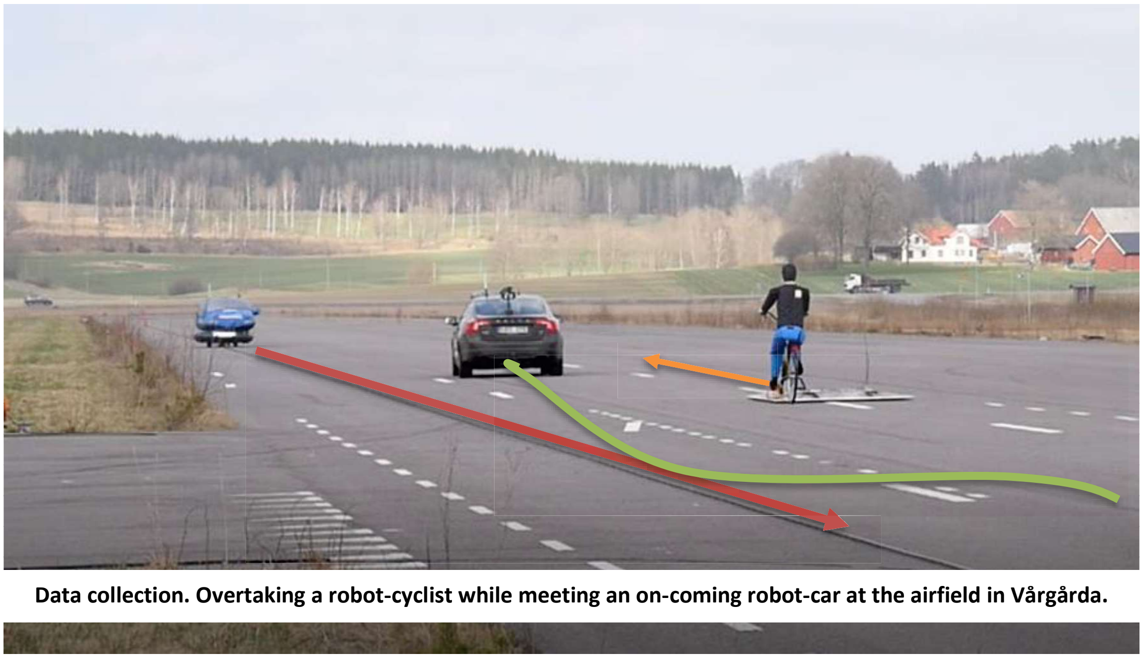
MICA

Modelling Interaction between Cyclists and Automobiles

Public report



Data collection. Overtaking a robot-cyclist while meeting an on-coming robot-car at the airfield in Vårgårda.

MICA was sponsored within the call: Cyklar och andra fordon i säker och smart samverkan.

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Content

1. Summary

The MICA project modelled driver behaviour, focusing on the approaching phase of an overtaking manoeuvre, when a driver moved toward a cyclist while facing oncoming traffic (Euro NCAP test protocols inspired this scenario.). The model predicts the probability for drivers to brake or steer as they approach the cyclists to perform an accelerative (overtake *after* the oncoming traffic has passed) or flying (overtake *before* the oncoming traffic has passed) manoeuvre, respectively. This model has been integrated into a *smart* collision-avoidance system, that provides early (and yet acceptable) warnings and interventions. A virtual assessment estimated the safety benefits of the smart collision-avoidance system using UDRIVE naturalistic data. Our analyses show that the new smart collision-avoidance system can significantly reduce fatalities and severe injuries when compared to traditional collision-avoidance systems, with the new collision warning alone promising a reduction of fatalities by 53-96% and a reduction of serious injuries by 43-93%. This work has been carried out by three PhD students and is now continuing in the MICA2 project.

The main deliverables of the project were:

1) a *unique dataset* collected on the airfield in Vårgårda where participants interacted with two robots,
2) a *new modelling framework* that helps to identify interaction on a scenario basis,
3) a *novel driver model*, which can predict overtaking strategy in real-time,
4) a *smart collision-avoidance system* which uses the driver model to generate warnings and automated interventions, and
5) a *safety benefit analysis*, proving the potential for the new collision-avoidance systems to save lives and reduce injuries from naturalistic European data.

Nine scientific contributions describe MICA's results: one licentiate thesis, two podium presentations to the International Cycling Safety Conference (2018 and 2019, respectively), one conference paper submitted to the Transport Research Arena 2020, and five journal papers.

MICA highlighted that:

1) Modelling the interaction between the overtaking vehicle and the *oncoming vehicle* is an essential step to increase overtaking safety.
2) The approaching phase of an overtaking manoeuvre is not necessarily the riskiest; the most significant margin for improving safety may lay in developing systems that support the drivers in the *returning phase*.
3) In the approaching phase of an overtaking manoeuvre, the potential safety benefits from *automated emergency steering* (a system not addressed in MICA) is substantial.

4) As an overtaking manoeuvre develops from the approaching to the steering, passing, and returning phase, vehicle kinematics and proximities become more critical, challenging active safety systems and calling for *new passive safety solutions*.
5) More experimental data, collected in more critical situations than what was possible in MICA, is needed to address overtaking safety properly. *New methodologies*, such as augmented reality and virtual reality, offer the best opportunities to collect such data without ethical concerns.
6) More *naturalistic data* is needed to validate our driver models and the new systems that we started developing in MICA.
7) Interaction among road users is complex and models of vulnerable road-user behaviour are also needed to make robust predictions. As we move from an overtaking scenario to a crossing scenario, this aspect will become even more crucial.

