SEBRA

Public report

Project within FFI Cyklar och andra fordon i säker och smart samverkan för en hållbar framtid

Author Thanh Hai Bui, Jonas Andersson, Daban Rizgary Azra Habibovic

Date 2020-02-27

FFI Fordonsstrategisk Forskning och Innovation

Content

1 Summary

The overall trend in Sweden is that the number of fatalities and severely injured in traffic is constantly decreasing. However, bicyclists are the group of road-users that often suffer the most severe injuries when involved in accidents. In this project we want to investigate if a radar mounted on bicycles can help bicycle riders to get better situational awareness and thereby avoid getting into dangerous situations.

For active safety in vehicles, the state of art integrates radar-, lidar-, and camera-based sensors to create awareness for the vehicle and driver. To apply this kind of system on a bicycle would be unfeasible, since the cost would in some cases be as much as the entire bicycle. In this project we therefore propose a low-cost sensor solution that improves traffic safety for bicycles that consist of only one of these sensors - the radar - it is the cheapest and most robust solution.

The project first identifies the most relevant traffic safety related use-cases that involve bicycles. Secondly, a radar-based safety system for bicycles is developed with both sensor and human interface. Finally, the system is evaluated in different traffic situations.

The research questions the project investigates are:

- What safety issues can be addressed by a radar-based safety system mounted on bicycles?
- What performance requirements (field-of-view, computational capacity, power consumption, etc.) should such a system fulfil?
- How should the interaction with the bicyclists be designed to give a high level of safety and user experience?

2 Sammanfattning på svenska

Den övergripande trenden i Sverige är att antalet dödsolyckor och allvarligt skadade i trafiken ständigt minskar. Cyklister är dock den grupp trafikanter som ofta drabbas av de allvarligaste skadorna när de är inblandade i olyckor. I detta projekt vill vi undersöka om en radar monterad på cyklar kan hjälpa cyklister att få bättre situationsmedvetenhet och därmed undvika att komma in i farliga situationer.

Projektet har identifierat de mest relevanta trafiksäkerhetsrelaterade användningsfallen som involverar cyklar. Sedan har ett radarbaserat säkerhetssystem för cyklar med både sensor och HMI utvecklats. Slutligen har systemet utvärderats i relevanta trafiksituationer.

Forskningsfrågorna som projektet har undersökt är:

- Vilka säkerhetsfrågor kan hanteras av ett radarbaserat säkerhetssystem monterat på cyklar?

- Vilka prestandakrav (synfält, beräkningskapacitet, strömförbrukning etc.) ska ett sådant system uppfylla?
- Hur ska interaktionen med cyklisterna utformas för att ge en hög säkerhetsnivå och användarupplevelse?

3 Background

Motorized vehicles are today equipped with various safety technologies providing support to their drivers and passengers. In the meantime, such technologies may be the last line of defense to protect vulnerable bicyclists. While motorist deaths are on the overall decline in Europe, fatalities from bicyclist have stagnated over the past few years. In 2017, 21% of all people killed on roads were pedestrians. In general, pedestrian fatalities have decreased at a lower rate than for other road-users (by 15% from 2010 to 2017, compared to a total fatality decrease of 20%). Cyclists accounted for 8% of all road accident victims in 2017. The number of cyclist fatalities decreased by only 2% between 2010 and 2017, which is much lower than the total fatality decreases (20%). Motorcyclists accounted for 15% of road accident fatalities [1].

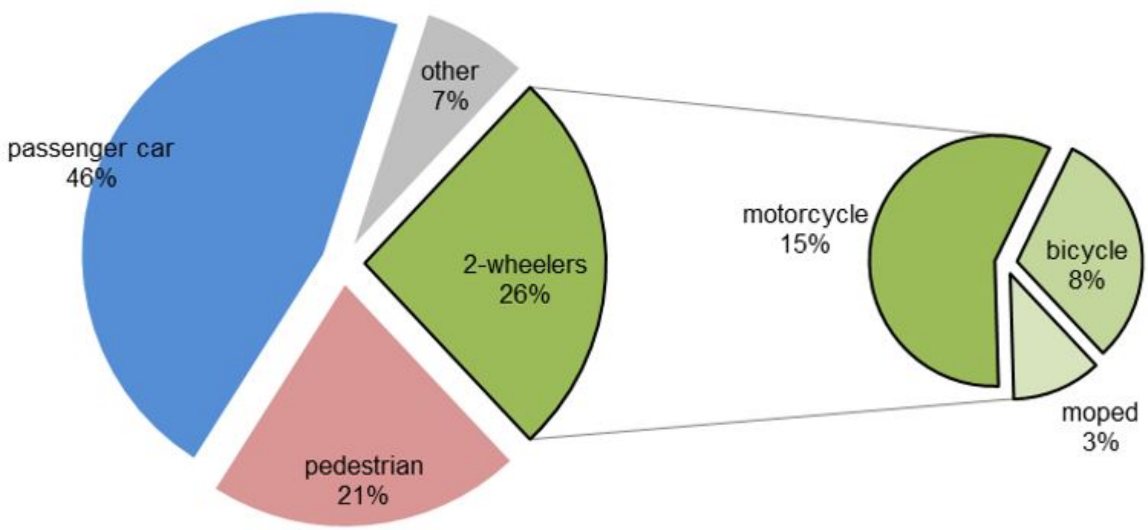

Figure 1: Road fatalities in the EU by transport mode in 2017

Accident distributions in urban areas are different from those on rural roads and motorways. Inside urban areas, 40% of the fatalities are pedestrians, 12% are cyclists and 18% are powered two-wheelers. 70% of the total fatalities in urban areas are vulnerable road users, while outside of urban areas, this percentage is 34%[1]

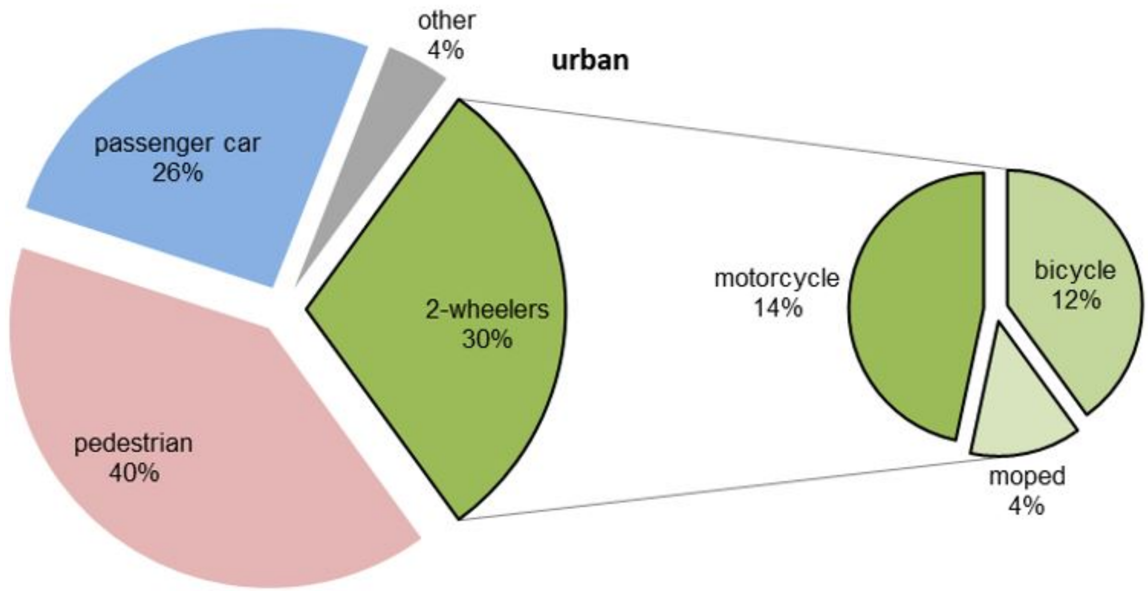

Figure 2: Percentage of road fatalities on urban roads by means of transport in 2017

A similar trend is noticed in Sweden where the number of fatalities and severely injured in traffic is constantly decreasing, while the number of bicyclist fatalities is still stubbornly high. In 2016, 56% of the fatalities in traffic were persons in cars, trucks or busses, 16% were motorcycles and mopeds and 8% were bicycles. Accidents with bicyclists are most frequent in mixed traffic (with cars) and in intersections. For bicyclists, the most common accidents are single accidents. Bicyclists is also the group of road-users that suffer the most severe injuries [2]. Right turning trucks in intersections and collision with cars in high speed are two examples of common accidents between bicycles and cars.

These numbers largely reflect the investment and innovation prioritizations made by the industry and society under the last decades – safety of vehicle drivers and passengers. To ensure that bicyclists don't remain "second-class citizens in traffic" in the future, we need to look for new efficient ways to cut down the fatality and injury numbers. While vehicle-based systems addressing bicyclists' safety can help in this direction, we believe that an approach increasing bicyclists situation awareness is also needed.

To increase bicyclists' situation awareness and thereby increase traffic safety for the user-group, in this project we propose a radar-based safety system mounted on the bicycle as the very first attempt of integrating bicycles into the connected smart transportation system. It detects hazards and informs bicyclists and surrounding traffic about them.

