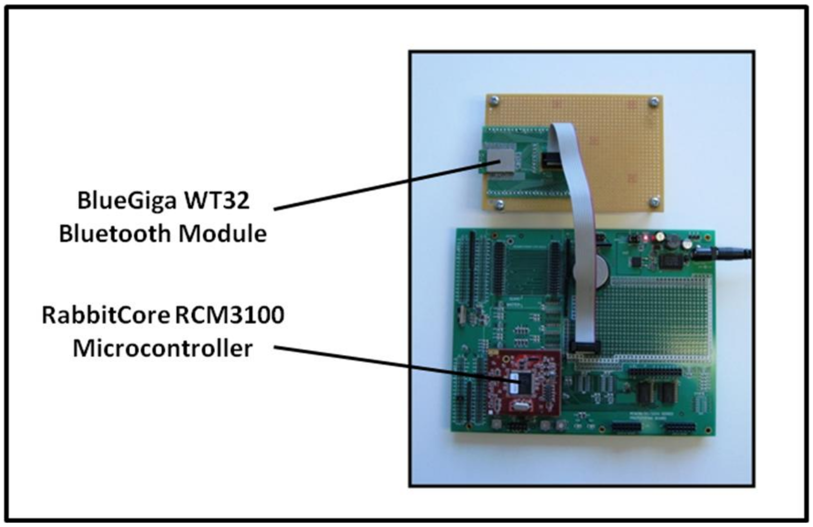

Figure 2.2 User Interface Components.

The Microcontroller used in the project is the RabbitCore RCM3100 with the Rabbit 3000. It was chosen for its powerful processing power, extensive RAM and flash memory, and multiple serial communication capabilities. The program for microcontroller is developed using Dynamic C programming environment. Once the program is compiled it is then sent via serial connection to be installed in the Microcontroller’s flash memory. The program starts to execute on power up. The BlueGiga WT32 Bluetooth Module is chosen as it is Bluetooth 2.0 compliant and Bluetooth 2.1 ready, and it is a Class 2 Bluetooth device built with an integrated antenna featuring iWRAP firmware, which enables it to be controlled through the Microcontroller in order to pair devices, establish connections, and send traffic safety messages for transmission to a cell phone user interface.

Figure 2.3 Mobile Phones Used for Testing.

Bluetooth enabled mobile phones were chosen to present the safety messages to the driver as most drivers own a phone and the technology behind it is a proven technology which makes it an ideal choice. Two popular mobile platforms, Symbian and Windows mobile were chosen to be tested and the user interface programs were written for each platform and run on the basic phone models assuming if the basic models can run the program, the advanced phone models would also be able to run the program (Figure 2.3). As the popular mobile phone platform Android is also java based it is expected that the application can be easily adapted from the java based Symbian platform. Please note that a similar application could also be developed for an iPhone if needed. The mobile phone should support Bluetooth connectivity in order to be able to receive messages from Bluetooth radio module. The user interface program is able to receive safety messages via Bluetooth connection and convey the message as a text message for the driver. The phone will connect to the system automatically except in the case of some phones where a onetime consent is needed, which can be given when a person enters the vehicle. Please note that a different user interface e.g., a dashboard display or a built in navigational system could have been used for the safety information relay system to be developed in the current phase of the research.

2.2 System Functionality

The GPS locations of the vehicles passing through the work zone are transmitted to the RSU along with the current time and their speed to create a profile of the congestion so that SLoC and TT can be detected. The message exchange between the RSU and OBU is ordained to ensure that only the vehicles on the work zone road will participate in the communication.

2.2.1 Usage of GPS Technology

During the project GPS units were tested to make sure that none of them had any abnormal location inaccuracies. The GPS receiver type used in this project is the BU-353 GPS receiver manufactured by USGlobalSat. Having a magnetic underside it can be attached to the roof of the vehicle for better GPS signal reception. Both the GPS data and the power are transferred through a USB cable connection, so no batteries or any other power source is needed. The GPS unit supports the Wide Area Augmentation System (WAAS) which means the location error is advertised to be about 5m. The GPS receiver is used only by the OBU and transfers data using USB cable at 4800 baud rate. Once in communication with the RSU it sends its current GPS location reading, speed and time to the RSU to be stored and later be used for calculations to find the TT and SLoC. The GPS is assumed to have been turned on at the same time as the vehicle so there is no warm up time when the application starts to execute. While the GPS unit can update information faster, the OBU program only accesses the data at a desired time interval. This is because there is no benefit of updating frequently in small time intervals. The error effect from location inaccuracy is significantly higher for smaller time periods in calculating the distance traveled or the direction of travel. In order to estimate the distance between the two locations or the direction of travel between the two locations, it is important to estimate the location itself accurately. We measured the location accuracy, distance accuracy and the direction accuracy of our GPS units used and the details of these tests follows.

2.2.1.1 Location Accuracy

To measure the location accuracy of the GPS receiver when in an open area, measurements were taken using 3 GPS receivers at 4 different locations with 6 readings per location. As can be seen from the Figure 2.4 (a) where 6 different GPS location readings for a given location and GPS receiver are shown, each time a GPS reading (longitude and latitude points) is taken, it could give a different reading. The farther these points are scattered from each other, the lower the location accuracy will be. The measurements were taken non-consecutively by placing the GPS receiver in a chosen location, then allowing it to stabilize, moving to another location once a reading was taken. For the 6 readings of data associated with a particular GPS unit and location, 15 distance measurements could be calculated by cross referencing as seen in the Figure 2.4 a. This results in a total of 180 data points i.e., 15 distance measurements times per location *times* 4 locations per GPS receiver *times* 3 GPS receivers. This distance measurement between two points at any given location represents the location inaccuracy or error. These 180 distance measurements are shown as a histogram in Figure 2.4 b, x axis representing the calculated location error and the two y axis representing the frequency and the cumulative percentage. From Figure 2.4(b) it can be seen that in most cases the error is less than 2m. It can be said with 93% confidence the error is less than 3m and 98% confidence that the error is less than 4m.

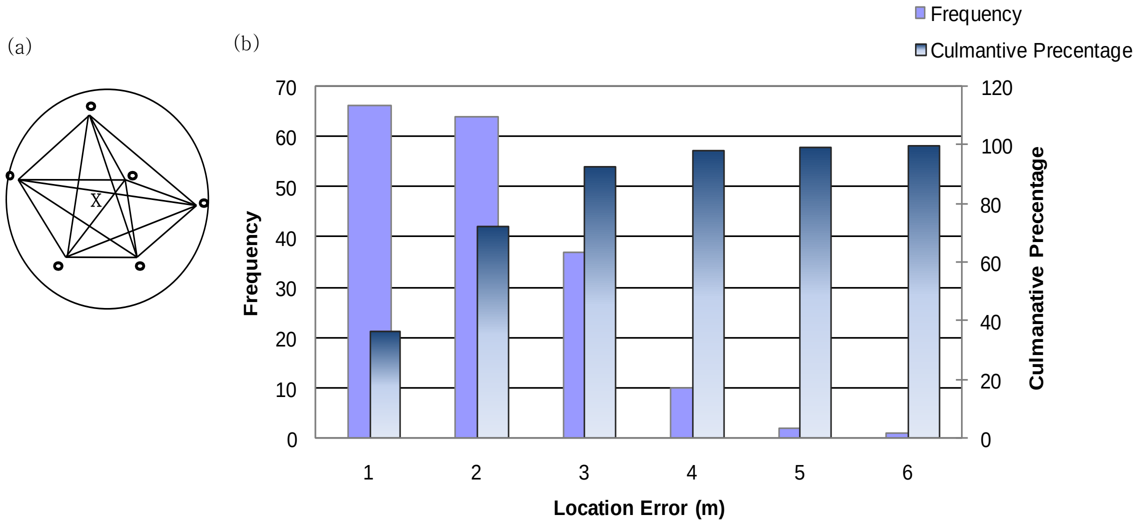

Figure 2.4 (a) The Location Inaccuracy Concept Diagram (b) The Location Inaccuracy Distribution.

2.2.1.2 Relative Distance Accuracy

The relative distance inaccuracy stems from the location inaccuracy shown earlier in Figure 2.4 a. When calculating the distance between points X and Y, the calculated distance may be smaller or greater than the true distance because the distance between the two points X and Y could be between any measured point on X to any measured point on Y as shown in Figure 2.5. The distance between the two points for a known distance was calculated measuring each location five times. By cross referencing this data 25 measurements are found as shown in Figure 2.5. Each location measurement was repeated with all three GPS receiver units giving 75 distinct distance measurements for each of the known distance. This experiment was conducted for the known distances of 5 m, 10 m and 15 m under different settings of urban and rural settings. The urban setting measurements were done in a parking lot of UMD surrounding buildings while the rural setting measurements were done on a relatively secluded rural highway in Mora, MN. The distance was measured by a tape and was used as known distance, and then the GPS unit was placed at each end taking the location reading.

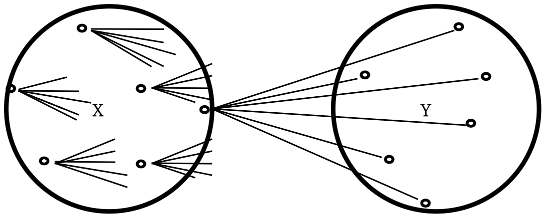

Figure 2.5 The Relative Distance Inaccuracy Concept Diagram.

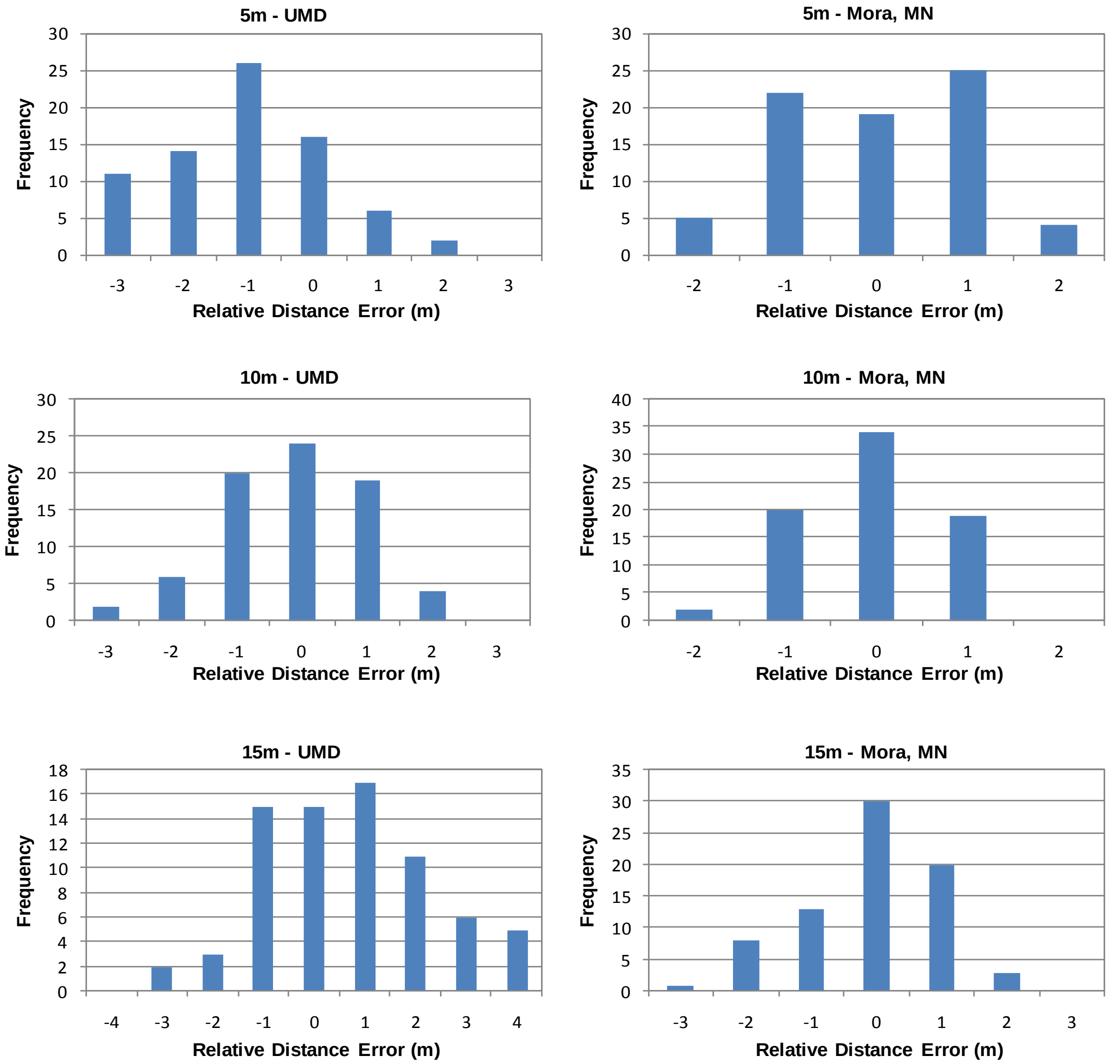

Figure 2.6 The Relative Distance Inaccuracy Distribution for 5, 10 and 15 m for Urban Environment (UMD), and for Rural Environment (Mora).