MICA2, a new FFI project including Volvo Cars, Autoliv, Veoneer, Viscando, if, VTI, and Chalmers, will now address these issues.

2. Sammanfattning på svenska

Cyklister är de mest skadade trafikanterna i Sverige [1]. Alltför ofta skadar sig cyklister på landsvägar i olyckor med ett motorfordon [2]. Nuvarande system för aktiv säkerhet stöder inte förare fullt ut i dessa scenarier och använder inte förarmodeller för att hjälpa till de aktiva säkerhetssystemen att förstå om en förare närmar sig till en cyklist på ett säkert sätt.

MICA-projektet modellerade förarens beteende i den första fasen av en omkörningsmanöver, när en förare närmade sig en cyklist bakifrån med mötande trafik (Euro NCAP-testprotokoll inspirerade det här scenariot). Modellen förutsäger sannolikheten att en förare kommer att bromsa eller styra när de närmar sig cyklisterna för att strategiskt utföra en accelererande (köra *efter* den mötande trafiken har passerat) respektive flygande (köra *innan* den mötande trafiken har passerat) manöver. Denna modell har integrerats i ett koncept för smart aktivt säkerhetssystem för att undvika kollisioner, som ger tidiga (och ändå acceptabla) varningar och ingripanden.

Med simuleringar har säkerhetsnyttan uppskattats med det smarta aktiva säkerhetssystemet med hjälp av data från UDRIVE-naturalistiska databas. Våra analyser visar att det nya smarta systemet kan minska dödsolyckor och allvarliga skador betydligt jämfört med traditionella system; det nya FCW på egen hand estimerats minska antalet dödsolyckor med 53-96% och en minskning av skadorna med 43-93%. Detta arbete har utförts av tre doktorander vilka nu också fortsätter i det uppföljande MICA2-projektet.

De viktigaste leveranserna av projektet har varit:
1) ett dataset insamlat på flygfältet i Vårgårda där testförare interagerade med två robotar,
2) ett modelleringsramverk som hjälper till att identifiera interaktion mellan väganvändare på en scenariebasis,
3) en ny förarmodell, som kan förutsäga strategi för omkörning i realtid,
4) ett smart system för att undvika kollisioner som använder modellen för att generera varningar och automatiserade ingripanden, och
5) en säkerhetsnyttoanalys som visar att de nya systemen för att undvika kollisioner kan rädda liv och minska skador.

Nio vetenskapliga bidrag beskriver resultaten från projektet: en licentiatuppsats, två presentationer för International Cycling Safety Conference (2018 respektive 2019), ett konferensbidrag som lämnats in till Transport Research Arena 2020 och fem vetenskapliga artiklar.

Huvudsyftet med MICA var att stödja den svenska bilindustrin upprätthålla sin ledande roll i utformningen av avancerade lösningar för aktiv säkerhet. Medan man fokuserade på sitt primära mål nådde MICA också några andra mål som indirekt visar påverkan av resultaten från detta projekt.

1) MICA tillhandahöll relevant input till Euro NCAP genom att 1) framhäva vilka faktorer som kan ha en betydanderoll i scenariet för omkörning av cyklister och som borde inkluderas i framtida testprotokoll och 2) benchmarka det nya systemet för att undvika kollisioner med de nuvarande kraven för FCW från Euro NCAP-testprotokollet.
2) MICA behandlade målen för hållbar utveckling 3 och 11 från FN-målen genom att främja högre standarder för cykelsäkerhet.
3) MICA:s resultat kan användas för utformningen av automatiserade fordon genom att tillhandahålla en modell för mänskligt beteende som automatiserade fordon kan efterlikna genom att inte överraska eller skrämma andra trafikanter under en omkörningsmanöver
4) MICA:s resultat kan användas för sensorteknologins design genom att visa vikten av att monitorera den kommande trafiken och den tidpunkt som behövs för att göra det. (Aktiva säkerhetssystem på marknaden använder inte denna information idag.)
5) MICA:s resultat kan användas för utformningen av kooperativa applikationer genom att 1) visa potentialen med trådlös kommunikation mellan det förbipasserande fordonet, det kommande fordonet och cyklisten, och 2) visa de tidpunkter som krävs för denna kommunikation i den närmande fasen av en omkörningsmanöver. (Dessa tidpunkter är användbara för att härleda krav för trådlös kommunikation).
6) MICA gynnade nätverkande mellan olika svenska intressenter som gick med i MICA:s rådgivande styrelse och nu blivit aktiva partners i MICA2.
7) MICA bidrog till att synliggöra svensk forskning i den internationella forskarvärlden genom att delta i internationella konferenser och publicera i internationella vetenskapliga tidskrifter.

8) MICA bidrog till utbildning av framtida forskare inom trafiksäkerhetsområdet som en del i deras doktorandstudier
9) MICA främjade jämställdhetsbalansen genom att, i så stor utsträckning som möjligt, inkludera både kvinnliga och manliga förarens olika beteende, och genom att inkludera kvinnliga forskare och studenter i ett projekt inom en forskningsmiljö där män är i stor majoritet.

