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Positioning and collision alert investigation for DSRC-equipped light vehicles through a case study in CITI

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Abstract

Recent advancements in vehicle-to-vehicle communications have paved the way for testing new solutions to reduce congestion and prevent traffic incidents. The main objective of multiple transport agencies is to improve road safety by providing reliable and flexible solutions to all drivers on the roads. While significant effort has been made in the development of regulations and operating standards, many questions regarding the practical performance and accuracy of such technologies are yet to be answered.

This paper presents the results obtained from an ongoing investigation focusing on testing the capabilities of Dedicated Short Range Communications (DSRC) to meet critical levels of road safety in terms of positioning accuracy. After previous analysis of positioning accuracy of heavy vehicles on a test-bed in the Illawarra, New South Wales, Australia, this paper focuses on testing the accuracy of positioning transmitted by two light vehicles while engaged in five different experiments of potential traffic collisions. Firstly, as ground truth is not available, we conduct a comparative analysis of transmitted positioning through Basic Safety Messages by using both Open Street Map and Google Street Map as a ground reference, and show the latter provides better accuracy in computing the positioning error. Secondly, we present the results obtained when analysing the collision alerts generated during the collision experiments. The findings indicate that speed, braking and DSRC installation might influence the successful generation of collision alerts in the vehicles and can be used as a guideline for future settings of DSRC equipped vehicles in light vehicles.

KEYWORDS:
DSRC, connected vehicles, positioning accuracy, collision alert investigation, road safety.

1. Introduction

Traffic congestion and road vehicle collisions are one of the most important problems in concentrated urban areas around the globe, leading to almost 1.24 million road traffic deaths per annum [1]. In order to address this issue, advanced technologies such as vehicle-to-vehicle (V2V) and vehicle-to-infrastructure (V2I) communications are already being tested and recent studies show the benefits of adopting these technologies in terms of lives saved and economic impact [2].

Recent advancements in wireless communication technologies have led to the emergence of dedicated short-range communication (DSRC), which has been designed to support V2X (both V2V and V2I) communications, enhance mobility and improve road safety [3]. As vehicular communications need fast interoperability, the United States, Europe and Japan have assigned dedicated bandwidths for DSRC communications [4]. In order to assess the performance and safety benefits of DSRC, various projects and test-bed initiatives have concentrated on: testing the effective communication range between two vehicles and security protocols [5], analysing the probability of successful message reception [6], detecting collision situations and sending drivers early alerts [7], analysing collision timing [8], or investigating signal priority for connected vehicles (CV) at signalized intersections [9]. Despite a high DSRC reliability indicated by these studies, in 2014 the United States National Highway Transportation Safety Administration (NHTSA) stated a need to further investigate open research problems before an official rule-making to mandate the deployment of V2V communication systems is made [10].

One of the biggest problems to be addressed by CV systems for building safety applications such as proximity collision alerts, automated braking, intersection signal alerts, etc., is to have an accurate vehicle positioning capability. Current systems use Global Navigation Satellite System (GNSS) [11]. Although in ideal operating conditions (clear sky, no obstructions), GNSS can usually meet the positioning accuracy required for most DSRC applications, in areas such as dense urban zones or tunnels the GNSS signal can be limited or result in inaccurate positioning [12]. Some CV applications need sub-metre accuracy at the lane level, especially for real-time situational awareness [13]. Bridging the gap between positioning accuracy and the requirements for CV applications is an important challenge still to be tackled. Jiangchen et al [14] proposed a Bayesian approach for using received signal strength data from roadside equipment (RSE) to update and improve GPS positioning. While this approach can work well when RSE is available and ready to use, many test-beds have insufficient RSE or they are located at sparse locations throughout the study network. Other studies propose integrating GNSS and navigation information such as map data [11, 15], which contains "metadata" for travellers. However, until such maps are developed and shared across a large fleet, the cost to maintain a huge map database can become prohibitive especially for rapidly growing cities.

The Cooperative Intelligent Transport Initiative (CITI) is a project currently undertaken by Transport for New South Wales (TfNSW), with the aim of building Australia's first semi-permanent test-bed for testing the DRSC technology over an area of 917 km^2 in the Illawarra Region of NSW, south of Sydney [16]. As road safety is the main focus of CITI, one of the main problems to investigate in the project is the accurate generation of collision alerts. The risk is that generating false alerts might hinder driving and could result in a mistrust of the technology/system. The first step to better understand the possible cause of false alerts is to investigate the accuracy of the transmitted positioning between connected vehicles, as reported in the Basic Safety Messages (BSMs). Our previous studies [17] on positoning accuracy for heavy vehicles indicated that almost 37.89% of transmitted BSMs during a specific period of time were incomplete or empty (possibly due to incomplete logs), while some heavy vehicles presented various anomalies in positioning (for example, one of the most active trucks showed positioning that didn't correlate to the chosen base-maps for 9% of the transmitted BSMs). The work presented in this paper is therefore a continuation of previous results to test and detect anomalous behaviour in positioning or collision alert generation for light vehicles equipped with DSRC. The main objectives of this study are:

a) investigate the error (noise) in the transmitted GPS positioning for two DSRC-equipped light vehicles
b) analyse the generation of collision alerts during experiments which simulated real-life collision situations
c) identify the factors that might hinder the generation of correct collision alerts.

