An In-Vehicle Lane Departure and Erratic Driving Warning System using V2V Communication and Standard GPS Technology

A THESIS
SUBMITTED TO THE FACULTY OF THE
UNIVERSITY OF MINNESOTA
BY

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IN PARTIAL FULFILLMENT OF THE REQUIREMENTS
FOR THE DEGREE OF
MASTER OF SCIENCE

Professor Dr. Imran Hayee, Advisor

June 2021

ACKNOWLEDGMENTS

I would like to take the opportunity to thank everyone who helped me completing this thesis. First and foremost, I am thankful to my advisor Professor Dr. Imran Hayee for taking me in his group. His organized guidance and continuous support were indispensable to understand the basic concepts of my thesis, gain advanced knowledge, and solve every problem to complete it successfully. Also, I would like to thank my colleague, Shahnewaz Chowdhury. We worked together as teammates to tackle every problem.

I am grateful to Dr. Umair Ibrahim, a dear friend and alumni of our group, who helped me a lot during this research by sharing his knowledge and spending precious time. I am also grateful to Dr. Hua Tang and Dr. Eleazar Leal for being kind enough to be in my thesis committee.

Last but not the least, I like to acknowledge the Minnesota Department of Transportation (MnDOT) and Minnesota Local Research Board (LRRB) as a part of this study was funded by them.

DEDICATION

I dedicate this to my father whose continuous and relentless support has always been my greatest strength for success in every stage of life.

ABSTRACT

Some of the critical features of Advanced Driver Assistance Systems (ADAS), including unintentional lane departure warning and erratic driving warning have significant potential to reduce crashes. Generally, these systems use either various image processing techniques or Global Positioning System (GPS) technology with lane-level resolution maps. However, these are expensive to implement as well as have some limitations, such as harsh weather or irregular lane markings can drastically reduce their performance. Previously, we developed a lane departure warning system (LDWS) where we generated road reference heading (RRH) form a vehicle's past travel trajectories acquired by GPS to detect unintentional lane departure. But when a vehicle travels for the first time on a given road, it does not have any past trajectory of that road to generate RRH of that road needed to detect unintentional lane departure. So, in this thesis, we have improved our previously developed LDWS by adding a vehicle to vehicle (V2V) communication feature to the existing LDWS so that a vehicle traveling on a road for the first time can acquire the RRH of that road from a nearby vehicle via V2V communication. Furthermore, we have also enhanced the existing LDWS by adding a parallel erratic driving warning system (EWDS) to detect erratic driving behavior of a vehicle so that the system can issue timely warnings to alert the driver. We have considered two most common erratic driving scenarios; inter lane change and intra lane change erratic driving. We have developed an algorithm to detect both erratic driving behaviors and implemented the algorithm in a prototype system. We have extensively tested the V2V communication feature of LDWS as well as the

EDWS in the field to evaluate their accuracy in real-time. Our field test results show an RRH successfully transfers from one vehicle to another, and the EDWS can detect each erratic driving scenario during the test drives accurately in a timely manner.

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LIST OF ABBREVIATIONS

ADAS	Advance Driver Assistance Systems
GPS	Global Positioning System
LDWS	Lane Departure Warning System
EDWS	Erratic Driving Warning System
RRH	Road Reference Heading
LS	Lateral Shift
ALS	Accumulated Lateral Shift
LCT	Lane Change Time
ILCT	Inter Lane Change Time

CHAPTER 1: INTRODUCTION

1.1 BACKGROUND

All modern vehicles are equipped with different Advanced Driver Assistance Systems (ADAS) to improve safe driving [1]. Lane departure as well as erratic driving behavior warning are two important ADAS features which can prevent accidents on highways and freeways when a vehicle is about to unintentionally drift away from its lane or when a vehicle is driven in an erratic manner e.g., changing lanes too quickly posing a hazard for neighboring vehicles. According to American Association of State Highway and Transportation Officials (AASHTO) almost 60% of the fatal accidents are caused by an unintentional lane drifting of a vehicle on major roads [2]. In a recent study which compared crashes with and without a lane departure warning system (LDWS), it was found that an in-vehicle LDWS was helpful in reducing crashes of all severities by 18%, with injuries by 24%, and with fatalities by 86% without considering for driver demographics [3]. Similarly, erratic driving can cause serious road accidents and majority of these accidents involve crossing of an edge line, center line, or otherwise leaving the intended lane or trajectory [4]. In other words, erratic driving during lane change is one of the major causes of road accidents.

Most available lane departure warning systems typically use a single camera and a processor to identify the imminent lane departure [5-8], while other modern systems use optical scanning and Light Detection and Ranging (LIDAR) sensors [9]. A careful view of camera-based systems reveals that the calibration of a camera is an important element.

However, there are systems available that can detect the lateral offset of a vehicle even with an uncalibrated camera [10]. Most of these camera-based systems use different image processing techniques such as linear parabolic lane model [11] or the extended edge-linking algorithm [12], which extract the lane markings from consecutive picture frames to calculate lateral shift of a vehicle. Earlier camera-based systems were vulnerable to lighting conditions, hence not capable to accurately recognize the lane markings at nighttime. However, image processing techniques have advanced over the past couple of decades overcoming the limitation of diminished lighting conditions to successfully detect lane drifting even in the low lighting or night-time [13]. For example, a Video-Based Lane Estimation and Tracking (VioLET) system, which uses steerable filters, is an efficient method for detecting solid-line and segmented-line markings under varying lighting and road conditions for robust and accurate lane-marking detection [14]. Similarly, optical scanning systems which comprise of a linear array of infrared transmitting devices to scan the lateral area of the highway for lane markings, are inherently independent of the varying lighting conditions [15]. Although camera and optical sensor-based systems work well in favorable weather and road conditions in day or night light, their performance deteriorates when the road conditions are not favorable such as an absent or irregular/broken lane marking or harsh weather conditions such as fog, rain, and snow resulting in inaccurate lane departure detection. Moreover, there are also some systems which integrate Global Positioning System (GPS) data with a camera based LDWS to increase the reliability of lane departure detection in adverse road and weather conditions. However, such systems require GPS technology, inertial navigation sensor, and access to digital maps of lane-level resolution to correct the GPS position [16], making such systems more complex and expensive to implement.

While lane departure warning system detect unintentional lane departure, various existing ADAS to mitigate road accidents caused by erratic driving either predict the driver's intent of lane change [17], monitor attentive state during driving [18-19] and/or provide map-based route guidance [20]. Most of the erratic driving detection systems are designed either by detecting vehicle's real-time driving pattern and/or monitoring driver's physical behavior [21]. G. C. M. Quintero et. al. proposed an intelligent erratic driving diagnosis system which uses artificial neural networks (ANNs) to analyze signals from modern on-board diagnostic systems (OBD-II), global positioning system (GPS), and other localization sensors [22]. Erratic driving detection system using image processing information and fuzzy neural networks (FNNs) based decision strategy has also been proposed [23-24]. Besides, K. Saruwatari et. al. proposed a method to detect erratic driving behavior in a group of vehicles using multilinear relationship among vehicle camera images [25]. However, all these existing erratic driving detection systems use some kind of image processing technique and are expensive to implement as well as have some limitations, such as harsh weather or irregular lane markings can drastically reduce their performance.

In this thesis, we enhanced a lane departure warning system by adding erratic driving warning feature as well as solved a critical issue in the current lane departure warning system by including a Vehicle to Vehicle (V2V) communication component in the system. We also proposed an algorithm for erratic driving behavior detection. Both lane departure and erratic driving behavior detection algorithms use standard GPS technology and V2V communication to issue warning in case of an unintentional lane departure or erratic driving behavior. Previously, we developed a methodology to generate Road Reference Heading (RRH), using vehicle's past trajectories of any given road, that can be used to detect unintentional lane departure [26]. Our proposed algorithm for LDWS compares vehicle's trajectory on a road to the generated RRH of that road to determine the lateral shift of a vehicle for potential lane departure detection. To successfully generate the RRH for a given road from a vehicle's past trajectories on that road, it is necessary for the vehicle to have traveled on that road for at least once in the past. So, for a vehicle traveling on a road for the first time, we added the provision of V2V communication to our developed LDWS to transfer RRH. Thus, any vehicle traveling on a road for the first time, can receive RRH of that road from a nearby vehicle having the RRH of that road and equipped with V2V communication. Simultaneously, our proposed algorithm for EDWS detects erratic lane change behavior using the same RRH used by the LDWS algorithm. By comparing the lane change duration and lane change preparation time respectively with the minimum standard lane change duration and lane change preparation time, our developed system can detect both inter lane change and intra lane change erratic driving behavior in real-time.

We have implemented both of our proposed algorithms in a prototype device and have performed many field tests to detect unintentional lane departure as well as both inter lane and intra lane erratic driving behaviors to warn the driver accordingly. Our field tests results show that our developed system can accurately detect unintentional lane departure and erratic driving behavior to generate timely warning for the driver. Both of our LDWS and EDWS are explained in detail in the next chapters.

1.2 OBJECTIVES

The major objectives of this thesis include design and development of two algorithms: V2V communication-based lane departure warning algorithm and erratic driving warning algorithm.

1.2.1 V2V Communication-based Lane Departure Detection

We previously developed an LDWS incorporating Road Reference Heading (RRH) generation system that uses a vehicle's past traveling trajectories on a road to generate RRH of that road [26]. This generated RRH is used by the LDWS which compared vehicle's trajectory to RRH to determine the lateral shift of a vehicle for potential lane departure detection. In this research, one of the objectives is to incorporate V2V communication in our previously developed LDWS and develop a V2V communication-based LDWS. The provision of V2V communication enables a vehicle having RRH of a road to transfer the RRH to any other vehicle traveling for the first time on that road; provided both the vehicles are equipped with V2V communication device. By using the RRH received from another vehicle, our developed LDWS detects any lane departure during the travel and issues warning in a timely manner.

1.2.2 Erratic Driving Behavior Detection

We propose an EDWS using standard GPS technology. We have limited our detection algorithm to detect erratic lane change behavior as it is the most common erratic behavior that causes fatal road accidents. Our proposed system uses only standard GPS receiver and a road reference heading (RRH) of the road on which the vehicle is traveling. Previously, we developed a methodology to generate RRH, using vehicle's past trajectories of any given road, that can be used to detect unintentional lane departure [26]. Building upon that, we now propose our erratic driving warning system that uses the same RRH to detect erratic lane change behavior. We have developed an algorithm for erratic driving behavior detection which can detect both inter lane change and intra lane change erratic driving behavior in real-time.

1.3 METHODOLOGY AND SYSTEM ARCHITECTURE

The proposed system relies on standard GPS receiver to acquire the position of a vehicle and a basic processor to detect lane departure and erratic driving behavior. The processor does the necessary calculations to find lateral shift of a given vehicle to detect unintentional lane departure. Simultaneously, the processor also calculates inter and intra lane change time to detect erratic driving behavior whenever an intentional lane change is done by a vehicle.

