BikeCOM: cooperative safety application supporting cyclists and drivers at intersections

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Abstract

In 2010, 2083 cyclists died while riding bicycles in Europe. Many of those accidents occurred at road intersections, typically involving one vehicle and one bicycle, and were caused by distraction or inattention of either the driver or the cyclist.

This study describes the development and verification of BikeCOM: a cooperative smartphone application able to prevent accidents at intersections by warning both the driver and cyclist in case of an imminent threat. The BikeCOM application runs on Android smartphones and relies on bicycle-to-vehicle communication to exchange safety relevant information.

Naturalistic cycling data from the BikeSAFE and BikeSAFER projects was used to identify the safety critical situation to be addressed. This safety critical situation was described with use cases to envision different application scenarios and derive technical and functional requirements. After the prototype implementation, a pilot test was performed to 1) test the application, 2) develop a data analysis tool, and 3) design the protocol for a larger experiment. Both a bicycle and a car were used in this larger experiment to recreate the safety critical situation in a controlled real-world scenario.

Results from this experiment show that cooperative applications based on smartphones and connecting bicycles and cars are feasible and possibly desirable. However, present limitations on positioning and latency strongly limit their reliability.

The BikeCOM application promoted smartphones from a distraction hazard to a distraction countermeasure; proposing that banning smartphone technology from traffic might, in the long-term, harm safety and suggesting that integration of safety applications to more traditional and distractive applications such as SMS writing, dialing, and mailing, may be an acceptable solution to limiting distraction from smartphones.

Introduction

Increased societal awareness of environmental problems, such as carbon dioxide emissions and depletion of non-renewable resources, results in a growing number of people using bicycles to reduce emissions and preserve natural resources. Another reason for people choosing to switch to the bicycle is economic, as bicycles neither need expensive fuel nor are they taxed as motorized vehicles. Finally, yet another reason to cycle is the healthy workout obtained from riding a bicycle (de Hartog, Boogaard, Nijland, & Hoek, 2010).

However, the increased usage of bicycles in urban areas, i.e. where cyclists are most exposed to vehicles, leads to a higher risk of collisions between bicycles and motorized vehicles, at least in the short term (Elvik, 2009). Considering the vulnerability of bicyclists, collisions with motorized vehicles are a significant concern as they may cause serious injuries and deaths. In 2010, 2083 bicyclists died in Europe. 81% of these fatalities involved a collision with a motorized vehicle and 33 % happened in proximity of an intersection (CARE Community database on Accidents on the Roads in Europe).

Distraction and inattention are among the major causes of collisions at intersections (Choi, 2010) and mainly involve drivers, but also bicyclists in many cases (Räsänen & Summala, 1998). Specifically, in 37% of the collisions, neither driver nor cyclist realized the danger or had time to yield (Räsänen & Summala, 1998). Several countermeasures have been proposed against distraction, examples include active safety systems such as frontal collision warning which relies on sensors to estimate the probability of collision and warn the driver in case of an imminent threat (An & Harris, 1996). Active safety systems are also envisioned to combat distraction at intersections, even if the requirements for these systems are mainly intended for motorized vehicles and aim at alerting only one road user: the driver (Habibovic & Davidsson).

Intersections with visual obstructions are particularly unsafe. A recent study using naturalistic cycling data (M. Dozza, 2013) shows that a visual obstruction at an intersection increases risk threefold. When visibility is reduced, the time to assess the presence of potential threats may be very short, making any instance of distraction and inattention critical. Furthermore, traditional active safety systems based on radars and cameras are hindered by visual obstruction as they cannot see through hedges or walls, which may partly be covering the intersection. On the contrary, cooperative systems, i.e. active safety systems using wireless communication, may be aware of what is behind a wall or a hedge as long as the communication of positioning among road users is timely and reliable. Cooperative systems using vehicle-to-vehicle communication exist already and promise to extend the capabilities of traditional sensors, offering new safety applications such as Curve Speed Warning and Road Condition Warning (Bishop, 2005). Despite the need for a high penetration rate has so far hindered their exploitation, cooperative systems are currently being field tested in the Safety Pilot project ("Safety Pilot Project - http://www.its.dot.gov/safety_pilot/index.htm," 2013), however communication is limited to vehicles and infrastructures and does not include vulnerable road users such as pedestrians and cyclists.

