Acquisition of Relative Trajectories of Surrounding Vehicles using GPS and DSRC based V2V Communication with Lane Level Resolution

Zhiyuan Peng[1], Shah Hussain[1], M. I. Hayee[1] and Max Donath[2]
[1]*University of Minnesota Duluth, Duluth, MN 55812, U.S.A.*
[2]*University of Minnesota Twin Cities, Minneapolis, MN 55455, U.S.A.*

Keywords: Connected Vehicle Technology, V2V Communication, DSRC, Relative Trajectory, Relative Distance Accuracy.

Abstract: Due to the anticipated benefits of connected vehicle technology, the Intelligent Transportation Systems Joint Program Office (ITSJPO) of the US Department of Transportation continues to emphasize the need for 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. Many techniques, such as vision- or sensor-based systems and differential GPS receivers, 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 so that a given vehicle can differentiate the vehicles in its own lane from the vehicles in 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 traveling in multiple lanes towards a merging junction with an accuracy less than half of the lane width. The achieved accuracy level of the relative trajectory was sufficient to differentiate vehicles traveling in adjacent lanes of a multiple-lane freeway.

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 (USDOT factsheet a, b). 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 (Harding, J., Powell, et al 2014, NHTSA USDOT factsheet). 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 (D. Jie and M. J. Barth, 2008). 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 (S. Ammoun, F. Nashashibi et al. 2007, D. Desiraju, T. Chantem 2015). 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 (A.T. McCartt et al. 2004, Bruce N. Janson et al. 1998). 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 (Basav Sen et al. 2003, G. M. Fitch et al. 2009). Another report that analyzed crash data from 2005 to 2007 concluded that 11 percent of vehicles

Peng, Z., Hussain, S., Hayee, M. and Donath, M.
Acquisition of Relative Trajectories of Surrounding Vehicles using GPS and SRC based V2V Communication with Lane Level Resolution.
DOI: 10.5220/0006304202420251
In *Proceedings of the 3rd International Conference on Vehicle Technology and Intelligent Transport Systems (VEHITS 2017)*, pages 242-251
ISBN: 978-989-758-242-4

involved in an accident had failed to stay in the proper lane (NHTSA: Report to congress, 2008).

An important technological milestone in the development of a lane-change or merge-assist application is to acquire the relative positions of surrounding vehicles in real time. 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 (D Chun.; K, Stol. 2012, Abdelfatah, W.F., et al. 2011, Qingquan Li et al. 2014, H. Zhao et al. 2009). 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 (A. Bansal et al. 2014). 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 (R. Toledo-Moreo et al. 2007, N. Mattern et al. 2010, R. G. García-García et al. 2007, J. Juang et al. 2015, S. Rezaei and R. Sengupta 2007). 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 (N. Alam et al. 2013). 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 (J. Farrell, T. Givargis 2000, FHWA factsheet). 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 less than half of the lane width 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.

The next section of this paper will describe the concept of relative GPS positioning among surrounding vehicles. The following section will discuss the results from field tests to statistically characterize the accuracy of the relative trajectories of multiple vehicles using standard GPS receivers. In the next section, the results from field tests to acquire relative trajectories of surrounding vehicles with lane-level accuracy using DSRC-based V2V communication will be discussed. The last section will summarize the conclusions.

2 CONCEPT OF RELATIVE GPS POSITIONING AMONG SURROUNDING VEHICLES

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 (William J. Hughes, 2014). 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 Figure 1a, 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.

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 (D. K. Schrader 2013, R. B. Langley 1997). Satellite ephemeris error is due to