The system is inspired by a mock-up installation previously made by Aptiv. The mock-up was initially installed on a scooter to facilitate robust installation and power supply. The initial results indicated that the idea was sound and worth further investigation and development.

Radar technology has been around for more than 100 years, and sophisticated automotive radar-based systems for active safety are available for vehicles, however the research around radar-based safety systems for bicycles is to our knowledge very limited. Thus, further research around radar, mainly to adapt hardware and software to conform to the

bicycle, and the specific use-cases, is needed. In addition, modes of interacting with / communicating to the bicyclist also require investigation.
Radar sensors have become standard equipment in cars, thanks to its performance features against the reasonable cost. Its detection capability is independent from environmental conditions such as light and weather. A radar performs under conditions where other sensor types fail, and it is capable to virtually look through vehicles (trans vision effect) by exploiting reflections between the road surface and vehicle floor and hence makes the invisible visible [3].
For active safety in vehicles, the state of art fuse radar-, lidar-, and camera-based sensors to create awareness for the vehicle and driver [4]. To apply this kind of system on a bicycle would be unfeasible, since the cost would, in some cases, be as much as the entire bicycle. Consequently, a low-cost sensor that improves traffic safety for bicycles could consist of only one of these sensors, and the radar is the cheapest and most robust solution among these [5].

Radar-based system for bicycles is still a very new area for researchers and commercial applications. Research is very limited in the literature including: how to make radar application being more acceptable for consumers [5], [6], how to increase the detection rate of bicyclists for automotive radars [8], [9], and preliminary studies on how radar information can be used for bicyclists [10]–[12]. The research in [11] investigates the feasibility of radar application to detect approaching vehicles using FMCW radar with 24.1 GHz frequency. In [10], the functionality of radar object detection and the design to overlay radar captured information into a video is investigated. The master thesis work pursued in Halmstad University [12] further investigates the use of FMCW radar for bicyclists, equipped with a laptop for signal processing. However, none of these investigation shows a functioning bicycle radar that can be mounted on a bike, nor does it consider more complex traffic scenarios.

Besides the academic researches, the only available commercial product (up to the time of this writing) that opts the idea is the Garmin Varia Rearview Bike Radar. It is a consumer product resulted from the Garmin's acquisition of a Kickstarter project namely Backtracker. The gadget is working with 2.4 GHz ANT+® wireless communication protocol and addresses the simple use case of early detection and alert of approaching vehicle(s) from behind. This product, however, does not consider more complex scenarios such as overtaking intension or busy traffic situation, neither considering different HMI designs to attract biker awareness with less unnecessary distractions by leveraging threat assessments [13], [14].
In this project, our goal is to have a somewhat wider perspective. We aim to investigate how a radar-based safety system on bicycles can be used to address a wider range of accidents and incidents with motorized vehicles, not only rear-end. We will also explore how it can be used to detect and estimate both longitudinal and lateral distance to upcoming overtaking vehicles and thereby help bicyclists obtaining an improved awareness of their surroundings. It will be the first step of the intended research series to motivate the penetration of car-related technologies into the so far "disconnected" vehicles in the collaborative traffic.

4 Purpose, research questions and method

4.1 Aim and Purpose

The overall purpose of SEBRA project is to help bring advanced active safety solutions available in car into bicycles. This is the first step of the long terms journey to include vulnerable road users as active actors of the intelligent transport systems.

The project aims to investigate how consequences of collisions between bicycles and other vehicles can be reduced using radar sensor technology mounted on bicycles. The radar system developed for use on cars will be modified and mounted on a bicycle. Other product development and V&V processes are also inherited from automotive industry.

The results of the project can be used as motivation to attract more actors in ITS ecosystems into the ideas and create a future inclusive ITS where all road users will equally enjoy the advantage of new technologies.

4.2 Research questions

The research questions addressed within the scope of this project are:

- What safety issues can be addressed by a radar-based safety system mounted on bicycles?
- What performance requirements (field-of-view, computational capacity, power consumption, etc.) should such a system fulfil?
- How should the interaction with the bicyclists be designed to give a high level of safety and user experience?

4.3 Methods

The following methodology is used throughout the project:

- Specify requirements: Requirements are drafted from the literature summaries as safety critical scenarios involving bicyclists in similar traffic environments. Technical requirements of the system prototypes are developed from the selected scenarios, using test environments.
- Test environments including AstaZero test track, Victalab simulator and confined traffic area are used for finetuning the technical requirements and also technical developments in an agile approach.
- The development process consists of hardware configuration, customization of software and development of HMI

- The evaluations are performed in confined traffic area with test persons to evaluate the results from different perspectives and also in semi-controlled tests in real traffic environment.

5 Objectives

Project objectives derived from project aim and purpose, map to the FFI objectives as described below:

FFI objective	Results
Increasing the Swedish capacity for research and innovation, thereby ensuring competitiveness and jobs in the field of vehicle industry	The SEBRA project has helped Aptiv in expanding their knowledge into the bicycle industry, the bicycle experts within the project has helped Aptiv to understand the needs of bicyclists as well as giving insights in bicycles.
Developing internationally interconnected and competitive research and innovation environments in Sweden	The project has participated in international conferences and traffic safety events. The project results have also been disseminated through academic papers, social media and news media in both Sweden and Europe. The project has gotten attention from other research groups in Europe.
Promoting the participation of small and medium-sized companies	Aptiv is an active member of the project and has both delivered competence to the bicycle industry as well as receiving valuable insights about the bicycling industry together with Liri.
Promoting cross-industrial cooperation	The project has required cooperation between different industrial innovation entities, including smart transportation, HMI, bicycle, and radar technology, all present in the project.
Promoting cooperation between industry, universities and higher education institutions	The project has involved students to develop and work with the bike throughout the project via Aptiv's student involvement program.

FFI objective	Results
Knowledge and competence development at research institutes and companies	The cross-industrial cooperation between automotive and bicycles has help the partners including RISE to develop knowledge and competence within the area of bicycling and its connection to smart transportation.

Program objective	Motivation
Reduce the environmental impact of road transport	The main contribution is that the new sensor system will make bicycling safer, which is a step towards making the bicycle a more attractive mode of transport. Especially in city areas with lots of traffic and higher risk of crashes. Cycling contributes to reduction the environmental impact, regarding e.g. greenhouse gases, particles and noise. The project will also help to increase predictability of bicyclists as active participants in the smart transportation, thus will enable green-related optimizations and controls in urban traffics.
Reduce the number of injured and killed in traffic	The whole idea with the project is to increase the situation awareness of the bicyclist and thus improve traffic safety. We have showed thath introduction of sensors in bicycles could provide early warnings of potential collisions, as well as integrating the bicycles into the overall smart transportation strategy in long term. The use cases studied within this project were selected with regards to the final goal to reduce the number of injured and killed in traffic.

6 Results and deliverables

The project was divided into 5 work packages:

- WP1- Scenario description and business case study
- WP2- Radar-system development and modification to light weight
- WP3- HMI Development
- WP4- Evaluation

- WP5- Project Management

The links between WPs are illustrated in Figure 3

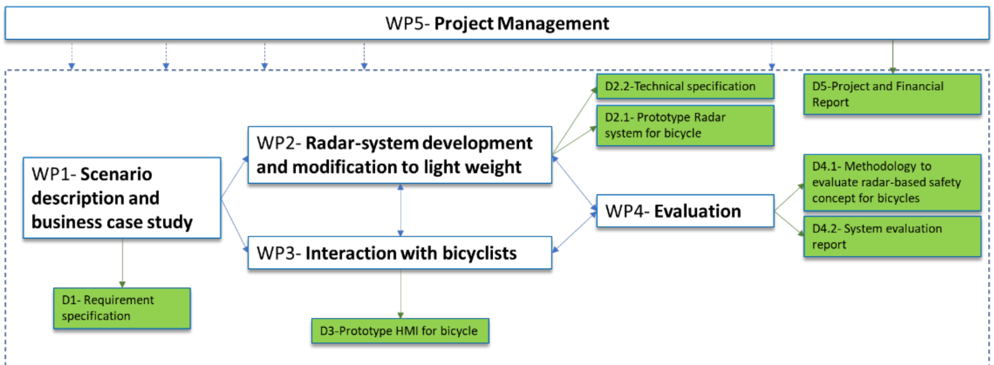

Figure 3: Project work packages

6.1 Results from WP1 - Scenario description and business case study

6.1.1 Literature study

We reviewed the available statistics of accidents involving bicyclist for Sweden, Europe and the United States. Based on this investigation, the scenarios for further investigation were selected from those causing (i) the most severe injury to cyclists, and (ii) cyclists' fatalities.
Statistics of bicycle accidents in the US had been derived from FARS accident database [15]. Figure 4 shows the distribution of bicycle fatal crashes in the US occurred during 2014-2017. Among 16 main scenarios, the most critical are groups of (i) motorist overtakes same direction, and (ii) front crash motorist from left/right, accounting for 1897/3205 cases (59%).

