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Providing Real-time Driver Advisories in Connected Vehicles: A Data-Driven Approach Supported by Field Experimentation

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Providing Real-time Driver Advisories in Connected Vehicles: A Data-Driven Approach Supported by Field Experimentation

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This thesis is dedicated to my beloved wife, Dr. Farhana Afroz, and my three children Ruwaifi, Adiyan and Rozana.

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Abstract

Approximately 94% of the annual transportation crashes in the U.S. involve driver errors and violations contributing to the $1 Trillion losses in the economy. Recent V2X communication technologies enabled by Dedicated Short Range Communication (DSRC) and Cellular-V2X (C-V2X) can provide cost effective solutions for many of these transportation safety applications and help reduce crashes up to 85%. This research aims towards two primary goals. First, understanding the feasibility of deploying V2V-based safety critical applications under the constraints of limited communication ranges and adverse roadway conditions. Second, to develop a prototype application for providing real-time advisories for hazardous driving behaviors and to notify neighboring vehicles using available wireless communication platform. Towards accomplishing the first goal, we have developed a mathematical model to quantify V2V communication parameters and constraints pertaining to a DSRC-based "Safe pass advisory" application and validated the theoretical model using field experiments by measuring the communication ranges between two oncoming vehicles. We also investigated the impacts of varying altitudes, vehicle-interior obstacles, and OBU placement on V2V communication reliability and its implications. Along the direction of the second goal, we derived a data-driven model to characterize the acceleration/deceleration profile of a regular passenger vehicle with respect to speed and throttle position. As a proof of concept demonstration, we implemented an IoT-based communication architecture for disseminating the hazardous driving alerts to vulnerable drivers through cellular and/or V2X communication infrastructure.

Table of Contents

List of Tables

List of Figures

Chapter 1

Introduction

Vehicle collisions are regarded as one of the primary areas of study in transportation safety research. Recent developments in vehicle-to-everything (V2X) communication technologies, such as Dedicated Short Range Communication (DSRC) [1] or Cellular-V2X, enable the deployment of safety-critical transportation applications that provide real-time warnings to drivers in order to reduce vehicle collisions. On December 17, 2003, the Federal Communications Commission (FCC) allocated 75 MHz “for the Dedicated Short Range Communications (DSRC) Service in the Intelligent Transportation Systems (ITS) Radio Service in the 5.850-5.925 GHz band” to increase traveler safety, reduce fuel consumption and pollution, and continue to advance the nation’s economy [2]. IEEE adopted the DSRC band as 802.11p standard used by Wireless Access in Vehicular Environments (WAVE) as the mode of operation for 802.11 devices, while 5G Automotive Association is also utilizing the same band for cellular-based V2X communications. Vehicles equipped with V2X communication capabilities will be able to simultaneously communicate with multiple vehicles and roadside infrastructure devices to substantially reduce traffic fatalities. In addition to safety-critical application, V2X communication enable numerous potential environmental and dynamic mobility applications such as the reduction of traffic congestion, efficient scheduling, electronic toll collection (ETC), and the collection of data. A large variety of industrial and commercial markets will likely implement this technology because of its versatility.

The scope of this research includes the dependability analyses of V2X communication for a specific safety-critical application along with studying the feasibility of deploying real-time alerting mechanisms to notify drivers about hazardous driving situations. The overall goal is to understand the feasibility of developing connected vehicle applications to provide real-time warnings through vehicular wireless communications. The following two sections describe the two tightly coupled dimensions of this transportation safety oriented research.

1.1 Reliability of V2X communication for a Safe-pass warning application

Similar to all other wireless technologies, DSRC can be prone to failure and unreliability. There is a lack of experimental studies within academia to investigate the communication ranges or the total duration of communication between two vehicles when they approach each other from opposite directions in freeways. Application and system developers need this information because the connection time defines the maximum amount of data that can be shared between the two vehicles in opposite traffic before they go out of range. Our recent work [3, 4] presented how the reliability of V2V communication is affected by Doppler effects in case of opposing traffic. Representative applications [5, 6, 7, 8, 9, 10, 11, 12, 13, 14, 15, 16, 17, 18, 19, 20] have illustrated the importance of V2V communication reliability in safety critical applications. To this extent, we attempt to investigate the two following research questions in chapter 2:

1. ***What factors affect the communication range and reliability of DSRC?*** Does vehicle speed, altitude differences between vehicles, and interior obstacles (the orientation depending on the placement of DSRC device and vehicle type) affect the communication range (from the front and rear of the vehicle) and reliability (in terms of packet delivery ratio) of V2V communications in the implementation of a safety-critical CAV applications?

2. ***How will the available range and reliability of DSRC change the efficacy of specific CAV applications that depend on V2V communication?***

To investigate this issue, we elaborate the research problems arising from a particular CAV application: the "Safe pass advisory."

We present the results of experimental testing and use them to study the previously mentioned aspects (communication ranges and the total duration of V2V communication between two vehicles driving in opposite lanes). In addition, we explore the impacts of altitude changes and OBU placements for BSM packet delivery using actual DSRC devices in uncontrolled roadway environments. These two aspects are also critical factors that can affect the communication ranges in the forward and reverse directions.

The empirical data collected in our study was obtained by driving two vehicles equipped with DSRC on-board unit (OBU) in opposite directions in freeway and city environments. The freeway experiments were conducted on interstate I-26 through the rural town of Erwin, TN and the city experiments were conducted near the business corridor of Johnson City, TN. Two OBUs communicating using DSRC/WAVE provided single hop measurements for communication reliability as the vehicles moved toward and away from each other. The study provides insightful data about the reliability of V2V communication and its implications for the development of connected vehicle applications.

1.2 Real-time Alert for Hazardous Driving Behaviour

Vehicle to infrastructure (V2I) communication, one of the modes of V2X technologies, enable communication between vehicles and transportation infrastructure, informing drivers of their environment and relaying vehicle operational data to stakeholders (government, fellow drivers, pedestrians, etc.). It is possible that V2I solutions can be deployed to improve safety and mobility by alerting drivers and their vehicles to hazardous driving in their vicinity, such as hard braking, hard acceleration, and severe steering inputs. The NTSB reported in 2012 to 2014, half of two-vehicle crashes were rear-end collisions, killing 1700 people per year [40]. IIHS also reported that forward collision warning systems could prevent 879 fatal crashes annually, and lane departure warnings 247 crashes annually [41]. Experiences suggests that along with traffic situation, driving maneuvers also have a great impact on these fatalities. Most commonly, this has been the primary reason for auto manufacturers to install collision avoidance systems on most new vehicles and deploy applications to monitor drivers' behavior. However, millions of existing vehicles have no such systems, and retrofitting them is cost prohibitive.

Recent research advocated systems to combine external and internal sensors embedded in a vehicle to detect anomalous events and driving behavior in a vehicular system. However, using external sensors can be exorbitant. In literature, different economical methods are proposed for effective collision avoidance systems. There are applications that combines smart-phone sensors and embedded vehicle sensors for real time data collection. For example, in [42] only a three-axis accelerometer and GPS of a Nexas one model smart-phone is used to detect road anomaly, acceleration deceleration events and other properties like lane change and gear shift. DriverSafe, an iPhone based app uses three accelerometers and three gyroscopes along with microphone and GPS to detect inattentive driving behavior [43]. It scores drivers based on their driving performance and notifies them if any event like drowsiness or distraction is detected. Another scoring based platform, SenseFleet detects perilous driving maneuvers by collecting data from vehicle and smartphone and analyzing that data using fuzzy logic [44]. Instead of external sensors, vehicle data can also be detected through vehicle controller area network (CAN) bus and on-board diagnostics (OBD). OBD is an interface to collect vehicle sensor data [45, 46]. It is also economical because (OBD) interface, described by SAE J1979, has been present in all vehicles manufactured for the US market since the 1996 model year. The current version, OBD-II, is required to provide sufficient data to measure emissions, but often provides access to data from every electronic module. The basic OBD dataset (mode 01) provides at least vehicle speed, throttle position, engine RPM, and other fundamental powertrain data. This is sufficient to detect many hazardous driving events, although many manufacturers provide finer grained data through proprietary interfaces. Insurers such as Progressive and State Farm have made use of OBD and manufacturer telematics systems such as GMs OnStar for gathering driver behavior data. Similar systems are equipped in commercial trucks to provide automatic logging compliance. The insurer or employer provides either a self-contained OBD module for the driver to install in the vehicle, or accesses a B2B API sourced with telematics data from the vehicle. Driver behavior is then assessed over a period of months to determine if a discount is warranted.

These systems make use of the cellular network for data transmission and are not currently equipped to provide real-time alerts to infrastructure.

In chapter 3, an IoT-based hazardous driving detection mechanism is proposed, which is interfaced to the OBD system that can gather vehicle data, detects these hazards, and relays them in real-time to infrastructure and other vehicles. The Dedicated Short Range Communications (DSRC) and Cellular-V2X are two of the candidate communication technologies for this type of real-time alerts. The system can also make use of 4G connection to relay hazard events to a third party.

The architecture of the alerting system is described in the chapter. A mathematical model has been established to characterize the acceleration profile and throttle position for various speeds. The algorithm for event detection is based on streaming vehicle kinematics data obtained through OBD port. Upon detecting anomalous and hazardous driving behavior such as, hard braking and hard acceleration, alerts were sent successfully during the experimental cycle.

Chapter 2

Reliability for Vehicle-to-Vehicle Communication in Safety Critical Applications: An Experimental Study

2.1 Introduction

Vehicle-to-Vehicle (V2V) communication using Dedicated Short Range Communications (DSRC) technology promises to help drastically reduce vehicle collisions. DSRC allows vehicles in a highly mobile and complex network to send and receive safety messages with more reliability and lower latency compared to other wireless technologies used for automotive communications. However, there are many factors that could cause a safety-critical automotive application to become unreliable due to communication failures. While the reliability of V2V communication has been a subject of study by several researchers, there are still open questions regarding how the placement of the DSRC devices (inside or outside the host vehicle), the vehicle's interior elements and the differences in altitude can affect the V2V communications. This chapter provides experimental testing data and analyses in order to quantify the impacts of relative vehicle speeds, altitude differences between vehicles, and interior obstacles on V2V communication range and reliability for opposite traffic, in both city and highway environments. We discuss how these results can adversely affect the design parameters of safety critical applications by considering the V2V application "Safe Pass Advisory" on two-lane rural highways.

2.2 Related Work

Bai et. al. [21] were the first to experimentally demonstrate the reliability of DSRC wireless communication from application perspective using three vehicles. The authors defined a novel reliability metric for application level named *T-window reliability*. Their experiments laid the foundation of initiating the deployments of DSRC-based safety applications within the automotive industry. Four types of safety applications were considered in their research —forward collision warning (FCW), stopped vehicle ahead (SVA), emergency electronic brake light alert (EEBL), lane change advisory (LCA)—. Results from their studies proved that all the four applications demonstrated sufficient packet delivery ratios in various scenarios. However, their experiments were carried out for V2V communication between vehicles heading towards the same direction, not between opposite traffic. Applications such as the "Do Not Pass Warning" requires communication between opposite traffic, and has some additional constraints that will be discussed in the next section. In addition, it was not clear from [21] how the packet delivery ratios depend on the relative speed of the vehicles, since the speed was not reported within the results.

