On the Reliability of VANET Safety Applications for Bicycles

Mohammad Baqer
Computer Science Department
University of Idaho
Moscow, USA
mbaqer@uidaho.edu

Axel Krings
Computer Science Department
University of Idaho
Moscow, USA
krings@uidaho.edu

***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 bicycle safety. This research 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.**

***Index Terms*—VANET, connected vehicles, vehicle-to-vehicle communication, safety applications, bicycle safety**

I. 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 application 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 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 which are therefore capable of V2V and V2I communication.

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 paper we will focus on DSRC, however, the general issues discussed are expected to have similar implication is C-V2X as well.

The rest of the paper is organized as follows. Section II will introduce relevant background information. A Bicycle Safety Application is presented in Section III, and the results of field test are shown in Section IV. Final conclusions are given in Section V.

II. BACKGROUND

In connected vehicles, each vehicle is assumed to have an On-Board Unit (OBU), and the infrastructure is equipped with Road Side 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.

A. 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.

B. 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 consist 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.

C. DSRC Safety Applications

In a report by the USDoT and the Crash Avoidance Metrics Partnership on behave of the Vehicle Safety Communications 2 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 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.

D. 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.

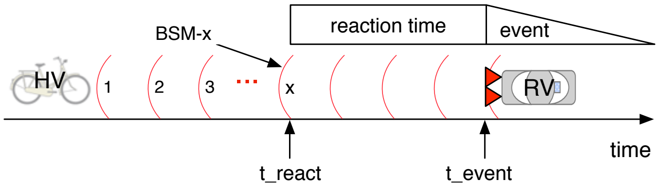

Fig. 1. BSM Propagation and Timing

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., BSM$_1$, ..., 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.

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.

III. BICYCLE SAFETY APPLICATION

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}.

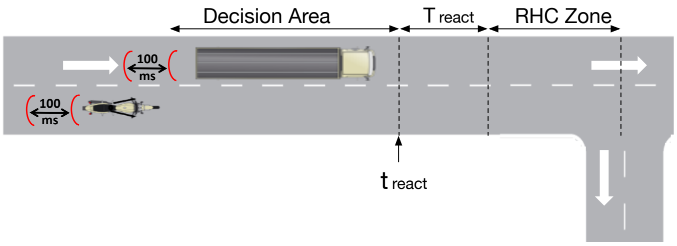

Fig. 2. Scenario leading up to potential Right Hook Conflict

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.

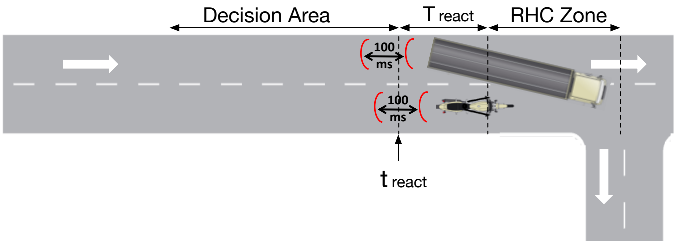

Fig. 3. Right Hook Conflict

In the discussion of the safety applications in Subsection II-C, 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.

A. 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 IV below.

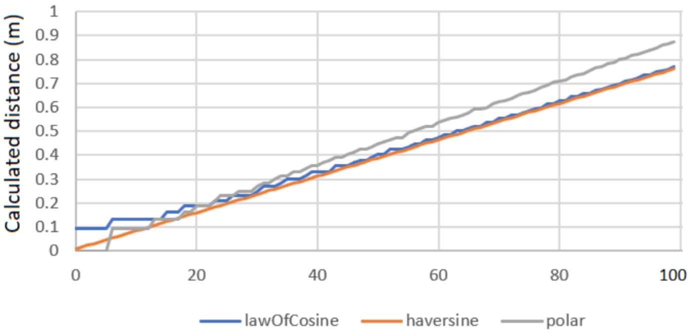

Fig. 4. Calculated results for different methods. The x-axis is the distance in multiples of degree 0.000001, which corresponds to 1.11cm.

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

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

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:

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

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 3. 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.

B. 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 turns 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 paper.

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 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.

