# Development of a Traffic Information System using Ad-hoc Control and DSRC based V2V Communication

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# Dedication

I dedicate this scholarly work to Allah, the Lord of the heavens and the earth, and all that is in between them. He is the one who created me, and guides me; it is He who feeds me and gives me drink; and when I am ill, He cures me. Whenever I faced hardship, He eased for me my task, and untied the knot from my tongue so that people understood my speech. When I found myself incapable, I asked Him, and when I felt indolent, I turned to Him, the Giver of opportunity. When I couldn’t find my way out, He provided me from the places I did not expect. If whatever trees upon the earth were pens and the sea was ink, replenished thereafter by seven more seas, the words of Him would not be exhausted. Indeed, my prayer, my rites of sacrifice, my living and my dying are for Allah, Lord of the worlds.

# Abstract

A lane closure can significantly reduce the vehicles speed through the freeway bottleneck, resulting in the congestion buildup. As the queue length grows past the posted static warning signs in the congested zone surprising many drivers which can greatly increase the probability of rear end vehicle crash. In such circumstances, a real time traffic safety information system could help minimize rear end collisions. Current traffic information systems use radio, internet, or cellular communication to convey the information of congestion to the drivers. This information is generated using static sensor probes that often give a rough estimate of traffic parameters e.g., end-of-queue location, and travel time. Additionally, the update to the traffic data occurs quite infrequently and sometimes is obsolete by the time when a driver receives it. However, these systems suffer from issues such as latency and reliance on third party and/or dedicated infrastructure support.

This paper presents architecture, functionality, and field evaluation of a newly developed real-time traffic information system using DSRC based V2V communication without needing any roadside infrastructure support. The developed system utilizes an ad-hoc host vehicle acting as central control from among the DSRC equipped vehicles present on the road to dynamically acquire important traffic parameters such as starting and ending locations of congestion, and travel time. Furthermore, it provides useful traffic alerts to DSRC equipped vehicles to improve drivers' situational awareness.

The algorithm designed for the system makes it fully adaptable to any congestion scenario whether due to a work zone or an incident, or due to regular rush hour traffic.

The developed system is well suited for operational deployment in future, particularly during the initial phase of the DSRC market penetration, because it incorporates DSRC equipped programmable changeable message signs (PCMSs) to convey the warning messages to non-DSRC equipped vehicles. Furthermore, a rigorous analysis has been conducted to investigate the minimum DSRC market penetration rate needed for the developed system to successfully acquire and disseminate TT and SLoC for the work zone. The results of this analysis suggest that a market penetration rate ranging from 20% to 35% is needed for the system to reliably work.

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| | |
|---|---|
| ACM | A la Carte Message |
| AASHTO | American Association of State Highway and Transportation Officials. |
| BSM | Basic Safety Message |
| DSRC | Dedicated Short Range Communication |
| EoMR | End of Monitoring Range |
| EoQ | End of queue. |
| FCC | Federal Communications Commission |
| FHWA | Federal Highway Administration |
| GCC | GNU Compiler Collection |
| GPS | Global positioning system |
| ITS | Intelligent Transportation systems |
| LoS | Line of Sight. |
| OBU | On Board Unit – DSRC Radio |
| RSU | Road Side Unit – DSRC Radio |
| SAE | Society of Automotive Engineers |
| SLoC | Starting Location of Congestion |
| TT | Travel Time |
| USDOT | United States Department of Transportation |
| V2I | Vehicle to Infrastructure |
| VII | Vehicle Infrastructure Integration |
| V2V | Vehicle to Vehicle |
| PCMS | Programmable Changeable Message Sign |

# Chapter 1

# Introduction

## 1.1 Background and Prior Art:

Due to growing traffic demands and frequent lane closures, long traffic queues and delays are very common [1]. As result of lane closures due to work zone or traffic incidents, queues can build fairly quickly and often grow past the advanced static warning signs, especially during the rush hour traffic. In such situations, many drivers catch the back of the queue with a surprise increasing the probability of rear end collisions [2-4]. Some studies have found the rear-end collision to be the primary accident factor on freeway at the work zones and an important measure to counter such rear-end collisions is to provide advanced safety messages to the drivers of the vehicles that are approaching the back of the queue [5-6]. A number of research studies and field experiments have estimated that an advanced warning can help prevent rear-end collisions by 20-90% [7]. In addition to avoiding rear-end collisions, advanced warning messages can guide drivers approaching the end of the queue to take an alternative route, which in turn helps lower the congestion and thereby improve traffic mobility [8].

Many traffic information systems are being developed using a variety of wireless technologies e.g., cellular, Bluetooth, and radio frequency identification, to estimate traffic parameters and warn the drivers in a timely manner [9-18]. However, all these traffic information systems require special roadside infrastructure support as well as depend on a third party cellular infrastructure to acquire, process and disseminate traffic data. Furthermore, such systems gather traffic data only where infrastructure support is available and usually these traffic data updates are quite infrequent. Therefore, the traffic data gathered by such systems is mainly useful for traffic management and general advisory purposes at a macro scale. However, such sporadic and infrequent traffic data may not be useful at a micro scale to help drivers facing dynamically changing traffic situations, make informed decisions in real time.

## 1.2 Research Objectives and Methodology:

Dedicated short range communication (DSRC) technology has turned out to be a viable candidate to overcome the above mentioned limitations in monitoring the real time traffic situations and providing necessary warning messages to drivers in a timely manner, thereby enhancing roadside traffic safety and mobility [19-22]. The DSRC based traffic information systems could either use vehicle to infrastructure (V2I) and/or vehicle to vehicle (V2V) communication to estimate dynamic traffic parameters, and disseminate to the same to the drivers on the road, in real time [23-25]. Usually, DSRC based traffic information systems using V2V communication, are preferred over those using V2I communication due to infrastructure deployment cost in addition to other benefits such as short message delivery, and low latency [26-27]. Therefore, the recent research trends in DSRC technology are especially geared towards improving the road safety and mobility through DSRC based V2V communication using ad-hoc vehicular networks [28].

The objective of the study being described in this paper is to develop a DSRC based traffic information system to acquire and disseminate traffic data in real time using V2V communication without need of any DSRC roadside infrastructure. The developed system can detect congestion buildup on a given road using V2V communication, and dynamically estimates parameters such as travel time (TT), starting location of congestion (SLoC), and ending location of congestion (ELoC) using an ad-hoc host selected from among many DSRC equipped vehicles on the road. In addition to the information acquisition, the ad-hoc host utilizes V2V communication to periodically broadcast the estimated traffic parameters to the vehicles approaching the back of the queue on the same road.

Normally, DSRC-based traffic-information systems have two important components, (i) acquisition of traffic parameters such as travel time (TT), and starting location of congestion (SLoC), and (ii) dissemination of these parameters to the vehicles coming towards the congestion area. Usually, both acquisition and dissemination of the traffic parameters, e.g., TT and SLoC is accomplished using DSRC-based V2I and/or V2V communication. However, only those vehicles which are capable of DSRC technology will be able to take advantage of the disseminated information message. Therefore, such automated information systems may not benefit those vehicles which are not DSRC equipped. Assuming a slow DSRC market penetration rate, especially in the beginning phase of future DSRC deployment, there must be an efficient way to communicate the traffic parameters to all vehicles, with or without DSRC capability.

Portable changeable message signs (PCMS) have been used extensively for traffic control, and to display crucial travel related information in the work zone environment related information [29-30]. They are believed to command more attention to the motorists than static message signs and can be dynamically configured at any time through both local and remote means [31]. As long as the traffic parameters can be acquired and disseminated with less than 100 percent DSRC market penetration rate, these parameters can be communicated to the non-DSRC equipped vehicles via PCMSs strategically placed alongside the road. To integrate PCMSs within the DSRC-based traffic-information system, a DSRC-PCMS interface needs to be developed. The PCMS can then be configured to update itself with new traffic parameters received via any nearby DSRC equipped vehicle on the road. As an integral part of this research work, development of DSRC-based hybrid information systems for the work zone using PCMSs is also described.

For the developed systems to reliably work, both acquisition and dissemination of traffic parameters can be performed with less than 100 percent DSRC market penetration rate. We have also done a rigorous analysis to formulate criteria to find out the minimum DSRC penetration rate needed for reliable functionality of the developed system for both acquisition and dissemination of travel parameters. Using realistic traffic flow conditions, we have found the minimum DSRC market penetration rate needed for a variety of traffic scenarios to deploy the developed real time traffic information system.

## 1.3 Report Organization:

The rest of the report is organized into four additional chapters. The second chapter explains the developed traffic information system using Ad-hoc control and DSRC based V2V Communication. The third chapter describes the detailed system functionality and required procedural steps for successful operation. The fourth chapter discusses the system field evaluation and finally, the fifth chapter summarizes the conclusions and future recommendations.

# Chapter 2

# System Architecture

## 2.1) Prior system architecture with RSU:

In the initial phase of this research, we designed and successfully demonstrated a DSRC based work zone traffic information system that used both V2V and V2I communication shown in figure 2.1 [32]. In that system a portable single DSRC roadside unit acted as central control and used both V2I and V2V communication to engage the DSRC equipped vehicles present on the road to acquire and disseminate traffic parameters such as TT and SLoC. We estimated that only about 20% of the vehicles needed to be equipped with DSRC technology for that system to successfully acquire these traffic parameters. Therefore, that system could reliably operate in the early phases of future DSRC deployment when DSRC market penetration will be low or slowly increasing. However, to truly benefit from that system, all the vehicles on the road whether DSRC equipped or not, need to have access to the acquired traffic parameters. To address that concern, we added in our system the DSRC equipped programmable changeable message signs (PCMSs) which were strategically placed alongside the work zone road to display the traffic parameters for the benefit of those vehicles which lacked DSRC capability [33].

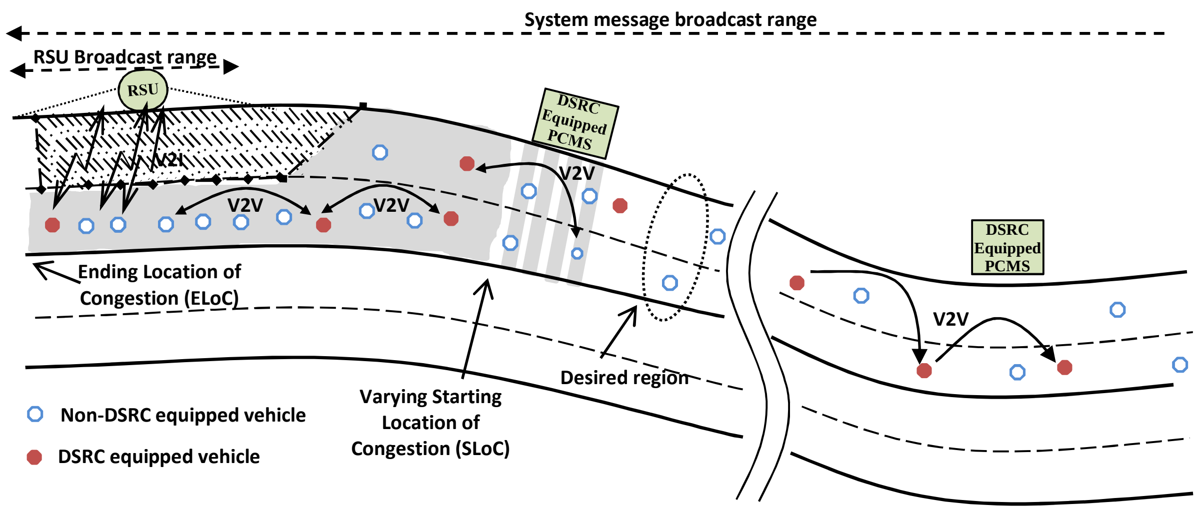


**Figure 2.1 Conceptual architectural diagram of the previously developed hybrid DSRC-PCMS information system for work zone.**

The central RSU is installed and initialized with typical user input parameters such as ELoC, posted speed limit, direction etc., according to the specific work zone environment [34]. After being initialized, the software of the central RSU will control the back and forth DSRC-based communication with all DSRC equipped vehicles passing through the work zone congestion area using V2I or V2V communication depending upon whether a vehicle is within or beyond its direct wireless access range. The vehicle hardware contains DSRC radio communication capability as well as global positioning system (GPS) receiver. The GPS capability in the vehicle is needed so that the current location of the vehicle can be known.

The main objective of the newly developed traffic information system is to acquire TT and SLoC using DSRC technology, and to disseminate those parameters to the vehicles which are farther away and traveling towards the work zone congestion, using a hybrid of DSRC and PCMS technologies. Each time, a new set of TT and SLoC is estimated, both these parameters are periodically disseminated to the DSRC equipped vehicles as well as to the DSRC equipped PCMSs strategically placed across the road side, using DSRC-based V2V communication. The vehicles which have the DSRC capability, can directly take advantage of these parameters (TT and SLoC) by creating an internal alert for the driver. And the drivers of those vehicles lacking the DSRC capability can gather this information by looking at a roadside PCMS displaying the updated TT and SLoC.

## *2.2) Traffic flow and Density Requirements for Work Zone Hybrid System*

In the developed hybrid DSRC-PCMS system, the role of central RSU is critical which engages other vehicles on the road to acquire travel parameters such as TT and SLoC. The acquisition of TT and SLoC is accomplished by selecting a vehicle in the *Desired Region* (Figure 2.1) and then periodically monitoring the speed and location information of the selected vehicle. To accomplish this task, both DSRC-based V2I and V2V communication are needed because the *Desired Region* is quite far and well beyond the direct wireless access range of the central RSU. Similarly, the acquired parameters are needed to be disseminated to the DSRC equipped vehicles and PCMSs, well beyond the SLoC, so V2V communication is a key to accomplish this task as well.

The reliable acquisition of TT and SLoC requires that a DSRC equipped vehicle can be found and selected in a timely manner whenever the central RSU starts looking for a new DSRC equipped vehicle in the *Desired Region*. Similarly, the reliable dissemination of the TT and SLoC require that there are enough DSRC equipped vehicles available to facilitate message propagation using DSRC-based V2V communication. Therefore, a minimum traffic flow rate and a minimum traffic density for a given DSRC penetration rate is needed to successfully accomplish the tasks of acquisition and dissemination of TT and SLoC.

