

**CONNECTED VEHICLE SAFETY APPLICATIONS
USING V2X UNDER CONSIDERATION OF BICYCLES,
PEDESTRIANS AND PERSONS WITH SPECIAL NEEDS
FINAL PROJECT REPORT**

by

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16. Abstract In the context of connected vehicles, the focus of safety applications has mainly been on accident avoidance of motor vehicles, and little attention has been given to the safety of other traffic participants like bicycles, wheelchair operators, or visually impaired persons. This research first presents a bicycle safety application for connected vehicles. The safety application aims to reduce the so-called right hook conflict, a common accident scenario where a right-turning vehicle causes a crash with an adjacent bicycle. The information exchanged during normal beacon messages of vehicles is used by the application to alert drivers of potential collisions with bicycles, without introducing addition message overhead or deviating from current standards. The proposed safety application was implemented using commercial equipment, installed in the vehicle and bicycle, and the effectiveness was evaluated based on real-world field experiments. The same was considered for the other aforementioned traffic participants.			
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Executive Summary

In the context of connected vehicles, the focus of safety applications has mainly been on accident avoidance of motor vehicles, and little attention has been given to the safety of other traffic participants like bicycles, wheelchair operators, or visually impaired persons. This research first presents a bicycle safety application for connected vehicles. The safety application aims to reduce the so-called right hook conflict, a common accident scenario where a right-turning vehicle causes a crash with an adjacent bicycle. The information exchanged during normal beacon messages of vehicles is used by the application to alert drivers of potential collisions with bicycles, without introducing additional message overhead or deviating from current standards.

The safety applications use Basic Safety Messages of vehicle-to-vehicle and vehicle-to-pedestrian communication. The BSMs provided information like speed and geographic locations, which was then used to alert drivers of possible right hook crash scenarios. Different safety applications were introduced with different algorithms for diverse traffic user scenarios. In general, the applications alert participants when the minimum stopping sight distance of the bicycle or other user is greater than or equal to the distance between them. However, since this distance is calculated from the GPS coordinates broadcast in the BSMs, it is affected by GPS inaccuracies. Field tests showed that in the absence of large buildings effective right hook alerts for bicyclists could be issued. Only when the safety application operated in very narrow confined areas was the GPS inaccuracy large enough to greatly reduce its effectiveness. The research also considered the special issues related to diverse traffic participants like wheelchair users, and visually impaired persons. The fundamental issues related to the specific mobility models, which are very different than those of motorized vehicles like cars or trucks, were addressed.

CHAPTER 1 INTRODUCTION

One of the essential goals of Intelligent Transportation Systems (ITS) is to increase safety and reduce accidents. Lately, in the context of connected vehicles, Safety Applications (SA) were introduced that rely on communication between vehicles and with the infrastructure, such as traffic lights in an intersection. These safety applications are expected to reduce road accidents by up to 82% and eventually will save thousands of lives in the United States [1]. In the past SA were mainly discussed in the context of vehicle-to-vehicle (V2V) and vehicle-to-infrastructure (V2I). However, little consideration has been given to bicycles and their special needs. A particular common source of bicycle accidents is the so-called Right Hook, where a turning vehicle crashes with a bicycle to its right, while performing the turn. The study in [2] showed that vehicles were almost unaware of the adjacent bicyclists when performing the right turn.

This research first introduces a bicycle safety application that uses the same basic communication capabilities as vehicles, thus allowing vehicle-to-bicycle communication. We will simply assume that bicycles are vehicles and are therefore capable of V2V and V2I communication. Next, we will expand our consideration to other traffic participants.

The main two technologies that facilitate communications are Dedicated Short Range Communication (DSRC) [1], and cellular vehicle-to-everything (C-V2X), which has been driven by the Third Generation Partnership Project (3GPP). Whereas in general cellular networks, communication includes base stations; C-V2X communication can be directly between vehicles in a Device-to-Device (D2D) fashion [3]. In this work, we will focus on DSRC; however, the general issues discussed are expected to have similar implication is C-V2X as well.

CHAPTER 2 BACKGROUND

In connected vehicles, each vehicle is assumed to have an On-Board Unit (OBU), and the infrastructure is equipped with Roadside Units (RSU). The communicating nodes in V2V and V2I, also referred to as V2X, are said to implement a Vehicular Ad Hoc Network (VANET). The concept of VANET is similar to Mobile Ad Hoc Networks (MANET), however, VANET assumes short message exchanges in a fast-changing topology.

2.1 DSRC

The Federal Communications Commission (FCC) together with the US Department of Transportation (USDOT) assigned 75MHz of dedicated bandwidth at 5.9GHz to be used for DSRC communication in 1999 [4]. Within this spectrum of 5.850- 5.925 GHz, six service channels and one control channel are defined. A 10MHz channel, Channel CH172, is assigned to safety applications. In line with the standard, CH172 will also be used in the proposed bicycle safety application.

2.2 Basic Safety Message

The most important message related to safety applications is the Basic Safety Message (BSM). It is a beacon message broadcast by each vehicle every 100ms [1]. According to standard SAE J2735, the BSM has a mandatory part 1, and an optional part 2.

The mandatory part consists of fourteen fields as described in [5]: *MessageID* is a one-byte field used to indicate the message type, so the receiver knows how to interpret the remaining bytes. *MsgCount* is a one-byte field, which is a sequence number of successive BSMs sent by a specific vehicle. *TemporaryID* is a four-byte field, which is a temporary id of a sender. *DSecond* is a two-byte field that encodes the current time. *Latitude* and *Longitude* are four bytes each and hold the geographic latitude and longitude. *Elevation* is a two-byte field used to

indicate the geographic position above or below sea level. *PositionalAccuracy* is a four-byte field used to indicate the position error along different axis. *TransmissionAndSpeed* is a two-byte field indicating the transmission's gear and the speed in meters per second. *Heading* is a two-byte field showing the current heading of the vehicle's motion. *SteeringwheelAngle* is a one-byte field indicating the angle of the steering wheel. *AccelerationSet4Way* is a four-byte field providing longitudinal, lateral, and vertical acceleration, in addition to the yaw rate. *BrakeSystemStatus* is a two-byte field used to indicate information about the current brake system status, such as brake usage, or anti-lock brake status. Lastly, *VehicleSize* is a three-byte field used to provide the vehicle length and width. The optional BSM part 2 is used to provide additional information for specific applications. The most significant BSM fields used in this research are the GPS position fields, the speed and steering wheel angle. Other fields can be used to filter out vehicles not relevant to the safety application, e.g., using Heading to filter out vehicles in opposite direction on a divided multi-lane highway.

2.3 DSRC Safety Applications

In a report by the USDOT and the Crash Avoidance Metrics Partnership–Vehicle Safety Communications 2 (CAMP-VSC2) Consortium [6] several crash scenarios and safety applications were identified. The goal of the safety applications is accident prevention and hazard avoidance. The safety applications use information from the periodically exchanged BSMs, such as GPS coordinates or vehicle status information to issue alerts to drivers in case of hazards. Safety applications will be described from the viewpoint of a Host Vehicle (HV), which receives beacon messages from Remote Vehicles (RV). When specific event information received in the BSM from an RV suggests a critical situation, the driver of the HV is issued an alert.

The report, [6], identified the following seven safety applications. Emergency Electronic Brake Lights (EEBL) refers to the situation where a vehicle is subjected to a potential rear-end collision. When a vehicle brakes hard, the so-called hard-braking event is broadcasted in its BSMs. When an HV receives such event from the RV's BSM, it can issue an alert to the driver. This is particularly helpful when the driver's line of sight to the initiating RV is obstructed. Forward Collision Warning (FCW) is similar, in that it warns the driver of the HV of a potential rear-end-collision with a vehicle in the same lane and direction of travel. Blind Spot Warning+Lane Change Warning (BSW+LCW) addresses situations related to lane changes, when vehicles are hidden in the blind spot. Do Not Pass Warning (DNPW) warns the driver of the HV during a passing maneuver attempt that it is unsafe, due to an oncoming vehicle in the passing zone. Intersection Movement Assist (IMA) warns the driver of the HV that it is not safe to enter an intersection due to a potential crash with an RV in an intersection. Lastly, Control Loss Warning (CLW) allows to warn a driver in response to a *control loss event* broadcast from an RV that has lost control.