Sammantaget lyfter MICA-projektet fram följande lärdomar:

1) Modellering av interaktion mellan det omkörande fordonet och det mötande fordonet som ett viktigt steg för att öka säkerheten i omkörningar.
2) Att den första fasen (närmande cyklisten bakifrån) i en omkörning är inte nödvändigtvis den riskablaste. Den viktigaste marginalen för att förbättra säkerheten kan ligga i att utveckla system som stöder förarna i de följande faserna.
3) I den första fasen av en omkörningsmanöver så kan visar projektet på en påtaglig potentiell säkerhetsnytta att komplettera AEB med ett aktivt säkerhetssystem som undviker kollision genom styrning.
4) I takt med att manövern går från närmande, till utstyrning, till passering och slutligen retur-fasen, blir fordonskinematik och avstånd mer kritiskt, vilket utmanar aktiva säkerhetssystem och kräver nya passiva säkerhetslösningar.
5) Mer experimentell data, insamlad i mer kritiska situationer än vad som var möjligt i MICA, behövs för att hantera omkörningssäkerhet ännu bättre. Nya metoder, som Augmented Reality och Virtual Reality, erbjuder bättre möjligheter att samla in sådana data utan etiska dilemman.
6) Mer naturalistiska data behövs för att validera våra förarmodeller och för de nya system som började utvecklas i MICA.
7) Samverkan mellan trafikanter är komplext och modeller av oskyddade trafikanters beteende behövs också för att göra mer robusta system. När vi går från ett omkörningsscenario till ett korsnings scenario kommer denna aspekt att bli ännu mer kritisk.

MICA2, ett nytt FFI-projekt med följande partners: Volvo Cars, Autoliv, Veoneer, Viscando, if, VTI och Chalmers, kommer nu att ta itu med dessa frågor.

3. Background

Cyclist safety

In 2014, *cyclist fatalities* accounted for 4% of all road traffic fatalities worldwide [3], for 8% in the EU, and 12% in Sweden, and for 25% in the Netherlands [4]. In recent years, cyclist fatalities have decreased; however, at a slower pace compared to fatalities for car occupants [4], raising some important safety concerns. For lower severity injuries in Sweden in 2012, cyclists were the dominant group among all road users, accounting for 55% of all hospital reported MAIS2+ road traffic injuries, and also dominating RPMI1%+ injuries [1]. According to predictions, in 2030 cyclists will continue leading RPMI1%+ [5]. As cyclists have a much *higher injury risk* compared to car occupants, switching transportation mode from car to bicycle for commuting to work in Stockholm was estimated to lead to increased injury outcome, highlighting the need to take measures to protect cyclists [6], and showing the importance of addressing cycling safety to achieve the UN sustainable development goals in Sweden [7].

Safety systems

Softer vehicle front/rear design [8], automated emergency braking (AEB) [9], and combinations of the two [10] have been shown to reduce cyclist casualties substantially. Adding helmet use, and limiting driving speed, decreases cyclist casualties even more [11]. However, when a collision happens, cyclists are likely to get injured, even at low speed and even if they are wearing a helmet. For this reason, *intelligent vehicle systems* such as forwards collision warning (FCW) and AEB, that aim at *preventing* collisions, may be particularly beneficial to cycling safety.

From 2018, *Euro NCAP* assesses AEB and FCW for cyclists in a few test scenarios to promote such systems [12]. The key to AEB and FCW effectiveness is *intervention time* and, today, our knowledge about when and how AEB and FCW should intervene in conflicts with cyclists is still limited. For Euro NCAP *scenarios with crossing cyclists*, system intervention to achieve full score may take place after the driver's comfort boundaries [13] whereas, *in longitudinal scenarios*, flying overtaking manoeuvres may be initiated later than the specified warning time in Euro NCAP [14], highlighting a potential conflict between driver comfort and system operation. Furthermore, *interaction* has been highlighted as relevant in negotiating intersections [15] and overtaking [14] but has not yet been modelled or included in the threat assessment and decision making of current intelligent vehicle systems. This project *modelled* such interaction to improve FCW and AEB algorithms. The new FCW and AEB systems were verified with test-track and field data, and their safety benefits virtually assessed with using field test and *naturalistic* data [14][16].

Driver models

Driver models can be used with time-to-collision algorithms for AEB [17][18] through a refined definition of intervention time; the intervention threshold may no longer be based on physical avoidance, but also on driver comfort boundaries, as exemplified by Lubbe and Kullgren [19] for pedestrian AEB and proposed by Duan et al. [20] for cyclist AEB. Also, AEB algorithms based on the likelihood that a collision can be avoided by own or opponent action [21][22] can be improved by advanced modelling of interaction. In fact, if avoidance manoeuvres can be excluded, included, or assigned a probability, the potential of avoiding a collision will increase as a consequence of a more accurate threat assessment.

Integration of driver models in safety systems and safety benefit assessment

Previous FFI projects, such as EFRAME (https://www.vinnova.se/p/analysis-framework-for-safety-systems-and-services/) and QUADRA (https://www.vinnova.se/p/kvantitativ-forarbeteendemodellering-for-utvardering-av-aktiva-sakerhetssystem-quadra/), already provided a *modelling framework* for developing driver models, as well as models for driver behaviour, which were mainly applied to rear-end scenarios. Current work in QUADRAE (https://www.vinnova.se/p/quantitative-driver-behaviour-modelling-for-active-safety-assessment--expansion-quadrae/) 1) sets the modelling effort within the predictive processing framework [23]

2) includes automation and automation failure and 3) applies driver models to *virtual simulations for safety benefits* (i.e. counterfactual simulations; [24][25]). This project complements the modelling framework from EFRAME, focusing on how to identify and model the interaction among road users depending on the different scenario at hand [26]. Further, following the example of QUADRAE, this project developed models that can be applied to virtual simulation for safety benefits. These simulations evaluate the extent to which a new safety system (for instance a FCW or an AEB boosted by the models developed in this project) outperforms commercial ones. System performance in virtual simulation is typically measured as number of reduced crashes or reduced crash severity.