By examining the distribution of the calculated distances the accuracy of the GPS was found to be ± 2 m in rural area and ± 3 m in urban area. Figure 2.6 shows the distribution of distance inaccuracy for each of the known distance of 5 m 10 m and 15 m, in both urban and rural settings. The higher inaccuracy in the distance measurement for the urban setting is attributed to the higher interference of the GPS signals from the buildings and other sources found to be more in effect in urban areas.

Before we move to the next section, it can be of interest to the reader how we calculated the distance between the two GPS locations. The GPS location data is used with spherical geometry knowledge for calculating the distance between the two points. The equation used to calculate the distance between two points is the haversine formula [36]. The haversine formula assumes a spherical geometry and for the purpose of calculations, the radius of the earth, R is taken as 6317 km, i.e., the mean radius of the earth.

The distance between 2 GPS coordination points is calculated by equation 1.1

$$\mathrm{distance} = R * c \tag{1.1}$$

Where R is 6317 km and the variable *c* is the angular distance which is calculated by equation 1.2

$$c = 2a\tan 2(\sqrt{a\sqrt{(1-a)}}) \tag{1.2}$$

Where variable a is half the chord length between points given by equation 1.3

$$a = \sin^2(\Delta\mathrm{lat}/2) + \cos(\mathrm{lat}1) * \cos(\mathrm{lat}2) * \sin^2(\Delta\mathrm{long}/2) \tag{1.3}$$

Where the variable Δlat and Δlong are difference between the latitude and longitudes of the two GPS readings and are calculated by equation 1.4

$$\Delta lat = lat2 - lat1, \Delta long = long2 - long1 \tag{1.4}$$

2.2.1.3 Directional Accuracy

In the beginning of the RSU monitoring range where the OBU is selected, there will be OBU's traveling on nearby roads and OBU's traveling in opposite direction on the monitored road that may get selected unless filtered out. To this purpose when an OBU gets an invite message from the RSU, it will calculate its current direction of travel using two consecutive GPS location points. The calculated direction value is compared against a value communicated by the RSU as the desired direction of travel for a vehicle traveling within the valid response range. The direction is presented in range of 0-360 degrees where 0^0 stands for North with the direction angle increasing clockwise. Because of the location inaccuracy in GPS readings as shown earlier in Figure 3.1 a, the calculated direction between two points could represent any angle between a cone as shown in Figure 3.4 a, where the angle represents the bound of the direction inaccuracy. If the two points are located far from each other, the direction inaccuracy will be smaller as compared to if the two points are located close to each other (Figure 2.7 a). To test the directional accuracy, two points a known distance apart connecting through a North-South line was each measured 5 times, leading to 25 distance measurements through cross referencing. The location measurements were taken at 3 separate locations leading to a total of 75 sets of angle measurements each for the distances 1, 2, 3, 5, 10 and 15 m apart used for gathering data. For distance less than 5 m the uncertainty induced by the location error is found to be too great for it to be used for direction calculation. For points 10 m apart the uncertainty for direction between the two points was about ± 8 degrees as shown in Figure 2.7 b where the distribution of the frequency of angle error is shown.

Although the direction inaccuracy ± 8 m seems to be large, for our application purpose it is acceptable to filter out vehicles traveling in other directions than desired. For distances 15 m apart the angle error is found to be further reduced to ± 6 degrees.

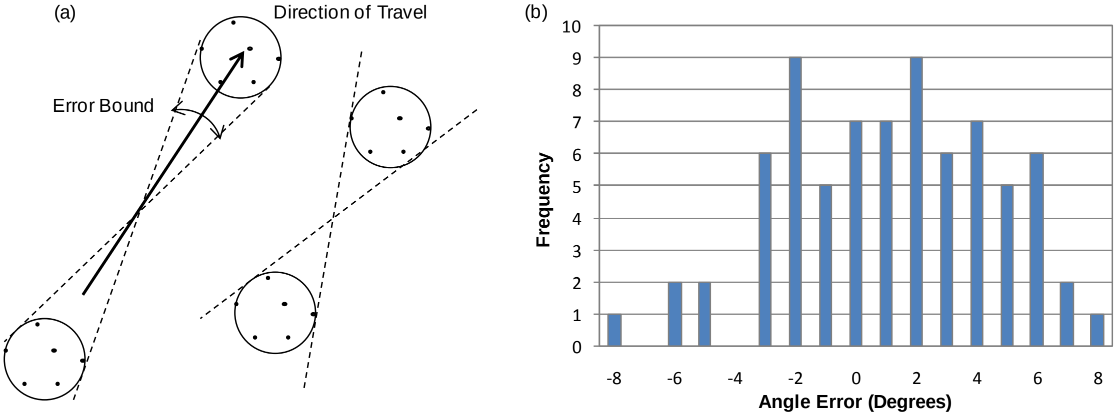

Figure 2.7 (a) The Direction Inaccuracy Concept Diagram. (b) The Direction Inaccuracy Distribution for Points 10 m Apart.

When using the GPS to calculate the direction of travel it's critically important that the two points are chosen far enough so that the impact of the location inaccuracy is reduced. Through field experiments it was found that a distance of at least 10 m is desired between the two points, the RSU communicates a time period for the OBU to wait between taking the two points to ensure that this requirement is met.

Before we move to the next section, it can be of interest to the reader how we calculated the direction (bearing) between the two GPS locations. To calculate the direction of travel between two points, the points are taken as on a great circle path (orthodrome) and the initial bearing calculated in angle Phi. The term initial bearing is used because the formula gives the direction of travel using the 1st GPS location as the point of reference. The direction of travel angle ϕ is found by equation 2.1, normalizing angle Δ to compass bearing of 0-360 degrees measured clockwise, for ease of reference [28].

$$\phi = \text{modulus } (\Delta, 360) \qquad (2.1)$$

Where angle Δ is found by equation 2.2, converting the angle Θ from radians in to degrees

$$\Delta = \Theta * \frac{180}{\pi} \qquad (2.2)$$

Where the angle Θ is found by equation 2.3

$$\Theta = \text{atan2}(\sin(\text{long2} - \text{long1}) * \cos(\text{lat2}), \cos(\text{lat1}) * \sin(\text{lat2}) - \sin(\text{lat1}) * \cos(\text{lat2}) \\ * \cos(\text{long2} - \text{long1})) \qquad (2.3)$$

The latitude and longitude values need to be converted to radians before being plugged into the equation 2.3. The resultant angle Theta is in a range of -π to π radians.

2.2.3 Message Functionality

There are five types of messages listed below that are used in V2V assisted V2I communication system to acquire traffic data.

1. *Invite*
2. *Accept*
3. *Chosen*
4. *Notify*
5. *Info*

The message types are just descriptive names to describe the functionality of our system as well as the corresponding data contents in each of these messages. The need for interoperability between different DSRC applications is an important issue that focuses the attention on need for standardizing the DSRC messages. The Society of Automotive Engineers (SAE) has specified the safety message composition for DSRC applications in their draft standard J2735 [37]. In our work we have used message formats that comply with these standards and contain the mandatory fields of the message types such as the A la Carte Message (ACM) and Basic Safety Message (BSM). The messages which our protocols use contain the data fields as specified in J2735 standards and the entire message is encoded and communicated according to J2735 standards. However, the directional message broadcast is controlled by the protocol designed and implemented in the software developed for this application. The data content of each of the five messages is described in Table 2.2. Please note that an 'X' in front of a data content type indicates that a given message type would have that data content.

Table 2.2 Data Contents of the Message Types

Data Content	Invite	Accept	Chosen	Notify	Info
Message Id	X	X	X	X	X
Message Type	X	X	X	X	X
Max Distance	X	X	X	X	X
Reference Angle	X	X	X	X	X
Transmission	X	X	X	X	X

Origin					
Angular Region Direction	X	X	X	X	X
Angular Region Half-width Angle	X	X	X	X	X
Angular Region Focal Point	X	X	X	X	X
Time	X	X	X	X	X
Preliminary Circle GPS location	X				
Preliminary Circle Radius	X				
Invite Time Interval (ITI)	X				
Vehicle Id		X	X	X	
Previous Location		X			
Current Location		X		X	
Preliminary Circle Identifier		X			
Speed		X		X	
Communication			X		

Time Interval (CTI)					
Ending Location of Congestion (ELoC)			X		
ELoC radius			X		
ELoC indicator				X	
Road Name					X
TT					X
Starting Location of Congestion (SLoC)					X

Once the RSU is active and has been given the input parameters, it will scan the road for an OBU in the *Desired Region* to engage in communication. The RSU will achieve this by transmitting *invite* messages, which will be received by the OBUs on the road. If the OBU location is within the *Desired Region* it will respond back with an *accept* message intended for the RSU [36]. The RSU upon receiving the *accept* messages from more than one OBU, will select a message from the order received and do further checks for validity of the *Desired Region* and upon passing responds to the relevant OBU with a *chosen* message. If that *accept* message fails the check, the RSU will select the next *accept* message to be received for checking. Once the *chosen* message is received by the OBU, it sends its current speed, location and time updates to the RSU using *notify* messages. Once the OBU detects that it has travelled past the ELoC, it indicates this event in *notify* messages. Every second the OBU checks whether it has crossed the ELoC by seeing if it's within a circle centered on the ELoC point. The ELoC point and the proximity distance threshold for the ELoC test are sent to the OBU in the *chosen* message. Upon receiving the *notify* message with ELoC indicator, the RSU will end the communication with OBU and start calculating the SLoC and TT from the stored speed profile acquired from the OBU. In parallel to this message exchange, the RSU will be periodically (set to 1 sec in our demonstration) sending *info* messages containing traffic safety parameters to all the vehicles that are within the broadcast range of the V2V assisted V2I communication system as shown in Figure 2.8 where the left side is for the traffic data acquisition and the right side is for the traffic parameters broadcasting. All the vehicles receiving the *info* message are able to estimate their distance to the SLoC from their own current location. Then the TT, distance to SLoC and the descriptive name of the road are sent to the driver using a user interface. This message exchange is shown in more detail using flow charts in appendix A and B (given at the end of this report) for the RSU and OBU respectively. Please note that currently, the user interface is a Bluetooth (BT) enabled cell phone where message is displayed as a text message to the driver [38]. A different user interface e.g., a dashboard display or a built in navigational system could be similarly used for displaying the safety information system in future.