The minimum traffic flow rate along with the DSRC penetration rate will ensure that a DSRC equipped vehicle is available to be found and selected whenever central RSU needs to update TT and SLoC. Similarly, a minimum traffic density along with the DSRC penetration rate will ensure that there are enough DSRC equipped vehicles on the road to facilitate V2V communication needed for both acquisition and dissemination of TT and SLoC.

Traffic flow and density will give rise to statistical distribution of vehicles in time and space, respectively. The most commonly followed stochastic traffic model is Cowan’s headway model [35]. According to Cowan’s model, vehicle distribution in time and space is Poisson in nature. This is generally applicable when the traffic flow density is light so that free traffic condition exists i.e., the arrival of a given vehicle is not affected by any other vehicle preceding it. However, when the traffic flow density becomes large enough leading towards congested traffic condition, then the vehicle distribution both in time and space becomes uniform instead of Poisson. We have applied the relevant vehicle distribution models to determine the minimum traffic flow and density needed for reliable acquisition and dissemination of TT and SLoC, and hence have found the minimum DSRC market penetration rate needed for reliable functionality of the developed system.

#### *2.1.1.1) Traffic flow rate and acquisition of TT and SLoC:*

Reliable acquisition of TT and SLoC depends upon the central RSU's ability to timely find and select a DSRC equipped vehicle within the *Desired Region*, which depends upon the total number of vehicles crossing the *Desired Region* in a given time i.e., the traffic flow and the DSRC penetration rate. If the traffic flow and/or the DSRC market penetration rate are small, the central RSU may have to wait for a long time before a DSRC equipped vehicle passes through the *Desired Region* and therefore, the acquisition cycle may not proceed efficiently.

The *Desired Region* is placed well before the SLoC by the central RSU (figure 2.1). As congestion grows, the central RSU has ability to dynamically move the *Desired Region* away from the SLoC. Because the *Desired Region* is always located well before the congestion starts, the traffic flow through the *Desired Region* can be considered as free flow as opposed to the bounded flow which gradually builds up after the *Desired Region* leading towards congested flow around SLoC. Please note that during the rush hours, this situation may not exist because the congestion stretches for a much longer distance. In that case, the SLoC is located at a point from where TT needs to be calculated because there is no SLoC in reality. The traffic flow of incoming vehicles will determine how many vehicles will cross the *Desired Region* in a given time. Considering the free flow condition, for a given traffic flow rate, $q$ Veh/sec, there will be total of $q\Delta T$ vehicles crossing the center point of the *Desired Region* in time $\Delta T$. Assuming Poisson arrival distribution, the probability that exactly $n$ vehicles cross the center point of the *Desired Region* in time $\Delta t$ is described by equation 1 [36]:

$$p(n) = (q\Delta T)^n \frac{e^{-q\Delta T}}{n!} \quad \ldots\ldots\ldots\ldots \; (1)$$

From this equation the probability that no vehicle crosses ($n = 0$) the center point of the *Desired Region* will determine the cumulative probability of time headway, $h$, as described in equation 2.

$$p(h \leq \Delta T) = 1 - e^{-q\Delta T} \quad \ldots\ldots\ldots\ldots \; (2)$$

The equation 2 gives the proportion of the total number of vehicles ($q\Delta T$) in time $\Delta T$ with time headway $h \leq \Delta T$. Therefore, the total number of vehicles, $N$, with time headway $h \leq \Delta T$, will be given by equation 3.

$$(q\Delta T)\left(1 - e^{-q\Delta T}\right) = N \quad \ldots\ldots\ldots\ldots \; (3)$$

Now assuming that the DSRC penetration rate is $k$ (fraction of the total number of vehicles), the number of DSRC equipped vehicles crossing the center of the *Desired Region* in time $\Delta T$ is $kN$. We numerically solved the equation 3 to find out $\Delta T$ in which one DSRC equipped vehicle crosses the center of the *Desired Region*, for a given traffic flow, $q$, using different values of DSRC penetration rate, $k$. For example, if the penetration rate is 10% ($k = 0.1$), the equation 3 is solved for $N = 10$ assuming that one vehicle from every 10 vehicles, on average, crossing the center of the *Desired Region* in time $\Delta T$, will be DSRC equipped vehicle. The results are shown in figure 2.2 where $\Delta T$ –

average time lapse between two DSRC equipped vehicles crossing the center of the *Desired Region* – is plotted vs. *q* for different values of *k*.

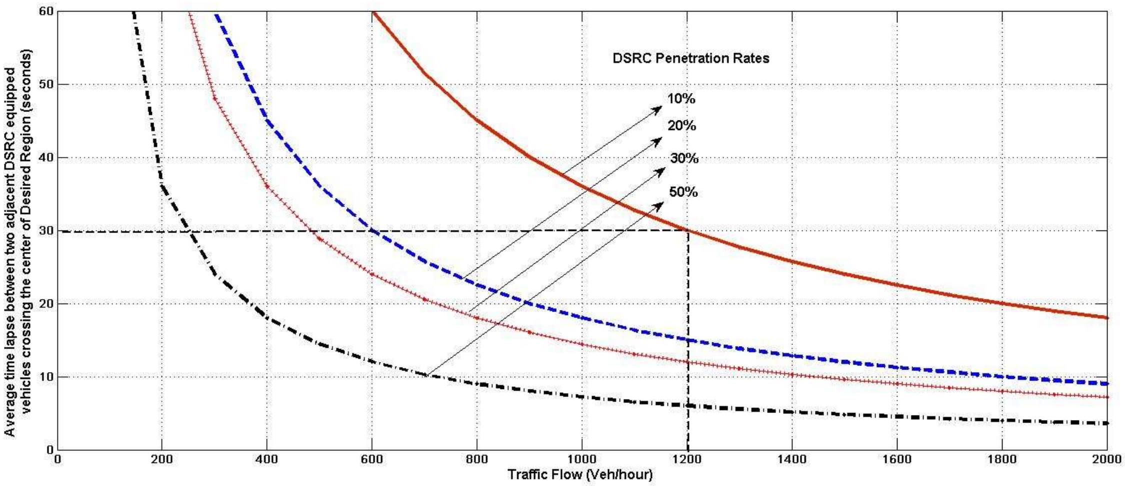


**Figure 2.2 Average time lapse between two adjacent DSRC equipped vehicles crossing the center of the *Desired Region* as a function of traffic flow for different DSRC penetration rates.**

Figure 2.2 shows average time lapse between two DSRC equipped vehicles crossing the center of the *Desired Region* for free flow traffic condition i.e., assuming Poisson temporal distribution. However, if the congestion spreads to much longer distances so that free flow traffic condition does not hold true anymore, the vehicle temporal distribution effectively becomes narrowly uniform around average time headway. Considering the narrow uniform temporal distribution, the average time lapse between two DSRC equipped vehicles crossing the center of the *Desired Region* will become 1/(*kq*), which turns out to be very comparable to the results of Figure 2.2. Therefore, figure 2.2 can be represented for both free flow and congested flow conditions to find out the average time lapse between two DSRC equipped vehicles crossing the center of the *Desired Region* for any traffic flow rate $q$ and DSRC penetration rate $k$.

Figure 2.2 can help estimate the DSRC penetration rate needed for the central RSU to find and select a DSRC equipped vehicle in a reasonable time interval. The reasonable time interval should be a small fraction of the *Update Time* after which the central RSU starts searching for a new DSRC equipped vehicle in the *Desired Region.* We chose 30 sec as reasonable time interval assuming an *Update Time* of 10 minutes – which is the case with most practical scenarios of interest where TT is generally much more than 10 minutes – i.e., 5 percent of the *Update Time.* We will use this criterion to determine the DSRC penetration rate needed for a given traffic flow for the central RSU to successfully find and select a DSRC equipped vehicle in the *Desired Region* for acquisition of TT and SLoC.

#### *2.1.1.2)* *Traffic Flow Density and Dissemination of TT and SLoC:*

As described earlier, for dissemination of TT and SLoC, a minimum traffic flow density is needed to sustain DSRC-based V2V communication for a given DSRC penetration rate. For any given traffic flow density, the vehicles on the road are spatially distributed in random fashion. Just like the temporal distribution or time headway, the spatial distribution or space headway can also be derived from the Poisson distribution for free flow condition. The similar analytical approach as developed in the previous section for time headway, can be used to have a modified equation for the total number of vehicles in length $\Delta L$ having space headway less than $\Delta L$ for a given vehicle density $D$.

$$(D\Delta L)(1- e^{-D\Delta L}) = N \quad \ldots\ldots\ldots\ (4)$$

Now assuming that the DSRC penetration rate is $k$, there will be $kN$ number of DSRC equipped vehicles, present on each road section of length $\Delta L$. We numerically solved the equation 4 to determine the average distance $\Delta L$ in which one DSRC equipped vehicle is present, for different DSRC penetration rates. The results are shown in Figure 2.3 where average distance between two adjacent DSRC equipped vehicles is shown versus traffic flow density for different DSRC penetration rates. Please note that the equation 7 is applicable to free flow condition but if the traffic flow is quite congested, the average distance between two adjacent DSRC equipped vehicles become $1/kD$ for a given vehicle density D and DSRC penetration rate $k$.

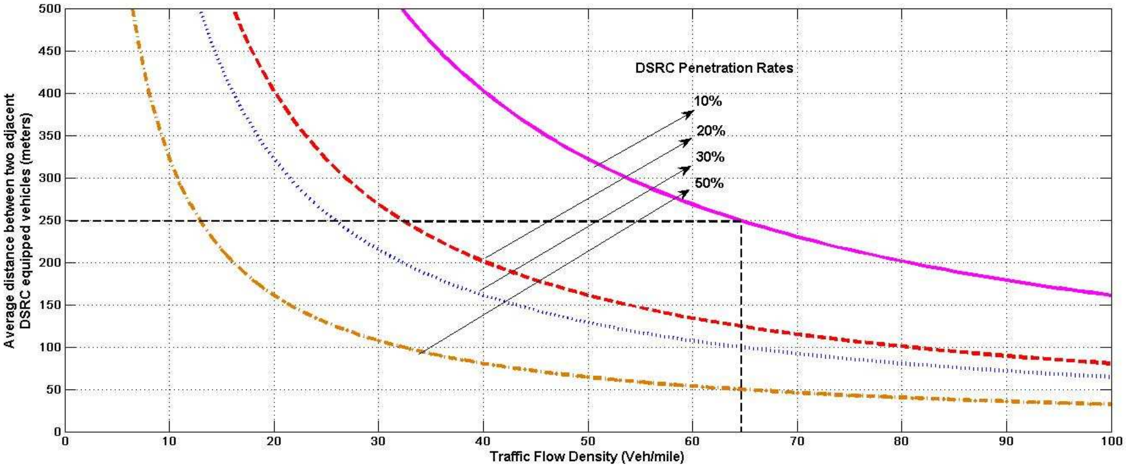


**Figure 2.3 Average distance between two adjacent DSRC equipped vehicles as a function of traffic flow density for different DSRC penetration rates.**

As in time headway analysis, we found that the average distance between two adjacent DSRC equipped vehicles remains same for congested and free flow condition for a given vehicle density D and DSRC penetration rate k. Therefore, figure 2.3 represents the average distance between two DSRC equipped vehicles for both free and congested traffic flow scenarios. However, the difference comes in the spatial distribution of the DSRC equipped vehicles, which is narrowly uniform in congested flow and Poisson in free flow.

Figure 2.3 can help estimate the required DSRC penetration rate needed to sustain the V2V communication needed for dissemination of TT and SLoC. Although, on average, the distance between any two adjacent DSRC equipped vehicles will be $\Delta L$, the crucial length to consider for sustaining V2V communication is $2\Delta L$ because the maximum distance between two adjacent DSRC equipped vehicles could be $2\Delta L$ in some sections of the road. This is the worst case scenario where a DSRC equipped vehicle is present on the extreme left side of the road section of length $\Delta L$, and on the adjacent road section of same length, a DSRC equipped vehicle is present on the extreme right side, thereby making the distance between the two DSRC equipped vehicles to be $2\Delta L$.

Considering the direct wireless range of the DSRC units to be 500 m, the distance between any two adjacent DSRC equipped vehicles should be at most 500 m to sustain the V2V communication. Therefore, the average distance between the two DSRC equipped vehicles should be 250 m.  However, if for any reasons, including temporary loss of the line of sight, or a given vehicle’s DSRC unit being turned off, there is a possibility of V2V communication chain to be interrupted, thereby harming the reliable dissemination of TT and SLoC. One way to get around this situation is to consider an average distance of 125 m instead of 250 m between two adjacent DSRC equipped vehicles to double the number of DSRC equipped vehicles available for V2V communication. However, assuming the practical work zone road situation, where generally there are two lanes in each direction, the number of vehicles available for V2V communication will, in fact, be twice including the DSRC equipped vehicles for both lanes. Furthermore, the DSRC equipped vehicles on two lanes of opposite direction could also help sustain the V2V communication as provisioned in our developed system [34]. Therefore, we have used the criterion of an average distance between two DSRC equipped vehicles to be 250 m to reliably sustain the V2V communication needed for dissemination of TT and SLoC**.**

#### *2.1.1.3)* *<u>DSRC Penetration Rate Requirement for Hybrid DSRC-PCMS System</u>*

As explained above, using the criteria of finding a DSRC equipped vehicle in 30 second interval for acquisition of TT and SLoC, and an average distance between the two DSRC equipped vehicles of 250 m to sustain V2V communication needed for dissemination of TT and SLoC, the required traffic flow and vehicle density for a given DSRC penetration rate can be estimated from figures 2.2 and 2.3, respectively. For example, for 10% DSRC market penetration rate, a 30 sec interval criterion means that the traffic flow rate should be 1200 Veh/sec (figure 2.4). Similarly, for 10% DSRC market penetration rate, the criterion of 250 m average distance between two DSRC equipped vehicles, suggests that the traffic density should be 65 Veh/mile for a given lane (Figure 2.3). Using the same method, the required traffic flow and densities for different DSRC market penetration rates are estimated for different values of DSRC penetration rate, and the results are shown in figure 2.4. Figure 2.4 can help estimate the required DSRC penetration rate for the developed system to reliably function on a given work zone road for known traffic conditions, i.e., traffic flow and density.