In the aforementioned safety applications bicycles play only a peripheral, limited role. For example, bicycles often drive at lower speeds, they may occupy limited space in the right lane, are often overlooked by the drivers of vehicles, and the riders are much more vulnerable and susceptible to injuries in an accident, e.g., a right hook collision.

2.4 Safety Applications Reliability

In the general field of dependability, reliability $R(t)$ is the probability that the system functions up to specifications during the entire time interval $[0, t]$ [7]. In the context of safety applications, this means that at least one BSM indicating an event generated from the RV is received by the HV, to be able to generate an alert before it is too late to react.

Consider Figure 1, where the RV broadcasts BSMs every 100ms indicating an event starting at t_{event} . The HV needs to receive at least one BSM to warn the driver timely, before t_{react} . The safety application fails only if no BSM is received by the HV in time. This is the case when all x BSMs, i.e., BSM₁, ..., BSM_x, were lost. Receiving a BSM at or after t_{react} will not help, as the driver will not have enough time to react to the event.

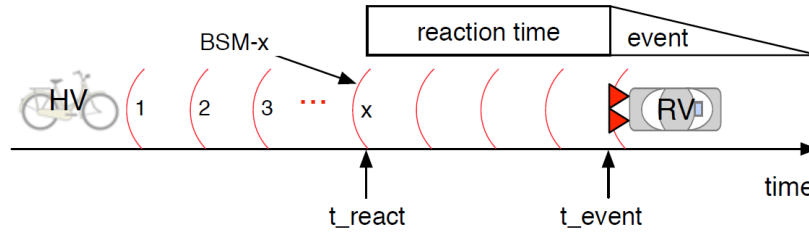


Figure 1 BSM Propagation and Timing

Let $Q(t) = 1 - R(t)$ be the safety application unreliability. Under the assumption that BSM packet delivery is independent of that of another BSM, the probability that all x messages are lost is:

$$Q(t) = \prod_{i=1}^x Q_i(t_i) \tag{1}$$

where $Q_i(t_i)$ is the probability that BSM_{*i*} was not received by the HV, and t_i is the time it should have been received. In [8] Q_i was computed based on packet error rates and packet delivery ratio.

CHAPTER 3 BICYCLE SAFETY APPLICATION FOR NON-MALICIOUS ENVIRONMENTS

In the following discussion we assume a non-malicious environment. Thus, we do not consider malicious interference or tampering with the application, which will be addressed further down in this report.

A very common source of bicycle accidents is the aforementioned Right Hook [2]. In this scenario a vehicle turns right into an adjacent bicyclist. Consider Figure 2, which shows the scenario leading to the right hook situation depicted in Figure 3. The bicycle is traveling in the right lane, e.g., a bicycle lane. Assume that the truck in the left lane has the intention of turning right. Several areas are of interest. The right hook conflict zone, RHC Zone, is the area where potential right hook accidents may occur. To avoid such accident, a driver needs to be alerted to the potential accident before it is too late to react. Let T_{react} denote a reaction time. The reaction time of a bicyclist is approximately 1 second [9]; however, the combined perception and brake reaction time is 2.5 seconds [10]. The reaction time of a truck driver, described as the driver's time to initial steering, which is the duration of time until the driver starts steering to avoid an accident, is about 1.7 seconds. This was based on field tests and simulation results in [11]. The bicycle safety application (BSA) needs to alert drivers about a potential accident, based on BSM information acquired in the decision area, before it is too late to react. Thus, the alert has to be given before t_{react} .

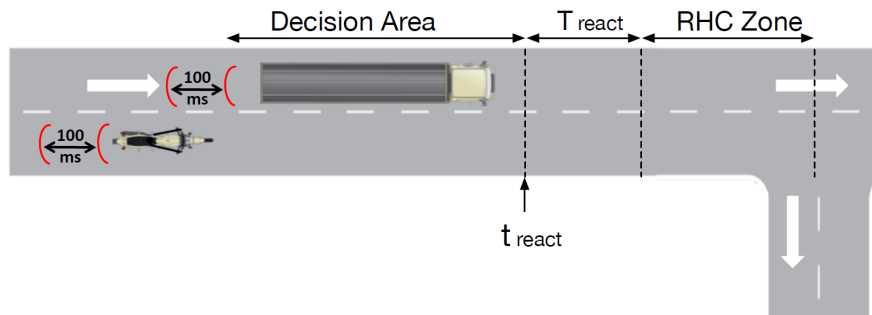


Figure 2 Scenario leading up to potential Right Hook Conflict

In the RHC Zone timing is critical, as distances between the bicycle and the truck may be short. In fact, the bicycle and truck may be next to each other, as shown in Figure 3. This will leave little time for both drivers to react.

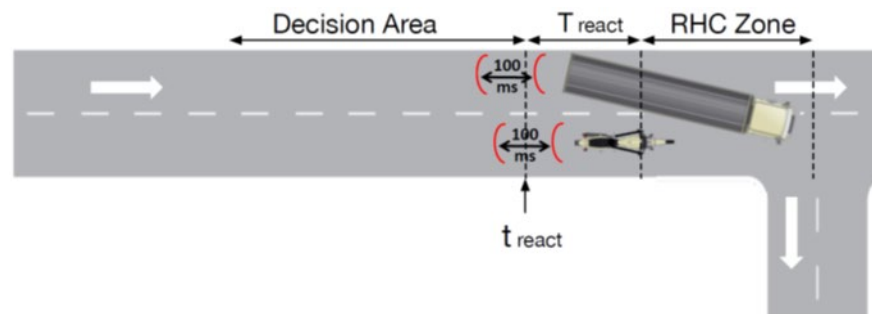


Figure 3 Right Hook Conflict

In the discussion of the safety applications in Subsection 2.3, it was clear which vehicle was the HV and which was the RV. For example, in the EEBL safety application it was the vehicle following the hard-braking vehicle that needed to be alerted, in order to avoid a potential rear-end collision with the hard-braking vehicle. In the context of the BSA, both the cyclist and the truck driver have the potential to react in order to avoid an accident. We will describe the BSA from the viewpoint of the truck for right-hand driving roads. For left-hand driving roads the logic has to be reversed due to the mirrored geometry. Since vehicle behavior in the RHC zone, and especially time is very critical, tracking a right turn of the truck based on GPS information alone may be too slow. It takes multiple BSM's to be able to detect the turn based on the

differences between consecutive BSMs to detect a right turn trajectory. Furthermore, the accuracy of GPS coordinates depends heavily on the number of satellites locked with the OBU. Rather than considering differences in GPS coordinates, it may be better to use the steering wheel angle to detect the turn. This information can be provided from the vehicle via its CAN bus, to be used in the BSM's SteeringwheelAngle field.

3.1 BSA Detection Mechanism

The positions of participating nodes in VANET are determined by GPS coordinates, broadcast in the BSMs. The distance between two vehicles is therefore determined by the relative distance of two sets of coordinates. Let $Lat(B)$, $Long(B)$, $Lat(T)$, and $Long(T)$ be the geographical coordinates for the bicycle and truck respectively. The differences in longitudes and latitude between the two are denoted by $\Delta_{Long(TB)}$ and $\Delta_{Lat(TB)}$. Multiple methods for determining distances between coordinates have been used, e.g., Law of Cosine, the Polar Coordinate Flat-Earth formula, and the haversine formula. Since the bicycle (RV) and the truck (HV) may be very close, a method capable of calculating accurately even for small distances is desirable. An accuracy comparison of the aforementioned methods is shown in Figure 4. For given angular differences from the GPS data, the corresponding distances in meters are calculated. As can be seen, haversine has the most accurate results, especially for short distances. The computational error in very small angular differences was also described in [12], where the authors suggested to use haversine for such situations. The differences are in the order of decimeters in the worst case. It is this accuracy that was experienced in the experiments described in Section 3.4 below.