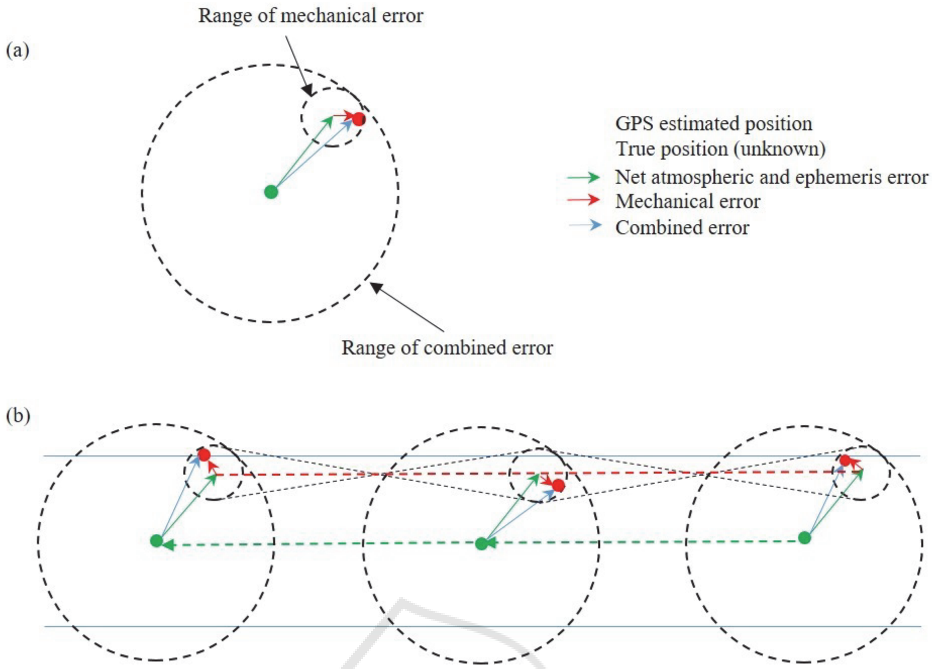

Figure 1: Conceptual GPS receiver error model of a single GPS receiver showing ranges of different GPS error types for (a) a stationary vehicle at a single time instance and (b) a moving vehicle at three adjacent time instances.

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. Atmospheric error, 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 (J. Farrell, T. Givargis 2000, FHWA factsheet). Similarly, ephemeris error will remain almost the same for the satellite constellation used by GPS receivers in close proximity to each other (Ahmed El-Rabbany 2002). Theoretically, a GPS-estimated position can be anywhere in the larger circle as shown in Figure 1a, 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. 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 1a. Therefore, subsequent estimates of the same position by a given GPS receiver will remain confined to a smaller circle shown in the Figure 1a, representing the range of mechanical error.

In addition to the three errors described above, multipath error 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) (T. Kos et al. 2010). 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.

Figure 1a 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 1b, 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 1b. 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.

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 Figure 2 (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 Figure 2 (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

