ITS INSTITUTE
Intelligent Transportation Systems

Development and Field Demonstration of DSRC-Based V2I Traffic Information System for the Work Zone

Final Report

Prepared by:

Buddhika Maitipe
M. Imran Hayee

Department of Electrical and Computer Engineering
University of Minnesota Duluth

Northland Advanced Transportation Systems Research Laboratory
University of Minnesota Duluth

CTS 10-15

Technical Report Documentation Page

1. Report No. CTS 10-15	2.	3. Recipients Accession No.
4. Title and Subtitle Development and Field Demonstration of DSRC-Based V2I Traffic Information System for the Work Zone		5. Report Date December 2010 6.
7. Author(s) Buddhika Maitipe and M. Imran Hayee		8. Performing Organization Report No.
9. Performing Organization Name and Address Department of Electrical and Computer Engineering University of Minnesota Duluth 1023 University Drive Duluth, MN 55812		10. Project/Task/Work Unit No. CTS Project # 2010005 11. Contract (C) or Grant (G) No.
12. Sponsoring Organization Name and Address Intelligent Transportation Systems Institute Center for Transportation Studies University of Minnesota 511 Washington Avenue SE, Suite 200 Minneapolis, Minnesota 55455		13. Type of Report and Period Covered Final Report 14. Sponsoring Agency Code
15. Supplementary Notes http://www.cts.umn.edu/Publications/ResearchReports/		

16. Abstract (Limit: 250 words)

This report describes the architecture, functionality and the field demonstration of a newly developed dedicated short range communication (DSRC)-based Vehicle to Infrastructure (V2I) communication system for improving traffic efficiency and safety in the work-zone related congestion buildup on US roadways. The goal was to develop a portable system that can be easily deployed at a work zone site to acquire and communicate important travel information, e.g., travel time (TT) and start of congestion (SoC) location to the driver. By providing this information, i.e., SoC location and TT, drivers can make informed decisions on route choice and be prepared for upcoming congestion. The system is composed of a portable road-side unit (RSU) that can engage the on board units (OBUs) of the traveling vehicles using DSRC technology to acquire necessary traffic data (speed, time, and location). From the acquired data, the RSU periodically estimates the SoC location and TT that are broadcast to all vehicles in its coverage range. An OBU receiving the broadcast message calculates the distance to the SoC location. The distance to the SoC location and TT are then relayed to the driver, who can make smart decisions regarding whether to seek an alternate route and when to expect a sudden speed reduction. Results from the field demonstration have shown that the developed system can adapt to changing work-zone environments smoothly under various congestion patterns on the road.

17. Document Analysis/Descriptors Dedicated short range communications, Traffic safety, Data, Bluetooth technology, Work zones, Travel time, Vehicle infrastructure integration, Vehicle to vehicle communications, IntelliDrive (Program), Intelligent transportation systems		18. Availability Statement	
19. Security Class (this report) Unclassified	20. Security Class (this page) Unclassified	21. No. of Pages 46	22. Price

Development and Field Demonstration of DSRC-Based V2I Traffic Information System for the Work Zone

Final Report

Prepared by:

Buddhika Maitipe
M. Imran Hayee

Department of Electrical and Computer Engineering
University of Minnesota Duluth

Northland Advanced Transportation Systems Research Laboratory
University of Minnesota Duluth

December 2010

Published by:

Intelligent Transportation Systems Institute
Center for Transportation Studies
University of Minnesota
200 Transportation and Safety Building
511 Washington Ave SE
Minneapolis, Minnesota 55455

SI* (MODERN METRIC) CONVERSION FACTORS

APPROXIMATE CONVERSIONS TO SI UNITS

Symbol	When You Know	Multiply By	To Find	Symbol
		LENGTH		
in	inches	25.4	millimeters	mm
ft	feet	0.305	meters	m
yd	yards	0.914	meters	m
mi	miles	1.61	kilometers	km
		AREA		
in^2	square inches	645.2	square millimeters	mm^2
ft^2	square feet	0.093	square meters	m^2
yd^2	square yard	0.836	square meters	m^2
ac	acres	0.405	hectares	ha
mi^2	square miles	2.59	square kilometers	km^2
		VOLUME		
fl oz	fluid ounces	29.57	milliliters	mL
gal	gallons	3.785	liters	L
ft^3	cubic feet	0.028	cubic meters	m^3
yd^3	cubic yards	0.765	cubic meters	m^3
		NOTE: volumes greater than 1000 L shall be shown in m^3		
		MASS		
oz	ounces	28.35	grams	g
lb	pounds	0.454	kilograms	kg
T	short tons (2000 lb)	0.907	megagrams (or "metric ton")	Mg (or "t")
		TEMPERATURE (exact degrees)		
^oF	Fahrenheit	5 (F-32)/9 or (F-32)/1.8	Celsius	^oC
		ILLUMINATION		
fc	foot-candles	10.76	lux	lx
fl	foot-Lamberts	3.426	candela/m^2	cd/m^2
		FORCE and PRESSURE or STRESS		
lbf	poundforce	4.45	newtons	N
lbf/in^2	poundforce per square inch	6.89	kilopascals	kPa

APPROXIMATE CONVERSIONS FROM SI UNITS

Symbol	When You Know	Multiply By	To Find	Symbol
		LENGTH		
mm	millimeters	0.039	inches	in
m	meters	3.28	feet	ft
m	meters	1.09	yards	yd
km	kilometers	0.621	miles	mi
		AREA		
mm^2	square millimeters	0.0016	square inches	in^2
m^2	square meters	10.764	square feet	ft^2
m^2	square meters	1.195	square yards	yd^2
ha	hectares	2.47	acres	ac
km^2	square kilometers	0.386	square miles	mi^2
		VOLUME		
mL	milliliters	0.034	fluid ounces	fl oz
L	liters	0.264	gallons	gal
m^3	cubic meters	35.314	cubic feet	ft^3
m^3	cubic meters	1.307	cubic yards	yd^3
		MASS		
g	grams	0.035	ounces	oz
kg	kilograms	2.202	pounds	lb
Mg (or "t")	megagrams (or "metric ton")	1.103	short tons (2000 lb)	T
		TEMPERATURE (exact degrees)		
^oC	Celsius	1.8C+32	Fahrenheit	^oF
		ILLUMINATION		
lx	lux	0.0929	foot-candles	fc
cd/m^2	candela/m^2	0.2919	foot-Lamberts	fl
		FORCE and PRESSURE or STRESS		
N	newtons	0.225	poundforce	lbf
kPa	kilopascals	0.145	poundforce per square inch	lbf/in^2

*SI is the symbol for the International System of Units. Appropriate rounding should be made to comply with Section 4 of ASTM E380. (Revised March 2003)

Acknowledgments

The authors would like to thank Dr. Eil Kwon, director of Northland Advanced Transportation Systems Research Laboratory (NATSRL) for his support and feedback; Hai Quang Dinh, a UMD graduate student, for his invaluable help during the field demonstration; Ravi Puvvala, from Savari Networks for his help with understanding the DSRC units; and Beau Roodell, a former UMD graduate student, for his insight and advice on work done on an early phase of the project.

The author(s) wish to acknowledge those who made this research possible. The study was funded by the Intelligent Transportation Systems (ITS) Institute, a program of the University of Minnesota's Center for Transportation Studies (CTS). Financial support was provided by the United States Department of Transportation's Research and Innovative Technologies Administration (RITA).

This project is funded by NATSRL, a cooperative research program of the Minnesota Department of Transportation (Mn/DOT), University of Minnesota Center for Transportation Studies (CTS) and CTS's Intelligent Transportation Systems (ITS) Institute, and Swenson College of Science and Engineering at the University of Minnesota Duluth.

Table of Contents

Chapter 1. Introduction 1
1.1 Project Background 1
1.2 DSRC Background 1
1.3 Prior Art 2
1.4 Project Objective 3
1.5 Report Organization 4
Chapter 2. System Architecture 5
2.1 System Architecture Overview 5
2.2 DSRC Road Side Unit 6
2.3 DSRC On Board Unit 7
2.4 User Interface 8
2.4.1 Overview 8
2.4.2 Communication Interface Device (CID) 8
2.4.3 Mobile Phone 8
Chapter 3. System Design and Implementation 9
3.1 System Design Overview 9
3.2 Usage of GPS Technology 9
3.2.1 Overview of GPS Technology 9
3.2.2 Location Accuracy 9
3.2.3 Relative Distance Accuracy 10
3.2.4 Directional Accuracy 12
3.3 DSRC Units 14
3.3.1 System Setup 14
3.3.2 Application Description 16
3.3.3 Direction Check 17
3.3.4 Location Check 17
3.3.5 Travel Time and Start of Congestion Estimation 19
3.4 User Interface 20
3.4.1 Communication Interface Device (CID) 20
3.4.2 Mobile Phone 21
Chapter 4. Field Demonstration – Results and Discussion 23
4.1 Description 23
4.2 Results and Discussion 24

Chapter 5. Conclusions and Recommendations 27
5.1 Conclusions 27
5.2 Recommendations for Future Work 27
References 29
Appendix A: The RSU Program Flowchart
Appendix B: The OBU Program Flowchart

List of Tables

Table 2.1 RSU Input Parameters 7

List of Figures

Figure 1.1 DSRC Channel Frequency Assignments.. 2

Figure 2.1 DSRC System Setup.. 5

Figure 3.1 (a) The Location Accuracy Concept Diagram... 10

Figure 3.2 The Relative Distance Accuracy Concept Diagram.. 11

Figure 3.3 The Relative Distance Inaccuracy Distribution for 5, 10 and 15 m for Urban Environment (UMD) on Left Column, and for Rural Environment (Mora) on Right Column. 11

Figure 3.4 a) The Direction Accuracy Concept Diagram. 13

Figure 3.5 Schematic Diagram Showing RSU Placement across a Work Zone and Desired Location to Start Engaging the Vehicles on the Road for V2I Communication. 15

Figure 3.6 Message Flow between the RSU and the OBU... 16

Figure 3.7 Detection Circles for Preliminary and Fine Location Checks in the DSRC OBU and RSU Respectively. 18

Figure 3.8 CID Components [27]. 21

Figure 3.9 Mobile Phones Used for Testing [27]. 22

Figure 4.1 The Field Demonstration Site Showing Placement of RSU, Its Coverage Range, EoC location and Varying SoC Locations. 23

Figure 4.2 (a) The Speed of the Vehicle Traveling Through the Congestion vs. Relative Distance. (b) The Same Speed is Shown vs. Time. 25

Figure 4.3 The Speed of the Vehicle Traveling Through the Congestion vs. Relative Distance for (a) Varying SoC Location and Similar Congestion Depth, and (b) for Both Varying SoC Location and Congestion Depth.. 26

List of Abbreviations

API	Application Programming Interface
CID	Communication Interface Device
CDLC	Connected Limited Device Configuration Java specification
CTI	Communication Time Interval
DSRC	Dedicated Short-Range Communication
DVI	Driver Vehicle Interface
EoMR	End of the RSU Monitoring Range
GPS	Global positioning system
ITI	Invite Time Interval
IVBSS	Integrated Vehicle Based Safety System – Univ. of Michigan
ITS	Intelligent Transportation systems
JSR-82	Java Application Programming Interface for Bluetooth applications
LoS	Line of Sight
MIDP	Mobile Information Device Profile Java specification
NEMA	National Electrical Manufacturers Association
OBU	On Board Unit – DSRC Radio
PATH	Partners for Advanced Transit and Highways
RSU	Road Side Unit – DSRC Radio
SoC	Start of Congestion
SoMR	Start of the RSU Monitoring Range
TT	Travel Time
TTTh	Travel Time Threshold
UUID	Universally Unique IDentifier
USDOT	United States Department of Transportation
V2I	Vehicle to Infrastructure
V2V	Vehicle to Vehicle

Executive Summary

The United States Department of Transportation's (USDOT's) Intelligent Transportation Systems (ITS) program is focusing on crash prevention through the integration of intelligent vehicles and intelligent infrastructure in its IntelliDrive^{SM} research initiative. By having access to the real-time traffic safety information made possible through such a system, drivers can avoid many scenarios where an accident can potentially happen. In addition to directly avoiding fatal crashes, the safety information can give drivers more options such as rerouting to avoid adverse road conditions, thus making the traffic flow more efficient in line with the IntelliDrive's goal of increasing traffic safety, mobility and environmental friendliness. To obtain this goal, many vehicle to vehicle (V2V) and vehicle to infrastructure (V2I) applications have been proposed and their feasibility proven by the research interest groups.