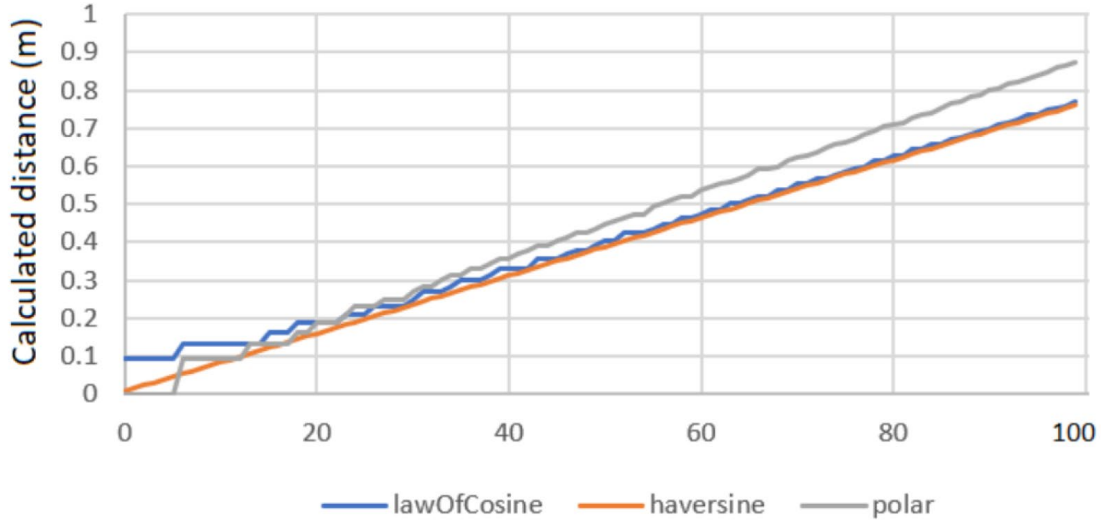


Figure 4 Calculated results for different methods. The x-axis is the distance in multiples of degree 0.000001, which corresponds to 1.11cm.

Since the calculations are using polar coordinates and the coordinate points from the OBUs are in geographical degree form, one needs to convert the coordinates from degree to radian.

The haversine formula in Equation 2 [13] is used to calculate the distance d_{TB} between the truck and the bicycle as:

$$d_{TB} = 2r_{earth} \sin^{-1} \left\{ \sin^2 \left(\frac{\Delta_{Long}(TB)}{2} \right) + \cos(Lat(B)) \cos(Lat(T)) \sin^2 \left(\frac{\Delta_{Lat}(TB)}{2} \right) \right\}^{1/2} \quad (2)$$

where r_{earth} is the earth's radius in meters. To find the bicycle's stopping distance S [in meters] under consideration of the combined perception and brake reaction time, the Minimum Stopping Sight Distance Equation from [14] is used:

$$S = \left(\frac{V^2}{254(f \pm G)} + \frac{V}{1.4} \right) \quad (3)$$

where V is the velocity [in km/h], f is the coefficient of friction (which is 0.32 for dry condition [14]), 1.4 is the distance of the bicyclist's eye above the pavement, and G is the grade.

Next, distance d_{TB} from Equation 2 is compared with stopping distance S from Equation 11. Only if $S < d_{TB}$ is not met will the truck driver be alerted. Note: in our implementation we increased the S value by 10% to be on the conservative side.

3.2 Bicycle Safety Application Algorithm for Truck

The algorithm of the BSA, as implemented in the truck's OBU, is shown in Figure 5. When a BSM is received from a bicycle that has not been seen before, it is registered. Then a time stamp is recorded. To reduce the number of false alerts to the truck driver, a mechanism is needed to enable alerts within the BSA only when it is relevant. In our implementation, we assume the truck's blinker has to be engaged. At this time, the truck starts including a right-blinker-flag indicating the intention to turn in its BSM, e.g., in its optional BSM Part 2. This can be used by the bicycle to start its BSA. Next, the bicycle's coordinates and speed are extracted from the BSM to calculate the distance between the bicycle and the truck, as well as the bicycle's Minimum Stopping Sight Distance S . If $S < d_{TB}$ it is safe to the truck to turn. However, if $S \geq d_{TB}$ the truck driver needs to be alerted of a possible collision with the bicycle.

A less effective alternative to using the blinker as a means to indicate that the truck is turning, could be the steering wheel angle. This should be available in the truck and it is a BSM field. However, timing is much more critical in this option, as it implies that the turn is already in progress. Whether it is useful to include both, blinker and the steering wheel angle, is not the scope of this project.

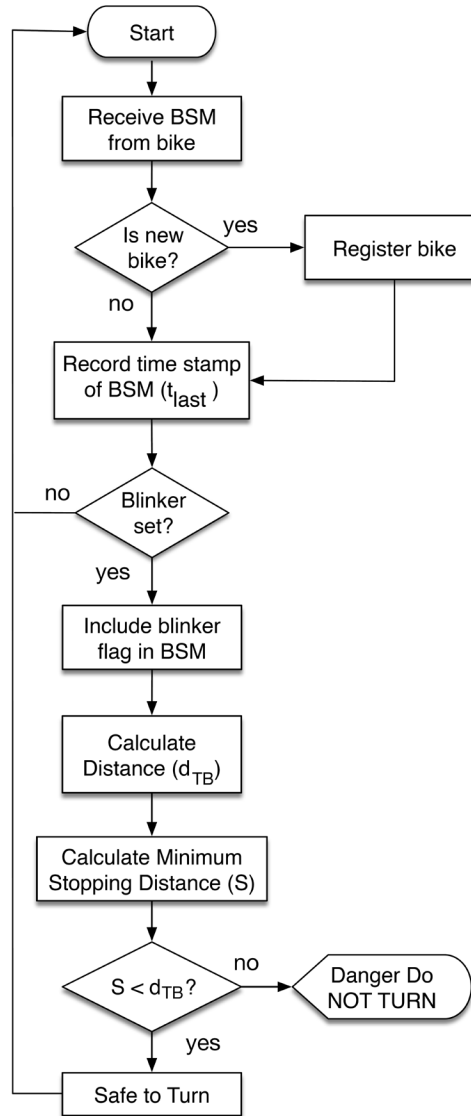


Figure 5 BSA Algorithm executed in truck's OBU

The algorithm in Figure 5 registers bicycles, but there is no explicit mechanism to unregister them. To avoid keeping track of bicycles that are out of range, we execute a periodic cleanup thread. Specifically, the recorded time stamp T_{last} of each registered bicycle is compared to the current time. If the values differ by more than some threshold T_{max} , the bicycle is considered no more to be relevant, and it is unregistered. In our application T_{max} was set to 10 seconds, which for consecutive BSM omissions would account for 100 missed BSMs.

3.3 BSA Algorithm for Bicycle

The BSA algorithm executing on the OBU of the bicycle is simpler. It is engaged when a BSM with a right-blinker-flag set is received. Now, just as in the truck's BSA, d_{TB} and S are computed and an alert is issued if $S \geq d_{TB}$.

3.4 Field Experiments and Results

3.4.1 A note on experiments and assumptions about data presented:

The results presented here were not based on simulations but on real field tests using off-the-shelf equipment. When using a simulator, it is straight forward to simulate a large number of scenarios. When conducting real field tests, the efforts associated with every single test for a scenario are rather high. A typical test requires personnel and equipment. In some cases, this included a vehicle with a driver and an extra person to operate the vehicle's OBU, in addition to a bicycle driver or another equipped vehicle, and a person to control a jammer acting as an attacker. The setup time for a single iteration of an experiment could take hours. Moreover, experiments were often affected by delays due to weather conditions, often requiring postponement by days and weeks. Asking volunteers to help repeatedly during all this time was a real test of friendship. This is very different from setting the number of experiments using a variable in a simulator. As a result, the number of scenarios conducted in each experiment was in the order of tens rather than hundreds. Whereas often metrics like average, medium, or standard deviation are of interest, we were looking for worst-case or best-case scenarios. In many cases however the results were simply "typical", meaning cases differed, but no consistent pattern could be extracted. When this occurred the data from representative cases were used. In other cases, we could conclude outcomes with only few test scenarios based on similar observations during years of extensive field testing. Thus, given the amount of effort, only a small number of

field tests was conducted. For example, certain results were coherent with the outcomes from similar experiments conducted for other research projects.

