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Development of Hybrid DSRC-PCMS Information Systems for Snowplow Operations and Work Zones

Final Report

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16. Abstract (Limit: 250 words)

The future deployment of dedicated short range communication (DSRC) technology requires that DSRC-based applications are integrated with existing traffic management techniques so that non-DSRC-equipped vehicles at the early stage of DSRC deployment can also reap the potential benefits of DSRC technology. We have successfully developed and field demonstrated a hybrid traffic-information system combining DSRC technology and portable changeable message signs (PCMS) for work zone environment to improve traffic mobility, and thereby, driver safety. The developed system uses DSRC-based V2I and V2V communication to acquire travel safety parameters such as travel time (TT) and starting location of congestion (SLoC), and disseminate these parameters to both DSRC-equipped vehicles and DSRC-equipped PCMSs, which are strategically placed alongside the road. Using the DSRC-PCMS interface designed for this purpose, PCMSs can receive these travel safety parameters from nearby DSRC-equipped vehicles on the road via DSRC-based V2V communication, and display them for the drivers of the vehicles lacking DSRC capability. Such a system can be useful for an early stage of DSRC deployment when the DSRC market penetration is low. Additionally, a rigorous analysis has been conducted to investigate the minimum DSRC market penetration rate needed for successful functionality of the developed system with respect to both acquisition and dissemination of TT and SLoC. Using realistic traffic flow model, guidelines are developed to estimate a minimum DSRC penetration rate needed to deploy the developed system for a variety of traffic scenarios on a given work zone road.

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List of Abbreviations

ACM	A la Carte Message
BSM	Basic Safety Message
DSRC	Dedicated Short Range Communication
EoMR	End of Monitoring Range
FCC	Federal Communications Commission
FHWA	Federal Highway Administration
GCC	GNU Compiler Collection
GPS	Global positioning system
ITS	Intelligent Transportation systems
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	Variable Message Sign

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)

Executive Summary

Congestion and hazardous traffic situations for the drivers on the road can occur around work zones and snowplow operation during the winter season due to low visibility. An information warning system for such environments can improve traffic mobility and thereby driver safety. Intelligent transportation systems (ITS) and other related technologies are being aggressively pursued to devise such automated traffic-information systems. Dedicated short-range communication (DSRC) has been considered as a key enabling wireless communication technology to realize such automated traffic warning systems. DSRC-based traffic-information systems use vehicle-to-vehicle (V2V) and/or vehicle-to-infrastructure (V2I) communication using DSRC technology to acquire and disseminate travel safety information. To take advantage of the disseminated information messages, a vehicle needs to be equipped with DSRC technology.

The future deployment of DSRC technology requires that DSRC-based applications are integrated with existing traffic management techniques so that non-DSRC-equipped vehicles at the early stage of future DSRC deployment can also reap the potential benefit of DSRC technology. We have successfully developed and field demonstrated a hybrid traffic-information system combining DSRC technology and portable changeable message signs (PCMS) for snowplow operation and work zone environment to improve traffic mobility, and thereby, driver safety.

The developed system uses DSRC-based V2I and V2V communication to acquire safety parameters such as travel time (TT), starting location of congestion (SLoC), and location of snowplow, and disseminates these parameters to both DSRC-equipped vehicles and DSRC-equipped PCMSs which are strategically placed alongside the road. Using the DSRC-PCMS interface designed for this purpose, PCMSs can receive these safety parameters from nearby DSRC-equipped vehicles via DSRC-based V2V communication and display them for the drivers of the vehicles lacking DSRC capability. Such a system can be useful for an early stage of DSRC deployment when the DSRC market penetration is low.

The developed traffic-information system is fully portable and can be installed easily on any roadside of interest to monitor the congestion buildup around the work zone or to help display advisory messages on the PCMSs while snowplow operation is in process. Once powered up, the system seamlessly and securely gathers the required traffic parameters such as TT, SLoC, and location of the snowplow on the road. The acquired information is processed and then disseminated periodically to the vehicles as well as to PCMSs having DSRC capability using a combination of both V2I and V2V communication.

Furthermore, a rigorous analysis has been conducted to investigate the minimum DSRC market penetration rate needed for the developed hybrid 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. The lower penetration rate is needed for rush hour traffic because the vehicle densities are much higher in rush hours 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.

