SEBRA
Sensor based awareness for bicyclists

Final Report, OpenResearch at AstaZero

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CONTENTS

1 EXECUTIVE 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 study and 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 identified the most relevant use-cases and in conjunction to this, identify a business model that can make the safety system attractive for end-users. Secondly, a radar-based safety system for bicycles is developed with both sensor and human interface. Finally, the system is evaluated in relevant traffic situations.

The SEBRA project aims for the following research questions:

- RQ1: What safety issues can be addressed by a radar-based safety system mounted on bicycles?
- RQ2: What performance requirements (field-of-view, computational capacity, power consumption, etc.) should such a system fulfil?
- RQ3: How should the interaction with the bicyclists be designed to give a high level of safety and user experience?
- RQ4: How can incentives and business models be developed to create a viable utility device for bicycles?

Within the scope of Open Research at AstaZero, we plan to simulate the selected scenarios from literature in the test track environment to finalize the answer for RQ1 and build answer for RQ2. The tests also contribute initial insights for RQ3 answer.

2 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. According to a report

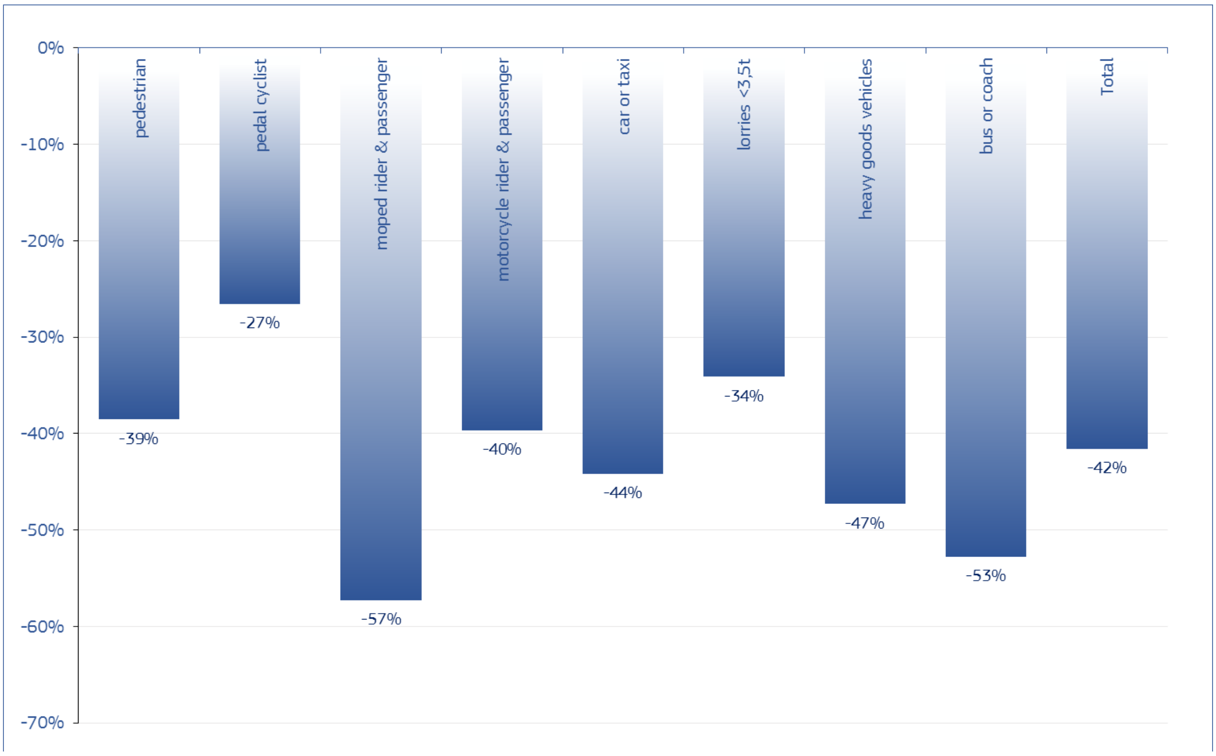
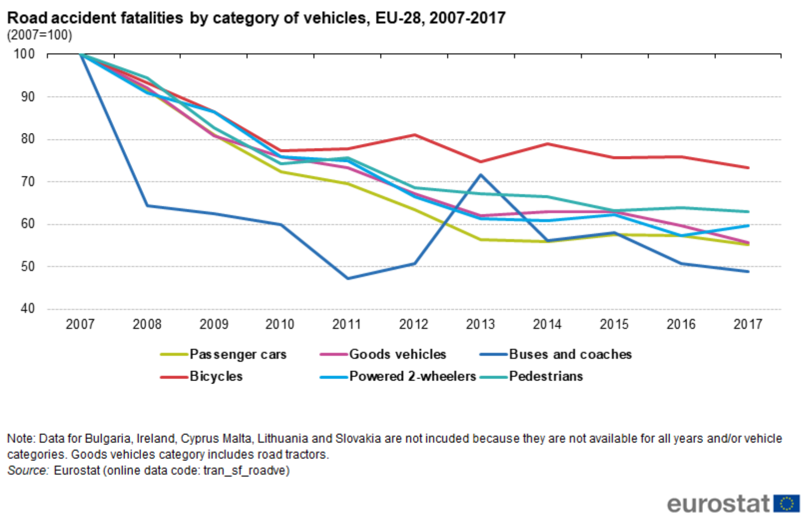