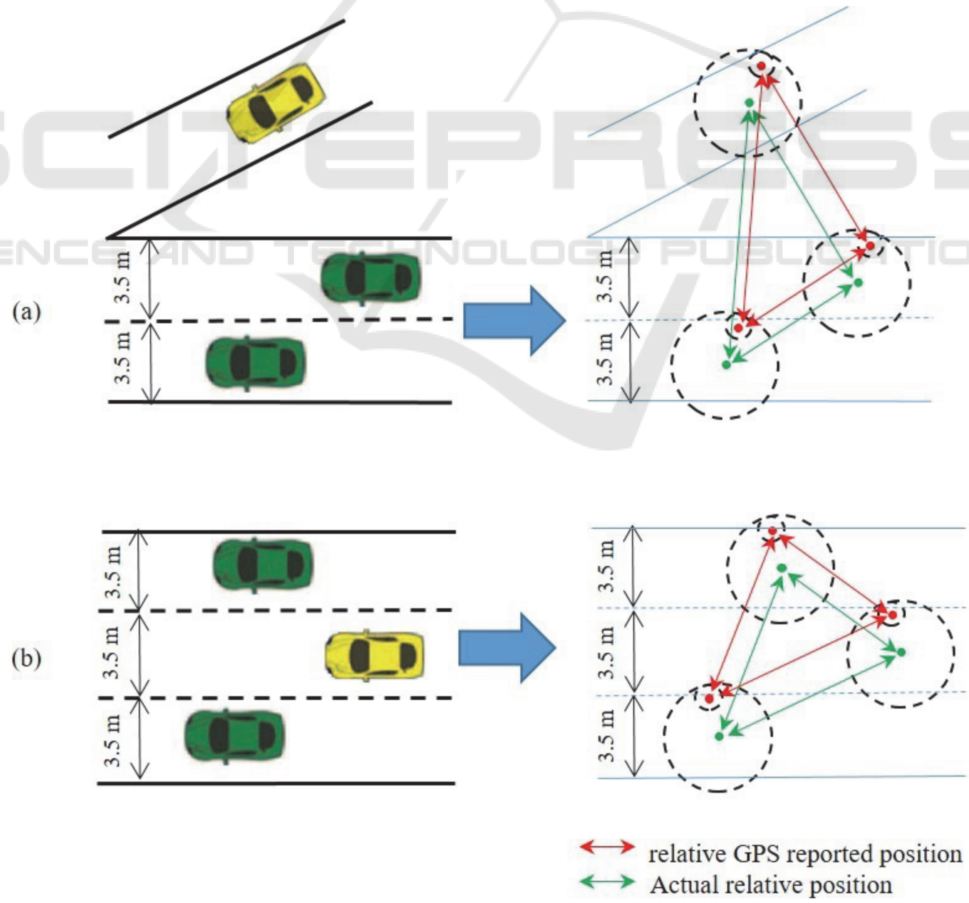

Figure 2: Concept of relative GPS accuracy: (a) Lane-merging scenario (b) Lane-changing scenario.

both scenarios calculated from the estimated positions of the GPS receivers on the two vehicles will have a small variance determined by the mechanical 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.

3 CHARACTERIZATION OF THE GPS RELATIVE DISTANCE ACCURACY

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 ± 2m 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 ± 0.5m 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 Figure 3. A top view of the vehicle used for the field tests is shown in Figure 3a, and Figure 3b 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.

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

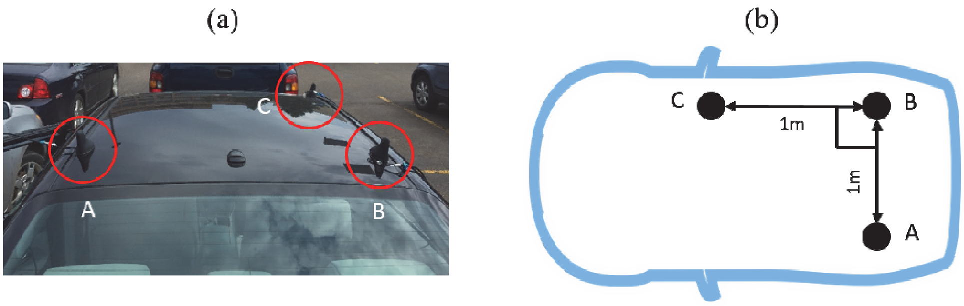

Figure 3: The top view of the vehicle used for the field tests with (a) pictorial view and (b) schematic view, showing three installed antennas and their relative locations.