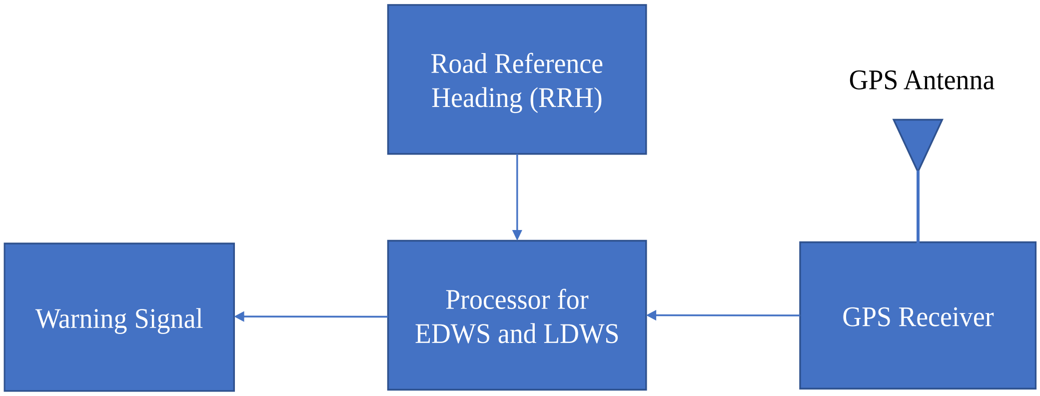


Figure 1.1 Block diagram of the proposed lane departure and erratic driving warning system.

The conceptual architecture of the proposed system using a standard GPS receiver is shown in Figure 1.1. The GPS receiver periodically obtains longitude and latitude of a vehicle's current position. The onboard processor calculates the direction of travel of the vehicle utilizing two or more consecutive positions of the vehicle acquired by the GPS. A road reference heading (RRH) is acquired via V2V communication and stored in the onboard processor. By comparing the vehicle's current direction of travel to the RRH, the processor calculates instantaneous lateral shift of the moving vehicle. The processor also calculates the inter lane change and intra lane change time whenever a vehicle does an intentional lane change. With every new acquired GPS coordinate, the system keeps accumulating the lateral shift and issues a lane departure warning to alert the driver if the accumulative lateral shift exceeds a certain threshold. Simultaneously, comparing calculated inter and intra lane change time with standard inter and intra lane change time [27-29] respectively, the processor can detect an erratic driving behavior to issue warning.

We have implemented our system in a prototype device and have performed many field tests to detect lane departure and erratic driving behaviors to warn the driver accordingly. Our field tests results show that our developed system can accurately detect lane departure as well as erratic behavior in both intra lane change and inter lane change scenarios to generate timely warning for the driver.

1.3.1 Gradual Development of the System

The system architecture for the previously developed LDWS and the currently developed lane departure along with erratic driving warning system is shown in Figure 1.2. We have added the provision of V2V communication to our previously developed LDWS to develop a V2V communication-based LDWS and also developed an EDWS which works simultaneously with the LDWS in real-time. In figure 1.2, the green and blue shaded rectangles show the scope of the previously developed LDWS which was successfully completed previously. The yellow shaded areas within the red dashed rectangle in figure 1.2 represents the scope of this thesis which will be described in detail in the next chapters. In particular, we will discuss the yellow marked areas of the Figure 1.2 which are the two objectives of this thesis.

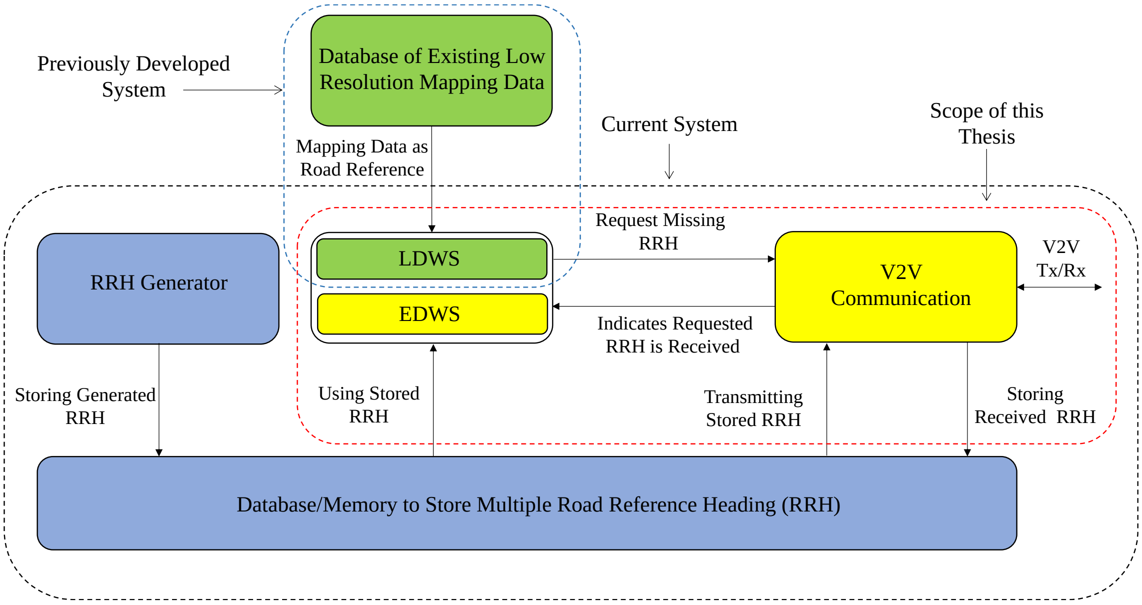
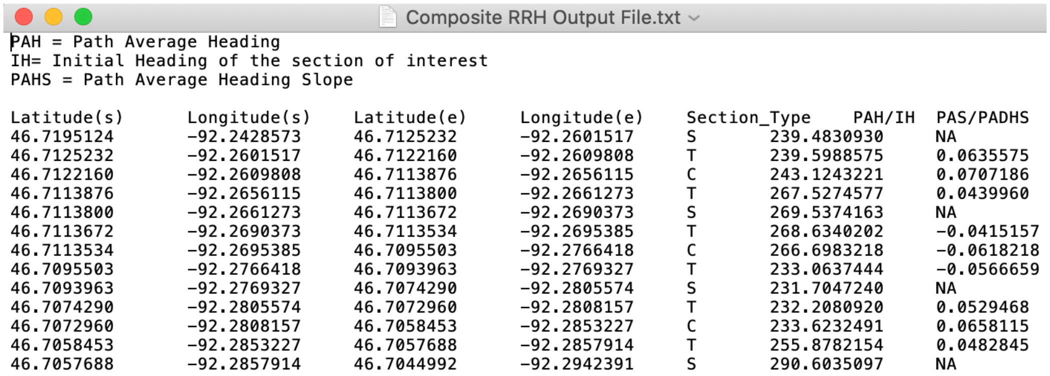


Figure 1.2 System architecture showing the gradual development of the lane departure and erratic driving warning system.

Our developed LDWS relies on the past trajectories of a vehicle on any given road to generate an RRH for that road to detect a future unintentional lane departure. Once a vehicle travels on a road, its trajectory is acquired using GPS receiver to generate an RRH for that road which is stored in the database for future use (Figure 1.2). However, while traveling on a road for the first time, a vehicle does not have the necessary RRH for that road in its database. In this case, the vehicle can request the RRH for that road from a neighboring vehicle which has traveled on that road before and have previously generated and stored the RRH for that road. This process can be facilitated either using cellular vehicle to vehicle (C-V2V) communication or via dedicated short-range communication (DSRC). Once an RRH is successfully received from a nearby vehicle, it can be stored in the receiving vehicle's memory/database for future use. Please note that the generation of road reference heading is an integral and prerequisite part of our developed system. Though generation of RRH algorithm was done in a parallel research but that is out of the scope of this thesis, we will discuss it briefly in the following section.

1.4 GENERATION OF ROAD REFERENCE HEADING

As shown in Figure 1.1, for our developed system, it is mandatory to have an RRH of a given road to detect lane departure or erratic driving on that road which is generated from one or more past trajectories. Generation of RRH, from a vehicle's past trajectories, works in three stages. In the first stage, all straight, curve, and transition sections of any road are identified from the given GPS trajectory on that road. In the second stage, each identified section is characterized with a set of optimized parameters defining road reference heading value at each point on that road section. After identifying and characterizing each section with an optimal set of parameters, all sections are combined to generate a composite RRH for that road. The typical RRH file for a given road is shown in Figure 1.3, where each row represents an individual section of the road defined by its beginning and ending points (in terms of latitude and longitude), the optimized parameter values, and the section type (S: Straight, C:Curve, and T:Transition). Please note that an “N” indicates that the corresponding parameter is not applicable for that section. This file has all the necessary information to completely define RRH at any point along the road. The details of RRH generation can be found in our previous work [26].



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PAH = Path Average Heading
IH= Initial Heading of the section of interest
PAHS = Path Average Heading Slope