The frequency band for dedicated short-range communication (DSRC) operates around the 5.9 GHz frequency band, and is assigned by USDOT for automotive safety applications use. DSRC communication is a secure and reliable form of communication making it the focus of many V2V or V2I applications.

The purpose of this project is to develop, implement and demonstrate a DSRC-based V2I information relay system for improving traffic efficiency and safety in the work-zone related congestion buildup on US roadways. The newly developed system is a portable system that can be easily deployed at a work-zone site to acquire and communicate important travel information, e.g., travel time (TT) and start of congestion (SoC) location to the driver. By having access to this information, i.e., SoC location and TT, drivers can make informed decisions on route choice and be prepared for upcoming congestion. The system consists of a portable road-side unit (RSU) and vehicle on board units (OBUs). The RSU engages the OBUs of the traveling vehicles using DSRC technology to acquire necessary traffic data (speed, time, and location). From the acquired data, the RSU periodically estimates the SoC location and TT, which are broadcast to all vehicles in its coverage range. An OBU receiving the broadcast message calculates the distance to the SoC location using its own location and the SoC location. The distance to the SoC location and TT are then relayed to the driver through the user interface. The driver can then make smart decisions regarding whether to seek an alternate route and when to expect a sudden speed reduction. The information messages containing distance to the SoC location and TT are displayed to the driver as a text message through the Bluetooth-enabled mobile phone – a component of the user interface developed earlier.

Important features of the developed application are portability, privacy, security and low-cost. Portability is achieved by enabling the application to work on any road once RSU program parameters are updated. RSU plays a central role and all the OBUs on that road receive the communication parameters e.g., data acquisition frequency and communication intervals etc. from the RSU. Once RSU is installed covering the end of congestion (EoC) location on one side of the road to be monitored, it can be initialized by inputting road parameters in a onetime operation that will allow it to function without being further managed. Privacy of the application is achieved by the RSU having a temporary access to location and speed information from the OBU without knowing the identity of the vehicle. The location and speed data are associated and are stored in the RSU with a randomly generated ID for the vehicle containing the OBU during

the temporary information exchange session. The data in the RSU are discarded after TT and SoC location calculation. Security is built into the DSRC communication protocols used in this project. It addresses attempts to eavesdrop, spoof and other attacks. Furthermore, the trusted applications using DSRC are uniquely identified while giving safety applications the highest priority. The low cost of the system is achieved by incorporation of mobile phones as part of the user interface as most drivers own a mobile phone and mobile phones are a proven technology.

After development was complete, the system was tested on Rice Lake Rd., Duluth, MN, with two vehicles containing the DSRC units. The DSRC unit placed in a stationary vehicle acted as the RSU. The DSRC unit in a mobile vehicle acted as the OBU. During the demo, various congestion scenarios were simulated and many communication parameters were varied to ascertain the usability and reliability of the system. The congestion scenarios tested were

1. Fixed SoC and fixed EoC location
2. Varying SoC and fixed EoC location
3. Varying EoC and SoC location

The vehicle carrying the OBU would start slowing down at different places using different decelerations and alter the moving speed through the congested area to simulate the above scenarios.

Results from the field demonstration show that the developed system can adapt to changing work-zone environments under various congestion patterns on the road both smoothly and successfully.

One finding of the field demonstration is that the line of sight (LoS) plays a critical path in the range of the DSRC communication. The project setup of having the RSU on the top of the vehicle and OBU on the dashboard of the vehicle afforded a good LoS when moving toward the RSU. However, the range was drastically shortened when moving away from the RSU, being shielded from the back of the vehicle. To counter this effect, the RSU is moved nearer to the EoC location point, so that its range still covered the EoC location point. Also when the vehicle carrying the OBU turned a corner, or traffic obstructed the LoS between the RSU and the OBU, the messages could be intermittently lost, with the effect growing greater nearer to the ends of the RSU range. Please note that in the V2V-based system to be planned in the next phase of research, this problem will not pose a hurdle because the message will be originated from many sources, with some of them in close proximity of the destination DSRC unit.

Chapter 1. Introduction

1.1 Project Background

Safety, mobility and environment friendliness are three main issues in improving the transportation industry. To put this into perspective, in 2008 there were 37,000 fatalities through vehicle accidents, 4.2 billion hours lost stuck in traffic and 2.8 billion gallons of fuel wasted [1].

The Intelligent Transportation systems (ITS) program of the U.S. Department of transportation (USDOT) aims to solve these issues by integration of intelligent vehicles and intelligent infrastructure [2]. The goal of IntelliDrive, a major initiative of the ITS, is to provide connectivity between vehicles, infrastructure and passenger wireless devices to ensure safety, mobility and environmental benefits [2]. The Wireless communication designed for these automotive connectivity purposes is the dedicated short-range communication (DSRC). It is a 75 MHz of spectrum in the 5.9 GHz band assigned for automotive use by U.S. Federal Communication Commission in order to increase traffic safety and efficiency. In its five year ITS strategic plan, the USDOT is committing to the use of Wireless technology such as DSRC for active safety in both vehicle to vehicle (V2V) and vehicle to infrastructure (V2I) applications [3]. The DSRC communication is designed as the best available choice for its low latency, high speed and high tolerance for message loss [4].

By using the real-time traffic data it’s possible for drivers to be kept updated about the traffic conditions to make driving safer and efficient. Some of the applications that have been deemed feasible using DSRC communication are

1. Cooperative Adaptive Cruise Control
2. Forward Collision Warning
3. Land departure Warning
4. Lane Changing Warning
5. Intersection Collision Avoidance
6. Approaching Emergency Vehicle Warning
7. Electronic Toll Collection
8. Curve Speed Warning

Another possible scenario where the DSRC communication can help is the congestion on U.S roads caused by a work zone environment or due to an accident on a road. Congestion, in turn, can cause accidents when the driver is not expecting the speed reduction when entering the congested zone or through error of judgment due to frustration. This application was developed as a possible method of warning the drivers of the congestion ahead of time so that the driver can choose alternate route or be prepared for the speed drop leading to a safer and efficient traffic flow.

1.2 DSRC Background

Dedicated short-range communication (DSRC) is a short to medium range (< 1 km) high-speed (up to 27 Mbps) wireless communications protocol specifically designed for automotive use (vehicle speeds up to 120 mph), where minimizing latency (50 ms) and isolating relatively small communication zones are important [5]. DSRC is designed to be used in both V2I and V2V communication, and is implemented in the 5.850-5.925 GHz frequency range. It consists of seven 10 MHz channels with data rates available from 3-27 Mbps (also offered is the option of combining two sets of two 10 MHz channels (174/176 and 180/182) into two 20 MHz channels with data rates available from 6-54 Mbps) [5], with the first channel (172) set aside strictly for vehicle safety (Figure 1.1).

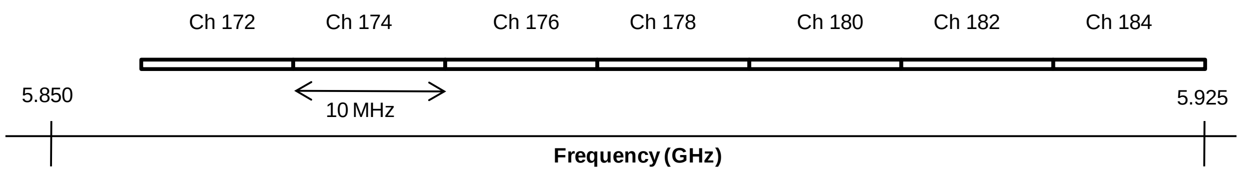


Figure 1.1 DSRC Channel Frequency Assignments.

The DSRC technology is selected as the communication method in this project because the properties of the DSRC technology given below [4].

1. Operates in a licensed frequency band
2. Geared for safety applications
3. Low latency and high speed communication
4. Secure communication
5. Immunity to extreme weather conditions
6. High tolerance for message loss
7. Supports both V2I and V2V communication
8. Supports high vehicle speed conditions

1.3 Prior Art

The benefit of using ITS technology other than DSRC technology to manage the traffic has being examined in more than one study [6-12]. Benefits of using ITS technology have been demonstrated through savings in costs and improved efficiency [6]. Through the use of cameras and other traffic sensors, traffic flow is monitored and detours are recommended via message boards when congestion occurs [7, 8]. In addition, travel time [9], lane merge [10], and speed advisory [11] information can be gathered from this data and used to manage traffic in real time [12]. In summary, ITS technology can be applied in work zones for many purposes such as described below:

- Traffic monitoring and management
- Providing traveler information
- Incident management
- Enhancing safety of both the road user and worker
- Increasing traffic capacity
- Enforcement
- Tracking and evaluation of contract incentives/disincentives (performance-based contracting)
- Work zone planning

DSRC is another form of ITS technology which can serve most of the purposes stated above. The distinguishing feature between the DSRC and the other ITS technologies is that DSRC technology requires data acquisition through the vehicles travelling on the road as the OBU component of the system comes from the vehicle. That means that a majority of the vehicles on the road should possessed DSRC units. This makes it necessary to have a wide acceptance from the vehicle manufacturers in order for system as a whole to be accurate and efficient. Once the DSRC technology is accepted as a standard, it can bring a new dimension to the traffic safety as a traffic managing system can be easily setup on the fly with minimal infrastructure needed.

The interest in applications using DSRC communication has been shown jointly by automobile manufacturers and the U.S. Government. In the academia, University of Michigan's Integrated Vehicle Based Safety System (IVBSS) program which is a cooperative research effort with USDOT, the University of California's Partners for Advanced Transit and Highways (PATH) program and other universities have researched and verified many DSRC application capabilities. DSRC message protocols have been proposed addressing channel congestion, broadcast performance, security [13-15] and DSRC communication reliability [16]. Additionally remote collision avoidance system using DSRC-based V2V communication protocols has been proposed [17-18] and verified [18].

PATH projects have shown the feasibility of highly reliable, low delay message transmission using DSRC communication where safety messages are sent to a vehicle onboard radio unit [14]. In another project GPS-enabled cell phones were anonymously surveyed for location information. This information is then relayed to users, providing information about travel route times [19]. The PATH program is continuing the work on cooperative adaptive cruise control in addition to transmitting traffic information such as travel time, incident information, work zone safety warning, intersection collision warning, curve over speed warning, etc between vehicles and infrastructure [20].

The University of Michigan is involved in the Integrated Vehicle-Based Safety Systems (IVBSS) program where applications for forward collision, curve over speed and lane departure and change warnings are being developed [21-24]. In addition, the IVBSS program aims to integrate several collision warning systems into one vehicle making it possible to alert drivers to potential collision threats with an effective Driver Vehicle Interface (DVI), while minimizing the number of excessive warnings presented to the driver [21]. Most importantly, the University of Michigan has setup a testing bed for vehicles where various developing DSRC application scenarios can be implemented and tested [22-23]. One such application relevant to the research interest focused on in this project uses DSRC to warn motorists of imminent changes to their operating environments, such as the approach of an emergency vehicle or an upcoming work zone [25].