In [22], reliability related QoS metrics in MAC-level and application-level including packet reception ratio, T-window reliability, and awareness probability are derived. Impact of hidden terminal problem in packet reception ration was analytically determined to show how the concurrent transmission can impact the reliability on the same DSRC channel. Several researchers have studied the impact of V2V communication reliability due to jamming and congestion in control channels [23, 24, 25]. However, most of these studies were all based on simulation, and hence, did not capture the issues related to field-experiments that is described in our current work.

Recently, some researchers have conducted experimental studies under controlled environments in order to understand the potential impacts of obstructions in V2V communication [26, 27]. Previous studies indicate that DSRC signals experience a significant amount of attenuation when they pass through vehicles, especially large trucks [26]. The effects of large buildings was even more pronounced [26]. In [27], researchers used a measurement system to characterize V2V 5.9 GHz wireless communication channels. These experiments, conducted in suburban areas, were able to establish some understandings about the impacts of speed and separation distance on the Doppler spectrum. The authors observed a correlation between speed and separation and interpreted it in terms of driver behavior. The Speed-Separation diagram introduced in this study shows that the Doppler spread is proportional to effective speed and can be used to predict how the Doppler spread and coherence time will depend on the separation between the vehicles. Bloessl et al. [28] presented field-test results from a software-defined radio that evaluated the performance of several IEEE 802.11 protocols for V2V communication in highway, city and rural environments. These experiments were conducted while the vehicles stayed within close proximity of each other. Zinchenko et. al. [29] evaluated the reliability of V2V communications in a congested network in an urban scenario. Through simulations, the authors evaluate different intersection topologies, i.e., closed, half open and open. For each scenario, they vary the penetration rate, the message generation rate and the positions of the transmitter and receiver (relative to the center of the intersection) and measure the information freshness, the communication range, the stopping distance and the degradation distance to evaluate the level of reliability. The authors found that the best performance under most of the scenarios that were considered was achieved in the closed intersection topology and they highlighted that a message generation rate of 10 Hz brings a good balance between information freshness and network load. With the aim to evaluate the reliability of V2V communications in the case of an urban expressway, the authors in [30] recorded the communication process of two vehicles while being driven on actual traffic. Then, they classified the collected data according to the Line-Of-Sight (LOS) conditions using a fuzzy classification method and evaluated each data set in terms of received signal strength, packet delivery rate and communication latency. The data analysis revealed that road slope and traffic density are critical factors impacting the LOS on an urban expressway and consequently, the communication reliability becomes very unstable. This study also confirmed the trade-off that exists between the communication reliability and the communication distance.

2.3 Background and Problem Statement

2.3.1 Research Questions

In order to ensure that a safety critical application can be implemented as a failure-free application within a Connected and Autonomous Vehicle (CAV) environment, several factors of V2V communication over DSRC must be tested and understood under realistic driving conditions. The objective of this research is to investigate the following factors:

1. ***What factors affect the communication range and reliability of DSRC?***
   Does vehicle speed, altitude differences between vehicles, and interior obstacles (the orientation depending on the placement of DSRC device and vehicle type) affect the communication range (from the front and rear of the vehicle) and reliability (in terms of packet delivery ratio) of V2V communications in the implementation of a safety-critical CAV applications?

2. ***How will the available range and reliability of DSRC change the efficacy of specific CAV applications that depend on V2V communication?***
   To investigate this issue, we elaborate the research problems arising from a particular CAV application: the "Safe pass advisory."

2.3.2 Application-specific Research Questions

The "Do Not Pass Warning" application [31] is listed as a prioritized safety application by the U.S. Department of Transportation. This application relies on V2V communication to warn drivers attempting to pass a slow-moving vehicle of vehicles within the DSRC communication range approaching from the opposite direction. The application will fail to provide any warning if the oncoming vehicle is out of the DSRC communication range. A driver could visually detect a distant oncoming vehicle traveling at a high speed but interpret the situation as a "safe-to-pass situation" due to the absence of a warning message. The driver would therefore attempt to pass the slower moving vehicle potentially causing a severe head-on collision if the driver has inaccurately estimated the speed of the oncoming vehicle. DSRC communication ranges need to be large enough so that this situation is prevented.

Hence the application specific research questions are as follows:

1. *Is it feasible to design and implement a "Safe Pass Advisory" application that advises the driver when it is safe to pass using single-hop V2V communication, assuming that the vehicles are non-cooperative (meaning none of the vehicles reduce speed)?*

2. *If there is an out-of-range oncoming vehicle approaching with high speed but the V2V based "Do Not Pass Warning" application fails to provide a warning because it was not able to receive a signal from opposing traffic, should the driver interpret the absence of a warning as a safe-to-pass situation?*

2.4 Methodology

In order to evaluate the feasibility of implementing the "Safe Pass Advisory" application, first a theoretical model was developed to formulate the constraints of DSRC communication ranges and the minimum duration for seamless communication using kinematic equations. Then a series of field experiments were conducted with two vehicles approaching from opposite direction on an interstate freeway (I-26) to estimate the actual communication duration and range available between opposite traffic to validate the theoretical model.

2.4.1 Mathematical Model for Safe Pass Advisory Application

Figure 2.1 displays three vehicles on a two-lane rural highway at two different times: t_0 (the moment right before the eastbound car attempts to pass the eastbound truck) and t_1 (the moment immediately after the pass is completed). In this model, it is assumed that during the passing maneuver, the westbound vehicle and the truck maintain their speed constant. Also, there is no curve in the road and the road grade is zero. Here,

v_1: speed of eastbound car and truck at t_0

v_2: speed of westbound car at t_0

r_t: driver reaction time

h_{t_0}: space gap at t_0

h_{t_1}: space gap at t_1

l_c: length of car

l_t: length of truck

d_1: distance covered by the eastbound car to complete passing the truck

d_2: minimum safety margin required to avoid head-on collision

d_3: distance covered by the westbound car to allow passing

Based on Figure 2.1, we can write:

$$d_1 + d_2 + d_3 < x_{v_1,v_2} \tag{2.1}$$

where, x_{v_1,v_2} is the maximum DSRC communication range for 2 vehicles approaching each other at v_1 and v_2 speeds obtained from field experimentation. From Equation (2.1), we can write:

$$r_t v_1 + v_1(t_1 - t_0) + \frac{1}{2}a(t_1 - t_0)^2 + d_2 + v_2(t_1 - t_0) < x_{v_1,v_2}$$

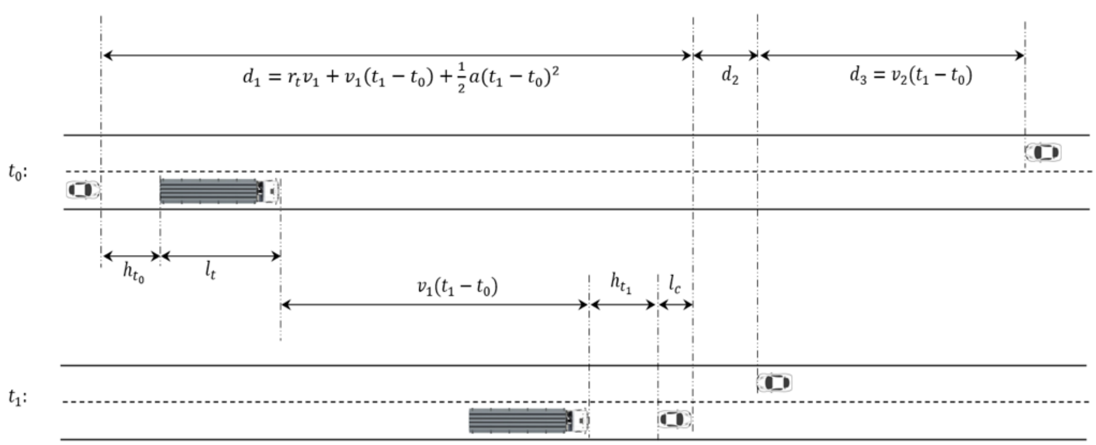

Figure 2.1: Conceptual Diagram to derive mathematical model

For simplicity, let's consider $v_1 = v_2 = v$. This implies that, $x_{v_1,v_2} = x_v$. Hence:

$$\begin{aligned} r_t v + v(t_1 - t_0) + \frac{1}{2}a(t_1 - t_0)^2 + d_2 + v(t_1 - t_0) \leq x_v \\ r_t v + vt_v + \frac{1}{2}at_v^2 + d_2 + vt_v \leq x_v \\ r_t v + 2vt_v + \frac{1}{2}at_v^2 + d_2 \leq x_v \end{aligned} \tag{2.2}$$

where t_v is the maximum feasible communication time, obtained experimentally, between two vehicles approaching each other at speed v before crossing each other. Based on Figure 1, we can also write:

$$r_t v + \frac{1}{2}at_v^2 = h_{t_0} + h_{t_1} + l_c + l_t \tag{2.3}$$

Let's consider, $h_{t_0} = h_{t_1} = h_v =$ the minimum safe headway required between two vehicles moving at speed v

$a = a^v_{max} =$ maximum acceleration feasible for a car moving with a speed of v.

To avoid head-on collision with opposite traffic,

$$t_v \geq \sqrt{\frac{2(2h_v + l_c + l_t - r_t v)}{a^v_{max}}} \tag{2.4}$$

From Equations (2) and (3):

$$x_v \geq (2h_v + l_c + l_t) + d_2 + 2v\sqrt{\frac{2(2h_v + l_c + l_t - r_t v)}{a^v_{max}}} \tag{2.5}$$

Hence, the feasibility of successfully implementing a "Safe Pass Advisory" application that uses DSRC technology is constrained by Equations (4) and (5) where Equation (4) defines the time constraint for the communication and Equation (5) defines the constraint associated with the communication range.

We made the following considerations and assumptions in order to estimate the minimum required time (t_v) and range (x_v) for the implementation of our safe-to-pass advisory system. These factors were taken from a realistic scenario involving a two-lane highway with a maximum speed limit of 55 mph. We considered a 1 second standard reaction time from the driver. Modeling the actual behavior of the driver in a passing scenario would require more rigorous field tests with a large number of human drivers from diverse demography. The driver behavior study was out of scope for our experiments since we primarily focused on the technology parameters.

$l_c = 5m$ (standard full size sedan car)
$l_t = 20m$ (typical length of a truck)
$a_{max}^5 5 = 0.67m/s^2$ (maximum acceleration at 55 mph) [32, 33]
$h_v = 24.6m$ (considering 1 second headway between the vehicle and the truck)
$r_t = 1s$ (driver reaction time)
$d_2 = 40m$

By using these values in (3) and (4) we obtain: $t_v \geq 12.16s$ and $x_v \geq 712.4m$.

2.4.2 Field Experimentation

To determine the achievable V2V communication time and range (t_v and x_v) values, we conducted experiments using two vehicles in real freeway environments as well as in city environments. Due to the fact that human drivers were involved in the experiments, official approval was obtained from the Institutional Review Board (IRB) prior to conducting the field experiments in uncontrolled roadway conditions.