3.4.2 Experiment setup and results:

The BSA was implemented using an ARADA LocoMate Classic OBU for the vehicle and an ARADA LocoMate ME, which is a battery powered small OBU, mounted on the bicycle. Experiments were conducted in open space and in close proximity, and in-between buildings of the university campus. Both OBUs used the standard transmission rate of 10 BSMs per second and a transmission power of 23 dBm, using Safety Channel CH172. A summary of the field test parameters is given in Table 1.

Table 1 Field Experiment Configuration Parameters for Bicycles

Truck OBU Model	Arada Systems LocoMate Classic
Bicycle OBU Model	Arada Systems LocoMate Mobile ME
Test range	Open space road, and building block
Speed open space	Varying between 1-6 m/s
Speed building block	Approximately 3 m/s fixed
BSM generation	10 BSM/s
Channel	Safety Channel 172
Transmitter power	23 dBm
Data rate	3Mbps

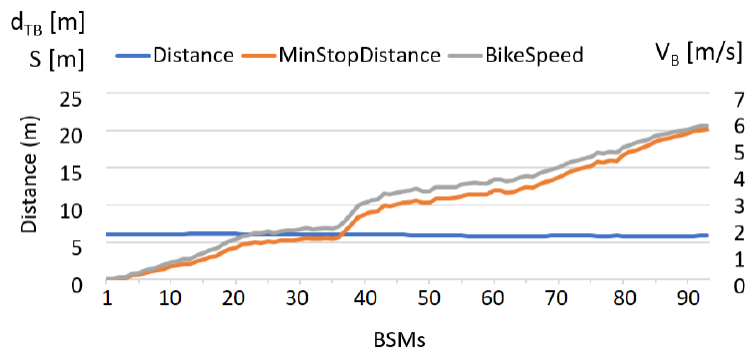


Figure 6 Experiment with 4m fixed distance between vehicle and bicycle

Figure 6 shows the results of a typical experiment conducted in open space. The GPS antennas of the vehicle and bicycle were spaced at a distance of 4 meters, i.e., the vehicle and the

bicycle were driving next to each other at an exact distance of 4m. The plots shown in the figure span over a time period of about 9 seconds, during which over ninety BSMs were received by each OBU. The blue plot shows the calculated distance between both antennas, d_{TB} , using Equation 2.

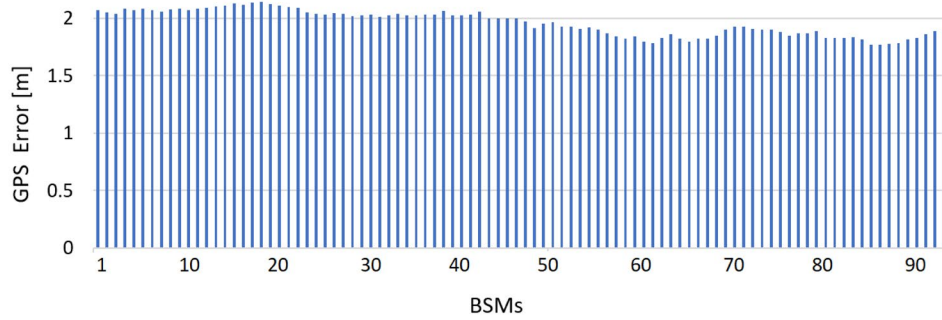


Figure 7 Error due to GPS inaccuracies

As can be seen, the calculated distances are slightly larger than the actual distance of 4m, as GPS inaccuracies of up to 2m were observed. The exact distance errors produced due to GPS inaccuracy can be seen in Figure 7 for each BSM in Figure 6. This error was calculated as d_{TB} minus the actual distance, which was precisely know during the experiment.

As the vehicle and bicycle increased their speeds (grey plot) from 0 to 6 m/s, the minimum stopping distance S (orange plot) also increased. The driver alert is issued when $S \geq d_{TB}$, which occurred starting with the BSM₃₇ in the figure.

Whereas the GSP inaccuracies of the field test described above was rather stable around 2m, other field tests showed much better accuracy. Figure 8 is such an example, where mostly sub-meter accuracy was observed when the vehicle and bicycle were stationary.

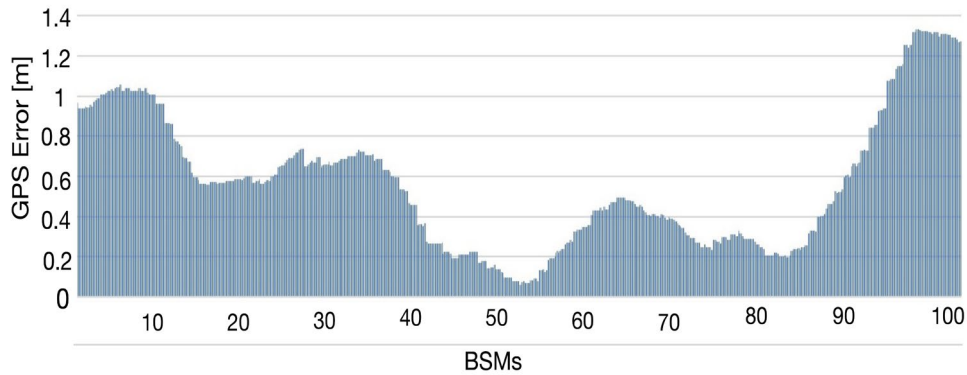


Figure 8 Error due to GPS inaccuracies, stationary test

To test the BSA in extreme situations, a test was conducted on the University of Idaho campus location shown in Figure 9. As in the previous experiments the distance between the OBU antennas was fixed at 4m. The accuracy of d_{TB} from the starting point all around the circular path indicated is given in Figure 10. For the first 4s of the southbound test area, i.e., BSM₁ through BSM₄₀ the accuracy was in the sub-meter range. However, once the GPS antennas entered the constricted area between buildings, before and after turning west into the narrow area between buildings, the accuracy was greatly reduced. Even after turning north, on S Line St., errors within 5m were achieved only starting with BSM₅₂₅. We attributed this behavior, experienced in many test runs, to the time required by the OBUs to acquire more satellites once space opened up, e.g., going east-bound on W 6th Street, back to the starting point.

In most field tests, positive errors were observed. Only in rare cases was the error negative, which, given our short antenna distance of 4m, comes to no surprise. The most significant impact of the error is that it affects d_{TB} , and thus the alert criteria, i.e., when $S \geq d_{TB}$. The errors have no impact on S, which is based on parameters such as bicycle speed and reaction time. This means that in areas with low GPS accuracy, e.g., the narrow corridor in Figure 9, the probability of *false negatives* is higher. A false negative implies that an alert is not issued, when in fact it should have been. High false negatives should be seen in the context of the physical

space where they occur. One may argue that a bicyclist riding in a narrow constricted area is assumed to be more aware of potential right hook. False positives may be less of an issue, as negative errors were only experienced in rare cases, and then the errors were very small, much less than the 4m antenna distance.



Figure 9 University of Idaho campus test area

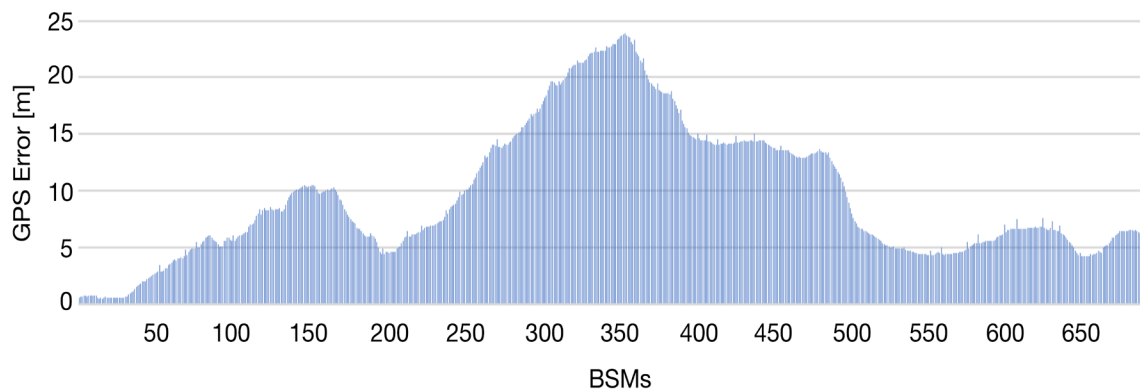


Figure 10 Error due to GPS inaccuracies, block drive

CHAPTER 4 CONSIDERING MALICIOUS ENVIRONMENTS

In this section we consider that the safety application is subjected to a malicious act. Specifically, we consider the case of denial of service, where vehicles are prevented from sending or receiving safety messages. Such scenarios can be demonstrated using jamming attacks.