Automated and connected vehicles

Securing a safe interaction between vehicles and other road-users is arguably the most critical challenge for *automated vehicles* (AV) and intelligent systems today. While automated vehicles with low automation level are increasingly present, it will take decades before all vehicles on the road will become fully automated [27]. In this mixed environment, where AV are expected to behave as human-driven vehicles, the models from this project may help AV overtaking cyclists without *discomfort* for either the cyclist or the driver/passenger. Previous studies already indicated that some key features of the infrastructure (e.g. curvature and slope; [14]) and the behaviour of other road users (i.e. oncoming traffic; [14]) may influence how safe an overtaking manoeuvre is. By modelling these features, this project indirectly determined which key information is missing in current sensor technology and may be worth communicating in a cooperative environment where *connected vehicles (and connected bicycles)* could collaborate to improve comfort and safety mutually.

4. Purpose, research questions and method

The main **purpose** of the MICA project was to increase traffic safety and, specifically, reduce the toll that drivers in motorized vehicles take on cyclist injuries and lives. Toward this purpose the MICA project 1) developed driver models that predict the drivers' intention as they approach a cyclist during an overtaking manoeuvre, 2) integrated these models in a smart collision-avoidance system, 3) verified that this system did not produce false activations, and 4) estimated the safety benefit of this new system with a virtual assessment.

The **research questions** in MICA focused on drivers overtaking cyclists and included:

1) How do we model driver behaviour in overtaking manoeuvres with cyclists?
2) How do we integrate driver models in active safety?
3) How do we verify that active-safety systems do not produce false activations?
4) How do we estimate the safety benefits for new active-safety systems in a virtual environment (while preserving the ecological validity of the simulation)?

To tackle these research questions, the MICA project combined several methodologies and data types, which are reported in Table 1.

Table 1 – Research questions and corresponding main deliverables, methodologies applied to address the research question, data used within the methodology, and work package (WP).

RQ	Deliverable	Methodology	Data	WP
1	Modelling framework Dataset from test-track Driver models	Unified modelling language Bayesian statistics and machine learning	Test-track data	1, 2, 3
2	Collision-avoidance system	Threat-assessment and decision-making algorithms based on kinematics and vehicle dynamics.	Test-track data	4
3	Verification of the system	Simulations of kinematics and vehicle dynamics.	Field data and test-track data	4
4	Safety-benefit evaluation of the system	Counterfactual simulations	Naturalistic data	5

General methods

The first research question was addressed in the work packages 1, 2, and 3 (see Figure below). In work package 3, Alexander Rasch developed a driver model that predicts driver overtaking strategy (either flying or accelerative; [28] as the driver approaches the cyclist. The model is based on the data collected in work package 2 from Veoneer in Vårgårda. This data is unique and required a complex set-up where two robots needed to be synchronized in real-time with the participants actions. The same data was also used for statistical modelling to determine the most influential factors to include in the *predictive* model [29]. The framework, developed in work package 1 [30], guided the development of the predictive driver model.

Prateek Thalya addressed the second and third research question by integrating the predictive model in a smart collision-avoiding system [31] within work package 4. In principle, this system compares braking and steering actions from the vehicle network with the predictions from the driver model. In other words, the safety system leverages the discrepancy between "what the driver is supposed to do" and "what the driver actually does" to inform the threat assessment, so that warnings and interventions are not based on kinematics alone and happen outside a driver comfort zone. Although this principle may appear obvious, very few of the systems on the market consider driver comfort zone and leverage the mismatch between driver models and driver action to deliver warnings and interventions. Interestingly, the system was verified both 1) on the test-track data, to estimate false negatives and true negatives and 2) on field data, to estimate false positives and true negatives. This second type of verification is seldom performed and yet very informative because it makes sure that safety benefits do not occur at the expenses of acceptability.

Finally, Jordanka Kovaceva estimated the safety benefit of the smart collision-avoidance system within work package 5 [32]. This assessment highlighted the margins for safety improvements of the new system and benchmarked it with traditional systems from the literature [33]. This safety benefit estimation used counterfactual simulations and naturalistic data [34]. By using injury and fatality curves, this analysis could also quantify the potential safety benefits as reduced injuries and fatalities.

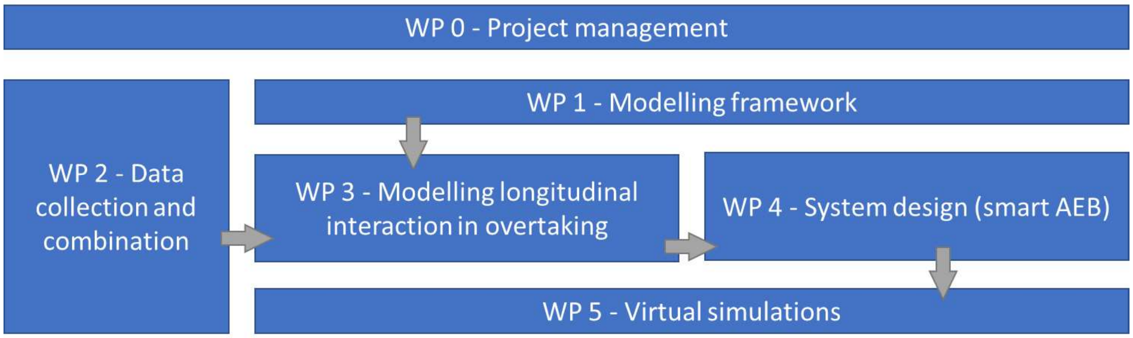

Figure 1 – The work breakdown in MICA. Arrows indicate the relation between the work packages (WP).