Chapter 1. Introduction

1.1 Background and Prior Art

Growing congestion, gridlocks, & traffic jams on US roadways necessitate expanding or repairing existing highway infrastructure, improving mobility and safety for commuters. Many roads in need of repair or expansion, add to growing number of work zones throughout the US leading to congestion buildups near work zones resulting in dangerous traffic conditions and increased frequency of crashes [1-2]. Although, most of the road repair work is done in summer season, winter season has its own roadway bottlenecks. Snow in winter season gives rise to increased number of snowplows on the US roadways which further adds to the hazardous driving conditions. While in operation, snowplows significantly reduce driver visibility and therefore can create dangerous traffic situations on the road so there is need for a traffic-information system that could timely warn the drivers of the ongoing snowplow operation as well as provide the snowplow vicinity on the road [3].

The work zone related congestion can grow very quickly which highlights the need for a traffic-information system to warn the drivers of timely updates on travel time and congestion lengths [4-5]. Similarly, in winter season, a warning system for snowplow is considered equally beneficial in terms of safety which can let the drivers know about the speed and whereabouts of the snowplow so that they can be ready for a snowplow ahead by adjusting their vehicle's speed or taking a detour. Therefore, an automated traffic warning system can help in both work zone as well as in snow plow scenarios. Many research reports by Federal Highway Administration (FHWA) have clearly shown that an automated traffic-Information system is highly desired to minimize backups and improve safety [6-9]. Intelligent transportation systems (ITS) and other such coexisting technologies are being aggressively pursued to devise such automated traffic-information systems [10-15].

Several feasibility studies have been conducted [16-21] as well as a few prototypes have been demonstrated [22-23] to justify the immense impact of using dedicated short-range communication (DSRC) as a key enabling wireless communication technology in automated traffic-information systems. Although, most of these feasibility studies and prototype demonstrations revolve around an information system for work zone environment, a similar system could also work for a winter snowplow environment. In such automated traffic-information systems, DSRC communication can be used as vehicle-to-infrastructure (V2I), vehicle-to-vehicle (V2V), or a hybrid of both depending upon the application. The wireless frequency band 5.9 GHz has been allocated by the Federal Communications Commission (FCC) as DSRC channel, intended to be used solely for automotive safety communication applications. The USDOT currently holds the DSRC as the only wireless communication technique that provides desired qualities for vehicular communication such as fast network acquisition time, low latency, high reliability, priority for safety applications, interoperability, security and privacy etc.

1.2 Research Objectives and Methodology

Normally, DSRC-based traffic-information systems have two important components, (i) acquisition of traffic parameters such as travel time (TT), starting location of congestion (SLoC), and location of snowplow, and (ii) dissemination of these parameters to the vehicles coming towards the work zone congestion area. Usually, both acquisition and dissemination of the traffic parameters, e.g., TT and SLoC, and location of snowplow 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.

To enable a smooth transition towards full deployment of DSRC-based work zone traffic-information systems, integration of such systems with existing technology is a necessary choice. Portable changeable message signs (PCMS) have been used extensively for traffic control, and to display crucial travel related information in the work zone environment as well as for the snowplow operation related information [24-25]. 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 [26].

To accomplish both acquisition and dissemination of travel parameters using DSRC-based V2V and/or V2I communication, it is not necessary that all vehicles present on the road must be equipped with DSRC technology. 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.

In this research report, development and field demonstration of DSRC-based hybrid information systems for the work zone as well as for the snowplow using PCMSs is described. These hybrid systems are an extension of an already developed DSRC-based work zone travel information system which fully relied on DSRC technology for both acquisition and dissemination of TT and SLoC [23]. In the newly developed hybrid system, acquisition of TT and SLoC and snowplow location is still done using DSRC communication, but DSRC-equipped PCMSs are placed at strategic locations to disseminate the updated traffic parameters for those vehicles which lack DSRC capability.

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 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 hybrid information system for the work zone.