2. CITI project background

The Cooperative Intelligent Transport Initiative (CITI) is a project deployed by Transport for NSW (TfNSW) in partnership with Data61|CSIRO and the Australian Federal Government's Heavy Vehicle Safety Productivity Program. The main goal of the project is to assess V2V/V2I communication technology that could reduce the number of road crashes, with a focus on the Illawarra region, in both urban and rural traffic conditions. In order to address this problem and the high cost generated by truck crashes, CITI aims at building a semi-permanent test-bed for evaluating and further testing of the Cooperative Intelligent Transport Systems (CITS) technology, especially DSRC equipped vehicles.

2.1 Current deployment and location

During the first stage, the CITI project has installed DSRC devices in 58 heavy vehicles, 2 light vehicles (operating in the area marked in Figure 1a), 1 roadside unit and 3 signalized intersections (Figure 1b). CITI currently utilizes Cohda Wireless MK4 and MK5 DSRC units [18] running Cohda's alert software in vehicles and roadside software for infrastructure deployment. Cohda's DSRC systems are using the US standards, including the IEEE 1609 family, SAE J2735 and IEEE 802.11p standards. For positioning, while the heavy vehicles have only GPS antennas, the light vehicles used for the current study have a combination of GPS/GLONASS, potentially providing more accurate positioning. Inside the vehicles, the DSRC unit is connected to a Nexus 7 tablet for audio and visual display of generated alerts, such as Forward Collision Warning (FCW), Intersection Collision Warning (ICW), Electronic Brake Light Warning (EBLW), as well as two custom alerts.

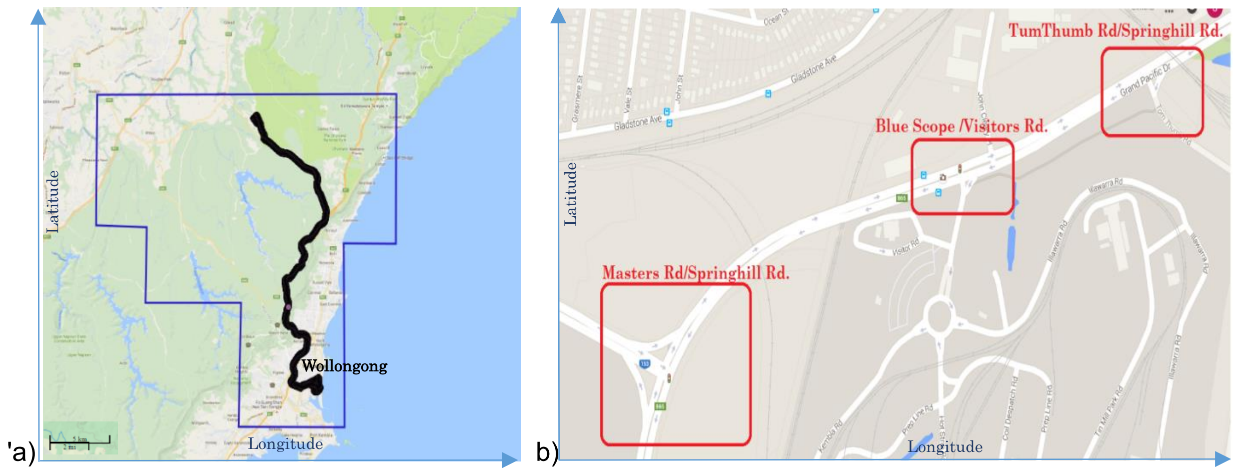


Figure 1 a) CITI operating area with an example of daily trip: (150.558,-34.51) x (151.318,-34.109) (Google maps source). b) DSRC equipped intersections: (150.874,- 34.447 x 150.889,-34.439) (Google maps source).

2.2 Challenges

Vehicles in the trial broadcast their position 10 times per second in a message known as the Basic Safety Message (BSM). The positioning information in these messages is based on GNSS measurements extrapolated from last known data in a process known as "dead reckoning" [19]. However, in CITI, no additional sensors are connected to the DSRC unit and dead reckoning is restricted to interpolations from previous GPS/GLONASS locations. For the remainder of this article, we will use "GPS" as a shorthand to refer to the GPS/GLONASS based positioning information with "dead reckoning" as broadcast by a vehicle in a BSM. Therefore, the accuracy of the "transmitted GPS positioning" is not independent of the DSRC unit, but is a mix of processing and transmission methods.

Large variations in the transmitted location to other connected vehicles can trigger false collision alerts, or hinder driver's response to alerts. As road safety is the main focus of the CITI project, a major concern is to identify the risks that drivers face when exposed to false alarms or when false and correct alarms cannot be distinguished. As our previous investigations on heavy vehicles revealed some anomalies in terms of positioning accuracy while operating in various road sections of the test-field area, the current analysis focuses on: a) assessing the accuracy transmitted by light vehicles in urban areas near Wollongong; b) investigating the successful detection and transmission of collision alerts by simulating real-life potential collision scenarios. In terms of ground truth, this investigation used the closest mapped road position from both Google Street Maps (GSM) and Open Street Map (OSM) to determine the "error" or noise in the DSRC transmitted GPS position. The simulated incidents were also filmed to verify the lane positioning of the vehicles during the tests.