5. Objective

The main objective of MICA was to support the Swedish automotive industry maintaining its world-leading role in the design of cutting-edge solutions for active safety. To reach this objective, MICA developed a novel driver model, able to predict driver intention as she approaches a cyclist from behind to perform an overtaking manoeuvre. A new smart collision-avoidance system was developed, verified, and validated within the project. The main novelty of this active safety system is the integration of the driver model to provide more effective and yet acceptable interventions to improve overtaking safety. This type of safety system was at TRL (technology-readiness-level) 1-2 at the beginning of the project and is now at TRL 4. However, its validation in virtual simulation is not complete yet.

While focusing on its primary objective, MICA also reached some other goals that indirectly show the impact of the results from this project.

1) MICA provided input *to Euro NCAP* by 1) highlighting which factors may play a role in the cyclist-overtaking scenario and should be considered in future protocols and 2) benchmarking the new the smart-collision avoidance system with the current requirements for FCW from the Euro NCAP test protocol.
2) MICA addressed the *sustainable development goals* 3 and 11 from the United Nations by promoting higher standards of cycling safety.
3) MICA informed the *design of automated vehicles* by providing a model of human behaviour that AV may mimic not to surprise or scare other road-users during an overtaking manoeuvre
4) MICA informed the *design of sensor technology* by showing the importance to monitor the oncoming traffic and the timing necessary to do so. Currently, sensors for on-the-market active safety systems do not provide this information.

5) MICA informed the *design of cooperative applications* by 1) showing the potential for wireless communication between the overtaking vehicle, the oncoming vehicle, and the cyclist, and 2) showing the timings necessary for this communication in the approaching phase of an overtaking manoeuvre. These timings are useful to derive requirements for wireless communication.
6) MICA favoured networking among different *Swedish stakeholders* who joined the MICA advisory board and are now active partners in MICA2.
7) MICA brought Swedish research to the attention of the *international scientific community* by contributing to international conferences and publishing in international scientific journals.
8) MICA contributed to the *education* of future traffic-safety researchers by fostering three PhD students that will complete their degree in MICA2.
9) MICA promoted *gender balance* by assessing, when possible, the different behaviour of female and male drivers, and by including female researchers and students in a project within a research environment where men are a vast majority.

6. Results and deliverables

6.1 Main results

The main results of the MICA project are described in nine scientific contributions (fully referenced in section 7.2) and include these deliverables:

1) a *dataset* collected on the airfield in Vårgårda with two robots,
2) a *modelling framework* that helps to identify interaction on a scenario basis,
3) a novel *driver model*, which can predict overtaking strategy in real-time,
4) a *smart collision-avoidance system* which uses the model to generate warnings and automated interventions, and
5) a *safety benefit analysis*, proving the potential for the new collision-avoidance systems to save lives and reduce injuries.

The dataset was the basis for the driver model, that was created within the modelling framework and integrated into the smart collision-avoidance system. The safety benefit analysis compared the smart collision-avoidance system with a reference collision-avoidance system (Euro NCAP).

Dataset from test-track
Twenty-three participants overtook a robot-cyclist while facing an oncoming robot-car on a test-track. We tested different combinations of speed, cyclist overlap, and time-to-collision with the oncoming robot-car. The final dataset included 27 accelerative manoeuvres (waiting for the oncoming robot-car to pass before passing the robot-cyclist) and 41 flying manoeuvres (completing the overtaking manoeuvre before the oncoming robot-car had passed). Figure 2 shows photos of the robot-cyclist and the robot-car.

Figure 2 – A participant approaches the robot-cyclist on the airfield in Vårgårda (left). The robot-car used as oncoming traffic in the experiment (right).

The following videos were collected during a pilot experiment and show the experimental protocol:

- Flying manoeuvre (inside view): https://www.youtube.com/watch?v=AixQ189hMi4;
- Accelerative manoeuvre (outside view): https://www.youtube.com/watch?v=GSVPrXSHLSI;
- Flying manoeuvre (inside view): https://www.youtube.com/watch?v=W1O2E0vYhCY;

The videos acknowledge Toyota Motor Europe, that contributed to MICA via the DIV project. Rasch et al. 2019 report all details about the protocol, the dataset, the analyses, and the statistical modelling [29].

Modelling framework

At the beginning of the project, we developed a framework for modelling driver behaviour in interaction with other road-users. The framework explains step by step how to identify actors and interactions for a given scenario. According to the unified modelling language, use-case-, state-machine-, and sequence-diagrams are used to describe the actors and their interactions. Figure 3 shows an example of a use-case diagram. This framework was presented at the International Cycling Safety Conference 2018 [35] and is also reported in detail in Thalya et al. 2020 [30].