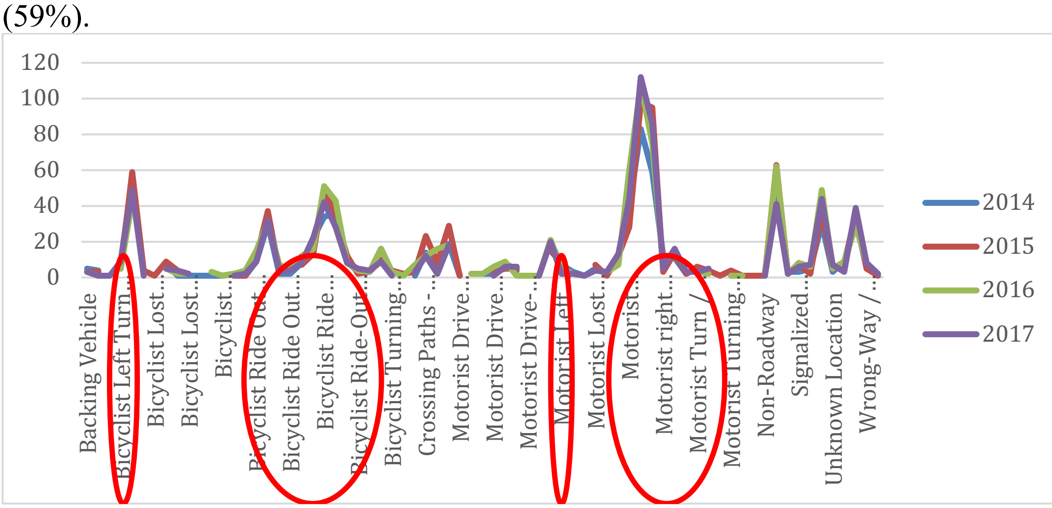

Figure 4: US bicyclist accidents per scenarios (2014-2017)

The EU CATS research project develops definition table of bicycle crash scenarios as shown in Figure 5. An analysis under this project[16] using available bicycle accident data (1999-2014) from 6 European countries[1] observes that the dominant scenarios are (i) Front crash from left/right, and (ii) Motorist overtakes same direction (C1/C2 and L respectively). These dominant scenarios account for 78% of the fatalities of cyclists and 63% of the seriously injured.

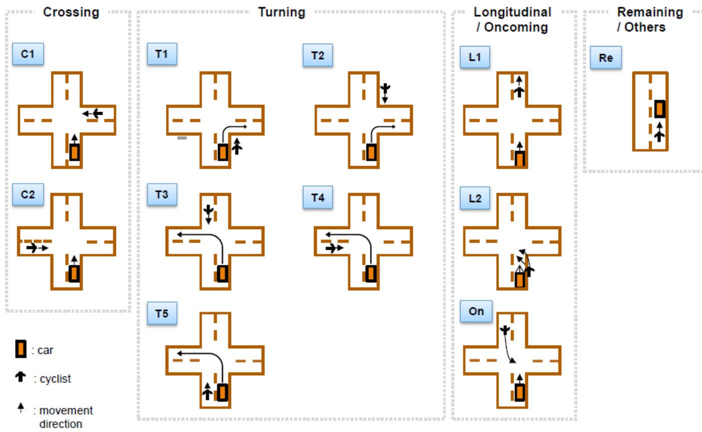

Figure 5: Bicycle accident scenario definition (from the EU CATS project)

In Sweden, according to a related study[17], the most frequent scenarios are C1, C2, T1, T3, L2, L1, and On, accounting for 78% severely injured (AIS2+) and 89% fatal accident cases (Figure 6).

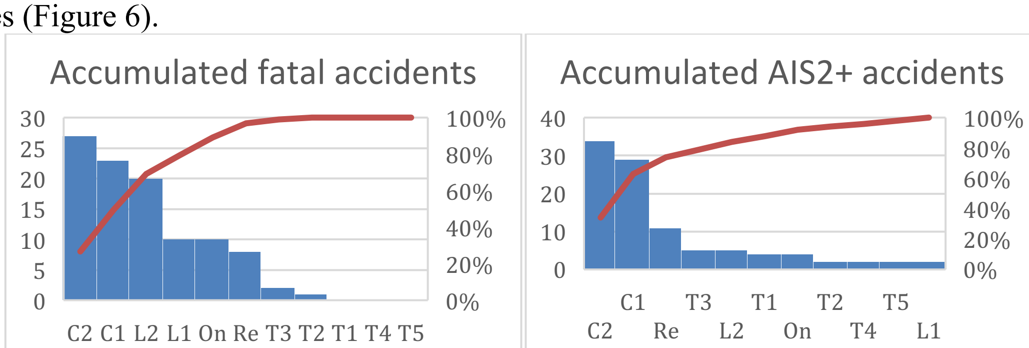

Figure 6: Sweden bicyclist accident distribution per scenario (1)

For both continents, while the priority order of scenarios may vary per country, the top 3 most frequent fatal accident scenarios remains the same: (i) Car/bike in same direction and (ii), (iii) car/bike in perpendicular direction from left or right respectively. In the US and some countries in Europe (e.g. Hungary, France) the fatalities were observed more for "car/bike in same direction" scenario, while in other European countries (e.g. Germany, Sweden), "car/bike in perpendicular directions" are considered more dangerous situations. This difference could be caused by the infrastructure difference such as dedicated bicycle lanes.

[1] France, Germany, Italy, Netherlands, Sweden and UK

From this observation, we select the common list of most frequent scenarios and group them into 4 main categories depending on approaching direction: S1 (L1/L2/T1), S2 (C1), S3 (C2) and S4 (On/T2/T3). These 4 scenarios will be used for further investigation in the project (Figure 7).

6.1.2 User requirements

The user requirements consist of:

- Ability to detect safety critical scenarios from the list of selected scenarios, and information traces of the approaching vehicles
- Ability to inform to traffic participants in right time to reduce the collision risks.
- Understandable communications
- Feasibility (form factor, energy, usage)

The recompilation of the selected scenarios will be used as the baseline for the project.

A brief assessment indicates that, with only information from radar sensors, recognition of traffic location type (road or intersection) cannot be achieved with adequate accuracy. Therefore, we exclude this information from the scenario definitions and recompile the selected scenarios into bicycle's perspective (relative direction with regards to bicycle as basis):

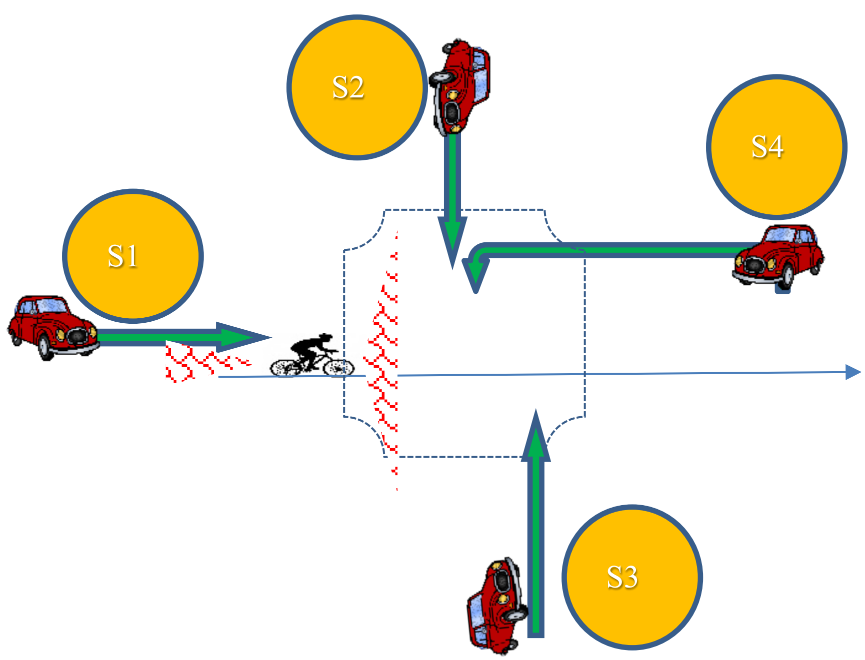

Figure 7: Project selected bicyclist accident scenarios

- Car in same direction (S1)
    - Car approaching from behind, rear collision risk (L1)
    - Car overtaking, side collision risk (L2/T1)

- Car from perpendicular direction
    - Car from left, front collision risk (S2)
    - Car from right, front collision risk (S3)
- Car from opposite direction: front collision risk (S4)

The following information should be provided by the system:
- Detected safety critical scenario
- (Warning) information of approaching vehicle distance, speed and heading
- Communicate the detected information to relevant actors: Bicyclists and driver

Understandability of the communication:
- The information should not present ambiguity or unnecessary distractions
- The information should be received on time and consistent

Usage
- The system should be easy to use and understand
- The system should be able to operate by itself with no dependency on other external systems

6.1.3 Technical requirements

6.1.3.1 Scenarios requirements

Based on the selected scenarios, detail technical specifications of these scenarios are defined for the technical system to be complied. The specifications are influenced from NCAP specifications. Further development of the specifications will be required when the system targets for higher TRL.