1.4 Project Objective

The objective of this project is to design, implement and demonstrate protocols and programs for a portable DSRC communication system capable of communicating in real-time estimates of traffic safety parameters to the drivers within range. The traffic safety parameters to be communicated are the travel time (TT) through a congested road and the distance to the start of congestion (SoC) location. The setup is composed of the DSRC-based RSU and one or more OBUs where the OBU sends its travel information to the RSU to be stored and to be used for calculating traffic safety parameters. The RSU then informs all the OBU's in range of the safety parameters, which are then presented to the driver. This information would help improve the safety and efficiency of the traffic. The traffic efficiency can be improved by letting the driver know the travel time through a congested area, which allows the driver to make an informed decision as to whether to seek an alternate route or to stay on the road. The driver's safety can be improved by communicating how far the SoC location is from the current location of the driver is so that he/she can be prepared for a sudden breaking situation ahead. The system is designed such that it is portable, transparent, secure and inexpensive. The field demonstration of the system, under various road parameter settings, is one of the main objectives of this project. The field demonstration was designed to test the system's reliability and adaptability with different roads and varying congestion scenarios.

1.5 Report Organization

The first chapter is the introduction where the background, prior literature and project objectives are explained to the reader. The second chapter is entitled "System Architecture" which gives a brief overview of the hardware and software used in the project. The third chapter, "System Design and Implementation" covers in detail the incorporation of GPS technology in to this project. Then the fourth chapter, "Field Demonstration - Results and Discussion" contains the setup of the field demonstration, obtained results and the discussion on the findings. Finally the fifth chapter "Conclusion and Recommendations" details the conclusions that followed the field demonstration results and recommendations for the future work. Following the main body of the report is the "References" and the Appendices.

Chapter 2. System Architecture

2.1 System Architecture Overview

The System consists of three major components.

1) DSRC RSU
2) DSRC OBU
3) User Interface

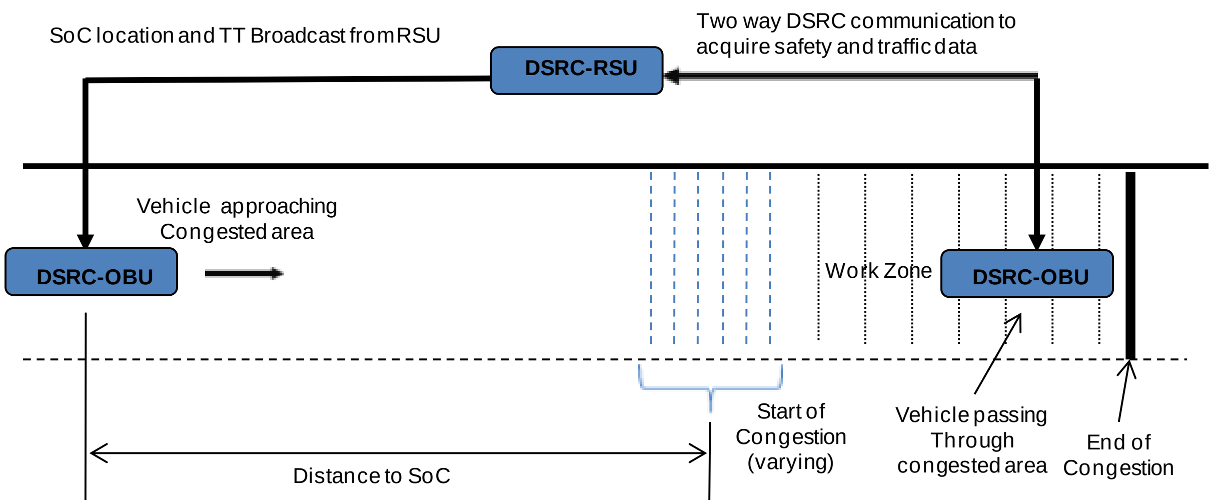


Figure 2.1 DSRC System Setup.

The system architecture was designed with the focus on increasing driver safety and efficiency with a portable, low cost information relay system. In order for system to be portable, the programs in the OBU and the RSU were written to be adaptable to road parameters. The OBU program does not need any input about the monitored road or any other parameters for it to function, being completely adaptable to any road. However, the program in the RSU needs to be given input parameters for the road to be monitored. The system can be configured to any congested road by simply inputting a few parameters in to the RSU that will allow it to know key GPS locations on the road and the settings to be used in OBU communication. A possible DSRC unit placement setup is shown in Figure 2.1 above. The RSU is placed near the road, its range covering the work zone and the EoC location. After being configured for a given road the RSU will communicate a request for participation to all OBU's in range, along with settings to be used. OBU's traveling on the road in desired direction will be selected by RSU to acquire data before the congestion occurs. Additional settings to be used by OBU are communicated once an OBU unit is chosen for acquiring data. The OBU will use these settings to adapt itself for communicating GPS data to the RSU. Once the OBU travels past the EoC location, it indicates this event in the information sent to the RSU and then stops communicating to the RSU. The RSU will use these data to find TT and SoC location and inform all OBU's in the range. The OBU unit upon receiving TT and SoC location will find the distance to the SoC location using its own location. OBU will then communicated to the driver both TT and distance to the SoC location through the user interface. In order to keep the system inexpensive, the possibility of using a mobile phone as a user interface was explored. In addition to the intended scenario of a congested work zone, this system is able to handle calculating the traffic parameters i.e., TT and SoC location in a scenario where a road is partially congested by an accident.

Each of the system components is described in detail in the sections below.

2.2 DSRC Road Side Unit

The DSRC RSU is a stationary device placed alongside the road such that its range on one side covers the end of the congestion (EoC) location. The RSU will try to select and establish a connection to communicate with vehicles with OBU's entering its range on the other side. The function of the RSU in a work zone traffic information system is to periodically broadcast safety messages containing TT and SoC location to all OBU's in range and to acquire current GPS location, speed and time data from chosen OBU's in order to update the travel information via DSRC communication.

Before starting the communication with OBU units, the RSU program needs to be adapted with input parameters (Table 2.1) for the road it's monitoring. Afterwards, the RSU initiates communication with any vehicles with OBU's coming into its range periodically. Once the communication is established and an OBU is selected for data acquisition, the RSU keeps storing the GPS location, speed and time data sent by the OBU. Then after the vehicle passes through the end of the congestion, and the end of the RSU monitoring range, it calculates TT and the start of congestion and updates the information in its DSRC broadcast which is received by all OBU's in range.

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 SoC location
Road Direction	Degrees	Angle relative to North, increasing clockwise direction. It is used for the Direction check in the OBU to eliminate vehicles going in other directions to the congestion on the same or other roads.
End of Congestion (EoC) Location	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 EoC location check in the OBU to disengage OBU from V2I communication with the RSU.
Start of the RSU Monitoring Range (SoMR) Location	Longitude, Latitude	This point is located well before the SoC location on the road where the RSU coverage range just begins. It is used to engage the vehicles with OBU to participate in V2I communication to estimate TT and SoC location.
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 that is broadcast along with TT and SoC location by the RSU for drivers to know whether a message pertains to them.

2.3 DSRC On Board Unit

The DSRC OBU is a mobile unit powered by the vehicle’s battery system. The OBU utilizes an omni-directional antenna in order to optimize wireless DSRC communications in a dynamic environment. The OBU should ideally be placed centrally on the roof of the vehicle to have a clear LoS with the RSU. The OBU program does not change regardless of location as it adapts its setting according to the RSU input. Once started the program activates the GPS link and monitors for the RSU request for communication. Once the request is received and then communication established, it sends messages containing current GPS location, speed and time to the RSU, until it moves out of the RSU range. In receiving the RSU broadcasts with traffic information it processes the message and passes the message via hard wire to the user interface for driver’s attention only if intended for driver’s attention and contains new information.

2.4 User Interface

2.4.1 Overview

The User Interface is in fact composed of two components, the Communication Interface Device (CID) and the mobile phone. The OBU passes the safety messages to the CID so that it can in turn send that message to the mobile phone where the driver can be informed of road conditions. The CID and Mobile phone component of the user interface are explained in the following sections.

2.4.2 Communication Interface Device (CID)

The purpose of the CID is to receive the RSU safety messages intended for the driver from the OBU and pass the received messages to the mobile phone wirelessly via Bluetooth link. Safety messages between the OBU and the CID are sent over a serial port connection. The CID monitors for the paired Bluetooth cell phone once the initial pairing has been made and automatically establishes the connection when in range. It is expected in the event of mass production that the CID and OBU may be combined so that there is only one device in the vehicle.

The CID as implemented in this project consists of two parts, a microcontroller and a Bluetooth radio. The microcontroller program handles two serial connections, the connection from OBU to the microcontroller and the connection from microcontroller to the Bluetooth radio. The Bluetooth radio module does not need to have any program written for it as the microcontroller is able to access the functionality of the Bluetooth radio through the serial connection, to setup connections and send the safety messages through to the mobile phone.

2.4.3 Mobile Phone

Bluetooth-enabled mobile phones were chosen as the user interface for presenting safety messages to the driver as the focus of this project was to make the most use out of accepted existing technology in order to keep the cost low. 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. 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 CID. 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. In the current phase, this system is used to convey the safety information parameters to the driver. 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.

Chapter 3. System Design and Implementation

3.1 System Design Overview

In this chapter the hardware and software implementation used in the system are explained along with the algorithms, equations and the tests done to ensure proper working. In the first section the GPS technology as it is incorporated to the system is explained along with the tests done to show the viability of using GPS technology. The equations used to calculate the distance and direction of travel using GPS coordinates are also presented in this section. In the following sections the implementation of the hardware and software of the system components presented in the previous chapter are described in detail.

3.2 Usage of GPS Technology

3.2.1 Overview of GPS Technology

During the project setup 3 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 5 m. 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 TT and SoC location. 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.

3.2.2 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 3.1 (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 location accuracy will be lower. 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 3.1 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 3.1 b, x axis representing the calculated location error and the two y axis representing the frequency and the cumulative percentage. From Figure 3.1(b) it can be seen that in most cases the error is less than 2 m. It can be said with 93% confidence the error is less than 3 m and 98% confidence that the error is less than 4 m.

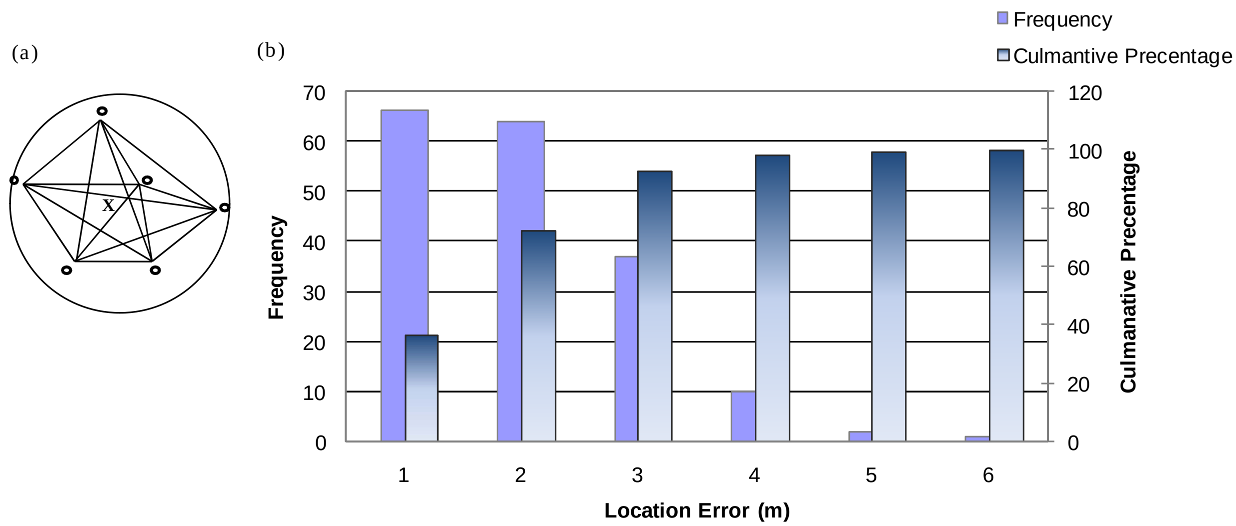


Figure 3.1 (a) The Location Accuracy Concept Diagram. The Points Are Measured GPS Readings of the Same Physical Location. (b) The Location Inaccuracy Distribution.