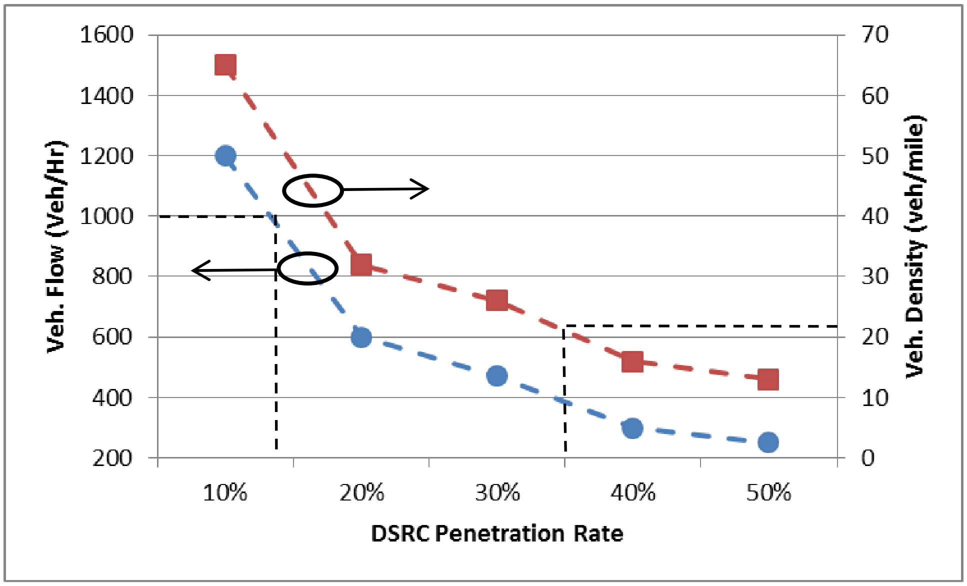


**Figure 2.4 Required traffic flow and density for a given DSRC penetration rate.**

As an example, we analyzed the real time data collected on a two lane road section in Minneapolis-St. Paul metropolitan area (South Bound I-169) containing flow, density and speed information during a typical work day driving conditions. Using figure 2.4, we determined the required DSRC penetration rates needed for this practical scenario. We analyzed the non-rush hours and rush hours traffic data separately.

The non-rush-hours (10:00 am to 2:0 pm) data suggests that during this time traffic flow ranges from 1000 to 1500 Veh/hour with corresponding traffic densities of 21 to 26 Veh/mile for a given lane, thereby maintaining an average speed of 55 MPH i.e. a free flow condition. In this situation, a DSRC penetration rate of about 15% (for the worst case traffic flow of 1000 Veh/hour) will be required as estimated from figure 2.4.

Similarly, a DSRC penetration rate of about 35% (for the worst case traffic density of 21 Veh/mile) is required as estimated from figure 2.4. Therefore, a DSRC penetration rate of at least 35% (dictated by minimum density) is needed for our developed system to successfully work under this scenario.

Similarly, the rush hour (6:00 am to 10:00 am) traffic data suggests that the traffic flow dominantly ranges from 1300 to 1800 Veh/hour per lane with vehicle densities to range from 30 – 80 Veh/mile per lane. With moderately higher flow than the non-rush-hours, but significantly higher densities means that the average speed reduced from 55 MPH to 25 MPH i.e., the congestion condition has been developed. However, in this situation, both worst case traffic flow (1300 Veh/hour) and density (30 Veh/mile) are large enough to warrant successful functionality of the developed system with a DSRC penetration rate of a little less than 20 percent.

### *2.1.2) DSRC-PCMS Interface*

To integrate the PCMS in our hybrid traffic-information systems for the work zone, a DSRC interface with PCMS was developed and field demonstrated. Using this interface, a PCMS could remotely receive the information message containing TT, and SLoC from a nearby DSRC equipped vehicle using V2V communication, and can show these updated parameters on its display matrix for the benefit of passing by drivers. The same interface can be used for the portable PCMSs so that portable PCMSs can be relocated as the congestion grows on a work zone, especially during the rush hours. While designing the DSRC-PCMS interface, the message format is kept according to the guidelines for using the PCMSs suggested by the manual on uniform traffic control devices (MUTCD) [37].

### *2.1.2.1) <u>Hardware Architecture:</u>*

The DSRC-PCMS hardware interface design is accomplished using the RS232 serial port connection between the DSRC unit and the PCMS. We used a PCMS device made by ADDCO® (an IMAGO® company) to interface with our DSRC units. A picture of the PCMS used is shown in figure 2.5 and consists of a display matrix (3 lines x 8 characters), a controller for display control, a power supply with solar panel, and a portable cart. This particular PCMS type is considered the most sold PCMS type in the North America and is fully compliant to the national transportation communications for ITS protocol (NTCIP) standards [32]. This PCMS comes with a proprietary logic controller, called SC4, and utilizes modified higher data link layer control (HDLC) language to let the external agents communicate with the controller.

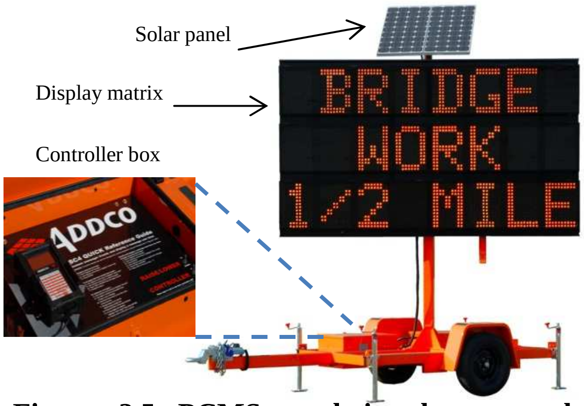


**Figure 2.5 PCMS used in the research project.**

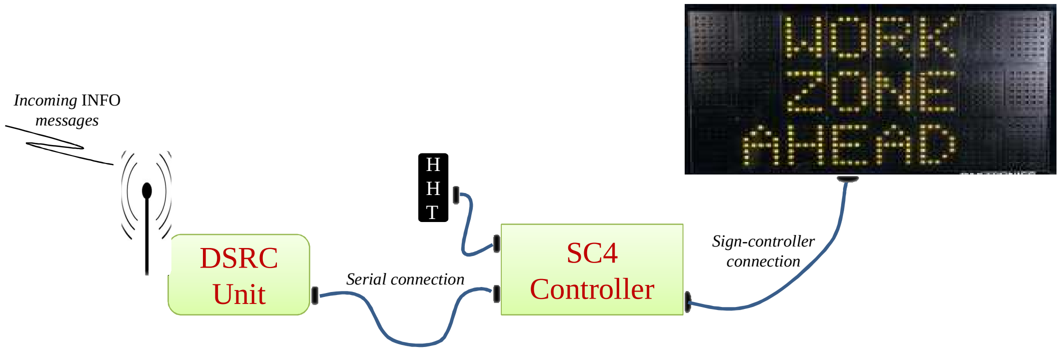


**Figure 2.6 Schematic diagram of DSRC-PCMS hardware interface.**

The schematic of the DSRC-PCMS interface is shown in figure 2.6. DSRC unit connected with the PCMS constantly looks for the updated safety message and once it finds a new message, it will process it and communicate it to the SC4 controller of the PCMS which displays it accordingly as explained earlier. The typical messages for the work zone operation systems are shown in figure 2.6.

#### ***2.1.2.2)*** ***Interface Software Functionality:***

The SC4 controller is capable of providing key functionalities such as local creation, editing, and storage of messages etc. The SC4 controller is also capable of displaying messages through remote communications using three different ports, *Sign*, *Central, and Auxiliary* as shown in figure 2.7(a). The commands given locally using a hand held terminal (HHT) to the SC4 for display are called *Sign* commands. When the commands to display a particular message are sent to the SC4 controller remotely using either wired, or wireless communication, these are called *Central* commands. For our purpose, we used the SC4 controller in the *Central* command mode allowing the DSRC unit to automatically communicate with it. Please note that SC4 controller comes in two versions: Standard and Deluxe, and *Central* port is only available in the deluxe version. The DSRC unit's serial port is connected with the SC4 controller's *Central* port and a serial connection is conducted to transfer the data. The top

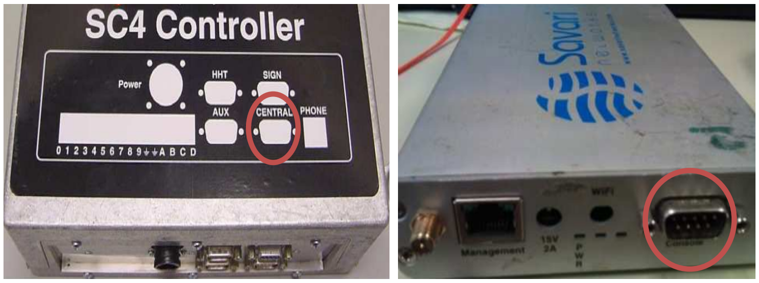


**Figure 2.7 (a)Top view of the SC4 controller deluxe version, and (b) Serial console of SAVARI DSRC unit.**

view of SC4 controller is shown in Figure 2.7(a) and the DSRC unit used is shown in Figure 2.7(b).

The SC4 controller can only understand the information sent to it which is encoded in higher data link layer control (HDLC) language. For that purpose, the DSRC is programmed such that it encapsulates the information to be displayed with HDLC encoding before sending it to the SC4 controller. Please note that SC4 controller’s *Central* port is first configured with correct initial parameters using HHT so that it can accept any communication from external agent on *Central* port. Initial *Central* port parameters that are set each time communication happens are baud rate (19200), number of data bits per character (8), parity (none), and number of stop bits (1). The DSRC unit’s serial port must also be configured with the same values in order to serially transfer the data correctly. Please note that we used Savari’s DSRC units, which have a built in serial port (figure 2.7(b)). Once the serial ports on both sides are properly configured, only then the DSRC unit is ready to send out the encapsulated messages to be displayed on the display matrix of the PCMS. The data formatted in proper HDLC encoded message is then serially communicated to the PCMS controller (SC4). The PCMS controller then processes the received HDLC encoded message to create a display pixel map which is then sent to the display matrix in proper format to light the corresponding LEDs.

Whenever DSRC unit needs to send a message to the PCMS for display, it will encode the message in proprietary encoded frame and then send it to the SC4 controller via serial communication. Please note that we cannot disclose the information on proprietary encoded format under a nondisclosure agreement (NDA) which we signed with ADDCO. As soon as the SC4 controller receives the message data in proprietary encoded format, it will strip the message out of that and then will send the appropriate pixel lighting commands to the display matrix. However, if the display matrix already has a message being displayed, it must be sent a blank out command, first, which should be controlled by the DSRC program. The blank out command is needed to erase the previously shown contents before displaying the updated information. Please note that a minimum amount of time (about 4 sec) is required before sending out a different command to the SC4 controller for changing the contents of display matrix. Although, the SC4 controller is quite fast in responding to the user commands, its internal communication with the display matrix adds a considerable delay in quickly changing its display contents. The reason is that the display matrix needs a minimum time to safely shut down all the LEDs before lighting them up for a new message display.

The DSRC unit connected with the PCMS continuously searches for the new broadcast messages within its direct wireless access range, while continuing to display the latest received TT and SLoC information. Once the updated information message is received by the DSRC unit of the PCMS, the DSRC unit compares the values that are currently being displayed on the display matrix with the newly received values. If there is a difference then the DSRC unit’s program issues a command to the controller asking to blank the display matrix from displaying the expired information. The DSRC unit program abstains from sending out any further command to the SC4 controller until the display matrix properly shuts down all the LEDs.

The DSRC unit connected with the PCMS is also equipped with GPS which helps calculate the distance from its current location to the SLoC which is displayed as distance to the queue ahead. The TT and the distance to the SLoC data are then properly encoded in HDLC packet and are sent to the SC4 controller for display. The message is then continued to be displayed on the display matrix until an updated information message containing a new value of TT and SLoC is received.  The TT and the distance to the queue ahead are displayed alternatively with 3 second interval because both these parameters cannot fit into the 3 lines x 8 characters display matrix. The frequency of alternating messages within one frame can be easily changed by making few changes in the HDLC frame being sent from the DSRC unit. Please note that these two alternating messages are encapsulated into one frame and hence do not require an additional blank command to be sent from the SC4 to the display matrix. However, if the either data (TT or distance to the queue ahead) contained in the frame is to be updated, the DSRC unit's program must send out a blank command to the SC4 before dispatching updated frame.

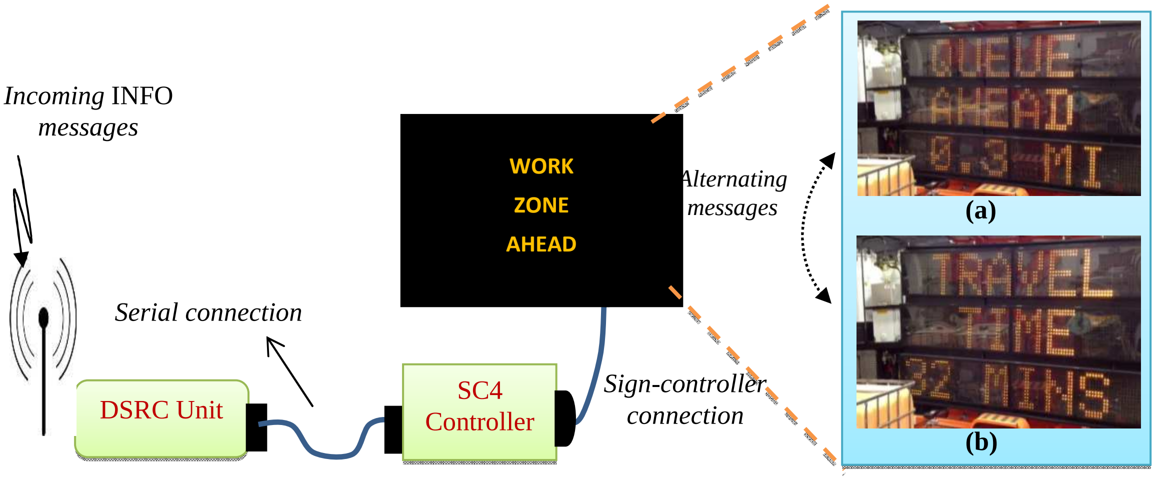


**Figure 2.8 Snapshots of the PCMS display matrix showing alternate messages of (a) distance to the queue ahead and (b) travel time.**

Typical snapshots of the TT and distance to queue-ahead messages displays from the field demonstration are shown in figure 2.8(a) and 2.8(b), respectively. Please note that we used the time resolution of one minute to display the TT and a distance resolution of one tenth of a mile to display the distance to the queue ahead.