This paper presents a smartphone application to fight distraction and inattention at intersections, especially in situations where a visual obstruction is present. This application is novel in its effort to warn multiple road users. For instance, warning both the driver and bicyclist on a collision path near an intersection. By using smartphones, this cooperative application, namely BikeCOM, is able to transfer information among road users and warn them accordingly with the vehicle type and traffic situation. The BikeCOM application is not intended for commercial use but to show the potential of cooperative systems including bicycle communication and the potential of naturalistic data to guide active safety development. In fact, in contrast to most of the active safety systems on the market, the use cases for requirement specification and the test scenarios for the application were driven by the analysis of naturalistic cycling data. The results presented in this paper offer a new image of smartphones as potential countermeasures to distraction and inattention as opposed to plain distraction hazards.

Method

Scenario Selection

The first step was to select a safety critical situation, i.e. a scenario relevant for cycling safety and with a high potential for saving lives. In order to identify this safety critical situation, two sources of information were used. The first source was accident statistics from ERSO (European Road Safety Observatory, 2011), and the second was naturalistic cycling data, available from the BikeSAFE project (Marco Dozza, Werneke, & Fernandez, 2012). The BikeSAFE project had, at that time, data from 8 different bicyclists who rode an instrumented bicycle during their daily activity for sixteen weeks (2 weeks for each bicyclist). Naturalistic cycling data included video from a forward looking camera as well as kinematics data and GPS information. Video review identified several critical situations which were categorized and clustered according to the traffic situation (e.g., environmental, cyclist and traffic characteristics, as well as the type of conflict or danger). The data from ERSO was then used to determine whether the safety critical situations from the naturalistic cycling videos were actually representative of real accidents and their contribution to cyclists' fatalities. By combining information from naturalistic data and accident databases it was found that addressing conflicts between motorized vehicles and bicycles at intersections presented the highest potential for saving lives.

Deriving Use Cases from the Selected Scenario

By analyzing all video clips presenting the selected safety critical situation (conflicts between vehicles and bicycles at intersections), several use cases were derived. A schematic of the traffic situation addressed by the use cases is presented in Figure 1. In this traffic situation, the bicycle is travelling on a two-way bicycle road that runs parallel to a common two-way vehicle road. The bicycle can travel in any of the two directions. When the bicycle approaches the intersection, any motorized vehicle travelling on the road perpendicular to the bike lane, that is also approaching the intersection, is considered as an actor in the use case, because it is on a collision path with the bicycle.

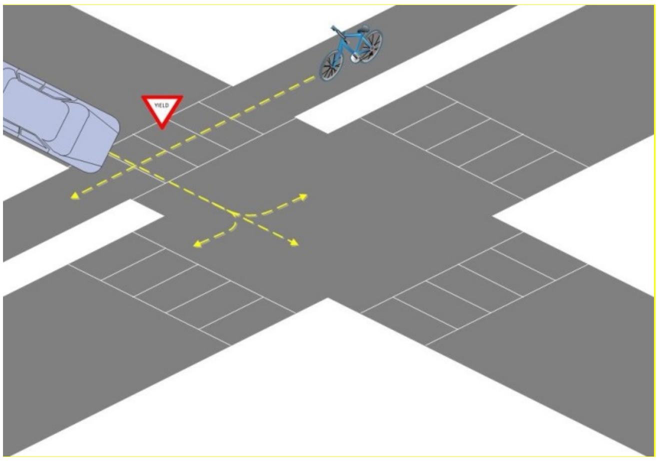

Figure 1 Schematic of the traffic situation to be addressed with the safety application.