The two vehicles were equipped with after-market DSRC on-board units (OBUs) manufactured by Arada Systems (currently part of Lear Corporation). All of the application layer protocols that utilized WAVE Short Message Protocol (WSMP) and BSM broadcast were developed in-house. The live trajectory data collected during the field tests were stored in real-time on USB drives attached to the OBUs as space separated values in text files. The data elements included the transmitting device ID, GPS positions (latitude, longitude, and altitude), GPS time, speed, and direction of vehicle heading. The commercial GPS receivers integrated with DSRC OBUs were mounted on roof for both vehicles. The precision level of the GPS sensor was very high as evident from the actual trajectories validated using Google maps (within 10 cm error margin). For the safe-pass advisory application, an error margin of up to 1 meter would still be considered reasonably accurate due to the 40 meter safety margin (d_2) considered for avoiding head-to-head collisions in our theoretical model. To calculate the distance between two GPS coordinates we used the precise greater circle distance instead of an equi-rectangle approximation. We considered the Haversine formula [34] for calculation of the distances between two GPS coordinates, as shown below:

$$a = sin^2(\frac{\phi_1 - \phi_2}{2}) + cos\phi_1 cos\phi_2 sin^2(\frac{\lambda_1 - \lambda_2}{2}) \tag{2.6}$$

$$c = 2tan^{-1}(\frac{\sqrt{a}}{\sqrt{1-a}}) \tag{2.7}$$

$$d = Rc \tag{2.8}$$

$$\tag{2.9}$$

Here,

ϕ_1 = latitude of point 1 in radians

ϕ_2 = latitude of point 2 in radians

λ_1 = longitude of point 1 in radians

λ_2 = longitude of point 2 in radians

R = Mean radius of Earth (approximately 6371 km)

Figure 2.2 shows the placement of OBUs in the vehicles. The rooftop OBUs were secured using adhesive tapes with the antennas facing towards the rear side of the vehicle. The DSRC communication parameters used for all the field tests are described in Table 2.1. The summary of the experimental cases is described in Table 2.2.

(a) OBU mounted on roof of one vehicle

(c) OBU on the roof of second vehicle

(b) OBU placed inside the vehicle

Figure 2.2: Placements of OBUs (rooftop and inside)

2.5 Results From Field Tests

2.5.1 Impact of OBU Placement

OBU placed inside vehicles

The first set of experiments were conducted with the OBU placed inside vehicles (as shown in figure 2.2c). Two drivers had driven two vehicles from opposite directions on interstate highway (I-26) at constant cruising speeds. The selected segment for the experiment was straight and the grade was lower than 6 percent. During the first test, both vehicles approached each other at 55 mph, while in the second test the speed was 70 mph. Even though the OBU has an omni-directional antenna, from these two experiments, we found that the communication range in the forward direction was more than double to that of the reverse direction when the OBU was placed inside.

Table 2.1: Communication Parameters

Wireless Protocol	WAVE Short Message Protocol (WSMP)
Channel Number	178 (Control channel)
Center Frequency	5890 MHz
Channel Bandwidth	10 MHz
Transmission Power	20 dBm

Table 2.2: Summary of cases for field experiments

Environment	Test Location	OBU Placement	Avg. Speed (mph)
Freeway	I-26 near Erwin, TN	Inside vehicle	55, 70
Freeway	I-26 near Erwin, TN	Rooftop	50, 55, 60, 65, 70, 75
City	Johnson City, TN	Rooftop	30, 34, 39, 42

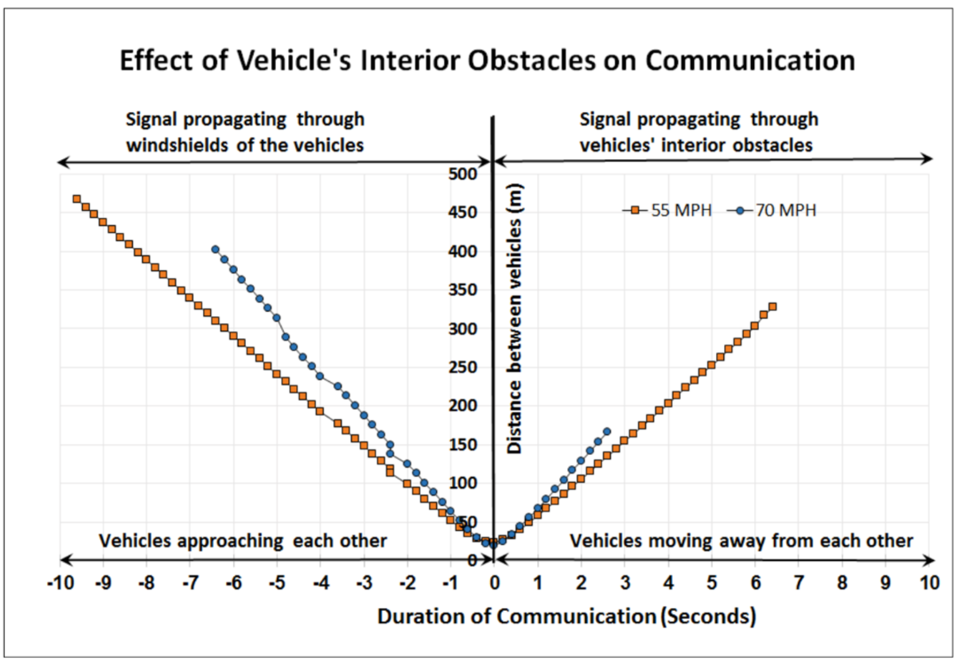

Figure 2.3: DSRC Communication range and duration between opposite vehicular traffic (with OBU placed inside the vehicles)

Impact on Communication range and time: Figure 2.3 shows the effect of the vehicle's interior obstacles on V2V communication. When the DSRC transceiver is placed inside the

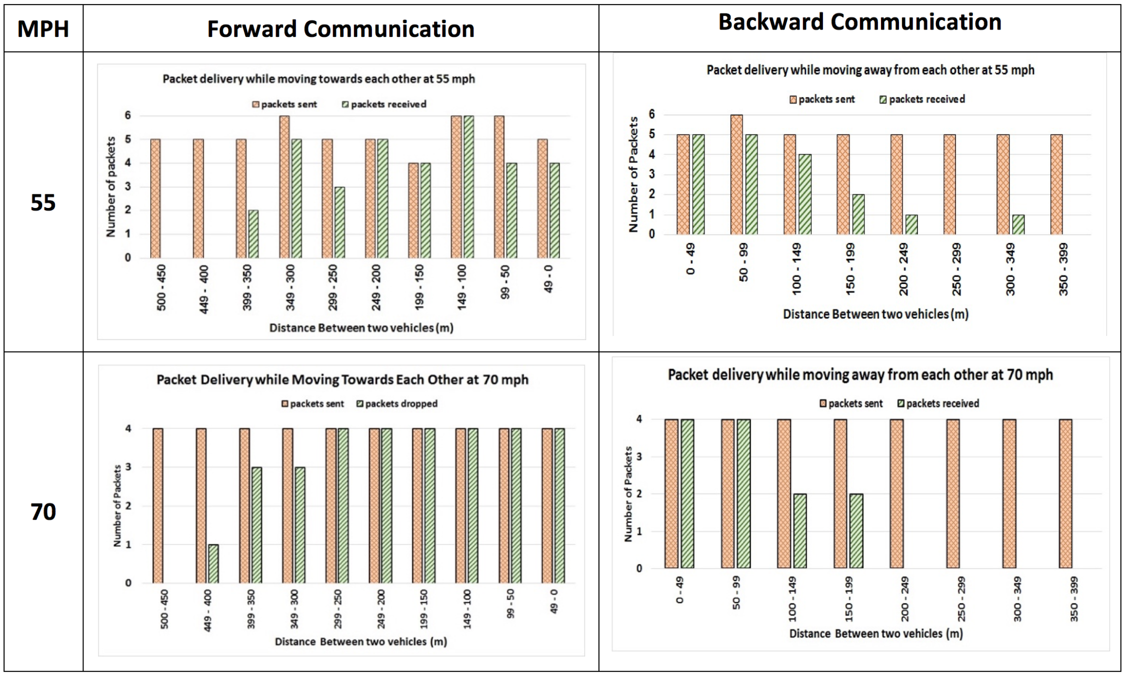

Figure 2.4: Packet delivery ratio for front and rear communication for 55 and 70 mph

vehicle, the forward communication propagates through the windshield of the vehicle. On the other hand, for backward communication, depending on the placement of the OBU and vehicle type, have to make their way through various interior obstructions such as back seats, cargo space/trunk, etc. Figure 2.3 plots the space-time diagram of the two vehicle's positions, where the vehicles cross each other at time=0. It was observed that the communication range in the forward direction is about 466 m when both vehicles are approaching each other at 55 mph. This means that the vehicles can only communicate with each other for a duration of about 10s until they cross paths. According to the previously found minimum values for t_v and x_v, the actual communication time and range are not enough for the implementation of a "Safe Pass Advisory" application. The communication time is even worse when the vehicles are traveling at 70 mph. Even with significantly high transmission power, the range is about 401 m. The graph shows that two vehicles approaching at 70 mph are able to communicate with each other for less than 7 seconds after receiving the first signal, which is clearly not enough time to complete the maneuvers needed to pass a slower moving vehicle. In addition, the results for backward communication are far worse than forward

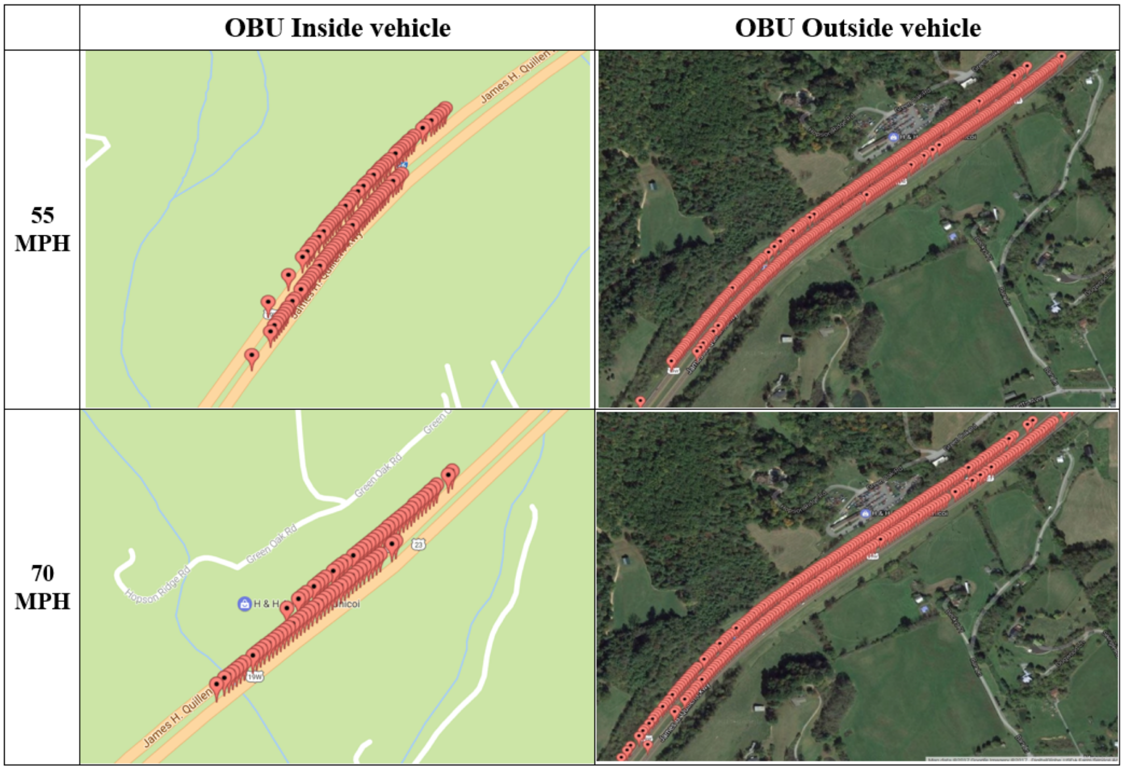

Figure 2.5: Comparison of forward and backward communication ranges

communication, where the total communication duration is less than 3 seconds. With multi-hop communication, the communication range in the backward direction (180 degrees from the vehicle's driving direction) is very important. For example, in order to propagate a message about a downstream traffic congestion through opposite traffic to notify upstream traffic, both multi-hop and backward communication will play a vital role [35, 36]. From the graph, it is evident that, the communication ranges dropped from 466 m to 327 m in the reverse direction for 55 mph and from 400 m to 170 m for 70 mph.