3. Positioning analysis for light vehicles

3.1 Context

Two light vehicles belonging to Transport for NSW and equipped with DSRC systems were involved in various test-case scenarios in which the DSRC system generated alert messages to the drivers in order to inform them of potential collisions between the two vehicles. This demonstration took place in Wollongong, on 8 April 2016 at around 11 am local time for approximatively one hour, and generated approximately 35,000 BSMs for each vehicle, as represented in Table 1.

Table 1 Transmission times for collision scenarios.

	Start time	End Time	BSM number
Vehicle 1	Apr 8, 2016 10:42:10.094388000	Apr 8, 2016 11:40:31.994325000	35,001
Vehicle 2	Apr 8, 2016 10:42:10.006401000	Apr 8, 2016 11:40:31.902105000	35,006

Figure 2 shows the paths that the vehicles took during the experiment, covering a range of road categories from the city centre to peripheral arterial roads.

Figure 2 Trajectory of two DSRC-equipped light vehicles (QGIS, Google Satellite).

The following driving scenarios were tested:

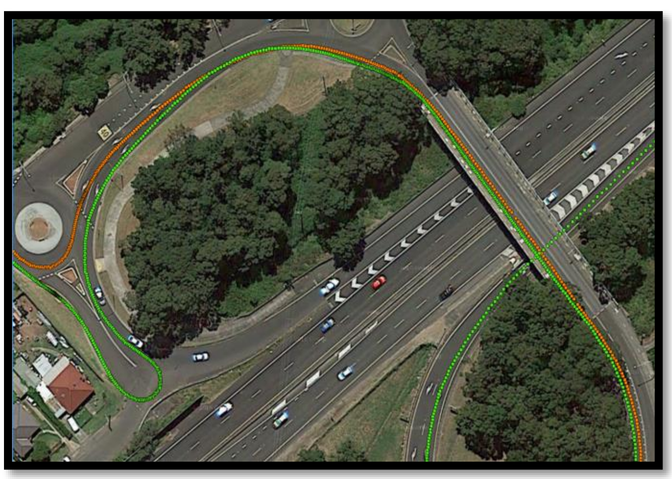
1. *Forward collision experiment* – testing the forward collision scenario with successfully generated collision alert message (first vehicle decelerates, second vehicle (following) receives alert message);
2. *Forward collision experiment, reversed roles* – testing the forward collision scenario with successfully generated collision alert message when the roles of the vehicles were reversed;
3. *First T-intersection collision experiment* – first test of collision scenario at a (non-signalised) T-intersection (low visibility) with failed collision alert message.
4. *Second T-intersection collision experiment* – second test of collision scenario at a (non-signalised) T-intersection (low visibility) with successfully generated collision alert message.
5. *Signal Phase and Timing (SPaT) Equipped intersection experiment* – successful generation of red light alerts based on traffic signal messages received by both connected vehicles.

3.2 Data sources and noise processing

The data transmitted by the DSRC-equipped vehicles is logged locally and automatically uploaded when vehicles are stopped near 2 equipped trailers in Port Kembla. Data can also be collected manually from the two light vehicles. The logs contain all transmitted and received DSRC messages, including BSMs. After initial data format reading and verification, we batch processed and extracted only the necessary messages and fields required for data analysis. In our case, we processed the BSMs containing positioning, speed, heading, acceleration, brakes, elevation, time, as well as the collision alert messages with exact timing and type of collision warning alerts generated during the scenarios. The mean deviations or noise from the road centre were computed by using the procedures previously proposed by Mihaita et al [17], which consist of a map-matching procedure to identify DSRC GPS positions with a position relative to the road, followed by noise deviation computation for the trial experiments.

When analysing the generated trajectories plotted on satellite imagery, the GPS location transmitted by light vehicles seems to be generally accurate, smooth and follow the projection of the street, as shown in Figure 3a). However, the orange trace around the roundabout presents some jitter between consecutive GPS locations. A possible explanation for this phenomenon is related to the role of dead reckoning in the DSRC device. As BSMs are generated at regular intervals and not at every GPS position received, the positionings in the BSMs are probably interpolated based on GPS updates. If GPS updates are less than 10 times a second, then interpolations may be imprecise, especially if the vehicle is changing direction, as occurs on a roundabout. Similar results have been previously observed for heavy vehicles when turning or navigating roundabouts. By attentively analyzing the GPS location when vehicles are passing over the bridge, there is a difference of almost half lane width between the traces of the vehicles. While this could be a different GPS error, we suspect that it is an accurate reflection of a different configuration of the GPS antenna in the vehicle creating an offset, as will be confirmed in a subsequent section.

A particular behavior of position reporting based on GPS is observed when vehicles are stopped with their engines on (Figure 3b). While this behavior does not raise large problems when the vehicles are parked, it might be important to analyse the impact of this behavior when the vehicles are stopped and waiting at red traffic lights. It may also be an indicator of typical drift in positioning that is harder to detect in data from a moving vehicle. A brief examination of the plot indicates different patterns in the drift of each vehicle but this may be due to the vehicles not being in those stationary positions at the same time.



a)

b)

Figure 3a). Accurate transmission of GPS location for 2 light vehicles with DSRC
b) Variations of GPS signal while vehicles are waiting for passengers.