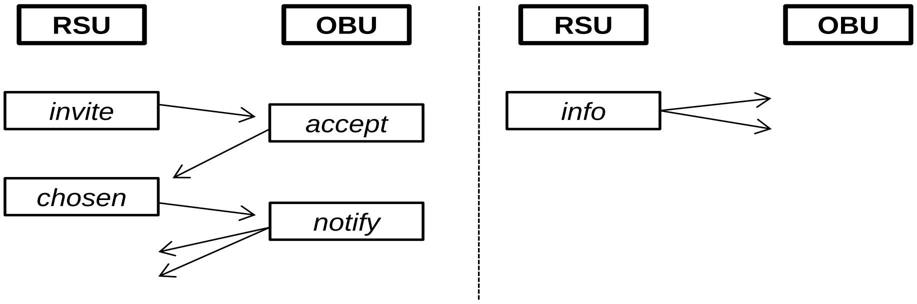

Figure 2.8 Message Flow of the Traffic Information System.

Please note that the OBU once in communication with RSU will send *notify* messages along with ELoC identifier every one second. However the OBU will update the current location, speed and time every communication time interval (CTI) which is sent to the OBU in the *chosen* message. The CTI could be one or more seconds depending upon the travel time and congestion length. Therefore, whenever CTI is greater than one second, more than one *notify* messages sent to the RSU will have the same time, location, speed and ELoC indicator. The redundancy is beneficial if the LoS is temporarily blocked by the surrounding vehicles of the selected OBU. In this case, redundancy ensures that RSU gets more opportunity to receive data even if one or more *notify* messages are lost due to a temporarily blocked LoS.

For the purpose of the calculation of the SLoC and TT, a threshold based definition of SLoC is used. In this application the SLoC is defined as the location where the speed of the vehicle falls below 50% of the normal rated speed of the road. The TT is defined as the time needed to travel from SLoC to ELoC. If the vehicle speed does not fall below 50% limit, the road is regarded as uncongested and the threshold is progressively redefined as 60%, 70%, 80%, 90%, and 100% of the rated speed to ensure that the TT calculation takes place in the RSU. If the TT is small as compared to travel time threshold (TTTh) set by the user, the system will move to update itself once SLoC is calculated by engaging another vehicle in communication. However if the TT becomes larger than the predefined value of TTTH, the system can engage more than one OBU at the same time, leading to faster updates of the SLoC and TT values. In this case RSU engages an OBU in communication and then sends another *invite* message to engage another OBU in communication after waiting for a predefined fraction of the current TT, so the travel data acquired from OBUs are distinct. By having more frequent updates the driver get to see a more accurate picture of the congestion behavior.

Once RSU determines the TT and SLoC, the info message is updated with new values for the TT and SLoC. Once an OBU receives an info message, it can calculate its distance from the SLoC. This distance along with the TT and the descriptive road name is transmitted to the driver. If the SLoC is growing longer near the current *Desired Region*, the RSU will update the *invite* message with a *Desired Region* that is further away, so that OBUs can be engaged well before the new SLoC for better estimation. Similarly, if the SLoC is shrinking it will update the *invite* message with a *Desired Region* that is closer to the RSU.

Both programs in RSU and OBU have a reset time associated with them which is triggered by not receiving any messages for a predefined time period during the communication between the selected OBU and the RSU. This is to handle unexpected scenarios such as vehicle stopping in the congested area for a rest, the OBU being shut down from the vehicle or vehicle containing the OBU taking a U-turn to avoid congestion.

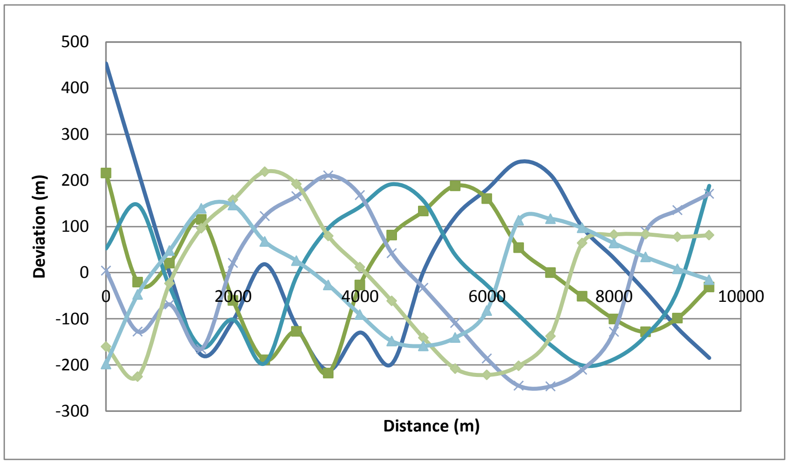

Figure 2.9 The Deviation of the Polynomial Fit Calculated Distance from the Actual Road Distance in Multiple Road Segments.

One issue is that as the roads are not in a straight path, the distance calculated from the current vehicle position to the SLoC might differ from the actual distance, significantly. To address this concern we tried using a polynomial fit method specifically tailored for a particular road, so the calculated distance can be approximated to the actual distance. Our findings, using several Highway roads, indicated that a second order polynomial equation could be used satisfactorily for the purpose of the polynomial fitting. Because the SLoC could vary, the road was segmented and different values of coefficients were used to adapt the polynomial fit equation depending on which road segment the SLoC was located. The polynomial coefficients would be sent with the info message and the receiving OBUs would use it to find more accurate distance to the

SLoC. While the receiving vehicle could be located anywhere, the polynomial fit made the distance calculation more accurate by this change. However examining real world conditions we found that the difference between the calculated and the actual value for the distance to the SLoC is not as significant especially if the calculated distance is larger. For example a difference of ±250 m was observed when considering a distance from 1 km to 10 kms shown in Figure 2.9. If a driver is estimating the time to reach the SLoC point, this difference becomes negligibly small. Considering the added bandwidth needed to communicate the variable of the polynomial fit equation and the additional processing needed to be done at both the RSU and the OBU, this feature was not implemented in the current phase of the project.

Chapter 3
V2V Communication System Protocol

3.1 Communication Protocol Overview

The developed system can work using only DSRC based V2I communication as long as the congestion length is less than half a km and the information needs to be disseminated not beyond 1 km from the RSU. However, as the congestion length increases, the V2I communication does not remain effective anymore and V2V assistance is needed to exchange the handshake messages between the desired vehicles and the RSU.

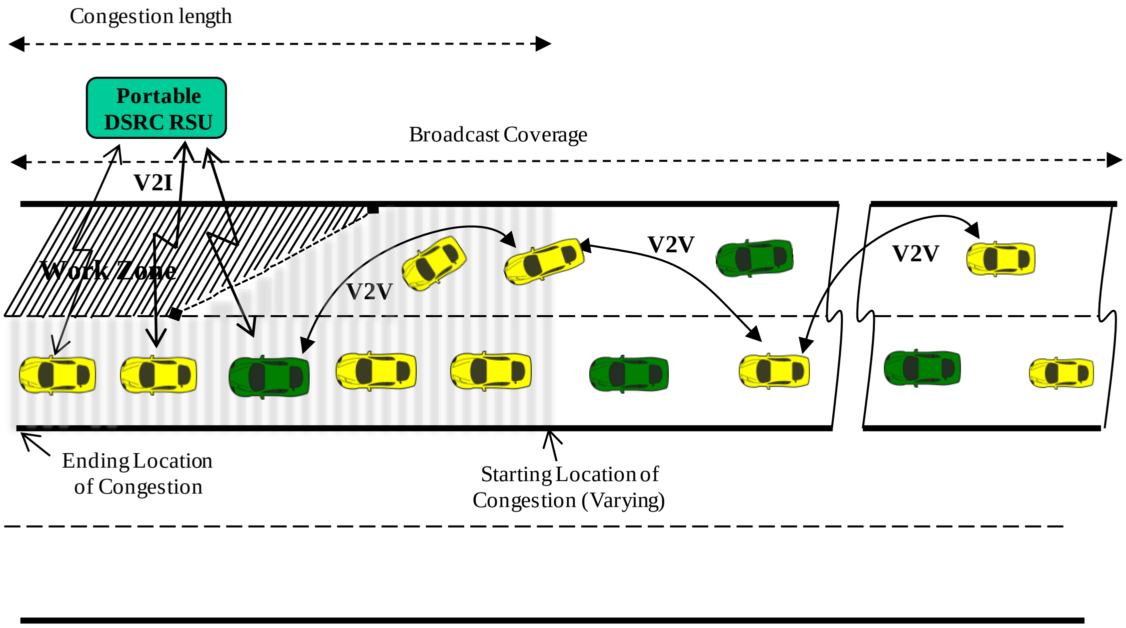

Figure 3.1 Conceptual Architectural Diagram of the Developed Traffic Information System Using V2I Communication with V2V Assistance.

3.2 V2V assisted V2I Message Protocol

In the developed system, the V2V-assisted V2I communication protocol have been designed in such a way that it is transparent to the vehicles whether they need to use V2I communication or V2V-assisted V2I communication. The central control is in RSU and once it sends a handshake message to nearby vehicles within its direct wireless access range, based upon their location, the vehicles will receive and process the message to determine if a given message is intended for their internal use and/or to be relayed forward to be used for other vehicles. If the message is for the vehicle's own use, it will act accordingly and/or if the message is to be relayed forward, it will do it using V2V communication protocol [36]. The conceptual V2V communication scenario is shown in Figure 3.1. In using V2V communication, following two key rules are considered.

Selective Relay: Not all the vehicles receiving a message should relay the same message forward as it will create a broadcast storm [17]. Rather, only one of the vehicles should relay the message forward and the selection of that one vehicle should be such that the number of hops can be minimized when conveying a given message to the intended recipient vehicle.

Directional relay: Similarly, the message propagation should be only in the desired direction (forward or backward direction depending upon the message type) to avoid the same message to relay back and forth causing message congestion. If an information message is going from RSU to the vehicles, it should only be relayed towards the direction of the road from which the vehicles are approaching to the congestion. If directional relay is not maintained, the messages will be going in both direction and will be relayed back and forth building up message congestion.

The above two rules handle the message propagation until the message reaches to the intended recipient vehicle or the RSU. The implementation details of the two rules are given below.

3.2.1 Selective Relay

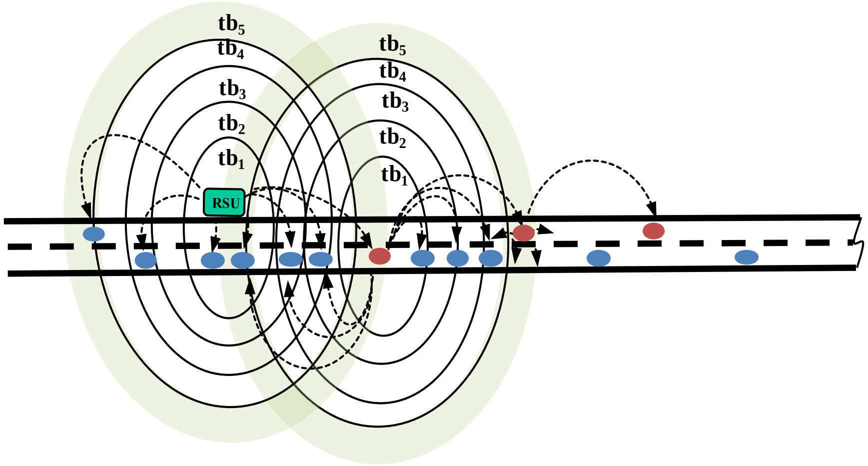

Figure 3.2 Selective Relay Functionality of V2V Assisted V2I Communication Protocol.

When a message is originated from the RSU or an OBU and needs to be relayed, it will be received by many vehicles in its vicinity. It's been already discussed that the antenna of DSRC RSU or OBUs should be omni-directional to obtain the best efficiency [36]. So a given message is received all around the message originating RSU or OBU, and some of the receiving OBUs will be near the message originating unit and some will be further away as shown in Figure 3.2.