4.1 SA Prediction Algorithm

This bicycle safety application uses a prediction algorithm that is capable of mitigating against jamming attacks. The description to follow will be from the viewpoint of the truck.

When BSMs from a bicycle, known to the truck from previous BSMs, are not received in a timely manner, the position of the bicycle needs to be estimated. This projection will be based on Dead Reckoning [16], which calculates the estimated position of the bicycle based on the last known position. This requires information like the speed and the last recorded coordinates, available from the last received BSM, and computed last recorded bearing. The time elapsed since the last received BSM and the bearing are computed locally.

Recall that $Lat(B)$, $Long(B)$ and $Lat(T)$, $Long(T)$ denote the geographical coordinates for the bicycle and truck respectively, and $\Delta_{Long(T B)}$ $\Delta_{Lat(T B)}$ or $\Delta_{Long(BT)}$ $\Delta_{Lat(BT)}$ their respective differences in longitude and latitude. When it is necessary to indicate whether coordinates are in degree or radian, a d or r will be added in parenthesis, e.g., $Lat(B[d])$ indicates the latitude of a bicycle in degree, and $Lat(T[r])$ latitude of a truck in radian.

Since the calculations are using polar equations and the coordinate points from the OBUs are in geographical degree form, one needs to convert from degree to radian to get the polar coordinates. The Bearing (Azimuth) [17] starts from north clockwise 0° 360° . It is denoted by β_T

$B[d]$ and is determined using the truck and bike coordinates as shown in Equation 4, which was derived from [18]

$$\beta_{TB[d]} = \tan^{-1} \left\{ \frac{\sin(\Delta_{Long}(TB)) \cos(Lat(B))}{\cos(Lat(T)) \sin(Lat(B)) - \gamma} \right\} \quad (4)$$

with $\gamma = \sin(Lat(T)) \cos(Lat(B)) \cos(\Delta_{Long}(TB))$

Next, the haversine Formula of [19], restated from Equation 2 for readability, is used to calculate the distance, d_{TB} , between the truck and the bike:

$$d_{TB} = 2r_{earth} \sin^{-1} \left\{ \sin^2 \left(\frac{\Delta_{Long}(TB)}{2} \right) + \cos(Lat(B)) \cos(Lat(T)) \sin^2 \left(\frac{\Delta_{Lat}(TB)}{2} \right) \right\}^{1/2} \quad (5)$$

where r_{earth} is the earth's radius in meters. Let $C_T(t)$ be the clock value of the truck at real time t [in ms]. Furthermore, let $C_T(t_{rec(B)})$ be the recorded time of the truck's clock when the last BSM of the bike was received. Based on the bicycle's velocity v_B from its last BSM, the truck can estimate the bike's distance, d'_B , traveled in any direction since the last BSM was recorded. If the speed of the truck v_T is less than or equal to the average approaching right-turn speed, i.e., there is no deceleration, d'_B is calculated using:

$$d'_B = v_B [C_T(t) - C_T(t_{rec(B)})] \quad (6)$$

One needs to find the time the truck will take to reach a speed less than or equal to that of an average truck about to make a right turn. Based on [20] v_{RT} was determined as 10 m/s. We use the maximum truck deceleration, denoted by a_T^{-1} , which is $0.8m/s^2$ [21]. The difference in speed between the truck and the average truck's speed on approaching to right-turn, Δv_T , is $\Delta v_T = v_T - v_{RT}$.

How much will the bicycle have moved by the time the truck will have reached its right-turn-approaching speed? The truck's estimated time to reach this turning speed is $T_{ToReachTurnSpeed}$

$= \Delta v_T / a_T^{-1}$. The time the bicycles is moving unobserved by the truck (due to jamming) is the time that has passed since the truck received the bicycle's last BSM, $C_T(t_{rec(B)})$, plus

$T_{ToReachTurnSpeed}$. Thus, the bicycle will move for a duration of:

$$T_{BikeMoving} = [C_T(t) - C_T(t_{rec(B)})] + \frac{\Delta v_T}{a_T^{-1}} \quad (7)$$

and its projected distance covered is

$$d'_B = v_B T_{BikeMoving} \quad (8)$$

To find the bike's angular distance ratio, α_B , under consideration of the earth curvature, d'_B is divided by the earth radius [in km], $\alpha_B = \frac{d'_B}{6371}$. The estimated latitude and longitude of the bicycle are:

$$EstLat(B[r]) = \sin^{-1} \left\{ \sin(Lat(T)) \cos(\alpha_B) + \cos(Lat(T)) \sin(\alpha_B) \cos(\beta_{TB}) \right\} \quad (9)$$

$$EstLong(B[r]) = Long(T) \tan^{-1} \left\{ \frac{\sin(\beta_{TB}) \sin(\alpha_B) \cos(Lat(T))}{\cos(\alpha_B) - \sin(Lat(T)) \sin(Lat(B))} \right\} \quad (10)$$

The latitude and longitude of the truck are calculated analogously, except its time base is $T_{ToReachTurnSpeed}$ rather than $T_{BikeMoving}$. The Minimum Stopping Sight Distance from [22] is used to find the bike's stopping distance as:

$$S = \frac{V^2}{254(f \pm G)} + \frac{V}{1.4} \quad (11)$$

where V is its velocity [in km/h], f is the coefficient of friction (which is 0.32 for dry condition), 1.4 is the distance of the bicyclist's eye above the pavement, and G is the grade. Note: since a flat road is assumed, G can be neglected. Now, d_{TB} from Equation 2 is compared with S from Equation 11. A driver alert should be issued if $S \geq d_{TB}$.

4.2 SA Algorithm for Malicious Environments

This bicycle safety application implements Dead Reckoning and is shown in Figure 11. The shaded area to the right shows the algorithm's behavior if a BSM is received. It is similar to the benign-case algorithm described above. If a BSM from a new bicycle is received, this bike is registered. Next the OBU's time of BSM reception, t_{last} , is recorded. This time serves as a reference for bicycle BSM omissions, e.g., due to jamming or shadowing. It is used for dead reckoning when messages are not received. If the truck's blinker is set, indicating the intention to turn right, a blinker flag is included in its BSMs, which is used by the bicycle safety application. Next the distance between the two vehicles, d_{TB} , and the minimum stopping distance S are calculated. If S is less than d_{TB} , then it is safe to turn. Otherwise an alert needs to be issued.

The case when no BSM was received is shown in the left area of Figure 11. An omission is detected if no BSM is received within the BSM inter-arrival time of approximately 100ms. Omission counter b_{missed} keeps track of the number of consecutively missed BSMs. A predetermined b_{max} specifies the threshold of omissions before the bicycle should be unregistered. This avoids tracking bicycles that are no longer relevant, e.g., they are out of range or the units have been shut down. When a BSM is received from a bicycle, the counter b_{missed} is reset.

In [15] it was argued that BSM's older than 500ms, 5 BSM intervals, should be considered outdated. We assume that if the number of missed BSM's has not reached this threshold σ , i.e., if $b_{missed} < \sigma = 5$, then the omissions do not pose immediate threats. Otherwise, we assume a DoS is ongoing. Given the knowledge of the bicycle's last position and velocity, as well as the time that has expired since then, the bicycle's coordinates can be estimated as shown in Subsection IV-A. This initiates the transition to the part of the algorithm that determines if the

bicycle's position could pose a danger in the RHC-zone, i.e., if $S \geq d_{TB}$, in which case an alert should be issued.