Rear collision use case technical requirements
- Both car and bike go straight in the same direction with constant speed
- Lateral distance: <1m
- Bike speed: 0-25 km/h
- Car approaching speed: 10-80km/h (rel)
- Longitudinal distance: equivalent to 0-3s TTC (i.e. 0 upto 8-67m)

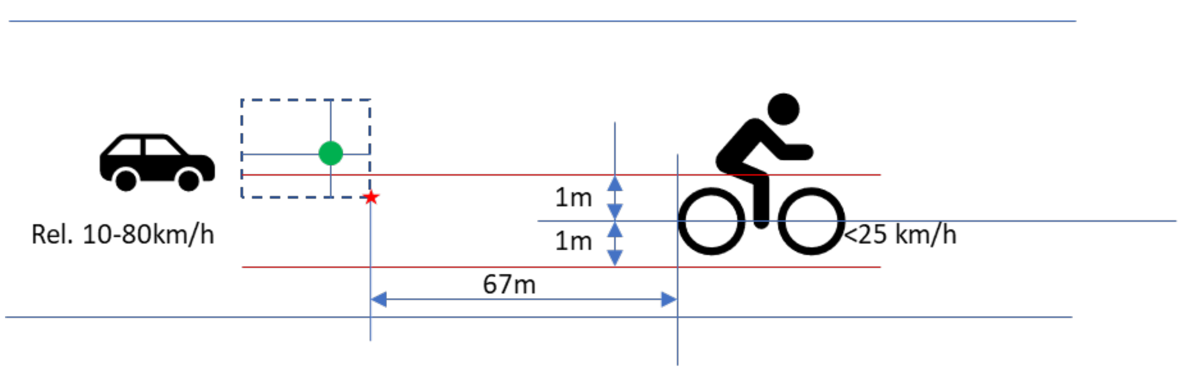

Figure 8 Rear closing vehicle use case

Overtaking use case

- Both car and bike go straight in the same direction with constant speed
- Lateral distance: 1-2m
- Bike speed: 0-25 km/h
- Car approaching speed: 10-80km/h (rel)
- Longitudinal distance: equivalent to 0-3s TTC (0 upto 8-67m)

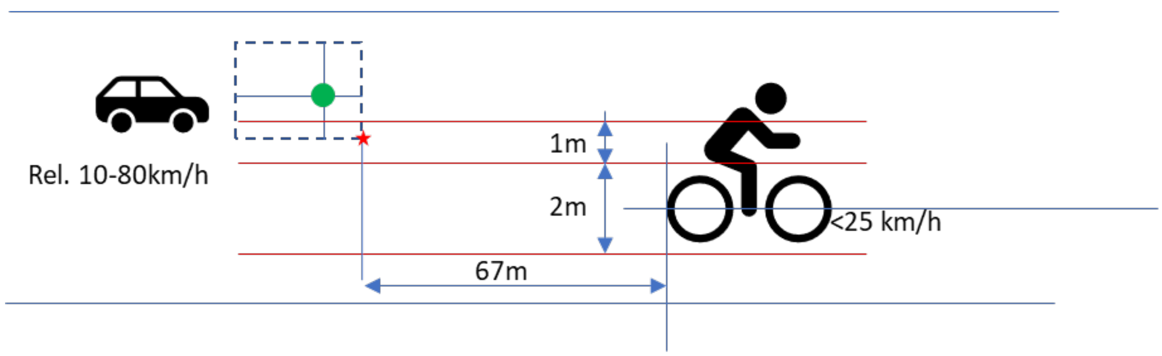

Figure 9: Overtaking use case

Front collision use case (from left or right)

- Bike speed: v_b = 0-25 km/h
- Car speed: v_c = 20-100km/h
- Approaching speed: $v_a = \sqrt{v_c^2 + v_b^2}$
- Approaching angle: $\alpha = arctan\left(\frac{v_c}{v_b}\right)$
- Approaching distance (0-3s TTC): $\mathrm{d} = 0 \rightarrow \frac{v_a}{1.2}\ (m)$

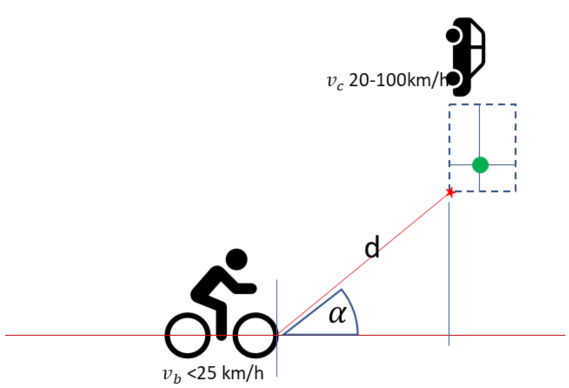

Figure 10: Front collision use cases (left, right)

6.1.3.2 Radar system requirements

The following requirements are made:

- Ability to detect and track movable objects from all direction approaching the host vehicle (bicycle).
- Ability to detect the traffic object involved in detected safety critical scenario, and provide enough technical information for the messaging system to inform bicyclist and driver

- Up to 90m detection range
- Information update frequency of at least 10Hz
- Ability to mount on bike and use the bike's battery

6.1.3.3 HMI requirements

Following HMI requirements are compiled:

- Ability to inform both bicyclist and driver the safety critical information on time
- Minimal unnecessary distractions
- Intuitive in terms of understanding the system with minimum prior knowledge

6.1.4 Business case study

In this section the business case study for advanced safety features on e-bikes is presented. The study has been done by Liri AB, as bike market experts in the project.

6.1.4.1 Different type of bicycle users

Below is a rough categorization of most bicycle users who use their bicycles on roads, in traffic.

<u>Everyday infrequent/casual use</u>

The most common type of user, most often with a bike in lower price categories. We can also include junior riders in this category.

<u>Commuter</u>

More demanding user who commutes frequently or infrequently and rides longer distances than the everyday casual user.

<u>Public bike share user</u>

Uses the bike share programs in bigger cities. May be a frequent user but most often for short distances.

<u>Work related user</u>

Mail delivery, bike messengers, and the like, who frequently uses the bike for work transportation.

<u>Sport/training user</u>

Recreational user who rides longer distances and most often use more expensive bikes with a high technical level.

6.1.4.2 Where is the demand?

<u>Everyday infrequent/casual user</u>

For the everyday irregular/casual rider, the threshold is probably high to add an advanced collision warning system to the bike. Ordinary simple utility bikes and junior bikes are likely to have such a low price level that a collision warning system feels too expensive. In addition, simple utility bikes, without electric assist are currently decreasing in sales numbers. The decrease can partly be explained by electric assisted bicycles, but also to an extent by public bike share bicycles in big cities.

Commuters

Bicycle commuters are probably the most obvious target group for a collision warning system. They have traditionally been buying bikes from a number of different categories. Such as traditional coaster brake bikes, City bikes and trekking/hybrid bikes. At the moment this is changing and commute riders are increasingly choosing electric assist bikes also known as pedalecs or pedal electric bikes or simply e-bikes for transportation. This trend is quite strong and it is likely that a big part, if not the majority, of commuters in most European countries, will use e-bikes in the near future. If we look at the sales figures for bicycles in major European markets, the shift over to e-bikes is clear and even in countries with relatively high market share of pedalecs, sales continue to increase (see separate statistics page).
There are a number of factors in the increase in electric assist bicycle sales that could positively affect the acceptance of a radar warning system.

- The entry of electric bicycles into the market has meant that the average price for a commuter bike has increased, and continues to increase, quite remarkably. This should make the additional cost of a collision warning system less problematic. The buyer of an electric bicycle has already decided to spend a considerable amount of money on the bicycle purchase and could therefore possibly have a lower threshold to accept the additional cost of a collision warning system, compared to buyers of bicycles in lower price categories.

- The acceptance of a technologically advanced systems as part of the bicycle increases when they get more advanced, with more technological content. With electric assistance, you are already adding motor, computer and battery to a "low tech" product that the commuter bike has traditionally been.

- From an aesthetic point of view, there is probably an increased acceptance for adding “bulky” equipment such as radar sensors, controllers and cables on a bicycle, since the e-bike has already changed the aesthetics / design of the bicycle in that direction. There has traditionally been a very conservative view of the bike as a quite minimalistic design product. This may be, in part, due to the lack of covers / body that makes all components visible. The added weight is also negative for the biking experience. With the addition of large batteries, cables and motors, this aesthetic code is less valid and the acceptance for more bulky components has increased.

- The development of electric bicycles continues to move towards higher technology content. From initially being built with simple relatively inexpensive systems with hub motors to more complex and expensive systems with center motor units and torque sensing. This is also visible in the fact that the average price for an e-bike is still increasing. The product matures and the consumer is gradually willing to pay more for better and more reliable systems. This should also affect the acceptance of new technical equipment on the bike in a positive direction.

- As seen on the prototype SEBRA bikes a benefit of adding the radar system to an e-bike is also power supply. The collision warning system could most likely be powered by the e-bikes main battery. This also makes it less likely that the system runs out of power since the user only has one battery to manage and pedal assist is a good incentive to keep it powered up.