In V2V communication it is important to choose the farthest reliable OBU to relay the message forward. This decreases the number of hops which in turn avoids delay and bandwidth congestion. To achieve this, whenever an OBU receives a message it will check its distance from the last message origination unit and randomly selects a waiting time from a predetermined time band depending upon its distance from the last message origination unit. The waiting time will decrease as the distance from the last message origination unit increases as shown in Figure 3.2, where $t_5 < t_4 < t_3 < t_2 < t_1$. Please note that t_x is the middle of the time band tb_x. Once all of the receiving OBUs are in the waiting mode to retransmit, one of the OBUs in the farthest distance band from the message originating unit will have the least amount of waiting time and will be the first to relay the message. The other OBU’s waiting to relay will detect receiving the same message again and will discard the rebroadcast message and come out of the waiting mode to retransmit. In this way, only one of the OBUs which are in the farthest distance band will relay the message. This chain will keep repeating to keep move the message forward. This will also ensure that minimum number of hops is needed to relay a given message to its destination.

For our system, we have divided the distance in 5 distance bands of 100m width as shown in Figure 3.2. This is because the reliable practical wireless access range of our DSRC units using omni-directional antennas is a little more than 500 meters. All of the receiving OBUs in the farthest distance band (400 - 500 m) will randomly select a waiting time from 0-5 ms and the next distance band (300 – 400 m) will randomly select a waiting time from 5 – 10 ms and so on while the OBUs in the nearest distance band (0 –

100 m) will randomly select a waiting time from 20 – 25 ms. This scheme ensures that one of the OBUs in the outer most distance band will relay first and also allows for the possibility of having no DSRC units in the outer bands at a given time, in which case one of the inner band units will be able to transmit. This could happen because of less than 100% DSRC market penetration as well as due to light traffic conditions at certain times and locations. Furthermore, the random time delay ensures that not more than one unit can transmit at the same time to avoid message collision.

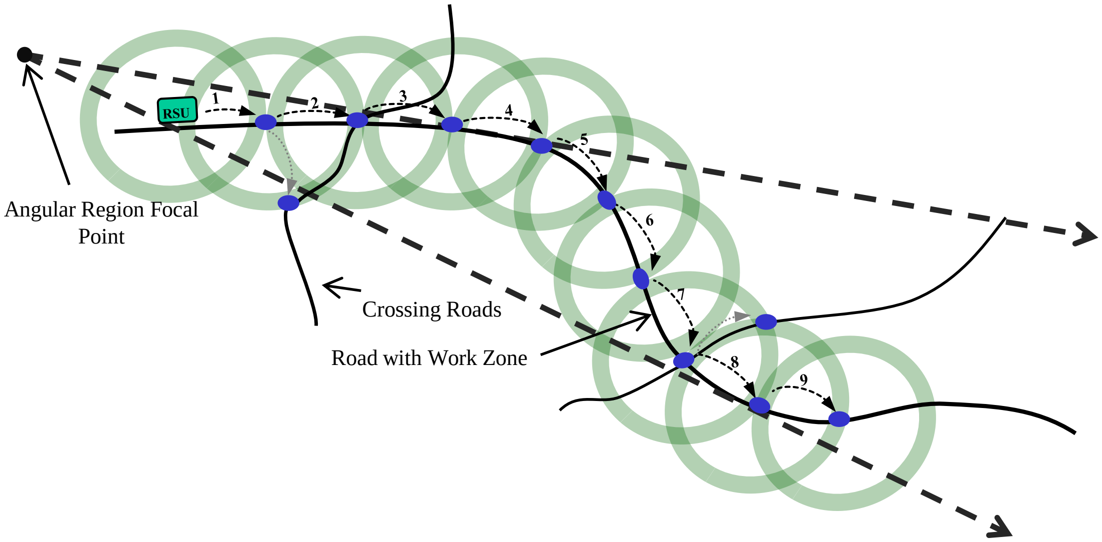

Figure 3.3 Directional Relay Functionality of V2V Assisted V2I Communication Protocol.

3.2.2 Directional Relay

Selective relay limits only one vehicle to relay a given message as well as minimizes the number of hops to convey a given message to the intended destination. However, this scheme alone can’t ensure that the message is only relayed in one direction e.g., left-to-right direction used for depiction in Figure 3.3. To avoid back and forth relaying of any given message, which can ultimately cause message congestion to build up, it is important to ensure that the message goes in only one direction. Similarly, the OBU's on a road that crosses or runs parallel to the concerned road i. e work zone road, have to be rejected from taking part in V2V communication to avoid unnecessary build up of the message congestion. To ensure the message propagates only in the desired direction, there are a few checks that are included in the V2V communication protocol and are explained below.

3.2.2.1 Direction Check

One critical aspect of the system is the ability to identify whether a vehicle is traveling in the right direction i.e., approaching the work zone area so that it can be selected to acquire relevant traffic data. The direction check is done for this purpose in the OBU. When an *invite* message is sent by the RSU, it is received by all vehicles within the coverage range. The *Data* in the *invite* message will include the desired direction of travel in terms of an angle (North being 0 degrees, and angle increasing in clockwise direction). Upon receiving the *invite* message, OBU will take an immediate GPS reading (longitude and latitude) and then take another GPS reading after waiting for a finite period of initial time interval (ITI) defined in the *Data* of the *invite* message. Once it has the two GPS readings, it calculates the angle of travel and compares it with the desired angle of travel defined in the *Data* of the *invite* message. If the angle of travel of the vehicle is within +/- 8 degrees of the desired angle, it will pass the direction test and move on to perform the location test. Please note that +/-8 degrees of tolerance is chosen to eliminate the vehicles traveling in the opposite direction of congestion while still within the error bounds of the angle calculation of GPS technology. When characterized, the error bounds of the GPS units used in this system turned out to be +/- 8 degrees for two points at least 10 meters apart with error bound decreasing for larger separation. In addition ITI is intentionally chosen by the RSU based upon the nominal speed limit of the road to ensure that the two points are at least 10 meters apart. In actual practice, they are much larger than 10 m. It must be pointed out that a vehicle past the valid response range but traveling in the correct direction may pass the direction check only to fail the location check.

3.2.2.2 Location Check

The direction check alone as described above, cannot ensure that the selected vehicle is on the desired location as a vehicle located near the end of the congestion or on a nearby parallel road would also have desired direction even through choosing it would fail the purpose of the application. The acquisition of data should be started before entering congestion in order to identify the start of congestion. For that purpose, a location check is needed. The location check is performed in two steps; one is the preliminary detection circle check that is performed in OBU and the other is the fine detection circle check that is performed in RSU. The idea behind the preliminary detection circle check is that the desired location area on the congested road is split into overlapping circles as shown in Figure 3.4. The inset is zoomed version of two consecutive fine detection circles showing the radius (R), and their separation (D) with respect to one sided road width (W). Preliminary circles are chosen with a much larger radius than the road width (about 10-20 times) so that they cover all of the desired location on the congested road. The center points and the radius of the preliminary circles are sent as *Data* of the *invite* message from the RSU to the OBU. Ideally, one preliminary circle with large enough radius is sufficient for the test. However, a few more overlapping circles are used to make the V2I communication more efficient by reducing and distributing the processing burden on both the OBU and the RSU. The OBU after passing a direction check will perform a preliminary location check by comparing the distance between its location and the center of a preliminary circle. If the distance is less than the radius of the preliminary circle, it passes the test and potentially could be on the desired location. If not it will repeat the process for all the consecutive preliminary circles.

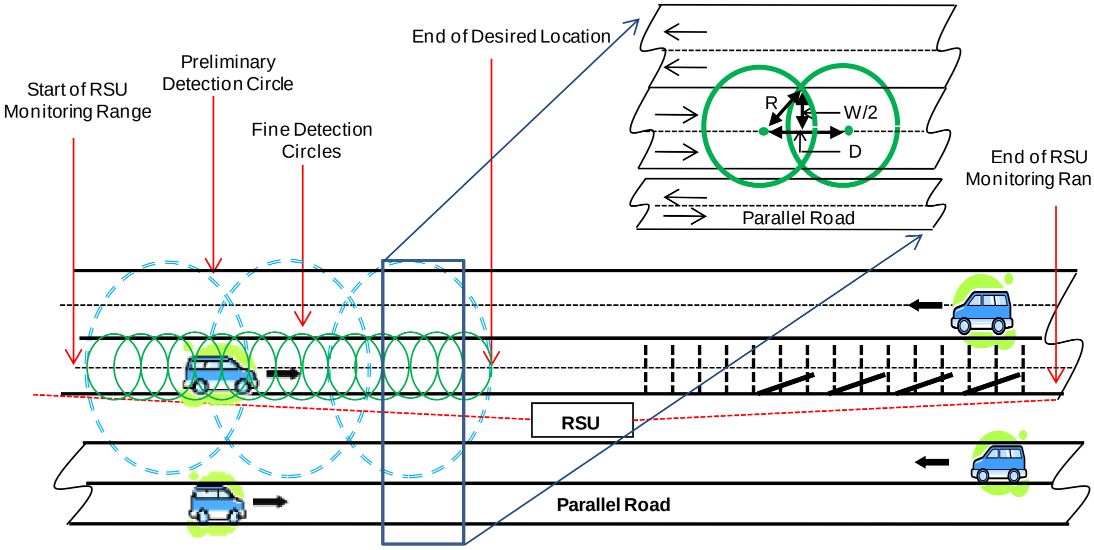

Figure 3.4 Detection Circles for Preliminary and Fine Location Checks in the DSRC OBU and RSU Respectively.

The radius of the preliminary detection circle is quite large so it is possible that a vehicle which passes the preliminary circle test, could still be on a nearby parallel road as shown in Figure 3.7. To ensure that the vehicle is on the desired road, a fine location check is performed in the RSU. The idea of the fine location test is very similar to the preliminary circle test. The major difference is that the radius for the fine circle test is much smaller. The radius of the fine detection circle is chosen in such a way that the two consecutive overlapping circles cover the whole of the road width as shown as the inset of Figure 3.4. The condition shown in the inset of Figure 3.4 is described by the following equation 3.1

$$R^2 = (D/2)^2 + (W/2)^2 \qquad (3.1)$$

Where R is the radius of the circle, D is the distance between the centers of the two consecutive circles and W is the one-sided road width.

Please note that there is a range of values for R and D that can fulfill the above equation. However, one limitation on the size of R is that it should be small enough not to include another parallel road and still larger than W/2 to cover the full one-sided road width (W). We have found that the optimal R is when D = W. That will bring R to be 0.7W using equation 3.1, which is small enough not to include another parallel road and still larger than W/2.

Please note that the RSU only needs to check the fine detection circles associated with one preliminary circle passed by OBU. This information is sent by the OBU to the RSU as the *Data* of the *accept* message. The RSU then checks the OBU location in the fine detection circle test with GPS data points for the associated preliminary circle. After passing the fine location check in the RSU, it is finally determined that the chosen vehicle is traveling in the right direction on the desired road and is positioned at desired location.

3.2.2.3 Angular Region Check

The purpose of the *Angular Region check* is to block the OBUs, outside of the broadcast coverage region, from participating in the V2V communication. There might be roads that run parallel to the desired work-zone road inside the broadcast coverage range. While the OBU's on those roads may be able to contribute to V2V communication, it is not necessary and if allowed to join could cause message congestion to grow rapidly. To avoid this, an angular region is defined around the desired work zone road for a given broadcast coverage range as shown in Figure 3.3. The angular region is defined using three parameters: focal point, direction, and half-width angle. These parameters are set in the RSU upon initialization which in turn sends these parameters to the surrounding vehicles in message handshake process as part of the message format. Please note that angular region focal point could be taken same as the RSU location or a different location to minimize the angular region half-width angle. We have looked at many practical road scenarios and found that a half-width angle width of less than 10 degrees is sufficient to cover a large span of 20 – 30 kms of curved roads. Whenever an OBU receives a message, it checks whether it's within the angular region before processing the message any further. If the receiving OBU is within the angular region, it will process the message and relay the message forward to the vehicles ahead. If a receiving OBU fails the *Angular*

Region check, it will drop the message immediately. Figure 3.3 depicts a similar scenario, where after the hop #2, the OBU outside of the angular region will not be selected and the OBU located within the angular region will continue the relay. Please note that the messages are given a desired direction (downstream or upstream) to be transmitted upon origin and propagation in that direction can be facilitated by any OBUs traveling either in upstream or downstream direction as long as they are in the angular region. This can make the message broadcast more efficient in scenario of less than optimal market penetration of the DSRC units.