Figure 1: Percentage change in number of fatalities by mode of transport in the EU, 2016 and 2007. Source: CARE (EU road accidents database) or national publications

by the European Commission[1], the number of cyclist fatalities dropped by 27% between 2007 and 2016, the lowest reduction rates of all transport modes. The percentage of cyclist fatalities of all road fatalities increased from 6% in 2007 to 8% in 2016.



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, however they are often caused by that the bicyclists are interacting with motor vehicles and are avoiding an accident with them. 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 cyclists 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.

To increase bicyclists' situation awareness and thereby increase traffic safety for the user-group, we propose a radar-based safety system mounted on the bicycle. It detects hazards and informs bicyclists about them.

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 communicating to the bicyclist also require investigation. And, most importantly, to make the product attractive, the business model, where the different consumer needs, expectations and values are identified, needs to be developed.

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.

3 PURPOSE, RESEARCH QUESTIONS AND METHOD

3.1 Aim and Purpose

The overall purpose of SEBRA project is to help bring active safety to bicyclists by way of investigating how consequences of collisions between bicycles and other vehicles can be reduced using radar sensor technology mounted on bicycles. The project uses radar sensors developed for use on cars mounted on a bicycle.

The overall purpose of the four test occasions at AstaZero, is to help test in a controlled environment where only relevant objects appear in the radars field of view.

Testing in real world environment is also important and produces a lot of useful data. It is on the other hand difficult to analyze that kind of data. Testing in dense areas with a lot of traffic collects a lot of unwanted objects that disrupt the experiment. Careful filtering is needed for that kind of analyze.

When testing at AstaZero, objects will only appear in predetermined positions based on test scenarios. Adding a high precision GPS positioning system will make it easy to distinguish between the objects and to understand how the sensors manage to track the targets that are of interest. It is a more reliable source of ground truthing data.

The Open research project goals are:

- To make data recordings of the dynamics of traffic scenarios from radar sensors mounted on a bicycle.
- To make recordings of the position and velocity of the vehicles in the scenarios using AstaZero's high-precision positioning instruments and tools.
- To investigate what differences in radar-sensor data are caused by moving sensors from a car to a bicycle.
- To investigate what is the quality of information that can be extracted from these data recordings.
- To evaluate the difficulty to use radar sensors to predict that there is a high risk of collision, for each of the selected scenarios.

From the project goals, the testing at AstaZero is broken down into sub-aims accordingly;

- To test the performance of the radar units and the tracker system.
- To explore what test scenarios are relevant to the performance, and the sensors possible detection margins.
- To explore what types of communication could help the road users in typical accident scenarios.

3.2 Research questions

The research questions addressed in this study are:

- 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 bike?
- How/when to warn a bicyclist against oncoming danger from rear, side and front?
- How to communicate and make the oncoming vehicle aware of the bicyclist?

Consequently, the expected results from this test in AstaZero are:

- Data representing vehicle dynamics and other objects in the world for the selected scenarios, from both the radar sensors and from AstaZero's instruments. These data will be used to calibrate the bicycle radar sensor measurements, and for the design and test of a vehicle tracking algorithm for use on a bicycle.
- A better understanding of how car radar sensors work when used on a bicycle.
- A better understanding of device mounting configurations on field.
- Understanding of the signalling requirements.