3.2 Noise analysis along the route

As a ground truth reference was not available for computing the noise (distance from the transmitted GPS locations to the actual real position of the vehicles), we used both Google Street Map (GSM) and Open Street Map (OSM) as pseudo “ground truths” and measured noise relative to the centre of the road. For a centralized comparison and analysis, statistical results are provided in Table 2. Results indicate an average noise for both vehicles below 5 metres when using both OSM and GSM. Knowing that the typical lane width in Australia is 3.5 metres and some of the roads present 2 lanes per direction, the noise remains inferior to 5.25 metres, which can be considered as a good accuracy compared to 10 meter positoning error of GPS which is acclaimed in various research studies. As well, we observe lower noise in the distance from the road centre for OSM when compared to GSM (24-36 cm). This is a similar result to our previous findings for the heavy vehicle positioning analysis. Higher noise levels are observed only in parking areas or at U-turns. These manoeuvres are deliberately taking the vehicle away from the road centre and so have not been taken into consideration for the present analysis. It would also be worth highlighting that some urban areas (in general roundabouts or various merging lanes) may be misrepresented in both OSM and GSM. Figure 4 shows the GPS locations transmitted by one light vehicle when passing through a roundabout (yellow). In this particular case, the GSM (violet line) seems to offer a better approximation of the path of the vehicle when compared to OSM (blue line), which provides a rough approximation of the road shape. When the vehicle is entering the roundabout, noise levels obtained with OSM are higher than the ones provided by GSM due to a different geometry of the path representation. However once inside the roundabout, the OSM shape file seems to better fit the reported path of the vehicle. Various similar examples can be found along the route. Therefore, in the next section, we focus on analyzing the noise mapping in the areas where the forward and intersection collision accidents were simulated, and use GSM as a main reference for noise computation.

Table 2 Errors between GSM and OSM for light vehicles noise analysis.

	GSM		OSM		Errors GSM- OSM	
	Average Noise [m]	Standard deviation [m]	Average Noise [m]	Standard deviation [m]	Average Noise [%]	Standard deviation [%]
Light Vehicle 1	4.3239	4.3641	4.6848	4.3360	7.7036 % (-0.36 m)	0.6481 (0.02 m)
Light Vehicle 2	4.6595	4.4316	4.9032	4.3506	4.9702 % (-0.24 m)	1.8618 (0.08 m)

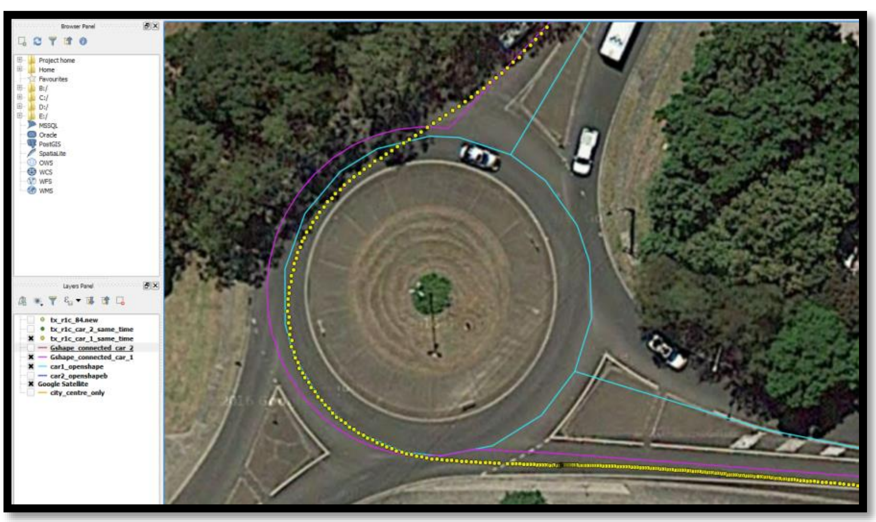


Figure 4 Example of roundabout representation in OSM, GSM and GPS locations from vehicle 1.

3.2 Noise analysis in the collision scenarios test-bed area

When analysing noise patterns in the collision area test-bed, we observed an average noise level of 3.86 metres for the first light vehicle and 4.84 metres for the second, as represented in Figure 5a) and c). As the light vehicles conducted a number of manoeuvres (such as U-turns and pulling to the side of the road) to set up the initial positioning of the vehicles before the trial experiments, and as they do not drive down the centre of the road itself but rather at an offset, we observe a good positioning accuracy with appropriate noise levels (average noise for first vehicle was 3.86 metres, while for the second vehicle 4.84 metres). As an observation, a particular driver might have a preference for driving at a different offset from the road centre or the configuration of the vehicle's devices may have an incorrect offset which might impact the broadcasted BSM position and therefore appear as an error. As well, the noise distributions of both vehicles indicate two peaks of 3 and 5 metres respectively from the GSM road centre, as represented in Figure 5b) and d). This reflects the true positioning of the vehicles during the experiments. In order to have a clear insight about the speed, noise and vehicle location during the collision experiments, in the next sections we provide a more detailed analysis of the noise during the collision experiments.