3.2.2.4 Reference Angle Check

Sometimes, when a given OBU receives a message within angular region, it is possible that this OBU is on a road that crosses the monitored road. If this OBU participates in re-transmission, it is likely to propagate away from the monitored road, and because of selective relay, the OBU on the monitored road (in the same distance band) will cease to propagate any further. This could change the message propagation direction and the message may never reach the *Desired Region* or remote vehicles on the work zone road. This can happen especially if the road has significant curvature and many crossing roads. As the road curvature can be diverse and over a long distance range it is a burden on data communication to specify values to filter out vehicles on so many other roads. Instead an angle check is used to ensure that message propagates along the natural curvature of the road. Whenever an OBU receives a message, it will calculate the direction from its current location to the last transmission origination, and compare that with the direction given in the last transmission hop. If the difference is within a certain error bound (±10 degrees in our case), which can be attributed to the road curvature, the message will be processed for rebroadcasting. However if the difference is too large, the message is not processed for rebroadcasting, avoiding unwanted propagation direction and ensuring that the message stays on the desired road. For example, in Figure 3.3, in hop #8, OBU on the crossing road will not pass the reference angle test and therefore will not relay the message. Instead the OBU on the desired road will propagate the message forward.

3.2.2.5 Back Propagation Check

When a message is being transmitted, it can be received by the OBUs that are behind the transmitting unit in addition to the units up ahead on the road. The units that are behind should not retransmit the message as message has reached the current location by passing through them. And if these units also retransmit, the message will continue keep on relaying back and forth. To avoid this, the *Back Propagation Check* is introduced. In this test the units will measure their current distance (d1) from a reference point e.g., the RSU location, and will compare that distance against the distance to the same reference point from previous transmission location (d2) as shown in Figure 3.5. By comparing the two distances, an OBU can determine if the message is being propagated in the forward or backward direction. If the message originates from RSU and is intended for a remote vehicle, it should only be relayed by an OBU which is farther from RSU as compared to the OBU at a previous transmission location. Similarly, if the message originates from a remote vehicle and is intended for RSU, it should be only relayed by an OBU which is closer to RSU as compared to the OBU at a previous transmission location. This test ensures that a message can smoothly propagate from RSU to a remote vehicle or vice versa and does not relay back and forth within the angular region causing message congestion.

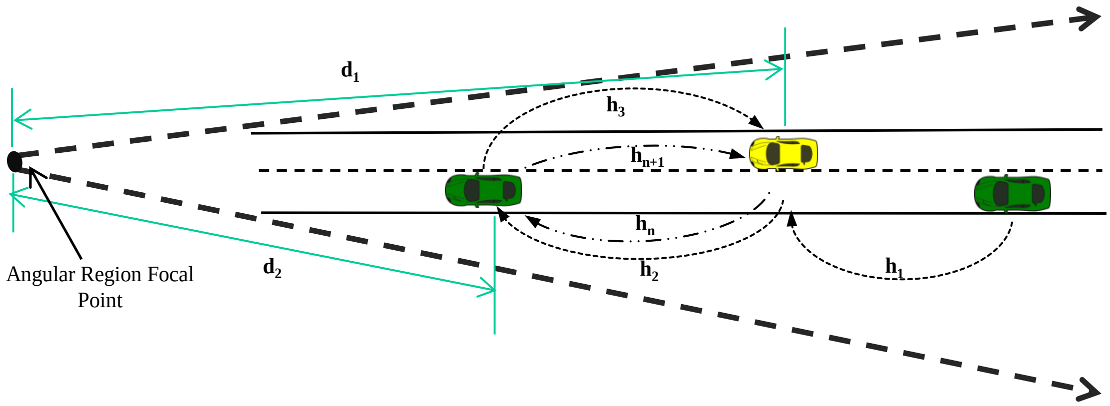

Figure 3.5 Conceptual Diagram Showing Handling of Message Back Propagation in V2V Assisted V2I Communication Protocol.

In summary, for message relay in V2V protocol, upon receiving any message the OBUs will always perform the *Angular Region Check*, to filter out vehicles from joining the V2V communication if they are outside a predefined area. It is possible for message to take multiple paths causing redundancy and consuming the bandwidth as the area width covered by the *Angular Region Check* grows larger as we move away from the angular focal point. Because of this, messages are given a direction to follow in their propagation, using the *Reference Angle Check*. If the direction of travel of the OBU differs greatly from the reference value, the OBU will not join the communication. As the road does not follow a straight path, the reference value is sent along with message and updated every time the message propagates. A received message could also be a message that has already passed through, being transmitted by an OBU nearer to the message destination. To avoid retransmitting in such cases the *Back Propagation Check* is done. Once all these checks are passed the OBU will continue processing the message and readies it for broadcasting.

Chapter 4
Field Demonstration

4.1 DSRC Unit Overview

Figure 4.1 The Placement of the OBU in Test Drive Vehicle

The RSU and OBU are identical capability-wise, the only differences being that RSU has a weatherproof covering and a directional antenna instead of an omni-directional antenna which is used in OBU. Another difference between the functionality of the two units in this project is that the OBUs have a global positioning system (GPS) receiver while RSU operates without a GPS receiver. The OBU needs the GPS capability in order to know its current location and time, which is included in the travel data updates sent back to the RSU. The RSU being stationary does not need the GPS capability to update its own location. DSRC functionality-wise there is no difference between the RSU and the OBU DSRC units. Because of this, to achieve more mobility during the field testing an OBU was used as a RSU throughout the demonstration.

The prototype DSRC units purchased from Savari Networks were used during the demonstration of this system and have the following hardware and software specifications. The units utilize 500 MHz AMD processors with DDR DRAM of 256 MB, and contain a compact flash memory of 512 MB. The Operating system installed in the DSRC units is built upon an embedded Linux platform, BusyBox. For communication and connectivity purposes the units have Ethernet, RS-232 Serial connection, USB, Wi-Fi and DSRC radio capability. In this project the Ethernet and Serial port connection were used to install and run programs on the units and to view status updates.

The programs development for the DSRC units took place in Linux environment, in Fedora 8 operating system. Once developed, the compilation of the programs was done with GNU Compiler Collection (GCC). Then the compiled software package is copied to the DSRC unit over an Ethernet connection and then installed in to the unit. The programs can be run and be monitored with ease over a Serial port connection using Minicom program or over an Ethernet port connection. Also the units can be configured to start the program automatically upon powering up. In addition, to extend the communication range and have better LoS between units, omni-directional antennas were used in DSRC units.

4.2 Field Testing Setup

The main objective of the field testing was to demonstrate the extended message broadcast range and congestion coverage range provided by the V2V assisted V2I communication and the reliable operation of the V2V communication protocol that made the extended range possible. The field demonstration site was chosen at Rice Lake Road, Duluth, MN. As the previously developed V2I-only system was also field tested at the same location, it provided basis of comparison to see the performance improvement. In the final field demonstration five DSRC units were used, one RSU and four OBUs. Once the ELoC was chosen, the RSU was installed nearby along the edge of the road on a signpost. An OBU placed on dashboard of the test drive vehicle as shown on Figure 4.1, while other OBUs were placed along the road at, on the rooftop of the other vehicles, regularly spaced to extend the V2I communication using V2V assistance.

In the actual field conditions, the communication range for the DSRC units was less than advertised range of 1km, when the OBU was placed inside the vehicle on the dashboard. We were able to get only about 500 m of range using the maximum power and omni directional antennas. Also, in the field demonstration setup, the coverage range of the RSU is asymmetric because when the test drive vehicle was traveling towards the RSU, the wind screen provided a clear LoS between the OBU on the vehicle and the RSU and the achievable range was about 500 m. However, when the OBU is moving away from the RSU, the structure of the vehicle blocks the LoS between the two units and cut down the effective communication range to only 250 m. This behavior is also present in communication between two OBUs, however as only the nearest unit to the message destination would relay the message, the unit at the back would not engage in communication. Please note that if the antenna of the DSRC OBU is placed on the roof top of the vehicle, problem does not occur. Unfortunately, we could not do this for the test drive vehicle during the demonstration.

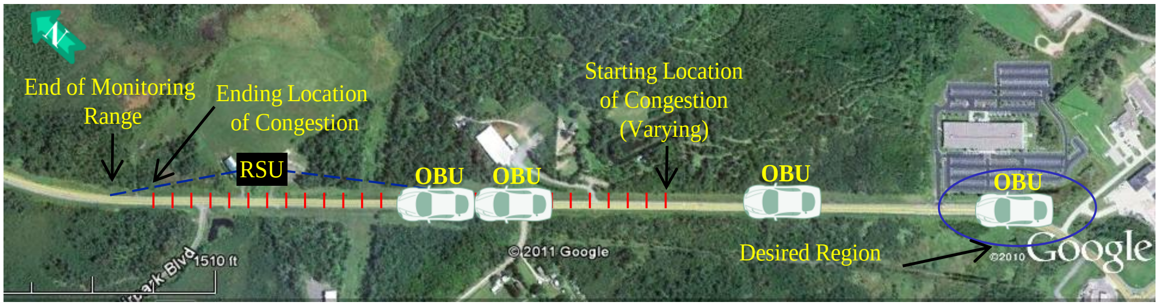

Figure 4.2 The Field Demonstration Site Showing Placement of DSRC Units and the Coverage Range of V2V Assisted VI Traffic System.

The RSU and OBU placements during the final demonstration along with SLoC, EoMR, and *Desired Region* are shown in the Figure 4.2. One of the OBU was placed in the test drive vehicle on its dashboard. Once the test drive vehicle enters the SLoC it's driven slowly on the shoulder of the road to simulate the congestion conditions while not hindering the ongoing traffic on the road.

In adapting the RSU program for the field demonstration, the speed limit of the Rice Lake road was taken as 40MPH (17.88 m/s). The monitored traffic's direction of travel is from right to left as shown in Figure 4.2. In the *info* message sent to the drivers with the descriptive road name, the direction of travel is shown as; Towards Airpark Blvd Rd. The test drive vehicle enters the SoMR from the left side of the road and once it is in communication with the RSU, the vehicle reduces the speed and enters the shoulder of the road at the varying point chosen as the SLoC. The test drive vehicle would exhibit all the characteristics of a vehicle in a congested road, such as momentarily stopping and varying speeds until it reaches the ELoC. Upon reaching the ELoC it will ramp the speed up and merge to the main road and exit the EoMR at a speed near the speed limit.

During the communication with RSU, the OBU on the test drive vehicle communicates the current speed, GPS location and time through the OBUs in front of it using the V2V communication. The messages being received and transmitted by the OBU on test drive vehicle are observed at all times using laptop terminal session via Ethernet/Serial RS 232 connection. The RSU will identify the messages from OBU by its self-assigned identifier and store all the traffic updates and once the OBU exits the EoMR, it will use the stored data to calculate the TT and SLoC and update the *info* message. After calculating the TT and SLoC, the RSU again monitors the road for potential OBUs to engage in communication using *invite* messages while transmitting the *info* message containing the calculated TT and SLoC every second. At the beginning of the field demonstration, the TT and SLoC in the *info* message are assigned zeros values to reflect no prior information existing on the traffic congestion. Once the test drive vehicle passes the EoMR, the system would keep sending the updated values until another vehicle is selected for communication and it passes the EoMR in its turn. While the traffic system is kept continuously running, the test drive vehicle would drive back without being selected for communication by RSU as it is travelling towards opposite direction and then repeat another test drive run using a different congestion profile.