## 2.2) Current system without using RSU:

A major limitation of our previously developed traffic information system was the need to have a DSRC roadside unit acting as central control. This could cause the whole system functionality to collapse if roadside unit encounters any failure in its normal operation. To address this problem, a traffic information system needs to be developed that does not depend on any DSRC roadside central control. Instead a DSRC equipped vehicle present on the road can be chosen as an ad-hoc central control which can accomplish the task of acquisition and dissemination of traffic parameters using only V2V communication. Once a new set of traffic parameters is acquired, and/or the ad-hoc central control vehicle leaves the congested road, the ad-hoc control can be passed on to another DSRC equipped vehicle present on the congested road, for the continuation of operation.

The conceptual diagram of the architecture of the newly developed traffic information system using ad-hoc control and DSCR based V2V communication is shown in figure 2.9. The system architecture is quite similar to the one we previously designed except that it does not have any roadside central control unit which in the previous design was installed near the ending location of congestion (ELoC) and had prior knowledge of it. The newly designed system estimates SLoC and ELoC as well as the TT, using V2V communication and an ad-hoc host which is selected from the DSRC equipped vehicles present on the road ahead of SLoC. The ad-hoc host also periodically broadcasts these parameters using V2V communication to the vehicles behind the congestion which yet have to approach the SLoC. All of the DSRC equipped vehicles approaching the SLoC can receive these messages for their own use as well as help rebroadcast for the vehicles that are behind. For the benefit of vehicles that lack DSRC capability, DSRC equipped PCMSs can be placed at strategic locations which can receive these parameters from a passing by DSRC equipped vehicle and display the useful traffic parameters (figure 2.9).

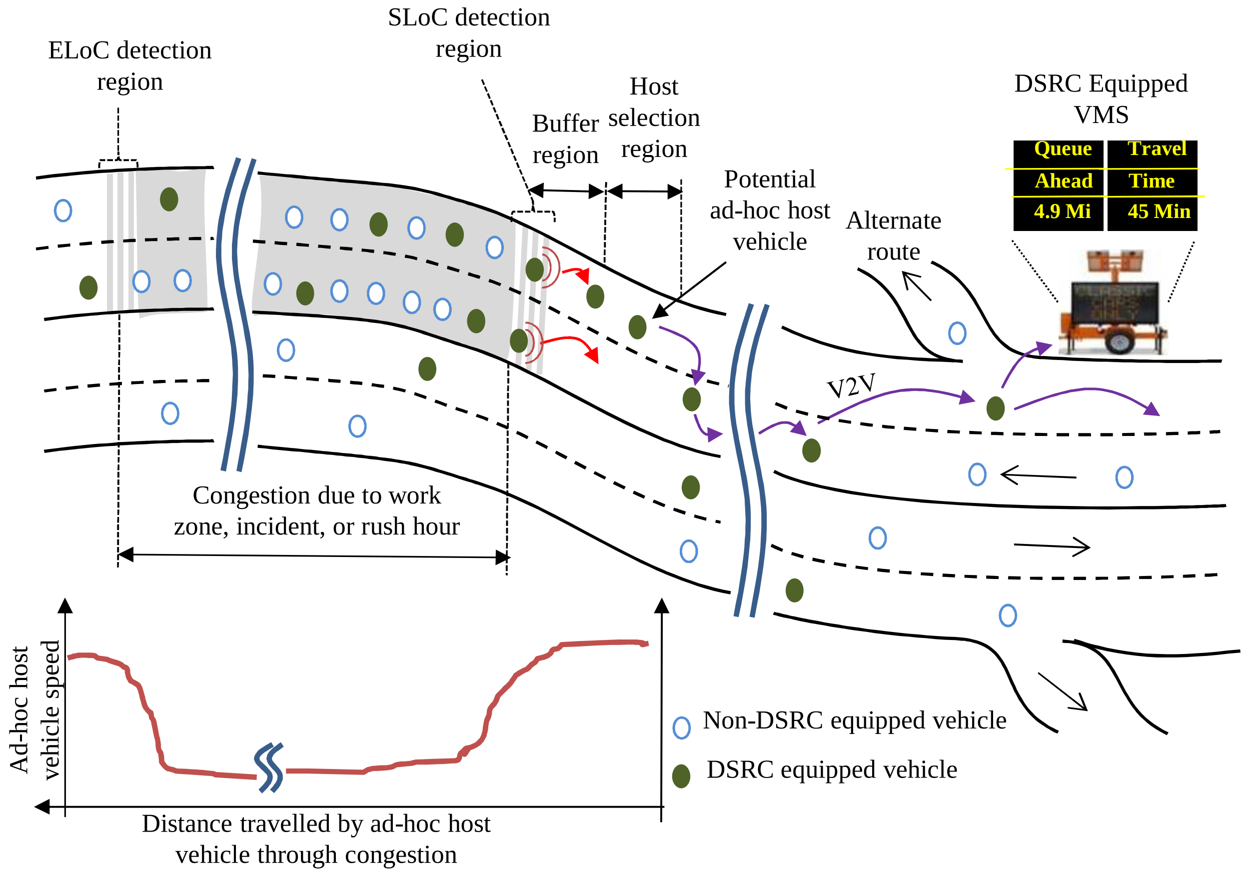


**Figure 2.9 Conceptual architectural diagram of the developed traffic information system using ad-hoc central control and DSRC based V2V communication.**

The developed system is fully adaptable and functional to estimate traffic parameters for any congestion on the road either caused by regular rush hour traffic or because of lane closure due to a work zone or an incident. All of the DSRC equipped vehicles on the road including the ad-hoc host vehicle will not require any external user input to initiate and control the V2V communication algorithm designed for this system to dynamically acquire and disseminate traffic parameters. However, the reliable operation of the developed system using V2V communication will require a minimum threshold of DSRC market penetration rate [38-39].

Each vehicle which is equipped with DSRC onboard unit (OBU) is also assumed to be equipped with a global positioning system (GPS) receiver. The GPS receiver is used by the vehicle DSRC onboard unit (OBU) to acquire the location, and calculate the speed, acceleration, and heading of the vehicle on the road on any given time. Using the DSRC technology, all DSRC equipped vehicles will exchange short messages with each other using V2V communication to estimate traffic parameters e.g., SLoC, ELoC and TT.

The short message format is assumed to be Basic Safety Message (BSM) format to comply with the standard J2735 as laid out by the Society of Automotive Safety Engineers (SAE) and shown in figure 2.10[40]. The BSM format allows many fields which could carry the information like traffic parameters (SLoC, ELoC, TT), or warnings about the detection of the back of the queue or about presence or absence of an ad-hoc vehicle. Similarly, some of the additional parameters needed to facilitate V2V communication to hop the message could also be accommodated in BSM [32].

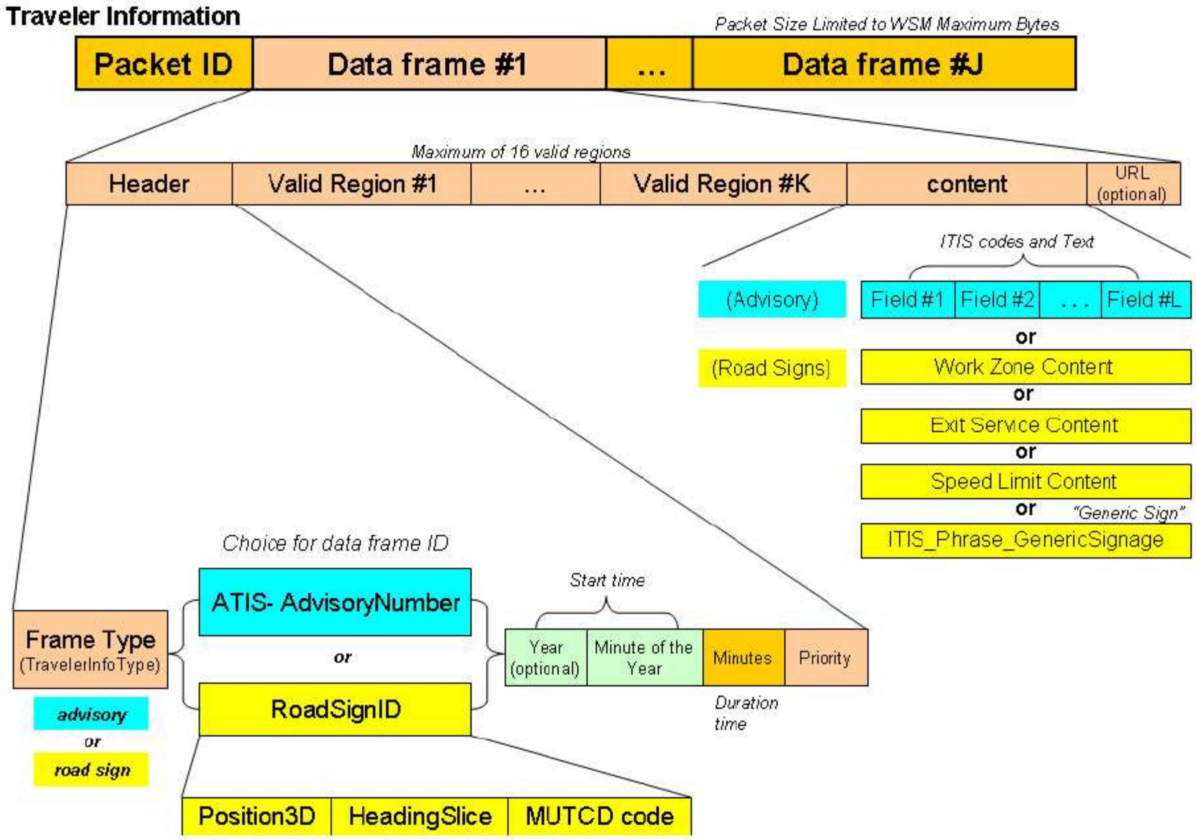


**Figure 2.10 Basic traveler information packet structure containing multiple individual advisories.**

Please note that during the whole traffic data acquisition and dissemination cycle, all the data is kept anonymous among the communicating vehicles using randomly assigned identifications to every message. Furthermore, any stored data in the OBUs is discarded immediately after each data acquisition cycle to uphold the privacy of the vehicles.

# Chapter 3

# System Operation

In the developed system, several DSRC equipped vehicles are assumed to be travelling on the road. Whenever congestion occurs in any section of the road, the vehicles travelling towards the congestion will experience a considerable speed differential upon entering the end of the queue. In the absence of any DSRC roadside central control unit, the back of the queue or the SLoC has to be detected solely by the traveling vehicles on the road.

When the traffic is running at a free flow speed, each OBU of the DSRC equipped vehicle is performing normal operation of periodically acquiring its location, and calculating speed and heading. However, when congestion starts to build up, the OBU of DSRC equipped vehicles that are entering the SLoC experience a sudden drop in speed. If the calculated deceleration at that instant is below a certain predetermined deceleration threshold, the OBU will broadcast a BSM, warning the vehicles in its direct wireless range using V2V communication of possible congestion ahead. Many vehicles could experience such speed reduction and broadcast warning BSMs within a short time interval.

These BSMs are received by the trailing DSRC equipped vehicles which are about to enter the back of the queue. One such trailing DSRC equipped vehicle, which receives these warning BSMs from multiple vehicles, is selected as an ad-hoc host, which will help estimate the traffic parameters e.g., SLoC, ELoC, and TT, while traveling through the congestion. The ad-hoc host will also be responsible to disseminate these parameters to the vehicles traveling far behind the back of the queue using DSRC based V2V communication. Furthermore, once the ad-hoc host estimates the traffic parameters, it will help select another ad-hoc host so that the process of estimation and dissemination of traffic parameters continues.

There are three crucial aspects of the whole operation of the newly developed traffic information system. The first aspect is to establish the predetermined deceleration threshold criteria for detecting the back of the queue, and the second is the selection criteria of an ad-hoc host out of many DSRC equipped vehicles. The third aspect is the reliable functionality of the ad-hoc host to estimate traffic parameters, and disseminate to the vehicles traveling far behind the back of the queue. In the following, these three aspects are described in further detail.

### 3.3) Deceleration Threshold to Detect Start of Congestion

On any given highway, congestion can occur when high-volume, high-speed, and free-flow traffic switches to low-volume low-speed glut of vehicles [41]. This congestion generally could be a result of a bottleneck created on the road due to lane closure in an active work zone or because of an incident on the road. The bottleneck brings the vehicles' speeds down from free flow speed to congested flow speeds, which could result in creating traffic queues over long stretch of the road. The vehicles that are arriving from behind at a free-flow speed will see the end of queue, and each driver will apply the brakes in its own unique fashion to avoid rear-end collision. This will result in a variety of deceleration profiles.

Each vehicle that experiences speed reduction before entering into the congestion will follow a unique deceleration profile. These deceleration profiles can be divided into three main categories; standard deceleration, cautious deceleration, and extreme deceleration. Standard deceleration is generally applicable to drivers braking while engaging in a normal avoidance maneuver due to a stationary object present on the road. Cautious deceleration is observed by the cautious drivers who apply rather hard brakes but early enough as compared to extreme deceleration which is observed by the drivers who apply hard brakes when encountered with an emergency situation. These three deceleration profiles have been extensively discussed in the literature and are documented by AASHTO in the green book for the geometric design of highways [42].

According to the AASHTO recommendations, around 90% of the vehicles comfortably acquire standard deceleration rate of $3.4 m/s^2$ to bring the vehicle to complete stop on a dry road [43]. The standard deceleration rate value is taken as $3.4 m/s^2$ in the literature, while the cautious and extreme deceleration rates are generally considered in the range of $6\ m/s^2$ and $8.5\ m/s^2$, respectively [44].

When these deceleration rates are applied to a vehicle travelling at a given speed, three unique deceleration slopes are observed as shown in Figure 3.1 for a vehicle traveling at 60 MPH on a freeway. The time taken by the driver to bring the vehicle to a reduced speed or a complete stop depends on the deceleration rate, as shown in figure 3.1. If multiple vehicles travelling at a free flow speed, experience a deceleration at a rate equal to or greater than the standard deceleration rate for certain time duration, then it is likely due to the fact that these vehicles are entering the back of the queue on the road.

We have used this criterion to initiate BSMs containing warnings for the vehicles behind the back of the queue, so that one of those vehicles could be selected as an ad-hoc host.