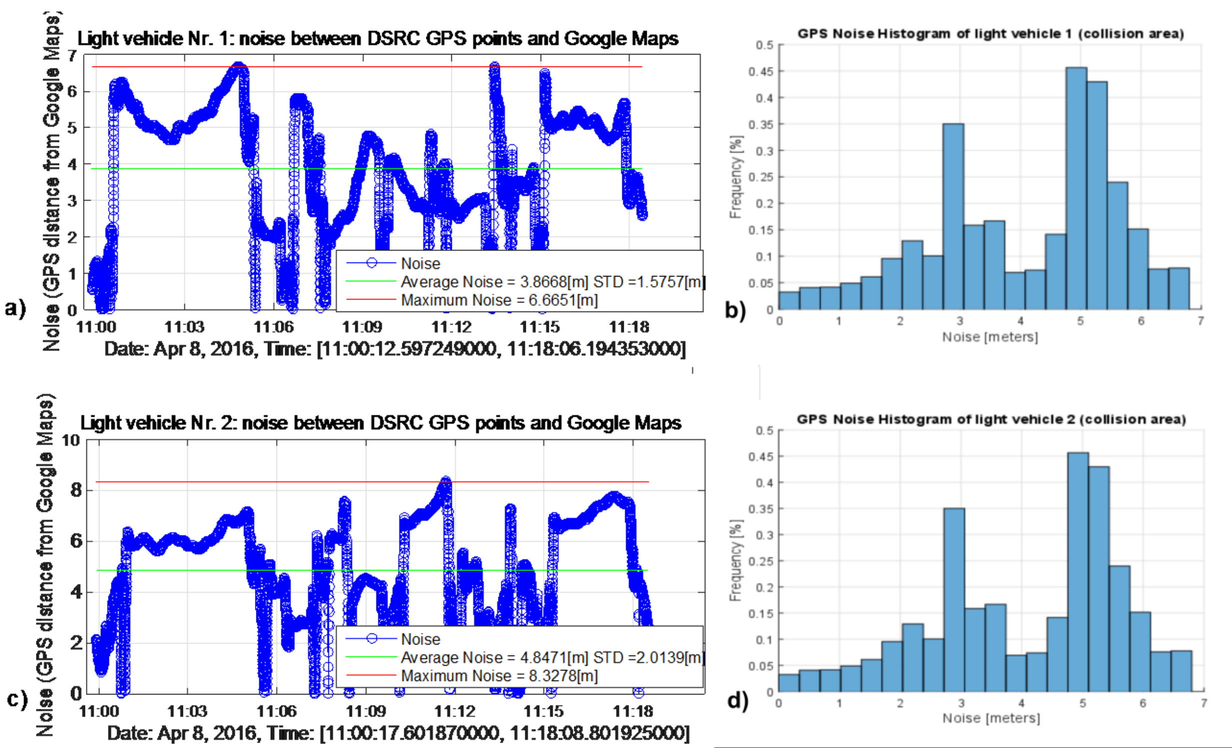


Figure 5 a) and c) indicate the evolution of noise for both vehicles while Figures b) and d) represent the noise histogram for the two light vehicles in the collision areas.

4. Collision alert investigation

4.1 Forward collision experiments

The scope of the first experimentation scenario included a forward collision demonstration in which both vehicles were travelling in the same lane at 40 to 50 km/h, one following the other. The leading vehicle braked abruptly causing the following vehicle to receive a Forward Collision Alert notification. In a real life situation, this alert is intended to allow the following driver to avoid the collision. The second experiment repeated the same setting but with vehicles in swapped positions. As both experiments had successful generation of collision alerts and had similar noise-speed behaviour, in the following we only provide our findings on the first experiment. Figure 6 presents a map of the trace and instant location of both vehicles based on the transmitted GPS location; the measured noise (distance from the road centre); and the speed profile for both vehicles. Low noise values are measured when the vehicles are travelling at higher speeds (40-50 km/h) (between 1-2 metres from GSM road centre) and follow the same evolution (as represented in Figure 6b), at time "11:06:20"). At lower speeds (<10 km/h), vehicle 1 presents higher noise levels; a possible explanation for this is that the vehicle pulled over to the kerb after the scenario ended. If this explanation is correct, this would indicate GPS tracking is accurately reflecting vehicle movements rather than presenting true "noise". The collision alert was generated at "11:06:27" which is indicated by a sudden deceleration in the speed profile of the light vehicle 2 (Figure 6b), followed by the same sudden deceleration of the vehicle 1 which was placed behind. It is important to note that these observations are representative only for the current study, and cannot be generalized to other vehicles that might have different noise/alerting behaviour.

