

Acquisition of relative vehicle trajectories to facilitate freeway merging using DSRC
based V2V communication

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Abstract

For the anticipated benefits of connected vehicle technology, Intelligent Transportation Systems Joint Program Office (ITSJPO) of the US Department of Transportation continues to emphasize the need for having Dedicated Short Range Communication (DSRC) based vehicle to vehicle (V2V) and/or vehicle to infrastructure (V2I) communication to enhance driver safety and traffic mobility. To take full advantage of connected vehicle technology in most safety applications, precise vehicle positioning information is needed in addition to V2V communication. Although, there are many techniques including vision or sensor based systems and differential GPS receivers, which can obtain precise absolute position of a vehicle at the expense of cost and complexity, some critical safety applications such as merge assist or lane change assist systems require only relative positions of surrounding vehicles with lane level resolution so a given vehicle can differentiate the vehicles on its own lane from the vehicles on adjacent lanes. We have adopted a simple approach to acquire accurate relative trajectories of surrounding vehicles using standard GPS receivers and DSRC based V2V communication. Using this approach, we have conducted field tests to successfully acquire relative trajectories of vehicles travelling on multiple lanes towards a merging junction with an accuracy of $\pm 0.5\text{m}$. The achieved accuracy level in relative trajectory was sufficient to differentiate vehicles travelling on adjacent lanes of a multiple-lane freeway.

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1 Introduction

The Intelligent Transportation Systems Joint Program Office (ITSJPO) of the US Department of Transportation (USDOT) continues to be committed to the use of dedicated short range communication (DSRC) for active safety applications using vehicle-to-vehicle (V2V) and/or vehicle-to-infrastructure (V2I) communication due to its designated licensed bandwidth, fast network acquisition, and low latency[1][2]. A USDOT research report estimates that V2V communication has the potential to help drivers avoid or mitigate 70 to 80 percent of vehicle crashes involving unimpaired drivers, which could help prevent thousands of deaths and injuries on roads every year[3][4]. To take full advantage of the potential safety benefits of connected vehicle technology, relative trajectories of the surrounding vehicles with lane-level resolution are needed in addition to V2V communication[5]. Accurate positioning information with lane-level resolution can enable many vehicular safety applications (e.g., freeway merge-assist, lane-change-assist, and lane-departure warning systems), which could potentially help avoid many crashes[6][7]. According to one study, 36 percent of the freeway accidents analyzed occurred on entrance ramps, and another study reported that 20–30 percent of total truck accidents nationwide occur on or near ramps[8][9]. Similarly, in 1991, lane-change accidents accounted for approximately 4 percent of all police-reported crashes that occurred in the United States; in 1999, those accidents rose to 9 percent[10][11]. Another report that analyzed crash data from 2005 to 2007 concluded that 11 percent of vehicles involved in an accident had failed to stay in the proper lane[12].

For critical safety applications such as merge-assist or lane-change-assist systems re-

quire only the relative positions of surrounding vehicles with lane-level resolution to allow a given vehicle to differentiate the vehicles in its own lane from the vehicles in adjacent lanes[13]. Therefore, in the approach presented in this paper, we have focused on acquiring the relative trajectories of surrounding vehicles using standard GPS receivers—without any additional correction system—and DSRC-based V2V communication. Our approach to acquire relative trajectories is based on the fact that a major part of GPS positioning error, caused by atmospheric effects, is highly correlated over a vast geographical area[14][15]. Therefore, multiple GPS receivers of the same kind on different vehicles in close proximity tend to have a similar atmospheric error at a given time. The common atmospheric error could be canceled out to obtain a more accurate estimate of the relative distance between any two vehicles as compared to the absolute position of each vehicle. Utilizing this approach, we have successfully acquired relative trajectories of vehicles traveling in multiple lanes toward a merging junction with an accuracy of $\pm 0.5\text{m}$ using DSRC-based V2V communication and standard GPS receivers. The accuracy of the acquired relative trajectory was sufficient to differentiate vehicles traveling in adjacent lanes of a multiple-lane freeway.

2 Background

The goal of this project is to acquire relative trajectories of vehicles travelling towards the merging junction on a freeway using DSRC based V2V communication and ordinary GPS receivers. The DSRC equipped vehicles travelling on the freeway and on the merging ramp will periodically exchange with each other important traffic parameters such as their location, direction of travel, and speed etc. Using this information, the relative trajectories of all DSRC equipped vehicles will be acquired and recorded in real time. The successful completion of this project could pave the way to provide visual merge assistance to the drivers on the merging ramp, or facilitate automatic merging of the vehicles when DSRC market penetration ramps up in future.

2.1 Objectives

There are two objectives in this project: travel parameters communication and travel parameters processing.

- **Travel parameters communication:** The purpose of this objective is to develop protocol and corresponding software for vehicles to exchange travel parameters with each other while traveling towards a merging junction. Each vehicle will be simultaneously transmitting to, and receiving from its surrounding vehicles using DSRC devices.
- **Travel parameters processing:** In this objective, the raw data (travel parameters

from multiple neighboring vehicles) in the vehicle on the merging ramp will be processed via software and the trajectories of the concerned vehicles will be extracted from it. For example, the trajectories of the vehicles from the faster freeway lanes will be extracted but trajectories from the vehicles on a nearby crossing road or vehicles trailing behind the concerned vehicle on the merging ramp will be filtered out because they are not relevant.

2.2 What is DSRC

DSRC stands for Dedicated Short-Range Vehicle Communications. It is a bi-directional short to medium range wireless communication technology that designed for automotive communication. A conceptual demonstration of this technology is shown in Firdure [2.1](#).

DSRC applications primarily targets the transportation industry and the following features of DSRC technology enable it to improve drivers' safety and traffic mobility.

- Designated licensed bandwidth: Federal Communications Commission (FCC) exclusively allocated 75 MHz bandwidth in the 5.9 GHz band.
- Full protocol support: IEEE 802.11p extends 802.11 wireless communication protocol family to support critical safety applications.
- Fast Network Acquisition: Active safety applications require the immediate establishment of communication and frequent updates.
- Low Latency: Active safety applications must recognize each other and transmit messages to each other in milliseconds without delay.
- High Reliability when Required. DSRC works in high vehicle speed mobility conditions and delivers performance immune to extreme weather conditions (e.g. rain,

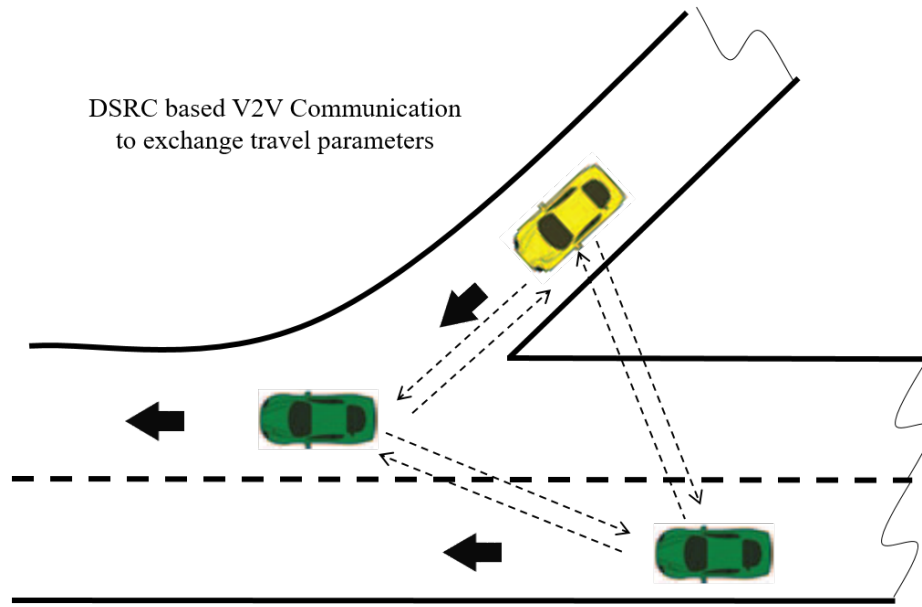


Figure 2.1: Conceptual illustration of DSRC technology

fog, snow, etc.).

The application of DSRC technology falls into two categories: Vehicle to Vehicle (V2V) communications and Vehicle to Infrastructure (V2I) communications.

V2V communication

DSRC technology enables vehicles to exchange their travel information on the road. For example, vehicle's travel speed and travel direction can be shared to other vehicle, so that potential collisions could be prevented. Drivers' awareness of surrounding vehicles also can be improved. This is specially helpful when drivers are near merging ramps or intersections where there is limited or no line-of-sight to other vehicle. Augmenting vehicular platoon with DSRC technology can help it achieve better speed and distance control.

V2I communication

V2I communications further explore the potentials of DSRC technology. For example, DSRC communication devices installed on frequently congested road intersections can help broadcast messages to nearby vehicle to inform drivers of choosing alternative routes. Near slippery road section or sharp turn area, well placed DSRC devices could give warnings to drivers about incoming high risk road conditions.

2.3 What is DGPS

DGPS stands for Differential GPS. It is an augmented GPS system, which have better accuracy (<10 m) than the traditional GPS system. The relative accuracy concept in this project originated from the methodology being used in DGPS system. Traditionally, GPS receivers receive signals from navigation satellites and then using triangulating method to determine its own position. What makes DGPS system different from the classic GPS system is its ground reference station, which is capable of broadcasting another position correction message to GPS receivers.