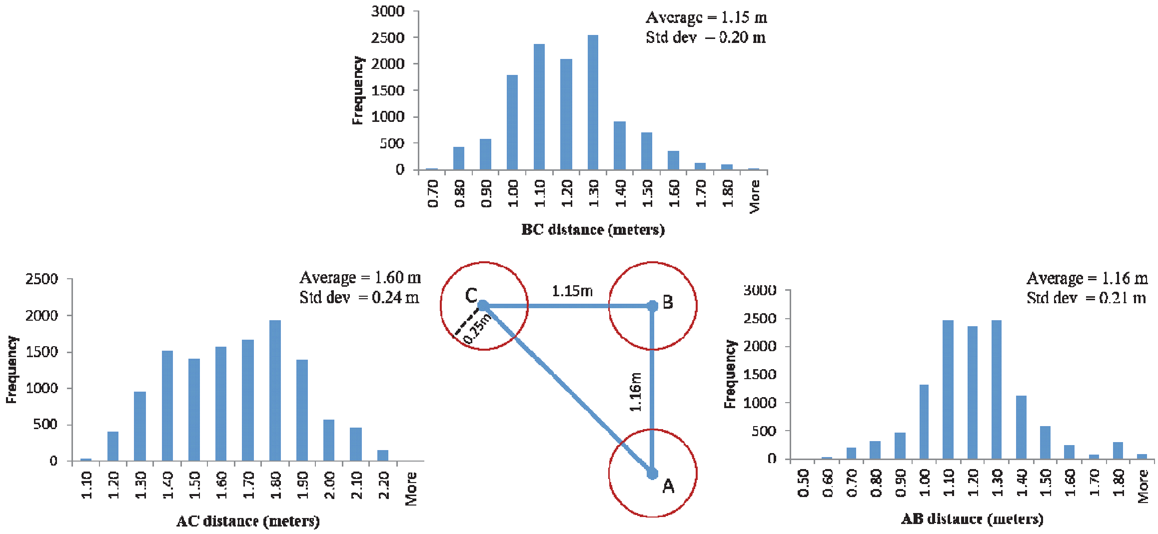

Figure 4: Average calculated distances of segments AB, BC, and AC. The histogram of each segment length is shown beside the segment. The average angle ∠ABC is 87.8 degrees.

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 of the relative distances of AB, BC, and AC is within ± 0.5m most of the time (>95%), as illustrated in the histogram of each segment in Figure 4. Furthermore, the histograms show that the maximum spread of each relative distance is within a ± 0.6m 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 ± 2m 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 cancelled 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

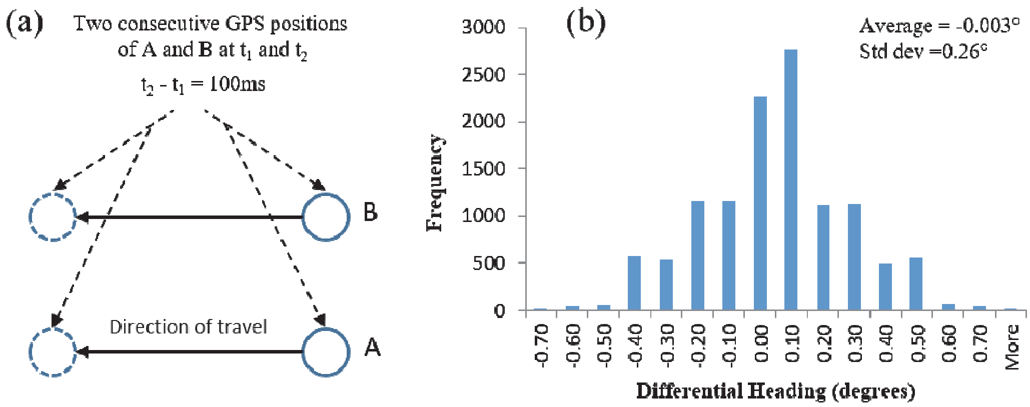

Figure 5: (a) The schematic diagram of calculated headings of the two GPS receivers at locations A and B, and (b) the histogram of the differential heading.

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 paper.

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 5a. Figure 5b 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 cause a displacement error of about 11cm in its expected position after one second.