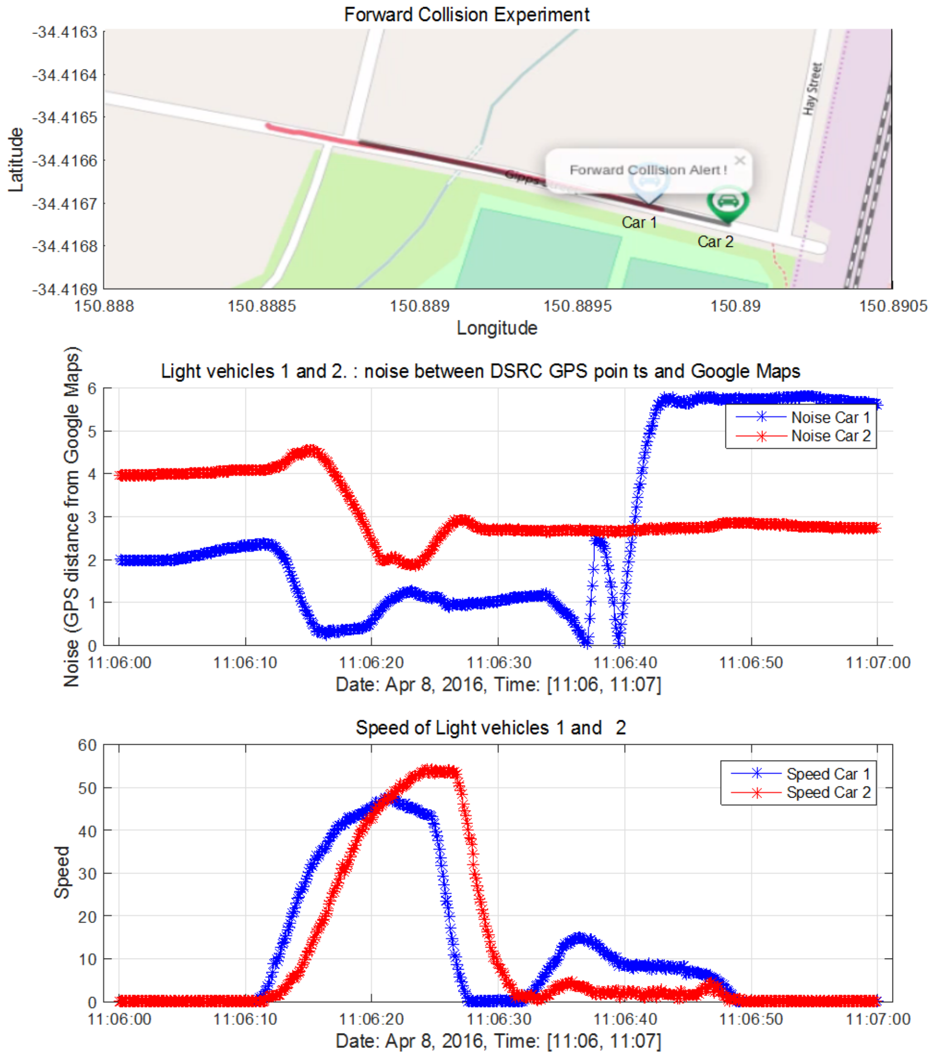


Figure 6 a) GPS location b) Noise c) Speed of both light vehicles during the forward collision test.

4.2 First T-intersection collision experiments

An important demonstration scenario for testing the advantages of using DSRC equipped light vehicles is around intersections, where visibility or sight distance may be restricted. This scenario is centred on a T-intersection with limited visibility. The main motivation behind this type of experiment is to detect when vehicles fail to yield. Receiving a collision alert in time from the on board DSRC system would help the drivers to reduce the risk of collision and improve their safety. The first T-intersection collision experiment failed to generate a "collision alert message" due to the execution and timing synchronisation of the collision not being precise enough (Figure 7a), while the second experiment concluded with a successful generation of the alert (Figure 7b).