3.3 Methods

3.3.1 Scenarios selection

A literature study has been conducted with the latest bicycle accident statistics from the US[3]–[6], Europe[7]–[9], and Sweden[2], [10].

The followings are observed as common findings from the literature:

- Drivers are at fault more than bicyclists in the crashes, while crashes involving at-fault bicyclists resulted in a greater percentage of fatal crashes compared to those involving at-fault drivers.
- More accidents in urban area compare to rural area.
- Impacts to the front of the vehicle make up the largest portion of cyclist crashes and fatalities.
- The most common accident scenarios resulting in seriously injuries or fatalities are motorist overtakes same direction and front crash motorist from left or right. These scenarios built up the top 3 most common scenarios, though the order may slightly change depending upon the country/area where the statistics were taken.

Traffic scenario classifications are different per reports, and are from the perspective of the vehicles.

For the purpose of this project, we map these scenarios into bicycle perspective and select the most common scenarios that result in severe injuries and fatalities to be further investigated in the project.

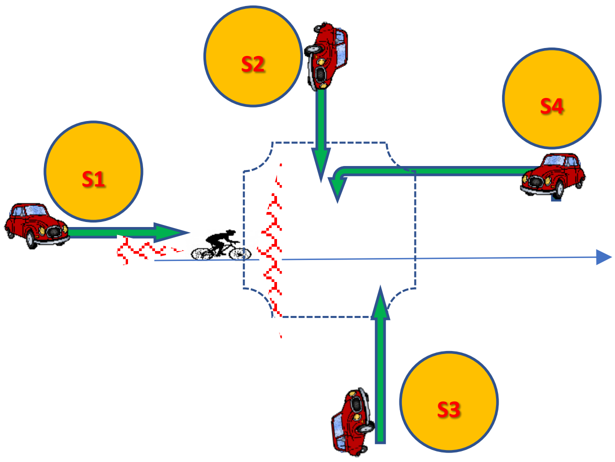


Figure 2: Selected safety critical scenarios

The intitial set of scenarios selected for further investigations within SEBRA project is provided in Figure 2, consisting of:

- 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)

This selection of focused scenarios will guide the configuration selections in the next sections.

3.3.2 Setup the initial configuration of the bike prototype

From the selected scenarios, we found that the followings are required for the first prototype to be built and test in AstaZero

- 360 degree detection coverage from the bike. This is to make sure that we will be able to capture all required data from the selected scenarios executing in AstaZero for later investigations.
- Ability to detect approaching objects with relative speed upto 50km/h and with time to collision (TTC) at least 3.5 seconds and upto 7 seconds. This lead to a maximum detection distance of around 90m. The minimum TTC requirement is based on the reaction time needed to avoid the collision from both vehicle and bicyclist.
- Devices should be of low energy consumption and able to be powered from the bike's battery.
- Being able to capture the other traffic situation data (besides radar sensor data). This reference data is needed to investigate the situation understanding and calibrate the understanding extracted from radar's data only.

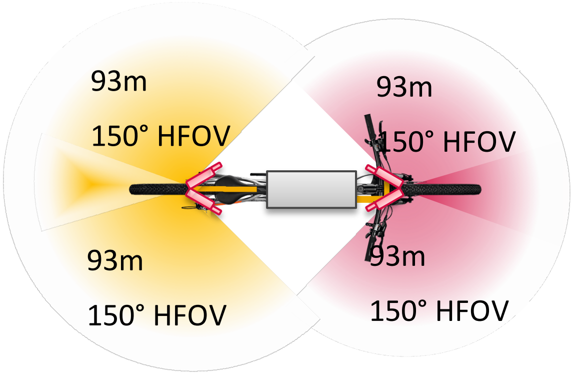


Figure 3: Radar configuration in prototypes

Two bicycle prototypes are used with the radar mounting configuration as illustrated in Figure 3. The first prototype was used to collect the radar sensor data, equipped also with GPS and imaging devices to build groundtruth dataset. The second prototype is equipped with developed system and also with HMI.