Technical and Functional Implementation

Smartphones were selected as a viable platform to develop the application because of their ability to communicate, fetch GPS data (position, speed, and heading), and provide a basic human-machine interface. Using smartphones was also a way to test the extent to which a device that is already highly accepted and ubiquitous could increase traffic safety. The algorithm flow chart in **Error! Reference source not found.** shows the workflow of the application running in the smartphone. Once the GPS was activated in the smartphone, the application connected to a server. Once the connection between the application and the server was established, the application posted and fetched data from the server. A threat assessment algorithm inside the smartphone estimated the probability of the critical situation to trigger a warning.

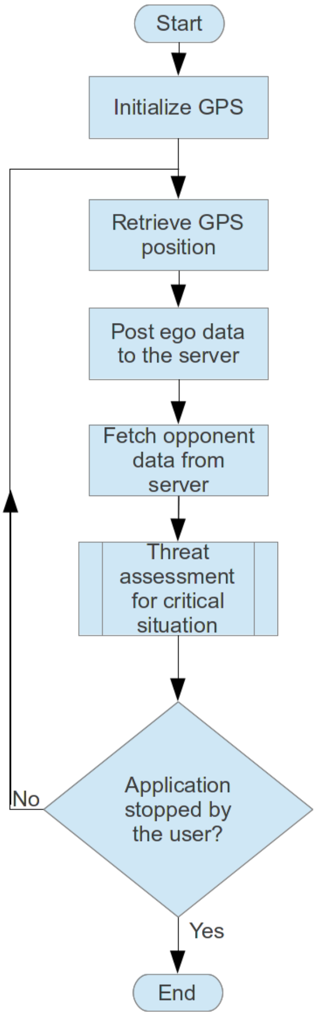

Figure 2 Algorithm main flowchart

Application workflow

In order to reduce the risk of collision due to misinterpreting or completely missing a warning, both the driver and the bicyclist could receive a warning. An acoustic warning was chosen to test the application and depended on an estimation of time-to-stop (TTS) from the threat assessment algorithms. Advantages for an acoustic warning include avoiding visual distraction and not requiring for the cellphone to be installed in a specific location. Tactile warning was also considered. On the one hand, a tactile warning may be easier to recognize as one’s own warning, especially in traffic; on the other hand, it would also require the cellphone to be in contact with the user. Since bicycles and cars have different dynamics and kinematics, the application expected several parameters from the user to explain the different braking behaviors of different vehicles. In this way it was possible, for instance, to warn a bicyclist earlier than a driver when entering a safety critical situation because a bicycle takes longer than a car to stop (assuming same initial speed).

More specifically, in order to set an appropriate safety margin for different users and/or bicycles, four factors were identified:

- Brake force: depending on the force applicable to stop the bicycle/car, the stopping distance changes and thereby the time of warning.
- Speed: higher speed requires longer distance to stop.
- Weight of the biker/car: affects the power needed to stop the carriage.
- Individual choice: shifts the time of warning, either closer or further away from impact for the bicyclist comfort. For instance, a rider with more experience may feel more comfortable during fast decelerations and decide to shift the warning closer to impact.

Threat assessment

In order to find the appropriate time of warning, a mathematical model was used to determine TTS, which was used as the main control variable for the threat assessment algorithm.

Assuming the friction force (F) is known, initial velocity is v_0 and the total mass for the system (bike plus cyclist) is M, the time to stop can be calculated. By neglecting other forces (i.e. aerodynamic forces and all friction forces but the braking force), equation [E1] is extracted using Newton's 3rd law:

$$M \times \vec{a} = \vec{F} \qquad [E1]$$

$$\vec{a} = \frac{\overrightarrow{dv}}{dt} \qquad [E2]$$

By combining [E1] and [E2] and projecting on the forward direction axis, the following equations can be found.

$$M \times a = -F \qquad [E3]$$

$$a = \frac{v(t_{end}) - v(t_o)}{t_{end} - t_o} = \frac{-v(t_o)}{t_{end} - t_o} = \frac{-v(t_o)}{t_{ts}} \qquad [E4]$$

Then TTS is extracted from [E3] and [E4] according to [E5]:

$$TTS = \frac{M \times v(t_o)}{F} \qquad [E5]$$

Tests in a simulated environment

The android application was developed and simulated using Android SDK tools ("Android development tool," 2012). In order to perform proper simulations, two Android smartphone emulators were used to simulate the safety critical situation between the bicyclist and the driver.