3.2.3 Relative Distance Accuracy

The relative distance inaccuracy stems from the location inaccuracy as shown earlier in Figure 3.1 a. When calculating the distance between two points X and Y, the calculated distance may be smaller or greater than the true distance because of the location inaccuracy as shown in Figure 3.2. 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 3.2. 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.

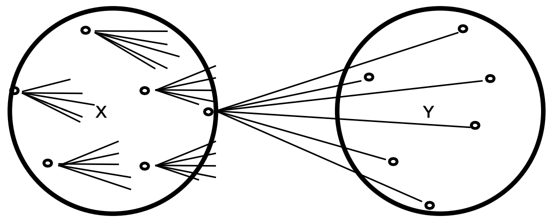


Figure 3.2 The Relative Distance Accuracy Concept Diagram. Distance between the Two Points, X and Y Could Be between Any Measured Point on X to Any Measured Point on Y.

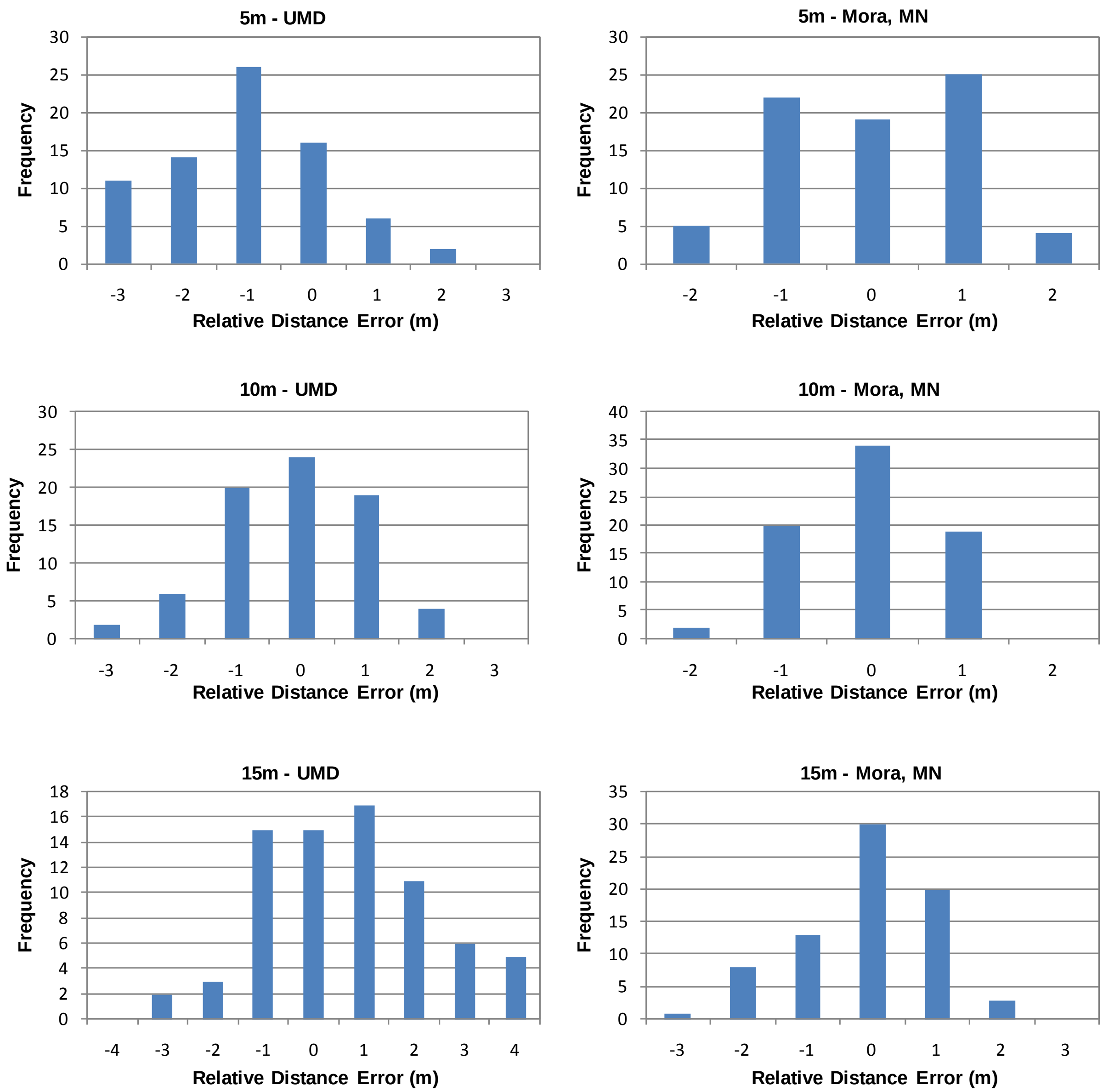


Figure 3.3 The Relative Distance Inaccuracy Distribution for 5, 10 and 15 m for Urban Environment (UMD) on Left Column, and for Rural Environment (Mora) on Right Column.

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 3.3 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 [26]. 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

$$\text{distance} = R * c \qquad (1.1)$$

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

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

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

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

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

$$\Delta lat = lat2 - lat1, \Delta long = long2 - long1 \qquad (1.4)$$

3.2.4 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 3.4 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 3.4 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.

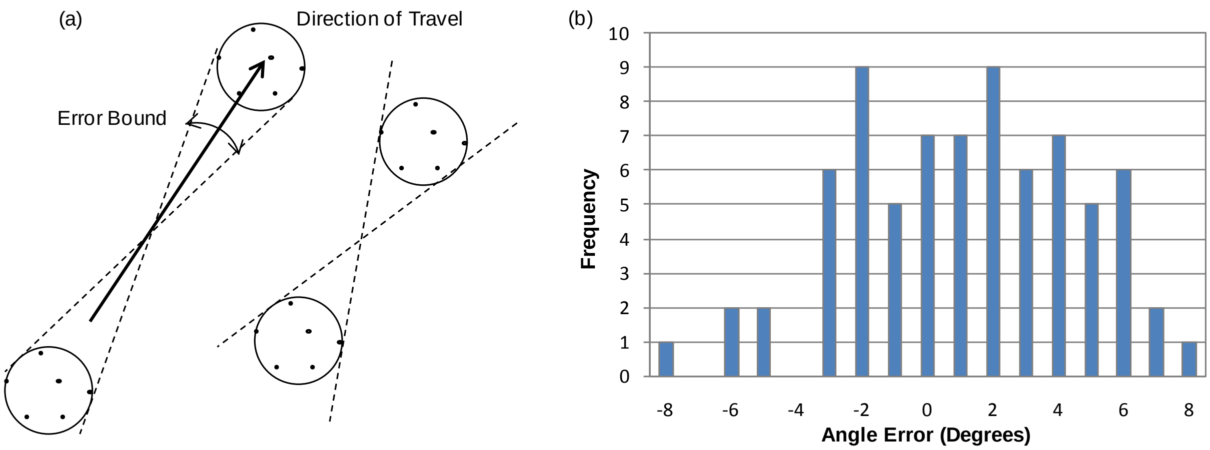


Figure 3.4 a) The Direction Accuracy Concept Diagram. Please Note That the Angle Inaccuracy Could Be More If the Two Points Are Close to Each Other. b) The Direction (Angle) Inaccuracy Distribution for Points 10 m Apart.

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 [26].

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

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

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

Where the angle Θ is found by equation 2.3

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

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.

3.3 DSRC Units

3.3.1 System Setup

Manufacturers of DSRC equipment offer both OBU and RSU units with DSRC capability enabling communication from the vehicle to the roadside (V2I) or from one vehicle to another (V2V). In this project when purchasing the DSRC units from Savari Networks a decision was made to use an OBU type unit in place of the RSU type unit to enhance the portability and versatility of testing the system. By having two OBU units V2I scenarios could be tested by assigning one of the OBU units as an RSU unit while V2V scenarios could be tested by placing the 2nd OBU in another vehicle. This was achieved without compromising any DSRC functionality as both RSU and OBU DSRC units offer the same functionality with differences solely being unit enclosure and antenna design. The RSU unit is enclosed in a sturdy NEMA 67 weather-proof enclosure as its designed to be a fixed, wireless gateway, while the OBU unit occupies a much smaller footprint and is intended to be placed in a protected environment (inside a vehicle). Likewise, the RSU unit is built with a directional antenna to increase the transmission signal range, while the OBU unit is built with an omni-directional antenna. The DSRC units used in this project provide a variety of peripheral support, such as USB, serial, and Ethernet port connection. In this project the OBU uses the USB port for the GPS receiver, the serial port for sending safety messages to the CID and the Ethernet port for program to be started from a computer. The RSU uses the serial port when simulating the Mn/DOT infrastructure messages to RSU and Ethernet port is used in connecting to the RSU to start the programs. In addition to DSRC communication ability used in this project the DSRC units also have Wi-Fi capability. In order to portray the inherent conditions of traffic safety messaging in a DSRC environment (low latency, clarity, cohesiveness), messages have a maximum of 100 characters and are composed of ASCII text, ending with a carriage return.

Once the RSU is initialized and running, it is placed such that its range is just beyond the EoC location on one end of the road and well before the SoC location on the opposite direction of the road as shown in Figure 3.5. Any point in the RSU coverage before the SoC location becomes a desired location from which point incoming vehicles having OBU and traveling towards congestion, could be engaged in V2I communication.

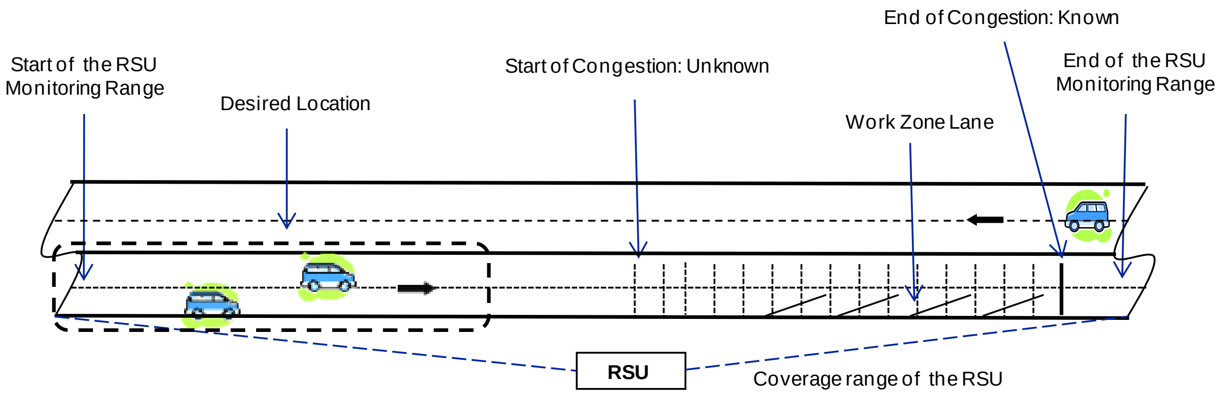


Figure 3.5 Schematic Diagram Showing RSU Placement across a Work Zone and Desired Location to Start Engaging the Vehicles on the Road for V2I Communication.

The V2I communication between the RSU and the OBUs is performed by exchanging short messages of general format as follows:

Header + *Operation* + *Data* + *Footer*

Where the purpose of the *Header* is to distinguish that the message is for a specific application and the purpose of the *Footer* is to ensure that the end of message has been reached in order to avoid data processing omissions. The *Operation* and *Data* fields are the distinctive features of each message with *Operation* being an identifier to determine the source, destination and processing of the associated *Data*.