During the demonstration, various RSU parameters were changed to control the DSRC communication. One such important parameter is the CTI, that control how often the OBU update the GPS location and speed values in the *notify* messages. So while the *notify* messages would be transmitted every second, the values will be updated every CTI seconds. In the field testing we used a CTI value of two seconds, communicated by the RSU to the OBU in the *chosen* message. The RSU will not store the value a second time if the message has already been received before. This enables the system to function smoothly even if a message was lost during that time period.

The V2V assisted V2I traffic system performed seamlessly relaying the RSU messages to the farthest OBUs and messages from the farthest OBUs to the RSU, leading to an increased congestion coverage and message broadcast ranges. During multiple test drive runs, the system was continuously running and RSU calculated the SLoC and TT every time when the test drive vehicle passed the ELoC. The RSU subsequently updated the *info* message correctly in each case, and scanned for other OBUs to engage in communication.

4.3 Results and Discussion

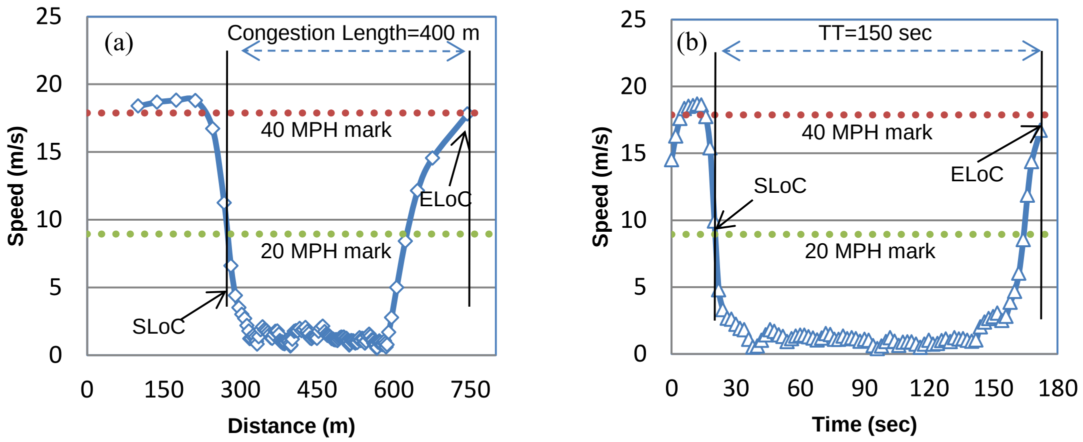

Figure 4.3 V2I Only Traffic Information System's (a) Vehicle Speed vs. Relative Distance. (b) Vehicle Speed vs. Time.

The speed, location and time update from the OBU in the test drive vehicle were stored at RSU and the SLoC and TT were calculated for each communication session once the test drive vehicle passed the ELoC. The TT for the each session varied according to the speed maintained and other driving behaviors. A set of data obtained during the field testing the V2I only traffic information system containing the speed of the test drive vehicle, captured by RSU to estimate TT and SLoC is shown in Figures 4.3a and 4.3b respectively, vs. distance and time. The congestion length covered by the system was found to be little short of 500 m from the data collected by the RSU during the field testing.

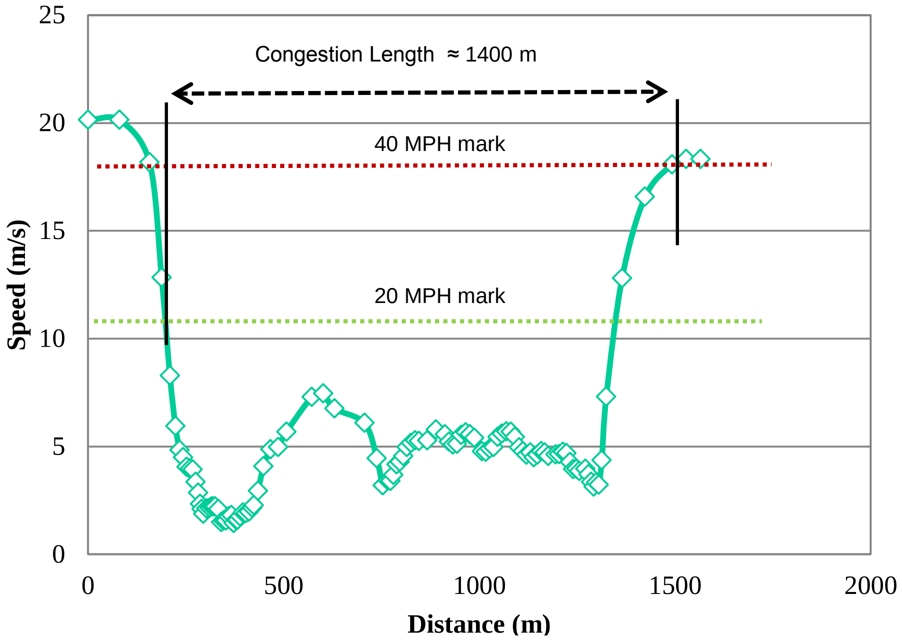

Figure 4.4 V2V assisted V2I Traffic Information System's Vehicle Speed vs. Relative Distance. (b) Vehicle Speed vs. Time.

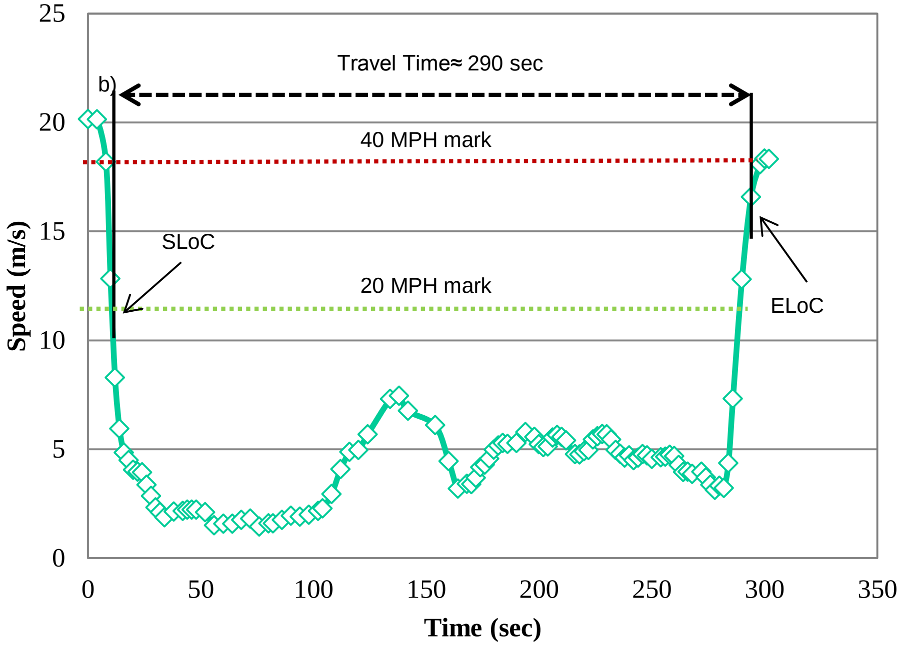

Figure 4.5 V2V assisted V2I Traffic Information System's Vehicle Speed vs. Time

In the later V2V assisted V2I traffic information system, the congestion coverage length was significantly improved. The resulting data collected by the RSU during the field testing was analyzed and the congestion length covered by the system was found to be over 1.4 km in some cases showing a marked improvement. Figure 4.4 and 4.5 shows a set of data obtained during field testing, where vehicle speed is measured vs. the distance and time respectively. In our application once the speed of the vehicle falls below 50% of the speed limit of the road, location at that time will be taken as the SLoC. Conversely once the ELoC which is a fixed point, is passed the vehicle would speed up and reach the speed limit of the road. The TT is defined as the time duration taken to reach the ELoC from the SLoC. However if the vehicle speed did not fall below the 50% mark set by the RSU, the threshold is progressively redefined to 60%, 70%, 80%, 90% and 100% to ensure the TT calculation takes place. The field tests results were successful each time in terms of acquiring data and estimating TT and SLoC. Once an OBU receives an info message it takes the SLoC location and calculates the distance from its own position to the SLoC location and then relays the value along with the TT and the descriptive road name to the driver.

During the field testing, congestion depth is varied during the field testing by changing the reduction of vehicle speed while in the congestion. By being able to handle different congestion depths and SLoC points, the V2I only traffic information system proved robust enough to estimate the SLoC and TT correctly as shown in Figure 4.6.

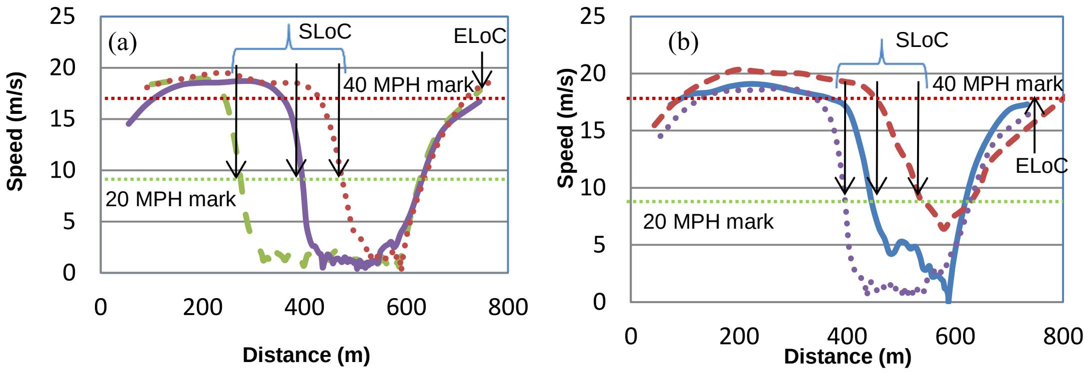

Figure 4.6 V2I Only Traffic Information System's Vehicle Speed vs. Relative Distance for (a) Varying SLoC and Similar Congestion Depth. (b) both Varying SLoC and Congestion Depth.

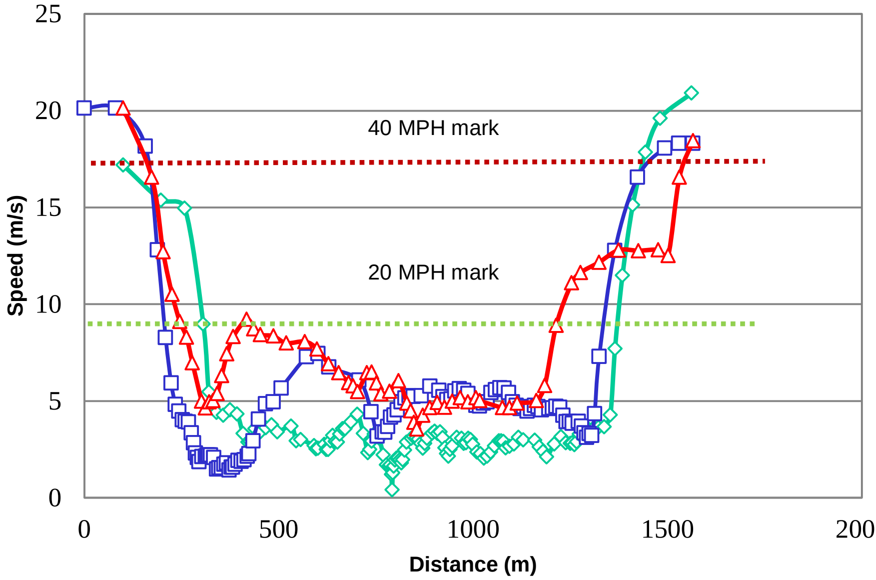

Figure 4.7 V2V assisted V2I Traffic Information System's Vehicle Speed vs. Relative Distance and Associated Time for Different Congestion Behaviors.