Reference Station is a known position GPS receiver constantly receiving navigation satellite signals. It calculates its measured position and finds the difference between measured position and its real location. Then this difference is broadcasted as correction message to nearby GPS receivers. As the other GPS receivers receive both the GPS signals and the correction message, it subtracts the difference reported by reference station from its calculated position, which gives a better position estimations. This process is illustrated in Figure 2.2. The key of this correction mechanism is based on the fact that achievable accuracy degrades at an approximate rate of 1 m for each 150 km distance from the broadcast site. So as the distance between a GPS receiver and reference station is within a reasonable

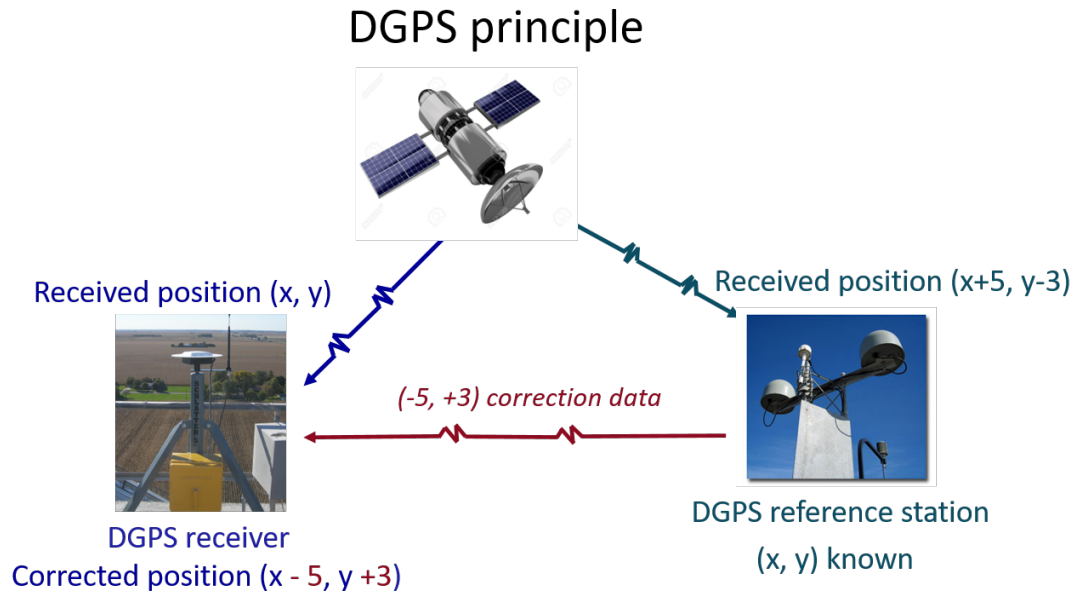


Figure 2.2: DGPS principle

range, the accuracy of DGPS system is better than what standalone GPS system can deliver.

2.4 GPS errors modelling

Our approach utilizes standard GPS receivers and DSRC-based V2V communication to acquire the relative trajectories of surrounding vehicles. The absolute position accuracy of a standard GPS receiver is in the range of 3–5m[16]. This means that a GPS receiver can estimate the position of a vehicle within a circle with a radius of 3–5m, as shown in 2.3, where the true position of the vehicle at a given time is shown by a green dot and the red dot shows the estimated position by the GPS receiver. The error vector from the true position to the estimated position represents the GPS position error. The total GPS position error is a combination of multiple errors resulting from different sources. Generally, the combined GPS position error is a result of three major errors: mechanical error, satellite ephemeris error, and atmospheric error.

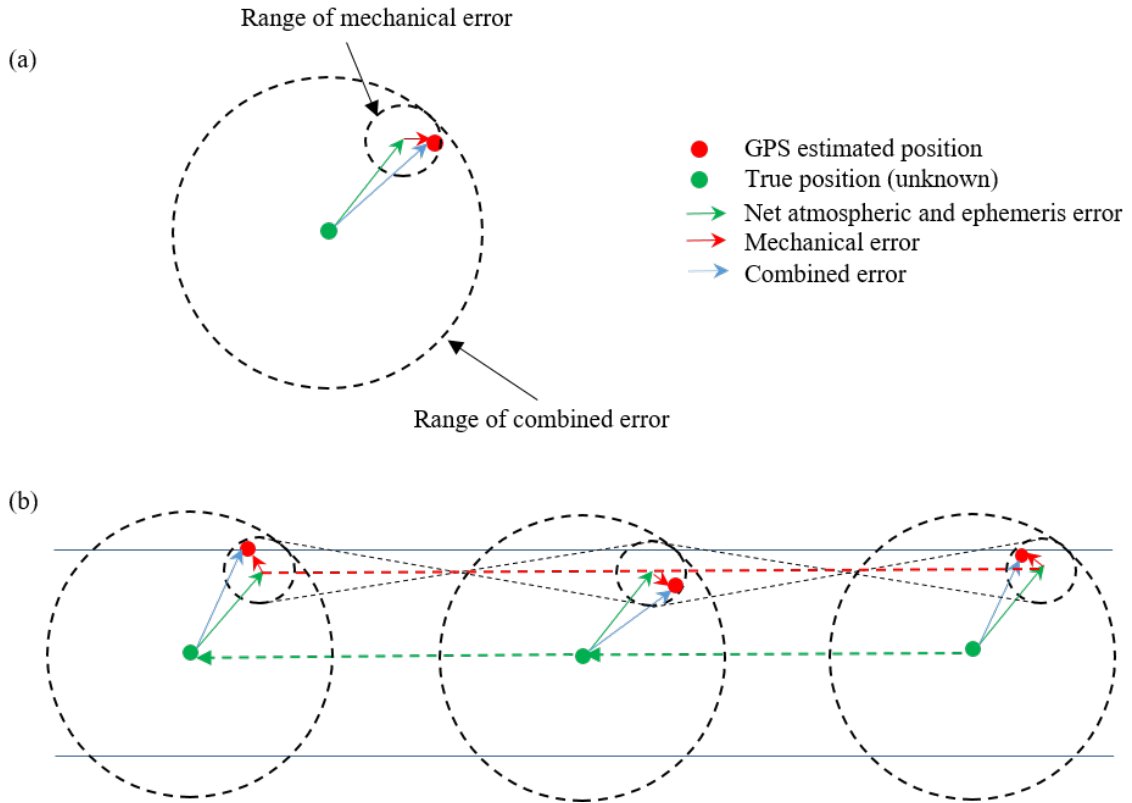


Figure 2.3: Conceptual GPS receiver error model of a single GPS receiver showing ranges of different GPS error types for (a) a stationary vehicle at a single time instance and (b) a moving vehicle at three adjacent time instances.

2.4.1 Static Error Analysis

The mechanical GPS error is caused by inherent noise or clock jitter of the crystal oscillator used in the GPS receiver, thermal effects, manufacturing differences, and residual mathematical error due to quantization and rounding [17][18]. Satellite ephemeris error is due to the fact that the expected orbital positions of the GPS satellites that the GPS receiver needs to estimate its own position, could be different than actual satellite positions.

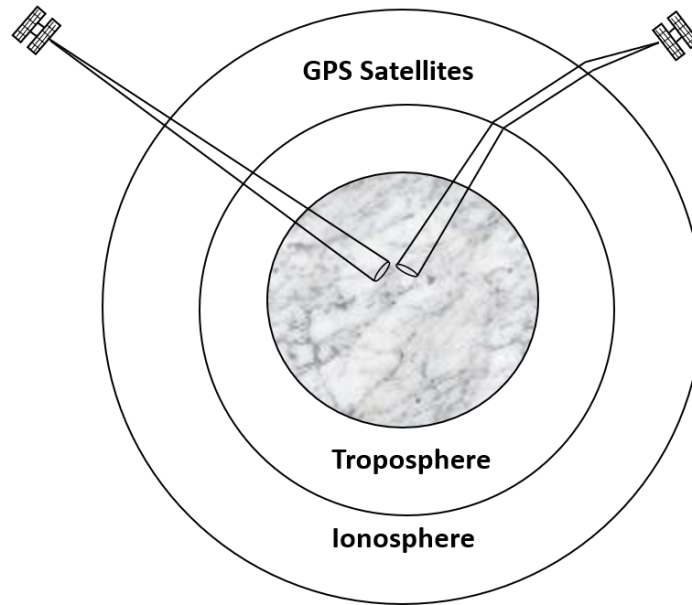


Figure 2.4: Atmospheric error

Atmospheric errors

Atmospheric error, Figure 2.4, the most significant portion of the combined GPS error, is caused by atmospheric effects that cause the GPS signal to bend while it travels through the atmosphere. Of all three errors, mechanical error is the only one that can vary randomly from one GPS receiver to another at any given time. It can also vary in the same GPS receiver with each subsequent position estimate over time. On the other hand, both ephemeris and atmospheric errors do not vary significantly for multiple GPS receivers in close geographical and temporal proximity. This is because atmospheric disturbances will remain the same over a wide geographical area and do not rapidly change with time[14][15].

Ephemeris error

Similarly, ephemeris error, Figure 2.5, will remain almost the same for the satellite constellation used by GPS receivers in close proximity to each other[19]. Theoretically, a GPS-estimated position can be anywhere in the larger circle as shown in Figure 2.3(a), rep-

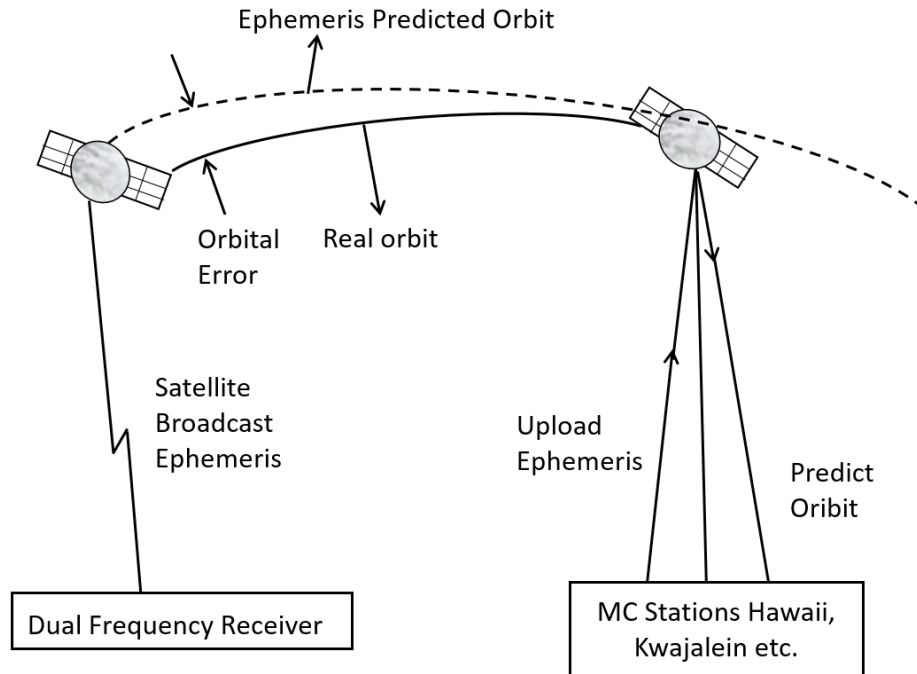


Figure 2.5: Ephemeris error

representing the range of combined GPS error. However, after a GPS receiver gets locked to certain satellites to estimate its position, its subsequent position estimates will not randomly vary over the entire large circle because atmospheric and ephemeris errors will remain the same for a considerable period of time.