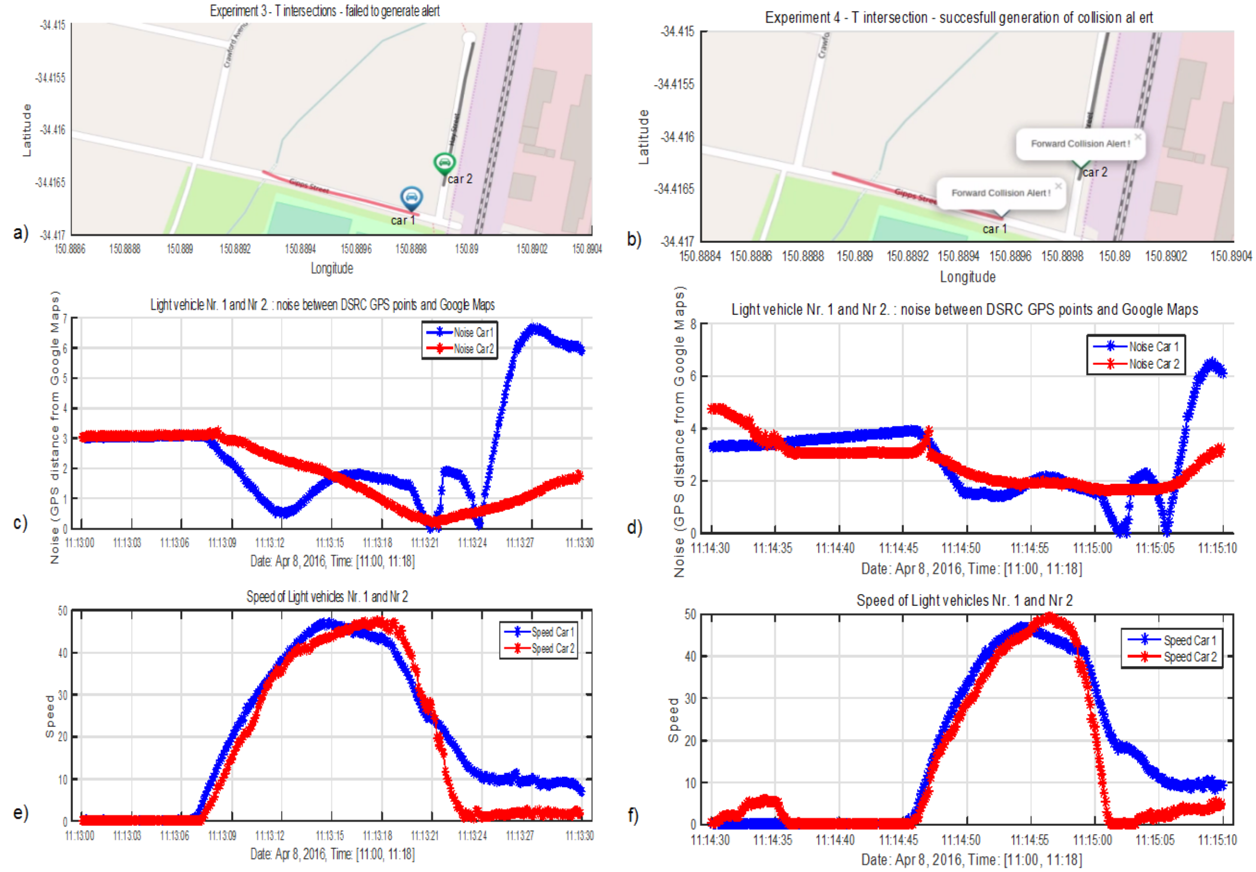


Figure 7 GPS location, noise and speed evolution during both T-intersection collision experiments with failed (a,c,e) and successful collision alert (b,d,f).

Figure 7 shows the mapping, positioning error (noise) and speed during the demonstration of both experiments: subfigures a), c), e) for failed alert and b), d), f) for successful collision alert. The positioning error recorded during the first collision experiment registered low levels of almost 0 metres (Figure 7c) at the moment of potential collision - around 11:13:17 AM), indicating that both vehicles were travelling close to the road centre (findings validated by video recording during the incident simulation). Accurate positioning was also recorded during the second collision experiment (below 2 metres at the moment of collision - 11:14:59 AM).

Analysing the speed of the vehicles in both experiments shows different braking behaviours. If during the first collision experiment the light vehicle 1 presented a longer deceleration time interval from the moment of receiving the collision alert (see Figure 7e),11:13:17 to 11:13:21), in the second collision experiment one would observe a shorter deceleration time-interval (from 11:14:59 to 11:15:01). While this initial observation regarding braking behaviour and success/failure of generating a collision alert is valid for the current study using the two light vehicles, further investigations and multiple demonstrations at a larger scale with different road topologies and various traffic conditions would need to be tested before validating the finding at a larger scale.