Latitude(s)       Longitude(s)      Latitude(e)      Longitude(e)      Section_Type     PAH/IH    PAS/PADHS
46.7195124        -92.2428573       46.7125232       -92.2601517       S         239.4830930      NA
46.7125232        -92.2601517       46.7122160       -92.2609808       T         239.5988575      0.0635575
46.7122160        -92.2609808       46.7113876       -92.2656115       C         243.1243221      0.0707186
46.7113876        -92.2656115       46.7113800       -92.2661273       T         267.5274577      0.0439960
46.7113800        -92.2661273       46.7113672       -92.2690373       S         269.5374163      NA
46.7113672        -92.2690373       46.7113534       -92.2695385       T         268.6340202      -0.0415157
46.7113534        -92.2695385       46.7095503       -92.2766418       C         266.6983218      -0.0618218
46.7095503        -92.2766418       46.7093963       -92.2769327       T         233.0637444      -0.0566659
46.7093963        -92.2769327       46.7074290       -92.2805574       S         231.7047240      NA
46.7074290        -92.2805574       46.7072960       -92.2808157       T         232.2080920      0.0529468
46.7072960        -92.2808157       46.7058453       -92.2853227       C         233.6232491      0.0658115
46.7058453        -92.2853227       46.7057688       -92.2857914       T         255.8782154      0.0482845
46.7057688        -92.2857914       46.7044992       -92.2942391       S         290.6035097      NA
```

Figure 1.3 Screenshot of an RRH file of a given road with all optimized parameters.

The RRH given in Figure 1.3 is from the 4.2 km segment of Interstate I-35 near Duluth, MN. We used this road segment in past to detect unintentional lane departure [26]. For our field tests, we used the same road segment.

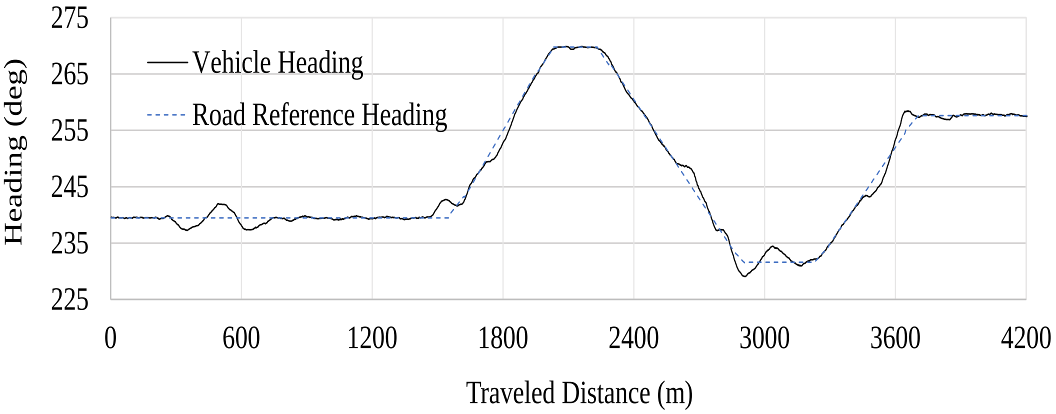


Figure 1.4 Vehicle heading and RRH vs traveled distance for one test drive.

Our test vehicle was driven on this road segment multiple times making many lane changes in each trip and accumulated lateral shift (ALS) was calculated in real-time to detect the lane changes. The vehicle heading for one such test trip vs. traveled distance is plotted along with the RRH of the road segment in Figure 1.4 showing that vehicle heading deviates significantly from the RRH in some positions during the vehicle's travel which are actually different lane changes done by the vehicle. Everywhere else in the trajectory when there is no lane change, the vehicle heading almost aligns with the RRH. Thus, Figure 1.4 clearly shows that all lane changes during a vehicle's travel can be identified on a road using the generated RRH of that road which helps to detect unintentional lane departure or erratic driving behavior while changing a lane.

CHAPTER 2: V2V COMMUNICATION FOR LANE DEPARTURE WARNING

Our previously developed LDWS extracted the needed RRH from an open-source mapping database which worked well on most roads except, occasionally, it gave false alarms i.e., it issued lane departure warnings even when the vehicle was within its lane [30]. So, we also developed a system to generate an accurate RRH from a vehicle's past trajectories, which when used by our LDWS, significantly improved its performance by minimizing the frequency of false alarms to almost zero [26]. To successfully generate the RRH for a given road from a vehicle's past trajectories on that road, it is necessary for the vehicle to have traveled on that road for at least once in the past. However, if a vehicle travels on a given road for the first time, it will not have the necessary travel trajectories to generate the RRH for unintentional lane departure detection. To overcome this problem, V2V communication can be used for a vehicle traveling for the first time on a given road to obtain the needed RRH from a nearby vehicle which has travelled on that road in the past and have already generated the RRH for it. To achieve this purpose, we have developed a V2V communication based LDWS which is one of the two objectives of this thesis. This chapter will highlight the design and development of V2V communication process needed to exchange RRH between two vehicles upon need.

2.1 V2V HANDSHAKE PROTOCOL

For successful transfer of an RRH from one vehicle to another, proper V2V handshake protocol is required to identify the most suitable neighboring vehicle to transfer RRH to the vehicle in need. A vehicle will request an RRH from neighboring vehicles only when it is traveling on a road for the very first time or does not have the RRH for that road. One such scenario showing a vehicle V_R traveling on a 4-lane road for the first time while not having the RRH for that road is illustrated in Figure 2.1. A total of 12 neighboring vehicles (V_1 to V_{12}) are also traveling on the same road (Figure 2.1). The vehicle V_R will need the RRH for that road to detect any unintentional lane departure. Therefore, it broadcasts a request for the RRH by transmitting a message called *REQUEST*. The *REQUEST* reaches all nearby vehicles within its communication range as shown by dashed arrows in Figure 2.1a. The data of *REQUEST* includes the direction of travel of the requesting vehicle (V_R) and its location coordinates. The direction of travel is needed to eliminate those vehicles which are traveling in the opposite direction of the requesting vehicle (V_R) because those vehicles will not stay within the communication range of the requesting vehicle long enough to complete the handshake protocol to transfer RRH.

All neighboring vehicles receiving the *REQUEST* will assess if they are traveling in the direction of the requesting vehicle and if they have the requested RRH to pass on. Any vehicle not having the requested RRH or traveling in the opposite direction of the requesting vehicle will ignore the *REQUEST*. Any vehicle having the requested RRH and traveling in the same direction as the requesting vehicle becomes a potential candidate vehicle to transfer RRH to the requesting vehicle (V_R). There are 4 such potential candidate vehicles (V_1, V_3, V_4, and V_5) shown in green color in the scenario of Figure 2.1. The rest of the vehicles (shown in grey color) are either traveling in the opposite direction or do not have the requested RRH. There is always a possibility to have more than one potential candidate vehicles to transmit RRH as in the scenario of Figure 2.1.

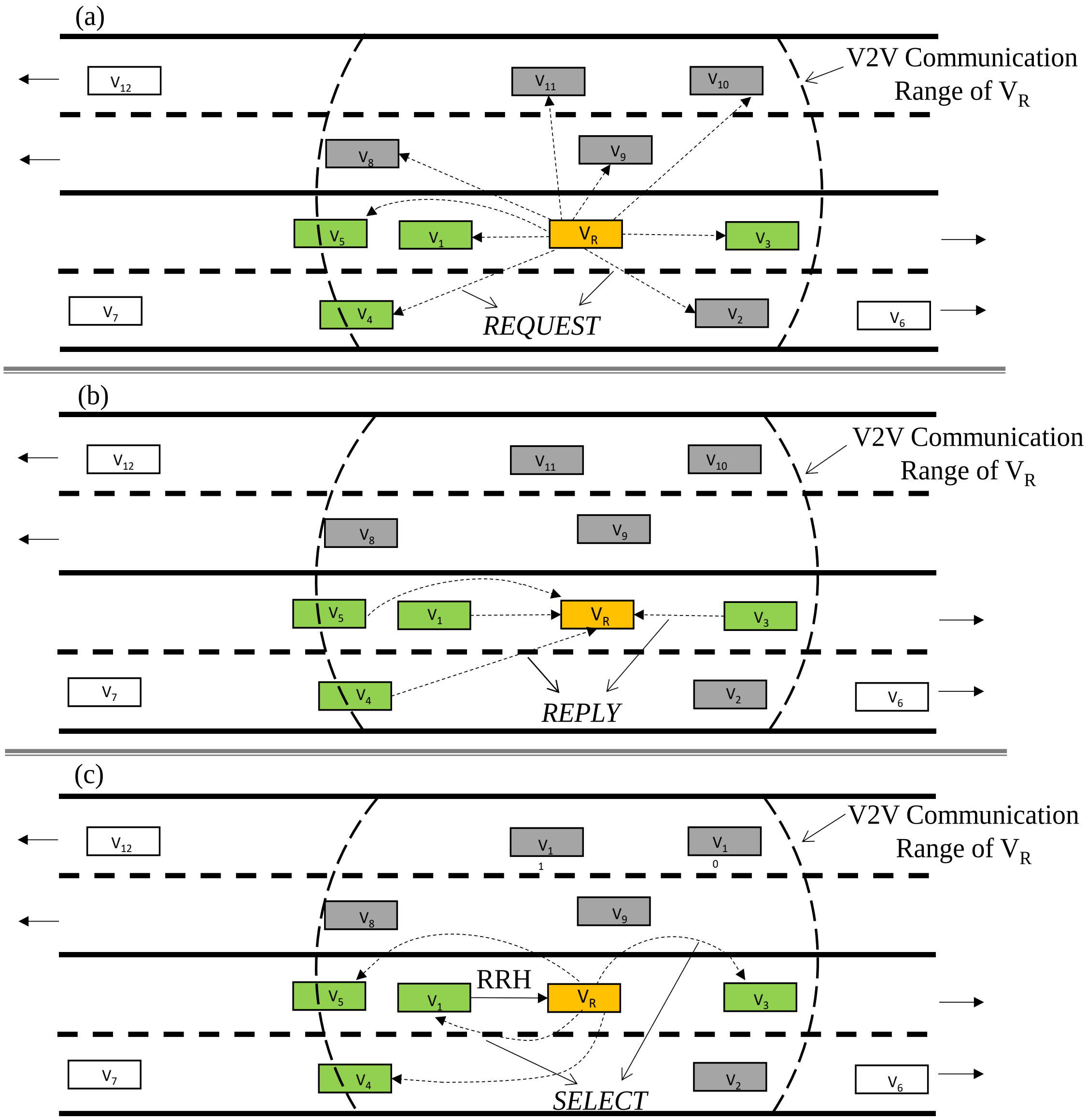


Figure 2.1 A scenario illustrating V2V handshake protocol where (a) a vehicle V_R in need of road reference heading (RRH) broadcasts a *REQUEST* to all neighboring vehicles within its V2V communication range, (b) all potential candidate vehicles (colored in green) send a *REPLY* message back to the requesting vehicle and (c) the requesting vehicle V_R sends a *SELECT* message to receive RRH from the most suitable potential candidate vehicle (V_1).

In case of more than one potential candidate vehicles having the needed RRH, it is important that only one of those vehicles is selected to transfer RRH to avoid broadcast congestion. Usually, a vehicle which is the nearest to the requesting vehicle should transfer the requested RRH for most reliable communication. To accomplish this, each potential candidate vehicle calculates its distance from the requesting vehicle (V_R) and transmits a message called *REPLY* back to the requesting vehicle as shown by dashed arrows in Figure 2.1b where the same scenario of Figure 2.1a is repeated showing communication paths of *REPLY* messages from all potential candidate vehicles. The data of each *REPLY* message from a potential candidate vehicle includes its distance from the requesting vehicle as well as a unique identifier (ID) so that the requesting vehicle can distinguish among all potential candidate vehicles.