Impact on Packet Delivery Ratio: Figure 2.4 illustrates the difference in packet delivery ratios (PDR), the ratio between the packets transmitted and the packets received, for forward and backward communication when the OBU is placed inside the vehicle. For both 55 and 70 mph cases, the PDR gradually increases while the vehicles approach each other and gradually decreases as they start moving away from each other.

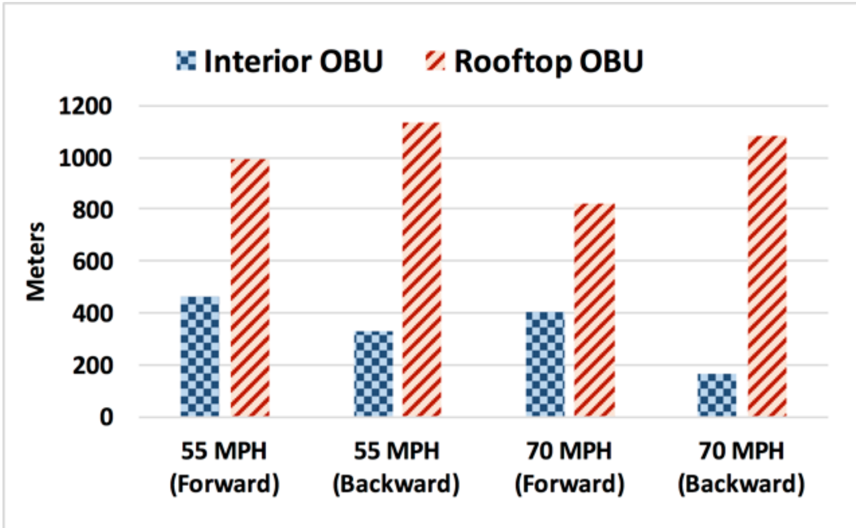

Figure 2.6: Comparison of DSRC Communication Ranges

OBU mounted on rooftop

The V2V communication results indicate a significant difference in terms of communication ranges when the OBU is mounted on the rooftop compared to when OBU is placed inside the vehicle. For a rooftop DSRC OBU, forward and backward communication ranges are similar due to the absence of obstructions from vehicle's interior infrastructure. In fact, the reverse direction has a slightly larger range than that of the forward direction for both 55 and 70 mph cases. This result is probably due to the orientation of the OBU (the antenna faces backwards). In general, the communication range is close to 1 km in all directions. Figure 2.5 shows the BSM traces collected from the two vehicles approaching from opposite directions. The red markers indicate where the BSM packets were successfully received. The figure clearly displays that the interior OBU placements result in asymmetric communication ranges for the front and back of the vehicle.

Figure 2.6 shows the increase in the communication ranges, both front and rear, when the OBU is placed on the rooftop instead of the dashboard. The forward communication range of less than 500 m that is achieved using an interior OBU is not sufficient for passing a slower moving vehicle. Based on these results, we conclude that it is not feasible to design a "Safe Pass Advisory" application with multi-hop V2V communication unless an

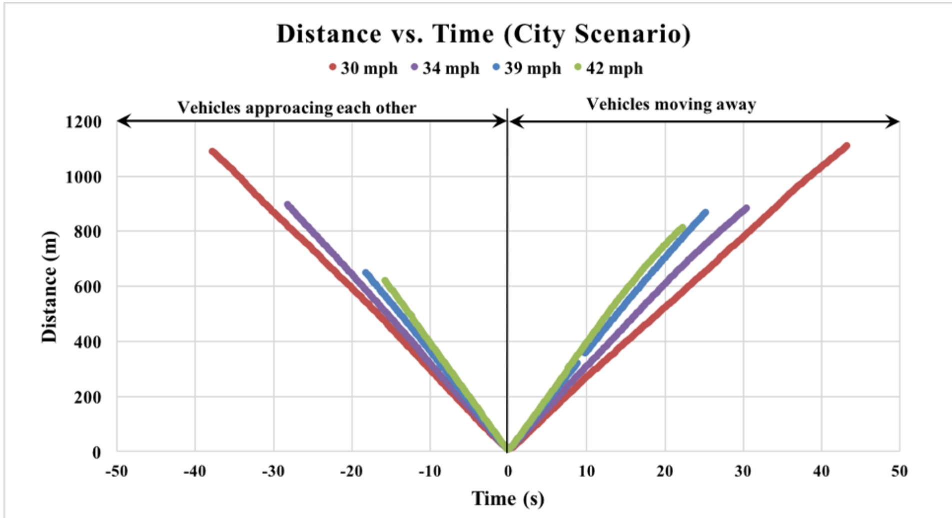

Figure 2.7: Duration of Connectivity and range for city environment (with rooftop OBU)

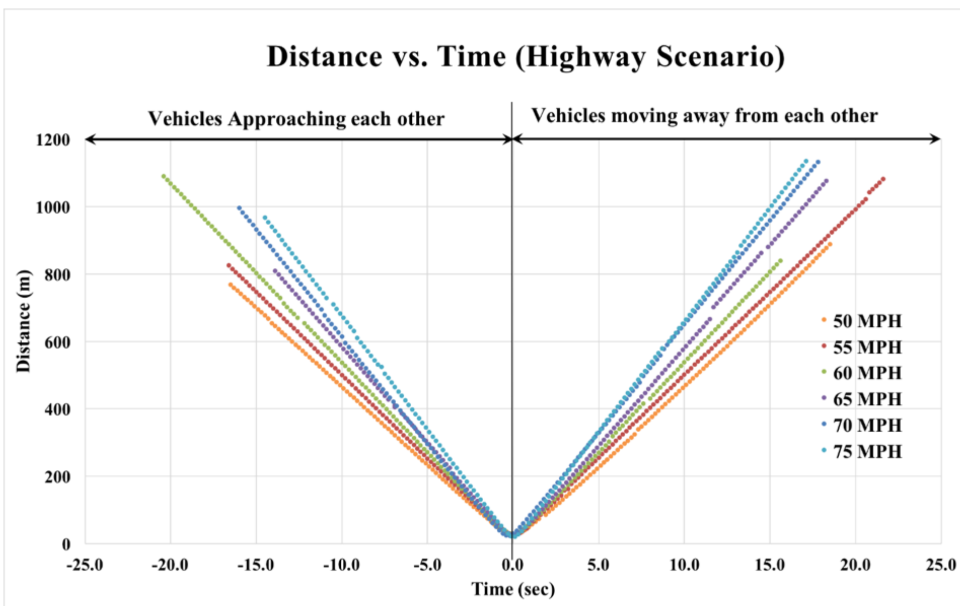

Figure 2.8: Duration of Connectivity and range for highway (with rooftop OBU)

outdoor DSRC antenna is used to maximize the communication range in both the forward and backward direction. In light of this conclusion, our subsequent experimentation studying other constraints pertaining to the implementation of the proposed application without any single points of failure only considered rooftop OBUs.

Figure 2.9: BSM traces obtained during city experiments

2.5.2 Duration of Connectivity between Opposing Traffic

The total communication period, or the duration of V2V connectivity between opposing vehicular traffic determines the amount of information that can be relayed to the opposing vehicle. An example case would be "detour advisory" information that is relayed to upstream traffic heading towards congestion due to a highway obstruction such as an accident. We have collected data in both urban and highway environments using two vehicles approaching towards each other from opposite directions with different speeds. Based on our experiments, figures 2.7 and 2.8 describe the duration of connectivity between opposing traffic in city and highway environments, respectively.

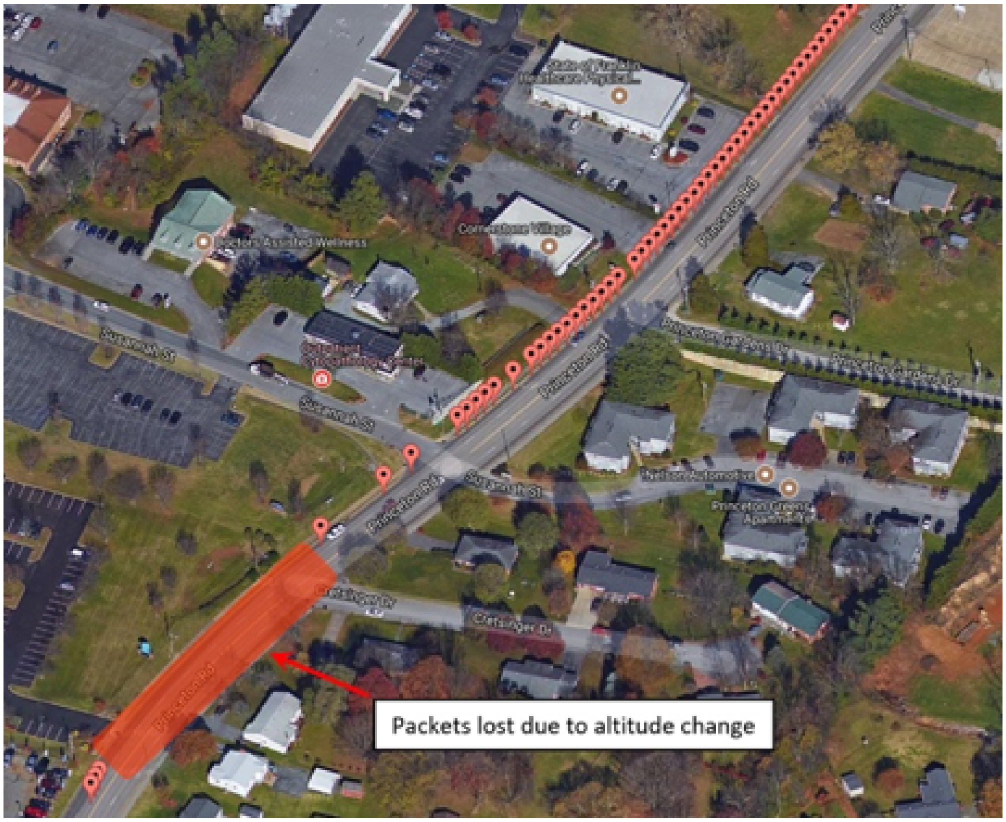

Figure 2.10: Packet loss due to altitude change

2.5.3 Effect of Obstructions from Altitude Change

Even on a straight road, altitude variations between the communicating vehicles can significantly reduce the reliability of V2V communication. The rate of packet drop increases when a road has alternating uphills and downhills. Figures 2.9, 2.10, **??** and 2.13 demonstrate the impacts of changing altitudes on communication reliability. Figure 2.11 is showing the geographical terrain of experiment location. Figure 2.9 indicates the trace of BSM received, while figure 2.10 shows a burst of packet loss in the urban environment when there is an altitude change between the vehicles approaching each other from opposite directions. Among the two vehicles, one of the vehicles was climbing uphill while the other one was moving downhill. The experiment was repeated 4 times, each time with one of four different average speeds for both the vehicles (30 mph, 34 mph, 39 mph, and 42 mph). In figures 2.12 and 2.13, the red dots correspond to the instances when no packet was received by