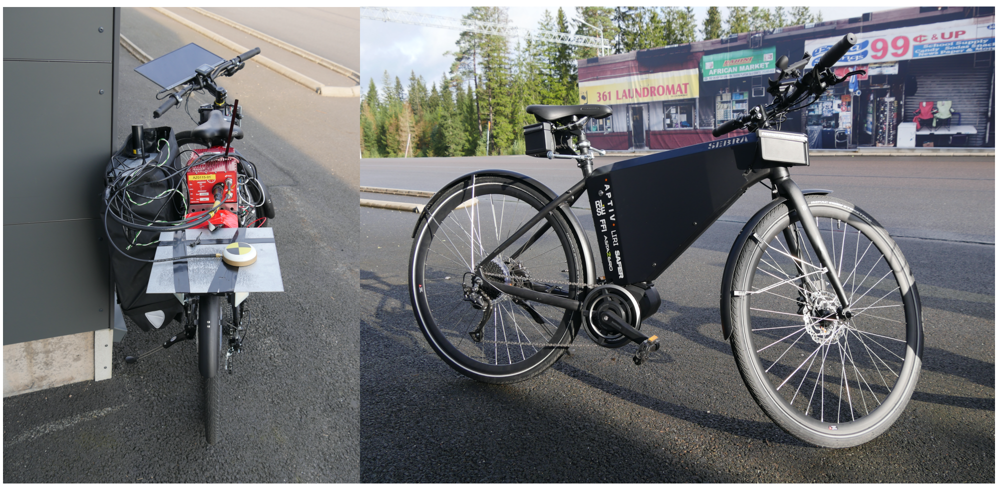


Figure 4: SEBRA prototype 1 with additional AstaZero equipments (Left) and Prototype 2 with HMI (Right)

3.3.3 Setup the test scenarios

The following 6 test scenarios are selected for the tests in AstaZero, with regards to the selected scenarios desribed in Section 3.3.1.

Table 1: Test traffic scenarios

Scenario	Description	Diagram
Scenario 1	Intersection with bicycle travelling upwards and car travelling from left to right (”C1”)	
Scenario 2	Intersection with bicycle travelling upwards and car travelling from right to left (“C2”)	
Scenario 3	Intersection with bicycle travelling straight upwards and car travelling downwards, turning left in the intersection (“T3”)	
Scenario 4	Intersection with bicycle travelling upwards, turning left in the intersection and car travelling straight down in the intersection (“On”)	
Scenario 5	Bicycle and car travelling in the same direction, bicycle travelling straight, car hits bicycle from behind (“L1”)	
Scenario 6	Bicycle and car travelling in the same direction, car travelling straight, bicycle turning left when overtaken (“L2”)	

3.3.4 Select test environment

The experiment was conducted at the test track AstaZero in Sandhult, Sweden. The plan of test track is illustrated in Figure 6. The test track consists of several traffic environments, one of which is the City Area (Figure 5, Figure 7) where the experiment took place, The posted speed limit is 50 km/h. The length of the main road section is approximately 500m where

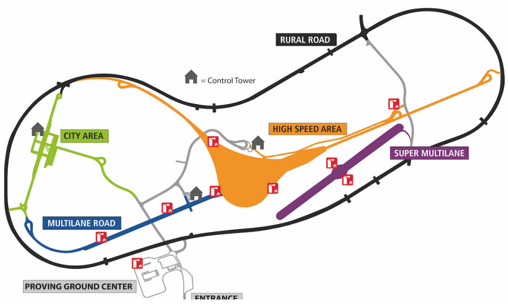


Figure 6: AstaZero test track plan

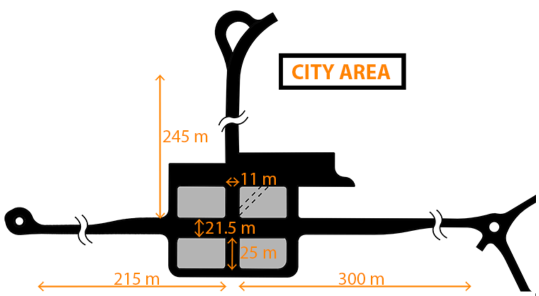


Figure 5: AstaZero City area plan

crossing traffic tests are possible as the city walls simulate real world stores and walls, typical of inner cities in the United States.

Figure 7: City area view at AstaZero

3.3.5 Setup the test plan

The experiment planning started in February 2019 and AstaZero called for a sync meeting regarding what was needed from their end. Four days at AstaZero were promised and a first pilot was carried out at the test track later on in April. Two days were used consecutively as the first day was completely dedicated to setting up the Motion Tracker system with AstaZero personnel, and to brief the upcoming tests on day number two.