1.3 Report Organization

The rest of the report is organized into five additional chapters. The second chapter explains the DSRC-PCMS interface needed to implement the hybrid traffic-information systems both for work zone and the snowplow operation. The third chapter will describe the hybrid DSRC-PCMS traffic-information system for snowplow operation. The fourth chapter will discuss the architecture and functionality of the hybrid DSRC-PCMS traffic-information system for the work zone. The fifth chapter talks about the detailed analysis done to investigate the minimum DSRC market penetration rate needed for successful functionality of the developed hybrid traffic-information system for the work zone with respect to both acquisition and dissemination of important traffic safety parameters. Finally, the sixth chapter summarizes the conclusions.

Chapter 2. DSRC-PCMS Interface

To integrate the PCMS in our hybrid traffic-information systems for snowplow operation as well as 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, SLoC or speed and location information of a snowplow, 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 or around a snowplow operation, 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) [27].

2.1 Hardware Architecture

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 2.1 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 [29]. 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.

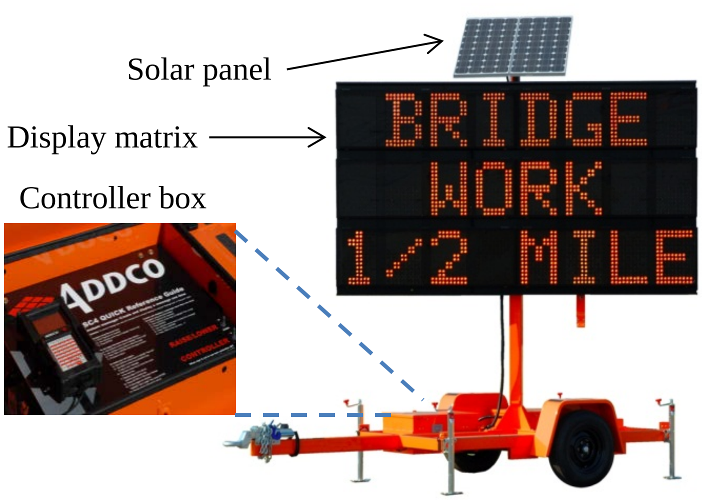

Figure 2.1: PCMS used in the research project.

The schematic of the DSRC-PCMS interface is shown in Figure 2.2. 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 and snowplow operation systems are shown in Figure 2.2.

Figure 2.2: Schematic diagram of DSRC-PCMS hardware interface.

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 2.3(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 view of SC4 controller is shown in Figure 2.3(a) and the DSRC unit used is shown in Figure 2.3(b).

Figure 2.3: (a) Top view of the SC4 controller deluxe version, and (b) Serial console of Savari DSRC unit.

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 2.3(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.

Chapter 3. Hybrid DSRC-PCMS Traffic-Information System for Snowplow

Using the DSRC-PCMS interface, we first developed a hybrid DSRC-PCMS information system for the snowplow operation. The primary objective of his hybrid information system is to utilize DSRC-based V2V and/or V2I communication to provide an advanced warning to drivers through DSRC-equipped PCMSs. Please note that the vehicles having the DSRC equipment can directly receive this message but for those vehicles which do not possess DSRC capability, the message is communicated via PCMSs.