Two sets of coordinates were used to simulate the paths of the two road users. The coordinate sets were chosen so that their paths intersected. Speed for both users was set to 8 m/s. This speed was considered reasonable in relation to what was observed in the naturalistic BikeSAFER study (M. Dozza, 2013), and would make it easy to reproduce and compare in the subsequent field tests. By allowing the two emulators to take turns in sending coordinates, the collision criteria could be checked and evaluated. Thus, the sensitivity of the application, during simulation, could be assessed. In order to validate the specificity of the application, coordinates were also chosen to result in a non-collision trajectory.

Field tests

Once the application was developed and tested in a simulated environment, the next step was to test its performance in a controlled traffic environment. The objectives of this test were the following:

1) Determining the bicycle normal braking force and thus calibrate it as an input for the application.
2) Assessing the application in terms of appropriateness of timing of the warning to a cyclist and a driver on a collision path.

Determining the bicycle normal braking force

According to the test protocol the bicycle ran along a straight path at a 20-km/h constant speed, and the rider was asked to brake with his normal braking force, i.e. not as an emergency braking, when reaching a specific spot. The time to stop was measured and used to calibrate the application running inside the cyclist's smartphone.

Assessing the application

In the second scenario the car and the bicycle were initially 60 m away from the intersection, driving towards it at a constant speed of 20 km/h, and with their trajectories forming an angle of 90° (see Figure 1). With this setup the safety critical situation was triggered, and it was thus possible to record if a warning was given or not at the right time. This scenario is performed with two different riders and one single car driver, with eleven runs for each rider.

Both the car and the bicycle were equipped with video cameras in order to record the road view of each of the vehicles. They were also equipped with Android smartphones which ran the application and communicated via the internet. The data being collected in the test runs for each vehicle were: GPS data (position, speed, and heading) and warning activation. The latter variable was retrieved from the application, while the other three were retrieved from the GPS of the smartphone. All the variables were stored in the remote server. After each test, the warning times for the rider and for the driver were annotated.

Results

Use Case Definition

The most common type of conflict encountered by the cyclists that participated in the BikeSAFE project (Marco Dozza et al., 2012) was with pedestrians, followed by conflicts with cars at intersections and conflicts with other bicycles. Table 1 summarizes the most frequent safety critical situations including conflicts which were identified from the analysis of naturalistic cycling videos.

Even if conflicts with pedestrians were significantly more frequent than conflicts with other road users, data from accident databases show that almost no cyclist fatalities occur when a bicycle collides with a pedestrian (Traffic Safety Basic Facts 2011). Furthermore, accident data shows that 64% of cyclists' fatalities in Europe occur at crossroads (Traffic Safety Basic Facts 2011, p.11-12). Taking this into account, situations where turning vehicles cross the bicycle's path was selected as the use case for developing the cooperative application, because it is one of the most commonly observed situations of conflict involving cars at intersections (Räsänen & Summala, 1998).

Table 1 Critical situations from naturalistic cycling data

Type of critical situation	**Occurrence**
Conflict with pedestrian	27%
Conflict with car at intersection	*20%*
Conflict with other bicycle	17%
Traffic rule violation	16%
Conflict with car on parallel driving	8%
Conflict with animal	6%
Self-conflict	6%

Simulation Test

The results of the simulation showed sensitivity and specificity of 100%, in other words, the application did not produce any false warnings and provided a true warning every time it was expected. Latency between the simulation computer and the server reached approximately 300 ms. These performances demonstrated that the algorithm worked flawlessly when used in the emulator and justified the field testing.

Field Tests

Preparatory tests to calibrate and inform the application.