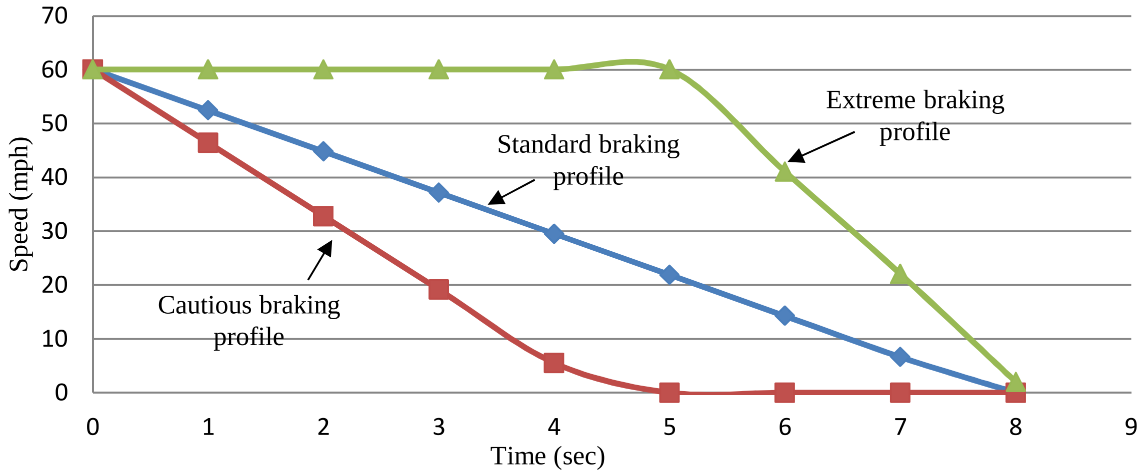


**Figure 3.1 Speed versus time of a typical vehicle showing three unique braking profiles.**

### 3.2) Ad-Hoc Host Selection

The most basic requirement for the developed system to meet its objective of acquiring traffic safety parameters is the selection of an ad-hoc host vehicle traveling at free flow, from among the DSRC equipped vehicles present on the road, which have yet to enter the back of the queue. A DSRC equipped vehicle is selected as an ad-hoc host if two procedural steps are fulfilled; (i) multiple vehicles traveling ahead of it on the congested road are entering back of the queue and issue BSMs with warning, and (ii) it receives those BSMs while travelling behind maintaining a certain distance from the back of the queue. In the following, these two procedural steps are explained in more detail.

### 3.2.1) *First Procedural Step: Back of the Queue Detection:*

Vehicles travelling towards the congestion experience speed differential on entering the back of the queue, i.e., SLoC. As soon as a DSRC equipped vehicle's speed drops below certain threshold experiencing a standard deceleration or higher, its OBU will transmit a BSM with warning. The criteria of issuing warning BSMs upon detection of the back of the queue is depicted in figure 3.2 highlighting a range of deceleration values and corresponding speed values for generating a warning BSM. The standard deceleration rate is shown as $a_{th}$ in Figure 3.2 and its value is taken as $3.4\mathrm{m/s}^2$.

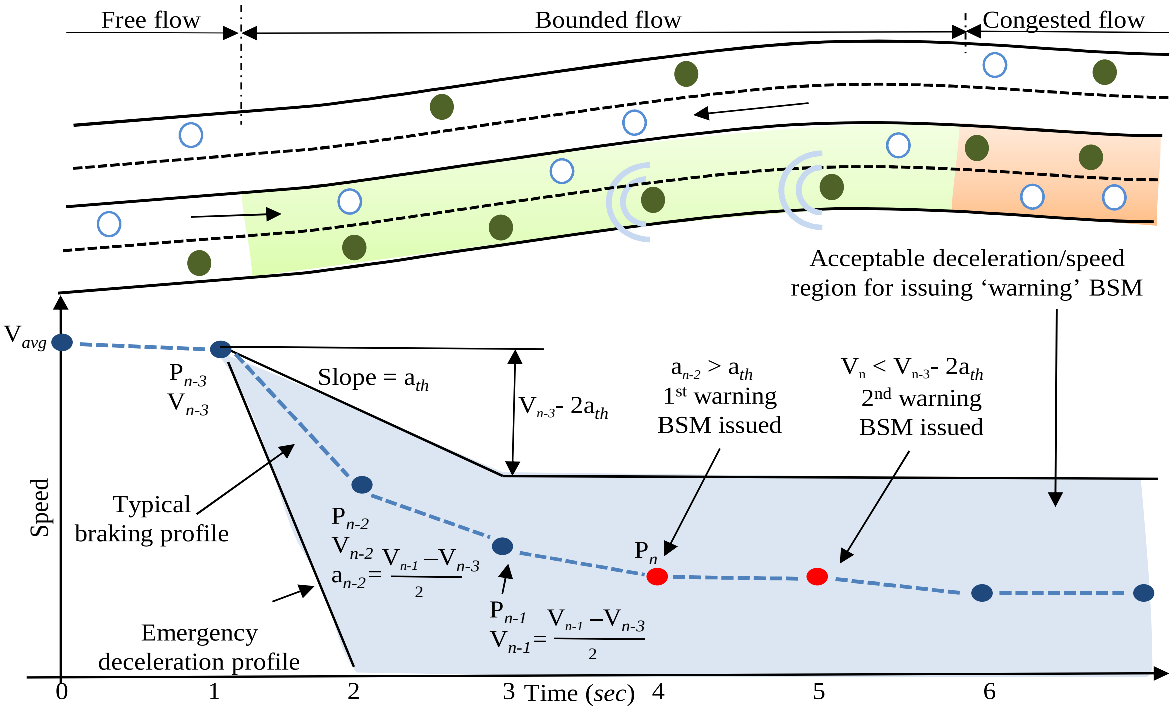


**Figure 3.2 Speed versus time of a typical vehicle showing conditions of issuing warning BSM upon experiencing a certain deceleration.**

Any vehicle entering the congestion must experience a deceleration value of at least $a_{th}$ or higher in order to generate warning BSMs. Please note that normally, the upper bound of deceleration value will not exceed the emergency deceleration profile unless a rear-end collision occurs. Using GPS receiver, each DSRC equipped vehicle is continuously acquiring its position every second, and stores 4 latest positions at any given time, n, to calculate needed speed and deceleration values as shown in Figure 3.2.

If the calculated deceleration is more than $a_{th}$, the vehicle is prepared to issue a ‘warning’ BSM. However, before it does that, it also needs to evaluate following two conditions:

i. 1) The vehicle will compare its free flow velocity prior to experiencing any deceleration, ($V_{n-3}$) in the typical trajectory shown in Figure 3.2 with a predetermined minimum threshold velocity $V_{th}$. If its velocity is more than $V_{th}$, then it will qualify to issue the warning BSM otherwise not. This threshold velocity comparison eliminates the possibility of issuing false warning BSMs in case a vehicle has not yet approached a freeway and is traveling in the city limits, taking turns and stopping at the signals and STOP signs. For demonstration purposes, we are assuming $V_{th}$ to be 30MPH, to ensure that vehicle experiencing deceleration is on a freeway, and have achieved a steady state speed.

ii. The vehicle will also need to check if it has received any other BSMs containing traffic parameters and/or request for a new ad-hoc host selection. If vehicle has not received any other BSM then it will proceed to issue a warning BSM. However, if the vehicle has received another BSM, it will only proceed if there is a request for a new ad-hoc host selection.

If a DSRC equipped vehicle's deceleration is higher than $a_{th}$, and it passes the above two tests, it will issue a warning BSM. After issuing the first warning BSM, the vehicle will acquire a new GPS position in the next time interval (1 sec) and recalculates its speed and deceleration. Now, based upon the new calculated values, as long as the vehicle's speed stays below ($V_{n-3}$- $2_{ath}$) i.e., stays within the acceptable deceleration/speed region as shown in Figure 3.2, it will issue a second warning BSM. The two warning BSMs are issued three times within 100msec to increase the probability of the warning BSM to be received by the vehicles behind in case of a temporary LoS blockage by a moving vehicle in the middle. Please note that travelling at 60MPH, a vehicle can travel about 9ft within 100msec, during which most moving obstacles can clear the LoS.

Each DSRC equipped vehicle also needs to calculate its heading to include in the warning BSM. Each vehicle will calculate its cumulative distance every second, and if it exceeds 50m, it will save that position and starts over the cumulative distance calculation. At any given time, it will keep record of last three consecutive 50m positions to calculate its heading over a distance of at least 100m travelled but not more than 150m at the time of issuing the warning BSM. Please note that each warning BSM carries with itself the location of the vehicle where the BSM was issued, as well as the calculated heading. Both these parameters will help a vehicle validate its capability to be a potential ad-hoc host.

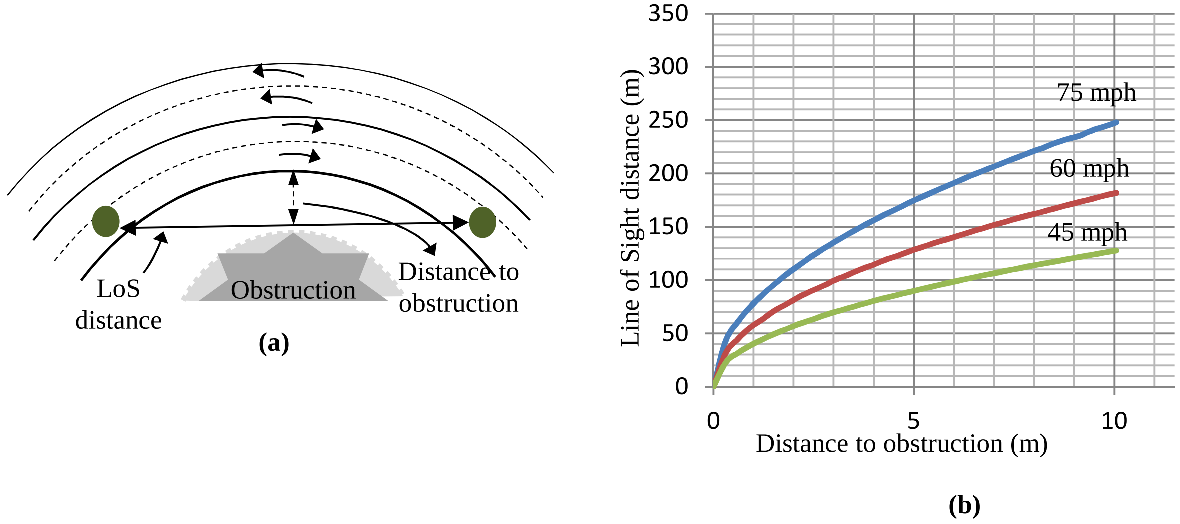
### *3.2.2) Second Procedural Step: Reception of Warning BSMs and Validation:*

Once a DSRC equipped vehicle entering the back of the queue passes the criteria as explained above, it issues the warning BSMs. These warning BSMs are intended for the potential ad-hoc hosts vehicles i.e., DSRC equipped vehicles travelling behind, on the same road. However, all vehicles, within the direct wireless access range of the warning BSM issuing vehicle, will receive those messages. All the unintended recipients need to be filtered out and only one of the intended recipients will be finally selected as an ad-hoc host. In the following, these two aspects of the reception of warning BSMs and the validation of intended recipients are being described in more detail.

**3.2.2.1) Reception of warning BSMs:** Once, a DSRC equipped vehicle issues warning BSM, it is broadcast in all directions with its direct wireless access range. Theoretically, the direct wireless access range is 500m, however, from our prior practical experience it turns out to be around 250m. That means that all DSRC equipped vehicles within a radius of 250m of the warning BSM issuing vehicle, will receive these messages. The intended recipients include the potential ad-hoc host vehicles which are travelling behind within 250m on the same road provided there is a clear LoS. The clear LoS will be affected by many factors including some moving obstacles i.e., non-DSRC equipped vehicles travelling in between the warning BSM issuing vehicle and potential ad-hoc host vehicles. The moving obstacles can be dealt with by transmitting each of the two warning BSMs, three times within a time interval of 100ms as explained earlier. Please note that travelling at 60MPH, a vehicle can travel about 9ft within 100ms, during which most moving obstacles can clear the LoS.

In addition to moving obstacles, road geometry features could also affect the LoS and thereby limit the reception range in which a warning BSM can be received. Broadly speaking, there are two major road geometry features that directly affect the LoS: horizontal road curvature and vertical road curvature i.e., road elevation. In the following both these limiting factors are described in an attempt to establish the guidelines to find out the practical LoS distance for reliable operation of DSRC based V2V communication.

(i) **Horizontal Road Curvature:** On a circular horizontal curve, the LoS between two vehicles is limited whenever an obstacle is present alongside the road, e.g., some natural growth or a concrete structure. On a freeway, the LoS distance is measured as the distance between two vehicles that are in the middle of the innermost lane, as shown in figure 3.3(a). The LoS distance will increase as the distance of the obstruction from the road increases, as shown in figure 3.3(b).



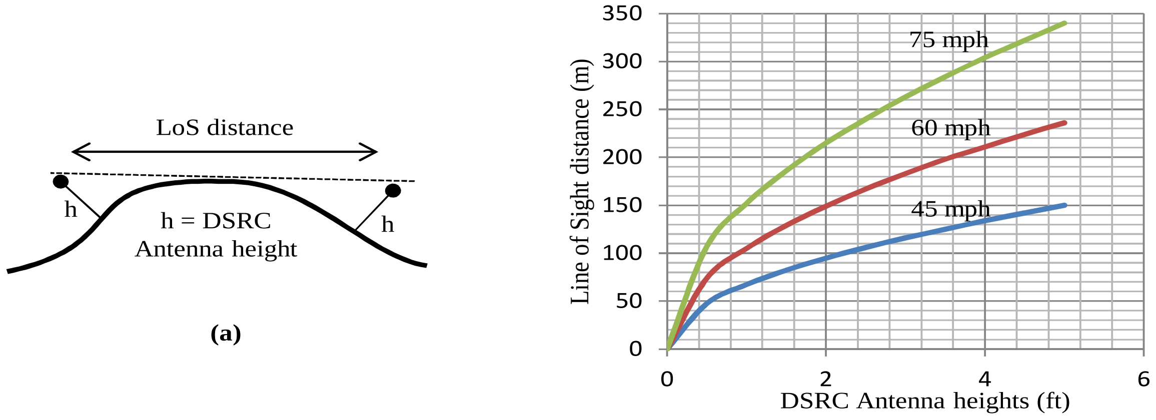
**(a)**

**(b)**

**Figure 3.3 LoS distance (a) on a horizontal curve, (b) versus distance to obstruction on a horizontal curved road.**

We calculated LoS distance as a function of distance to the obstruction for the design speeds of 45, 60, and 75MPH as shown in Figure 3.3(b) [45]. Please note that the design speed determines the degree of curvature of any roadway. The higher the design speed is, the lesser the degree of curvature and thereby the estimated LoS distance is greater (figure 3.3(b)). Although, distance to obstruction could vastly vary in an urban situation, generally, the recommended minimum horizontal curve obstruction distance is 6m [46] which gives an LoS distance of around 150m at the design speed of 60MPH (figure 3.3(b)). That means that on a curved road with design speed of 60MPH, the DSRC based V2V communication is limited to around 150m.