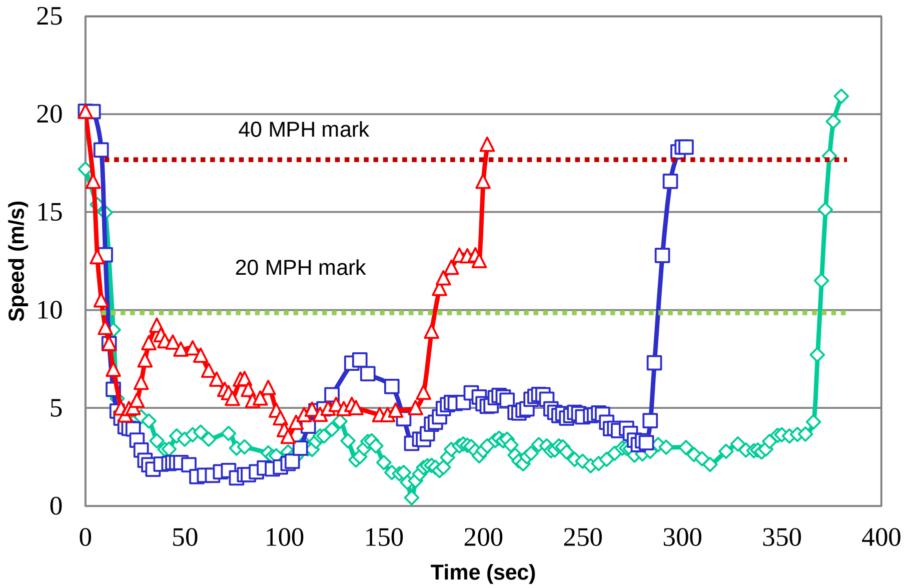

Figure 4.8 V2V assisted V2I Traffic Information System's Vehicle Speed vs. Associated Time for Different Congestion Behaviors.

During the field demonstration of V2V traffic information, we found the system able to detect the SLoC correctly and calculate the TT even with the extended congestion length where the vehicle would encounter SLoC at different points and would travel simulating light and heavy congestion scenarios as shown Figure 4.7 and Figure 4.8. In this field test we placed multiple OBU units near each other to test the delay mechanism, which was put on place to ensure only one unit would retransmit the message upon it being received by all the OBU units. The protocol worked as desired, only one unit transmitting at a time, proving the system able to handle the message congestion scenarios caused by many units transmitting redundantly.

The field demonstration was a success in extending the congestion coverage range and message broadcast range in the order of kms. The V2V assisted V2I traffic system handled various congestion scenarios smoothly and periodically broadcasted traffic safety information using info messages every second to be received by drivers. The range of the system could be further enhanced as our demonstration was limited by five DSRC units and more units would result in enhanced message broadcast and congestion coverage ranges.

We did face a few problems during the field testing which are worth mentioning. During the initial phase of the field testing, we faced a problem where the newly purchased DSRC units would not execute the programs correctly and would crash. The cause of the problem was tracked down to be a firmware update that made the DSRC units compliant to new industry standards. We had to update the programs to be compatible with the new system and upgraded all the DSRC units to the newer firmware. Another problem that we faced came up when setting the program to run through the laptop Ethernet connection. While the DSRC units can be configured to automatically start given programs after being powering up, we wanted to monitor the program execution in real-time whenever possible, which meant that the programs needed to be executed manually by the user. Whenever an Ethernet connection was used to start the program, upon removing the Ethernet cable we observed that the unit will randomly close the program after sometime. The problem was remedied when it was observed that incident did not occur when the serial communication port was used to run the program. Once the programs are running the serial port connection is removed and the units continued functioning smoothly.

To avoid the LoS problems experienced during previous system, the RSU was installed on a sign post at a height about 6 ft. nearby the road, giving it a better LoS with the test drive vehicle. Previously the RSU was installed on the rooftop of a vehicle parked at the shoulder of road. One instance of LoS problem occurred whenever the test drive vehicle carrying OBU on its dashboard was passed closely by other vehicles, blocking its LoS with the RSU. The other instance was when the test drive vehicle passed the RSU and the transmission became blocked by the back of the test drive vehicle cutting down its effective communication range. In the current demonstration, the message communication showed marked improvement in context of first instance and no difficulty was experienced even when there were multiple vehicles passing by the test drive vehicle.

Chapter 5
Conclusions and Recommendations

5.1 Conclusions

A portable DSRC based V2V assisted V2I traffic information system was developed for the work zone environment that informed and warned the drivers of the congestion conditions ahead. A much greater congestion coverage range and message broadcast range compared to what was possible with the previously designed V2I-only traffic information system was field demonstrated in this system. Furthermore, the coverage range could be scaled up to few tens of kms using OBUs to relay farther while still using a single RSU, to monitor a longer work zone site. This system can be installed on any roadway to monitor the congestion caused by work zone or an accident. Once installed, the system can accurately estimate the TT and SLoC in real time from traffic data gathered from the OBUs passing through the congestion. The estimated SLoC and TT are then broadcasted to all the vehicles approaching the congestion area using V2V assisted V2I communication. The OBU receiving the message finds the distance to the SLoC through the knowledge of SLoC and its own location and communicates the safety parameters to the driver. The hardware interface receives the message and sends the message via Bluetooth to be displayed in the driver’s BT-enabled cell phone. Please note that the user interface does not have to be a BT-enabled cell phone, it could be integrated in the dashboard of the vehicle. The knowledge of the TT and the distance to SLoC can help the drivers to be prepared for slow down and/or make an informed decision about rerouting their vehicles.

This system was extensively field tested using five DSRC units in multiple congestion scenarios where the congestion speed and SLoC were varied. During the demonstration, the vehicle containing the unit would enter the *Desired Region* of the demo site and once it was selected for communication by the RSU, the vehicle would be driven slowly along the shoulder of the road, simulating various congestion behaviors. Once the vehicle carrying the OBU passed through the congestion and exited the EoMR, the RSU correctly calculated the SLoC and the TT and updated the values in the info message broadcasted for other OBUs approaching the work zone site. The field demonstration results have shown that the newly developed system can adapt to changing road situations and works smoothly under various congestion scenarios on the road.

The objective of developing a portable system capable of using DSRC communication to increase the traffic safety and efficiency was achieved and demonstrated by the field demonstration. Once the RSU was given the initial parameters, no other intervention was necessary and the system was able to perform smoothly, engaging the OBU at the correct *Desired Region* and correctly calculating the TT and SLoC values from acquired traffic data. After correctly calculating the TT and SLoC, it engaged other vehicles to update these values again. The goal of ensuring the privacy of the users was accomplished as the OBUs used randomly generated identification numbers to identify themselves to the RSU when joining a communication session ensuring that the RSU cannot uniquely identify the OBU, easing privacy concerns. Once the safety parameters calculations were done and the vales found, the RSU erases all the data stored from that particular communication session guaranteeing that a vehicle cannot be identified by the random identification numbers.

The developed V2V assisted V2I traffic information system proved to be able to extend the congestion coverage range and message broadcast range significantly as compared to V2I-only system. The increased range would make it possible for drivers to receive information messages much earlier, when it is possible to make alternate route choices, leading to less congestion in the work zone. It was also able to smoothly handle various congestion behaviors within the work zone to calculate and disseminate the traffic safety parameters the TT and SLoC as the values varied with the traffic influx of the road.

5.2 Recommendations for Future Work

One of the possible paths for future research is the using the V2I and V2V communication of DSRC system to communicate with snowplows to provide nearby driving vehicles of its presence and actions. Snowplows usually go very slow when snowplowing as compared to regular traffic as well as blowing snow causes visibility problems for the following traffic, thereby posing a severe safety threat to the drivers especially at night time. If each snowplow is equipped with a DSRC OBU unit, then it can relay its speed and location and also whether it is snowplowing or not to any RSUs, if present. The RSUs can then transmit this information to the nearby variable message signs (VMS) via DSRC communication. This information can then be displayed on the VMSs and can stay there for a period of time so that passing by vehicles can take advantage of that and alert themselves that a snowplow operation is ahead. However, if a certain period of time passes by beyond which that information is no more effective, the message is removed from that particular VMS. Furthermore, the snowplow information can also be sent to a pickup truck carrying a portable VMS, if present, via V2V based DSRC communication. This information can then be displayed on the VMS and can stay there as long as snowplow is engaged in snowplowing.

Another application that is currently being worked on is a signal preemption system for Emergency vehicles (EVs) that will suggest the safest and the fastest available route. The proposed dynamic routing based EV system incorporates DSRC technology along with the GPS and GIS mapping data which locally resides in the EV or at the signal controller without any use of internet. This system will utilize DSRC based V2I communication as V2V communication is not required. Each EV will be equipped with DSRC radio, GPS receiver, and will have the GIS mapping data of the neighborhood roads. Each traffic signal will have the same except the GPS receiver because the location of the signal is fixed. Once a destination is given, The EV calculates the shortest route from the current location of the EV to the destination. The EV driver prefers to take the shortest route but may not be able to follow it throughout because of local traffic congestion. As the EV approaches towards a traffic signal, it sends its current location, destination location and speed ahead. The traffic signal will also calculate the shortest route to the EV destination from its own location and therefore, it would know if the approaching EV will need to go straight or make a right or left turn at this signal and accommodates to provide the green signal to the approaching EV. Furthermore, this traffic signal uses its DSRC radio to inform the neighboring signals of approaching EV and its destination so those signals and in turn all the signals in the shortest route are ready to preempt to accommodate the EV. However, if the EV driver decides not to follow the shortest route, due to local traffic congestion, the new shortest route is calculated and preemption sequence is repeated again and updated immediately on all the traffic signals on the new shortest route. The signals which were preparing for preemption earlier but do not fall on the shortest route any more, will resume normal operation.