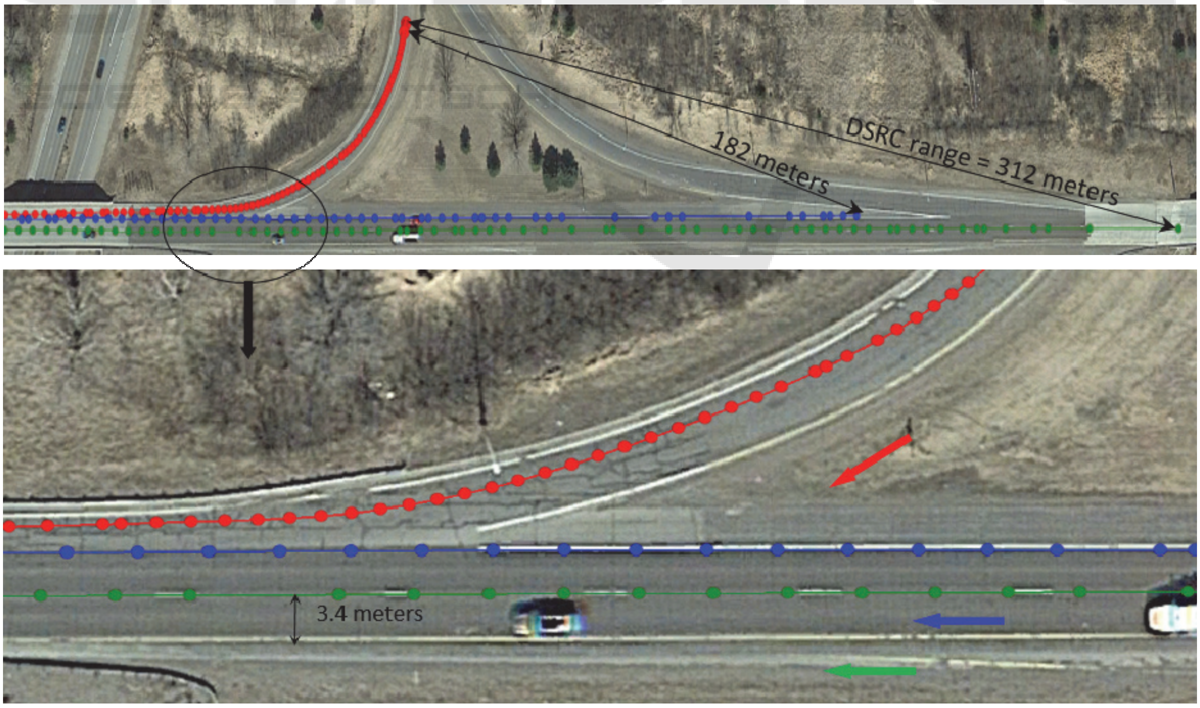

Figure 6: A typical scenario from field tests showing relative trajectories of three vehicles around a merge junction of a two lane freeway (I-35). The lower part of the Figure is the zoomed version of a smaller area in upper part showing accuracy of the acquired relative trajectories.

4 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 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 travelled on the freeway toward the merging junction 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 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 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 (D. Jiang 2006) 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-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 6 was estimated to be between 9 and 10 seconds, as illustrated in Figure 7,

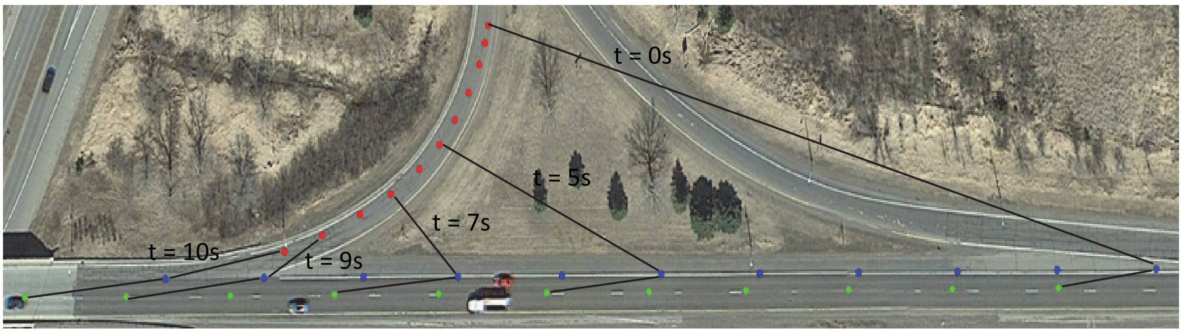

Figure 7: A field test scenario showing the relative trajectories of three vehicles with time stamps.

where yellow lines represent the relative positions of all three vehicles at a given time. The time stamp t = 0s in Figure 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

In this paper, we have presented 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 sufficient accuracy to distinguish two vehicles on separate or adjacent lanes of a multiple-lane freeway. However, we obtained the relative trajectories by post-processing GPS data acquired through DSRC-based V2V communication during our field tests. In the future, we plan to integrate the post-processing algorithm within the DSRC device of the vehicle to acquire the relative trajectories in real time.