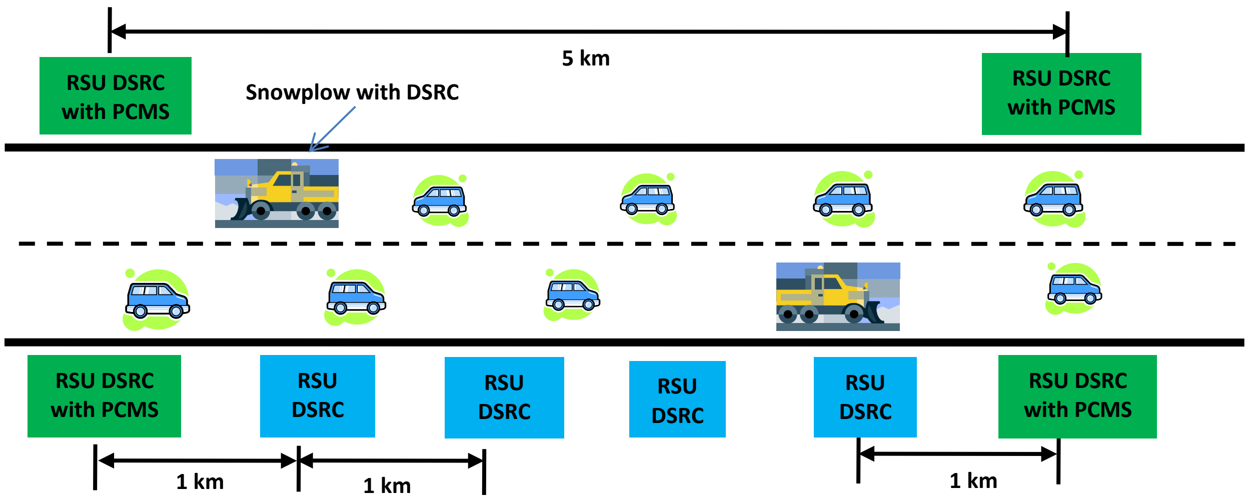

Figure 3.1: The schematic diagram of Snowplow Warning System using V2I and/or V2V based DSRC communication and PCMSs.

The schematic diagram of the architecture of this hybrid system is shown in Figure 3.1. To accomplish this, each snowplow needs to be equipped with a DSRC unit. This snowplow is also equipped with a sensor so that when it is engaged in snowplowing, that information can be acquired by its DSRC unit. A GPS unit is also interfaced with the snowplow DSRC unit so that it can acquire the speed and location of the snowplow. All this information, i.e., the speed and location of the snowplow, and whether the snowplow is active or not is then made available to the snowplow DSRC unit, which communicates this information to the surrounding roadside DSRC units using V2I based DSRC communication. The next step is to carry this information from the nearby roadside units to PCMSs present alongside the road, where this information can be displayed so that the passing vehicles can take advantage of that information and prepare themselves for the snowplow operation ahead. Please note that the DSRC roadside units need to be periodically installed on a given roadside to make this system effective especially, in the beginning phase of DSRC deployment when not many vehicles are equipped with DSRC units. Once this information is displayed on a given roadside PCMS, it will stay there for a finite amount of time for which this information is useful. After that duration of time, this information is taken off from the PCMS and PCMS can wait for the new useful information to be displayed.

An example of the information being displayed on DSRC-equipped PCMS is shown in figure 3.2. After receiving the speed and location information of a nearby snowplow, the RSU program processes the location information to determine how far the snowplow is from its location. This information coupled with road advisory is then transferred serially to the SC4 controller of the PCMS which prepares the display matrix to show this information.

Figure 3.2: Variable message signs showing critical information and portable PCMSs.

Once the snowplow information is communicated from the snowplow DSRC unit to the roadside DSRC unit and processed to be displayed on PCMS, then, the next step will be to control the timing of this information on a given PCMS, i.e., for how long this information is relevant and stay on the PCMS. Similarly, there could be many roadside DSRC units and corresponding PCMS present on a given highway. Not all the PCMS will need to display the information because it may not be relevant. For example, if snowplow is going eastbound, only eastbound PCMS need to display the information. Similarly, the PCMSs which are eastbound but ahead of snowplow also do not need to display the information. All this is controlled by the software of the DSRC units.

The software developed for the snowplow warning system is an extension of already developed system for the work zone [23]. The software is designed in a way to seamlessly support both V2I and V2V communication and is transparent to all the DSRC-equipped vehicles on the road. In the currently developed setup, the snowplow can either communicate with any of the RSUs installed along the road, or it can engage the DSRC-equipped vehicles on the road using V2V communication.

Depending upon the actual number and location of roadside PCMSs, the DSRC software can be modified to work accordingly. Unfortunately, we could not continue the full development of the software and the corresponding field demonstration due to inaccessibility to the snowplows and limited number of DSRC units. Therefore, we focused on developing a hybrid DSRC-PCMS traffic-information system for the work zone which is described in the next chapters.

Chapter 4. DSRC-PCMS Hybrid Traffic-Information System for Work Zone

In this section, the architecture, functionality, and DSRC-PCMS interface of the hybrid DSRC-PCMS system for work zone environment are described.