Controlled field tests determined that a 330-N braking force is compatible with bicycle dynamics and rider equilibrium, while already being well outside the comfort zone of normal cycling. With such a braking force, the joint bicycle-rider system (total mass 91kg) used in the field test was able to stop a bicycle travelling at 20 km/h in 1.53 seconds. This information was used for the threat assessment in the application.

Application tests

In only 1 of the 20 test runs the warning was felt by the rider and driver as relevant and appropriate. Due to technical issues regarding latency of the warning, in most of the cases the warning came very late or was not given at all. The results of the field tests for the selected use case are summarized in Table 2. Early and late warnings (Table 4) were defined subjectively according to the rider's perception and verified on the collected data.

Table 2 Results of the test 2

Warning type	No warning	Late warning	Appropriate Warning	Early warning
Occurrence	54%	36%	5%	5%

Figure shows the trajectories of both vehicles on the test site, plotted on Google Maps, for the test run that gave an appropriate warning.

Figure 3 Map with trajectories and markers for the test run with appropriate warning. The intersection scenario was simulated in a parking lot. The green line corresponds to the bicycle whereas the red line represents the car. The marker at the extremity of each trajectory path is the starting point while the second marker on the path is the position where the respective user got the warning.

Figure shows the speed of each vehicle over time as well as their respective warning signal, also for the test run with an appropriate warning.

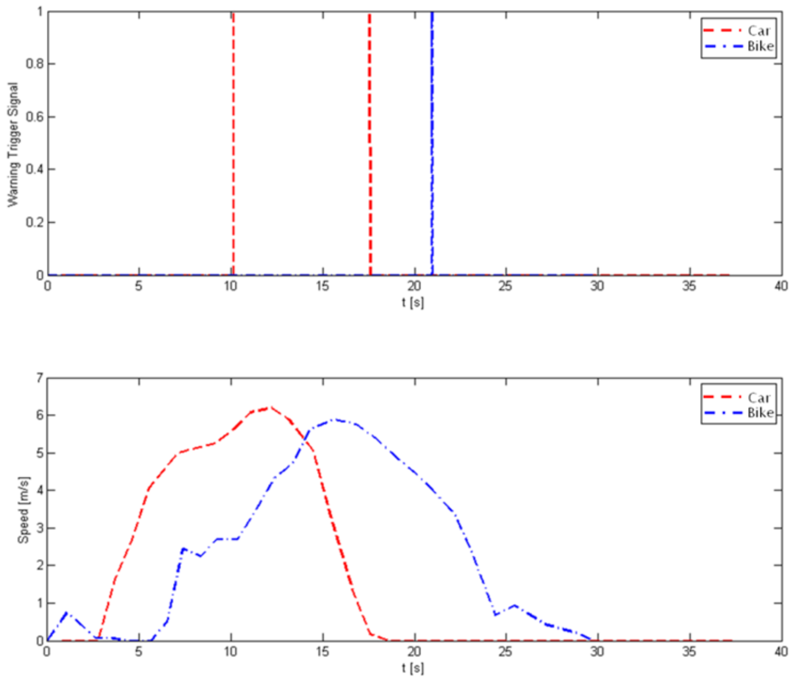

Figure 4 Warning and speed signals for the test run with appropriate warning.

In this test run, the car driver did not brake when the warning was received. This explains why the warning signal is longer for the car. On the other hand, the biker braked as soon as he received the warning, so he only received one single warning signal. Figure displays how the biker decreased his speed rapidly (braked) once he received the warning.

Discussion

The design of the BikeCOM application was based on naturalistic cycling data (Marco Dozza et al., 2012), which was used both to create use cases for the application development and to generate the real-world test scenarios. Despite the perfect performance in a simulated environment, proving its solid logic, the BikeCOM application was able to run flawlessly only once in the real world during the tests. Although this single time is sufficient to prove that such an application is feasible and could prevent distraction and inattention at intersections, it also shows that this application is not mature for the market. Other solutions that are already commercially available (e.g. www.eco-compteur.com), can address the same specific safety critical situation and do not suffer from the technical limitations currently encountered by BikeCOM. However, these solutions rely on special infrastructure, thus they are limited to work in specific spots. BikeCOM is a wireless application that, once perfected, could work everywhere. This section will focus on the present human-factors and technical issues to be solved in order for the BikeCOM application to enter the market and the potential benefit of intelligent systems addressing distraction in a cooperative environment.