There are five different types of Operations used in this system. Three of the five Operations, INVITE, CHOSEN and BROADCAST, are originated from the RSU and intended for the OBU while the remaining two Operations, ACCEPT and NOTIFY originated from the OBU and are intended for the RSU. The *Operation* portion of each message determines the associated *Data* format. The RSU initiates a communication exchange by sending INVITE message which request OBU participation. Each OBU receiving the INVITE message screens itself using the information contained in the *Data* of the INVITE message and if passes the screening, it will respond with the ACCEPT message. The RSU will screen the incoming ACCEPT messages to ensure that the OBU is on the monitored road and send the originating OBU of the first ACCEPT message to pass a CHOSEN message containing communication parameters to be used by OBU. OBU will then periodically communicate NOTIFY messages using the received parameters until it detects the EoC location point approaching at which point it will indicate to the RSU about this and will cease to send further NOTIFY messages. This RSU-OBU communication session is shown on left side of Figure 3.6. Even if the RSU is not in a communication session, it will be informing all the OBU's in its range of the traffic safety parameters at all times using the BROADCAST messages. In the case of the RSU starting a communication with OBU, the BROADCAST messages will continue to be sent in parallel as shown on the right hand side of Figure 3.6.

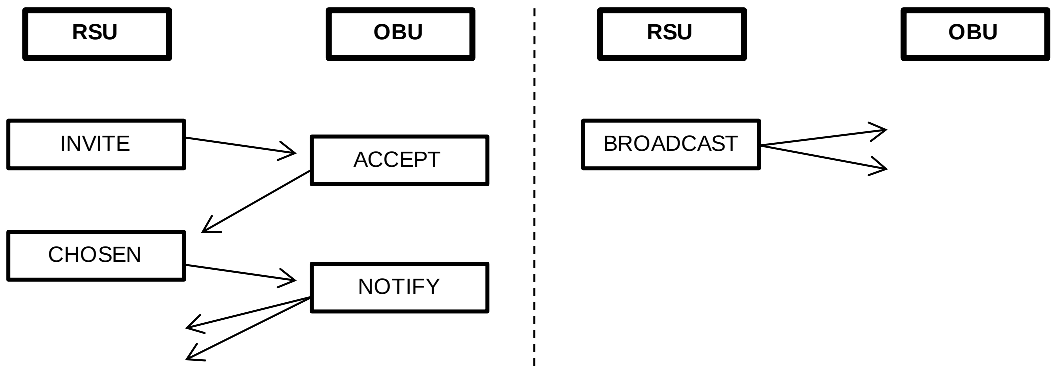


Figure 3.6 Message Flow between the RSU and the OBU. Left Side is for the Traffic Data Acquisition and the Right Side is for the Traffic Parameters Broadcasting.

3.3.2 Application Description

The program development for DSRC units was done in Fedora 8 Linux environment. The DSRC units implemented in this prototype system utilize 500 MHz AMD processors with 256 MB DDR DRAM, and 512 MB Compact Flash. The operating system is built upon an embedded Linux platform BusyBox. Once the RSU program and the OBU program were compiled on Linux environment, they are installed on the respective DSRC units using an UDP Ethernet network connection. The application can be started by configuring to start on DSRC unit power up, or by manually starting the application through a remote connection using another Linux machine. The flowcharts depicting the program flow of the DSRC RSU and OBU programs once powered up is given in the Appendix A and Appendix B respectively. The V2I DSRC Communication flow is explained in detail below.

After the RSU is initialized by giving the road parameters needed to adjust to the monitoring road, it transmits a message containing INVITE operation to all vehicles within its coverage range every one second. Upon receiving the INVITE message, all the vehicles having an OBU will perform a direction and preliminary location check. The purpose of the direction and preliminary location is to see if a vehicle is traveling in the right direction and whether it is positioned at a desired location of the road i.e., before the congestion. In the event of passing both the direction and preliminary location checks, OBU will send an ACCEPT message to the RSU. Please note that there may be multiple messages as more than one OBUs can pass the direction and preliminary location checks, and respond with the ACCEPT message to the RSU. The RSU will select an INVITE message to process in the order it is received. In processing the message the RSU will then perform a fine location check to ensure that the vehicle is indeed on the desired location on the correct road and not on a nearby parallel road. After ensuring the correct location of the vehicle, the RSU will send the CHOSEN message to the OBU to initiate communication and then will continue to acquire the time, location and speed of the selected vehicle through periodic OBU NOTIFY communications until the OBU passes all the way through the congestion and out of the RSU range. The NOTIFY messages from OBU contain time of message origination, GPS location, speed and EoC indicator as its *Data*.

Please note that the selected vehicle will not transmit its own identity at any time but rather a randomly generated ID generated by the work zone DSRC application that will be existing only for the duration of the communication. This temporary ID is used to identify the vehicle so that traffic data can be distinguished in case there is more than one vehicle transmitting the traffic data to the RSU at the same time. After the RSU receives a NOTIFY message containing the positive EoC indicator, it will estimate the travel time by identifying the SoC location from the received traffic data. The estimated TT and the SoC location along with the road name and descriptive location will be packaged as *Data* of the BROADCAST message and is sent to all vehicles within the coverage range of the RSU. While the BROADCAST message is transmitted every one second, TT and SoC location data is updated only in the event of an OBU passing the EoC location and the End of the RSU Monitoring Range (EoMR). New OBU are acquired periodically. This periodicity is set by RSU and may be every TT or a fraction of TT. All the vehicles receiving the BROADCAST message will be able to estimate their distance to the SoC location because their own current location is known through the GPS receiver. Then TT, distance to SoC location, and the descriptive name of the road will be sent as a text message to a Bluetooth-enabled cell phone in the vehicle.

3.3.3 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.

3.3.4 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 3.7. 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.

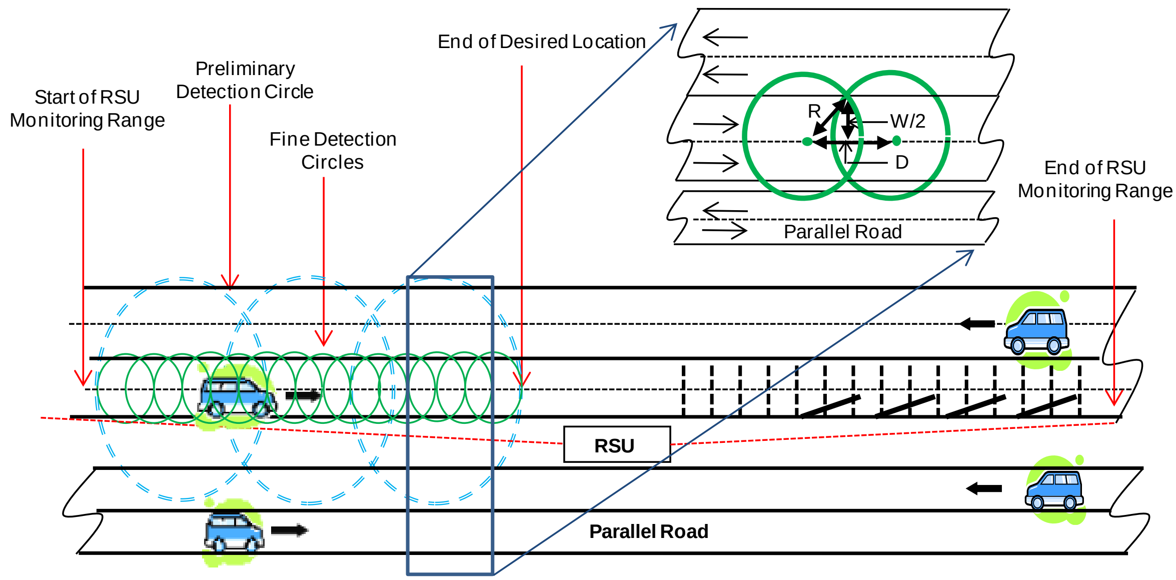


Figure 3.7 Detection Circles for Preliminary and Fine Location Checks in the DSRC OBU and RSU Respectively. The inset is zoomed version of two consecutive fine detection circles showing the radius (R), and their separation (D) with respect to one-sided road width (W).

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 3.7. The condition shown in the inset of Figure 3.7 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.

3.3.5 Travel Time and Start of Congestion Estimation

Once the fine location check is passed in the RSU, a CHOSEN message is sent to the selected OBU letting it know its selected for communication. Upon receiving CHOSEN message, the OBU periodically sends the NOTIFY messages containing time, speed, and location information to the RSU while it travels thought the congestion until it reaches the EoC location. To ensure that the OBU has crossed EoC location, an EoC location test is performed at the OBU. While this test was initially planned to be done in the RSU, it was decided to be implemented in the OBU to make the OBU standalone and self sufficient. The EoC location point and the proximity distance threshold for the EoC location test are sent to the OBU as *Data* of the CHOSEN message. When the EoC location test is passed in the OBU, it activates the EoC indicator in the *Data* of the NOTIFY message so that RSU knows that EoC location has been reached. Please note that the OBU once in communication with RSU will send NOTIFY messages along with EoC 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 as part of the *Data* in CHOSEN message. The CTI is usually a few seconds depending upon the travel time and congestion length. Therefore, more than one NOTIFY messages sent to the RSU will have the same *Data* in terms of time, location, speed and EoC indicator. The redundancy ensures that RSU gets more opportunity to receive data even if one or more OBU NOTIFY messages are lost due to a temporary blocked LoS. Upon receiving a NOTIFY message with a positive EoC indicator, the RSU will stop processing any more incoming NOTIFY messages from the OBU and will calculate and update SoC location and TT before preparing itself for communication with a newly selected OBU. The designed application is able to find the SoC location and TT in various congestion scenarios correctly. The three important scenarios considered are:

- TT between two fixed points.
- TT between a varying SoC location and fixed EoC location.
- TT between two congestion points where both SoC and EoC locations vary.

Although the developed application can handle all of the three scenarios described above, the second scenario is the most relevant for the work zone or accident related congestion. So the algorithm described below involves only this scenario. TT and start of SoC location is estimated through analyzing the data stored in RSU during one complete cycle of RSU-OBU handshake from SoMR to EoC location. The SoC location is defined as the location where the speed falls below 50% of the normal rated speed of the road. If the vehicle speed does not fall below 50% limit, the threshold is progressively redefined as 60%, 70%, 80%, 90%, and 100% of the rated speed. TT is the time to travel from the SoC location to the EoC location point. Once TT and SoC location are determined, the BROADCAST message is updated with new TT and SoC location. Please note that BROADCAST message is sent every one second to all the OBUs as described earlier. However, TT and SoC location are only updated when a CHOSEN vehicle reaches the EoC location point. Normally, only one vehicle is chosen and monitored at one time. However, at some hour of the day, if TT turns out to be greater than a predefined Travel Time Threshold (TTTh), then more vehicles are selected at one time to update TT and SoC location more frequency. Currently, TTTh is set to 10 minutes and if TT is larger than 10 minutes, another vehicle is selected every half of TT. This is performed by opening multiple channels of communication in RSU to establish V2I communication with more than one OBU at the same time.

Please note that both programs in the RSU and the OBU have a reset time associated with them. This reset time is triggered by not receiving any messages for a predefined time period, and, in the RSU's case also by exceeding a predefined counter of NOTIFY messages. This ensures that the programs are able to function correctly despite 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.

3.4 User Interface

3.4.1 Communication Interface Device (CID)

The responsibility of the CID is to transfer the received messages from OBU to the mobile phone. The message are received via a RS232 serial communication and sent to the mobile phone over a Bluetooth radio link.