Figure 2.11: Geographical terrain of the field experiment location obtained from Google Earth

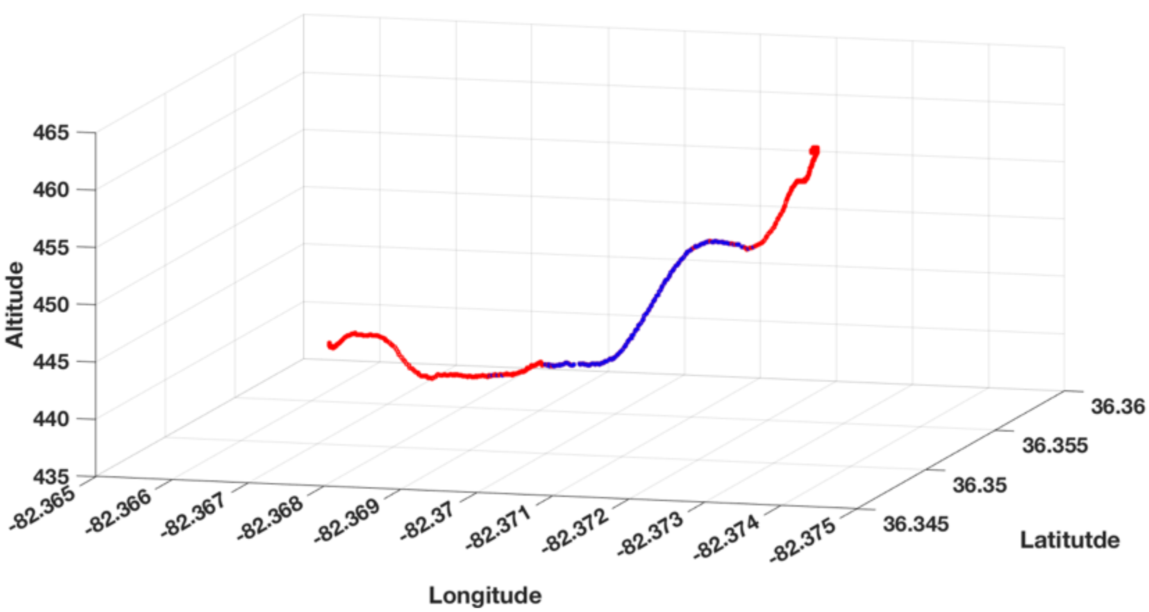

Figure 2.12: Altitude variation within the terrain (red dots indicate that no packet was received at that location)

the vehicles since one of the vehicles went hidden in a valley between a successive downhill

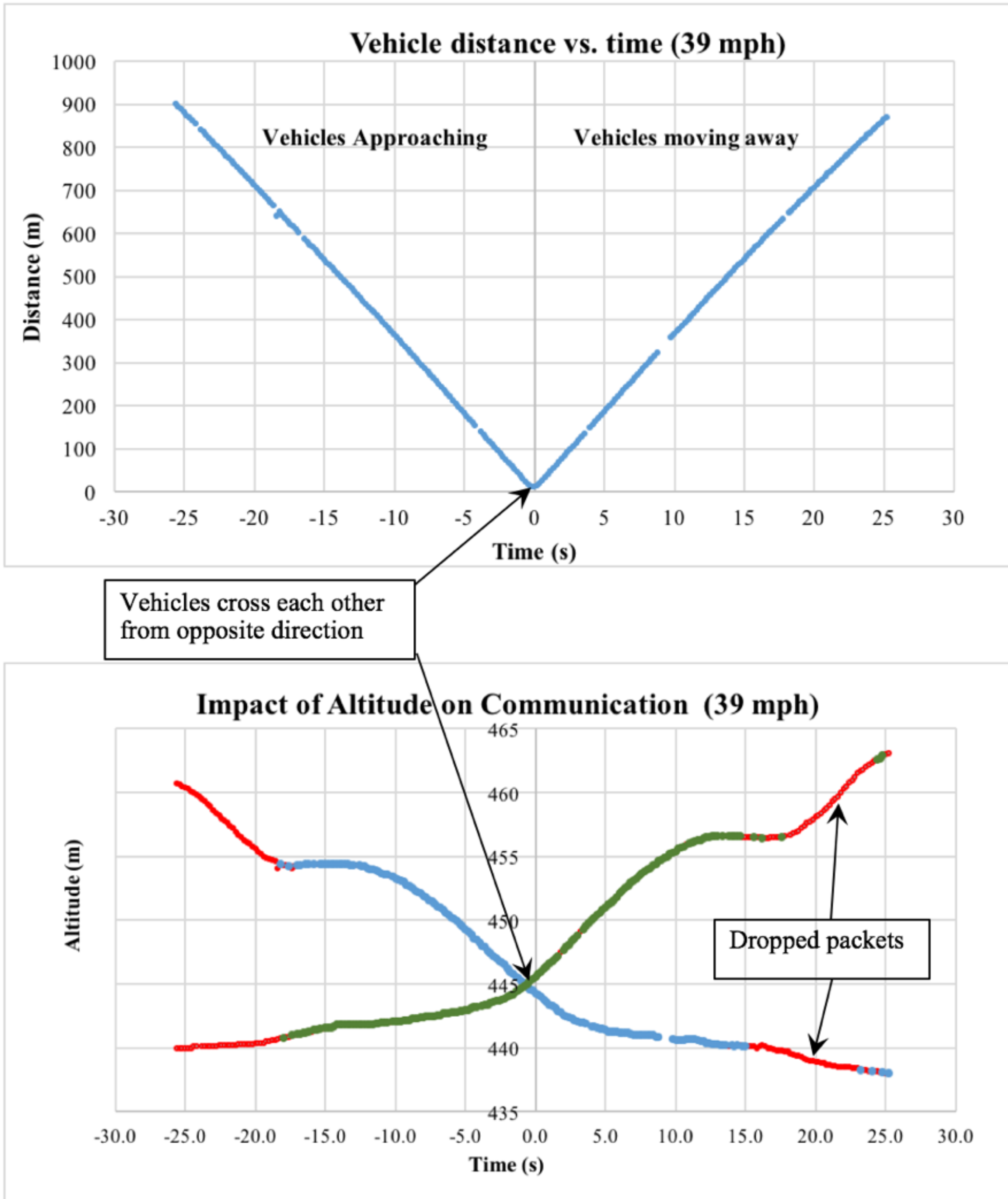

Figure 2.13: Unreliable V2V communication when one of the vehicles gets hidden by valley

and uphill terrain. It can be inferred that, whenever there is altitude variations, the V2V communication is not reliable even on straight roads due to significant loss in the packets.

Table 2.3: Results from Highway Experiments

Exp. #	Avg. Speed (MPH)	Total Commun. Time (s)	Packets Sent by V1	Packets rcvd by V2	Packets Sent by V2	Packets rcvd by V1	PDR V1	PDR V2	Avg. Packets Rcvd	Avg. PDR
1	50	35	175	160	175	168	96%	91.43%	164	93.71%
2	55	38.4	192	165	192	162	84.38%	85.94%	163.5	85.16%
3	60	35.8	179	132	179	134	74.86%	73.74%	133	74.30%
4	65	32	160	144	160	137	85.63%	90.00%	140.5	87.81%
5	70	34	170	144	170	140	82.35%	84.71%	142	83.53%
6	75	31.4	157	114	157	111	70.70%	72.61%	112.5	71.66%

Table 2.4: Results from City Experiments

Exp. #	Avg. Speed (MPH)	Total Commun. Time (s)	Packets Sent by V1	Packet Rcvd by V2	Packets Sent by V2	Packets Rcvd by V1	PDR V1	PDR V2	Avg. Packets Sent	Avg. Packets Rcvd	Avg. PDR
1	42	38	191	142	191	129	74%	68%	191	135.5	71%
2	39	43.4	216	159	212	155	74%	73%	214	157	73%
3	34	58.6	294	255	293	263	87%	90%	293.5	259	88%
4	30	81	406	289	406	294	71%	72%	406	291.5	72%

2.5.4 Packet Delivery Statistics (Rooftop OBU)

The PDRs range from 71% to 88% for all city experiments while they range from 71% to 93.7% for highway experiments. The speeds varied between 30 mph to 42 mph within the city and 50 to 75 mph on highways. The summary of results from both city and highway environments are described in Tables 2.3 and 2.4. In the highway environment, the maximum PDR is 93.7% where the average speed was 50 mph. In the urban environment, comparing the results with highway experiments, the PDRs is much lower. The maximum PDR achieved when the vehicles were traveling at 34 mph.

2.6 Conclusions

Freeway experiment results indicate that the communication range and connection period between two vehicles driving in opposite directions is more than doubled if the OBU is mounted on the rooftop instead of inside the vehicle. If the OBU is placed inside the vehicle, then the communication range in the backward direction is less than half of the range achieved in the forward direction. A reason behind this phenomenon is that when the signal propagates in forward direction it only goes through the windshield. On the contrary, when the signal propagates in the reverse direction it must find its way through backseats and trunk/cargo spaces, struggling with more obstacles. However, if the OBU (or just the DSRC antenna) is mounted on the roof, then the effective communication range is almost the same in every direction surrounding the vehicle. Our experimental results from the city environment provided us with some crucial information about how even with a rooftop OBU the V2V communication is obstructed by changes in altitude within a straight road segment. Changes in altitude translate into additional constraints for designing a safe pass advisory application involving two-lane rural highways.

Based on our analyses, a typical truck-passing maneuver on a two-lane U.S. highway with a speed limit of 55 mph takes at least 12.16 seconds and a minimum of 712 meters considering the maximum acceleration for that speed. From our experimental results, two on-coming vehicles traveling at 55 mph can only start communicating when they are a maximum of 466 meters away. However, with a rooftop OBU, two vehicles can start communicating from at maximum of 800 meters apart, making it possible to implement the safe pass advisory application. Multi-hop V2V communication increases the potential for actual implementation.

Acknowledgment

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Chapter 3

Real-Time Alerting of Hazardous Driving Behaviour Using Internet of Things (IoT) and Connected Vehicles

3.1 Introduction

Approximately 94% of the annual transportation crashes in the U.S. involve driver errors and violations as contributing factors, costing nearly $1 Trillion in losses. Several promising approaches are being considered, e.g., the Internet of Things (IoT) has emerged with ubiquitous computing and communication technology to enable cost effective solutions for smart city applications. The idea proposed in this research, uses an application connected with an IoT device to access vehicle kinematic information through vehicle CAN bus for event detection as well as to provide real-time warning to drivers for potential hazardous driving maneuvers. More generally, to detect perilous driving behaviors, internal and external sensors of a vehicle can be used to provide essential kinematic information. As the streams of vehicle kinematics become available through sensors, the data can be analyzed and processed to detect dangerous driving behaviors whose traces are reflected in vehicular kinematics e.g., speed, longitudinal and lateral acceleration, and throttle position. In particular, anomalies and deviations from the normal state can be detected by establishing customized thresholds by processing and using statistical analysis on real-time data streams. Then, appropriate driving assist warnings and alerts can be issued to the driver or proximate vehicles with purpose of avoiding crashes proactively. One important aspect of such technology adoption is the cost. Therefore, this research proposes a real time alert system using a Bluetooth based low cost OBD2 scanner to detect hazardous driving events.