Mechanical error

On the other hand, mechanical error can randomly vary in every new position estimate in any GPS receiver. The size of mechanical error is comparatively much smaller than the other two errors, which is highlighted by the relative sizes of the two circles in Figure 2.3(a). Therefore, subsequent estimates of the same position by a given GPS receiver will remain confined to a smaller circle shown in the Figure 2.3(a), representing the range of mechanical error.

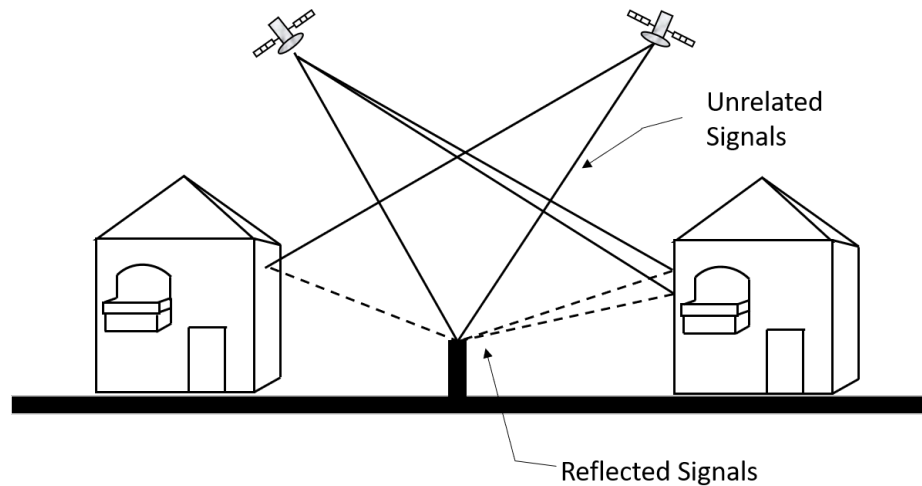


Figure 2.6: Multipath error

Multipath error

In addition to the three errors described above, multipath error, as shown in Figure 2.6 can significantly degrade the position estimation accuracy for any GPS receiver. Multipath error occurs when GPS signals arrive at the receiver antenna through multiple paths as a result of reflections from surrounding objects (e.g., high-rise buildings or overhead bridges) [20]. Multipath error is significant in urban areas where a roadway is surrounded by high-rise buildings. However, in rural and suburban areas, multipath error can be negligibly small and the significant errors are mechanical, ephemeris, and atmospheric, as described above

2.4.2 Dynamic error analysis

Figure 2.3(a) illustrated GPS receiver errors in static conditions. When such a GPS receiver is placed in a moving vehicle, it can be used to acquire a vehicle's trajectory by periodically estimating its position. This concept is illustrated in Figure 2.3(b), where three adjacent GPS positions of a fast-moving vehicle on a freeway (with minimal multipath

error) are shown as red dots. Each adjacent estimated position will vary only within the small circle (the mechanical error range) as opposed to randomly changing over the larger circle because the atmospheric and ephemeris errors will remain the same for each estimate. Consequently, the trajectory obtained by the GPS receiver may vary randomly, but the maximum variations will be limited to the zigzag pattern shown in Figure 2.3(b). The mean trajectory obtained by the GPS receiver (shown by the red dashed line) will have an offset from the true trajectory (shown by the green dashed line), but it will be a fixed offset and its size will be determined by the magnitude of net atmospheric and ephemeris error. Furthermore, the variance of the trajectory obtained by the GPS receiver will be determined by the magnitude of the mechanical error of the GPS receiver, which is generally small in size.

2.5 Related Work

Accurate positioning information can be obtained using either sensor-based systems or Global Navigation Satellite Systems (GNSSs). Both approaches have their limitations. Sensor-based systems utilize vision- or laser-based sensors to acquire the relative positions of surrounding vehicles [21][22][23][24]. However, environmental factors such as weather, variable lighting conditions, absence of line-of-sight (LoS), or worn out road markings can adversely affect the performance of these systems [25]. Similarly, GNSS-based technologies such as Global Positioning System (GPS) cannot predict the position of a vehicle with lane-level accuracy without using a correction or augmentation system e.g., differential GPS technology, inertial sensors, gyroscope, and/or high-resolution maps [26][27][28][29][30]. Furthermore, the deployment of either sensor-based or GPS-based system requires sophisticated hardware and software, resulting in increased complexity and higher overall costs.

The above-mentioned techniques can obtain the precise absolute position of a vehicle

at the expense of cost and complexity. However, some critical safety applications such as merge-assist or lane-change-assist systems require only the relative positions of surrounding vehicles with lane-level resolution to allow a given vehicle to differentiate the vehicles in its own lane from the vehicles in adjacent lanes [13]. Therefore, in the approach presented in this work, we have focused on acquiring the relative trajectories of surrounding vehicles using standard GPS receivers—without any additional correction system—and DSRC-based V2V communication.

3 Proposed System

In this thesis work, we plan to acquire real-time relative trajectories of the vehicles travelling on two separate roads towards a merging junction, using DSRC based V2V communication. The conceptual approach of the proposed system is described in the left side of Figure 3.1, where traffic is shown to merge on a fast moving single-lane road. Each vehicle approaching the merging junction is assumed to be equipped with global positioning system (GPS) receiver and DSRC equipment. Using the GPS technology and DSRC based V2V communication, critical travel parameters e.g., vehicle location, speed, and direction of travel will be periodically acquired and communicated to the surrounding vehicles. All this information will be processed in each vehicle present either on the fast moving road or on the merging road.

After applying the DGPS principle and following the GPS error model, we will be able to measure the relative distance between the two vehicles. This idea is conceptually shown on the right side of Figure 3.1, where the positions estimates obtained by two ordinary GPS receivers of the two vehicles on two different roads (one on the main road and one on the merging road) are shown as red dots. Please note that the green dots are actual positions of the vehicles and the red dots are estimated locations by ordinary GPS receivers. The error in the absolute position (bigger circle around actual position) of each of these vehicles is larger than the lane width (3.6 m) but the error in the relative distance between the two vehicles will be much less (smaller circle).

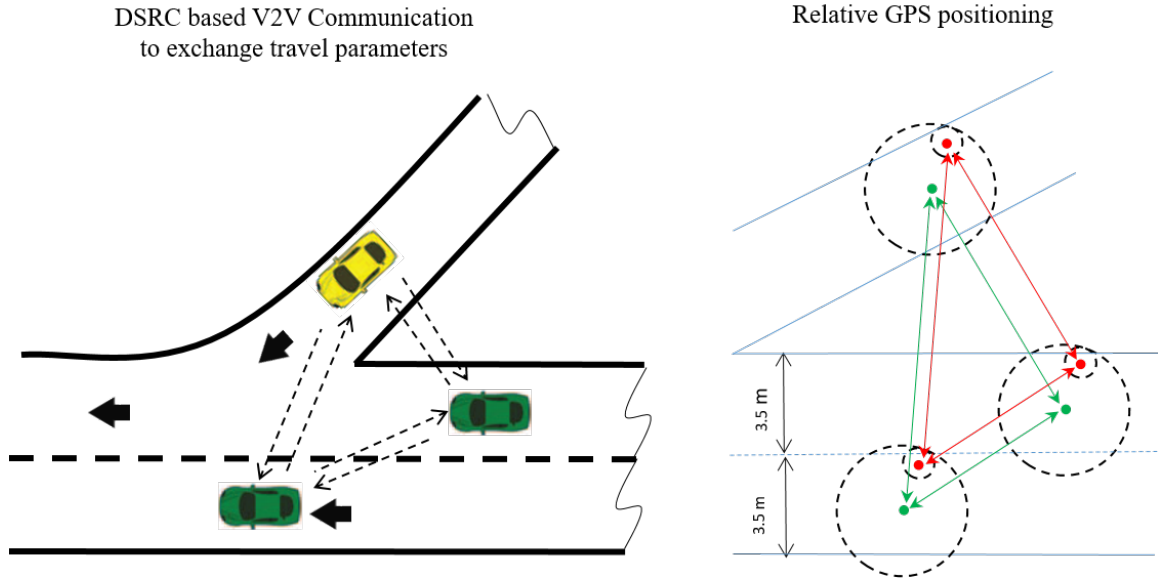


Figure 3.1: The conceptual approach of the proposed system. Left side: DSRC based V2V communication. Right side : Relative GPS positioning

3.1 DSRC Communication and Data Logging

We have developed the software for transmitting and receiving the travel parameters between multiple DSRC onboard units (OBUs) using wireless access in vehicular environments (WAVE) protocols. The travel information is encapsulated in Basic Safety Message based on SAE J2735 standard. We first achieved this by using older model Savari DSRC devices, S100, and achieved the same functionality using newer model of Savari Devices, S103 as well as using Arada Locomate 200 devices Figure 3.2.

Since each vehicle will be simultaneously transmitting to, and receiving from its surrounding vehicles using DSRC devices, we need to implement our software in a way that it supports bi-directional communications as well as data logging in each reception and transmission interval. The flow chart of implemented algorithm is shown in Figure 3.3.



Figure 3.2: DSRC onboard units: Savari S103 and Arada Locomate 200

3.2 Preliminary Tests

3.2.1 Theory Validation

In order to validate our relative accuracy theory. We performed our initial tests on Arrowhead Road at Duluth. As shown in Figure 3.4, we placed three Savari GPS receivers on the roof the our test vehicle in a straight line with equal spacing between them. We recorded the vehicle’s trajectory using these three GPS receivers while it was driving within a straight lane. The GPS receivers and their corresponding trajectories are color coded in following figures. In this test, we were trying to qualitatively evaluate the relative GPS accuracy of multiple GPS receivers within close proximity. We expected that the trajectories of these three GPS receivers stay close to each other.