4.1 Architecture

The conceptual diagram of the developed hybrid work zone information system showing a typical work zone with growing congestion due to lane closure is shown in Figure 4.1. Previously, we developed a work zone travel information system which relied on DSRC-based V2I and V2V communication for both acquisition and dissemination of TT and SLoC (22). By taking advantage of the fact that a small percentage of DSRC vehicles are needed for both acquisition and dissemination of TT and SLoC, we added the DSRC-equipped PCMSs in our previously designed system to make a hybrid work zone travel information system (Figure 4.1). By adding the DSRC-equipped PCMSs at strategic locations on the roadside, all those vehicles lacking the DSRC capability will also be able to take advantage of the updated TT and SLoC information. Depending upon the availability of the PCMSs, they can be located every couple of miles and/or just before an alternative route if present. Please note that MUTCD also provides guidelines for placement of PCMSs on a variety of traffic scenarios.

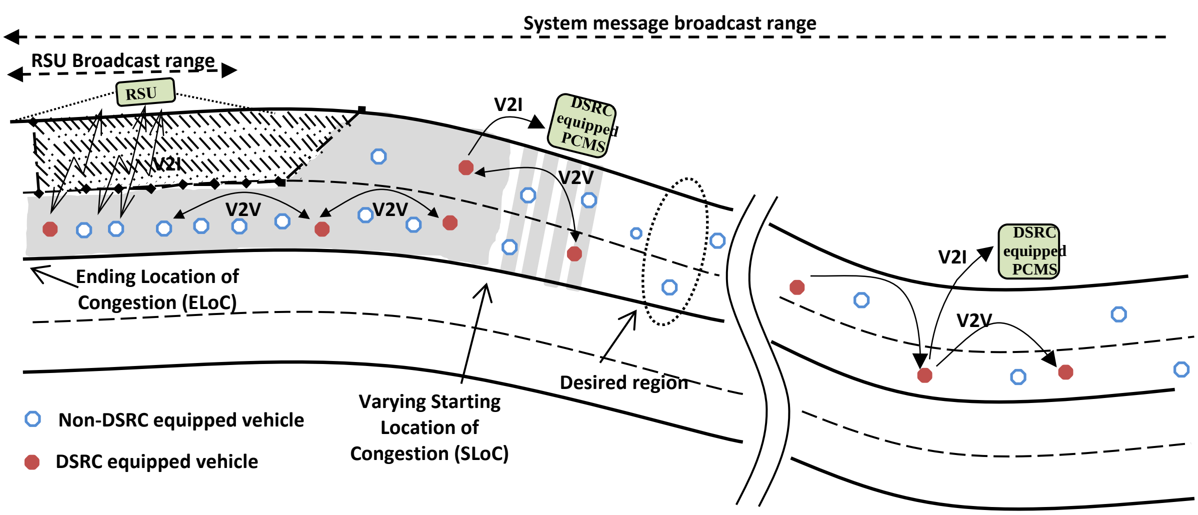

Figure 4.1: Conceptual architectural diagram of the developed hybrid DSRC-PCMS information system for work zone.

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 (22). 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 hybrid DSRC-PCMS work zone 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.

4.2 Functionality

After the central RSU is initialized, it selects a DSRC-equipped vehicle for monitoring its speed and location information to estimate TT and SLoC. The RSU selects a DSRC-equipped vehicle, preferably located well before the SLoC. The preferred area of selection before the SLoC is shown as *Desired Region* in Figure 4.1. Because the SLoC could vary depending upon the traffic influx, the RSU's software is designed to possess the capability to vary the *Desired Region* so that it always falls well before the SLoC.

To engage a vehicle for acquiring traffic information, the central RSU periodically transmits invitation messages to the DSRC-equipped vehicles using combination of V2I and V2V communication. DSRC-equipped vehicles located in the *Desired Region* will respond to the invitation messages by sending acknowledgements back to the RSU. One of the responding DSRC-equipped vehicles is selected by the central RSU for acquiring traffic data. The selected DSRC-equipped vehicle then periodically sends back to the central RSU its location and speed information while passing through the congestion area. When the selected DSRC-equipped vehicle travels beyond the ELoC, the central RSU estimates the TT and SLoC based upon the data received by this vehicle using a threshold based definition of congestion [23].