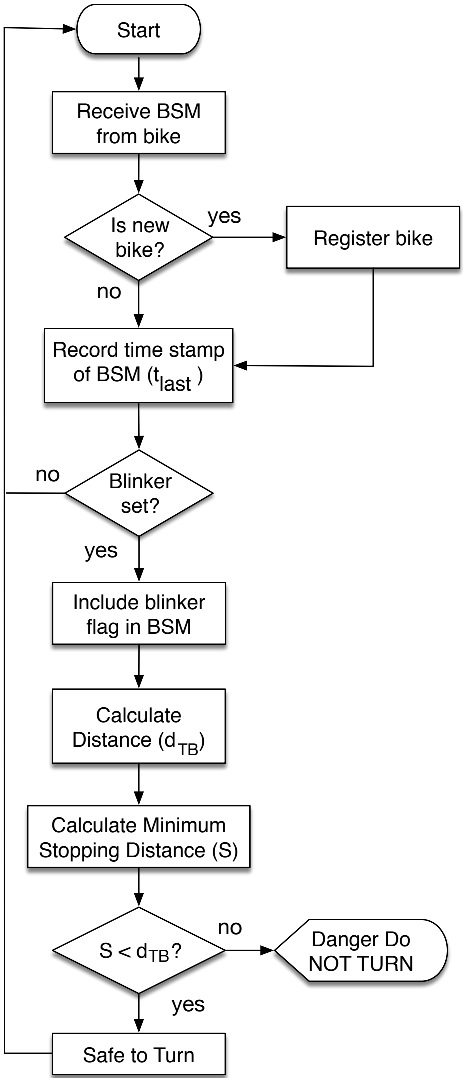

Fig. 5. BSA Algorithm executed in truck's OBU

C. 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 $S \geq d_{TB}$.

IV. EXPERIMENTAL 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 I.

TABLE I
FIELD EXPERIMENT CONFIGURATION PARAMETERS

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

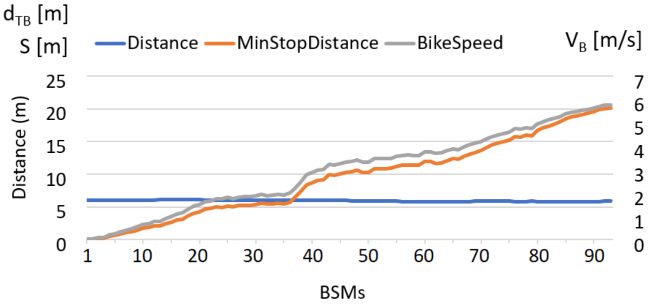

Fig. 6. Experiment with 4m fixed distance between vehicle and bicycle

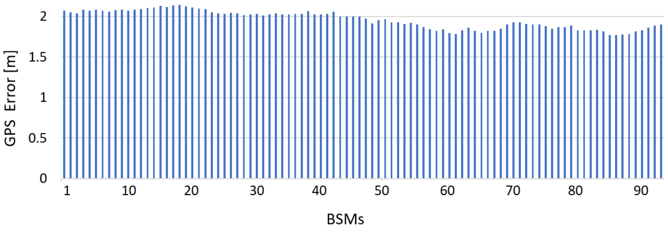

Fig. 7. Error due to GPS inaccuracies

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.

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 BSM_{37} 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.

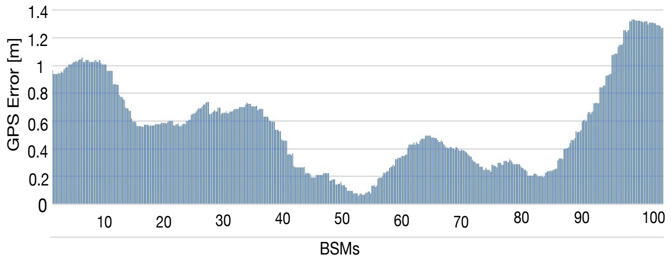

Fig. 8. Error due to GPS inaccuracies, stationary test

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., BSM_1 through BSM_{40} 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 BSM_{525}. 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 St., 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.

Fig. 9. UI campus test area

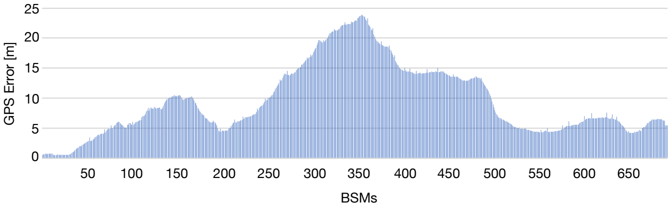

Fig. 10. Error due to GPS inaccuracies, block drive

V. CONCLUSIONS

A bicycle safety application was introduced that uses Basic Safety Messages of vehicle-to-vehicle communication in connected vehicles. The BSMs provided information like speed and geographic locations, which was then used to alert drivers of possible right hook crash scenarios. The safety application has different algorithms for vehicles and bicycles, however, both issue alerts when the minimum stopping sight distance of the bicycle 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 righ hook alerts could be issued. Only when the safety application operated in very narrow confined areas was the GPS inaccuracy large enough to greatly reduce it effectiveness.

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