Work related user

It is also worth mentioning that in addition to commuter bikes, cargo bikes and mail delivery bikes are also being electrified to a large extent. A category of bike users where working environment/safety may play a role as an argument for a collision warning system. These categories of bikes/riders, although small in numbers could possibly use a collision warning system developed for e-bikes.

Sport/training user

It is also likely that sport cyclists who regularly exercise on busy roads would benefit from a collision warning system. It is a group of cyclists who spends quite much money on their bikes, appreciate new technology, reads and educates themselves about their bicycle. But the market is much smaller in number of cyclists/units compared to the commuter market and the requirements for a system aimed at this group probably looks quite different with a need for even more compact format, lighter weight and an aesthetically pleasing design/packaging. In addition, I find it difficult to see bicycle manufacturers choosing to specify radar warning on this type of bicycle as an OE. It would primarily be an aftermarket product and the sales volumes then probably lower. The power supply is also different compared to an e-bike. A system on a road race bike must contain its own battery.

Others

A number of bicycle users such as mountain bikers, BMX riders, etc. are not taken into account as their use in traffic is limited or non-existent.

6.1.4.3 How can a product to market be designed?

The bicycle industry is used to using ready-made standard systems in the development of new bicycles. The typical product manager is choosing from systems and components already finalized for production by the supplier. Apart from the bicycle frame set that is most often designed by the bicycle brand, the product development is largely driven by suppliers and not by the bicycle manufacturers themselves. It is these system suppliers who develop a complete product and to a large extent also market themselves with a brand towards both bicycle manufacturers and consumers. Good examples of this is complete drivetrain systems from companies like SRAM and SHIMANO and pedalec systems from BOSCH, SHIMANO, YAMAHA. Therefore, it may be important to package a collision warning system as well as possible. Bicycle manufacturers are used to standard components and a "turnkey ready" system should have the best potential to reach high sales numbers.

An extended Safety system

It could also be worth to consider an extended system that, in addition to radar warning, also contains other safety functions. Offering a more comprehensive safety system would probably be more attractive than a one-function product with only radar-based collision warning. Since the system must already package computing power and HMI, the additional cost may be relatively small for added features.

Suggestions for relatively simple functions that may be added to such a system

- Tire pressure monitoring, eg with sensors in valve or inside rim. Low tire pressure = higher accident risk

- Front and rear light in the radar sensor unit. It could be made more advanced with the addition of a low beam light for riding at night. A feature normally not seen but most needed on bikes. Perhaps also with a flashing rear light to approaching cars.

- Icy/slippery road warning (temperature measurement)

- IOS / Android user app that handles software updates of the system. The consumer could be encouraged to install the app through content such as bicycle computer functions, mileage measurement, average speed, commuting / exercise encouragement goals.

- Service interval monitoring. Since service is most often done infrequently a simple odometer function can keep track of total mileage and notify the cyclist when the bike should be serviced. Since component failure is a part of accident statistics, this could be a good feature. If this is communicated via a user-app, you can also integrate booking a service event. This feature should also be interesting for the bike manufacturer since it promotes the the service/workshops and a possible increase in their turnover.

6.1.4.4 Conclusions from the business case study

It is our opinion that a well functioning radar collision warning system has potential in the bicycle market. Mostly as equipment on the fast growing e-bike segment, a category of bikes quickly becoming the major mean of bicycle commuting in Europe. These bikes have

both increased technical content and also command higher prices compared to normal bicycles. Both these factors are important for the acceptance of an additional system added, like collision warning. It should also aid the development of such a system that a power source, the main e-bike battery is already present.
It is also likely that more safety functions/features would make such a system more attractive to the market and may be relatively easy to add, since computing power and UI is already there. The system could then be promoted as a more comprehensive rider safety system rather than a one function product.

6.2 Results WP2 - Radar-system development and modification to light weight implementation on bike

6.2.1 Radar mounting configuration

An electric bicycle was selected for the project prototype, it has a pre-mounted battery that can power the radar system. From the selected scenarios, we recognize that unlike cars, bicyclists are more vulnerable to motorists driving same direction from behind, thus need a longer radar detection range from the rear and wider range for radars in front.
We opt for the largest possible radar detection coverage during this phase, i.e. with some redundancy in field of view. Optimal settings were finetuned based on the statistics and surveys collected during the pilot tests.
The mounting configuration is therefore selected with 4 identical Aptiv latest SRR5 radars, where 2 are mounted at rear and 2 at front. The radars are situated at a 30° offset angle from the bicycle's centre frame with 150° Horizontal field of view (HFOV) and 10° Vertical field of view (VFOV). This configuration provides a coverage of full 360°, not counting a small square shaped blind spot (Figure 11). The detection range is up to 93m according to the selected radar sensors.

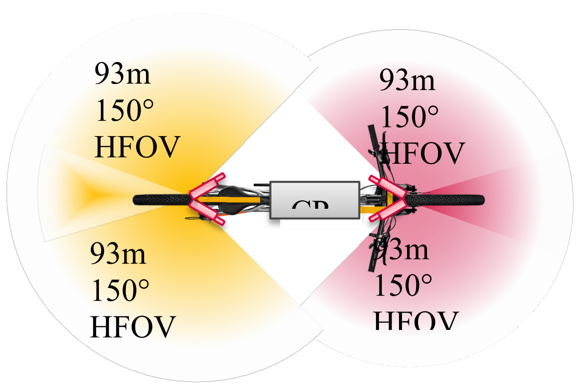

Figure 11: Radar mounting configuration in the prototype

6.2.2 Radar object detection software customization for bicycle

The software inherits the latest software applied for cars developed by Aptiv. The processing chain consists of the follow main modules:

- SENSORS: Pre-processing at the radar sensor level (4 mounted radar sensors).
- TRACKER: The outputs of these 4 radar sensors go to the tracker module. The tracker fuses detections from all radars, creates newly detected objects with assigned ID and tracks them over time. Identified objects are classified into movable or stationary. Movable objects are specified by a rectangle with moving direction, and in S4 scenario also include the predicted collision area with a predefined time-to-collision.
- FEATURE FUNCTIONS: The reduced list of identified objects provided by the tracker then feeds to feature functions. Feature functions module analyses objects created by the tracker, estimates the collision risk levels based on the scenario categories. The feature functions use predefined risk areas as described in Figure Figure 15: Logical danger zones as defined by the feature functions.
- HMI: The HMI gets information from the feature functions module (also directly from the tracker if needed), formulate HMI messages and present to bicyclist and/or vehicles through different channels. This can be used as the HMI presentation layer of the radar system, enabling required flexibility for HMI design approaches.

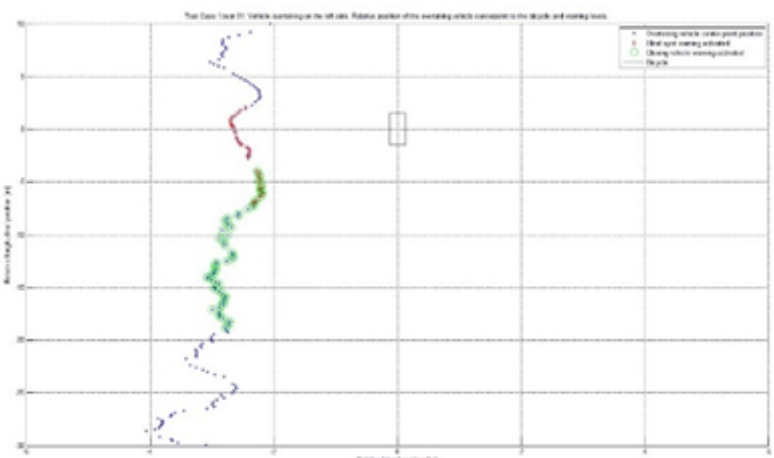

Figure 12: Overtaking scenario vehicle trajectory (AstaZero test track)

We leverage the existing maturity of sensors and tracker modules and focus the customizations on the feature functions and HMI modules. The following challenges were identified:

- ***Tilting***: Bicycle dynamics is fundamentally different from four-wheeler vehicles where yaw and roll creates measurement instabilities. Fortunately, the preliminary analysis of collected data from AstaZero test track indicates that the existing Radar and Tracker modules can handle the tilting effect with no essential reduction of object detection accuracy as required by the feature functions. The oscillation effects (for example shown in Figure 12) are detected in tracked target relative positions, however do not result in serious deterioration of the feature function performance (Figure 14 shows the trajectories of tracked target vehicle from Tracker module).