**(ii) Vertical Road Curve:** A vertical curve is a parabolic curve that is designed to make a transition between two grades on a given road [47]. Vertical curve could be sag or a crest vertical curve. While the sag curve does not limit LoS, the crest vertical curve does. The road surface itself is an obstruction to the LoS between two vehicles on a crest curve as shown in figure 3.4(a). On any freeway, the LoS distance is measured as the distance between two vehicles on the opposite side of the vertical crest curve (figure 3.4(a)) and depends upon the DSRC antenna height (h).



(a)

(b)

**Figure 3.4 LoS distance (a) on a vertical curve, (b) versus the DSRC antenna height for a vertical curved road.**

We calculated the LoS distance as a function of antenna height and plotted in figure 3.4(b) for the design speeds of 45, 60, and 75MPH. Generally, the antenna height is comparable to the driver eye height which is taken as 3.5ft for most vehicles [48]. Using this antenna height, the LoS distance for the design speed of 60MPH turns out to be around 200m.

**3.2.2.2) Validation of Intended Recipients:** Once the warning BSMs are broadcast, all vehicles within direct wireless access range of the warning BSM issuing vehicles, with clear LoS will receive those messages. The warning BSM will carry the following three parameters which will help filter out the unintended vehicles and validate only the potential ad-hoc hosts from which a single ad-hoc host is finally selected. In other words, the potential ad-hoc host identification process is accomplished with the help of the following three tests:

**(i) Speed:** The warning BSM will carry the highest of the three stored speeds of the BSM issuing vehicle prior to issuing the warning BSM. All the recipient vehicles will compare their own speed with this speed. The speed of the potential ad-hoc host vehicles travelling at free flow speeds should be comparable to this speed value within one standard deviation of average speed variability [48]. We have chosen the upper limit of one standard deviation to determine comparability in speed test. The vehicles which are ahead of the warning BSM generating vehicles on the same road will not have comparable speed because they have already entered in the congestion. Similarly, this test will also eliminate the vehicles on any parallel service road on which the free flow speed is assumed to be relatively less. Please note that the vehicles travelling on opposite lanes or any crossing freeway or road will be eliminated by using the heading parameter.

**(ii) Location:** The warning BSM will carry the location of the vehicle when it issued the warning BSM. Upon receiving the BSM, all vehicles travelling behind including the potential ad-hoc host vehicles, will calculate their distance to determine their proximity to the warning BSM issuing vehicle. The potential host could be very close to the warning issuing vehicle or as far as 250m (the upper end of the practical DSRC wireless access range) which is usually the case on a straight road with no elevation. It is not desired to choose a potential host too close to the warning BSM issuing vehicle which is already about to enter the back of the queue. Rather, a potential host should be behind at a comfortable buffer distance while still travelling at free flow speed, so that it can estimate SLoC by itself experiencing the change of speed from free flow to congested flow. We have chosen this buffer distance to be 50m which will help select the potential ad-hoc hosts travelling at free flow speed, and within reach of direct wireless access range even on a curved or an elevated road. That means that the potential host could be anywhere between 50 and 250m from the warning BSM issuing vehicle.

**(iii)Heading:** The warning BSM will also carry the heading of the BSM issuing vehicle calculated over its last travelled distance of 100 – 150m as described earlier and also shown in figure 3.5. All of the recipient vehicles which have passed the speed and distance tests will also calculate their own heading from their own location to the location of the warning BSM issuing vehicle. The vehicles which are travelling behind the warning BSM issuing vehicle should have a comparable heading.

The figure 3.5(a) shows the two headings i.e., the heading of the potential host to the warning BSM issuing vehicle, and the heading sent by the warning BSM vehicle, for a straight road section. Each of these two headings are calculated between two points in which first point (i.e., the location of warning BSM issuing vehicle) is common and the second point is variable as shown in Figure 3.5(a). The variability of the second point and therefore the difference in the two heading values will depend upon the relative locations of the potential ad-hoc host and warning BSM issuing vehicles. In case of a straight road, the difference between the two headings will be negligible regardless of the relative locations of the potential ad-hoc host and warning BSM issuing vehicles which could be 150m apart as shown in Figure 3.5(a).

In case of curved road the wireless access range will be limited and potential ad-hoc host will be only as far as 150m from the warning BSM issuing vehicle for a freeway with design speed of 60MPH as discussed earlier. Therefore, the maximum relative distance between potential ad-hoc host and warning BSM issuing vehicle will be 100m as shown in Figure 3.5(b). This will give a maximum differential heading of about $\pm 14.1^{o}$ because the standard road curvature design guidelines suggest that a freeway designed for the speed of 60MPH, can curve $0.141^{o}$ per meter at the most [42]. Therefore, we have used $\pm 15^{o}$ as a differential heading limit to check the comparability of the two headings. This will ensure elimination of all the vehicles on opposite lanes as well as on any crossing roads.

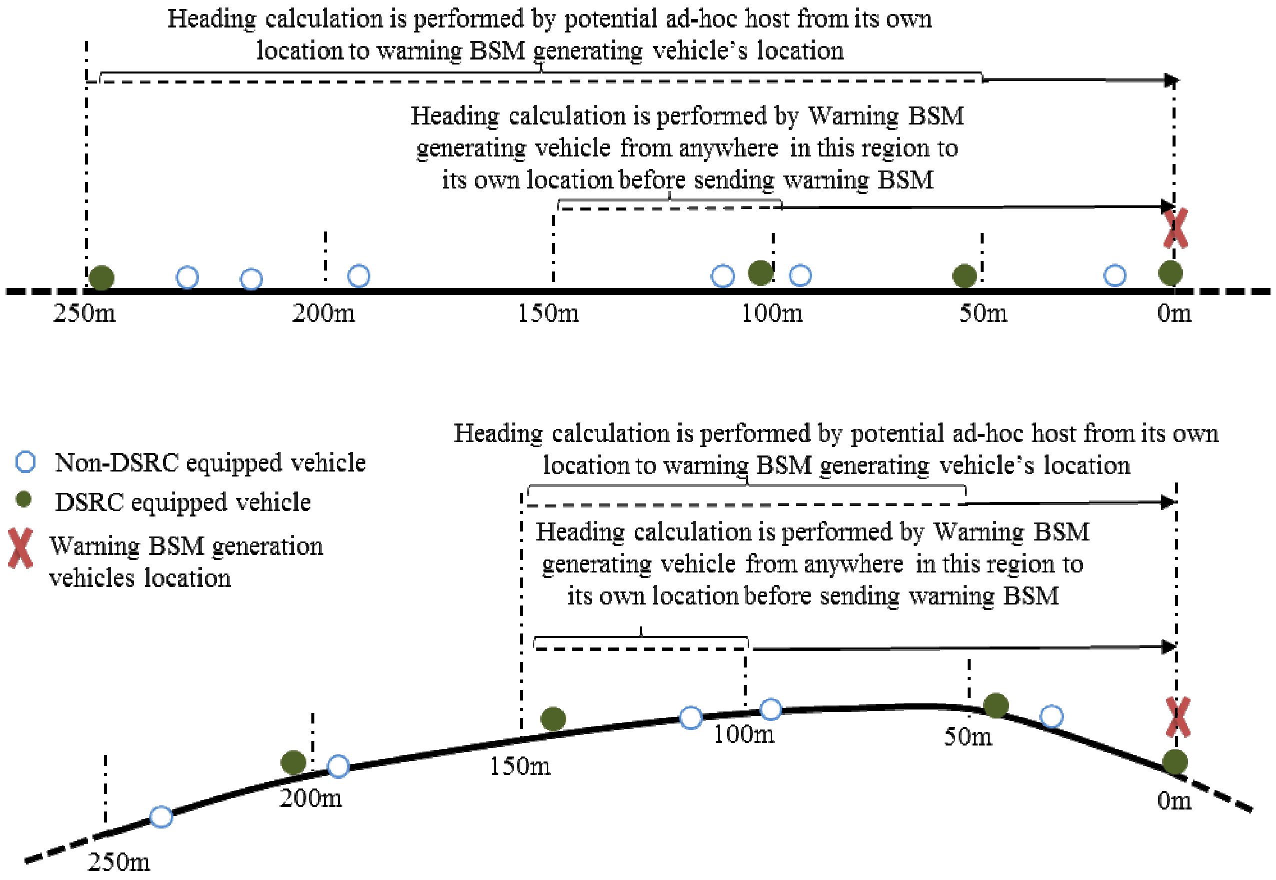


**Figure 3.5 Comparison of headings calculated by a potential ad-hoc host and the warning BSM issuing vehicle for (a) straight road, and (b) curved road.**

Any recipient vehicle which passes all of the above tests will become a potential ad-hoc host. However, if there are more than one such potential ad-hoc hosts identified at the same time, then it is necessary to single out one ad-hoc host from them. The final ad-hoc host selection is done based upon its distance from the warning BSM issuing vehicle. The preference is given to the potential host which is farther from the warning BSM issuing vehicle to ensure that the potential host is still in the free flow region. To achieve this, each potential host, immediately passing all the tests, will wait for a randomly selected waiting time period depending upon its distance. The larger the distance is the shorter the waiting time will be. The potential host which will come out of the waiting time routine first, will become the final ad-hoc host and will issue a BSM indicating that it has taken over as a new ad-hoc host.

There is a possibility that another potential host in waiting routine does not receive the newly selected ad-hoc host’s BSM due to a temporary loss of LoS, and claims to be the ad-hoc host itself upon coming out of the waiting time routine and thereby issuing a BSM indicating that it is also an ad-hoc host. In that case, the earliest selected ad-hoc host will be given preference to resolve the conflict and by comparing the time stamps of the newly selected ad-hoc hosts, one of them ceases to be the ad-hoc host. This can be accomplished within a short time period. In our evaluation, it took only 1-2 seconds to eliminate the two host conflict possibility.

### 3.3) Ad-Hoc Host functionality

Once a new ad-hoc host is selected, it’s role is to perform three important tasks; (i) periodic dissemination of an already estimated set of traffic parameters by a prior host, to the vehicles travelling behind the congested region, (ii) the acquisition of a new set of traffic data parameters i.e., SLoC, TT, and ELoC, and (iii) help transition ad-hoc control to another vehicle after estimating new set of traffic data parameters. These three tasks are described in more detail below.

### *3.3.1) Dissemination of Traffic Data*

The ad-hoc host will periodically broadcast the traffic data parameters to the vehicles behind the congestion region and approaching to the congestion using V2V communication. The traffic parameters are originated every sec from the ad-hoc host as a BSM which carries these traffic parameters as well as the indication that an active ad-hoc host exists in its data field. These information BSMs are intended for the vehicles on the same road, coming in the same direction towards the congestion. To accomplish this, these information BSMs are propagated in the intended direction on the road using the V2V communication protocol developed earlier in our prior work [32]. The maximum propagation distance can be set by the ad-hoc host which could be about 5 - 10 times the length of the congestion. Any DSRC vehicle on the same road behind the congestion will not only extract the traffic parameters for its own use from the information BSM but will also help relay the BSM. Please note that DSRC equipped PCMS which if present alongside the road will also receive these information BSMs from a passing by DSRC equipped vehicle, and will display the useful traffic parameters for those vehicles which lack DSRC capability [33].

### *3.3.2) Acquisition of new set of Traffic Parameters*

In addition to dissemination of traffic parameters, an important task of an ad-hoc host is to estimate new set of traffic parameters i.e., SLoC, ELoC, and TT. This is accomplished by acquiring its position every second using GPS receiver, and calculating speed and deceleration. By comparing the newly calculated deceleration every sec with $a_{th}$, it will estimate the SLoC. After the SLoC, the ad-hoc host enters the congestion and its speed is reduced to the congested flow speed. Once ad-hoc host is in the congestion, it will keep on acquiring its position every second, calculating its speed, and comparing it with its own free flow speed prior to entering the congestion. When the speed of the ad-hoc host increases beyond a certain threshold speed and stays above for 10 consecutive seconds, it will assume that ELoC has been reached. We have assumed the threshold speed to be 85% of ad-hoc host's initial free flow speed because the usual free flow speed variation could be within 15% [48]. After estimating ELoC, the ad-hoc host will estimate TT as the time passed between SLoC and ELoC.

Once, the new set of traffic parameters i.e., SLoC, ELoC, and TT are estimated, the ad-hoc host will update the corresponding fields of the information BSM with these new parameters and will change the status of the active ad-hoc host to inactive. After crossing ELoC, the ad-hoc host will be leaving the congested section of the road, and will no more be able to perform its duties as ad-hoc host. Therefore, it will take steps to hand over ad-hoc control to another DSRC equipped vehicle as explained below.

### *3.3.3)* *Ad-Hoc Host Transition*

After crossing ELoC, the ad-hoc host will continue to disseminate information BSMs with updated traffic parameters and ad-hoc host status change, for another 5 seconds before abandoning its role as an ad-hoc host. During these 5 seconds, the DSRC vehicles which are about to enter the SLoC, will receive the information BSMs and after knowing that there is no active ad-hoc host present, they will repeat the ad-hoc host selection routine in the same way as described earlier. The process will continue until congestion ends or for some reason, ad-hoc host cannot complete the process of updating the traffic parameters. For example, if ad-hoc host decides to pull over and wait for congestion to clear, or decides to take a U turn, or takes an exit from the freeway in the middle of the congestion. In the ad-hoc host routine, there will be periodic checks (e.g., heading check and position check) which will detect these situations, and force the ad-hoc host to change the status from active host to an inactive one, thereby initiate a new ad-hoc host selection exercise. Similarly, if for some reason, DSRC equipment of an ad-hoc host fails, it will stop transmitting information BSMs, which will also initiate the new ad-hoc host selection routine as described earlier.