After receiving the *REPLY* messages from all potential candidate vehicles, the requesting vehicle, V_R selects one potential candidate vehicle at the shortest distance. Please note that if two or more vehicles are at the same distance, then the requesting vehicle can randomly select any one of them. After selecting one of the potential candidate vehicles, the requesting vehicle (V_R) sends a message called *SELECT* back to all potential candidate vehicles as shown in Figure 2.1c where the same scenario is repeated showing the multiple communication paths of the SELECT message to all potential candidate vehicles. The data of the *SELECT* message includes the unique ID of only one potential candidate vehicle which is at the shortest distance from the requesting vehicle so that all other potential candidate vehicles can ignore this message except the one whose unique ID is carried in this message. This will complete the V2V handshake protocol by successfully selecting the most suitable vehicle to transfer RRH to the requesting vehicle. The potential candidate vehicle with matched unique ID (V_1 in case of the given scenario of Figure 2.1c) can now start transferring the requested RRH to the requesting vehicle (V_R) as shown by a solid arrow from V_1 to V_R in Figure 2.1c. The implementation details of the V2V handshake protocol and transfer of RRH are given in the rest of this chapter.

2.1.1 Implementation of V2V Communication using DSRC Device

After developing the V2V handshake protocol to identify the most suitable vehicle to transfer RRH to a vehicle in need, we implemented this protocol in our LDWS and did the necessary programming to successfully demonstrate its functionality. The flowchart of the developed software to implement the developed V2V handshake protocol is shown in

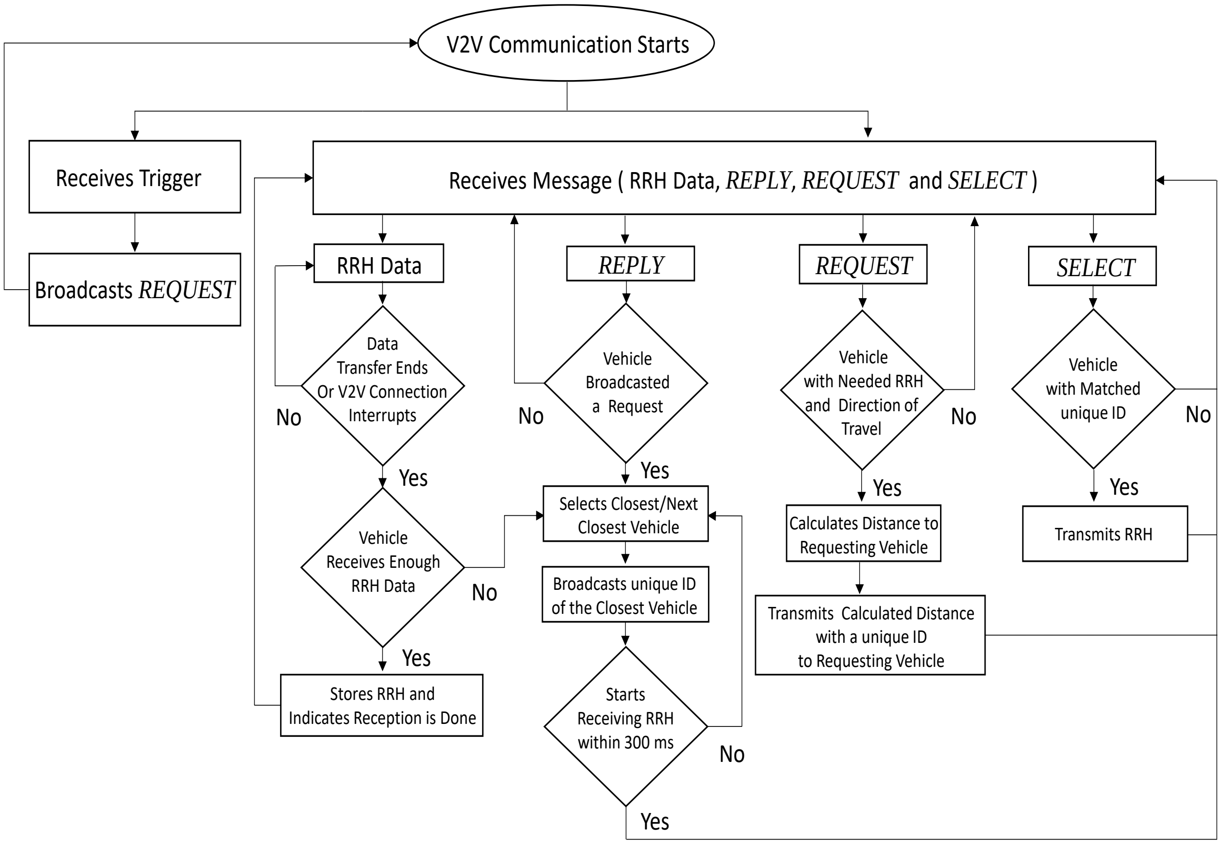


Figure 2.2 A flow chart of the V2V handshake protocol for a vehicle in need to receive RRH data of a given road from the most suitable neighboring vehicle on that road.

Figure 2.2. Please note that the software of flowchart given in Figure 2.2 will be running in each vehicle in addition to two other software i.e., RRH generation software and the lane departure detection software as developed earlier. The implementation platform of all the developed software is a DSRC based device which has a built in GPS receiver and necessary processing power to run the developed software. The software of the flowchart given in Figure 2.2 to implement the V2V handshake protocol to transfer RRH from the most suitable neighboring vehicle to the requesting vehicle is explained below.

1. The vehicle in need of RRH, after receiving a trigger from the LDWS software, broadcasts a *REQUEST* message to all nearby vehicles within its DSRC range. The data of the *REQUEST* consists of requesting vehicle's location and direction of travel.

2. All nearby vehicles receiving the *REQUEST* process its data to check if they have the needed RRH and traveling in the same direction as the requesting vehicle.

3. Each vehicle having the needed RRH and traveling in the same direction as the requesting vehicle (potential candidate vehicle) calculates its distance from the requesting vehicle and sends a *REPLY* message back to the requesting vehicle. The data of each *REPLY* message consists of the calculated distance and a unique identifier (ID) of the corresponding potential candidate vehicle. At this point, each potential candidate vehicle keeps waiting for the response back from the requesting vehicle to decide if it will need to transfer RRH to the requesting vehicle.

4. The requesting vehicle in need of RRH receives the *REPLY* messages from all the potential candidate vehicles and process all messages to select the closest potential candidate

vehicle. If two or more vehicles are at same distance, then the requesting vehicle can randomly select any one of them.

5. The requesting vehicle in need of RRH now broadcasts a *SELECT* message containing the unique ID of the selected potential candidate vehicle.

6. All potential candidate vehicles process the received unique ID in the *SELECT* message to see if it matches with their unique ID. Any potential candidate vehicle not having a match with the unique ID will come out of the waiting routine and resume the normal operation by starting over. Please note that for some reason, if a potential candidate vehicle does not receive the *SELECT* message, it will assume that it is now out of communication range of the requesting vehicle and will resume normal operation after waiting for 300 ms (3 DSRC communication cycles).

7. The potential candidate vehicle with matched unique ID will now start transferring RRH data to the requesting vehicle. The process of actual transfer of RRH data takes place in next several cycles of DSRC communication (100 ms each) depending upon the length of data in RRH. The complete process of RRH data transfer is described later below.

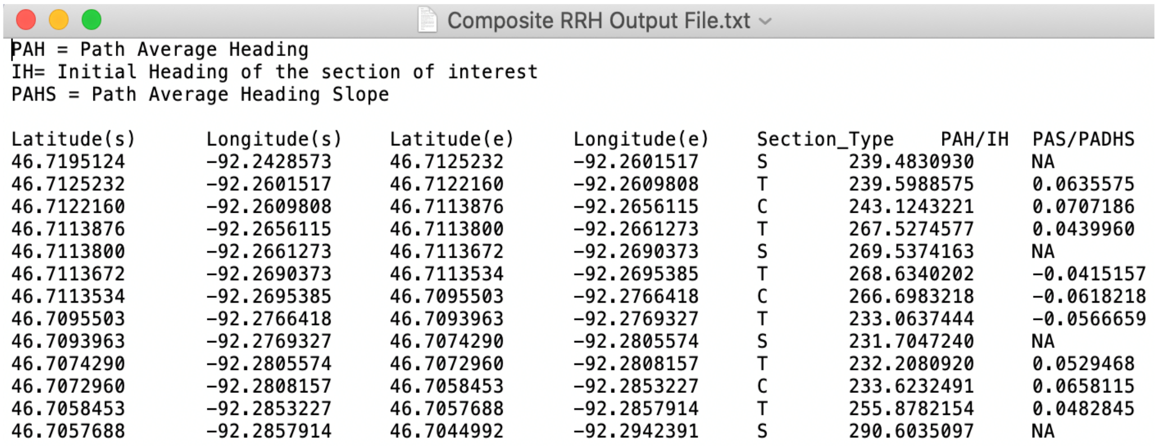
8. The requesting vehicle receives the RRH data and checks received data periodically after every DSRC communication cycle (100 ms) to evaluate if it has received enough length of RRH data. For some reason, if the connection between the requesting vehicle in need of RRH and the selected potential candidate vehicle is lost/interrupted before receiving enough data (e.g., 1 mile), then the requesting vehicle sends the *SELECT* message again but with the unique ID of the next closest potential candidate vehicle. However, if the

connection between the two vehicles is lost after enough RRH data has been received by the requesting vehicle, then it will initiate another *REQUEST* at a later time upon need to start the whole process again.

2.2 V2V TRANSFER OF RRH

The handshake protocol to select the most suitable vehicle to transfer RRH to the vehicle in need is described above. After the most suitable vehicle is identified and selected, the process to transfer RRH takes place slowly over next several cycles of DSRC communication depending upon the amount of RRH data. The data of RRH generated from past vehicle trajectories using our proposed algorithm as developed earlier is included in a text file containing many rows as shown in Figure 2.3 where a screenshot of a typical RRH data file for a 4.2 km road segment of the Interstate I-35 is shown. Each row describes an individual section (straight, curve or transition) of the road and there are 13 sections (rows) in the given text file. Each section is defined by its beginning and ending points (in terms of latitude and longitude), the optimized values of relevant parameters, and the section type. Please note that an “N” indicates that the corresponding parameter is not applicable to that section. This text file has the necessary information to completely define the road reference heading at any point along the road and can be used by LDWS to detect any unintentional lane departure in real-time. Although each section of the road in RRH data file contains seven parameters to fully characterize the given section, one of the 7 parameters (the section type shown in Figure 2.3) is not necessarily needed as it can be deduced from the other parameters. Therefore, in our developed system, each section can be transmitted using only six parameters.

In DSRC based V2V communication, each data transfer cycle is 100 ms and any data transfer can take place during this cycle. We have implemented RRH data transfer process section by section but in such a way that only two parameters can be transferred in one communication cycle (100 ms). As there are six useful parameters in each section of RRH data for any given road, we need three cycles (300 ms or 0.3 s) to completely transfer one section. Depending upon the number of sections of the road in an RRH text file, it can take up to a few seconds to complete the RRH transfer process. For example, there are 13 sections in the RRH text file of Figure 2.3, therefore, it will take 3.9 seconds (13 x 0.3 s) to completely transfer all the sections of this RRH. After successfully completing the transfer of all the sections present in the RRH data file, a final message is sent to the receiving vehicle to indicate that all the data has been sent. Please note that an additional communication cycle (0.1 s) will be needed for the final message indicating the data transfer completion. For some reason, if the connection is lost before the transfer of RRH



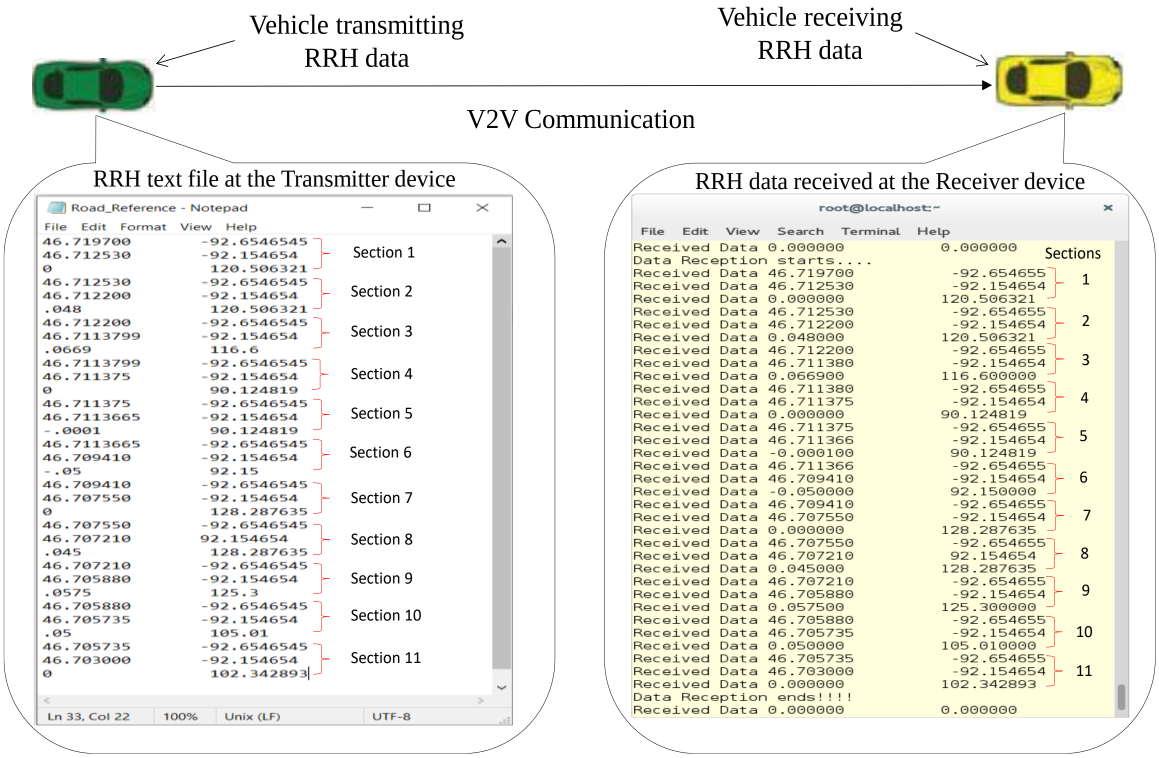
```
PAH = Path Average Heading
IH= Initial Heading of the section of interest
PAHS = Path Average Heading Slope