The CID is composed of two major hardware components (Figure 3.8):

1. Microcontroller
2. Bluetooth Radio Module

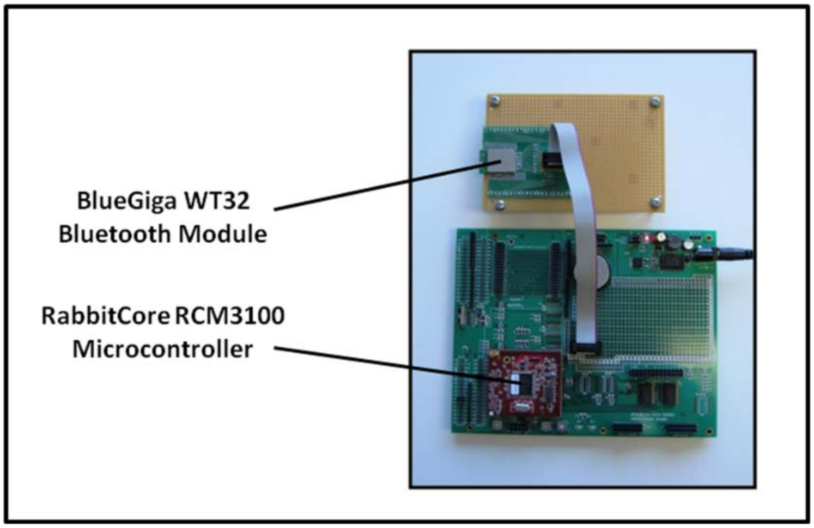


Figure 3.8 CID Components [27].

The microcontroller receives the incoming DSRC traffic safety messages through 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 RS232 serial connection. As characters are received by the Bluetooth radio module, they are sent to the cell phone.

The Microcontroller used in the project is the RabbitCore RCM3100 with the Rabbit 3000 microprocessor running at 29.4 MHz, 512 KB of static RAM, and 512 KB of flash memory. It was chosen for its powerful processing power, extensive RAM and flash memory, and multiple serial communication capabilities. The BlueGiga WT32 Bluetooth Module is chosen as it is Bluetooth 2.0 compliant and Bluetooth 2.1 ready, and is a certified Bluetooth End Product, so further FCC certification is not required by OEM's. It is a Class 2 Bluetooth device built with an integrated antenna featuring BlueGiga's 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

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.

3.4.2 Mobile Phone

There is need for a user interface to present the safety messages for the driver in non intrusive way. Mobile phone is chosen as it equipment most drivers would have. The program written for the mobile phone is able to receive the safety messages through the Bluetooth connection and display them as a text message. The phone would be placed in a cradle where the driver would be able to see the messages without taking his eyes off the road.

This program is developed separately for two popular mobile phone platforms, Java and Windows Mobile, and tested in Nokia 6085 and HTC S310 phones respectively (Figure 3.9).

Figure 3.9 Mobile Phones Used for Testing [27].

The program for the Java platform is developed in Netbeans Integrated Development Environment (IDE) with the “Netbeans Mobility Pack”, an add-on required for mobile application development allowing the use of Java ME programming language which is the compact version of java used in mobile phones. It also supports Mobile Information Device Profile (MIDP) Java specification which, combined with the Connected Limited Device Configuration (CDLC) Java specification, is the Java runtime environment used in mobile devices. The mobile phone needs to support the Java Application Programming Interface (API) JSR-82, the set of Java functionality which controls the Bluetooth functionality in a Bluetooth-enabled devices. The resulting executable .jar file from compiling is transferred to the cell phone. For the application to start automatically in response to an incoming Bluetooth connection identifying itself by a known Universally Unique Identifier (UUID), it needs to use Push Registry functionality. To make the UUID known to the system, user must manually run the application one time. Then once the cell phone is paired with the CID using the phone’s Bluetooth connection, the application will automatically start when in range of the CID.

The application program for Windows Mobile is developed in C++ using Microsoft Visual Studio program. In order for having mobile environment support, Windows Embedded CE 6.0 add-on is required. The program is compiled in Visual Studio, resulting in an exe file which is transferred to the cell phone. Whenever the phone powers up the program is placed in the startup menu. The application runs in the background making all of the phone’s functionality available for the user. When the CID sends a safety message, the application shows the safety message in a window which will be updated for new safety messages. The driver can send the message window to the background until the next safety message arrives.

Chapter 4. Field Demonstration – Results and Discussion

4.1 Description

For the field demonstration, two DSRC OBU units from Savari Networks were used, one acting as an RSU unit. The OBU unit was equipped with a GPS unit connected through the USB port. Also, the OBU was connected with the previously developed CID for relaying the BROADCAST message to the Bluetooth-enabled cell phone in the vehicle. The programs in the two units were field tested from time to time on various roads. However, the final demonstration was done on the Rice Lake Road, Duluth, MN as shown in Figure 4. This particular road was chosen because it had no changes in elevation, giving a clear LoS from RSU to OBU throughout the coverage range. It was found during the preliminary testing that the elevation of the road could hide the RSU from the OBU LoS completely at certain points leading to loss of messages. Please note that the RSU was placed on the top of a parked vehicle in this field demonstration. In actual practice, RSU should be installed at an elevation, sufficiently high to overcome the variation in elevation of the road, providing a clear LoS between the RSU and the OBU throughout the coverage range. The actual coverage range of the RSU, EoC location and EoMR used in field demonstration are shown in Figure 4.1. The RSU device covered a range of about 1 km (0.75 km on left and 0.25 km on right). The coverage range of the RSU was asymmetric because this coverage range is intended for the OBU which was placed on the dashboard of the vehicle traveling from left to right with the GPS receiver attached to the roof of the vehicle. When the vehicle was traveling towards the RSU (placed on the top of a parked vehicle), the wind screen provided a clear LoS. However, when the vehicle was going away from the RSU, the back side of the traveling vehicle blocked the LoS reducing the coverage range.

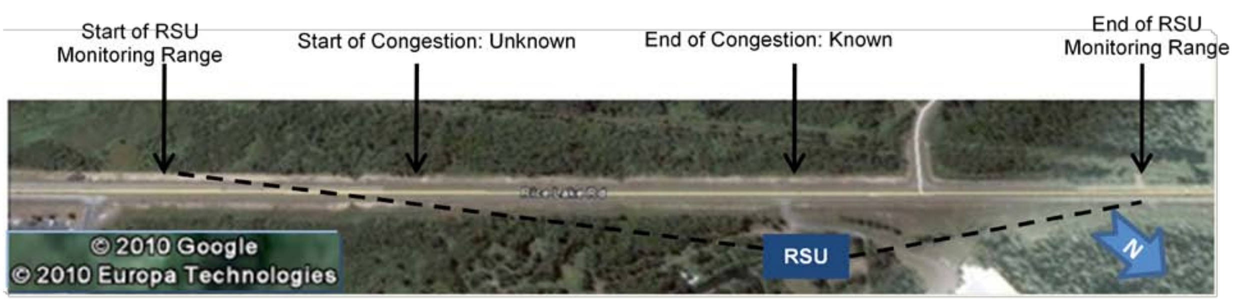


Figure 4.1 The Field Demonstration Site Showing Placement of RSU, Its Coverage Range, EoC location and Varying SoC Locations.

For the demonstration purpose, the RSU was powered up and the program was initialized with the input parameters for the Rice Lake Road traveling towards a certain direction. In this part of the demo, only one OBU was used traveling through the congestion and communicating with RSU. The vehicle containing OBU was driven at 40 MPH (17.88 m/s) from left to right many times reducing speed at varying SoC locations on the road and ramping up again to 40 MPH at the EoC location point. In the meanwhile, RSU established communication and captured the traffic data, current speed, GPS location and time from the OBU in frequent intervals and once it passed the EoC location point, estimated TT and the SoC location. The estimated TT and SoC location data was broadcast to all the OBU's in range every second by the RSU. After calculating TT and SoC location the RSU again monitors the road for potential OBU to engage in communication. During the demonstration, various RSU parameters were changed to test the control of the RSU on V2I DSRC communication. The parameters changed in the RSU were the nominal speed limit of the road and CTI. The ability to change CTI is desired when distances are large so that you can update less frequently to reduce the message traffic and get the same performance. The nominal speed limit is desired for correctly determining threshold where congestion occurs because otherwise the speed the vehicles are traveling through is capped by this parameter. Lastly a scenario was constructed where the speed was not reduced throughout the RSU monitoring range to find TT which would help to see TT found from other scenarios in perspective. The demonstration worked smoothly without needing to change any parameters in the OBU program in each case. The OBU program adapted to the changing parameters dictated by RSU during multiple runs of the field demonstration, and worked seamlessly to facilitate TT and SoC location estimate.

4.2 Results and Discussion

In the first step of field demonstration, a fixed landmark for the SoC location was chosen and the speed of the traveling vehicle containing the OBU was always reduced at that landmark for many runs. While the speed was reduced, the vehicle was driven on the shoulder of the road to give way to the regular traffic. With the fixed landmark for SoC location, the congestion length was a little short of 500 m. The estimated TT was between 100 and 200 seconds for various runs of demonstration. The variation in TT was caused by the speed control by the driver during the simulated congestion and also sometimes, there was traffic running at nominal speed limit on the road so merging from shoulder to the actual road and ramping up at EoC location was delayed in waiting a clear spot on the road.

A typical set of data containing the speed of the traveling vehicle, captured by RSU to estimate TT and SoC location is shown in Figure 5. The RSU captured this data while the selected OBU was traveling through the congestion and once it moved out of the RSU range, it estimated the SoC location and TT. One of the important RSU parameters sent to adapt the OBU program, CTI was varied to capture the data again and again and was found that SoC location and TT was estimated correctly, each time. The BROADCAST message was sent every one second that contained SoC location, TT, and the descriptive name and direction of the road as its *Data*. Please note that the SoC location was broadcast in terms of longitude and latitude format and TT in seconds to all the vehicles in the coverage range of RSU. The descriptive name of the road was *Rice Lake Rd Towards Airport*. Once an OBU received the three parameters, it calculated the distance from its own position to the SoC location and then relayed three parameters to the Bluetooth-enabled phone in the vehicle as text message. The three parameters were TT, distance to the SoC location, and the descriptive name of the road. The distance to the SoC location is an important safety parameter that allows the driver to slow down when the congestion is approaching. This message could also be intercepted by vehicles traveling on other roads. However it is assumed that the driver receiving the message would be able to distinguish the applicable messages using the descriptive name of the road.

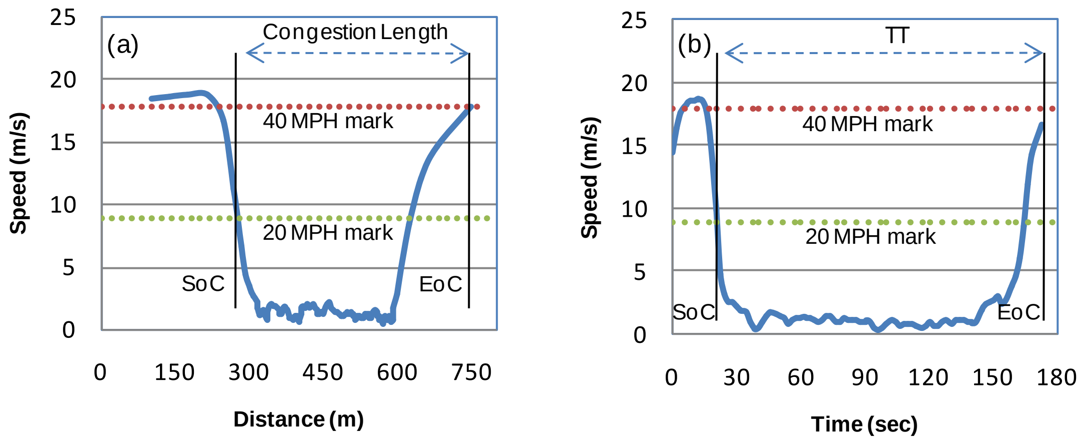


Figure 4.2 (a) The Speed of the Vehicle Traveling Through the Congestion vs. Relative Distance. (b) The Same Speed is shown vs. Time.