The result of this test is shown in Figure 3.5. The vehicle is driving from the right of the figure to the left. GPS points of 100-meter data are plotted on the Google map. As we expected, the trajectories of these GPS stay very close to each other. They were almost overlapping with each other, although a closer look of the data revealed that these three

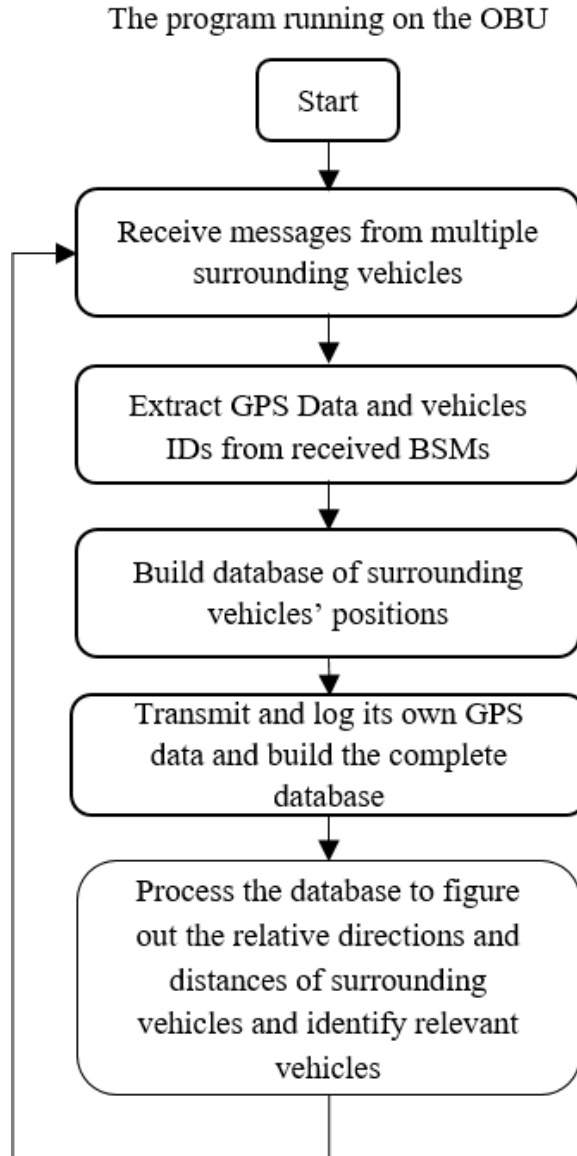


Figure 3.3: Algorithm: DSRC communication and data logging

trajectories were not perfectly staying on the same line and the 2nd GPS receiver appeared to stay closer to the 3rd GPS receiver than it actually did.

This was a promising result confirmed two points for us. 1) the trajectories received by GPS is not zig-zagged as shown in Figure 3.6b. Instead, the error of one particular GPS receiver was very stable and we believe this is the reason why the trajectory of each GPS

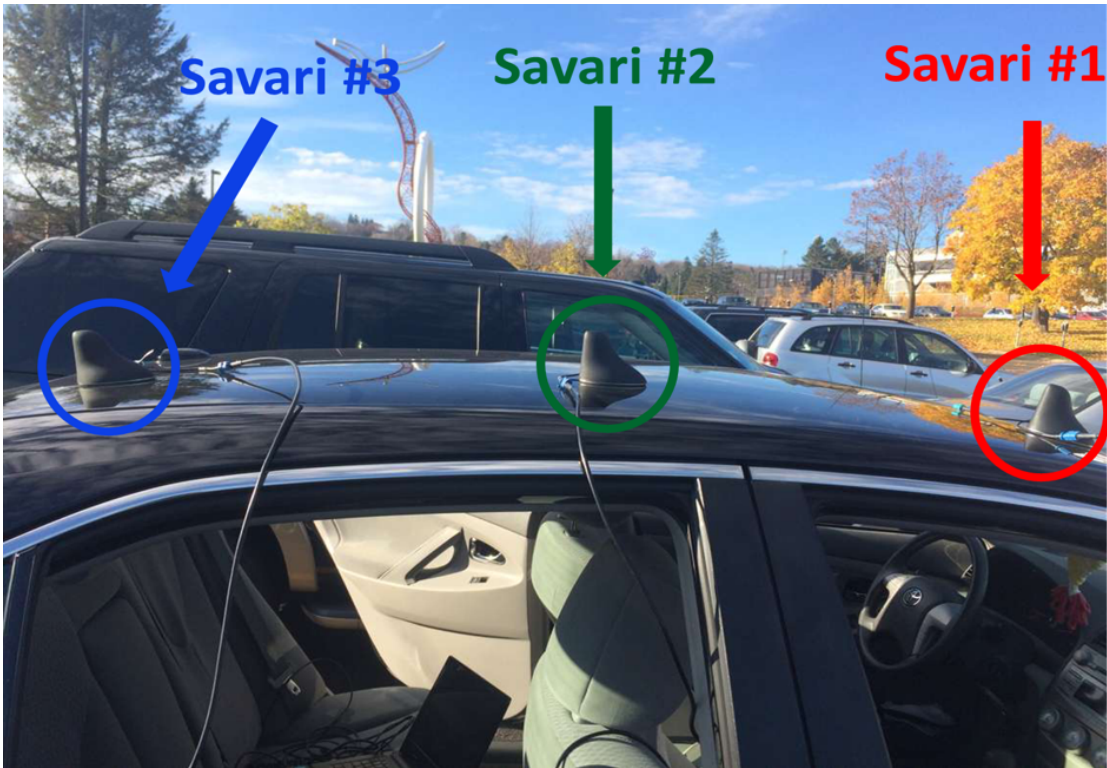


Figure 3.4: Preliminary test setup: Three Savari S103 GPS receivers placed on the top of the vehicle with equal spacing.

receiver appeared to be a straight line as shown in Figure 3.6a. 2) The relative accuracy of these three GPS receivers is noticeably less than the lane width. As shown in left top figure in Figure 3.5.

3.2.2 Regular street tests

In the regular street field trials, we used two vehicles equipped with DSRC devices and GPS receivers travelled on a two-lane road (W Arrowhead Rd). The speed limit on this road was 45 MPH. We collected data with two scenarios: (i) lane switching scenario, and (ii) lane merging scenario.

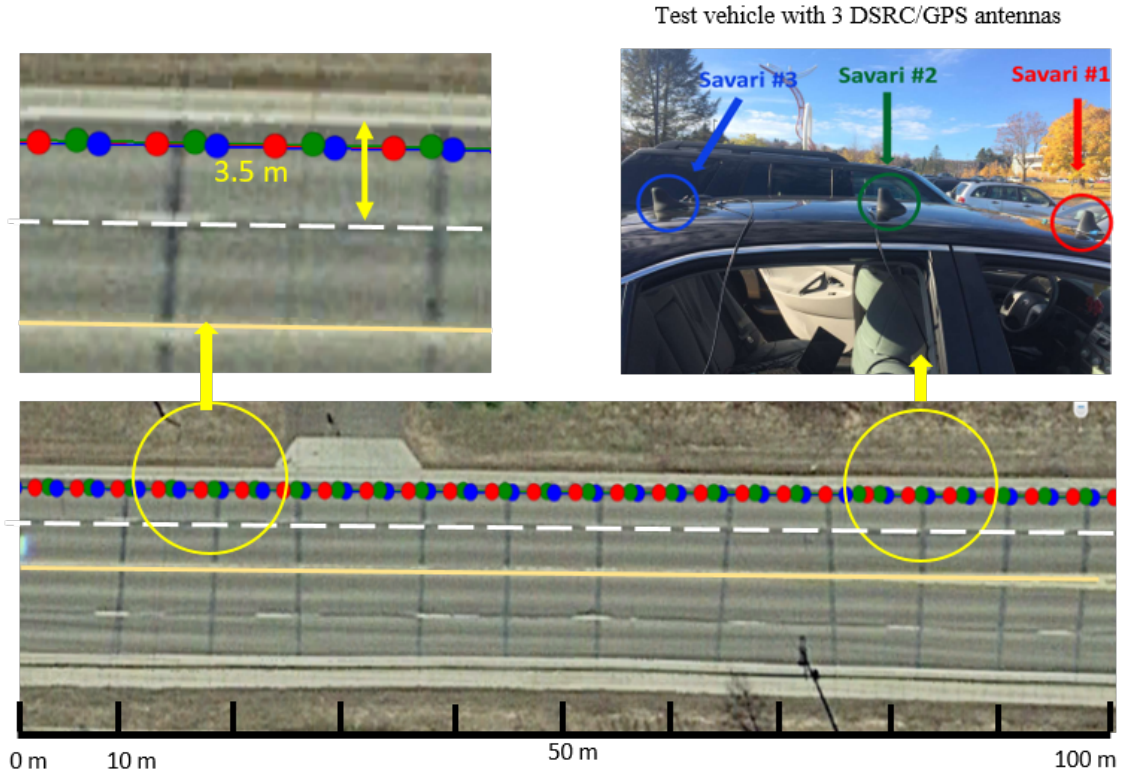


Figure 3.5: Preliminary test result: The top left figure shows a zoomed-in view of the recorded trajectories. The lane width is 3.5 meters as indicated in the figure.