Once TT and SLoC are estimated, the information message containing updated TT and SLoC parameters is broadcast to all DSRC-equipped vehicles and PCMSs, periodically (e.g., every few seconds) but the information message is updated with a new set of values of TT and SLoC only when a selected DSRC-equipped vehicle travels beyond the ELoC completing the information exchange cycle with the central RSU as highlighted above. Normally, only one vehicle is selected and monitored at one time. However, if the TT turns out to be greater than a predefined threshold, then a new vehicle is selected after every *Update Time* so that a new set of TT and SLoC can be acquired every *Update Time*. Usually, *Update Time* needs to be selected large enough in which SLoC or TT can appreciably change.

During this whole process of estimating TT and SLoC, many messages are exchanged between the selected DSRC-equipped vehicles and the central RSU using DSRC-based V2I and/or V2V communication. Please note that the Society of Automotive Engineers (SAE) has specified safety message composition for the DSRC communication in their draft standard SAE J2735 [28]. In our work, we have used the message formats that comply with these standards and contain mandatory fields of the message types such as A_la_Carte (ACM) and Basic Safety Message (BSM). The messages which our protocols use, contain the data fields as specified in J2735 standards and the entire message is encoded and communicated according to the same standards. Additionally, in the back and forth communication between the central RSU and DSRC-equipped vehicles, all information will be exchanged without retaining any vehicle identity information to maintain privacy.

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.

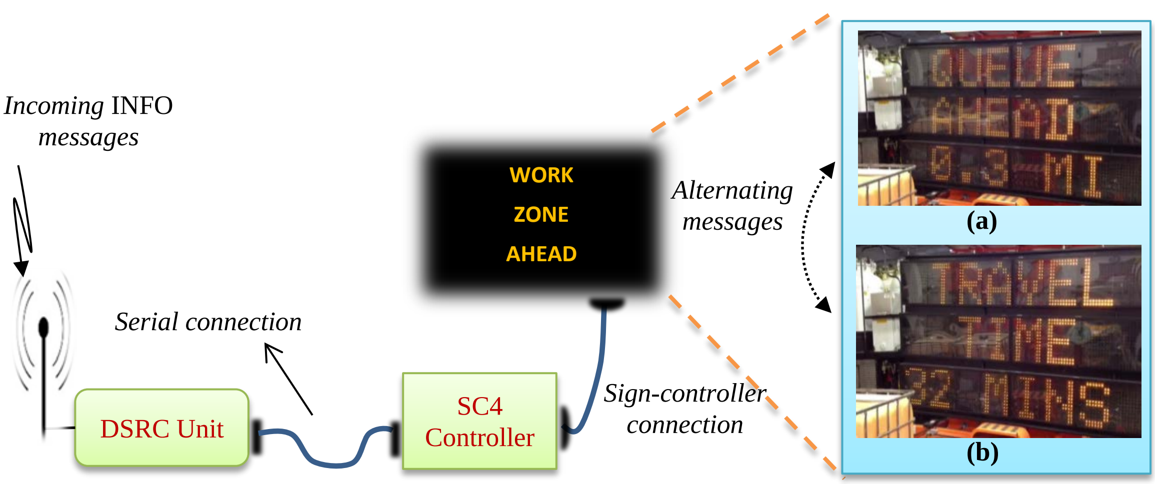

Figure 4.2: Snapshots of the PCMS display matrix showing alternate messages of (a) distance to the queue ahead and (b) travel time.

Typical snapshots of the TT and distance to queue-ahead messages displays from the field demonstration are shown in Figure 4.2(a) and 4.2(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.

Chapter 5. 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 4.1) 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 [30]. 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.

5.1 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 4.1). 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 ΔT. Assuming Poisson arrival distribution, the probability that exactly n vehicles cross the center point of the *Desired Region* in time Δt is described by equation 1 [31]:

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

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.

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

The equation 2 gives the proportion of the total number of vehicles ($q\Delta T$) in time ΔT 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.

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

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 ΔT is kN. We numerically solved the equation 3 to find out ΔT 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 ΔT, will be DSRC-equipped vehicle. The results are shown in Figure 5.1 where ΔT – average time lapse between two DSRC-equipped vehicles crossing the center of the *Desired Region* – is plotted vs. q for different values of k.