3.2 Related Works

There are three aspects of this research— first, the data collection scheme for information stack; second, the detection logic; and third, the methodology of the whole detection and information communication mechanism. Prior researches do not combine these aspects together. However, different researchers have proposed different approaches for addressing each of these issues. We studied the systems related to driving detection scheme in addition to the systems that uses OBU/CAN bus methodology. These systems are also classified into alert/suggestion based or non-alert based evaluation based systems.

CarSafe, is an alerting app that alerts drivers if they are drowsy or distracted using smartphones [47]. CarSafe both monitors internal and external condition of car along with driver's maneuvers. It also detects taligating, lane weaving and drifting. Salprasert et al. proposed a system to create speed profile timeline based on data collected through mobile sensors [48]. The system pops up alert if speed is violated by driver, however experiment also shows that 1 out of four warning messages misses due to 3G communication delay. Taha et al. [49] collects CAN bus data through OBD-II via Bluetooth or wifi and alerts driver about dangerous road conditions and weather; the system constantly updates road condition through a crowd sensing app. Driving coach considers parameters like speed, acceleration events and fuel consumption, monitors driving pattern of a driver and then suggests the driver fuel efficient maneuvers [50]. Although SMaRTCaR does not consider driving behavior, it uses special ScanTool device interface with CAN bus with the help of Arduino board to collect traffic and environmental information [51]. Collected information are broadcast to users smartphone based on available connections. VehicleICT – a social driving application, is evolved based on connected car concept in cloud architecture [52]. This eco-friendly app collects data like speed, mass air flow, coolant temperature, engine RPM (Rounds Per Minute) though OBD-II port or directly from CAN bus and smartphone sensors; user statistics is created from these data and shared among the network so that users can see their performance. Artemisa, is an application that monitors driving behavior and based on their driving pattern, recommends them fuel efficient driving [53]. For querying vehicle telemetry (acceleration, deceleration, RPM, positive kinetic energy), an android device sends PID for specific variable, and the OBD-II broadcasts its response via Bluetooth connection. AbuAli et al. proposes a system that monitors driving maneuvers and road conditions and takes action based on situation; like if accident is detected, it notifies nearest police station. The sensor information is collected through OBDII Bluetooth dongle from CAN bus. Apart from notification, it stores information about road anomaly in central database for future suggestion [54]. Although most of the researches so far have deployed and proposed strategies combining sensors from vehicle and smart-phone devices, our current research focuses on using cost-effective in-vehicle sensors to detect important events like hard braking and hard acceleration. It uses CAN bus sensors that can broadcast data though OBD-II port, and alerts the user after detecting hazardous behavior.

3.3 Data

This study used the information available in Basic Safety Messages (BSM) from Michigan Safety Pilot Deployment (SPMD). Around 3,000 vehicles equipped with Dedicated Short Range Communication (DSRC) devices participated in the program under real-world conditions. BSMs includes but not limited instantaneous vehicle information such as speed, acceleration, heading, throttle position, wiper status etc. at 10 Hz frequency. The data is publically available through US DOT website (https://data.transportation.gov/Automobiles/Safety-Pilot-Model-Deployment-Data/a7qq-9vfe). In particular, the vehicle speed, acceleration and throttle positions were used to obtain the critical values of alert generating purposes.

3.4 Methodology

3.4.1 Design Challenges and Considerations

The accurate identification of a hazardous driving behavior is complicated due to different operations of vehicles, limited sensing hardware, and the ethics of passing judgment on driver decisions possibly made under stress. The best approach for immediate accident avoidance may be different from establishing a driver profile for applications such as insurance. This research considers an arbitrary threshold to detect hazardous event if a control input or vehicle effect exceeds a certain limit. This threshold is chosen to be sufficiently high to avoid false positive alerting, but low enough to identify factors leading to an avoidable accident.

Hard braking and acceleration are chosen as two leading factors that contribute to dangerous events. In the case of hard braking and acceleration, this research attempts to identify dynamic acceleration/deceleration thresholds which are considered hazardous at the full range of driving speeds. If a constant threshold is chosen, then it must be large enough to accommodate the large but justifiable accelerations found on highways. At low speed, this will lead to false negative mischaracterization. By identifying the percent change in speed between data samples, the threshold adapts by narrowing the acceptable envelope at low speed. Below walking speed, harder braking activity to bring the vehicle to a halt may be excusable. Vehicle steering input is also sensitive to speed; a large input is less acceptable at high speed and more likely to cause an accident.

3.4.2 Driving Volatility

Before discussion of the developed system, it is beneficial to briefly discuss the concept of driving volatility. Driving volatility is meant to capture different types of extreme driving behaviors such as aggressive, hard braking, hard acceleration, sudden lateral movements, extreme lane change etc. by monitoring vehicles kinematics. Each of those behaviors leaves its trace on vehicle kinematics. Therefore, as per our previous studies, multiple measures of driving volatility are needed to capture all aspects of different types of driving volatility (i.e. different patterns of anomaly). In a comprehensive investigations of driving volatility

Table 3.1: Measures of Driving Volatility

No.	Measure	Equation [1]
1	Standard Deviation	$S_{dev} = \sqrt{\frac{1}{n-1}\sum_{i=1}^{n}(x_i - \bar{x})^2}$
2	Coefficient of Variance	$C_v = \frac{S_{dev}}{\lvert\bar{x}\rvert} * 100$
3	Mean Absolute Deviation	$D_{mean} = \frac{1}{n}\sum_{i=1}^{n}\lvert x_i - \bar{x}\rvert$
4	Quartile Coefficient of Variation	$Q_{cv} = \frac{Q_3 - Q_1}{Q_3 + Q_1} * 100$
5	Percent of Extreme Values	$\%T = \frac{c > Threshold}{n} * 100$ $Threshold = \bar{x} \pm z * S_{dev}$
6	Time-varying stochastic volatility	$r_i = \ln \frac{x_i}{x_{i-1}} * 100$ $V_f = \sqrt{\frac{1}{n-1}\sum_{i=1}^{n} r_i - \bar{r}^2}$

measures, Kamrani et al. [55] developed 37 measures of driving volatility and explored their associations with crash frequency at intersections. According to the results, there is a positive correlation between driving volatility and crash frequency [55, 56, 57]. The measures that can be used and applied to vehicle kinematics are provided in Table 3.1 [55].

In this study, we used a measure of driving volatility similar to number 5 shown in Table 3.1. This measure accounts for the decline in vehicles acceleration capability at higher speeds [56, 57]. Using Basic Safety Messages (BSM) from Michigan Safety Pilot Deployment has enabled us to show the phenomenon in real-world. Figure 3.1 is the product of plotting more than 65,000,000 data points showing the real-world speeds and accelerations of the vehicles. The upper and lower limits shown in red in the Figure are established by considering speed intervals each with 1 m/s width. For each speed bin, the 98 percentile values of accelerations and decelerations are calculated. Then, two polynomials are fitted separately to acceleration ($f_1(x)$) and deceleration ($f_2(x)$) to 98 percentiles:

$$\begin{aligned} f_1(v) = {} & -0.0000010312v^6 + 0.000088059v^5 - 0.0029486767v^4 + 0.0490422607v^3 \\ & -0.4205823266v^2 + 1.5828123807v + 1.6090633115 \end{aligned} \tag{3.1}$$

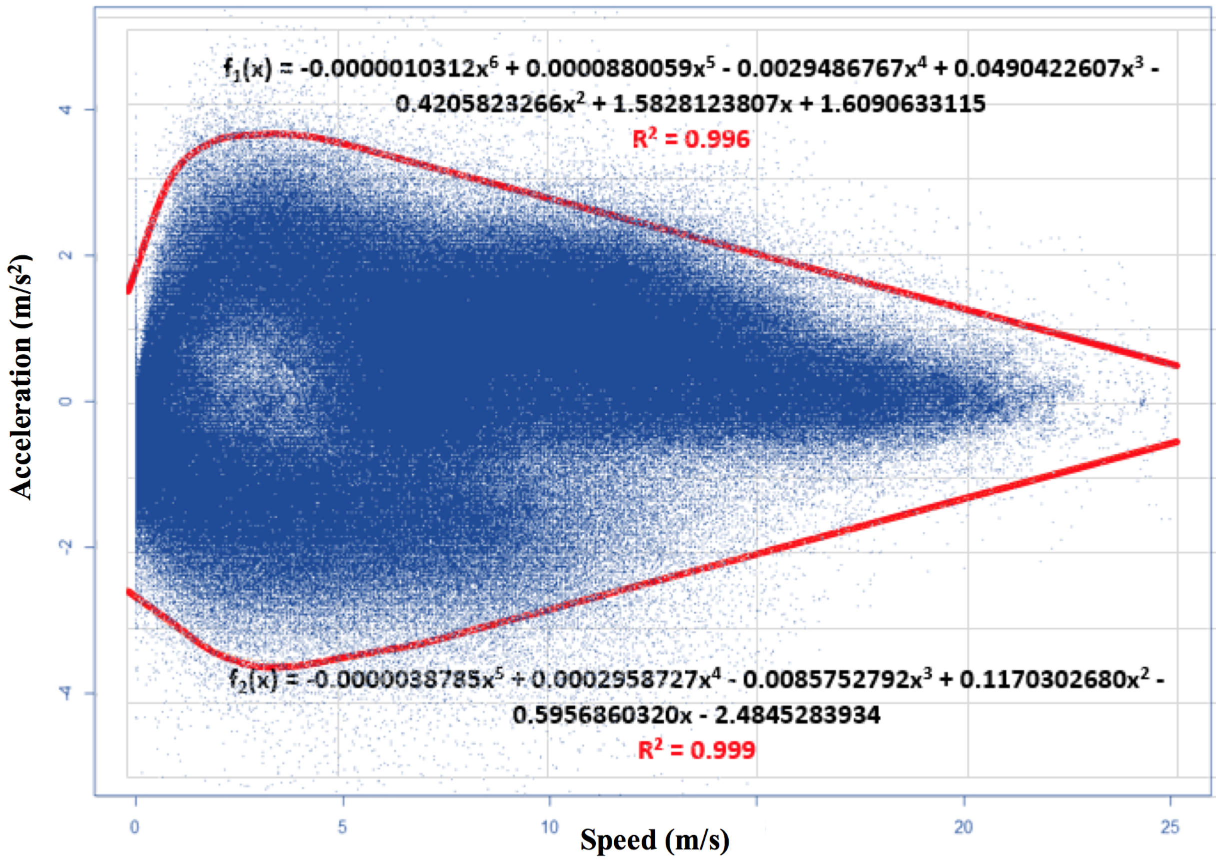

Figure 3.1: Real-world speed-acceleration relationship from Basic Safety Messages (N 65,000,000) and established upper and lower bounds

$$\begin{aligned} f_2(v) = -0.0000038785v^5 + 0.0002958727v^4 - 0.0085752792v^3 + 0.1170302680v^2 \\ -0.5956860320v - 2.4845283934 \end{aligned} \tag{3.2}$$

where is the speed of vehicle and and are functions evaluating the critical acceleration and deceleration value respectively. It should be noted that due to the degree of six and five polynomials, we use ten-digit decimals to obtain precise critical acceleration and deceleration threshold given the speed. Specially, at lower speeds, the values to the power of five and six become even smaller and their coefficients precision become significant to obtain accurate thresholds.