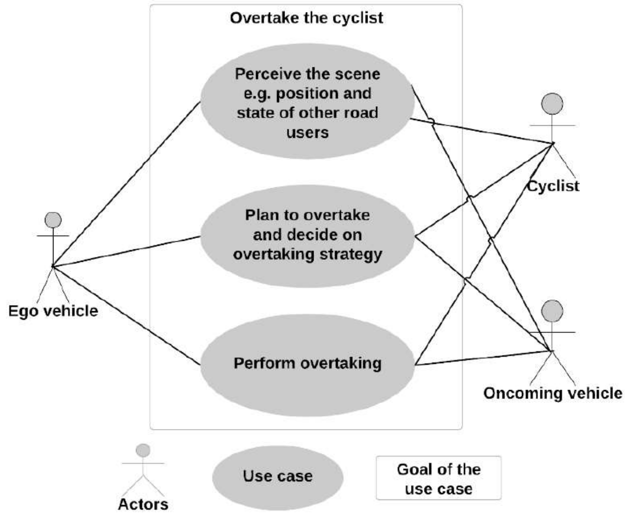

Figure 3 – Use case diagram from the modelling framework for the overtaking scenario in MICA.

Driver models

The data from the test track was modelled with Bayesian statistics to show how the factors controlled in the experiment influenced different parameters of an overtaking manoeuvre (such as the minimum time-to-collision to the cyclist). Rasch et al. 2019 fully describe this statistical model [29].

While accelerative manoeuvres required a braking action, flying manoeuvres required a steering action. A predictive model, able to estimate driver action in real-time, was developed using logistic regression. This model takes 1) the lateral distance between cyclist and oncoming vehicle, 2) the longitudinal distance to the cyclist, and 3) the longitudinal distance to the oncoming vehicle as inputs and estimates—in real-time—the probability for the driver to brake and steer. Figure 4 (left) shows that the probability of *steering* becomes much higher than the probability of *braking* as a driver approaches the cyclist to perform a *flying* manoeuvre. Figure 4 (right) shows that the probability of *braking* becomes much higher than the probability of *steering* as a driver approaches the cyclist to perform an *accelerative* manoeuvre. The model could identify drivers' intent to overtake with high sensitivity (0.88) and perfect specificity (1.00). Rasch et al. detail this predictive model [28].

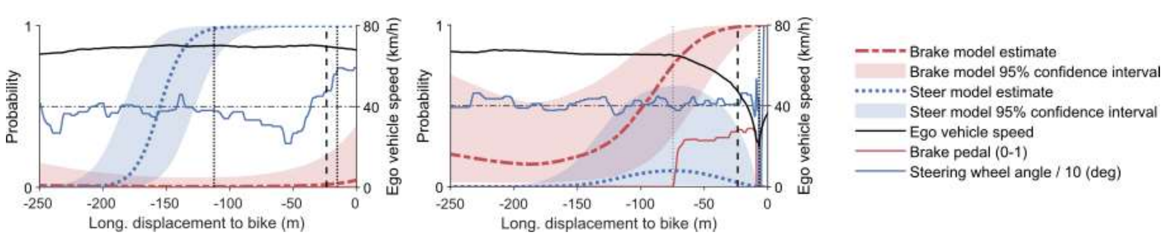

Figure 4 – Model prediction for steering and braking probability as a participant approaches a cyclist. Left panel: flying overtaking. Right panel: accelerative overtaking.

Smart collision-avoidance system
The predictive driver model was integrated into a collision-avoidance system. The collision avoidance system issues a warning depending on the *mismatch* between the actual braking and steering (from the vehicle network) and the braking and steering predicted by the model (Figure 5). This mismatch warrants the warning to happen outside a driver comfort zone. Therefore, the warning is likely acceptable even if produced when kinematics are not yet critical. AEB was then activated if a reaction to the warning was still missing and the predicted reaction too long delayed. Test-track data [29] and field data [14] supported system verification. While the test-track data confirmed that the system did not miss opportunities to warn (i.e. no false negatives), the field data verified that the system did not warn when it was not needed (i.e. no false positives). The collision-avoidance system is fully described in Thalya et al. [31].

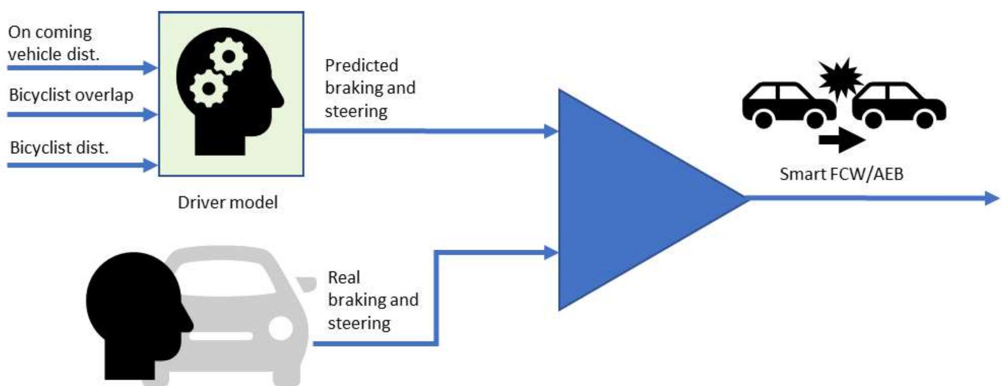

Figure 5 – Architecture of the collision-avoidance system.