Lane switching scenario

This field trial was conducted on W Arrowhead Rd with two vehicles having DSRC devices traveling in the same direction on two adjacent lanes. The total travelled distance was a little over one kilometer. The two vehicles started on two adjacent lanes and switched lanes in the middle of the trial. We acquired the trajectories of the two vehicles via DSRC devices which recorded GPS position of each vehicle at 5 Hz. We repeated this test twice, first using Arada Locomate-200 on both vehicles and then using Savari S100 on both vehicles. Please note that we did not have Savari S103 devices at the time of the field tests. After acquiring the GPS trajectories in long-lat format, we converted the trajectories to X-Y format based on the Universal Transverse Mercator (UTM) system. A portion of acquired

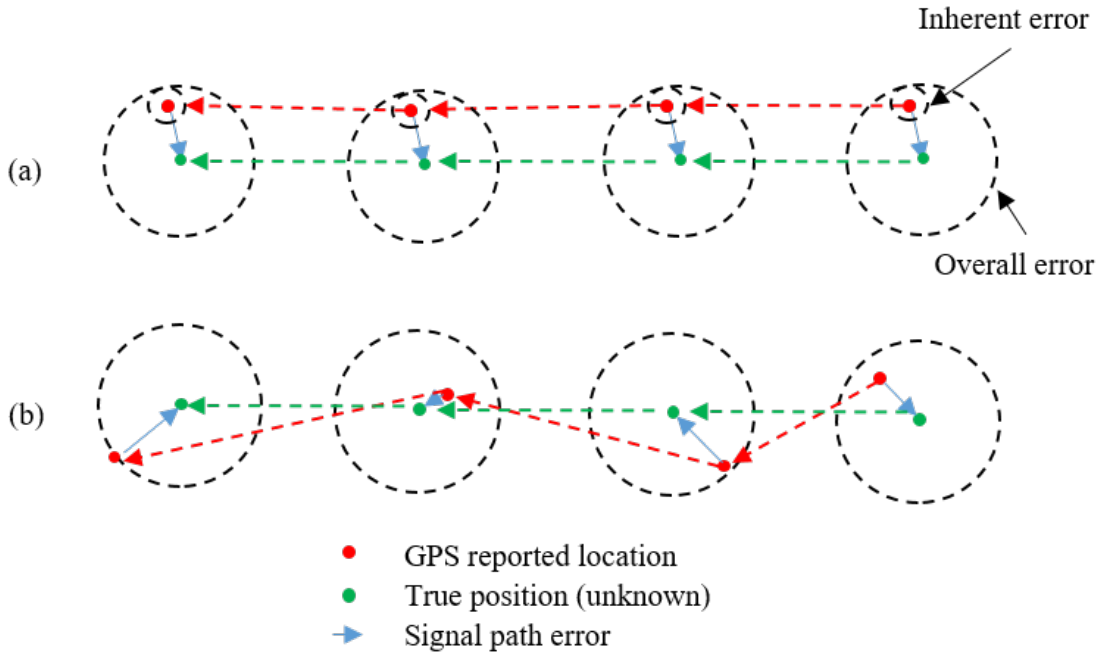


Figure 3.6: GPS error model: The inner circle represents the inherent error of the GPS receiver. The larger circle indicates the overall error. a) The GPS error is non-random b) The GPS error is random

trajectories of the two vehicles in X-Y format are shown in Figure 1 using Arada Locomate-200 devices.. The blue and red dotted lines show the relative positions of the two vehicles with respect to each other. The time line shows the relative position of the two vehicles at any given time. Please note that vehicle on the right lane (represented by red dotted line) was a little ahead of the vehicle on the left lane. For reference, we have also shown the relative position of the lane boundaries of the two lanes on which the two vehicles were driven. We used position coordinates from Google Earth to show the lane boundaries.

The lane width of W Arrowhead Rd is about 3.3 meters (measured from Google Earth). The acquired relative trajectories show that the average distance between the two vehicles is about one lane width. The vehicles were travelling almost in the middle of their respective lanes throughout the trial. This shows that relative accuracy of much less than the lane width can be achieved using this method. Please note that the relative distance between the

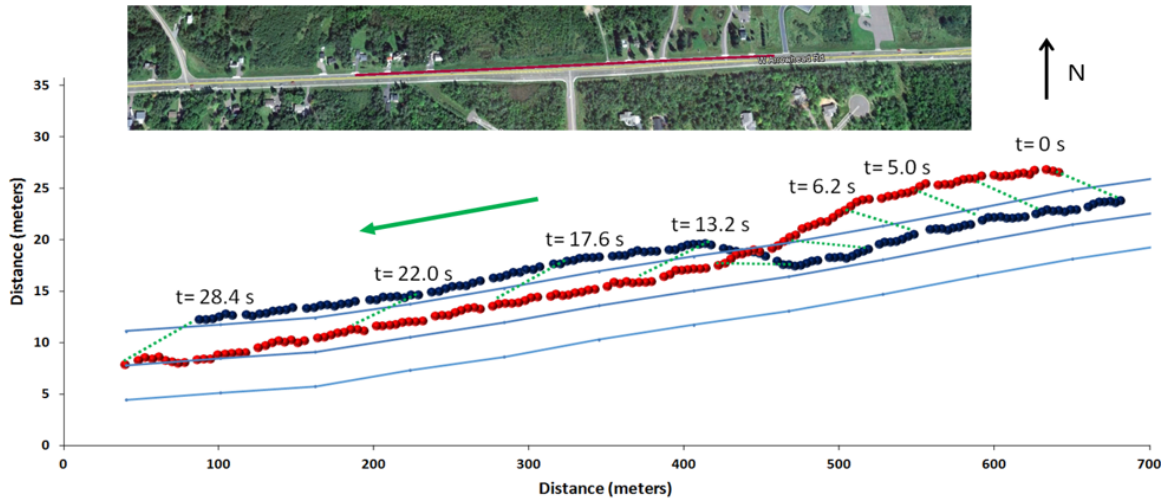


Figure 3.7: Trajectories of two vehicles in lane-switching scenario field test on W Arrowhead Rd using two Arada Locomate-200 DSRC devices. The top insert shows the field test location.

two vehicles is larger before lane switching (right side trajectory in Figure ??) as compared to after lane switching (left side trajectory in Figure ??). We believe this is due to different inherent errors of the two GPS receivers connected with the DSRC devices present in the two vehicles as illustrated in Figure 3.8, where two GPS readings of the two vehicles each – one before lane switching and one after lane switching – are graphically shown. The bigger circle shows the total position error of the GPS receiver from all sources including atmospheric errors and inherent GPS receiver error. Although, the error caused by atmospheric sources is supposed to be same for all nearby GPS receivers, the inherent GPS error will be different for each GPS receiver. The smaller circle represents the inherent GPS receiver's error. We believe that the inherent GPS receiver error vectors of the two GPS receivers of the two vehicles have a net vertical components (\square) in opposite direction (Figure 3.8) which can explain the differential distance between the two vehicles before and after the lane switching. Please note that net vertical error component means the error component perpendicular to the road direction. The differential distance between the two lanes becomes $LW + 2\square$ before the lane switching and becomes $LW - 2\square$ after the lane switching, where

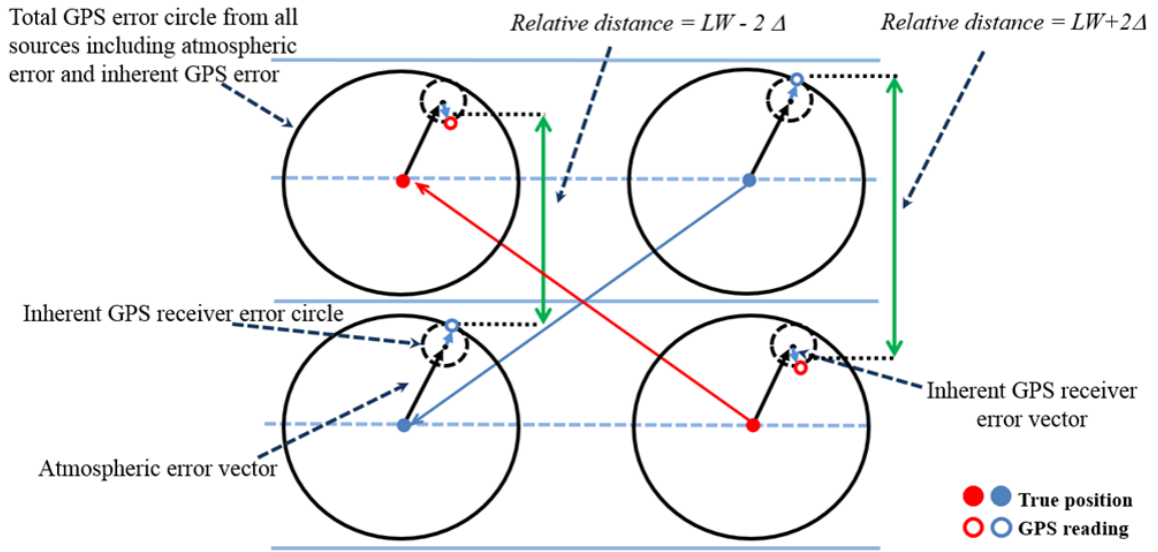


Figure 3.8: The impact of the inherent GPS receiver's error on the relative trajectory accuracy.

LW is the lane width. Please note that in the illustration of Figure 3.8, radii of inherent errors' circles and the net vertical error components (\square) of two GPS receivers are assumed to be same but they don't necessarily have to be same for all or any two GPS receivers.

Lane merging scenario

The lane merging scenario field test was also conducted on W Arrowhead Rd. In this trial, the two vehicles started on two adjacent and one vehicle merged into the other lane in the middle of the trial. We used the same Arada Locomate 200 DSRC devices for these tests as well. Please note that we also repeated the tests with Savari S100 DSRC devices but those results are not shown here. The acquired trajectories of the two vehicles using Arada Locomate 200 devices are shown in the Figure 3 in the same format as shown for lane switching scenario in Figure 2. The blue dotted lines represent the trajectory of the vehicle which merged on the same lane where the vehicle with the trajectory represented by red dotted lines was travelling.