To leave room for analyze and possible updates to the tracker system, the third test day was postponed from end of April to May. The final experiment was planned for July, however, due to some practicalities, it was postponed to the first week of September 2019.

We developed 15 test cases including the technical readiness tests and scenario tests. The first day was used to validate the feasibility of the test cases and test plan. The scenario tests are performed to collect data and initial inputs for optimizing hardware components and mounting. The data are used for tuning the software later. During the first 3 days, the first bike prototype was used, with basic settings of HMI functions.

At the last test day (later in September), we used the second prototype of the bike, executed the same test cases to validate the developed functionalities and also did some filming.

3.3.6 Personnel

Six to eight people were involved in the execution of the experiments during the 4 days at AstaZero.

A test leader who was responsible for communication and guidance of the test person(s) outside but also inside the test vehicles. That person was also responsible in making sure the scenarios were played out correctly and data logs were collected for each specific test scenario. In addition, he was also responsible for recording video material. Test engineers were involved in steering the host vehicle (bicycle) but also driving the target vehicle (car) and to initiate each log recording. Other participants from RISE and Aptiv monitored and helped setting up safe environment for the tests and other camera angles.

Two AstaZero personnel were in charge of the motion pack RT range system but also making sure tests were performed in a safe manner.

4 RESULTS

The following results were derived from the data collected on AstaZero and data collected in real traffic.

4.1 Control environment test

Initial testing of SEBRA bike in cluttered real-world environment produced a lot of useful, but hard to analyse data. Real world tests were performed in streets of Gothenburg, that is very dense environment with a lot of objects that disrupt the experiment. To analyse data from such data collection requires careful filtering of relevant objects or time-consuming annotation of collected data. Testing in control environment is way better in this aspect. Only relevant objects appear in scene and only in predetermined position based on test scenario. Need for data labelling is minimal and analysis of such control environment data is easier and faster. Benefit of such testing is even greater when reliable source of ground truth data is available. Having some hours of testing at AstaZero proving grounds was useful in collecting such controlled environment data.

Figure 8: A test conducted in AstaZero City area

4.2 Feasibility of reuse of existing automotive sensor setup and system

One of the questions that this project was supposed to answer was whether it is possible to reuse already well developed automotive ADAS systems for bikes. Existing out of the box solution was adapted to bike without significant effort and modifications. Automotive sensors were used without any hardware modification and with unmodified software, which is purely intended for automotive application. Tracker that is processing radar data was also reused as unmodified existing solution. Final block in this chain – feature functions (warning functions) also reused existing solution that just required some parameter tuning to fit the new use case.

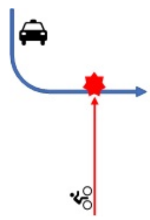
Data collected in real world and in controlled environment has shown that this approach is feasible and that it is possible to reuse existing automotive solutions for this new application.

This conclusion was based on subjective evaluation of system's performance in different scenarios. By system performance is meant system warning outputs for the bicycle's driver and surrounding vehicles' drivers. The whole processing tool chain: radar sensor, radar sensor low level data processing, radar object tracker, feature functions performed in similar way as it is commonly performing on vehicles. No formal performance metric was defined in this stage of the project.

The bike itself and the adapted warning functions were intended as proof of concept and not as a ready to market product. Current state of the proof of concept does not allow for further tuning without first properly identifying the tuning's targets. Well defined desired behaviour, proper and accurate use case definition are needed for that and that is not something that was ready in the proof of concept phase of this potential product. To turn the concept into the product it would be required to precisely define the scope, use cases, performance metrics, acceptable test methods – requirements in general. Based on the well-defined use cases the system requirements could be derived and that would allow for proper definition of test cases that would verify system's performance. Test protocols, that describe in detail test scenarios, would benchmark the product performance, similar to how Euro NCAP score and test protocols are used for benchmarking the automotive systems. Such feedback cycle or similar is necessary for proper product's development.

4.3 Scenario feasibility

4.3.1 Oncoming turn across path



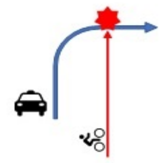
Intersection with bicycle travelling straight upwards and car travelling downwards, turning left in the intersection.

Initially this scenario was within the scope of the project. This scenario had to be removed from the scope of the project due to large number of false positives. Heading of oncoming objects in this scenario is extremely important input used to determine whether the oncoming object is going straight or is going to turn and cross the bike's predicted trajectory. Data collected for this scenario both from controlled environment and from real world has shown that tracker that uses only radar data can't produce output reliable enough to consistently distinguish between oncoming and oncoming-turning objects.