3.4.3 Event Detection Algorithm

Hard Brake and Hard Acceleration Alerts

An algorithm is developed to detect possible unsafe events like hard braking and hard acceleration. The algorithm is run by an application from Linux system on a Mac laptop. After the OBD - II adapter is connected to OBD port of a vehicle, the algorithm checks for active connection. If the car is connected, it instantiates query for two parameters, speed and throttle position. Once the OBD - II adapter fetches the data and passes these values to the algorithm, it then calculates the possibility of hard braking and hard acceleration events. If safe threshold value exceeds, alerts are generated. Given the speed and using Equations 3.2, the safe threshold of decelerations are calculated and compared with vehicle acceleration a deceleration value. If vehicles deceleration is below the value from obtained from Equation 3.2, the hard brake alert is issued. The procedure for hard acceleration is same but the algorithm compares the vehicles acceleration with the value obtained from Equation 3.1. Hard acceleration alerts can also be generated using the throttle position which is discussed next.

Hard Acceleration Alert Using Throttle Position

As Figure 3.1 shows, at lower speeds, the range of critical values of hard acceleration and hard deceleration is bigger than higher speeds. Therefore, it might be more appropriate to devise an alert for hard acceleration linked to throttle positions as well as the speed. As such, a multivariate regression analysis was used to estimate the relationship between acceleration, speed, and throttle position using Safety Pilot Model Deployment dataset. Based on the analysis, the acceleration is linearly dependent on speed and throttle position as per following equation:

$$a_c = -0.1929 - 0.0169 v_c + 0.0279 tp_c \tag{3.3}$$

where a_c, v_c and tp_c are current acceleration, speed and throttle position of vehicle respectively. Replacing a_c with threshold limit of safe acceleration from Equation 3.1:

$$-0.0000010312v_c^6 + 0.0000880059v_c^5 - 0.0029486767v_c^4 + 0.0490422607v_c^3 - 0.4205823266v_c^2 + 1.5828123807v_c + 1.6090633115 = -0.1929 - 0.0169v_c + 0.0279 * tp_c \tag{3.4}$$

This gives us the allowable threshold for throttle position as follows:

$$tp_{threshold} = (-0.0000010312v_c^6 + 0.0000880059v_c^5 - 0.0029486767v_c^4 + 0.0490422607v_c^3 - 0.4205823266 * v_c^2 + 1.5997123807v_c + 1.8019633115)/0.0279 \tag{3.5}$$

Event Detection Algorithm

Having established the thresholds for hard acceleration and hard braking, the following algorithm is developed. Let's consider the following parameters: V_c= Current vehicle speed V_p= Previous vehicle speed Tp_c= Vehicle's current throttle position Tp_p= Vehicle's previous throttle position

Algorithm 1 describes the steps of event detection algorithm are provided. As shown in the algorithm, hard brake alert is generated by comparing the vehicle current acceleration with the calculated deceleration threshold from Equation 3.2. For hard acceleration alerts, the vehicle current throttle position is compared with the threshold obtained from Equation 3.5.

3.5 System Architecture

The system works as follows: the onboard OBD-II of the vehicle interfaces with CAN bus to receive vehicle information from internal sensors, and sends the received data through a WiFi gateway. WiFi gateway constantly communicates with LTE network and a Raspberry pi 3 device. Raspberry is responsible for data collection. A software instantiates and monitors the data to identify threshold violation. If any threshold value exceeds, it

Algorithm 1: Event Detection Algorithm

```
begin
    Check Connection_Status
    if Connection_Status==false then
        Exit
    else
        speed_cmd ⟵ OBD.Commands.SPEED
        tp_cmd ⟵ OBD.Commands.THROTTLE_POS
        V_p ⟵ 1
        Tp_p ⟵ 1
        while true do
            V_p ⟵ query(speed_cmd)
            if (V_c–V_p)/t < f2(V_c) then
                Generate hard brake alert
            V_p ⟵ V_c
            Tp_c ⟵ query(tp_cmd)
            if tp_c > tp_threashold then
                Generate hard acceleration alert
```

generates corresponding alert. The alert system is comprised of several computation and communication modules: a vehicle, OBD adapter, alert computer, WiFi and Bluetooth adapters, and an application for receiving and recording alerts from the vehicle. The overall system architecture is described in Figure 3.2.

A vehicle needs to be equipped with an OBDII data link connector (DLC) and an onboard WiFi. The onboard WiFi is connected to a LTE gateway for event reporting. By law the DLC is required to be within 3 feet of the driver position, typically, in the left side of the foot well. A vehicle's internal sensors resides in a CAN bus. CAN bus was developed by Bosch to reduce the wiring demands in vehicles by permitting a bus or modified bus topology among modules. ISO 15765-4 defines the diagnostic protocol over CAN bus (DoCAN) which allows external equipment to interface with the DLC. CAN bus is oriented around broadcast messaging, where any device attached to the bus can opt to read or insert messages with a specific 11 or 29-bit arbitration ID. The sensor statuses of CAN bus can be read through an OBD-II interface. OBD is a function of the engine control unit (ECU), which provides

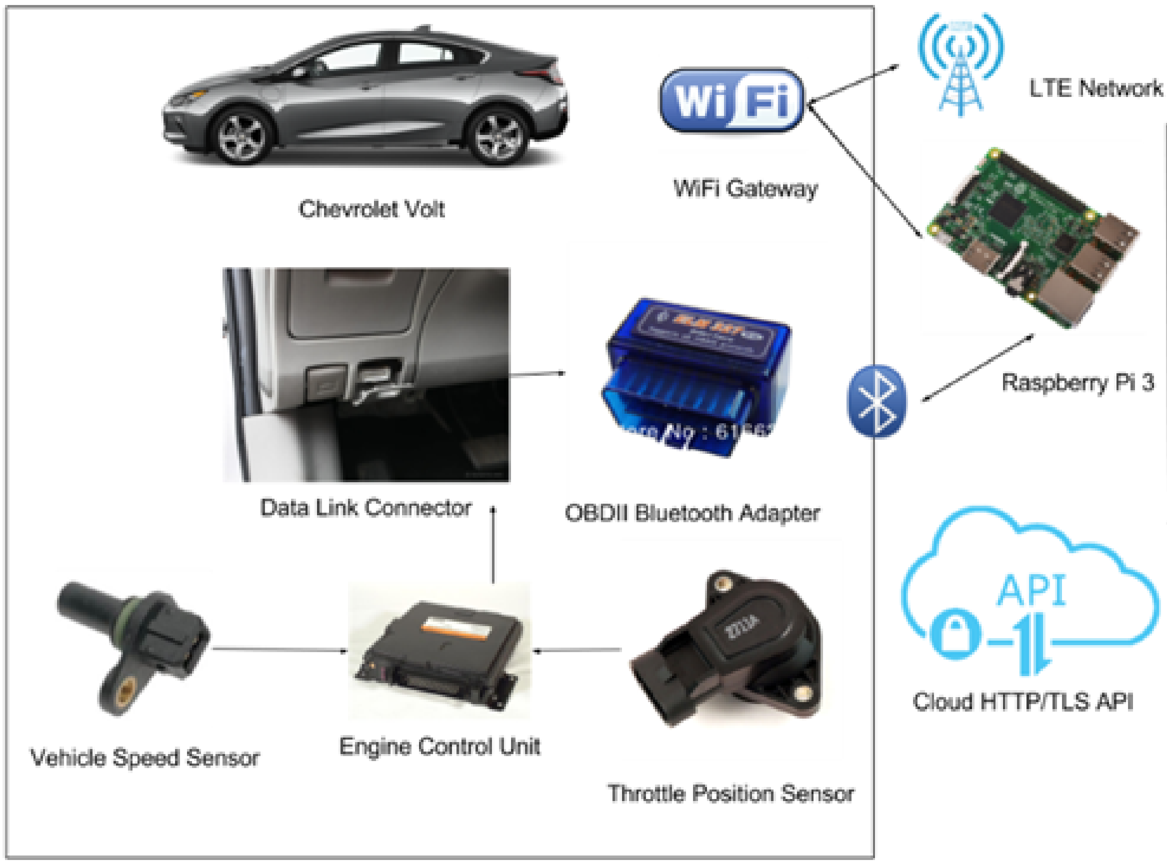

Figure 3.2: System architecture

critical feedback to the engine actuators to maintain performance and limit emissions. OBDII has specific PIDs (Parameter ID), each vehicle parameter is associated with a unique PID. Request to retrieve sensor data is instantiated by passing PID.

To query an ECU parameter, a user must provide PID. The mandatory set of PIDs which an OBDII implementation must support are contained in SAE standard J/1979. The mandatory PIDs are focused on the powertrain to support emissions testing. Mode 01 PIDs return raw data from engine sensors, while Mode 02 returns data from a freeze frame recorded during an engine problem such as a misfire. Mode 03 requests trouble codes, which are indicative a component failure or data received outside of tolerance. These codes may cause the dashboard malfunction indicator light (MIL) or check engine light to be illuminated.

Mode 04 commands cause the MIL to be turned off. Mode 05 contains comprehensive PIDs for oxygen sensor data, while Mode 09 reports vehicle-specific data such as the VIN. Many other non-standard PIDs exist that are manufacturer specific; these may proxy data from vehicle modules other than the ECU, such as the brake controller or climate control system. Unfortunately, access to documentation on these PIDs is tightly controlled and expensive.

For example, to measure engine RPM, a user sends the Mode 01, parameter 0C command (0x010C) to the adapter; the adapter prefixes this with the ECU query arbitration ID (0x7DF) and sends it on the CAN bus. The ECU reads the message and places its response on the bus, where it is read by the adapter and converted to ASCII byte format. Since the response may arrive any time after the query, the adapter has a configurable timeout that it waits to receive a response before returning an error to the user. While vehicle speed and the throttle position sensor data are included in Modes 01 and 02, the steering angle sensor is not. It is likely that this data is only available by paying license fees to each vehicle manufacturer; therefore, the steering wheel data was not part of the implementation.

The OBD-II Bluetooth adapters (ELM327) may be equipped with several serial converter options. The version used in this system is a Bluetooth (IEEE 802.15.1) adapter implementing the Radio Frequency Communications (RFCOMM) device profile. This emulates a reliable RS232 serial UART over the Bluetooth physical and data link layers.

Bluetooth communications are established between peer devices through manual pairing, which may require providing a PIN to guard against eavesdropping. For simplicity, the OBD adapter is programmed with a fixed well-known PIN, 1234. This however does not provide any encryption for the RFCOMM link. Since the OBD adapter allows injection of any command onto the vehicle bus (such as unlocking the doors or rolling down windows), it is disconnected from the DLC when not in use.

The Bluetooth interface is supported by nearly all PC models, making the computing infrastructure interchangeable. For development, an Apple MacBook Pro with Bluetooth running Ubuntu Linux 16.04 was used to interface with the OBD adapter. After pairing the adapter, the RFCOMM channel was set up using the bluez-tools software package. This software links the fixed RFCOMM channel (1) and device MAC address of the OBD adapter to a virtual serial port in the Linux device tree (/dev/rfcommXX). This virtual serial port can be consumed by any program which supports traditional RS232 serial ports. During data collection, the laptop was replaced by a Raspberry Pi 3 equipped with the same OS and software. The Python PyOBD library was selected to interface with the RFCOMM serial port. This provides an object based interface to the ELM327, and handles initialization and wire formatting of commands. To send a command to the ELM327, it is either selected from the well-known PID set, or a custom command is defined by specifying the byte format of the command and response. PyOBD translates the responses into a decimal format with appropriate units, and handles unit conversions if necessary.