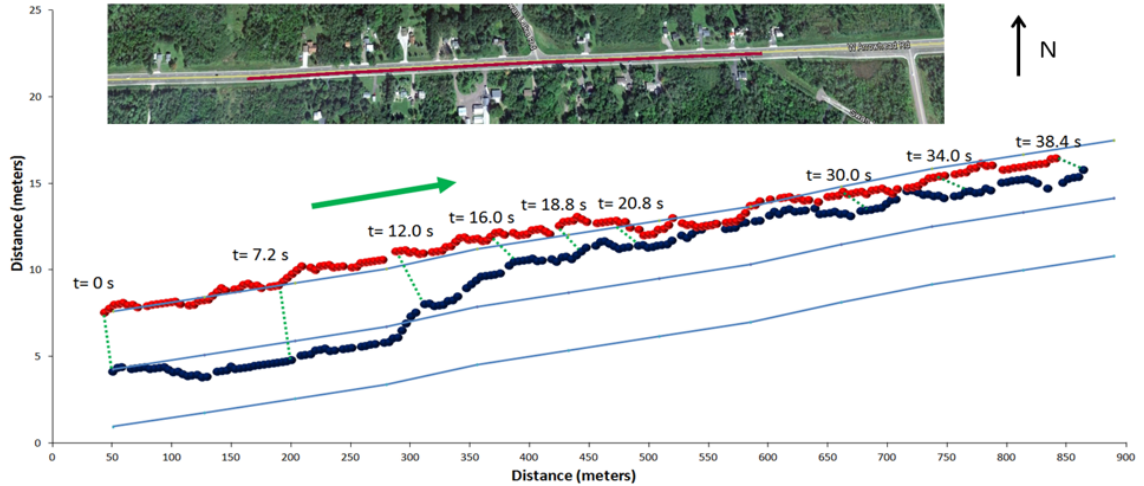


Figure 3.9: Lane-merging field test on W Arrowhead Rd using two Arada Locomate-200 DSRC devices.

The average distance between two trajectories is about one lane width prior to lane merging and is negligibly small for the most part after the lane merging. The small differential error is due to differential inherent GPS receiver errors as explained earlier. Please note that some inconsistency is also due to different driving behavior of the two drivers. In general, this result also shows that the relative position error between the two vehicles can be much less than the lane width.

4 Implementation

After qualitatively validated our proposed system as being detailed in previous chapter, we also accurately quantified the relative GPS positioning accuracy before conducting our road test using completely developed system. In this chapter, we will first elaborate the field test in which we statistically characterized the relative GPS positioning error and then give the results of our final freeway test using our full-fledged system.

4.1 Characterization of the GPS relative accuracy

Similar to the trajectory of a single vehicle, which can be obtained by a GPS receiver with a small variance, the relative trajectories of multiple vehicles in close proximity that have their own GPS receivers can also be obtained with comparable variances. Two practical scenarios involving multiple vehicles—merging and changing lanes on freeway—are depicted in 4.1 (left side). In both scenarios, the relative trajectories of surrounding vehicles, if accurately known, can be beneficial in the development of traffic safety applications. Using the GPS error model described above, the relative positions of three vehicles obtained by GPS receivers are shown in 4.1 (right side) at a given time. The estimated GPS position of each vehicle (shown by red dots) will have the same offset from the true position because the net atmospheric and ephemeris error remains the same for all three vehicles—provided they are equipped with GPS receivers of the same model. Therefore, the relative distance between any two vehicles in both scenarios calculated from the estimated positions of the GPS receivers on the two vehicles will have a small variance determined by the mechani-

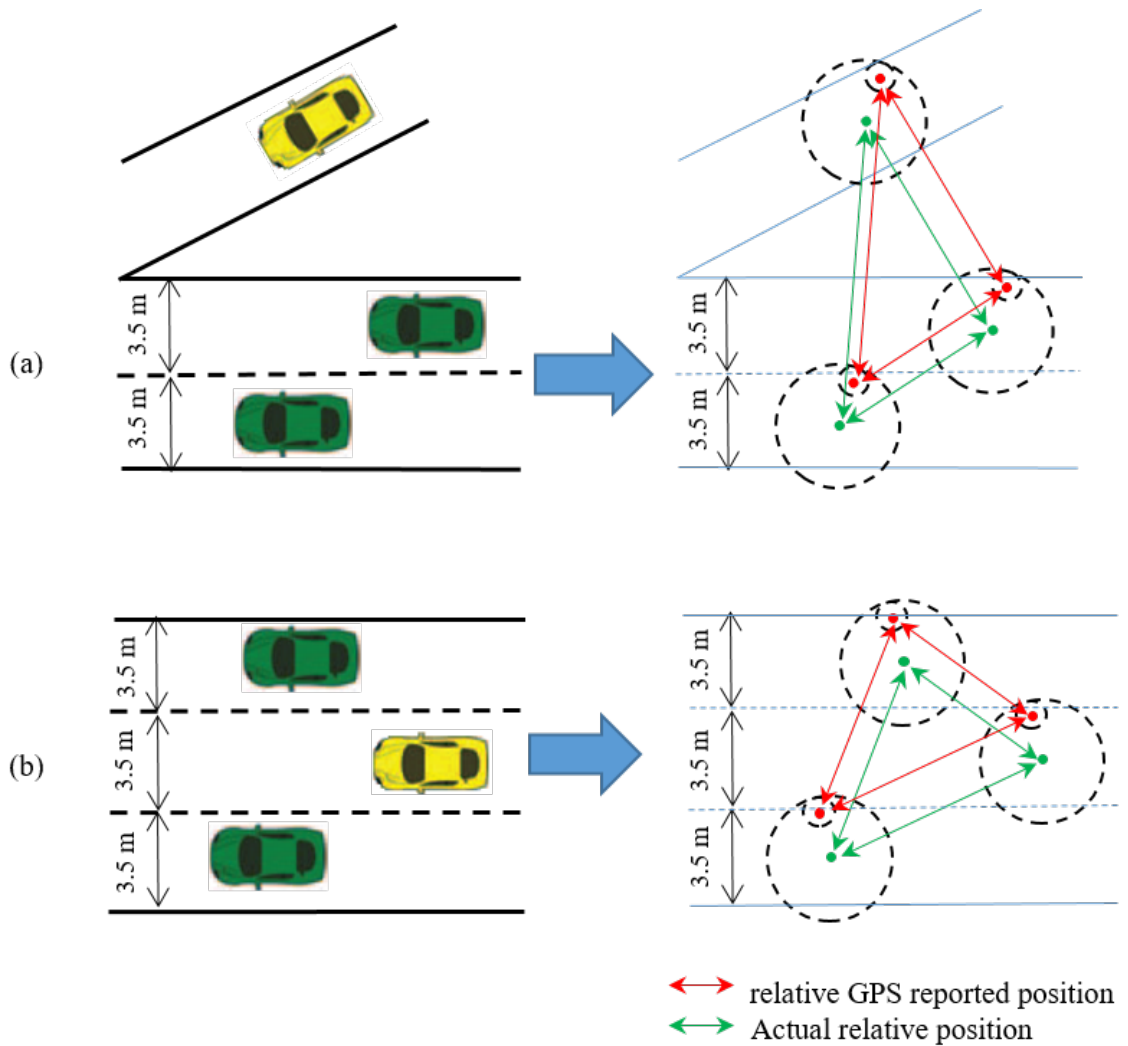


Figure 4.1: Concept of relative GPS accuracy: (a) Lane-merging scenario (b) Lane-changing scenario.

cal errors of the GPS receivers. An accurate estimate of relative distance between any two vehicles at a given time can lead toward an accurate estimate of the relative trajectories of those vehicles with respect to each other. The accuracy of the relative trajectories needs to be high enough for use in a potential safety application, such as a lane-merge or lane-change-assist system, where it is necessary to determine if a neighboring vehicle is in the same or adjacent lane.

4.1.1 Test setup

The relative trajectories of surrounding vehicles can be obtained for any given vehicle on the road provided it can receive the estimated GPS positions of the neighboring vehicles. We used DSRC-based V2V communication to exchange position information among surrounding vehicles that had standard GPS receivers, which allowed GPS position data from neighboring vehicles to be processed in any vehicle to obtain relative trajectories. Before conducting field tests to obtain relative trajectories of multiple vehicles on the road, the relative distance accuracy of the standard GPS receivers built in to the DSRC devices needed to be characterized to determine if it is sufficient to distinguish the neighboring vehicles in the same or adjacent lanes. Therefore, we statistically characterized the relative distance accuracy of the GPS receivers built in to the DSRC devices and later used the same devices to acquire the relative trajectories of multiple vehicles using DSRC-based V2V communication. The built-in GPS receivers use a UBlox LEA-6 chipset, which is specified as having a $\pm 2\text{m}$ absolute position accuracy with 50 percent circular error probability (CEP). Using these GPS receivers, we have been able to achieve the relative distance accuracy of $\pm 0.5\text{m}$ with 95 percent CEP in our field tests. We conducted field tests to statistically evaluate the accuracy of the relative distance obtained by the built-in GPS receivers of the DSRC devices. We installed antennas for three DSRC devices on top of one vehicle at locations A, B, and C, as shown in 4.2. A top view of the vehicle used for the field tests is shown in 4.2a, and 4.2b is a top-view schematic of the vehicle showing the three antenna locations (A, B, and C). The three locations formed a right-angle triangle with two shorter legs of length 1m each. We drove the equipped vehicle on I-35 near Duluth, MN, in a round trip between exit #239 and #242 at a speed of about 70 MPH (speed limit) while continuously acquiring GPS position data in all three devices at the rate of 10 Hz.

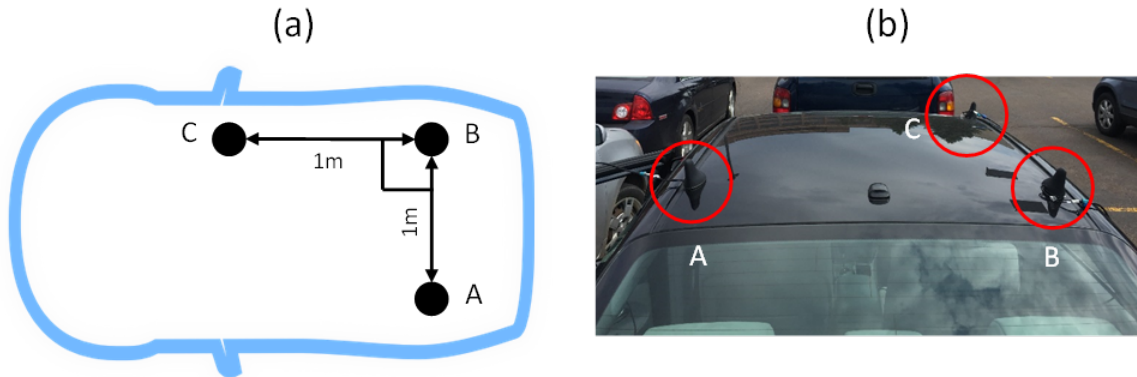


Figure 4.2: The top view of the vehicle used for the field tests with (a) pictorial view and (b) schematic view, showing three installed antennas and their relative locations.