Human Factors Constraints: Human-Machine Interface, Acceptability, and Trust

The BikeCOM application is only prototypic, and the major development efforts focused on its technical challenges, however during the test phase a few human-factored issues arose. For instance, the warning is currently limited to a beep signal with an adjustable sound frequency. Future development could actively adjust the sound of the warning according to the threat level and background noise. For example, when the threat is imminent the warning should be louder and more intense. The warning could also distinguish whether the threat is coming from the left or the right. In addition, the warning could be given as a vibration instead, avoiding the risk to be annoying or misleading to other road users, or to be covered by the traffic noise. Finally, future development of the BikeCOM application should also test the extent to which warning a user in proximity of an intersection may be distractive. This issue with providing a warning to the user is a problem common to all active safety systems. To optimize the warning strategy, tests should be performed to verify that the user reacts to the warning as intended. Further, as the BikeCOM application becomes more reliable, the best trade-off between warning and distraction may be based on the sensitivity and specificity of the application. Finally, the timing of the warning can be tuned to alert the user at the optimal point to react to the safety critical situation, minimizing distraction.

Another issue with the current implementation of the BikeCOM application is that the application interface was slow and unresponsive at times. From a technical point of view, this issue may be solved by optimizing the code. However, from a human factor point of view, this issue is very important as for cooperative applications, such as BikeCOM, a high penetration rate is necessary. Even a momentary malfunction of the application may have catastrophic consequences as it may trigger a domino effect where all users shut down the application. Restoring a sufficient penetration rate after such a situation occurs may be highly challenging. Nevertheless, it is worth noticing that issues such as penetration rate, security, reliability, and standardization do not just belong to BikeCOM but are challenges common to all cooperative systems (Bishop, 2005).

Every time a system is supposed to prevent a disastrous event through a warning, concerns focus on the user becoming over confident about the system ability to warn and stop paying attention. By over trusting a future (more reliable) version of the BikeCOM application a road user may become more distracted at intersections. However, similar concerns about electronic stability control or frontal collision warning systems have never been confirmed.

Technical Constraints: Positioning and Timing

The BikeCOM application worked perfectly during simulation. However, the application did not perform as well in the real world. Several problems regarding the application were brought to light during the real-world tests and resulted in the application warning at, or after, the intersection. The warning delay originated from: 1) poor internet transfer speed of the data which decreases the update frequency of the application, hence decreasing the accuracy of the system, 2) low positioning resolution from the GPS, and 3) possibly slow processing from the smartphones.

During the test, BikeCOM data was sent over a 3G network, which reaches transfer speeds of approximately 3.5 Mbit/s. When the application is used over a WiFi network, with transfer speeds of 50 Mbit/s, the speed of the application greatly increases. The upcoming 4G network would be highly interesting for the BikeCOM application, as it would provide performance similar to WiFi. However, it is worth noticing that the current DSRC (dedicated short-range communication) band dedicated to cooperative application already promise latency time below 100ms and would be a viable alternative to the cellphone network. Further, differently from the cellphone network, DSRC was developed to handle complex networks including ad-hoc networks, which may be necessary to handle the growing complexity as the penetration rate increases.

Threat assessment in the BikeCOM application depends on correct positioning. The current GPS has a 6-m uncertainty on latitude and longitude which challenges this application to give timely warnings, especially if speed would suddenly change. Combining GPS with map data would improve the BikeCOM application; however, trustworthy maps including bicycle paths are currently missing. Using maps in combination with elevation from the GPS would also enable the BikeCOM application to determine whether the intersection is real or the two road users are crossing paths at different altitudes (e.g. when one of the vehicles is on a bridge over a road where the second vehicle is travelling).