The monitoring software first sets up PyOBD by opening the serial port specified on the command line at the specified baud rate. The adapter is configured for machine to machine interaction, removing excess space and linefeeds. The program enters an infinite loop and executes the speed and throttle position commands. By including a call to time.sleep, the loop frequency is limited. The percent change in speed is calculated from the previous value, and if found to exceed a constant margin, a hard braking alert is generated on the console and sent via HTTP to a monitoring API endpoint. The same sequence is performed for the throttle position sensor data, except that the raw value, not percent change, is compared to the threshold. By exceeding the threshold, a hard acceleration event is reported. Figure 3.3 visualizes the events with brake alerts.

Although the events generated by the onboard software are intended to be sent via DSRC to neighboring infrastructure, this is rescinded due to hardware limitations. Instead, an ASP.NET Core HTTP API is created and events are relayed over the vehicles WiFi to LTE gateway. This API is hosted within the Microsoft Azure API Service cloud, making it accessible to any vehicle with an onboard LTE connection to the Internet. The onboard software generates an HTTP over TLS POST request containing the time and alert type

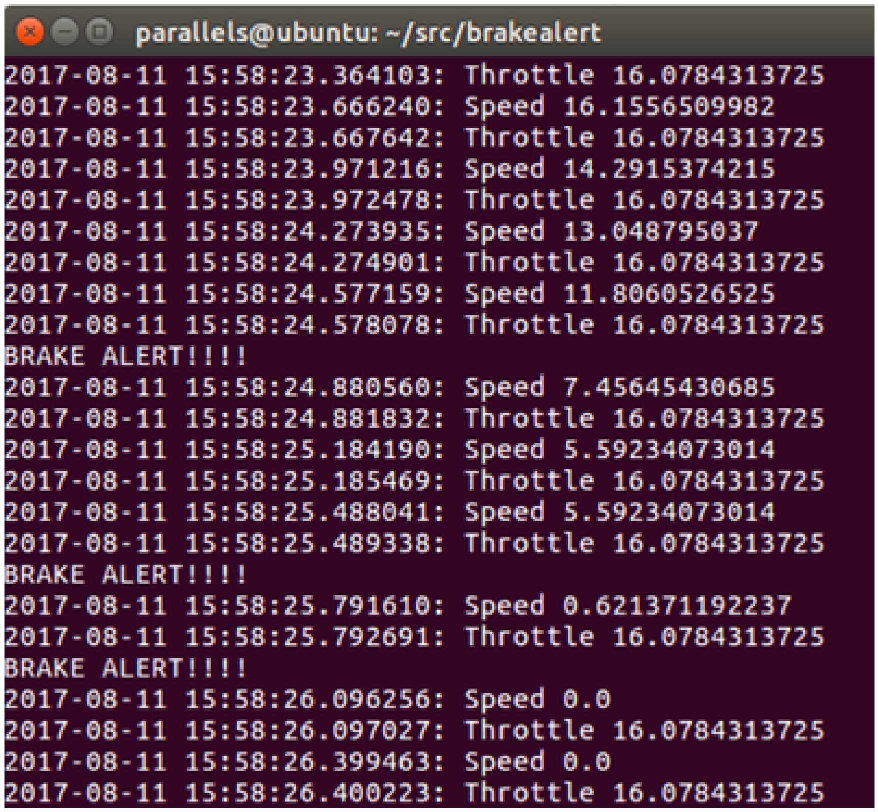

Figure 3.3: Collecting vehicle data during brake alert.

(Brake or Acceleration), which is received by the API and recorded into a MongoDB database for analysis.

3.6 Simulation and Experimentation

The study vehicle is a 2017 Chevrolet Volt sedan, equipped with an OBDII data link connector (DLC) and an onboard WiFi to LTE gateway for event reporting. The design of the onboard software is aided by developing with an OBD simulator package, obdsim. Figure 3.4 demonstrates the graphical interface of obdsim. The simulator presents a virtual serial port to the OS and responds to user commands similar to an ELM327. The fltk GUI included with obdsim allows the user to manually control the data values reported over OBD, or a random or cyclic function can generate them automatically or replay a log file. The onboard software was tested by connecting to obdsim and manually simulated hard braking

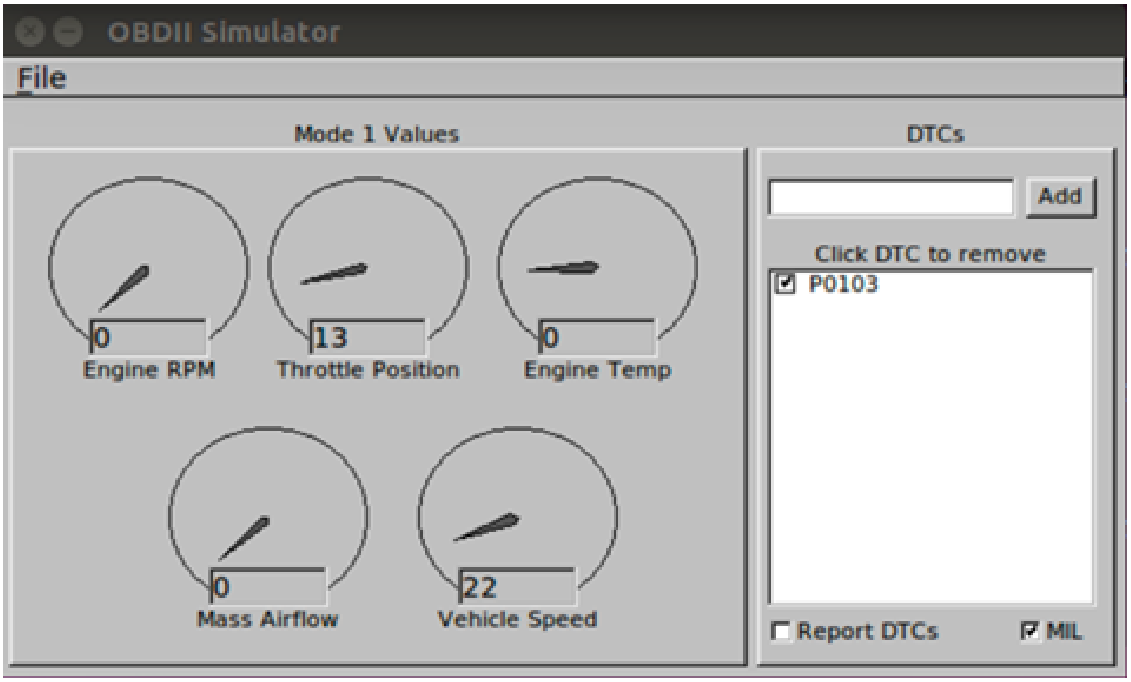

Figure 3.4: Simulation with OBDsim

and acceleration by manipulating the values in the GUI. The simulator reports the number of queries per second, which was used to determine the loop sleep time of 0.3 seconds and verify that the software would not burden the real ECU. The initial speed threshold was determined to be 30% per 0.3 second cycle, and throttle threshold at 50%.

After determining acceptable threshold values, the software was programmed into the Raspberry Pi 3 and set to automatically connect on startup to the ELM327. The Raspberry Pi was powered by onboard USB ports in the vehicle. A driving cycle consisting of repeated accelerations and hard braking was conducted on a private road to verify the accuracy of the simulation. After failing to receive any braking events, the threshold was lowered to 10% per 0.3 second interval. Hard brake and hard acceleration alerts (using Equation 1) were successfully generated. However, during the testing for hard acceleration alert through the throttle position, we realized that the throttle position sensor in the Chevrolet Volt was not directly representative of the accelerator pedal position as it is in most vehicles. As a series hybrid electric vehicle, traction power is provided exclusively by electric motors. The engine is under the full authority of the ECU, which activates it only when the traction battery is depleted or commanded by the driver to preserve battery charge. The engine throttle is controlled by the ECU to maximize efficiency, which may apply engine power to charge the battery independently of the accelerator pedal. Since the actual accelerator position is likely a proprietary PID like the steering angle sensor, it was not considered for this experiment, although monitoring the throttle position would generally work for any non-hybrid vehicle.

3.7 Discussions and Summary

In this chapter, an alerting system based on streaming vehicle kinematics data and capable of detecting and relaying anomalous and hazardous driving behavior, as determined by processing on OBD data is demonstrated. Hard braking and hard acceleration alerts based on anomalies were sent successfully during the experimental cycle. A key contribution of this research is that real-time big data from vehicle kinematics (speed, longitudinal and lateral acceleration, and throttle position) can be used to detect anomalies and volatility in driving patterns to generate helpful alerts and warnings for the driver or proximate vehicles.

While additional data from the CAN bus was desired, the proprietary nature of the data addresses made this impossible without paying licensing fees. Commercial products are able to do so by scaling out the fees across their customer base, which would allow this system to be developed for the aftermarket. If a commercialized DSRC transceivers became widely available, it could be interconnected with this system to provide hazard alerts in vehicles without factory collision avoidance systems. By enabling more of today's vehicles to be fitted with V2I alerting systems, potentially the incidence of driver errors (and hence some traffic collisions) can be reduced through alerts and warnings. Indeed, more research is needed on anomaly detection, how drivers respond to alerts and warnings, and whether these reduce the chances of collisions.

Chapter 4

Conclusions

Road traffic accidents are one of the most important yet preventable causes of death. According to 'global status report on road safety' 2015, more than 1.25 million people die and millions more suffer serious health injury per year due to a road traffic accident. Road traffic injuries are the number one cause of death among 15 to 29 years age group [58]. Safe driving is closely related to a driver's maneuvers. For example, an inattentive or distracted driver can create a dangerous situation on the road compared to a focused driver. Hence, this research focuses on understanding the feasibility of providing real-time driver advisories through vehicular wireless communications. To prevent any unwanted traffic incidents due to risky maneuver and hazardous driving behaviour through real-time driver advisories, it is important to ensure the reliability of V2X communication and also equally important to appropriately characterize the driving behaviour for avoiding unnecessary false warnings. The earlier factor has been investigated in chapter two, while the latter has been discussed in chapter three.

In chapter 2, we have described the results from the experimental studies on the reliability of V2X communications for a safe-pass warning application. The overall contributions of this research are as follows:

1. Development of mathematical analysis to understand the required V2V communication parameters and constraints pertaining to a DSRC-based "Safe pass advisory" application for two-lane rural highways.

2. Experimental quantification of V2V communication ranges and connectivity periods between two DSRC-equipped vehicles approaching each other from opposite directions with various speeds for both freeway and city environments. The data obtained from this experimentation helped determine the time and distance constraints for the proposed "Safe Pass Advisory" application.

3. Investigation of the impacts of varying altitudes on V2V communication reliability and its implications for safety-critical applications.

4. Evaluation of the impacts of vehicle-interior obstacles and OBU placement on the reliability, range and duration of V2V communications, both in the forward and reverse directions. The collected experimental data provided insights for utilizing multi-hop V2V communication in order to overcome limitations of the "Safe pass advisory" application.

In chapter 3, we described a proof-of-concept for utilizing V2X/IoT infrastructure to alert drivers of hazardous driving behaviours. A key contribution of this research is that real-time big data from vehicle kinematics (speed, longitudinal and lateral acceleration, and throttle position) can be used to detect anomalies and volatility in driving patterns to generate helpful alerts and warnings for the driver or proximate vehicles. In summary, the contributions of this research are as follows:

1. Derivation of a statistical regression model to characterise the acceleration/deceleration profile of a regular passenger vehicle with respect to speed and throttle position.

2. Development of an algorithm to provide real-time hard braking alert and hard acceleration alert through utilizing CAB-bus data.

3. Implementation of an IoT-based communication architecture for disseminating the hazardous driving alerts to vulnerable drivers through cellular and/or V2X communication infrastructure.

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42

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