4.1.2 Result Analysis

Distance Accuracy

We repeated the round trip six times, exchanging the positions of the antennas at locations A, B, and C after each trip and using all six possible permutations of the three devices. Each round trip produced three distinct sets of acquired GPS positions (one for each GPS receiver at location A, B and C) in terms of longitude and latitude at distinct time intervals synchronized with the GPS satellite time. There were more than 12,000 GPS points in each of the three sets of data (i.e., a net 20 minutes' worth of data with 10 Hz GPS acquisition rate). We then processed the data from all three DSRC devices to calculate three distances (AB, BC, and AC) for each set of three GPS points acquired at the same time because the clock of each GPS receiver was synchronized with the GPS satellite. The calculated average distances of AB, BC, and AC were 1.15, 1.16, and 1.6m, with standard deviations of 0.21, 0.20, and 0.24m, respectively, as shown in Figure 4. The calculated average distances of AB, BC, and AC are shown in Figure 4 where a circle with a 0.25m radius is drawn at each location (A, B, and C) to indicate the spread of the calculated relative distance because the standard deviation of each calculated distance is less than 0.25m. The variation

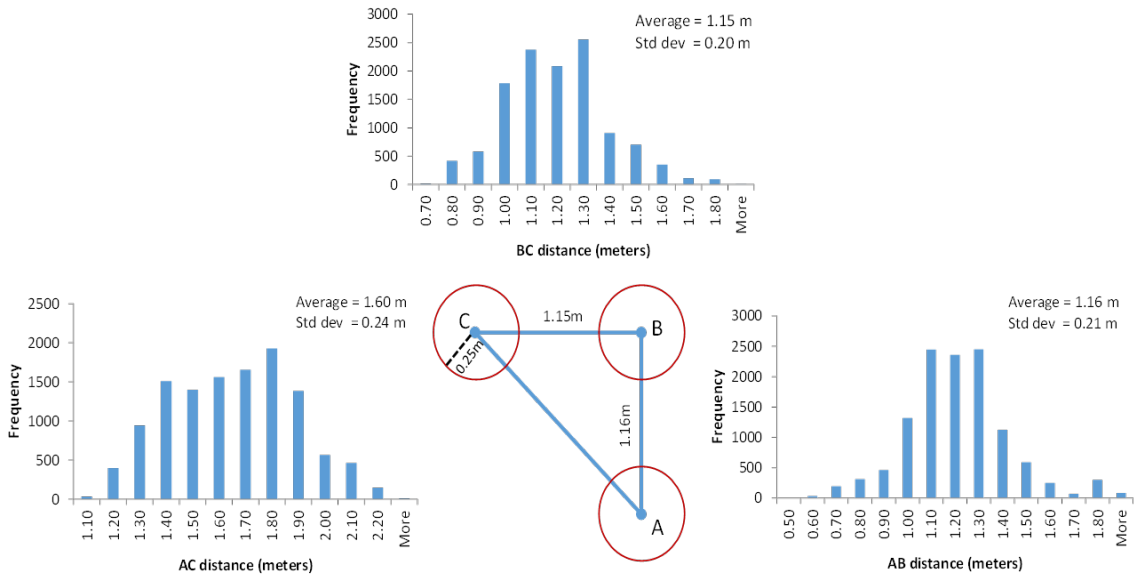


Figure 4.3: Average calculated distances of segments AB, BC, and AC. The histogram of each segment length is shown beside the segment. The average angle ABC is 87.8 degrees.

of the relative distances of AB, BC, and AC is within $\pm 0.5\text{m}$ most of the time ($>95\%$), as illustrated in the histogram of each segment in 4.3. Furthermore, the histograms show that the maximum spread of each relative distance is within a $\pm 0.6\text{m}$ limit (1.2m total spread), which is still less than half of the lane width, and therefore, is sufficient to differentiate vehicles on adjacent lanes.

Although the specified absolute position accuracy of each GPS receiver used was $\pm 2\text{m}$ with 50 percent CEP, the relative position accuracy between any two GPS receivers was much improved because the net ephemeris and atmospheric error in absolute position was similar in all three GPS receivers and was therefore canceled out in the relative distance calculation. In our approach to characterize relative distance accuracy, we used standard GPS receivers of the same hardware and firmware model. This was necessary because the post processing of the GPS signal may vary among different GPS chips being used on different DSRC devices. The processing algorithm may also be different among different versions of firmware on the same kind of GPS chip. Furthermore, the GPS receiver's field of view

is wide enough to receive signals from more than three or four GPS satellites, which is the minimum number of satellites required for two-dimensional or three-dimensional position calculation, respectively. In such scenarios, unless the post-processing algorithm of multiple GPS receivers is designed to lock to the same set of satellites, it is not guaranteed that the atmospheric and ephemeris errors will remain the same in each GPS receiver—thereby adversely affecting the relative distance accuracy. We experienced this phenomenon only twice during our early field tests when the offset of at least one of the three GPS receivers used was different from the others, indicating that this particular GPS receiver locked to a different set of satellites. In the built-in GPS receivers of our DSRC devices, we did not have any access to modify the GPS receiver firmware to make it lock to a particular set of satellites. However, we did not experience this phenomenon in any of our subsequent field tests, including the tests described in this thesis.

Direction Accuracy

We also evaluated the directional accuracy for each of the GPS receivers in this field test. We took two consecutive GPS positions (100msec apart in time) for each of the two GPS receivers at locations A and B and calculated individual headings for both, as shown in Figure 4.4a. Figure 4.4b shows the histogram of difference in headings of the GPS receivers at positions A and B for all available data points, covering six possible pairs of three distinct GPS receivers at two locations (A and B). The average and standard deviation of the differential heading is -0.003 degrees and 0.26 degrees, respectively. Both GPS receivers were traveling in the same direction, so the differential heading was expected to be zero. The results show that a standard GPS receiver can estimate the direction of travel with an accuracy of a quarter of a degree which is sufficient for use in a safety application e.g., a lane-change or merge-assist application. This is because a quarter of a degree mismatch between the actual and expected direction of travel of a vehicle traveling at 60 MPH will

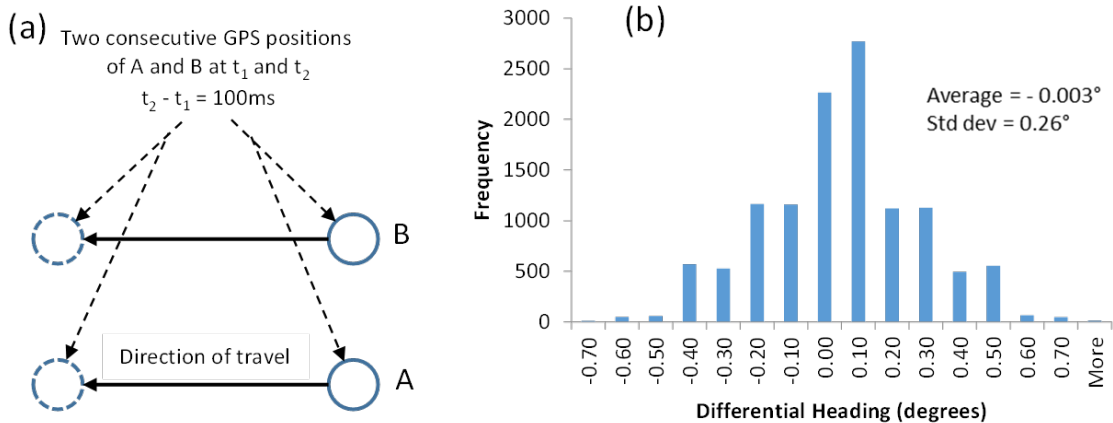


Figure 4.4: (a) The schematic diagram of calculated headings of the two GPS receivers at locations A and B, and (b) the histogram of the differential heading.

cause a displacement error of about 11cm in its expected position after one second.

4.2 Field Tests: relative trajectory acquisition using DSRC-based v2v communication

After statistically characterizing the relative distance accuracy for the built-in GPS receivers of the DSRC devices, we acquired relative trajectories of multiple vehicles using DSRC-based V2V communication. We installed three DSRC devices with built-in GPS receivers on three separate vehicles as depicted in Figure 4.5 that were programmed to transmit and receive DSRC-based Basic Safety Messages (BSMs). Using those vehicles, we conducted field tests to demonstrate the acquisition of accurate relative vehicle trajectories traveling in different lanes.

We conducted the field tests around Exit #239 on I-35 in Duluth, MN, which is a two-lane freeway. One of the vehicles waited on the entrance ramp of Exit #239 to merge on the freeway while the other two vehicles traveled on the freeway toward the merging junction

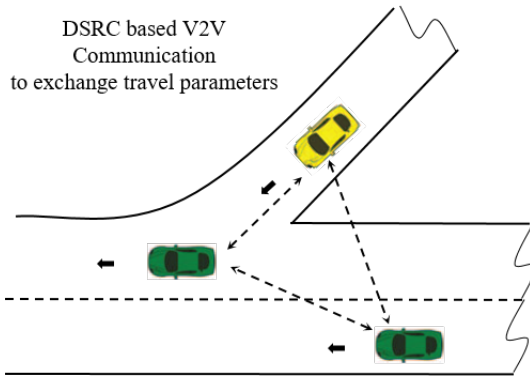


Figure 4.5: Field test setup: schematic view of the relative positions of testing vehicle (left). Placement of OBUs on the test vehicles

on two separate but adjacent lanes. When the two vehicles approached the merging junction, the vehicle waiting at the entrance ramp started to receive DSRC messages from the vehicles on the main freeway. Upon receiving the first message, the vehicle started to move and merged onto the freeway while continuing to receive DSRC messages from the two vehicles on the main freeway. The vehicle on the entrance ramp logged all of the received DSRC messages. This data was later analyzed to obtain relative trajectories of all three vehicles. We repeated the tests at least 12 times; each time, the acquired relative trajectories of the vehicles were accurate enough to identify each vehicle in its own lane.