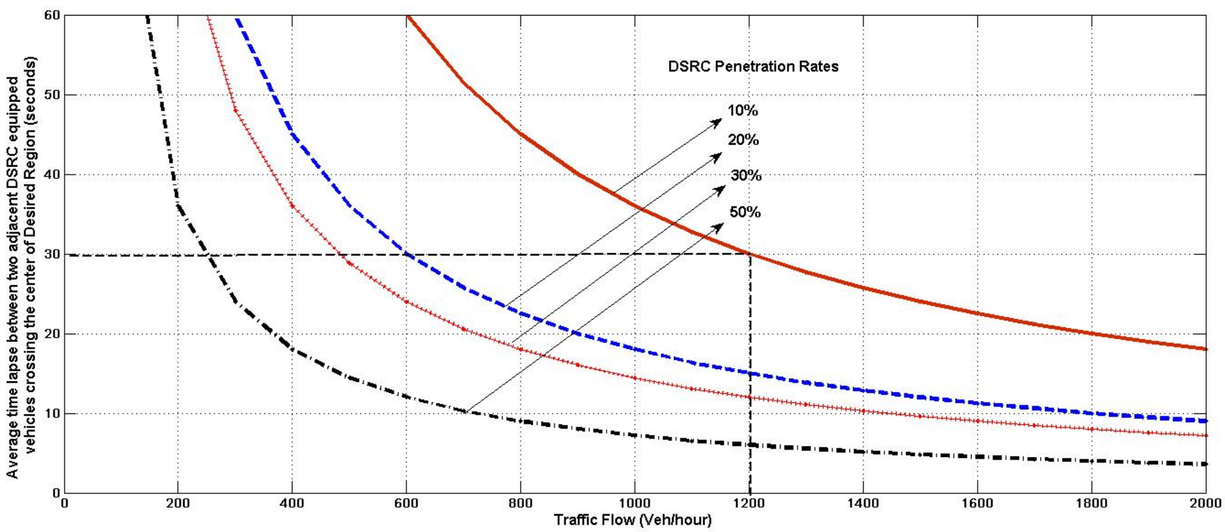

Figure 5.1: Average time lapse between two adjacent DSRC-Equipped vehicles crossing the center of the *Desired Region* as a function of traffic flow for different DSRC penetration rates.

Figure 5.1 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 5.1. Therefore, Figure 5.1 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 5.1 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.

5.2 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 ΔL having space headway less than ΔL for a given vehicle density *D*.

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

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 ΔL. We numerically solved the equation 4 to determine the average distance ΔL in which one DSRC-equipped vehicle is present, for different DSRC penetration rates. The results are shown in Figure 5.2 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*.

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 5.2 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.

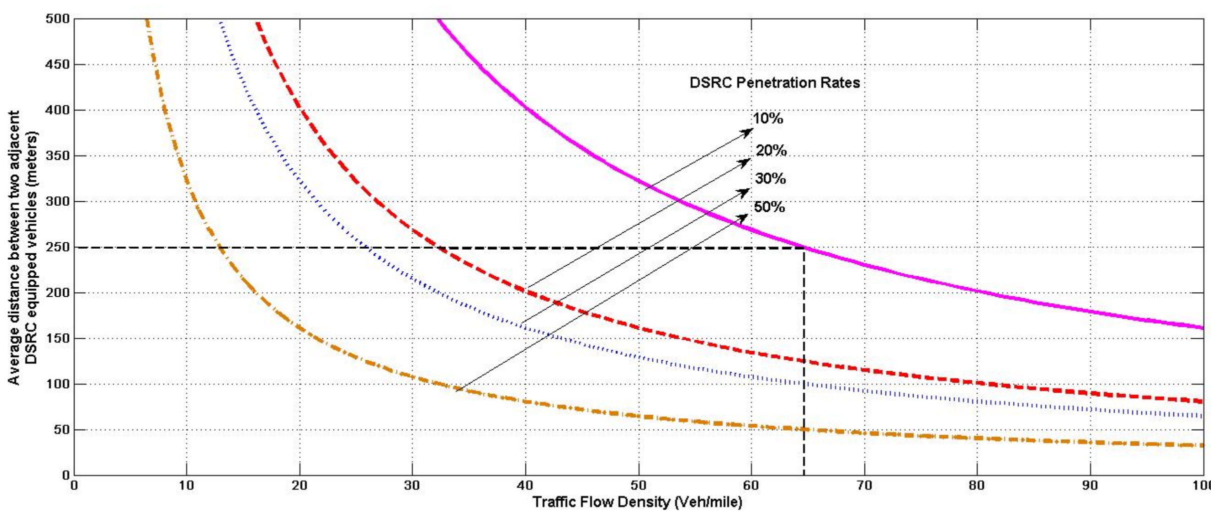

Figure 5.2: Average distance between two adjacent DSRC-Equipped vehicles as a function of traffic flow density for different DSRC penetration rates.