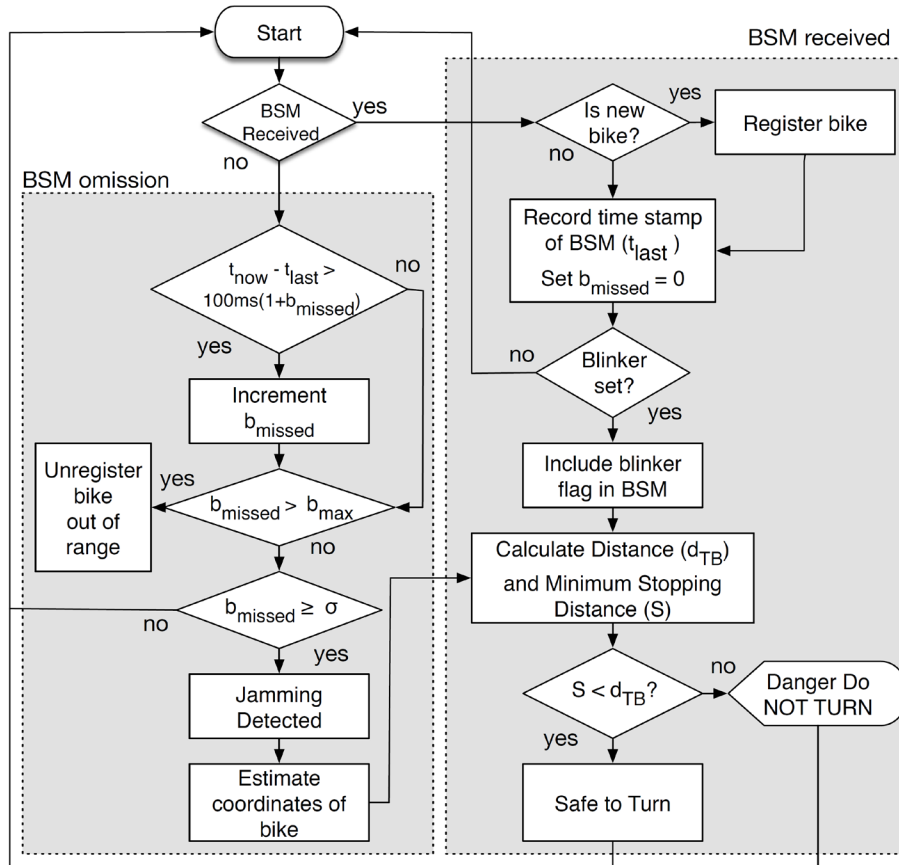


Figure 11 BSA Flowchart from the viewpoint of one bicycle

4.3 Experimental Results

The algorithm of Figure 11 was implemented using an ARADA LocoMate Classic OBU for the truck, and an ARADA LocoMate ME, a battery powered small OBU mounted on the bicycle. Experiments were conducted using a data rate of 3Mbps, 23 dBm transmitter power, and 100ms BSM spacing, in open space and close proximity of OBUs.

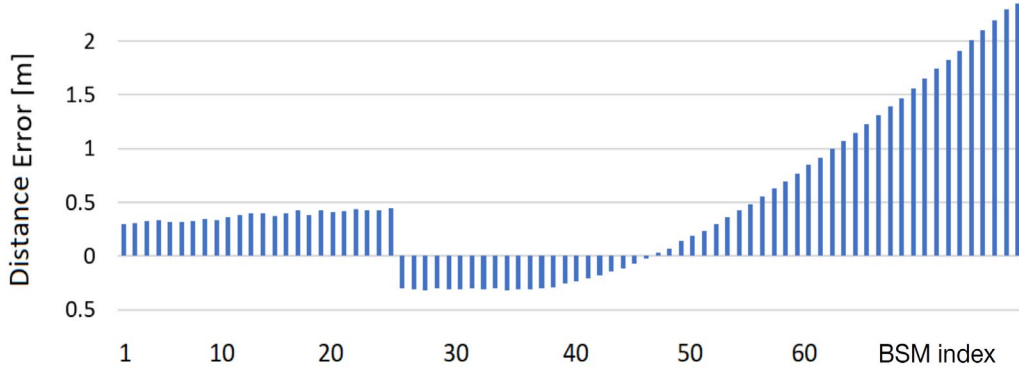


Figure 12 GPS error with 4m fixed distance between vehicle and bicycle. Truck speed is less than turning speed.

Many experiments were conducted with the truck's speed approaching the right turn less and more than the turning speed of $v_{RT} = 10$ m/s from [20]. Due to space limitations, we can only present one typical experiment conducted in open space. Figure 12 shows GPS errors, which are the calculated distance between both antennas, d_{TB} , using Equation 2 minus the actual known OBU distance. The GPS antennas of the vehicle and bicycle were spaced at a distance of 4 meters, i.e., the vehicle and the bicycle were driving next to each other at that exact distance. The x-axis represents BSM time slots, here referred to as BSM indices. Jamming started at 29, i.e., after 2.9s. The prediction algorithm started when b_{missed} reached σ . A sub-meter GPS error was observed most of the time. Only several seconds after jamming started did the error slightly grow as expected, due to dead reckoning errors.

Figure 13 shows the calculated distance between OBUs, and the minimum stopping distance from Equation 11, as it relates to the bicycle speed, which in this case was equal to the truck's speed. The blue graph shows the distance calculated by the algorithm up to jamming, and dead reckoning after its detection. The yellow line indicates what would happen without the algorithm, in which case the safety application would fail when the calculated OBU distance is falsely interpreted to be greater than the minimum stopping distance. This is the case when the

two graphs cross, as marked by the circle. Thus, without the algorithm a jammer could cause the safety application to fail, potentially giving an attacker the power to cause an accident.

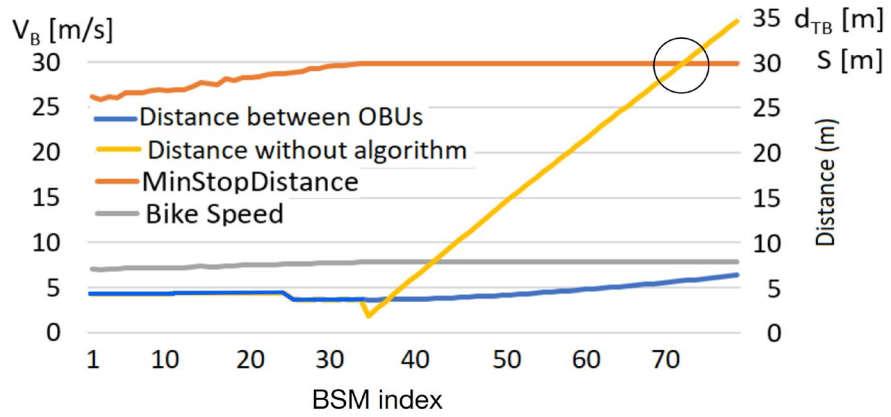


Figure 13 Graphs for speed less than turning speed.

CHAPTER 5 APPLICATIONS FOR VANETS WITH DIVERSE TRAFFIC

PARTICIPANTS

5.1 Considering people with disabilities

So far only motorized vehicles and bicycles have been considered. Now we extend the traffic participants to include visually impaired persons and wheelchair users.

The research that has been described up to this point considered a mobility model characterized by relatively fast-moving vehicles, e.g., motorized vehicles traveling at the speed limit or fast-moving bicycles. However, the two new traffic participants require an investigation of Safety Applications for slow moving traffic participants. For example, wheelchair users or visually impaired people who intend to cross a street will move at much lower speed. Both have one property in common in that they may change their heading over very short distances, e.g., a person may turn on the spot. This is very different from motorized vehicles, which have a much larger turning radius. We will describe scenarios using visually impaired people and wheelchair users. The terms heading, trajectory, and bearing will be used interchangeably to describe the direction of movement.