Latitude(s)      Longitude(s)     Latitude(e)     Longitude(e)     Section_Type    PAH/IH   PAS/PADHS
46.7195124       -92.2428573      46.7125232      -92.2601517      S        239.4830930     NA
46.7125232       -92.2601517      46.7122160      -92.2609808      T        239.5988575     0.0635575
46.7122160       -92.2609808      46.7113876      -92.2656115      C        243.1243221     0.0707186
46.7113876       -92.2656115      46.7113800      -92.2661273      T        267.5274577     0.0439960
46.7113800       -92.2661273      46.7113672      -92.2690373      S        269.5374163     NA
46.7113672       -92.2690373      46.7113534      -92.2695385      T        268.6340202     -0.0415157
46.7113534       -92.2695385      46.7095503      -92.2766418      C        266.6983218     -0.0618218
46.7095503       -92.2766418      46.7093963      -92.2769327      T        233.0637444     -0.0566659
46.7093963       -92.2769327      46.7074290      -92.2805574      S        231.7047240     NA
46.7074290       -92.2805574      46.7072960      -92.2808157      T        232.2080920     0.0529468
46.7072960       -92.2808157      46.7058453      -92.2853227      C        233.6232491     0.0658115
46.7058453       -92.2853227      46.7057688      -92.2857914      T        255.8782154     0.0482845
46.7057688       -92.2857914      46.7044992      -92.2942391      S        290.6035097     NA
```

Figure 2.3 Screenshot of an RRH file of a given road with all optimized parameters.

data is completed or before enough RRH data is transferred, our developed software can manage the situation by restarting the process as described above in the V2V handshake protocol.

After developing the software for V2V handshake protocol and RRH data transfer, we evaluated this in the lab by using two DSRC devices to simulate two vehicles, one vehicle without the RRH and the other with the RRH. One such lab evaluation scenario is illustrated in Figure 2.4 where the vehicle shown as yellow needs an RRH for a given road and the vehicle shown as green has that RRH. Once the V2V handshake protocol establishes the connection between the two vehicles (transmitting and receiving), the