Figure 5.2 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 ΔL, 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 ΔL, 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 (22). 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**.**

5.3 DSRC Penetration Rate Requirement for Hybrid DSRC-PCMS System

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 5.1 and 5.2, 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 3). 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 5.2). 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 5.3. Figure 5.3 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.

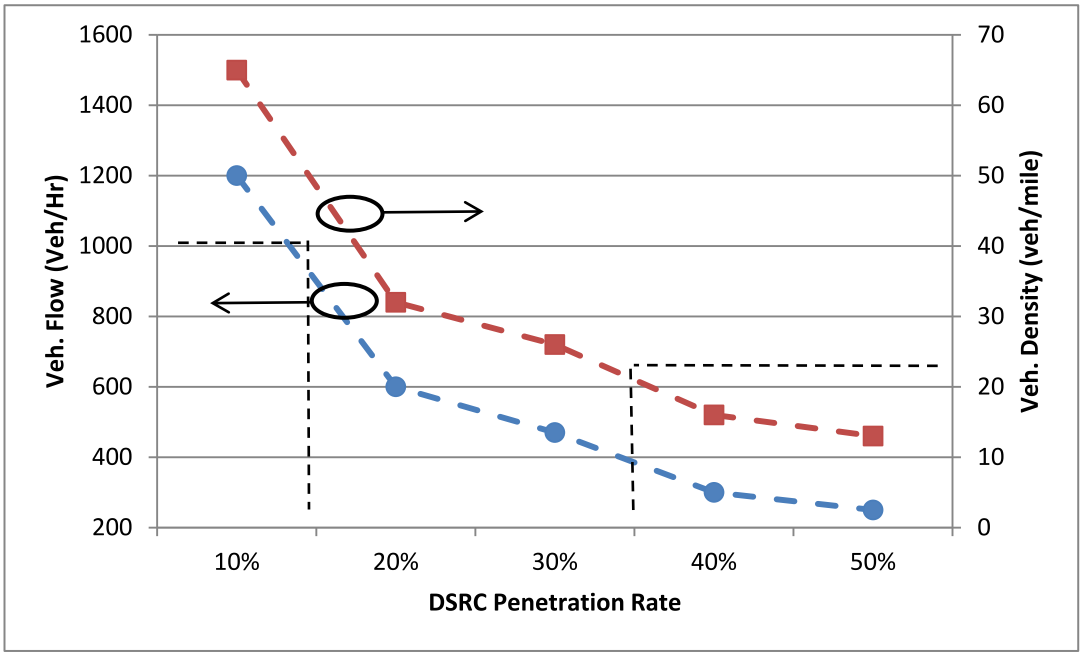

Figure 5.3: Required traffic flow and density for a given DSRC penetration rate.

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 5.3, 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 5.3. Similarly, a DSRC penetration rate of about 35% (for the worst case traffic density of 21 Veh/mile) is required as estimated from Figure 5.3. 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.

Chapter 6. Conclusions

In this paper, a newly developed Hybrid DSRC-PCMS information system for snowplow operation and work zone has been described. The developed system is capable of acquiring important safety-related information such as TT, SLoC, and snowplow location using DSRC-based V2I and V2V communication and then periodically broadcasts them back to the drivers of the DSRC-equipped vehicles as well as DSRC-equipped PCMSs. 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.

The developed traffic-information system can be installed easily on any roadside of interest to monitor the congestion buildup around the work zone, or to help display advisory messages on the PCMSs while snowplow operation is in progress. Once initialized properly, these systems seamlessly and securely gather the required traffic parameters such as TT, SLoC, and location of the snowplow on the road. The acquired information is processed and then disseminated periodically to the vehicles as well as PCMSs having DSRC capability using either V2I or V2V communication.

Furthermore, a rigorous analysis has been conducted to investigate the minimum DSRC market penetration rate needed for the 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.

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