4.3 Signal Phase and Timing (SPaT) Equipped intersections experiment

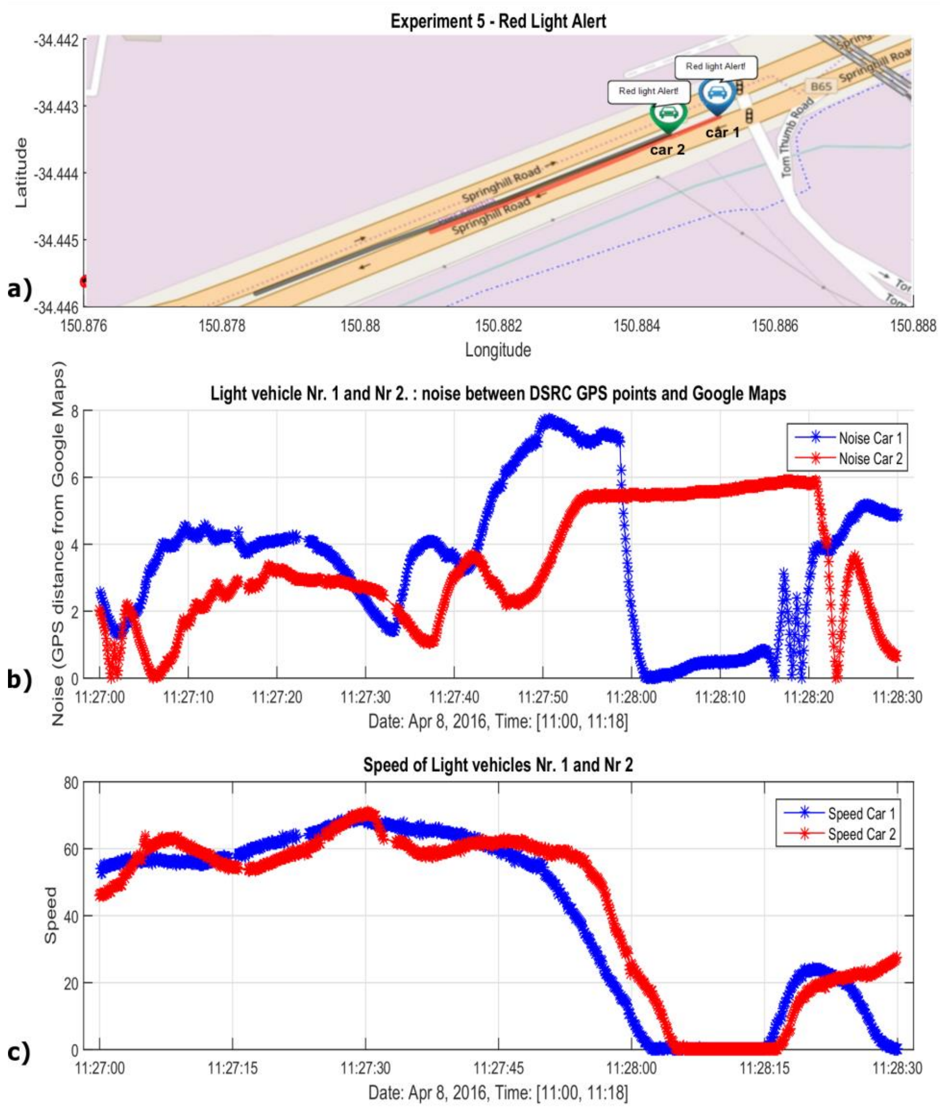


Figure 8 a) Positioning of vehicles before the signalized DSRC road-side unit b) noise and c) speed evolution before approaching the intersection and after.

The last experiment was a test of the reception of Signal Phase and Timing (SPaT) information and the generation of red light alerts when vehicles are approaching the 3 DSRC-equipped intersections. This is based on infrastructure to vehicle communication and each vehicle is independent of the other. Figure 8 a) shows the positioning of the vehicles while approaching the Tom Thumb Road intersection before stopping at the red signal and turning right. Both vehicles successfully received the SPaT information and generated a red light alert while approaching to turn right at the DSRC-equipped intersection. Figure 8b) shows the noise profiles of GPS from road centre for both vehicles which follow similar patterns before the vehicles arrived at the intersection. Although both vehicles were waiting in the same lane (the road has 4 lanes in this area), there is a slight drift to the right from the road centre which can be noticed for vehicle 1, as the noise reaches almost 8 metres from the road centre before entering the intersection. This finding is hard to explain as both vehicles were stationary in the lane closest to the road centre. This suggests that although the vehicles have been set up with the same initial configurations of the DSRC system, vehicle 2 might need further tests in order to detect if the problem is related to a drift in positioning of the GPS/GLONASS antenna belonging to this vehicle, or to other factors such as the DSRC physical installation, the accuracy of transmitted BSMs, the road geometry map used for noise calculation, etc. Otherwise, we believe this is solely a GPS positioning anomaly. This remaining question is worth further investigation as lane accuracy when approaching signalized intersections is very important in helping to determine what direction the vehicle is likely to turn and so which signal applies to that vehicle.

5. Conclusions

In this paper we presented the positioning accuracy of two light vehicles equipped with DSRC and investigated the incident analysis and detection through 5 scenario experiments. While overall noise levels remain in acceptable limits (averages below 5 metres) and for most of these, the "noise" represents actual movements of the vehicle from the centre line, a detailed analysis of positioning revealed circumstances where the noise drifted to a maximum of 8 metres from the road centre without explanation.

During the experiments, one non-signalised T-intersection experiment failed to generate a collision alert. To better understand the performance of collision alerts in DSRC-equipped vehicles, further analysis on speed, noise, generated alerts and GPS positioning could be conducted in order to help assess the potential road safety implications of such DSRC alert messaging.

The data derived for this study could also be used in studying the lane-switching behaviour of drivers, as well as studying the reaction of drivers to false alerts. Despite some issues with the GPS derived data and while lane accuracy is not currently possible on vehicles used in CITI, it is expected that lane movement analysis is possible. The recorded speed and acceleration of a vehicle is accurate enough to show immediate acceleration and deceleration of a vehicle. By correlating these reactions together with generated alerts, it should be possible to build a generic profile of "reaction to alerts" from the drivers. As well, it is believed the distance between the vehicles, noise, elevation, as well as the speed profiles of the vehicles at the moment of a collision can provide meaningful insights on when and why some safety alerts have not be generated.

Limitations

Due to the small number of incidents being analysed, we cannot apply a more complex or real-time statistical interpretation of incident detection during the light vehicle analysis. Compared to the heavy vehicles which operate daily and generate millions of BSMs, the light vehicles which are currently DSRC-equipped are not involved in as many trips. Additionally, to protect the privacy of staff who drive these vehicles, we restricted the analysis to specific trips. Ultimately, we believe that more data needs to be analysed in order to understand whether some changes in GPS noise as transmitted from BSMs indicate a change in drivers' reaction to collision alerts or they may indicate sudden global changes in the GPS positioning (for example due to changes in accessible satellites).

Perspectives

At the moment of the tests, vehicles were not equipped with accelerometers. Accelerometers are a primary measurement of acceleration (or force). Therefore, if acceleration was found to be an important measure to assess reactions to alerts (or for any other research purpose), more analysis is required. In particular, a comparison of data from accelerometers and BSM-based information should be made to fully assess whether BSMs are sufficient for studying drivers' behaviour when using connected vehicles. This work is an initial step in the positioning accuracy and incident alert investigation for improving road safety. CITI is an ongoing project, with aims to further investigate the potential of DSRC to improve road safety. This includes expanding DSRC use at signalised intersections and equipping public passenger buses with

DSRC. More light vehicles are currently being recruited for installation with CITS and accelerometers, and some vehicles may have video recording features for validation of tests.

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