While internet transfer speed is continuously increasing as new technologies such as 4G enter the market and GPS accuracy is a well-established problem which several projects are addressing (Ogaja, 2010), the slow processing issue may be solved by optimizing the BikeCOM application code. At the present time, uploading, downloading, and threat assessment are performed in separate computational threads. However, this must be investigated further, to identify exactly what parts of the code can be optimized and thereby increase the speed.

The above mentioned constraints show the utmost importance of field trials to verify results obtained from simulations. In this study, the simulation results showed an application working perfectly on a specific situation; however the experimental results for the same situation were not consistent with that outcome. Simulations are performed based on assumptions about the equipment and the environment with which it interacts. Nevertheless, those assumptions may sometimes be wrong as they might underestimate or ignore some parameters that only appear in real-world situations. It is hence critical to test these hypotheses and assumptions in real-world scenarios, as evidenced in this study.

Future Developments

At the current stage, the BikeCOM application is more of a proof of concept than a commercial application. However, the results presented in this paper show that technology is mature for a cooperative application running on a smartphone and supporting multiple road users including cyclists. Future development of the BikeCOM application should also address new issues that arise from a full community running the application at the same time. Technically speaking, this would include optimizing communication and threat assessment so that only relevant information is communicated and processed for threat assessment. From a human-factor perspective this includes acceptance issues at a societal level which could guarantee a continuous penetration level above the operational threshold for the application. In addition, the simple human-machine interface used to test the BikeCOM application should be further developed to make sure that warnings address the correct road user without confusion or nuisance.

The BikeCOM application shows that the same technology potentially increasing distraction (Hancock, Lesch, & Simmons, 2003) and leading to crashes (Hanowski, Perez, & Dingus, 2005) may be used as a distraction countermeasure to increase safety. This still-underdeveloped side of smartphones may be part of the answer to the current debate about smartphone safety. For instance, applications such as BikeCOM can make the smartphones aware of the traffic safety situation and can be integrated with current applications to regulate their operation according to accident risk. For instance, dialing may be allowed only at a certain distance from an intersection and if no other road user is on a potential collision path. In other words, by pushing safety application inside a smartphone, it would be possible to have a better control on its potentially distractive operation. Finally, as for cooperative systems penetration is one of the major issues, and relying on smartphones seems like a viable solution which may finally create the critical mass to trigger the deployment of these applications.

Conclusions

The BikeCOM application was able to warn both a driver and a cyclist on a collision path in the proximity of an intersection using wireless communication. Warnings were possible to time according to different vehicle's dynamics models and were provided to potentially distracted road users in time for each of them to individually avoid the collision by braking. The application worked on smartphones which 1) were used as a positioning system, 2) communicated wirelessly safety relevant information, 3) ran threat assessment algorithms, and 4) warned acoustically the road users.

Major criticisms to intelligent applications for vulnerable users, such as the one presented in this paper, have so far focused on portability and comfort of the hardware (i.e. systems were considered to be either too bulky or uncomfortable to wear), the BikeCOM application shows that it is possible to run intelligent application on highly accepted hardware such as smartphones. Acceptability concerns for intelligent applications for vulnerable users should then focus on the applications software tailing issues such as user friendliness and trust. User friendliness is essential as the success of a cooperative application depends on the number of users simultaneously running the application. Trust is also important to favor acceptability and needs to be controlled, as over trusting the system (e.g. getting more distracted at intersections because confident the system would warn in case of danger) may compromise safety. Nevertheless, concerns over trust for other systems such as electronic stability control or frontal collision warning have never been proven to be real.

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Future development of the BikeCOM application should address the current technical issues mainly related to delays, latencies, and positioning as well as address several human factors including optimizing the warning strategy. As the BikeCOM application would enter the market, it would need to face several issues common to all cooperative systems such as penetration, security, standardization, and reliability. Even if achieving high reliability through the cellphone network may be harder than with DSRC, some of the penetration, security, and standardization issues would definitely be easier to handle on the cellphone network than with DSRC.

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