ACKNOWLEDGEMENTS

The authors wish to acknowledge those who made this research possible. The study was funded by the Roadway Safety Institute, the University Transportation Center for USDOT Region 5, which includes Minnesota, Illinois, Indiana, Michigan, Ohio, and Wisconsin. Financial support was provided by the United States Department of Transportation's Office of the Assistant Secretary for Research and Technology (OST–R).

REFERENCES

Intelligent Transportation Systems - DSRC: The Future of Safer Driving Fact Sheet. 2017. Intelligent Transportation Systems - DSRC: The Future of Safer Driving Fact Sheet. [ONLINE] Available at: http://www.its.dot.gov/factsheets/dsrc_factsheet.htm. [Accessed 23 February 2017].

Intelligent Transportation Systems. 2017. Connected Vehicle Challenges: Potential Impact of Sharing the 5.9 GHZ Wireless Spectrum. [ONLINE] Available at: Http://www.its.dot.gov/cv_basics/pdf/CV_basics_DSRC_factsheet.pdf. [Accessed 23 February 2017].

Harding, J., Powell, G., R., Yoon, R., Fikentscher, J., Doyle, C., Sade, D., Lukuc, M., Simons, J., & Wang, J. (2014, August). Vehicle-to-vehicle communications: Readiness of V2V technology for application. (Report No. DOT HS 812 014). Washington, DC: National Highway Traffic Safety Administration.

U.S. Department of Transportation. 2017. Vehicle to Vehicle Communication Fact Sheet National Highway Traffic Safety Administration, US Department of Transportation. [ONLINE] Available at: Http://www.nhtsa.gov/pdf/v2v_fact_sheet-02032014.pdf. [Accessed 23 February 2017].

D. Jie and M. J. Barth, 2008. Next-generation automated vehicle location systems: Positioning at the lane level, IEEE Trans. Intell. Transp. Syst., vol. 9, no. 1, pp. 48-57, 2008.

S. Ammoun, F. Nashashibi and C. Laurgeau, 2007, An analysis of the lane changing manoeuvre on roads: The contribution of inter-vehicle cooperation via communication, IEEE Intelligent Vehicles Symposium pp. 1095-1100, June 2007.

D. Desiraju, T. Chantem. K. Heaslip, 2015. Minimizing the Disruption of Traffic Flow of Automated Vehicles During Lane Changes", Intelligent Transportation Systems, IEEE Transactions, pp. 1249 - 1258 Volume: 16, Issue: 3, June 2015.

A.T. McCartt et al., 2004. Types and characteristics of ramp-related motor vehicle crashes on urban interstate roadways in Northern Virginia", Journal of Safety Research, vol.35, 2004, pp. 107- 114.

Bruce N. Janson, Wael Awad, Juan Robles, Jake Kononov, Brian Pinkerton, 1998. Truck Accidents at Freeway Ramps: Data Analysis and High-Risk Site Identification, Journal of Transportation and Statistics, January 1998, pp. 75 – 92.

Basav Sen, John D. Smith, and Wassim G. Najm. 2003. Analysis of Lane Change Crashes. DOT-VNTSC-NHTSA-02-03 DOT HS 809 571, March 2003.

G. M. Fitch, S. E. Lee, S. Klauer, J. Hankey, J. Sudweeks, and T. Dingus, 2009. Analysis of Lane-Change Crashes and Near-Crashes DOT HS 811 147, June 2009.

National Highway Traffic Safety Administration. 2008. National Motor Vehicle Crash Causation Survey: Report to Congress. DOT HS 811 059, July 2008.

D Chun; K, Stol., 2012. Vehicle motion estimation using low-cost optical flow and sensor fusion, Mechatronics and Machine Vision in Practice (M2VIP), 2012 19th International Conference, pp. 507 - 512, Nov. 2012.

Abdelfatah, W.F., et al., 2011. "2D Mobile multi-sensor navigation system realization using FPGA-based embedded processors," Canadian Conference on Electrical and Computer Engineering (CCECE), 2011, pp. 1218-1221.