The motivation behind this research is from the number of incidents reported. According to a NHTSA of July 2015 [23] there were an average of 28 wheelchair users died in traffic crashes per year from 2007-2013. In a later report [24], it was estimated that in 2017 a pedestrian crash causing death occurred every 88 minutes and according to [25] 75% of the pedestrian crashes happened in the dark. To emphasize the latter, it should be noted that VANET safety applications are especially suitable for such scenarios of low visibility or no line of sight.

Figure 14 and Figure 15 illustrate two interesting scenarios. Figure 14 shows a vehicle and a visually impaired person with trajectories that could result in a collision. Whereas a vehicle

is assumed to have a fairly stable trajectory, the visually impaired person could change his/her trajectory on the spot. This opens the question as to how sensitive the OBUs are to changes in trajectory, especially changes over extreme short distances.

A scenario that initially does not suggest potential collisions is shown in Figure 15. Both, the vehicle and the wheelchair user are moving in the same direction, in this case both are north bound. Their line of sight is blocked by a large building so that the driver of the vehicle cannot see the wheelchair. The vehicle is approaching a turn, which will result in a change of bearing, ultimately resulting in intersecting trajectories.

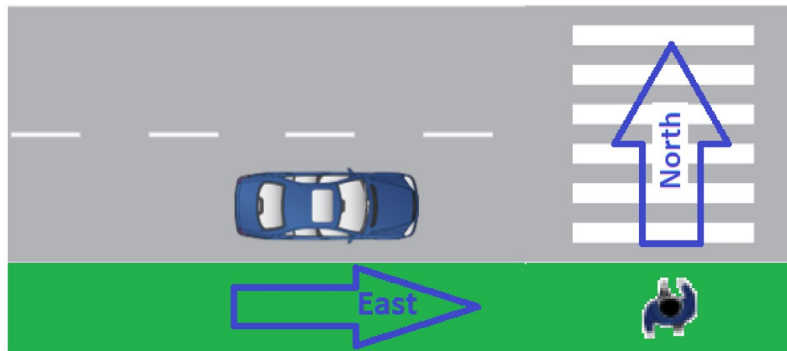


Figure 14 Detection of visually impaired person crossing the street at foggy night

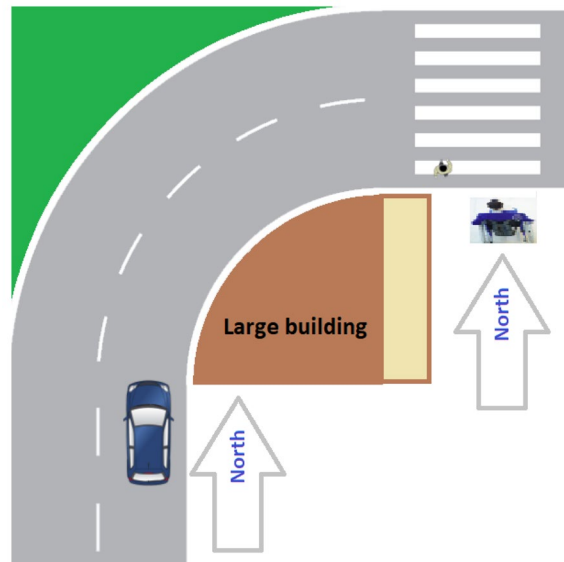


Figure 15 Graph for wheelchair and visually impaired person on crossing a street

5.2 Establish that errors will be small for long distances

In our previous work, we have considered close distance cases, e.g., a bicycle moving within a close distance to a vehicle [26], [27]. In this research we wanted to examine the reliability of the safety application for a large distance to see how reliable are the OBUs to provide parameters for a low mobility application such as a wheelchair. The experiment configuration parameters are shown in Table 2, and the result of this experiment is shown in Figure 16 where the calculated distance of two stationary OBUs apart from each other by 30 meters. To zoom into the GPS error for the calculated distance and to find the deviation from the actual distance, which is 30 meters fixed, Figure 17 shows a relatively small GPS error, which in the worst case was about 2.5 meters.

Table 2 Field Experiment Configuration Parameters for Low Mobiliy

Truck OBU Model	Arada Systems LocoMate Classic
Bicycle OBU Model	Arada Systems LocoMate Mobile ME
Test range	Residential area (Levick Street)
Speed	Stationary
BSM generation	10 BSM/s
Channel	Safety Channel 172
Transmitter power	23 dBm
Data rate	3Mbps

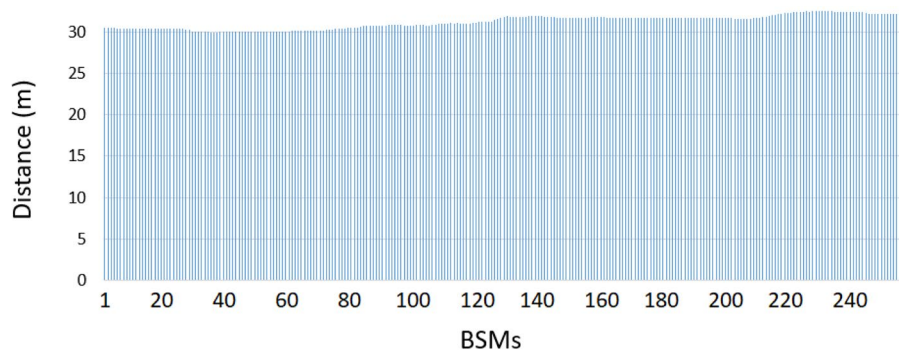


Figure 16 Calculated distance when two stationary OBUs were placed 30 meters apart

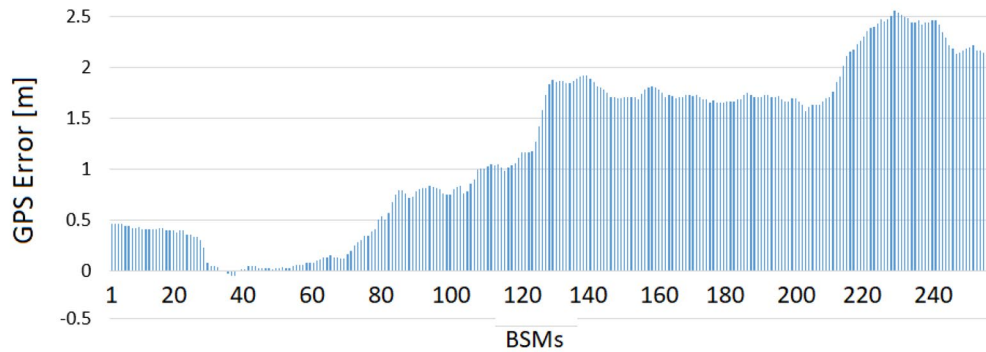


Figure 17 Graph for GPS error of two stationary OBUs at 30-meter distance

5.3 Investigation of accuracy and timeliness of OBU heading information

Next, we wanted to examine the OBUs to see if there is a built-in mechanism to detect the trajectory change on the spot. Our findings were that Arada OBUs do not have a mechanism to detect changes in heading on the spot. For example, there is no gyro like in most contemporary smart phones. Hence, an investigation is needed to find out how accurately and timely the OBUs can supply useful values for headings. Several experiments were conducted: First, the OBU was initially calibrated to indicate the west-bound heading with a sudden change, on the spot, to east-bound, e.g. a person turns from west to moves east. Our goal for this experiment was to find how long it takes (at what distance) to detect the correct new heading, which now is east. The result of two typical experiments will be shown next. The configuration parameters used for the experiments are shown in Table 3. A sophisticated GPS device, the GeoExplorer 3 from Trimble, was used as a reference to find the actual heading in degree.