This conclusion is not surprising. In automotive systems such scenario is challenging even with high end sensor setup (for example front camera fused with radars).

4.3.2 Following vehicle with turn across path

Intersection with bicycle travelling straight forward and car passing followed by right turn.



Initially this scenario was within the scope of the project. This scenario had to be removed from the scope of the project due to unfeasibility of such scenario. The vehicle that is approaching the bike from behind and then going along the bike is already handled by adapted rear collision warning and adapted blind spot warning functions. When vehicle overtakes bike and starts to turn across bike's path it is already too late to warn the vehicle's driver and it is also already too late to warn the bike's driver. The turning vehicle is also now fully in field of view of the bicyclist (so there is really no need to send further warning anyway.) There is not much to do for the bicyclist to mitigate collision in this scenario other than braking. Best approach seems to have the vehicle driver being aware of the bike's position in advance to prevent this scenario from happening in the first place. That is already achieved by adapted blind spot functionality/adapted rear collision warning functionality. Both of those functions improve bikes visibility by lighting up the rear warning lights on bike and thus it increases probability of the vehicle's driver to be aware of the bike's position. Driver that is well aware of bike's position is less likely to perform the turn across path manoeuvre that would lead to collision.

This scenario is close to impossible to safely test in real world. It requires well timed scenario execution possible either in simulation or in controlled environment. Data from controlled environment testing in AstaZero testing proved valuable to properly understand the scenario and allowed to draw conclusion on how to handle this scenario.

4.4 Roll angle issue

During the analysis of logs collected with the bike a new problem was identified. This problem is not common for vehicle use case. It is the dynamic movement of the bike's frame and thus the dynamic movement of bike's sensor setup – radars. When the bike's driver is pedalling the bike shows significant roll angle changes as the bike's frame is rolling to left and right. The more intense pedalling the bigger this effect gets. It is uncommon for vehicle to experience such quick periodic roll changes. Existing processing chain is not fully prepared for this unexpected behaviour and thus tracking performance is reduced. System is still working, but not in optimal way. No reliable roll angle estimation system was in place and it would require some further effort in tracker adaptation and proper roll angle estimation to minimize negative effects of big roll angle change.

Figure 9 shows the effect of roll angle changes on radar tracker performance. The tracker misclassifies some stationary objects into movable "ghost" objects when the roll angles change with high frequency. This oscillation effect can be removed using smoothing filters such as Kalman filter.