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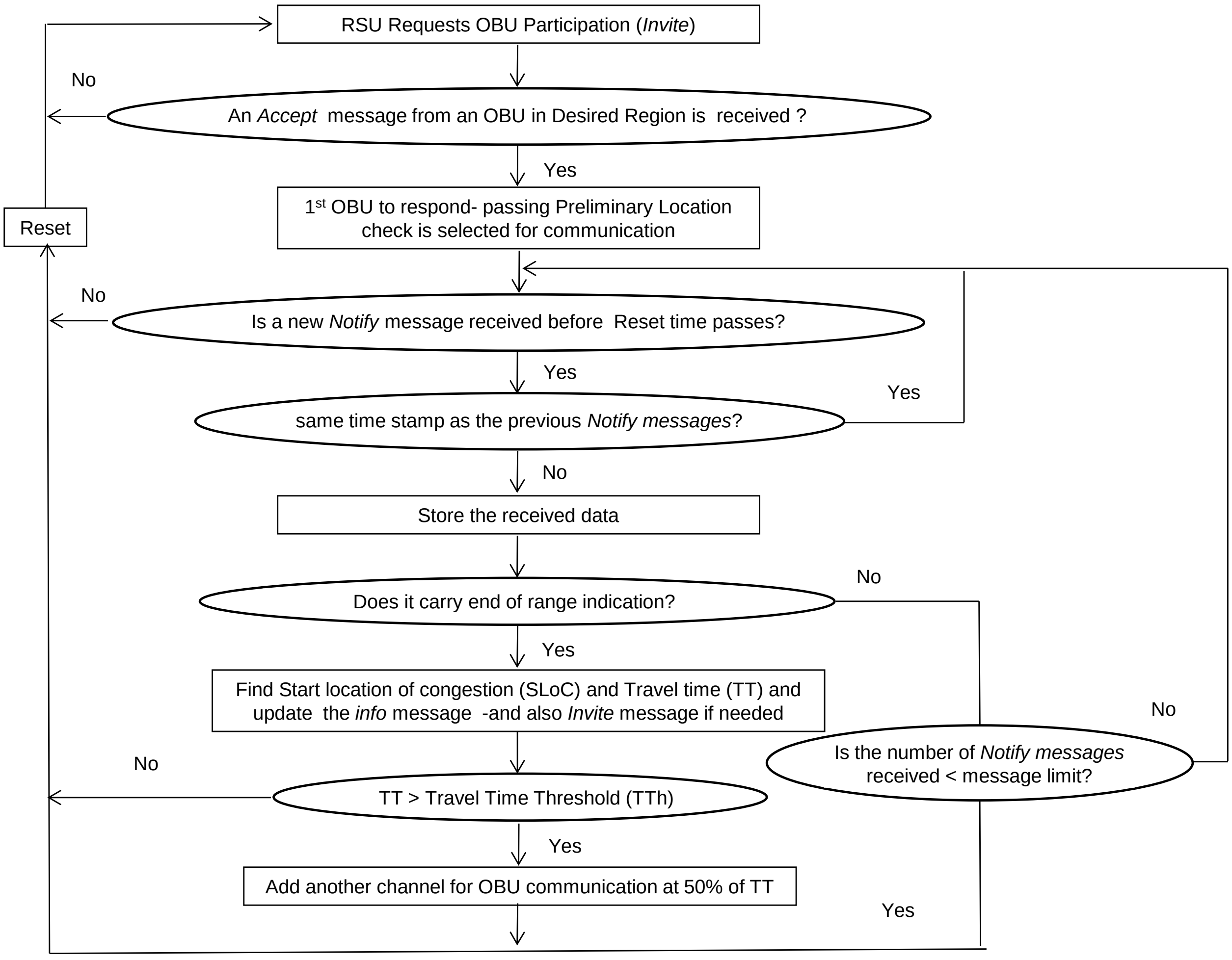
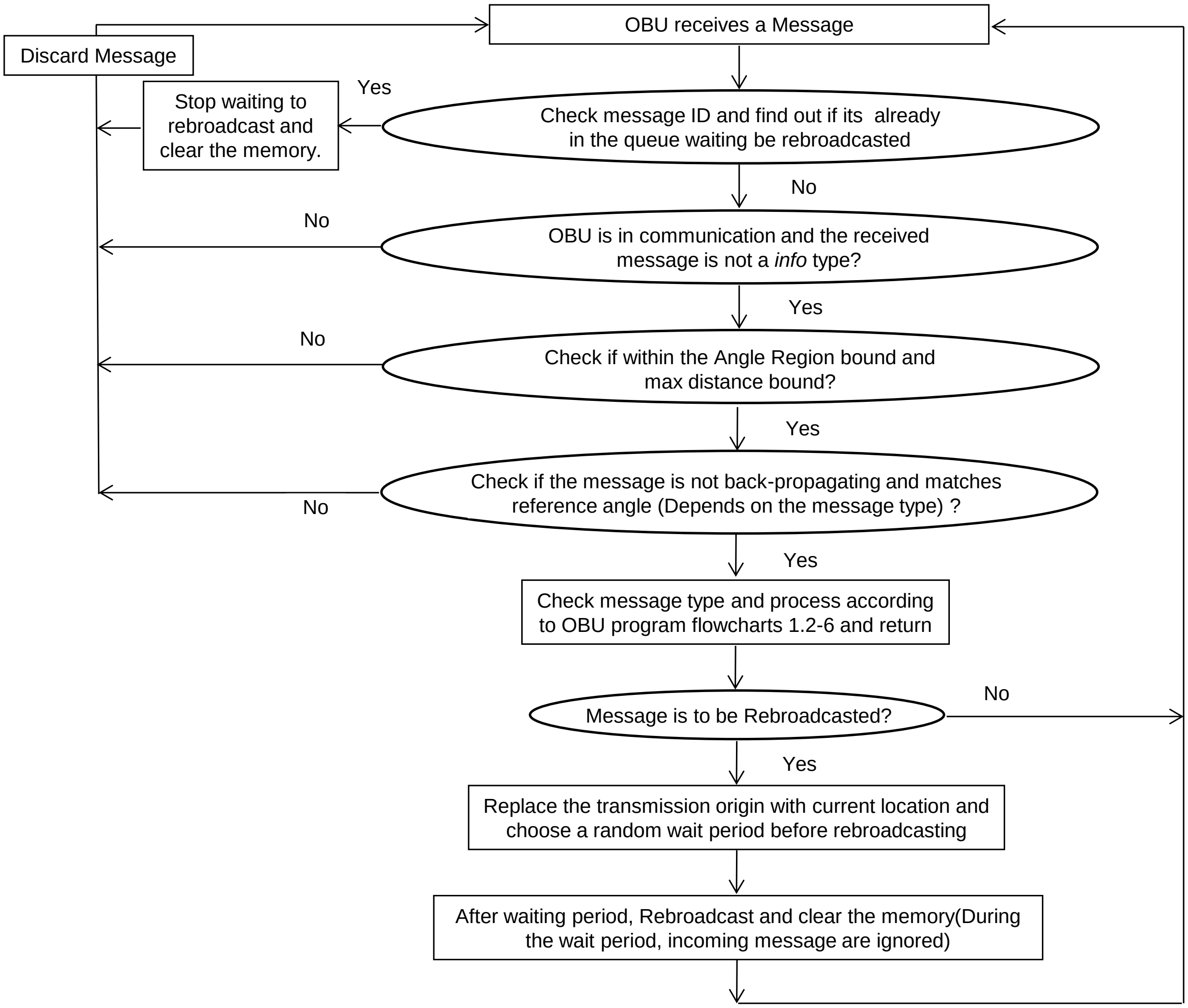
Appendix A

The RSU Program Flowchart

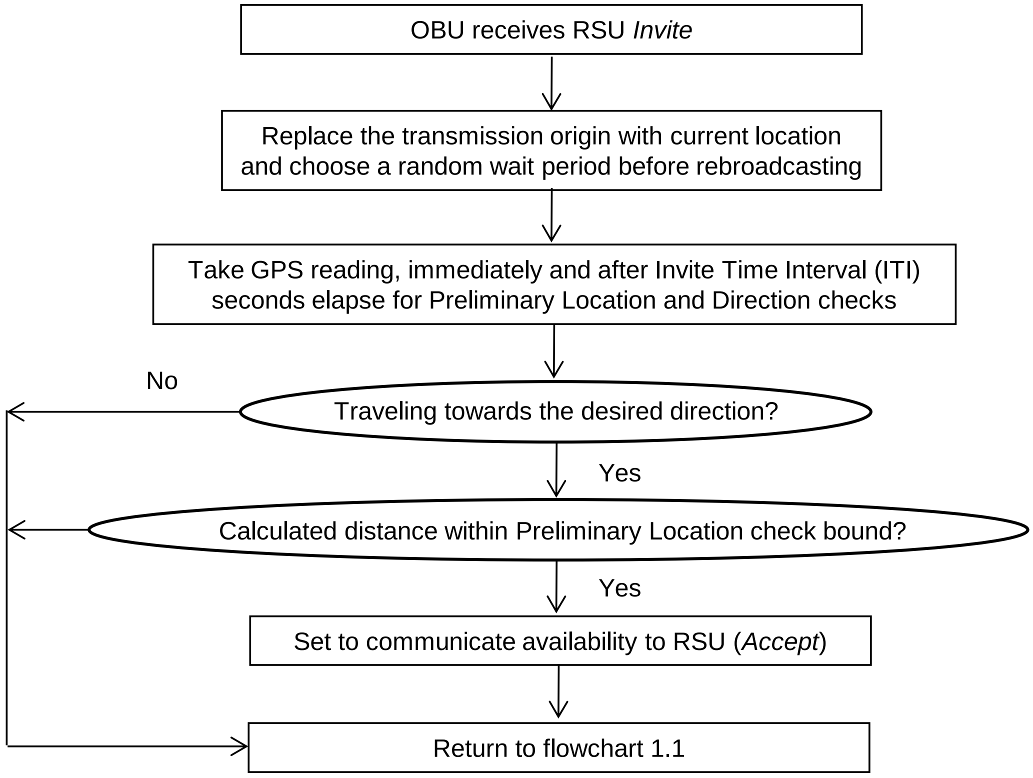


Appendix B

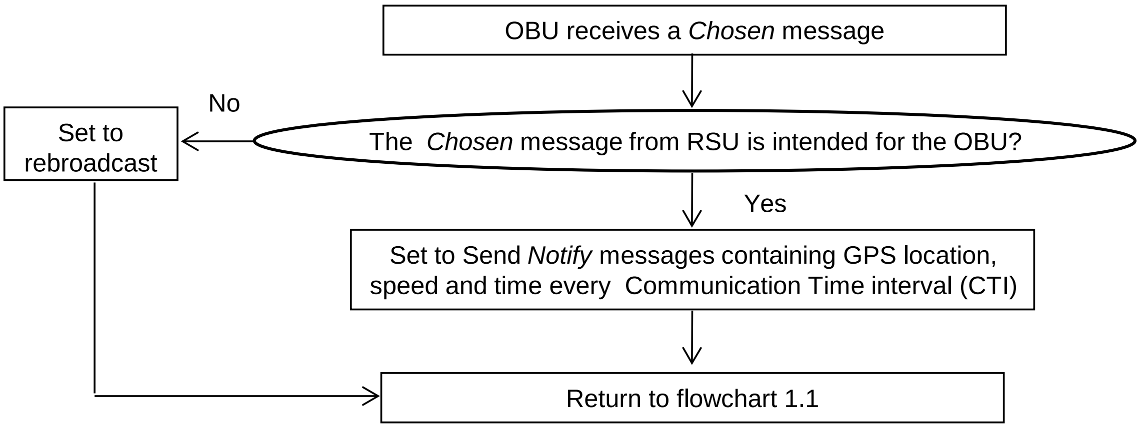
The OBU Program Flowchart 1.1



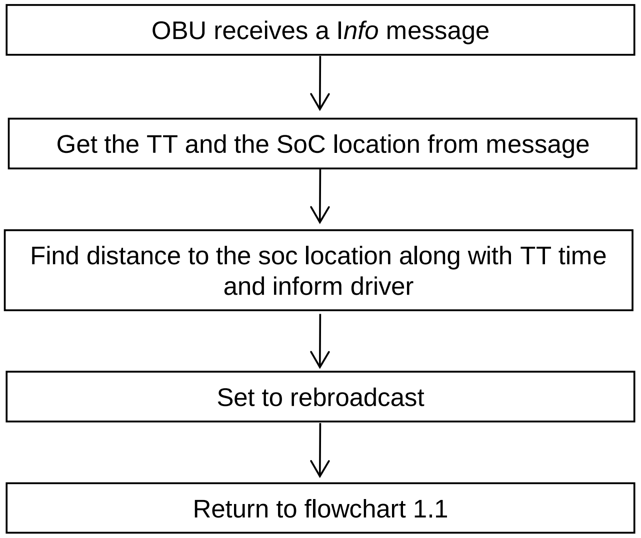
The OBU Program Flowchart 1.2 (handling *invite* message)



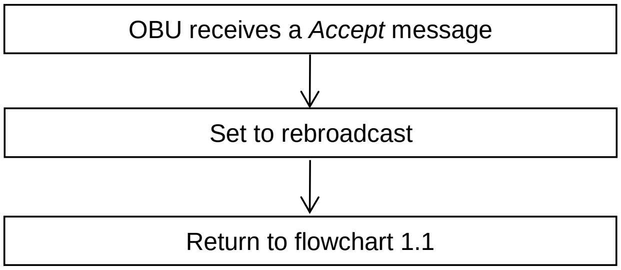
The OBU Program Flowchart 1.3 (handling *Chosen* message)



The OBU Program Flowchart 1.4 (handling *info* message)



The OBU Program Flowchart 1.5 (handling *Accept* message)



The OBU Program Flowchart 1.6 (handling *Notify* message)