Table 3 Field Experiment Configuration Parameters for Heading Sensitivity

Truck OBU Model	Arada Systems LocoMate Classic
Bicycle OBU Model	Arada Systems LocoMate Mobile ME
GPS device	GeoExplorer 3 Trimble
Test range	Kibbie Dome area
Speed	1 m/s
BSM generation	10 BSM/s
Channel	Safety Channel 172
Transmitter power	23 dBm
Data rate	3Mbps

The result of the first experiment is shown in Table 4, where each row indicates the heading information of a BSM. In this experiment, which lasted 1 second, hence 10 BSMs given the 100ms spacing, the OBU could not detect the correct heading over 10 received BSMs for a moving distance of 2 feet. Specifically, 10 BSM messages were sent, but all of them had the initial heading, the one before the turn. The results of another experiment are shown in Table 5. Here the OBU could detect the change of the heading as reflected in the 9th BSM, but with an error of +6 degrees.

In general, it was observed that it took about one meter for reliable heading information. These are only our observations from using the MobileMe units in a sequence of tests, two of which have been shown above, and we claim no responsibility for general accuracy of this result. It would require further test to establish the accuracy of the distance, as well as how it may differ between OBUs from different vendors.

Table 4 Observed Heading for Field Experiment over 2 Feet

BSM	Pedestrian OBU GPS Heading	Actual Heading	Deviation
BSM1	275	90	+185
BSM2	275	90	+185
BSM3	275	90	+185
BSM4	275	90	+185
BSM5	275	90	+185
BSM6	275	90	+185
BSM7	275	90	+185
BSM8	275	90	+185
BSM9	275	90	+185
BSM10	275	90	+185

Table 5 Observed Heading for Field Experiment over 3 Feet

BSM	Pedestrian OBU GPS Heading	Actual Heading	Deviation
BSM1	274	90	+184
BSM2	274	90	+184
BSM3	274	90	+184
BSM4	274	90	+184
BSM5	274	90	+184
BSM6	274	90	+184
BSM7	274	90	+184
BSM8	274	90	+184
BSM9	96	90	+6
BSM10	96	90	+6

5.4 Disability Safety Application

The safety application for people with disabilities, e.g., visually impaired person or wheelchair users, aims to reduce traffic accidents through alerting vehicle drivers of potential crashes. These VANET participants have micro-mobility and they can turn over very short distance. The effectiveness of the proposed algorithm for a safety application for these traffic participants can be describe using the scenario seen in Figure 14 and Figure 15. We will simply relate to a "participant", P, when we talk about the visually impaired person/wheelchair user.

In Figure 15 assuming it is dark or foggy so that both VANET participants have restricted vision. There is therefore a higher risk that this scenario may lead to a potential collision. The SA

will examine the heading of both participants to see if there will be a heading conflict within a specified radius indicated by the algorithm. In Figure 15 the vehicle is driving north with no line-of-sight, due to the large building, with a wheelchair user that is also moving north. Here, the vehicle will turn, eventually heading east, so that the headings of both participants will intersect potentially leading to a crash.

The algorithm for the SA is shown in Figure 18. First, after receiving BSM from a participant P calculate the distance d_{VP} between the two VANET participants using question 2. It should be noted that only those within the vicinity, of distance D , are of interest. Thus, D is the distance threshold, which was set at 30m in the field tests. Next, participants in the vicinity are registered. The reason for registration is to remember P in case of BSM omissions, e.g., due to OBU malfunction, natural phenomena like shadowing, or jamming. One needs to investigate if the vehicle and P are on potential collision course. For this purpose, a Trajectory Criticality Metric (TCM) and a Trajectory Criticality Threshold (TCT) are introduced. The TCM is a function that can have multiple variables and returns a numeric value indicating how likely there could be an intersection of the participant's trajectory in area of concern, e.g., a pedestrian crossing. Examples of TCM variables are:

- 1) Heading difference, which is the angle between two headings.
- 2) Speed and rate of change of the angle.

In our implementation option 1) was used. Specifically, the TCM used is the relative trajectory intersection angle of the two headings. The TCT was set to 20 degrees. The area of interest, i.e., of potential collision area, is the pedestrian crossing. This is similar to the RHC-zone in Chapter 3. If a collision is possible, the minimum stopping distance of the vehicle is

calculated using Equation 11. If this stopping distance is greater than or equal to d_{VP} an alert is issued.

The registration of P in the algorithm is used to predict the location of P in case of a DoS attack. As previously stated, we considered a jamming scenario for the bicycle safety application for malicious environments. When a number of BSMs were lost, e.g., due to jamming, the bicycle position had to be estimated. For slow moving participants this is relatively simple, since the position during a brief jamming period is expected to be rather stable compared to that of a fast-moving vehicle. For example, during a 1s jamming period a person is expected to move approximately 1m. This was very different in the case of bicycles, where speeds were much faster, e.g., 5-10 m/s. Hence, the algorithm in Fig 18 uses the last recorded BSM information to be used in case of BSM omissions.

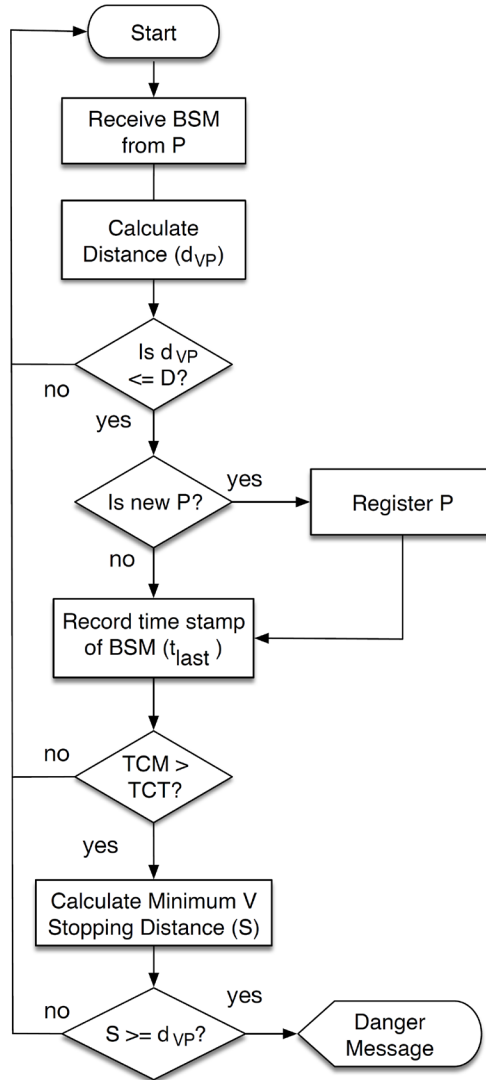


Figure 18 Flow Chart for safety application for people with disabilities

5.5 Conclusions

In conclusion, the safety application was introduced to mitigate traffic collision for different VANET participants such as visually impaired person, and wheelchair users that have a unique mobility model characterized as micro-mobility model. We investigated how reliable are the OBUs to produce accuracy for large range calculated distances. The experiment results showed small GPS errors for large calculated distances from sub-meter of accuracy to at most

2.5 meters. Next, we examined Arada OBUs to see how reliable their heading information is while changing directions over very small distances, e.g., on the spot.

The OBUs did not provide a mechanism to determine the heading in such situation. Therefore, we conducted experiments to find out how much distance it will take an OBU to move to produce a reliable heading accuracy. It turns out that the OBUs need at least 3 feet, about 1 meter, to produce a reliable trajectory.

CHAPTER 6 STUDY CONCLUSIONS

The topic of safety applications for bicycles and diverse other traffic participants was introduced. These safety applications use Basic Safety Messages of vehicle-to-vehicle and vehicle-to-pedestrian communication. The BSMs provided information like speed and geographic locations, which was then used to alert drivers of possible right hook crash scenarios. Different safety applications were introduced with different algorithms for diverse traffic user scenarios. In general, the applications alert participants when the minimum stopping sight distance of the bicycle or other user is greater than or equal to the distance between them. However, since this distance is calculated from the GPS coordinates broadcast in the BSMs, it is affected by GPS inaccuracies. Field tests showed that in the absence of large buildings effective right hook alerts for bicyclists could be issued. Only when the safety application operated in very narrow confined areas was the GPS inaccuracy large enough to greatly reduce its effectiveness. The research also considered the special issues related to diverse traffic participants like wheelchair users, and visually impaired persons. The fundamental issues related to the specific mobility models, which are very different than those of motorized vehicles like cars or trucks, were addressed.

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