Safety benefit analysis
Because early interventions will happen outside a driver comfort zone, the smart collision-avoidance system from MICA has the potential to improve safety without compromising acceptability. A counterfactual analysis was performed on UDRIVE naturalistic driving data to estimate this improvement. The counterfactual simulations compared the warning from the collision-avoidance system to a reference warning based on the Euro NCAP test protocol for longitudinal interaction with cyclists [36]. The counterfactual simulations included different driver models; Figure 6 compares the safety benefit in terms of reduced injuries and fatalities across the warning algorithms for one driver model. When considering different driver models, the range of safety benefit in terms of reduced fatalities was 53-96% for the smart system and 4-98% for the reference system. For severe injuries, these ranges were: 43-93% and 1-94%, respectively. The upper values of these estimations originate from the model of an idealistic driver: extremely attentive and with perfect reactions. Kovaceva et al. describe the complete safety benefit assessment [33]. The framework for the counterfactual simulation is detailed in the licentiate thesis from Jordanka Kovaceva [32]. This licentiate thesis includes a paper comparing driver models in counterfactual simulations [37]. This paper is essential because it proves the importance of driver models in counterfactual

simulations and justifies the use of multiple driver models to provide a reliable estimation from our safety benefit assessment.

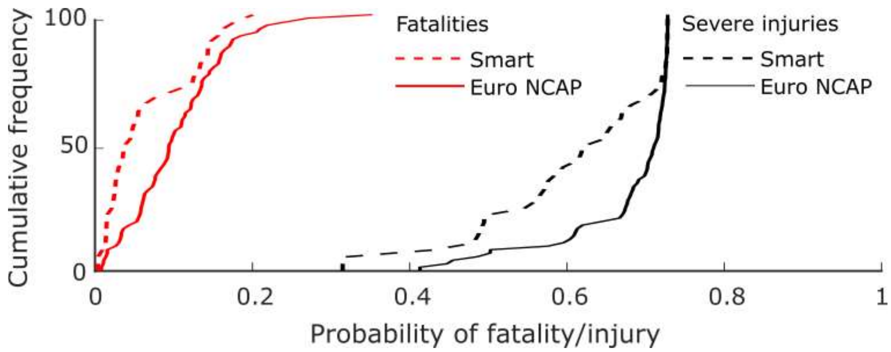

Figure 6 – Injury and fatality curves from the safety benefit analysis.

6.2 Lessons learned

As in most research projects, not everything went according to plan, and there were several opportunities to question our initial approach.

Some of the most important **lessons-learned** include:

1) The most critical interaction in an overtaking manoeuvre is between the vehicle overtaking and the *oncoming traffic*, while the interaction between the overtaking vehicle and the cyclist appears to be minimal and less critical. (We expected the cyclist to interact with the overtaking vehicle by changing her lateral displacement; however, we could not find this behaviour in the UDRIVE naturalistic dataset.)
2) The approaching phase may not be the riskiest phase of an overtaking manoeuvre. The largest margin for improving safety may lay in *other phases of the overtaking manoeuvre* (e.g. the returning phase), when an overtaking vehicle may cut-in and destabilize the cyclist) to avoid a head-on collision with the oncoming traffic.
3) As an overtaking manoeuvre develops from the approaching to the steering, passing, and returning phase [14], the kinematics become more critical.
    a. Therefore, *passive safety systems* become an important complement to active safety as we move away from the approaching phase.
    b. Data from situations with critical kinematics require *new methodologies* so that the testing can be ecologically valid and safe.
4) Synchronizing two robots with the behaviour of one driver proved to be very challenging, and the complexity from having two robots instead of one grew exponentially. On the one hand, this is yet another motivation for the development of virtual/augmented reality approaches on test-track. On a more visionary dimension, this suggests that NCAPs will

eventually need to move to virtual simulations as the scenarios under test become more complex and include several road users.

5) More naturalistic data with higher sensor resolution is needed to validate our models and make it possible to run accurate safety-benefit analyses. (The UDRIVE dataset used in MICA is the largest in Europe, and we were still able to only use 73 cases for our analysis).
6) Most of the safety benefit analyses focus on true positives and neglect false positives. The consequence is an overestimation of the safety benefit. Naturalistic data (when large enough) may help this estimation so that we can verify that early warnings are indeed as acceptable as we assume them to be because they happen outside a driver comfort zone.
7) For AV to safely overtake without surprising or scaring any road users (including the driver/passenger), understanding the relation to oncoming traffic is crucial. This information is not obvious from commercial sensors and may be more easily available via wireless communication. As a driver moves from the approaching phase to the following overtaking phases, the requirements for sensor technology and wireless communication may drastically increase.

The MICA2 proposal was built on these lessons learned.

6.3 Deviations from the initial plan

During the project, several major events happened. Soon after the project started, Autoliv created a new spinoff and the new company, Veoneer, took over the project. Toward the end of the project, COVID-19 struck our planet, creating unforeseen and unprecedented challenges for all research projects. Of course, the project had to accommodate for these events and find new solutions. For instance, the GIDAS database was suddenly not available (because it was a property of Autoliv) and UDRIVE data was used instead. This solution is arguably better than what was planned; therefore, this should not be seen as a limitation in the project results.

During the project, we realized that the largest margin for safety improvement, when integrating a driver model in active safety for our scenario, was on the collision warning. Therefore, while MICA promised a smart AEB, it delivered a smart collision-avoidance system, including collision warning and AEB instead.

The lessons learned (and specifically the second bullet in the list above) also explain why MICA2, that initially planned to address intersections, still focuses on the overtaking manoeuvre. In fact, MICA2 extends MICA to the entire overtaking manoeuvre, addresses new active and passive safety systems, and introduces new methodologies and data types to support the design and evaluation of driver models and safety systems.