- The front collision functions - relying on the prediction of potential collision areas using historical trajectories (of both bicycle and vehicle) - are negatively impacted for the S4 scenario where the relative angle between trajectories is closing to zero. For S2 and S3 scenarios (perpendicular directions from left or right) the results are acceptable and have been improved by assuming zero yaw rate of the bicycle.
- We decided to execute an additional experiment to further investigate the tilting effect. In this experiment, the bicycle with sensors is followed by another bicycle (acting target vehicle), both are going straight with minimum variation of lateral distance. In the first session we performed very aggressive pedalling with high roll angle changes. It is directly followed by another session where we did no pedalling at all. Aggressive pedalling causes an oscillation of higher frequency and created more "ghost" objects (mis-classified objects) by the Tracker. Smoothing filter will be needed to identify the real approaching target object(s). Figure 13 illustrates the differences between two pedalling cases, where the top part shows recorded timeseries of lateral distances and the lower are the detected objects by Tracker in the two cases accordingly.
- Prediction of the scenarios without GPS information: GPS information is actually not required by the system since the scenarios are already converted into bicycle perspective and no longer dependant on traffic location types. The same system in car does not use absolute positioning information for this function either.

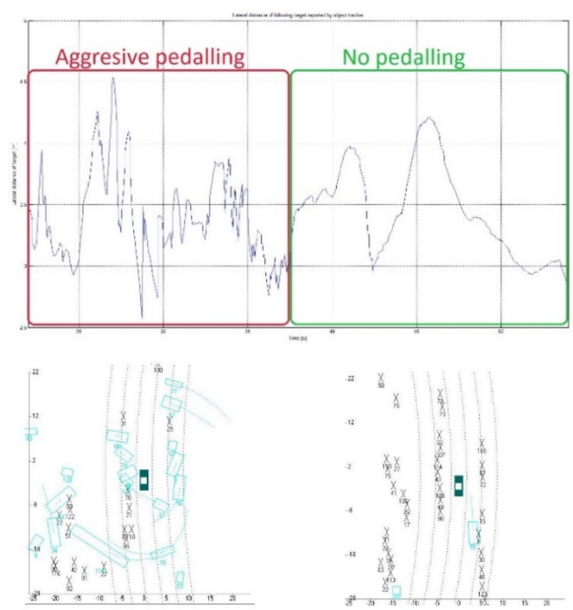

Figure 13: Aggressive pedaling (left) vs. gentle pedaling (right) and impacts on tracker performance. Aggressive pedaling create ghost objects.

- Stationary objects
    - The radars alone can detect stationary objects but cannot differentiate between objects and the scenery. In car system, the information is fused with camera information to solve this issue.
    - Radar only setup in bicycle thus results in a large amount of uninteresting stationary objects. However, collision with stationary objects (single accident) is not tackled within this research. The exception that was considered in this project is the special situation in scenario S1 where vehicle breaks in front of the bicycle after overtaking it.

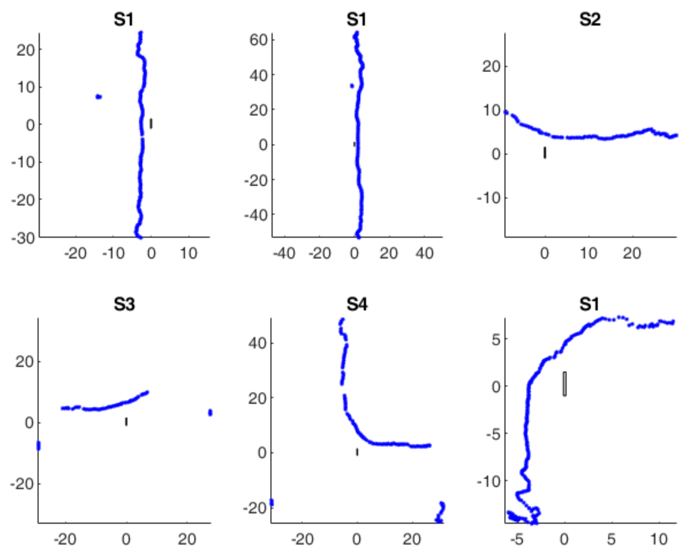

Figure 14: Tracked relative trajectories of approaching vehicles, different scenarios

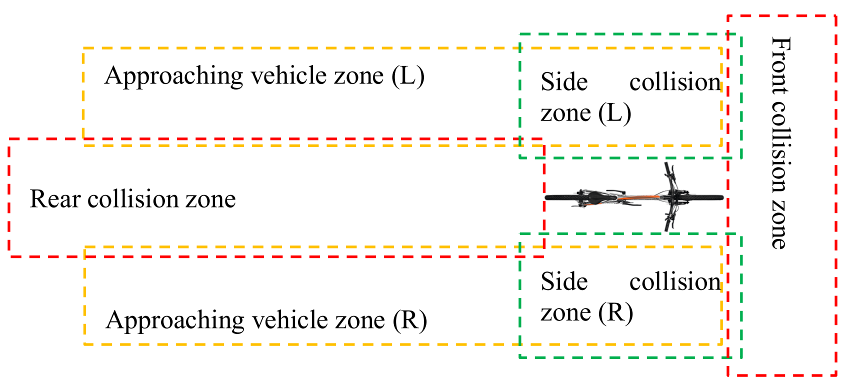

Figure 15: Logical danger zones as defined by the feature functions

6.3 Results WP3 - HMI Development

6.3.1 Identifying Requirements

Two workshops have been conducted involving experts within mobility and traffic safety to develop knowledge and collect ideas related to functions, interactions, problems and solutions of a device for increasing the situational awareness for a bicyclist in traffic.
Project-internal workshops were used to spawn ideas about what, how and when to communicate between the system and its users.
The ACD^3 framework for product development has been used to identify and specify requirements for the user interface further. ACD^3 is an iterative process for identifying and specifying requirements in tandem with design work[18].

6.3.2 Major Design Challenges

- Accidents are rare – the system function is critical (for the safety of the bicyclist) only on rare occasions and must work well on these occasions since consequences can be fatal if not.
- If the situation is critical there is little time to react. Thus, in a critical situation, the time to perceive, interpret and act must be short. Since critical situations are rare and interpretation must be quick, all user interfaces must be intuitive.
- The system is aimed for use in traffic. Distraction of the bicyclist and other road users in non-critical situations must be avoided for safety reasons.
- False positives reduce the (information) value of the signal sent to the bicyclist. It can reduce the bicyclist's trust in the system and make the response time longer.
- If the bicyclist has a high trust in the system, a false negative might make the bicyclist less perceptive of other signals of danger in the current situation.
- Preferably, all components should be mounted on the bicycle. The preference is to avoid components that should be worn.
- The sensors need 12 V electrical power supply.
- A bicycle has unstable vehicle dynamics. Therefore, active intervention, for example automatic braking, may be dangerous for the bicyclist.
- The system interaction can be designed to warn a user when certain conditions apply, or the system can be designed to communicate information of the current traffic state to a user – leaving to the user to assess the current level of risk.

6.3.3 Messaging requirements

The messaging mechanisms has been designed toward both actors: (i) the bicyclist and (ii) drivers of target vehicle(s). The purpose of (i) is to assist the bicyclist in situation awareness, while that of (ii) is to make the presence of the bicycle more salient to approaching vehicle’s driver.
The following messages are formulated and is accommodated by the designed HMI:

- Messages to bicyclist:
  - Target vehicle entering/leaving the danger zones: Information includes relative trajectory direction of the approaching vehicle, and the risk level. Frequency, intensity and vibration shifting between hexagon vibration motor array are used to encode the presence of vehicle in danger zone, direction and risk level. The HMI graphical display (mounted in handle bar) also shows the same information using visual modality.
  - Prevention or recommendation of bicyclist's specific action: Depending on the detected scenarios, prevention or recommendation of action (e.g. do not turn left when a vehicle is overtaking, or do not change speed/trajectory when front vehicle approaches but no collision risk if both keep current trajectories). This will be performed by special vibration pattern at handle grips and/or in HMI graphical display.
- Messages to vehicle:
  - Presence of bicycle in vehicle's trajectory with overlapped collision area: flashing light towards approaching vehicle to increase the vehicle awareness when the vehicle enters one of the danger zones and/or the predicted collision areas overlap.
  - Overtaking awareness.

6.3.4 Early Design Decisions

Because of the unstable vehicle dynamics of a bicycle, the system can inform the bicyclist while not interfering bicycle's motion. The bicyclist needs to take all actions.
The system will have two user interfaces. One interface is directed towards the bicyclist with the purpose to improve his/her chances to correctly understand dangers in a risky situation, defined by the selected scenarios. The other interface is directed towards (drivers of) other vehicles in the surrounding traffic environment with the intention to increase the bicycle's saliency in situations where there is a risk of collision.
The system will be developed for electrical bicycles for two reasons: (i) an electrical bicycle has a battery that can power the system, and (ii) the system will increase the price of the bicycle, but relatively less so for a more expensive e-bike. During development, using an electrical bicycle has been beneficial because this made it less demanding to ride the development prototype bicycle which became quite heavy from the extra added weight of the system, devices and equipment.

6.3.5 Simulations for Evaluation of the Design

The AstaZero test track has been used to simulate traffic scenarios in a controlled traffic environment. The prototype bicycle shown in Figure 16 was developed to record data from the radar sensors. These data have been used for the development and test of the radar system detection and tracking functions.