During the field demonstration, the RSU communication parameter CTI was kept fixed with a CTI of 2 seconds and the nominal speed limit of the road was taken as 40 MPH. The vehicle with OBU was driven through the congestion many times simulating growing congestion with time. The RSU kept on capturing the data successfully and estimated TT and SoC location correctly and updated the values of the BROADCAST message correctly each time. The three typical data sets for three different positions of SoC location are shown in Figure 4.2a. In Fig. 4.2a, the congestion length was varied from smaller to longer with increasing TT. TT associated with the three sets of curves was 78, 150, and 250 seconds, respectively, from shorter to the longest congestion length. Similarly, another set of scenario was tested for the same CTI by varying not only the SoC location but also the congestion depth by using a different speed to travel over the congested area. Please note that the congestion depth is defined as the relative speed reduction as compared to nominal speed limit. The different set of data captured by RSU is shown in Figure 4.2b. TT associated with three curves was, respectively, 22, 70, and 150 seconds from smallest to longest congestion depth. Each time, the SoC location and TT was estimated correctly and the BROADCAST message was received successfully.

Communication parameters which are conveyed to the OBU via the RSU to are the nominal speed limit of the road and the CTI. In the field demonstration, two speeds of, 40 MPH and 50 MPH were tested with three different values of CTI 1, 2, and 3 sec for multiple congestion scenarios described above. The tests results were successful each time in terms of acquiring data and estimating TT and SoC location.

Upon receiving the nominal value from the RSU the OBU program is seen to adjust its thresholds, redefining the cut off mark for congestion start. Also in the case of detecting the start of congestion speed where it did not fall below the 50% mark, the threshold is seen to be progressively redefined to 60%, 70%, 80%, 90% and 100%. Finally we conducted a run where the vehicle speed was not reduced at all, and found TT under optimal conditions where no congestion takes place.

By changing the RSU parameters CTI and nominal speed limit the adaptability of the OBU program was proven showing the portability of the system. By using a randomly generated ID for communication it is ensured that the RSU cannot uniquely identify the OBU, easing privacy concerns through program transparency. Congestion scenarios of varying SoC location and TT simulated by using scenarios of fixed SoC and EoC locations, varying SoC and fixed EoC locations and varying SoC and EoC locations were found to be accurately portrayed and calculated (Figure 4.3). Congestion depth is varied by changing the reduction in the vehicle speed through the congestion.

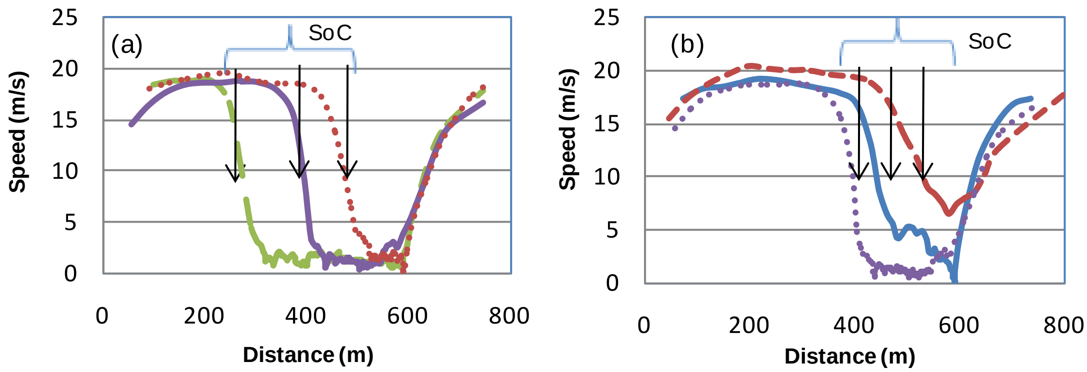


Figure 4.3 The Speed of the Vehicle Traveling Through the Congestion vs. Relative Distance for (a) Varying SoC Location and Similar Congestion Depth, and (b) for Both Varying SoC Location and Congestion Depth.

The field demonstration was a success in accurately estimating various congestion scenarios and periodically broadcasting messages containing travel information from the RSU and receiving the same in messages in the OBU to be sent to the user interface. However while the field demonstration was successful, the congestion length, and broadcast range handled by this V2I DSRC communication system was less than 1 km. This kind of system can be best utilized if the message broadcast range can be increased so that drivers of the vehicles have options to make some alternative decisions about their travel route based upon the prior information of TT and SoC location. If the vehicle is only within 1 km (half a mile) of the work zone when it receives the SoC location and TT information, this may give the traveler some awareness but may not help make an alternative route decisions. Providing alternate route choices in time to make the decisions to bypass the work zone is necessary for increased safety and managing rapid growth of traffic congestion on an already problematic roadway resulting from work zone or accident related congestion. Similarly, the practical lengths of congested US roadways initiated by work zone or accident could be much longer than 1 km. Therefore, it is necessary to come up with a scaling method which could increase both the congestion coverage length and message broadcast range in currently developed system. The other important limitation discovered is the LoS which plays a part in drastically reducing the RSU's range. In order to get the full benefit of the RSU's range the setup of the DSRC units needs to be improved to get a better LoS.

Chapter 5. Conclusions and Recommendations

5.1 Conclusions

A portable safety information system using DSRC-based V2I communication was developed for the work zone environment. This system can be installed on any US roadway having congestion caused by work zone or an accident. This system can accurately estimate the travel time and start of the congestion location, in real time, as these parameters change with varying traffic influx of the road. The estimated SoC location and TT are broadcast to all the vehicles approaching to the congestion area. The SoC location is converted to the distance to the SoC location for a given vehicle by OBU before it is communicated to the driver. TT and the distance to SoC location can help the drivers to be prepared for slow down and/or make an informed decision about rerouting their vehicles.

This system was extensively tested in a field demonstration using actual DSRC units in multiple congestion scenarios where the congestion speed and start of congestion was varied in addition to the communication parameters, nominal speed limit and CTI. By changing the communication parameters nominal speed limit and CTI, portability of the system is demonstrated. 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 system capable of using DSRC communication to inform driver's important traffic safety parameters to increase the traffic safety and efficiency has been shown to be working.

During the field demonstration, it has been seen that the LoS between the RSU and the OBU need to be preserved for better reception of the transmitted messages. The effect caused by loss of LoS is replicated in the case of the vehicle carrying OBU on its dashboard passing by the RSU, in which case the transmission becomes blocked by the back of the OBU vehicle. Please note that in V2V based system to be planned in next phase of research, this problem will not pose hurdle because of message is being originated from many sources some of them in close proximity of the destination DSRC unit.

5.2 Recommendations for Future Work

The user interface for the driver can be improved by addition of pictures, symbols and maps which can be incorporated to the system to give more information. However the ideal goal would be to incorporate a text to voice system replacing the text display. This would allow the driver to keep his/her attention on the roadway, rather than reading safety messages from a mobile device screen.

To improve the LoS between the RSU and the OBU, a valid suggestion would be to elevate the RSU positioning. Another possible course of action is to situate the OBU antenna on the roof of the vehicle. Both of these actions will lead to better LoS which in turn will lead to an increased range and more clear messages.

In order to increase the monitoring range of the work zone, extending the RSU range can be accomplished by changing the antenna in DSRC unit into a bi-directional antenna. However to achieve a significant increase in RSU monitoring range the solution would be multiple RSUs periodically placed across the road. This can help increase both congestion coverage and message broadcast range using V2I communication. The problem with this approach is V2I communication could be potentially more costly and require higher maintenance and management. A preferred solution could be to take advantage of the onboard DSRC units of the vehicles, utilizing V2V communication for increased congestion coverage length and message broadcast range. By doing so, the system will remain portable with the requirement of only one roadside DSRC unit at the congestion area which engages all the vehicles carrying onboard DSRC units to participate in the traffic data acquisition and to transmit traffic safety information back to the drivers. We are in the process of developing such a system which can handle much longer congestion lengths (up to a few kilometers) and much larger safety message broadcast range (up to a few tens of kilometers) using V2V DSRC communication. The resulting V2V system would have the same functionality for a much greater range for a fraction of the cost of installing multiple RSU's to increase the range.

References

[1] U.S. Department of Transportation (Internet), *IntelliDrive*, 2010, (accessed August 2010), http://www.its.dot.gov/intellidrive/index.htm.

[2] U.S. Department of Transportation (Internet), *ITS Overview*, 2010, (accessed August 2010), http://www.its.dot.gov/its_overview.htm.

[3] U.S. Department of Transportation (Internet), *ITS Strategic Research Plan 2010-2014*, 2010, (accessed August 2010), http://www.its.dot.gov/strat_plan/index.htm.

[4] U.S. Department of Transportation (Internet), *DSRC Frequently Asked Questions*, 2010, (accessed August 2010), http://www.intellidriveusa.org/about/dsrc-faqs.php.

[5] L. Armstrong, *Dedicated Short-range Communication (DSRC) at 5.9 GHz* (Internet), 2010, (accessed August 2010), http://www.itsmassachusetts.org/pdfs/04mtg/GHz.pdf.

[6] U.S. Department of Transportation (Internet), *Benefit of Using Intelligent Transportation Systems in Work Zones – A Summary Report*, 2008, (accessed September 2010), http://www.ops.fhwa.dot.gov/wz/its/wz_its_benefits_summ/wz_its_benefits_summ.pdf.

[7] U.S. Department of Transportation (Internet), *Intelligent Transportation Systems in Work Zones – A Case Study- Work-Zone Traffic and Incident Management System*, 2004, (accessed September 2010), http://www.ops.fhwa.dot.gov/wz/technologies/albuquerque/its_albuquerque.pdf.

[8] U.S. Department of Transportation (Internet), *Intelligent Transportation Systems in Work Zones – A Cross-Cutting Study*, 2002, (accessed September 2010), http://www.ops.fhwa.dot.gov/wz/docs/ITSWorkzones.pdf.

[9] U.S. Department of Transportation (Internet), *Intelligent Transportation Systems in Work Zones – A Case Study- Work-Zone Travel Time System*, 2004, (accessed September 2010), http://www.ops.fhwa.dot.gov/wz/technologies/arizona/arizona.pdf.

[10] U.S. Department of Transportation (Internet), *Intelligent Transportation Systems in Work Zones – A Case Study—Dynamic Lane Merge System*, 2004, (accessed September 2010), http://www.ops.fhwa.dot.gov/wz/technologies/michigan/michigan.pdf.

[11] U.S. Department of Transportation (Internet), *Evaluation of Work-Zone Advisory System*, 2010, (accessed September 2010), http://www.itsdocs.fhwa.dot.gov/JPODOCS/REPTS_TE/14057.htm.

[12] U.S. Department of Transportation (Internet), *Intelligent Transportation Systems in Work Zones – A Case Study—Real-time Work-Zone Traffic Control System*, 2004, (accessed September 2010), http://www.ops.fhwa.dot.gov/wz/technologies/springfield/springfield.pdf.

[13] D. Jiang, V. Taliwal, A. Meier, W. Holfelder, and R. Herrtwich, "Design of 5.9 GHz DSRC-based Vehicular Safety Communication," *IEEE Wireless Communications Magazine*, Oct. 2006, Vol. 13, No. 5.

[14] Q. Xu, T. Mak, J. Ko, and R. Sengupta, "Vehicle-to Vehicle Safety Messaging in DSRC," *Proc. 1st ACM Workshop on Vehicular Ad Hoc Networks (VANET)*, Philadelphia, PA, Oct. 2004.

[15] Y. Qian, K. Lu, and N. Moayeri, "A Secure VANET Mac Protocol for DSRC Applications," *Proc. IEEE Globecom 2008*, New Orleans, LA, Nov. 2008.

[16] F. Bai, and H. Krishnan, "Reliability Analysis of DSRC Wireless Communication for Vehicle Safety," *IEEE Intelligent Transportation Systems Conference*, Toronto, Ontario, Canada, 2006, pp. 355-362.