```
46.719700          -92.6546545
46.712530          -92.154654
0                   120.506321
46.712530          -92.6546545
46.712200          -92.154654
.048                120.506321
46.712200          -92.6546545
46.7113799         -92.154654
.0669               116.6
46.7113799         -92.6546545
46.711375          -92.154654
0                   90.124819
46.711375          -92.6546545
46.7113665         -92.154654
-.0001              90.124819
46.7113665         -92.6546545
46.709410          -92.154654
-.05                92.15
46.709410          -92.6546545
46.707550          -92.154654
0                   128.287635
46.707550          -92.6546545
46.707210          92.154654
.045                128.287635
46.707210          -92.6546545
46.705880          -92.154654
.0575               125.3
46.705880          -92.6546545
46.705735          -92.154654
.05                 105.01
46.705735          -92.6546545
46.703000          -92.154654
0                   102.342893
```

```
Received Data 0.000000           0.000000
Data Reception starts....
Received Data 46.719700           -92.654655
Received Data 46.712530           -92.154654
Received Data 0.000000           120.506321
Received Data 46.712530           -92.654655
Received Data 46.712200           -92.154654
Received Data 0.048000           120.506321
Received Data 46.712200           -92.654655
Received Data 46.711380           -92.154654
Received Data 0.066900           116.600000
Received Data 46.711380           -92.654655
Received Data 46.711375           -92.154654
Received Data 0.000000           90.124819
Received Data 46.711375           -92.654655
Received Data 46.711366           -92.154654
Received Data -0.000100           90.124819
Received Data 46.711366           -92.654655
Received Data 46.709410           -92.154654
Received Data -0.050000           92.150000
Received Data 46.709410           -92.654655
Received Data 46.707550           -92.154654
Received Data 0.000000           128.287635
Received Data 46.707550           -92.654655
Received Data 46.707210           92.154654
Received Data 0.045000           128.287635
Received Data 46.707210           -92.654655
Received Data 46.705880           -92.154654
Received Data 0.057500           125.300000
Received Data 46.705880           -92.654655
Received Data 46.705735           -92.154654
Received Data 0.050000           105.010000
Received Data 46.705735           -92.654655
Received Data 46.703000           -92.154654
Received Data 0.000000           102.342893
Data Reception ends!!!!
Received Data 0.000000           0.000000
```

Figure 2.4 Screenshot of the console of the DSRC device in the transmitter vehicle (left bubble box) showing a text file of RRH data stored in the device and screenshot of the console of the DSRC device in the receiving vehicle (right bubble box) when the RRH data is received via DSRC based V2V communication.

transfer of RRH data takes place section by section. The transfer of the RRH data is also illustrated in Figure 2.4 where the screenshots of the consoles of the two DSRC devices of the two corresponding vehicles are also shown.

The left-side console is for the transmitting vehicle’s device and shows the actual RRH data which is being transmitted to the other vehicle. The right-side console is for the device of the receiving vehicle and shows the actual received RRH data by the receiving vehicle’s device. There are 11 sections in the RRH of the text file used in this lab evaluation which was successfully transmitted in a total of 3.4 seconds. The transmission of each of the 11 sections in the RRH data file took 0.3 seconds so all 11 sections were successfully transmitted in 3.3 seconds (11 x 0.3 s). The final message (in the form of two consecutive zeros) took another 0.1 second indicating that the transfer was complete.

CHAPTER 3: ERRATIC DRIVING WARNING

3.1 ERRATIC DRIVING SCENARIOS

For a normal lane change, a minimum preparation time is needed before a lane change can be initiated. Similarly, after a lane change is initiated, the lane change should be completed in a normal time which cannot be smaller than a minimum threshold. Utilizing the minimum preparation time and minimum lane change duration as determined in prior research [27-29], our algorithm can identify erratic driving behavior whenever a vehicle changes its lane.

3.1.1 Intra Lane Change Erratic Driving

Intra lane change erratic driving is detected based on the standard lane change duration needed for a safe lane change. To get an idea of standard lane change duration, we have considered a mathematical model of freeway exiting behaviour by Fazio et al [29] as part of the model predicts the duration of a lane change. This model was evaluated in a study of National Cooperative Highway Research Program (NHCRP) by collecting videotaped data on seven different sites [27-29] and time for a normal lane change was predicted as 1.5 seconds which is considered safe. Therefore, we have considered 1.5 seconds for normal lane change duration. Our proposed algorithm calculates lane change time (LCT) and compares it with the standard time for executing a lane change. If the calculated LCT is below the standard lane change execution time, then an intra lane change erratic driving is detected.

3.1.2 Inter Lane Change Erratic Driving

Determining the standard preparation time for a lane change is a complex task as it depends on different factors, such as traffic density on road, driving experience, and driver's eye and head movement pattern, etc. Depending on driver's visual scanning pattern, the range of preparation time for a lane change varies from 3.7 seconds without traffic to as much as 6.1 seconds with traffic [27]. So, in this paper, 3.7 seconds is considered as the minimum standard lane change preparation time which a vehicle must spend after any lane change to initiate another lane change. After any lane change our proposed algorithm calculates the time interval between the current lane change and its preceding lane change. If this time interval is less than 3.7 seconds, an inter lane change erratic driving behaviour is detected and a warning is issued.

3.2 ERRATIC DRIVING DETECTION ALGORITHM

To detect erratic driving and issue warnings, our proposed algorithm works in two stages. In the first stage, the algorithm detects the starting and ending points of any lane change to calculate both lane change time (LCT) and inter lane change time (ILCT) during a vehicle's travel in real-time. The LCT of a single lane change is defined as the lane change duration of any given lane change. Similarly, ILCT for two consecutive lane changes is defined as the time interval between ending of any given lane change and starting of the preceding lane change. In the second stage, the algorithm compares the LCT with minimum standard actual lane change time for normal driving to detect if a given lane change will be an erratic lane change behavior. Similarly, ILCT is compared with the minimum standard lane change preparation time needed for any lane change to detect erratic driving behavior. The details of lane change detection including its starting and ending times are further discussed below.

As an example of each normal and erratic driving behaviour during the execution process of a lane change, two driving scenarios are depicted in Figure 3.1 where two separate trajectories are shown with two lane changes in each. One trajectory shown as solid blue line is considered normal driving behaviour because the LCT during both lane changes is more than the standard threshold of 1.5 seconds. Similarly, the ILCT between the two consecutive lane changes is also more than 3.7 seconds which falls in normal driving behaviour. However, in the trajectory shown as red dashed line, erratic driving behaviour is depicted because LCT during one of the two lane changes (first one) is less than 1.5 seconds showing that the vehicle completed the lane change too quickly so falls under

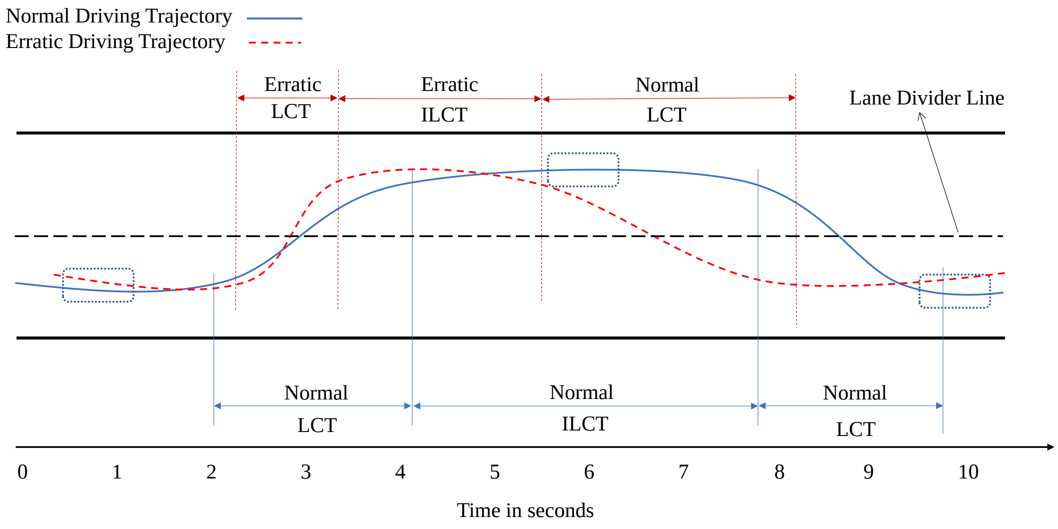


Figure 3.1 Schematic diagram showing vehicle's trajectory for normal driving and erratic driving during lane change.

erratic driving behaviour. Similarly, the ILCT between two lane changes in this trajectory is less than 3.7 seconds exhibiting the erratic driving behaviour.