It should be noted that for a few seconds (maximum up to 5 seconds), the vehicles that are behind the SLoC i.e., trailing the vehicles which issue warning BSMs, will keep on receiving the information message from both the old and newly selected ad-hoc hosts while former will indicate that there is no active ad-hoc host and the later will indicate that there is an active ad-hoc host. To resolve this confusion, the vehicles that are receiving both the information messages, will give priority to the information message indicating an active ad-hoc host.

# Chapter 4

# System Field Evaluation and Lab Testing

The whole operation of the developed information system using an ad-hoc control and DSRC based V2V communication as described in previous section is managed by the program running in the OBUs of all DSRC equipped vehicle on the road. A high level functional flow chart of the program is given in figure 4.1. Please note that all vehicles are running the exact same program. To demonstrate the whole operation in the field, we need many DSRC equipped vehicles on a congested road test bed. Please note that some parts of this operation as shown in right dashed box are similar to the ones which we have previously demonstrated in our prior works. These include acquisition and dissemination of traffic parameters to the DSRC equipped vehicles, and to the DSRC equipped PCMSs to display the traffic parameters for the vehicles lacking DSRC capability [33].

Please note that we have not done a full field demonstration of the whole operation of the newly developed system at this time rather for the most crucial parts of the operation which we have not previously demonstrated. These crucial parts consist of auto detection of SLoC by a DSRC equipped vehicle entering the back of the queue, and selection of an ad-hoc host from the vehicles which are travelling behind, and have yet to enter the back of the queue.

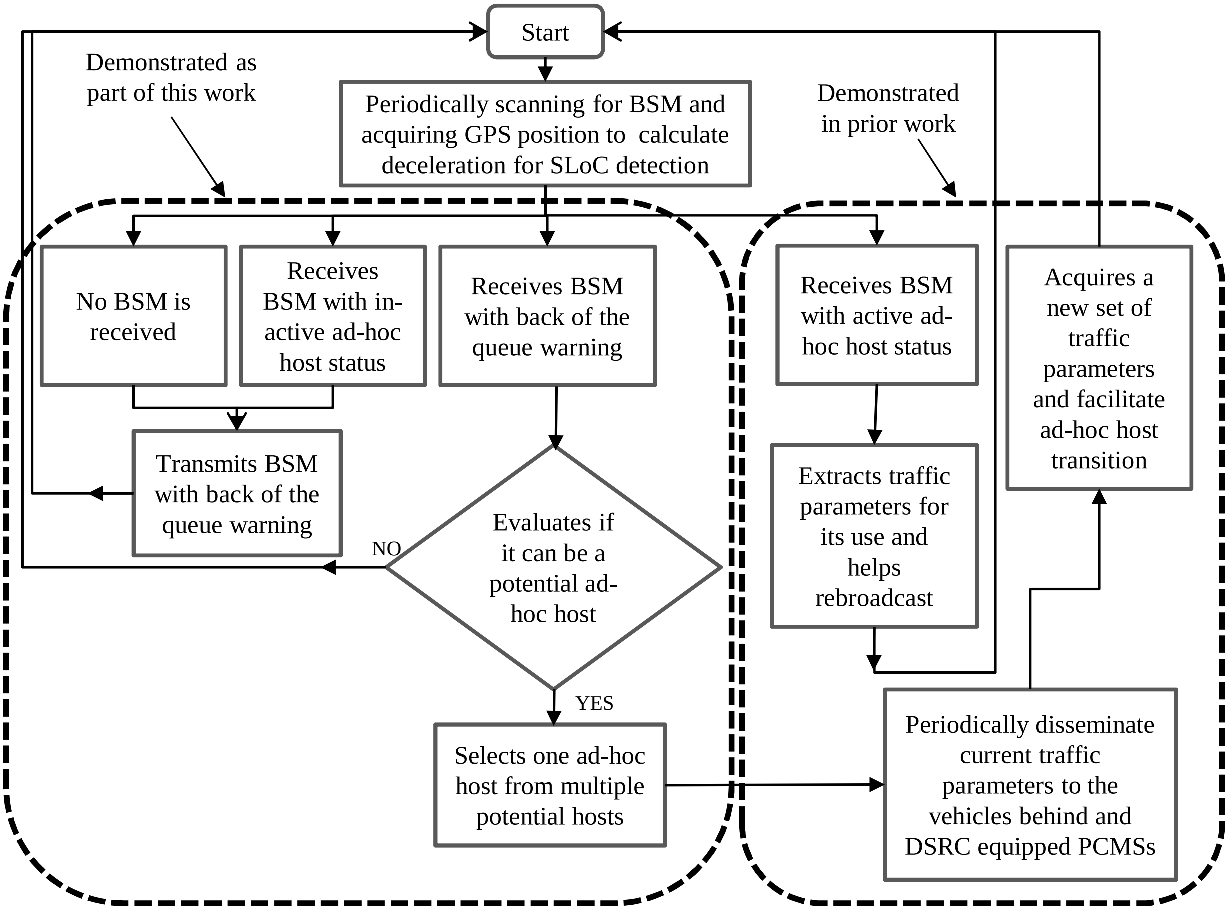
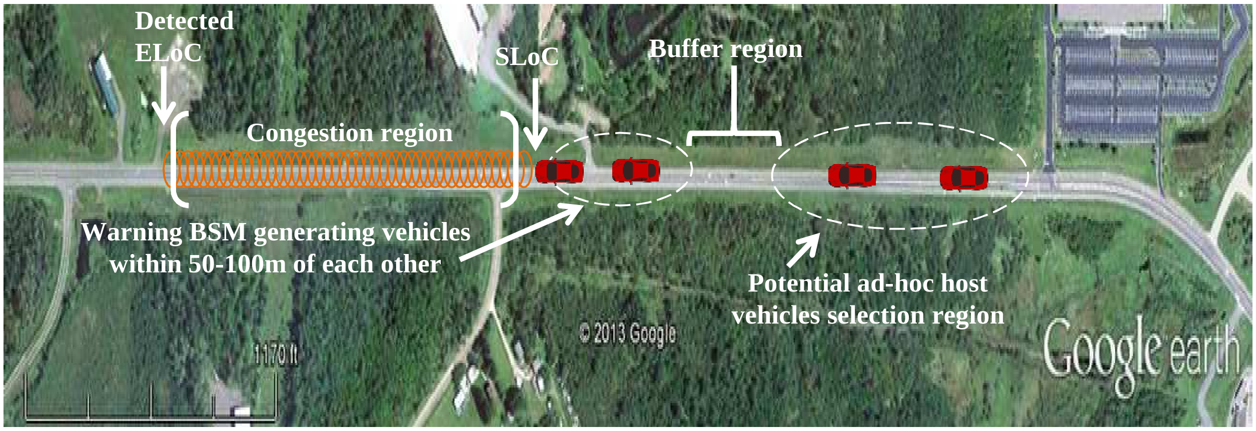


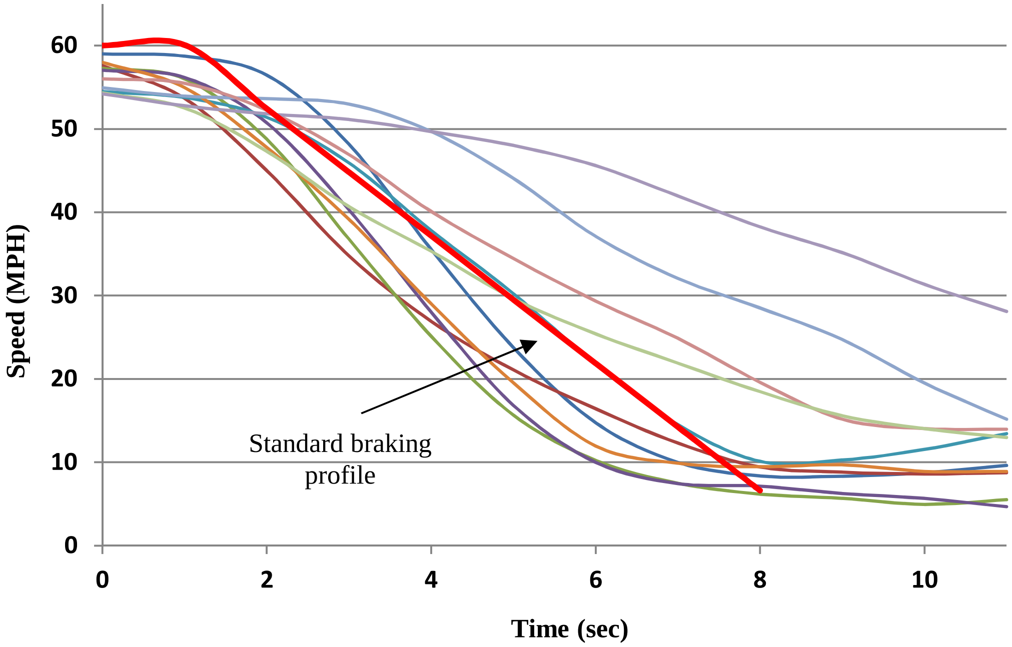
**Figure 4.1 High level program flow chart of the operation of the developed information system.**

For this field evaluation, we have chosen the same venue as in our previous demonstrations i.e., the Rice Lake Rd in Duluth, MN as shown in figure 4.2(a). We identified a congestion section on this road and drove two DSRC equipped vehicles at around the speed of 55MPH within 50 – 100m from each other and applied breaks before entering the identified SLoC point on the road. We repeated this process many times to simulate multiple braking profiles. These multiple braking profiles are shown in figure

4.2(b). Please note that a standard braking profile is also shown in figure 4.2(b) for comparison purposes.



(a)



(b)

**Figure 4.2 (a) The chosen field evaluation site showing congestion and DSRC equipped vehicles, and (b) multiple vehicle braking profiles acquired during field evaluation.**

Both these vehicles issued the warning BSMs each time when their braking profiles fulfilled the criteria of auto detection of SLoC. Please note that in a given test run, either both vehicles, or one of the two, or none of the vehicles issued warning BSMs. We had two more vehicles which were travelling 100 – 200 m behind the two warning BSM issuing vehicles within 50 – 100 m of each other as shown in figure 4.2(b). These two vehicles received the warning BSMs and depending upon their relative location, either one or both of them passed the potential ad-hoc host test. In either case, one of those vehicles was successfully chosen as ad-hoc host. In some cases, when one vehicle was chosen as an ad-hoc host, the other did not register and also claimed to be the ad-hoc host. However, based upon our designed protocols as explained earlier, this conflict was resolved successfully with a second or two. The ad-hoc host was then able to periodically broadcast an already estimated set of traffic parameters (SLoC, ELoC, and TT) as well estimated a new set of these parameters before helping select a new ad-hoc host.

Please note that to do this demonstration in the field we needed 4 synchronized drivers on the road at the same time. To repeat the test runs many times for different scenarios, it was logistically challenging. So we took multiple location profiles of all four DSRC units via GPS, while travelling alone on the road with various speeds and different braking profiles (figure 4.2(b)). We tested this data extensively in the lab environment to evaluate auto detection of SLoC and ad-hoc host selection. Every time, the auto detection of SLoC, and host selection was according to the criteria we designed.

# Chapter 5

# Conclusions and Future Work

## 3.2.2) Conclusion:

We have successfully developed and field evaluated a real-time traffic information system that utilizes DSRC based V2V communication to dynamically acquire and broadcast the traffic parameters such as SLoC, ELoC, and TT without requiring any roadside infrastructure support. The developed system relies on a DSRC equipped ad-hoc host vehicle to detect traffic parameters and periodically broadcast useful traffic alerts to the drivers who need timely information to make informed decisions. The ad-hoc host is chosen by detecting SLoC using  deceleration profile of multiple DSRC equipped vehicles entering the back of the queue, which, in turn, send warning BSMs to the vehicles trailing behind using DSRC based V2V communication. One of the DSRC equipped vehicles receiving the BSMs is selected as an ad-hoc host. We also established guidelines to find out the practical wireless access range of DSRC for V2V communication over a horizontal and vertical curved road. It was found that on a road designed for 60MPH speed, the horizontal curve restricts the DSRC range to 150m, while the vertical curve limits the range to 200m.

Once an ad-hoc host is selected, it periodically broadcast useful traffic parameters to the vehicles trailing far behind the SLoC as well as helps estimate a new set of traffic parameters. After successfully acquiring a new set of traffic parameters, the ad-hoc host helps transition the control to a new ad-hoc host and this process continues until the congestion ends. We did field testing to successfully evaluate the developed algorithms.

The speed profiles of the DSRC equipped vehicles necessary to generate warning BSM was gathered from the actual field, and the data was then utilized in the lab to evaluate the BSM generating algorithm. The vehicles behind the warning generating BSM vehicles received those messages and depending upon their relative location, either one or both of them passed the potential ad-hoc host test. One of those vehicles was successfully chosen as ad-hoc host.

In this hybrid system, the DSRC-equipped PCMSs are strategically placed alongside the work zone road, and are treated just like DSRC equipped vehicles as information messages recipients except that they can display the received information messages to many passing by drivers lacking the DSRC capability. For this purpose, a DSRC-PCMS interface was developed which helps PCMS to receive safety messages containing TT and SLoC from a nearby DSRC-equipped vehicle using DSRC-based V2V communication. Furthermore, a rigorous analysis has been conducted to investigate the minimum DSRC market penetration rate needed for the previously developed hybrid system to successfully acquire and disseminate TT and SLoC for the work zone. The results of this analysis when applied to a practical road scenario, indicated that a market penetration rate ranging from 20% to 35% is needed for the system to work with the lower rate needed for rush-hour conditions. Although, this was specific to a one-road situation, this implies that the required DSRC penetration rate in rush hour will generally be less than the DSRC penetration rate required in non-rush-hour condition for the developed system to reliably work. This is because the vehicle densities are much higher in rush hour to sustain DSRC-based V2V communication which is a limiting factor to determine the minimum DSRC penetration rate needed for reliable dissemination of the information message.

## 5.2) Future Recommendations:

In future, we plan on extending the current work to include multiple hosts selection to carry out timely acquisition of traffic data. While a chosen host is travelling through the congestion, another host can be selected after a specified time interval to acquire the updated traffic parameters and disseminate them at a reasonable frequency. Additionally, we also plan to include the Geographical Information System (GIS) support for displaying the safety information on a map. This information will include information such as real-time traffic flow speeds on the roads, road names, hazard zones such as sharp curves, weather alerts, and incident detection etc.