Figure 16: SEBRA bicycle prototype 1

A car-driving simulator in the VICTA Lab has been modified to support use of a bicycle for controlling the simulation, as shown in Figure 17. This simulator is used both for evaluation of the design of the bicyclist's user interface, and for simulating collision scenarios which are not safe to test in the real world. The simulator helps to explore different aspect of the user interface, including sensor modalities, different messages and different encoding of messages. The AstaZero test track is available in VictaLAB environment, the approaching vehicles are simulated by the mockup radar information generated for different scenarios. Recorded radar data can also be used in the simulation. The bike prototypes and the VictaLab simulator for bike will be used as part of the research platform for future research in this direction.

Figure 17: Bicycle simulator in Victalab (with other testbike)

6.3.6 Multimodal design of HMI

The HMI is design with multimodal approach; different modalities are used to inform involved actors at different time with different information. The vibration is used first to get intention of the bicyclist while vibrating pattern and also the Smartphone HMI will provide additional information on the direction and situations.

A subcomponent of HMI is also designed to inform the approaching vehicle to increase the bicycle saliency and raise proper awareness for the driver.

6.3.7 Haptics modality

Haptic motors are installed in the left and right handlebar and in the seat. Like the LED:s, and the haptic motors are controlled by a microcontroller (Arduino Nano) which is connected to the PC via USB. The haptic motors draw quite a lot of power and cannot be powered directly from the microcontroller. Instead, two ULN2003A NPN Darlington transistor arrays are used in combination with the microcontroller. The microcontroller controls the vibration patterns and the vibration intensity using pulse width modulation (PWM).

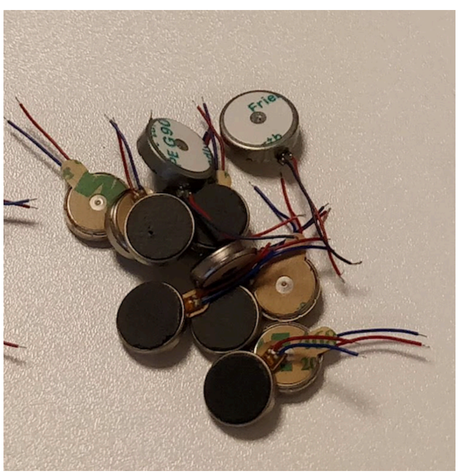

Figure 19: Haptic motors for handlebar

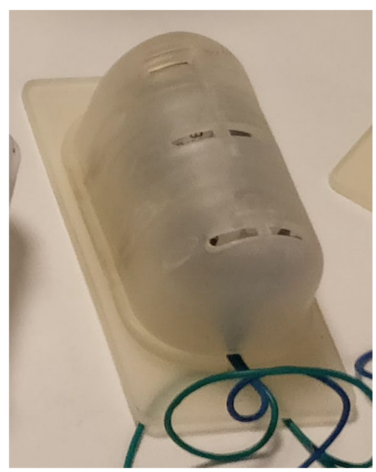

Figure 18: Haptic motor for the seat

6.3.8 Visual modality towards approaching vehicle(s)

To make other road users aware of the bike and warn them in case of potentially dangerous situations, LED lights are mounted in the front and rear of the bike. The LEDs can be controlled individually and are RGB capable and can therefore display a large range of colours. The rear lights are programmed to be red and the front to be white. The LEDs are controlled by a controlled by a microcontroller (Arduino Nano) which is connected to the PC via USB. The microcontroller controls the brightness, colour and blinking pattern of the LEDs.

Figure 21: Rear LED warning light

Figure 20: Front LED warning light

6.3.9 Technical HMI

A simple LCD HMI that visualizes how the system detects and classifies traffic situations is used for technical tests and calibration of the system. The HMI provides different visual alerts per scenarios via different display zones in the graphical display. Figure 22: Visual HMI shows an example when a vehicle is approaching from behind. The HMI provides a view of different zones defined relative to the bicycle. Definition of zones and verification algorithm to mark tracked object(s) entering/leaving zone(s) are provided by the customizations of feature functions.

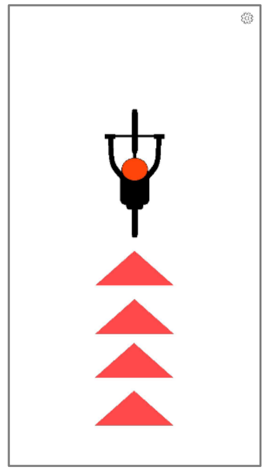

Figure 22: Visual HMI

6.3.10 Smartphone HMI

Figure 23: Smartphone HMI shows another version of the visual HMI showing objects that the radar tracker classifies as a moving object within a specified range. An Android smartphone is connected to the PC using a Wi-Fi connection provided by a small router mounted in the bike (tp-link TL-WR802N). The smartphone provides a visual HMI for the bicyclist. By connecting the smart phone to the bike, it is possible to live stream what the sensors are detecting. The arrow points out the Host (SEBRA bicycle) and all moving objects in radars field of view will show up on the smartphones' screen in the form of red rectangles.

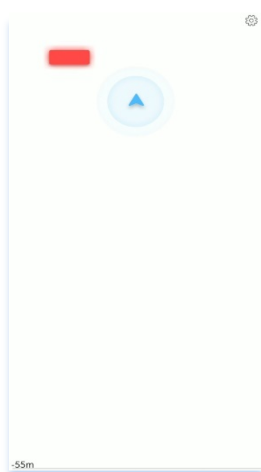

Figure 23: Smartphone HMI

6.4 Results WP4- Evaluation

6.4.1 Technical evaluation

The technical development and evaluation were made iteratively in the Aptiv garage and traffic surroundings. To control for contextual factors and noise a technical evaluation was also performed at AstaZero proving grounds in Borås.

The following questions were posed for the technical evaluation:

- Can the radar-based active safety system for car be used for bicycle with minimal customization efforts?
- How should we mount sensors and other systems on the bike?
- What challenges are in terms of sensor and tracker performance when mounting a radar developed for automotive purposes on a bike?

Within the project, the results from the technical evaluations and the data recorded from AstaZero have been used to customize the feature functions and warning activations.

The technical evaluation at AstaZero is described in Appendix A.

6.4.2 UX evaluations

The UX evaluations were planned in 2 iterations:

- Explorative UX evaluation
- Perceived safety benefit assessment of SEBRA active signaling system

6.4.2.1 Explorative UX evaluation (evaluation pilot)

The first test was an explorative assessment to evaluate the general UX and perceived benefit of using the SEBRA system in traffic and to explore if the timing of warning signals are appropriate. To evaluate the user experience and understandability of the system, data was collected on UX, perceived benefit, understandability, and timing of signals. To ensure that we have a good system for more extensive evaluations. The study was made with 7TP (RISE employees, during a short ride around 10-20min test on bike and in vehicle (to also evaluate the system from the drivers perspective). The test was done using a straight road, with overtaking and rear warning situation.

A majority of the participants did not acknowledge any haptic feedback for the first biking lap in this first iteration. After being informed that there was haptic feedback, and having biked for another lap, these same participants expressed that the haptic feedback was or could be mistaken for other vibrations coming from e.g. road or the electric motor. The haptic feedback was thus determined to be weak and were tuned for the next iteration.

Half of the participants expressed that the screen was or can be distracting, meaning that there was an issue of maintaining engagement in the environment around as well as looking at objects through the screen. The information in the screen was improved for the next iteration.

From the driver's perspective a majority of the participants had some confusions in interpreting the signals from the bike. Nevertheless, some participants noted that the signals catch the driver's attention, and half of the participant expressed that this system would be beneficial.

6.4.2.2 Semi-Naturalistic Operational Test

A semi-controlled test with 16 participants was performed as a follow up to the initial explorative study. Evaluations from this iteration revealed that haptic feedback especially in the handles are still weak, and statements about confusing haptic feedback with road conditions and other vibrations were still a theme. Assessments on the biking experience resulted in a majority of participants expressing that the feedback system is beneficial, but to some degree depends on the environment in which the feedback system is used. The screen containing radar-information was still experienced as distracting for some participants, and a few participants also mentioned that the elements of information can be improved regarding colour and size.

From the driver's perspective, nearly half of the participants had some uncertainty in interpreting the signals. A few participants interpreted the backlights as brake-lights, and some other participants questioned why the lights kept signalling during take-overs. Nearly half of the participants expressed that the signals are beneficial from a driver's perspective and that they increase awareness about the bike.

To conclude, the user experience evaluations show great diversion in how different persons both interpret signals and how they perceive the benefit of the system. Some are very critical, while some are very positive. The system enables use of many varieties in terms of messaging and modalities and that has to be further explored to find a human-system design that can be adapted to individuals at the same time as it levers the safety benefits of system.

6.4.3 Future studies and the bike as a research platform

To determine if the SEBRA signal towards other road users make any difference in terms of safety margins to passing vehicles future studies can be directed towards more quantitative approaches. Focus on rear approach/take-over is still relevant but can be complemented with side- and forward collision situations. These are however difficult to achieve in a safe way in real traffic. To retrieve data on the systems safety benefits the radar can be used to measure lat/long distances and compare trajectories with and without the signal towards traffic. A bike standing still could also be used and measure passing vehicles to improve comparability, however sacrificing some validity of the situation. The purpose would be to see if the SEBRA system leads to a larger safety boundary or "bubble" towards motor vehicles around the cyclist. In general, the bike has large potential as a research platform and measurement tool to study interactions in real traffic.