While a vehicle is moving, its GPS receiver periodically acquires its position coordinates. At any given time, n, using the current position of the vehicle and its previous position, the algorithm determines the vehicle's heading, θ_v using forward azimuth equation as well as the distance between two consecutive positions, D_n using haversine equation [31]. Once the θ_v is determined, it is used to calculate the deviation angle, θ_n by subtracting θ_v from the road reference heading (RRH) θ_{RRH} using equation 3.1. Subsequently, θ_n is used to determine the instantaneous lateral shift (LS) by using equation 3.2.

$$\theta_n = \theta_v - \theta_{RRH} \tag{3.1}$$

$$LS = D_n \sin(\theta_n) \tag{3.2}$$

A new LS is calculated upon acquiring every new set of GPS coordinate and is accumulated over time to get the accumulated lateral shift. ALS is calculated by using equation 3.3, where n is the current position and k's are the previous positions with $k = 1$ being the position where ALS was zero.

$$ALS = \sum_{k=1}^{n} D_k \sin(\theta_k) \tag{3.3}$$

If ALS at any given point crosses the threshold of one meter (1 m) [30], a lane change or a lane departure is detected. The intentional lane change is distinguished from unintentional lane departure by a presence of a lane change indicator signal. This phenomenon is depicted in Figure 3.2, where the ALS of a vehicle is shown versus traveled distance/time. In case of no lane change, a vehicle travels in parallel of RRH. In this case, ALS always remains below the threshold, not detecting any lane change. When the vehicle changes its lane from right to left, its ALS increases in positive direction and vice versa. A vehicle is considered to be in the process of changing its lane when the absolute value of ALS crosses the threshold of 1 m and the lane change indicator is on. When our algorithm detects a lane change from the ALS value, it traces back to the most recent point where ALS started to increase from zero and records it as the starting point of the lane change as shown in Figure 3.2. For any lane change *n*, the time at the starting point of the lane change will be defined as t_n.

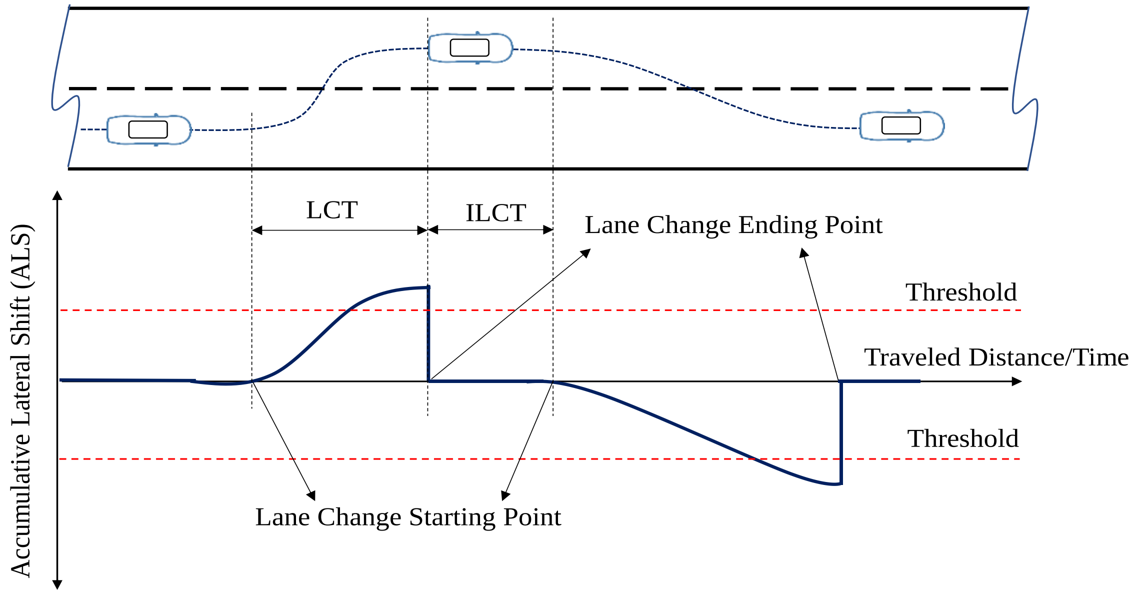


Figure 3.2 Schematic diagram showing lane change detection.

When a vehicle intentionally changes its lane, as in the scenario depicted in Figure 3.2, the increase in LS saturates, i.e., upon completion of lane change, any further increase in LS becomes negligibly small because the vehicle starts traveling in parallel to the road reference heading. This phenomenon is used to reset the ALS to zero for detecting future lane changes and the point where ALS is set to zero is considered as the ending point of that lane change, as shown in Figure 3.2. The corresponding time at the ending point of any lane change will be defined as $t_{n,e}$ for that lane change. Whenever a lane change is detected, a lane change time for the given lane change (LCT_n) is calculated using equation 3.4.

$$LCT_n = t_{n,e} - t_{n,s} \tag{3.4}$$

Similarly, an inter lane change time $ILCT_{n,n-1}$ after any lane change n, is calculated using equation 3.5. Please note that inter lane change time cannot be calculated after the first lane change during the travel. However, for every following lane change, an inter lane change time can be calculated using equation 3.5.

$$ILCT_{n,n-1} = t_{n,s} - t_{n-1,e} \tag{3.5}$$

We used a Savari MobiWAVE unit to implement our algorithm and evaluate its performance in the field. The Savari unit has a built in GPS receiver as well as sufficient processing power to implement our algorithm. The built-in GPS receiver had a UBlox LEA-6 chipset which is a common chipset in many GPS receivers. The prototype system periodically (every 100 msec) calculates instantaneous lateral shift and accumulates it over time to detect any lane change. Simultaneously, the system also calculates LCT and ILCT whenever a new lane change occurs. Newly calculated LCT and ILCT are compared with the thresholds to detect erratic driving behavior and issue warning in real-time. This whole cycle of calculation is repeated every 100 msec and warning is issued each time an erratic driving behavior is detected. The functional flow diagram of the erratic driving detection algorithm is shown in Figure 3.3.

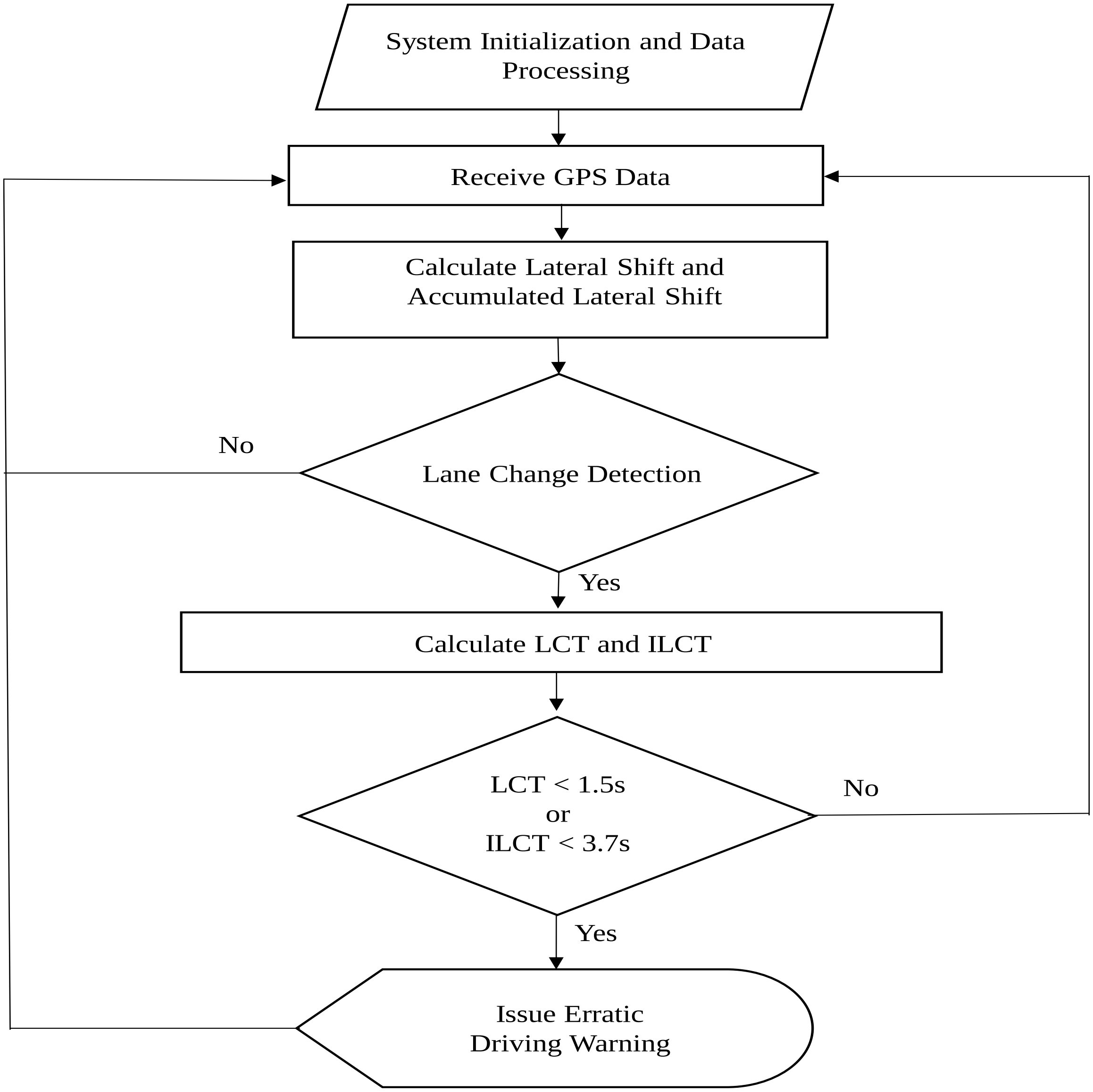


Figure 3.3 Flow diagram showing the complete functionality of erratic driving warning system where, LCT means Lane change Time and ILCT means Inter Lane Change Time.

CHAPTER 4: FIELD TESTS, RESULTS AND DISCUSSION

4.1 FIELD TESTS FOR V2V COMMUNICATION-BASED LANE DEPARTURE WARNING

After successfully developing and testing V2V handshake protocol and RRH data transfer software in the lab, we wanted to evaluate both in the field to detect unintentional lane departures. We have been using a 4.2 km long road segment of the Interstate I-35 as shown in Figure 4.1a for our previous field tests for which we have already extracted an RRH. We used the same road segment to test the V2V handshake protocol and RRH data transfer software. The complete field test involves driving at least two test vehicles, one of these two vehicles without having the RRH data file in its DSRC device and running only lane departure warning software while the other vehicle having the required RRH data file in its DSRC device. The two vehicles should be driven within the DSRC communication range of each other on the same road.

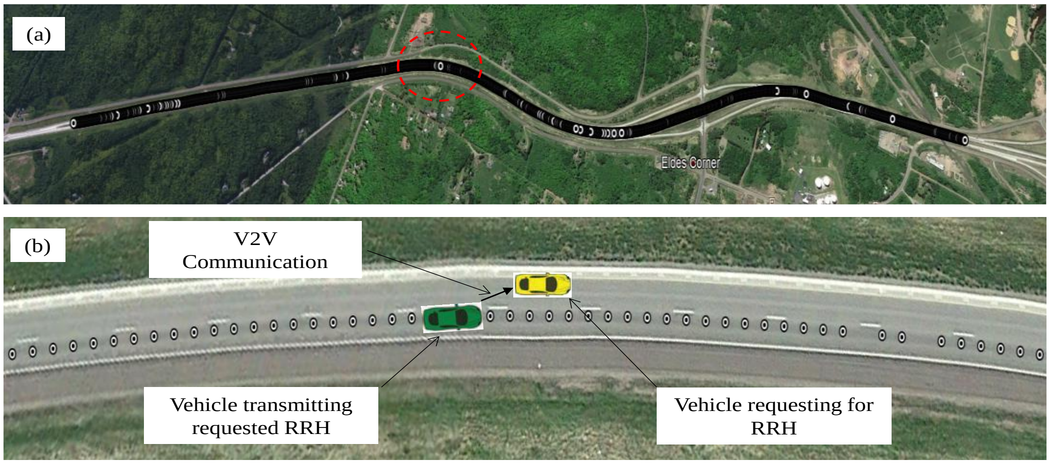


Figure 4.1 (a) Google Earth view of a travel trajectory of a 4.2 km road segment on the interstate I-35 and (b) Zoomed portion of (a) highlighted by red dashed circle illustrating a typical V2V communication scenario for transferring RRH data of that road segment.

We wanted to drive two test vehicles in close proximity on our test road segment as shown in Figure 4.1b which is a zoomed-in view of the portion of the I-35 of Figure 4.1a highlighted by the red dashed circle. However, because of the Covid-19, we were not able to go to the field as it required at least two people in each of the two vehicles for a prolonged period of time. Instead, we used an innovative method to test the full operation of all the pieces of our developed software including V2V handshake protocol, RRH data transfer, and lane departure detection. We had previously acquired and stored multiple GPS trajectories of a test vehicle on our test road segment. We used two such separate trajectories of two vehicles driven in close proximity of each other on the test road segment and stored them in two separate DSRC devices. The two DSRC devices represented two test vehicles traveling on the actual road. Each of the two DSRC devices was operated normally in the lab except that every new GPS point acquired by the GPS receiver of the corresponding DSRC device was replaced with one of the GPS points in stored trajectory. By doing this, each DSRC device appeared to be as it was being driven on the actual road. The DSRC device of one of the two vehicles (shown as yellow in Figure 4.1b) was running the lane departure detection software but did not have the corresponding RRH of that road segment so it needed to request RRH from a neighboring vehicle to detect lane departure and issue an audible warning. The other vehicle (shown as green in Figure 4.1b) acted as a neighboring vehicle having the necessary RRH data file in its DSRC device. In this test, only one of the two vehicles (yellow) without the needed RRH data file was tested for lane departure detection algorithm after successfully receiving the RRH data file from the neighboring vehicle (green).

Our lane departure detection algorithm calculates lateral shift of the test vehicle by comparing its calculated heading with the RRH of that road in real-time. The instantaneous lateral shift is accumulated over time and when the accumulated lateral shift (ALS) crosses 1 m threshold, an audible warning is issued. When a vehicle intentionally changes its lane, the increase in lateral distance saturates upon completion of its lane change because the vehicle starts to travel again in parallel to the RRH of the road. This phenomenon is used to reset the ALS to zero after every lane change to detect a future lane change or unintentional lane departure.