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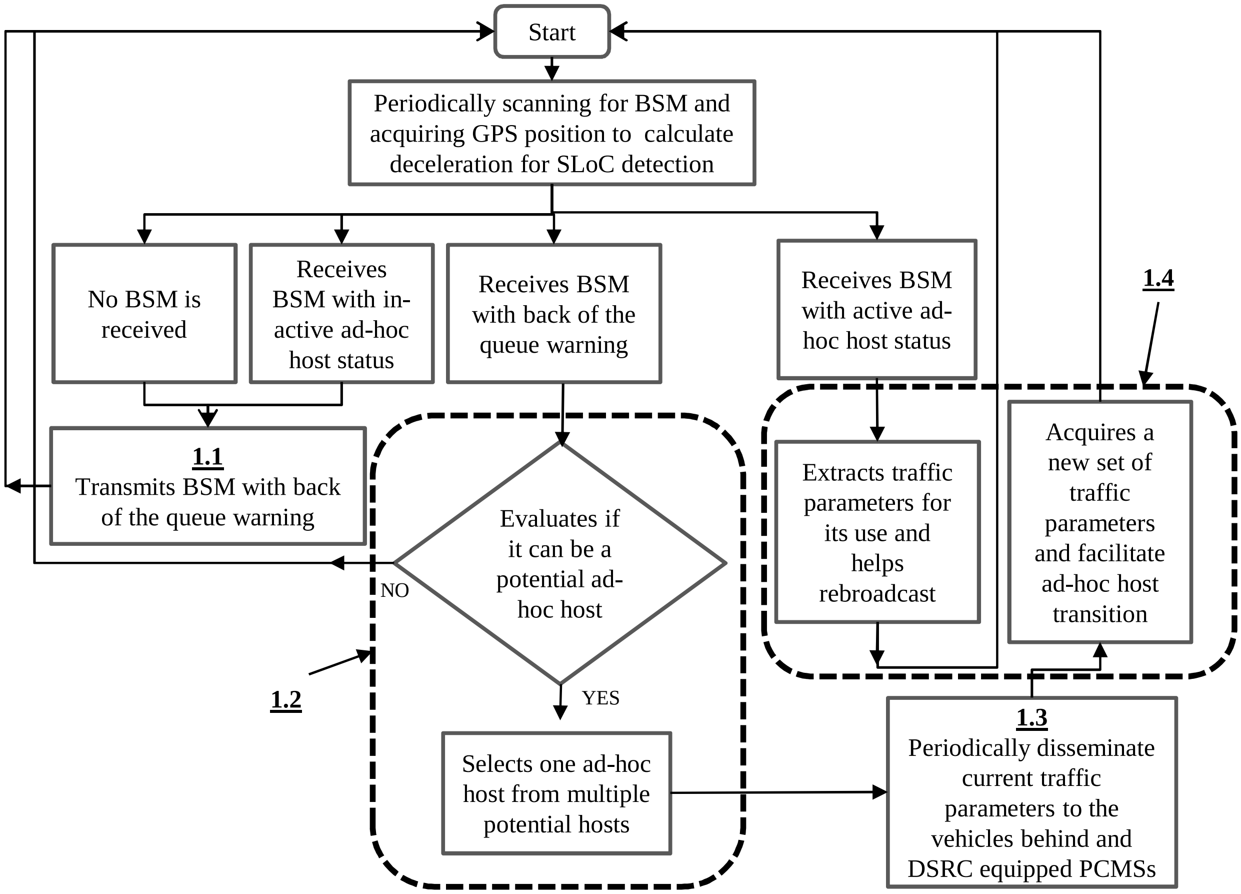
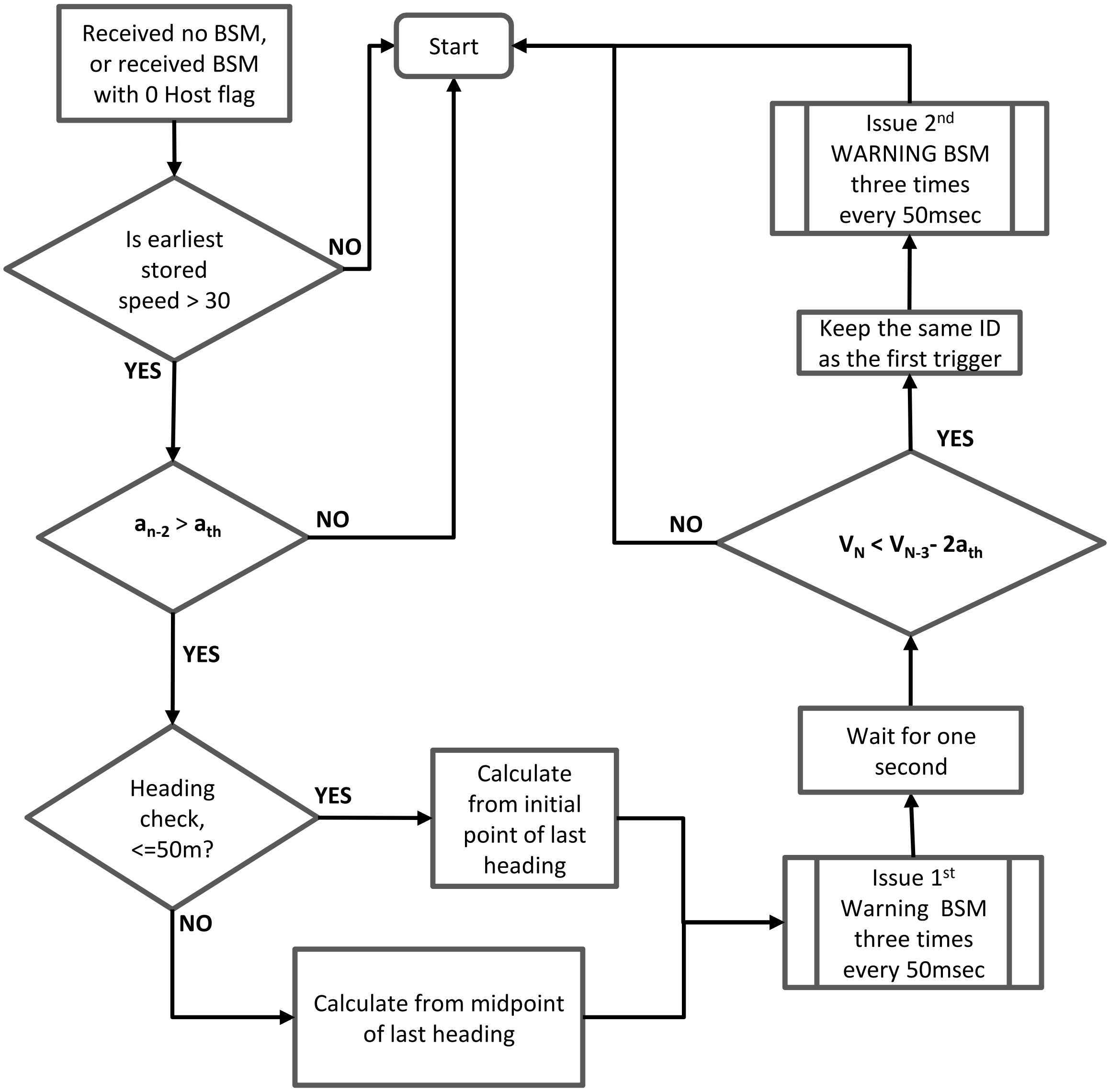
# Appendix A

## The OBU Program Flowchart

# 1. – Overall flowchart



## 1.1 - Warning BSM Generation



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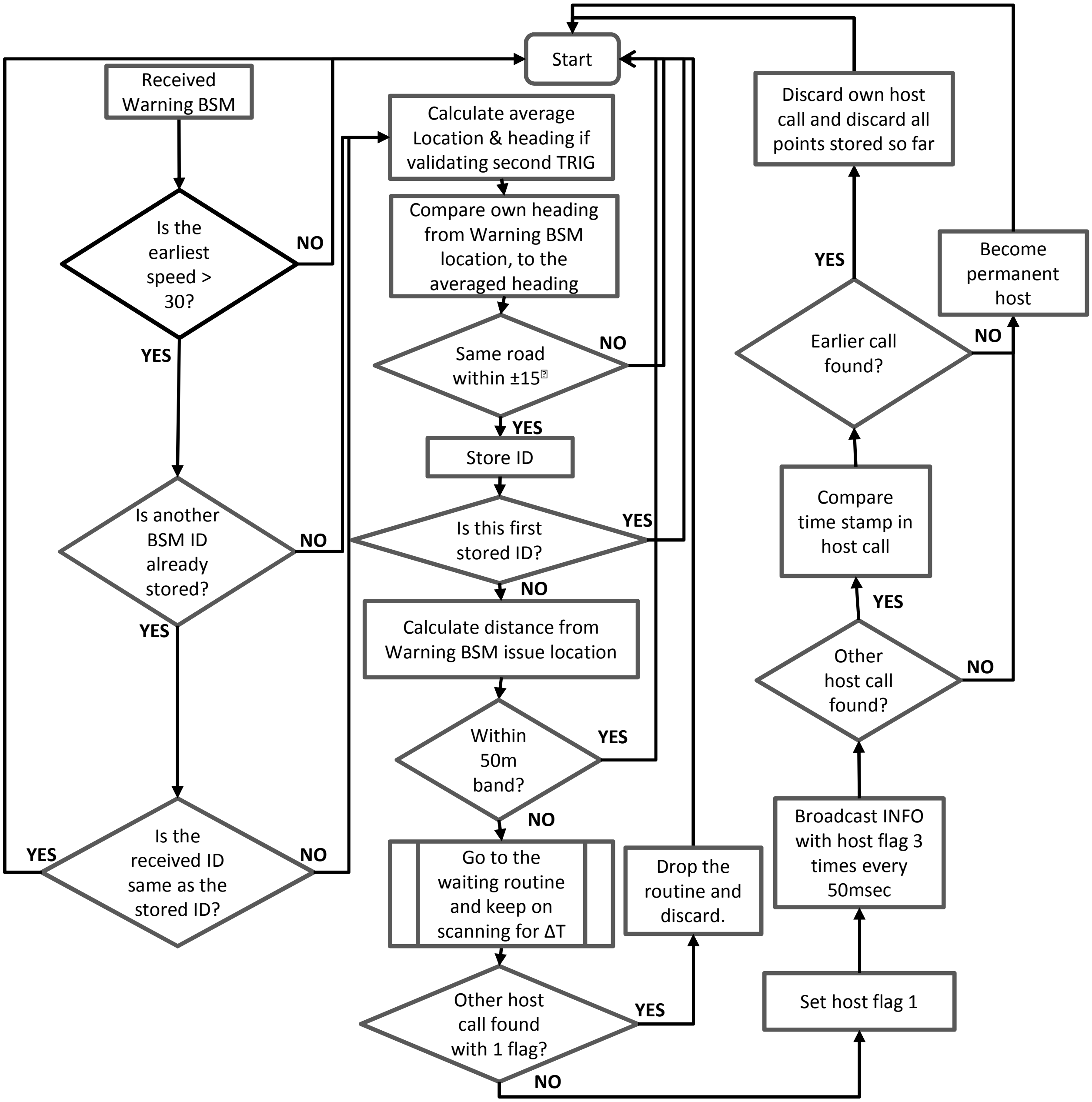
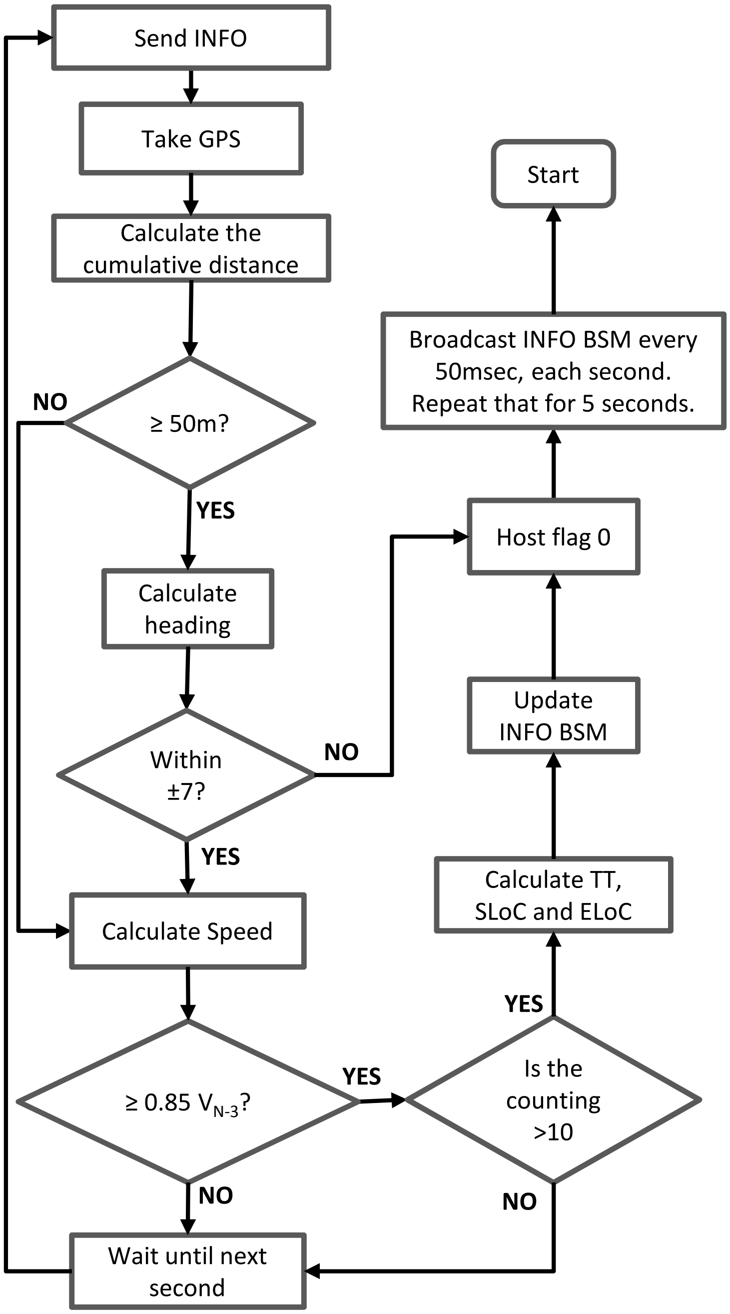


## 1.3 - Ad-hoc host functionality



## 1.4 - Parameter acquisition, dissemination, and host transition