Qingquan Li et al., 2014. A Sensor-Fusion Drivable-Region and Lane-Detection System for Autonomous Vehicle Navigation in Challenging Road Scenarios, Vehicular Technology, IEEE Transactions on, Volume: 63, Issue: 2, pp. 540 – 555, Feb. 2014.

H. Zhao, M. Chiba, R. Shibasaki, X. Shao, J. Cui and H. Zha, 2009. A laser-scanner-based approach toward driving safety and traffic data collection, IEEE Trans. Intell. Transp. Syst., vol. 10, no. 3, pp. 534-546, 2009.

A. Bansal, H. Badino and D. Huber, 2014. Understanding how camera configuration and environmental conditions affect appearance-based localization, Intelligent Vehicles Symposium Proceedings (IV), 2014 IEEE, pp. 800-807.

R. Toledo-Moreo, M. A. Zamora-Izquierdo, B. Ubeda-Minarro, and A. F. Gomez-Skarmeta, 2007. High-integrity IMM-EKF-based road vehicle navigation with low-cost GPS/SBAS/INS, IEEE Transaction on Intelligent Transportation Systems., vol. 8, no. 3, pp. 491-511, Sep. 2007.

N. Mattern, R. Schubert, and G. Wanielik, 2010. High-accurate vehicle localization using digital maps and coherency images, in Proc. IEEE Intell. Vehicles Symposium, La Jolla, CA, 2010, pp. 462–469.

R. G. García-García, M. A. Sotelo, I. Parra, D. Fernández, and M. Gavilán, 2007. 3D visual odometry for GPS navigation assistance, in Proc. IEEE Intell. Vehicles Symposium, Istanbul, Turkey, 2007, pp. 444–449.

J. Juang; C. Lin., 2015. A Sensor Fusion Scheme for the Estimation of Vehicular Speed and Heading Angle, Vehicular Technology, IEEE Transactions on, pp. 2773 - 2782 Volume: 64, Issue: 7, July 2015.

S. Rezaei and R. Sengupta, 2007. "Kalman filter-based integration of DGPS and vehicle sensors for localization," IEEE Trans. Control Syst. Technol., vol. 15, no. 6, pp. 1080–1088, Nov. 2007.

N. Alam, A. T. Balaei and A. G. Dempster, 2013. Relative positioning enhancement in VANETs: A tight integration approach", IEEE Trans. Intell. Transp. Syst., vol. 14, no. 1, pp. 47-55, 2013.

J. Farrell, T. Givargis, 2000. Differential GPS Reference Station Algorithm-design and Analysis. In IEEE Transactions on Control Systems Technology, Vol. 8, No. 3, May 2000, pp. 519-531.

High Accuracy-Nationwide Differential Global Positioning System Program Fact Sheet - FHWA-RD-03-039. 2017. High Accuracy-Nationwide Differential Global Positioning System Program Fact Sheet - FHWA-RD-03-039. [ONLINE] Available at: https://www.fhwa.dot.gov/publications/research/operations/03039/. [Accessed 23 February 2017].

William J. Hughes. July 2014. Federal Aviation Administration, Global Positioning System (GPS) Standard Positioning Service (SPS) Performance Analysis Report #86 Technical Centre NSTB/WAAS T&E Team.

D. K. Schrader, 2013. Combining Multiple, Inexpensive GPS Receivers to Improve Accuracy and Reliability", Sensors Applications Symposium (SAS), 2013 IEEE. pp. 33-37.

R. B. Langley, 1997. GPS receiver system noise, GPS World, vol. 8, no. 6, pp. 40–45, 1997.

Ahmed El-Rabbany, 2002. Introduction to GPS: The Global Positioning System. 2002, pp.29.

T. Kos, I. Markezic and J. Pokrajcic, 2010. Effects of multipath reception on GPS positioning performance, ELMAR, 52nd International Symposium EL MAR-2010, pp. 399-402.

D.Jiang, V.Taliwal, A.Meier and W. Holfelder, 2006. Design of 5.9 GHz DSRC-based Vehicular Safety Communication, IEEE Wireless Communications, Vol. 13, No 5, October 2006, pp.36-43.