We used two test vehicles' trajectories on the same road segment with the trajectory of one vehicle (shown as yellow in Figure 4.1b) having many lane changes present in it to test lane departure detection and warning. Please note that in all our field tests, we used lane change to test unintentional lane departure warning for safety reasons. One of the two test vehicles or the DSRC devices (shown as yellow in Figure 4.1b) did not have the necessary RRH while the other vehicle or the DSRC device (shown as green in Figure 4.1b) had the necessary RRH data file and both were always driven in close proximity of each other. In each new test drive, the vehicle (shown as yellow in Figure 4.1b) running the lane departure software successfully obtained the required RRH from the neighboring vehicle (shown as green in Figure 4.1b) using our developed V2V handshake protocol and RRH data transfer software. After obtaining the required RRH, a lane departure warning was issued upon each lane change.

For one such test run, the real-time vehicle heading and the corresponding RRH of the road is shown in Figure 4.2a where the heading is plotted versus traveled distance. A total of 10

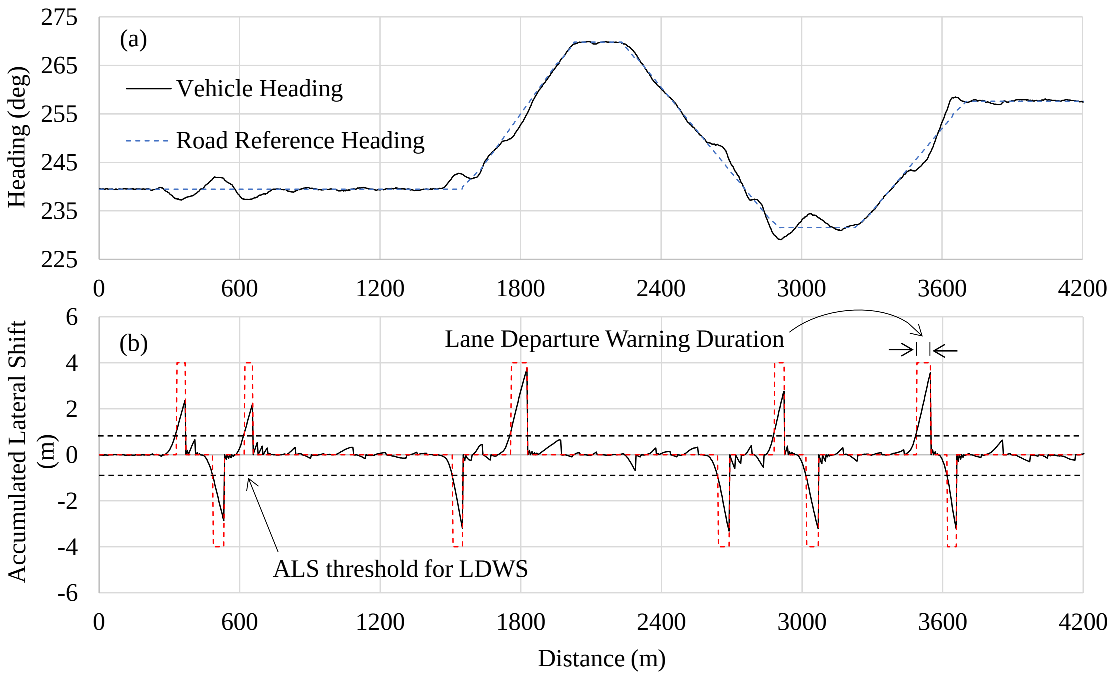


Figure 4.2 (a) Vehicle Heading and Road Reference Heading vs. traveled distance, and (b) ALS vs. traveled distance for a test run on the 4.2 km road segment of interstate I-35 with 10 lane changes. The red dashed line in (b) represents a digital mask for the duration of audible warning and the two black dashed lines in (b) represent ALS threshold for LDWS.

lane changes were made in this test drive and during each lane change the vehicle heading deviated from the RRH as evident from Figure 4.2a. Please note that the RRH is obtained on demand using our V2V handshake protocol and RRH data transfer software during each test run. The calculated ALS in this test run versus traveled distance is shown in Figure 4.2b. Our lane departure warning software issued audible warning upon each of the 10 lane changes whenever ALS crossed the 1 m threshold as shown by dashed black line in Figure 4.2b. A digital mask for audible lane departure warning signal is also superimposed in Figure 4.2b with dashed red line showing the start and end of the lane departure warning signal for each of the 10 lane changes. Lane departure audible warning signal becomes active when ALS crosses the threshold (1m) and is deactivated when the vehicle heading becomes parallel to the RRH of the road. In each of the 10 lane changes, our algorithm accurately detected all lane departures (or lane changes) in a timely manner and nowhere else along the trajectory, ALS crossed the threshold showing no false alarms.

4.2 FIELD TESTS FOR ERRATIC DRIVING WARNING

To evaluate the accuracy of the erratic driving warning system, field tests were performed by driving a test vehicle multiple times on the same 4.2 km segment of Interstate I-35 for which an average composite RRH was already generated. The test vehicle was driven at about speed limit (70 MPH) on this 4-lane freeway (2-lanes each way) and many back-and-forth lane changes were made. Some of the lane changes during the field tests were intentionally made in an erratic manner to test the algorithm. Our proposed algorithm calculated LCT and ILCT whenever a lane change was made during each trip to detect erratic driving behavior and issue warning in real-time.

The results from three such test trials are shown in Figures 4.3, 4.4, and 4.5 where the ALS is plotted vs. traveled distance as well as time. In each of these figures, the blue dashed rectangle shows presence of a lane change with its width representing lane change duration. Similarly, whenever an erratic behavior is detected, an audible warning was issued. The timing and location of that warning for each erratic behavior is shown as a red vertical line in all three figures.

In the test trial of Figure 4.3, there were a total of ten lane changes and four times erratic driving warning was issued during this trip. Please note that all 10 lane changes in this test trial were considered normal lane changes because the LCT for each of these lane changes was more than the threshold of 1.5 seconds. However, there were four warnings issued in this case and all 4 warnings were due to the fact that lane change preparation time was too short and ILCT was less than 3.7 seconds in each of the 4 warning cases.

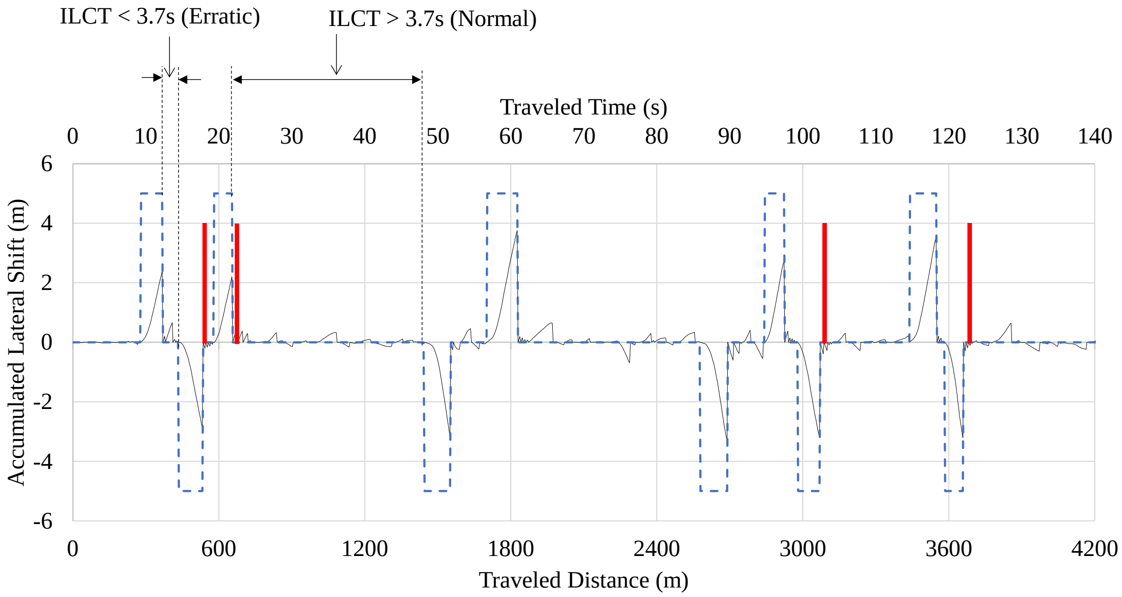


Figure 4.3 ALS vs traveled distance and time for a test drive on 4.2 km road section of interstate I-35 with only inter lane change erratic driving behavior.

Similarly, in the test trial of Figure 4.4, there were a total of eight lane changes and four instances of erratic driving behavior were detected. Corresponding timing and location of 4 warnings can be seen in the Figure. Two of the 4 warnings were due to the inter lane change time to be too short i.e., ILCT was less than 3.7 seconds, and the other two warnings were due to the fact that the lane was changed too quickly i.e., LCT was less than 1.5 seconds.

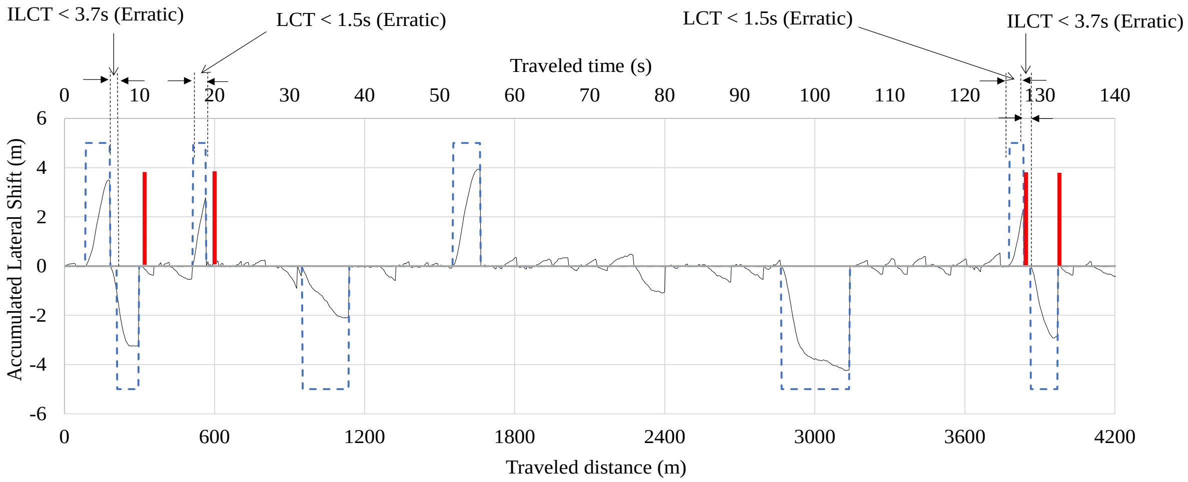


Figure 4.4 ALS vs traveled distance and time of a test drive on 4.2 km road section of interstate I-35 with both inter lane change and intra lane change erratic driving behavior.

Finally, in the test trial of Figure 4.5, there were a total of six lane changes and after three such lane changes an erratic driving warning was issued. The first of the three erratic driving warnings was due to LCT being too short but the following two warnings were issued because ILCT was too short, in fact it was almost zero for both warnings as can be seen in the Figure 4.5.

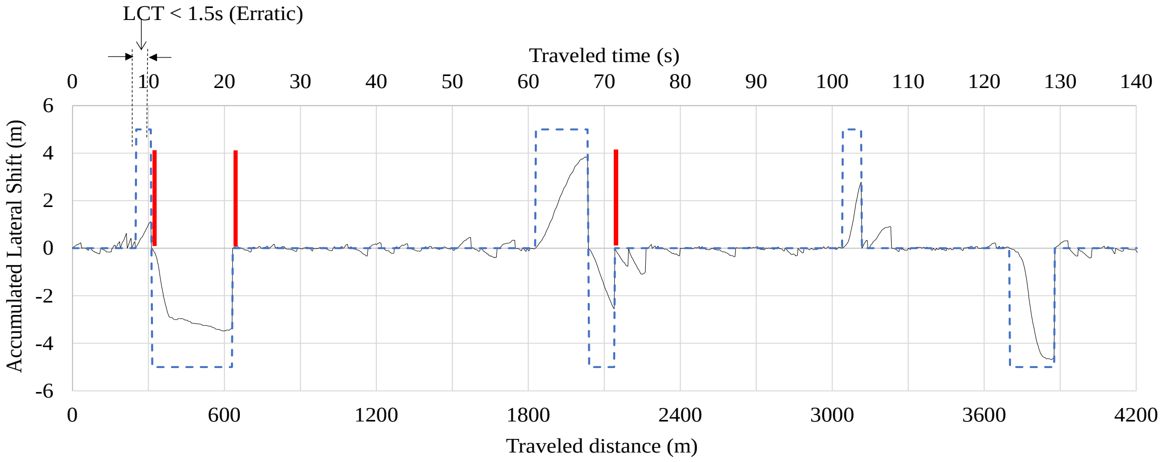


Figure 4.5 ALS vs traveled distance and time of a test drive on 4.2 km road section of interstate I-35 with both inter lane change and intra lane change erratic driving behavior.

4.3 CONCLUSION AND FUTURE WORKS

In this thesis, we have successfully improved our previously developed in-vehicle lane departure warning system (LDWS) by adding a DSRC based V2V communication provision to transfer RRH from one vehicle to another. We have developed the V2V handshake protocol using DSRC devices and developed the corresponding software to facilitate proper communication among vehicles to transfer RRH from one vehicle to another. We have used two DSRC devices simulating the two vehicles in the lab to test the developed V2V handshake protocol and RRH data transfer software. After developing and extensively testing our software, we have performed field tests to successfully detect lane departures using the RRH received via DSRC based V2V communication. The V2V communication based LDWS can be successfully implemented in large scale if the market penetration of V2V communication enabled vehicles reaches a critical level which is not there as of now. As an alternative to V2V communication, the developed LDWS can also be integrated into popular smartphone apps e.g., Waze, Google Maps or Apple Maps to take advantage of the vast database of multiple GPS trajectories which can be used to generate RRH for almost all roads making it available for a vehicle to detect its unintentional lane departure on any road even if the vehicle is driven on that road for the first time.

We have also enhanced our existing LDWS by adding an erratic driving warning system (EDWS) which works in parallel to the LDWS to detect erratic driving behavior when a vehicle changes its lane. Our proposed EDWS algorithm uses standard GPS receiver to acquire vehicle’s current trajectory, and our generated RRH for reference direction of travel to detect erratic driving behavior. We have implemented our EDWS in a prototype device and performed many field tests on a freeway with a variety of lane changes to evaluate the system. The results of the field tests show that the system can correctly detect erratic driving behavior and issue warnings. The developed EDWS can only detect erratic driving behavior in case of a lane change. Besides this, erratic or irregular driving can be of many other types, such as exceeding speed limit, over steering, over pedaling, zigzagging within a lane or between two lanes etc. The provisions to detect these different other erratic driving behaviors can be added to our developed EDWS.

In future, it is possible to develop a smartphone app for our developed LDWS and EDWS using a vehicle’s past trajectories. We have started working towards the development of such a prototype smartphone app already. The successful development of this app will pave the way for integration of the proposed algorithm into one of the popular smartphone apps.

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