[17] C. Hsu, C. Liang, L. Ke, and F. Huang, "Verification of On-Line Vehicle Collision Avoidance Warning System Using DSRC," *World Academy of Science, Engineering and Technology*, July 2009, Issue 55.

[18] University of Illinois at Urbana-Champaign, and Microsoft Research (Internet), *Vehicle-to-Vehicle Communication Protocol for Cooperative Collision Warning*, (accessed August 2010), http://research.microsoft.com/en-us/um/people/zhao/pubs/yang_x_v2v.pdf.

[19] IEEE Engaging the World (Internet), *Intelligent Transportation Systems, Cell Phone Enhancements Improve Mass Transit*, 2009, (accessed August 2010), http://newsmanager.commpartners.com/ieeetw/issues/2009-02-23/1.html#top.

[20] J.A. Misener, and S.E. Shladover, "PATH Investigations in Vehicle-Roadside Cooperation and Safety: A Foundation for Safety and Vehicle-Infrastructure Integration Research," *IEEE Intelligent Transportation Systems Conference 2006*, Toronto, Ontario, Canada, 2006, pp. 9-16.

[21] Battelle, Center for Human Performance and Safety (Internet), *Integrated Vehicle-Based Safety System – Arbitration of Heavy Truck Driver-Vehicle Interface (DVI) Warnings*, 2007, (accessed August 2010), http://deepblue.lib.umich.edu/bitstream/2027.42/58359/1/101061.pdf.

[22] Michigan Department of Transportation (Internet), *Michigan VII Update*, 2007, (accessed August 2010), http://www.umtri.umich.edu/content/MIVIIupdate1-1a.pdf.

[23] Michigan Department of Transportation Office of Research and National Best Practices (Internet), *Communication between Vehicles and Roadways is Next Step in Safety*, 2006, (accessed August 2010), http://www.michigan.gov/documents/mdot/2_2006_September_ORBP_Newsletter_240085_7.pdf.

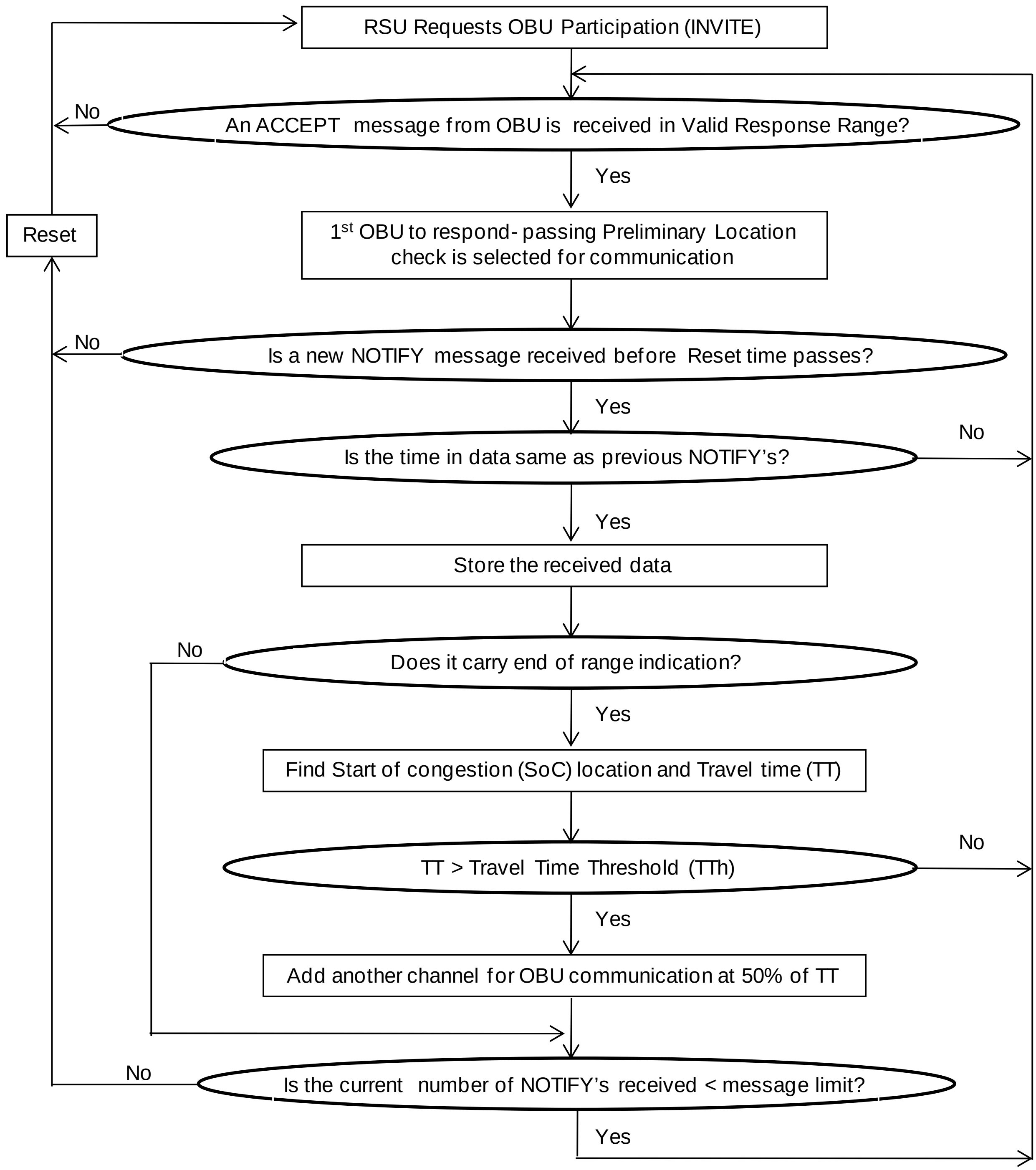
[24] Intelligent Vehicle Initiative Final Report (Internet), *Saving Lives through Advanced Vehicle Safety Technology*, 2005, (accessed August 2010), http://www.itsdocs.fhwa.dot.gov/JPODOCS/REPTS_PR/14153_files/ivi.pdf.

[25] U.S. Department of Transportation (Internet), *ITS Standards Advisory*, 2003, (accessed August 2010), http://www.standards.its.dot.gov/Documents/advisories/dsrc_advisory.htm.

[26] Movable Type Scripts (Internet), *Calculate Distance, Bearing and More between Latitude/Longitude Points*, (accessed August 2010), http://www.movable-type.co.uk/scripts/latlong.html.

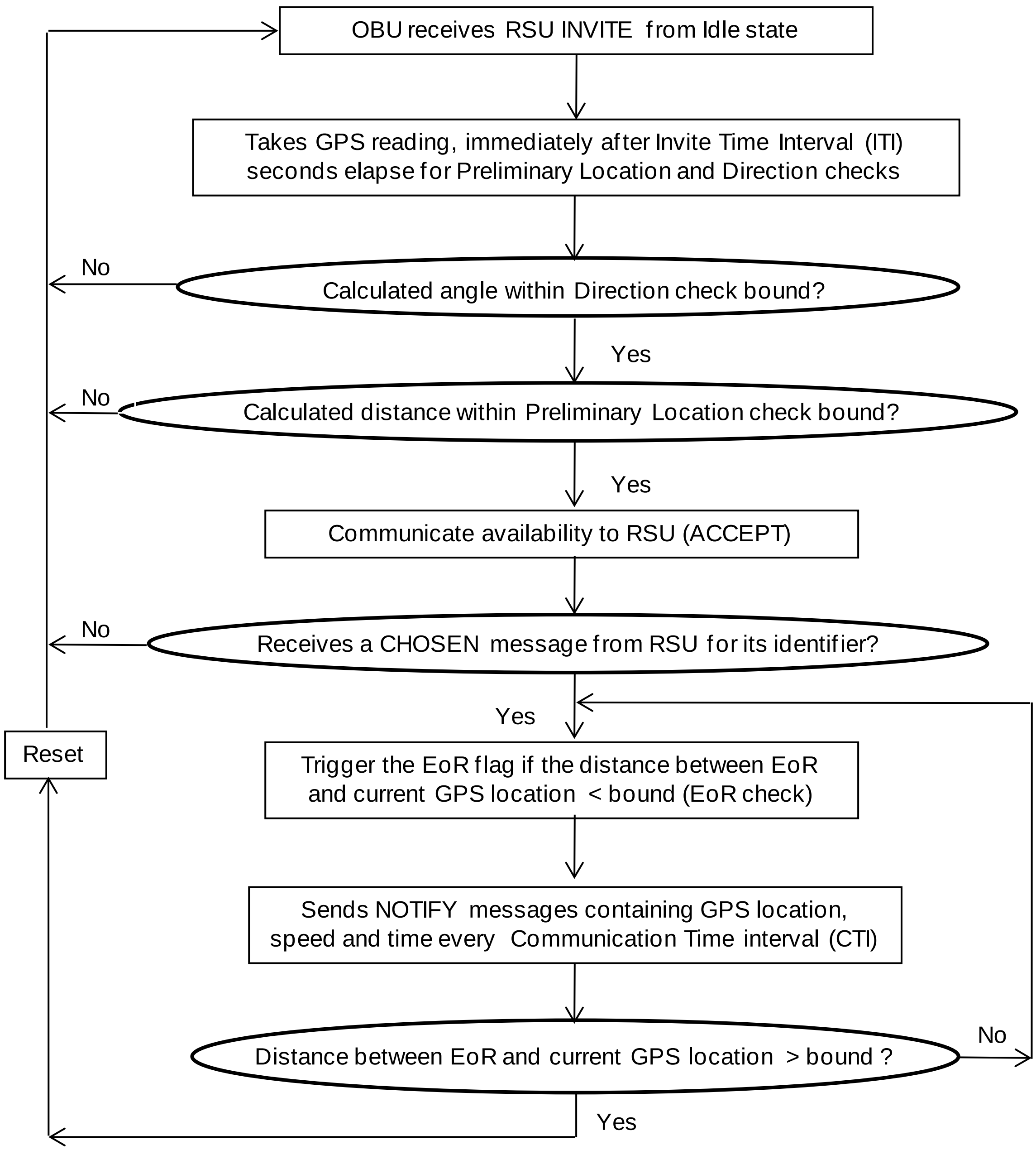
[27] B. Roodell, *Development of a Low-Cost Interface between Cell Phones and DSRC-Based Vehicle Unit for Efficient Use of VII Infrastructure*, 2009, Master's Thesis, University of Minnesota Duluth, Duluth, MN.

Appendix A: The RSU Program Flowchart



RSU Requests OBU Participation (INVITE)
No
An ACCEPT message from OBU is received in Valid Response Range?
Yes
Reset
1st OBU to respond- passing Preliminary Location check is selected for communication
No
Is a new NOTIFY message received before Reset time passes?
Yes
No
Is the time in data same as previous NOTIFY's?
Yes
Store the received data
No
Does it carry end of range indication?
Yes
Find Start of congestion (SoC) location and Travel time (TT)
No
TT > Travel Time Threshold (TTh)
Yes
Add another channel for OBU communication at 50% of TT
No
Is the current number of NOTIFY's received < message limit?
Yes

Appendix B: The OBU Program Flowchart


OBU receives RSU INVITE from Idle state
Takes GPS reading, immediately after Invite Time Interval (ITI) seconds elapse for Preliminary Location and Direction checks
No
Calculated angle within Direction check bound?
Yes
No
Calculated distance within Preliminary Location check bound?
Yes
Communicate availability to RSU (ACCEPT)
No
Receives a CHOSEN message from RSU for its identifier?
Yes
Reset
Trigger the EoR flag if the distance between EoR and current GPS location < bound (EoR check)
Sends NOTIFY messages containing GPS location, speed and time every Communication Time interval (CTI)
No
Distance between EoR and current GPS location > bound ?
Yes