7. Dissemination and publications

7.1 Dissemination of the project results

The results from MICA are described in seven scientific publications and two conference contributions (see next sub-section for full citations). The MICA results were presented at the International Cycling Safety Conference in 2018 and 2019, and are included in the proceeding of the 2020 TRA conference (that was unfortunately cancelled because of COVID-19). A SAFER seminar was organized on June 17th, "MICA 1 – Modelling Interaction between Cyclists and Automobiles", and the whole SAFER network was invited. MICA has a webpage on the Chalmers research website. Finally, the project's members met regularly with the advisory board. These meetings favoured the dissemination of preliminary results among several stakeholders and OEMs and were the basis for developing MICA2 (counting seven partners, instead of the only two in MICA). Of course, MICA2 was the opportunity for MICA's heritage to leverage the results from other projects, most notably CYCLA, CHRONOS, and COPPLAR. MICA2 will now continue the dissemination of the results from MICA.

7.2 Publications from MICA

Licentiate thesis

- Kovaceva J., "*Understanding and modelling car drivers overtaking cyclists: Toward the inclusion of driver models in virtual safety assessment of advanced driving assistance systems*", (2019), Licentiate thesis, Chalmers University of Technology, Gothenburg, Sweden.

Journal papers

- Rasch A., Boda C.-N., Thalya P., Aderum T., Knauss, A. & Dozza, M. (2020) "*How do oncoming traffic and cyclist lane position influence cyclist overtaking by drivers?*". Accident Analysis & Prevention, Vol. 142.
- Kovaceva J., Bärgman J., Dozza M., "*Enabling counterfactual analyses to estimate the safety benefit of advanced driving assistance systems: A comparison of driver models using naturalistic and test-track data from cyclist-overtaking maneuvers*", (submitted to TRF)
- Rasch, A., & Dozza, M., *"Modeling drivers' strategy when overtaking cyclists in the presence of oncoming traffic"*, (submitted to IEEE Transactions on Intelligent Transportation Systems).
- Kovaceva J., Bärgman J., Dozza M., "*The potential safety benefit of collision warning system for car to cyclist overtaking scenario*", (in preparation)
- Thalya P., Lubbe N., and Dozza M., "*How can driver models inform threat assessment for active safety? Implementation and evaluation of a new forward collision warning system.*", (in preparation)

The last two papers will be completed and published within MICA2.

Contributions to conferences

- Thalya, P., Kovaceva, J., Knauss, A., Lubbe, N., & Dozza, M. "*Modeling driver behavior in interactions with other road users*", Transportation Research Arena, Helsinki, Finland 27-30 Apr 2020.
- Kovaceva J., Thalya P., Lubbe N., Knauss A., Dozza M. "*A new framework for modelling road-user interaction and evaluating active safety systems*". 7th International Cycling Safety Conference, Barcelona, Spain, Oct. 10-11, 2018.
- Rasch A., Boda C.-N., Thalya P., Aderum T., Knauss, A. & Dozza, M. "*How do oncoming traffic and cyclist lane position influence cyclist overtaking by drivers?*" 8th International Cycling Safety Conference, Brisbane, Australia, 18-20 Nov 2019.

8. Conclusions and future research

MICA demonstrated that driver models may help reduce fatalities and injuries by improving active safety interventions.

MICA developed—and virtually assessed—a new, *smart collision-avoidance system* that integrates collision warning and automated braking to support a driver in the approaching phase of an overtaking manoeuvre with on-coming traffic present. The *system verification* proved that the systems do not introduce false positives (using field data) neither false negatives (using test-track data). The *virtual safety assessment* estimated that the new collision warning system alone may reduce fatalities by 53-96% and severe injuries by 43-93% using naturalistic data from UDRIVE. MICA collected *unique data on a test-track*, where two robots made it possible to measure how humans select overtaking manoeuvre strategies, depending on the time-to-collision to the oncoming traffic, in comfortable driving.

Further, MICA highlighted that:

1) Modelling the interaction between the overtaking vehicle and the *oncoming vehicle* is an essential step to increase overtaking safety.
2) The approaching phase of an overtaking manoeuvre is not necessarily the riskiest; the most significant margin for improving safety may lay in developing systems that support the drivers in the *returning phase*.
3) In the approaching phase of an overtaking manoeuvre, the potential safety benefits from *automated emergency steering* (a system not addressed in MICA) is substantial.
4) As an overtaking manoeuvre develops from the approaching to the steering, passing, and returning phase, vehicle kinematics and proximities become more

critical, challenging active safety systems and calling for *new passive safety solutions*.

5) More experimental data, collected in more critical situations than what was possible in MICA, is needed to address overtaking safety properly. *New methodologies*, such as augmented reality and virtual reality, offer the best opportunities to collect such data without ethical concerns.
6) More *naturalistic data* is needed to validate our driver models and the new systems that we started developing in MICA.
7) Interaction among road users is complex and models of vulnerable road-user behaviour are also needed to make robust predictions. As we move from an overtaking scenario to a crossing scenario, this aspect will become even more crucial.

MICA2 will now address the whole overtaking manoeuvre by 1) improving driver models to capture interaction among road-users, 2) including lateral-control systems, 3) estimating the potential safety benefits from safety systems in the four phases of the manoeuvre, 4) introducing passive safety systems, 5) leveraging new advances in technology such as virtual/augmented reality to acquire new data in critical situations, and 6) collecting new site-based naturalistic data.

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