One typical scenario of the field tests is shown in Figure 4.6, where the acquired relative trajectories of three vehicles are drawn in three different colors: red for the vehicle traveling on the entrance ramp and blue and green for the vehicles traveling on the main freeway in two adjacent lanes. The relative trajectories are superimposed onto Google Maps to establish a frame of reference. A zoomed-in version of the relative trajectories near the merge junction is also shown in Figure 6, illustrating that lane-level accuracy can be achieved using the built-in standard GPS receivers of the DSRC devices.

To measure the range of the V2V communication during the field tests, we calculated the distance between the vehicles on the main freeway and the vehicle on the entrance ramp

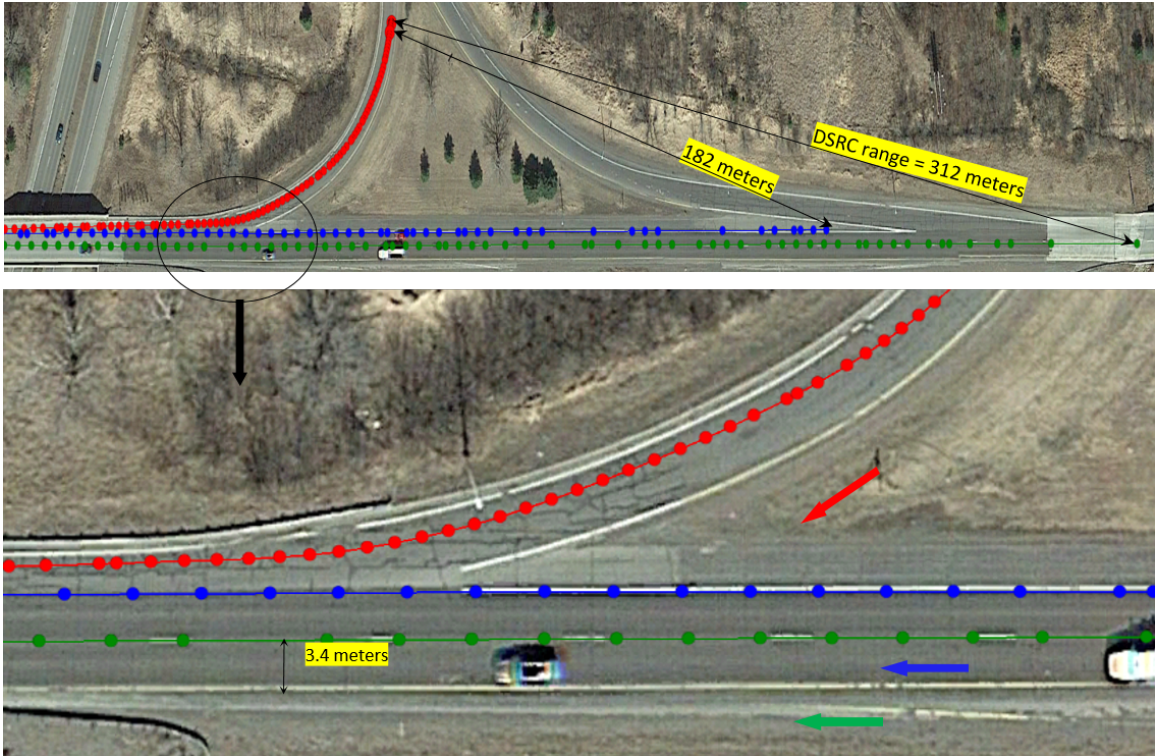


Figure 4.6: (a) A typical scenario from field tests showing relative trajectories of three vehicles around a merge junction of a two lane freeway (I-35). The lower part of the Figure is the zoomed version of a smaller area in upper part showing accuracy of the acquired relative trajectories.

when that vehicle received the first DSRC messages from each of the two vehicles on the main freeway. The measured DSRC ranges for the DSRC devices on the two vehicles in the test scenario of Figure 6 were 182 and 312m, respectively. In the rest of the tests, the DSRC range typically varied between 200–300m. The specified DSRC range is >500m (31) when a clear line of sight is available, but the actual achieved range (200 – 300m) was reduced due to some natural growth around the merge junction that caused some loss of signal strength

Although the relative trajectories obtained in the field tests have lane-level accuracy, these trajectories were obtained by post-processing GPS data acquired through DSRC-based V2V communication during the field tests. In the future, we plan to integrate the post-

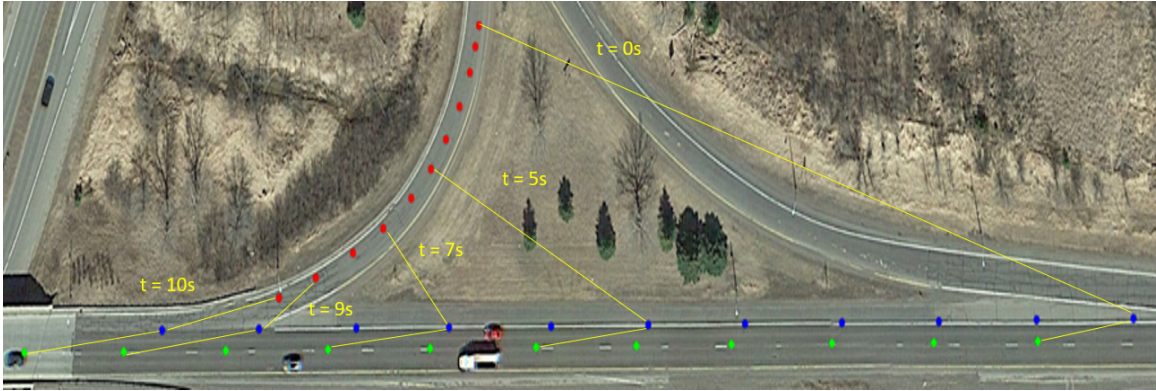


Figure 4.7: A field test scenario showing the relative trajectories of three vehicles with time stamps.

processing algorithm within the DSRC device of the vehicle on the merging ramp to acquire the relative trajectories in real time. Using the real-time trajectories, speed, and direction of travel information from the relevant vehicles, we can estimate a safe merge time cushion that could potentially be used as an important parameter to develop a merge-assist application.

We define the merge time cushion as the time it will take for a vehicle in the rightmost lane of the freeway to arrive at the merging junction after the vehicle on the entrance ramp has received the first BSM from this vehicle. The merge time cushion for the field test result of Figure 4.6 was estimated to be between 9 and 10 seconds, as illustrated in Figure 4.7, where yellow lines represent the relative positions of all three vehicles at a given time. The time stamp $t = 0s$ in Figure 4.7 indicates the time when the merging vehicle received the first BSM from the vehicle in the rightmost lane of the freeway. Similarly, the time stamp $t = 9s$ indicates the time when the vehicle in the rightmost lane of the main freeway arrives at the merging junction, giving the merging vehicle a merge time cushion of 9 seconds.

5 Conclusions and Future work

In this thesis work, we proposed a simple approach to acquire accurate relative trajectories of surrounding vehicles using standard GPS receivers and DSRC-based V2V communication. Using this approach, we have demonstrated that relative trajectories of the surrounding vehicles can be achieved with lane-level resolution. We conducted field tests to successfully acquire the relative trajectories of vehicles traveling on multiple lanes toward a merging junction with an accuracy of $\pm 0.5\text{m}$ with 95 percent CEP. The achieved accuracy level for the relative trajectory was sufficient to differentiate vehicles traveling in adjacent lanes of a multiple-lane freeway.

However, we obtained the relative trajectories by post-processing GPS data acquired

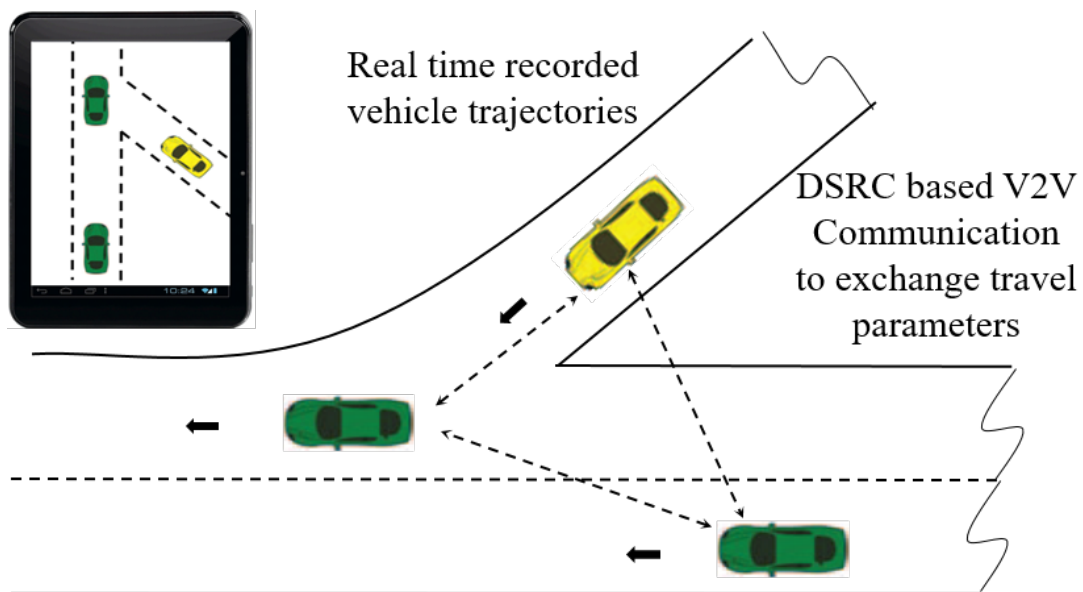


Figure 5.1: The schematic diagram of acquiring and displaying real-time relative vehicle trajectories for merging on a single lane road

through DSRC-based V2V communication during our field tests. In the future, we can integrate the post-processing algorithm within the DSRC device of the vehicle to acquire the relative trajectories in real time. Once trajectory coordinates of relevant vehicles are processed in the DSRC device of the test vehicle, these will be communicated to the graphical monitor for real time display. As shown [5.1](#), We can develop a software for the graphical monitor to display the relative trajectories of the test vehicle and relevant surrounding vehicles in real time.

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