6.5 Results WP5 Project management

The project has successfully coordinated different partners, engage the project with SAFER, AstaZero open research, FFI conferences, ITS World congress conference, UN Ministerial Conference on Traffic Safety in Stockholm, and other activities. A video representing this project has also been produced and made available to public (https://youtu.be/vUADY61-WBE).

The bicycle prototype and Victalab simulator has been made accessible to public at demo events. Several papers have been published and planned to publish shortly (Details are provided in section 7).

7 Dissemination and publications

7.1 Dissemination

The following dissemination activities have been performed where SEBRA project and the demonstration prototype were presented to different audience:

- Workshop "Cykelseminarium" held at Västerås, 2018/10/17 by Länstyrelsen Västmanlands län. Presentation: "Cykling igår, idag, imorgon"
- Workshop "SAFER's end of Stage 4 and start of Stage 5" held at Lindholmen, 2019/04/10 by SAFER.
- Workshop and Victa Lab demonstration to Ladies Circle, held at RISE Viktoria, 2019/22/21.
- Seminar "SAFER's engagement in India and China – current activities and future possibilities" held at Lindholmen, 2019/11/14 by SAFER.
- Conference "The automotive industry is changing: How can we meet the biggest social challenges?" held at Lindholmen, 2019/10/16 by FFI
- SAFER lunch seminar 2020/01/31
- To appear in TV4 science news during spring 2020
- Youtube film on RISE YouTube channel: https://youtu.be/vUADY61-WBE

International conferences:

- 11th International ACM Conference on Automotive User Interfaces and Interactive Vehicular Applications, 2019/09/22-25, The Netherlands
- 26th ITS World Congress, 2019/10/21-25, Singapore

- CES 2020 conference, 2020/01/07-10, Las Vegas. Bike showed in Aptiv area
- 3rd Global Ministerial Conference on Road Safety, 2020/02/19-20, Stockholm. Bike demonstrated in collaboration with SAFER

7.2 Publications

[1]D. Lindström et al., "Designing HMIs for an Active Safety System on Bicycles," in Proceedings of the 11th International Conference on Automotive User Interfaces and Interactive Vehicular Applications: Adjunct Proceedings, New York, NY, USA, 2019, pp. 125–129.
[2]C. Englund, H. Clasén, T. B. Hai, D. Lindström, and J. Andersson, "Radar system for bicycle - a new measure for safety," ITS World Congress, 2019.
[3] (To be submitted) "Transferring active safety technology from cars to bikes"
[4] (To be submitted) "Radar-based active safety for bicyclists and car drivers – experiments from real world testing"

8 Conclusions and future research

We have investigated how a radar system can enable the advanced safety functions accessible for bicyclist. Reconfiguration of radar settings and related safety software has been performed based on the accident pattern analysis. An integrated HMI system has also been prototyped that enhances situation awareness for both vehicle and bicyclist if potential accident risks are recognized at certain level. The project paves the way to include VRU's as active participants in the future smarter mobility ecosystem. Future researches can be conducted to further investigate the following research questions:

- Improve the traffic situation information with detected stationary objects (e.g. to classify environment types such as bicycle lane or intersection, highway, etc.)
- Integration with other types of sensors (camera, GPS, etc.)
- Improve radar system with ability to detect 3D information.
- Next step of inclusive ITS, to enhance communication between VRU and vehicles

9 Discussions

9.1 Bike specific problem- roll angle

Existing processing chain in the system is not fully prepared for quick rolling angle changes in bike, and thus tracking performance is reduced if bicyclist pedals aggressively. Fortunately, the system is still working but not in optimal way (with more falsely detected "ghost" objects). This suggests future research to tackle free 3D movements of the ego-vehicle.

9.2 Out of box automotive system is feasible

The experiments using data collected from AstaZero show that out of box automotive system can be used for bicycle. The most advanced and robust object tracker module on top of the radar fusion module are proven to work for bicycles, being able to detect all movable objects surrounding the bicycle within the specification's ranges. The only module that need to customize is the feature function module. Feature function module will take the tracked objects from tracker module, depending on specific rules to classify traffic situations, trigger the corresponding HMI messages.

This finding is important, since when the constant development of technology in car's active safety can be used, the system will benefit from all future developments with relatively little additional efforts required.

10 Participating parties and contact persons

RISE Research Institutes of Sweden AB
Lindholmspiren 3A
417 56 Göteborg
Contact: Jonas Andersson (Senior researcher)
jonas.andersson@ri.se

Aptiv Contracting Services AB
Mölndalsvägen 36,
412 63 Göteborg
Contact: Henrik Clasen (Technical Manager)
henrik.clasen@aptiv.com

Liri AB
Box 37
443 21 Lerum
Contact: Linus Lindgren (Board chairman)
linus@liri.se

References

[1] "European Commission - PRESS RELEASES - Press release - 2018 road safety statistics: what is behind the figures?" [Online]. Available: https://europa.eu/rapid/press-release_MEMO-19-1990_en.htm. [Accessed: 14-Oct-2019].

[2] A. Niska and J. Eriksson, *Statistik över cyklisters olyckor : faktaunderlag till gemensam strategi för säker cykling*. vti, 2013.

[3] J. Dickmann *et al.*, "Automotive radar the key technology for autonomous driving: From detection and ranging to environmental understanding," in *2016 IEEE Radar Conference (RadarConf)*, 2016, pp. 1–6.

[4] K. Ambak, R. A. A. O. K. Rahmat, and R. Ismail, "Intelligent transport system for motorcycle safety and issues," *European Journal of Scientific Research*, vol. 28, no. 4, pp. 601–612, 2009.

[5] F. Rosique, P. J. Navarro, C. Fernández, and A. Padilla, "A Systematic Review of Perception System and Simulators for Autonomous Vehicles Research," *Sensors*, vol. 19, no. 3, p. 648, Jan. 2019.

[6] R. J. Evans *et al.*, “Consumer radar: Technology and limitations,” in *2013 International Conference on Radar*, 2013, pp. 21–26.
[7] R. J. Evans *et al.*, “Consumer radar: Opportunities and challenges,” in *2014 11th European Radar Conference*, 2014, pp. 5–8.
[8] E. Coelingh, A. Eidehall, and M. Bengtsson, “Collision Warning with Full Auto Brake and Pedestrian Detection - a practical example of Automatic Emergency Braking,” in *13th International IEEE Conference on Intelligent Transportation Systems*, 2010, pp. 155–160.
[9] G.-R. Liu, M.-Z. Zhou, L.-L. Wang, and H. Wang, “A Radar-Based Door Open Warning Technology for Vehicle Active Safety,” in *2016 International Conference on Information System and Artificial Intelligence (ISAI)*, 2016, pp. 479–484.
[10] A. Johnson, C. Rupp, B. Wolf, L. Hong, and A. Mitra, “Collision-avoidance radar for bicyclist and runners,” in *Proceedings of the IEEE 2010 National Aerospace Electronics Conference*, 2010, pp. 84–91.
[11] T. Krejci and M. Mandlik, “Close vehicle warning for bicyclists based on FMCW radar,” in *2017 27th International Conference Radioelektronika (RADIOELEKTRONIKA)*, 2017, pp. 1–5.
[12] P. Werner, *Radarmodul till cykel för upptäckt av bakomvarande trafik*. 2014.
[13] M. Brannstrom, J. Sjoberg, and E. Coelingh, “A situation and threat assessment algorithm for a rear-end collision avoidance system,” in *2008 IEEE Intelligent Vehicles Symposium*, 2008, pp. 102–107.
[14] M. Brannstrom, E. Coelingh, and J. Sjoberg, “Model-Based Threat Assessment for Avoiding Arbitrary Vehicle Collisions,” *IEEE Transactions on Intelligent Transportation Systems*, vol. 11, no. 3, pp. 658–669, Sep. 2010.
[15] NCSA, ““Fatality Analysis Reporting System (FARS) Encyclopedia,” 1975. [Online]. Available: https://www-fars.nhtsa.dot.gov/QueryTool/QuerySection/SelectYear.aspx. [Accessed: 09-Aug-2019].
[16] J. Uittenbogaard, O. M. G. C. op den Camp, and S. van Montfort, “Overview of main accident parameters in car-to-cyclist accidents for use in AEB-system test protocol.” ICSC, 01-Jan-2016.
[17] R. Fredriksson, K. Fredriksson, and J. Strandroth, “Pre-crash motion and conditions of bicyclist-to-car crashes in Sweden,” presented at the International Cycling Safety Conference (ICSC2014), 3rd, 2014, Gothenburg, Sweden, 2014.
[18] C. Berlin and L.-O. Bligård, “An Activity Centered Design Framework for Determining Design Decision Levels in Production Systems,” in *Advances in Ergonomics of Manufacturing: Managing the Enterprise of the Future*, Cham, 2016, pp. 455–463.