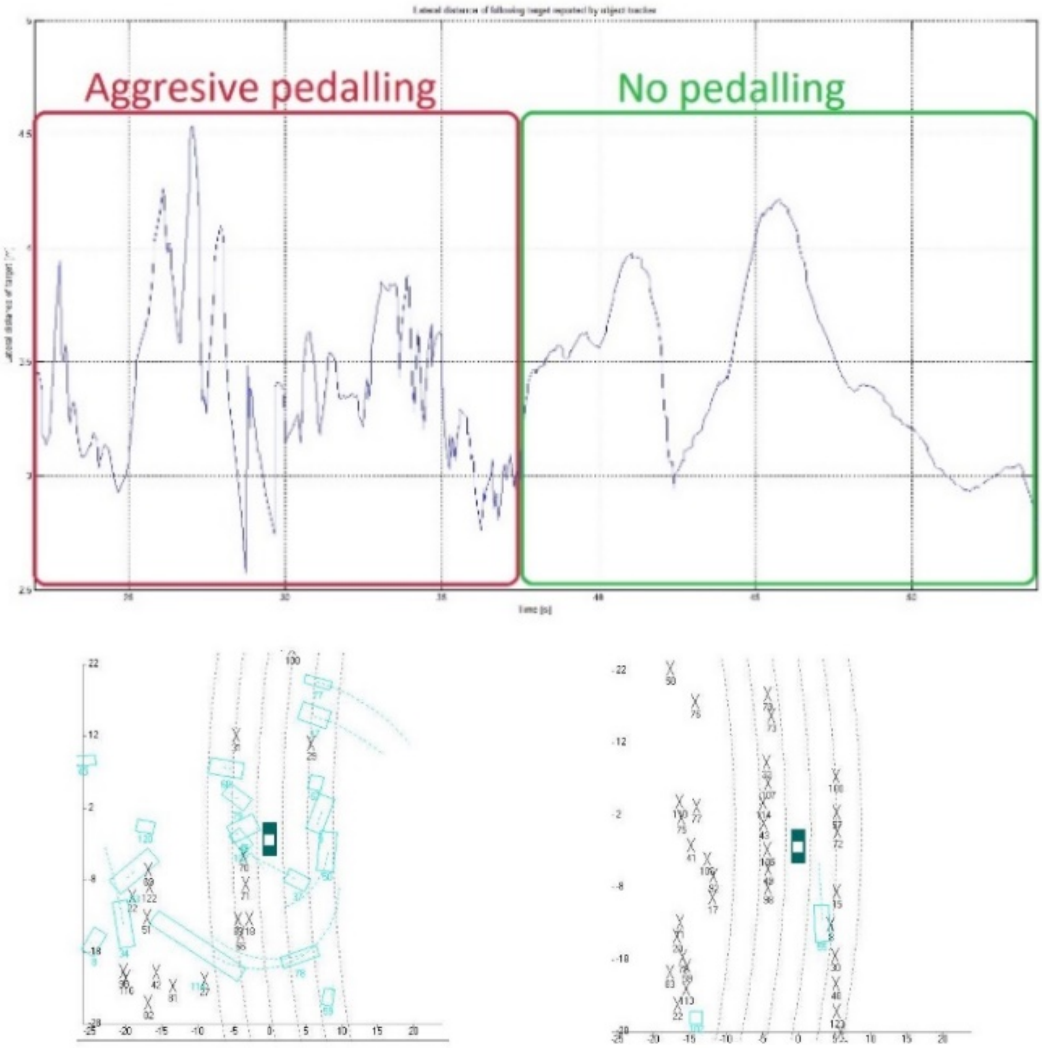


Figure 9: Aggressive pedaling (left) vs. gentle pedaling (right) and impacts on tracker performance

5 CONCLUSION AND OUTLOOK

Controlled environment testing's in AstaZero proved valuable to properly understand the literature-based selected traffic scenarios and allowed to draw conclusions on how to handle each scenario in the list.

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.

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.

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 bicycles. 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 be customized 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 no additional related efforts required.

Scope definition and proper test protocol definition

The bike itself and the adapted warning functions were intended as proof of concept and not as a ready to market product. Current state of the proof of concept does not allow for further tuning without first properly identifying the tuning's targets. Well defined desired behaviour, proper and accurate use case definition are needed for that and that is not something that was ready in the proof of concept phase of this potential product. To turn the concept into the product it would be required to precisely define the scope, use cases, performance metrics, acceptable test methods – requirements in general. Based on the well-defined use cases the system requirements could be derived and that would allow for proper definition of test cases that would verify system's performance. Test protocols, that describe in detail test scenarios, would benchmark the product performance, similar to how Euro NCAP scores and test protocols are used for benchmarking the automotive systems. Such feedback cycle is necessary for further product development.

6 LESSONS LEARNED, EXPERIENCE FROM TESTING AT ASTAZERO

Our overall impression from the experiment at the test track AstaZero is very positive. By conducting this study, we have gained knowledge on pros and cons with various data collection methods and approaches. The biggest challenges in setting up the controlled environment testing within the SEBRA project, is the safety aspect. The host (SEBRA bicycle) has to have a person riding it which means the person in question is always exposed to risk. Proper precautions have to be made to mitigate as much risk as possible. In real world city traffic, there might be many moving objects surrounding the bicyclist, raising the risk of an accident substantially. Objects appear and disappear constantly, and that kind of testing is obviously difficult to perform at AstaZero.

For future testing though perhaps a rig with a bicycle could be set up to aid in the research.

Things that did not go so well were:

- Setting up the GPS RT range system. Almost two half days were lost at AstaZero due to unpredicted problems occurring, despite the fact that we had a day to prepare and test everything. Those technical difficulties appeared with the small mobile GPS RT range system should be noted for future reference.

- Weather could be tricky this time of year (September). Constantly changing weather conditions caused minor problems for us as the SEBRA bike prototype is not made water proof. It was not worth the risk in damaging the log system when raining so the weather was often waited out until better conditions. Getting the SEBRA bike prototype and IP classed would have been preferred to be able to test without such issue.

AstaZero's staff were always friendly and helpful.

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