THESIS FOR THE DEGREE OF LICENTIATE OF ENGINEERING

Making overtaking cyclists safer
Driver intention models in threat assessment and decision-making of advanced driver assistance system

Prateek Thalya

Department of Machine and Maritime Sciences

CHALMERS UNIVERSITY OF TECHNOLOGY

Gothenburg, Sweden 2021

Making car overtaking a bicycle safer: Driver intention models in threat assessment and decision-making of advanced driver assistance system
Prateek Thalya

Technical report no 2021:08

Department of Machine and Maritime Science
Chalmers University of Technology
SE-412 96 Gothenburg
Sweden
Telephone + 46 (0)31-772 1000

Chalmers digitaltryck
Gothenburg, Sweden 2021

A product of my circumstances

Abstract

Introduction: The number of cyclist fatalities makes up 3% of all fatalities globally and 7.8% in the European Union. Cars overtaking cyclists on rural roads are complex situations. Miscommunication and misunderstandings between road users may lead to crashes and severe injuries, particularly to cyclists, due to lack of protection. When making a car overtaking a cyclist safer, it is important to understand the interaction between road users and use in the development of an Advanced Driver Assistance System (ADAS). **Methods**: First, a literature review was carried out on driver and interaction modeling. A Unified Modeling Language (UML) framework was introduced to operationalize the interaction definition to be used in the development of ADAS. Second, the threat assessment and decision-making algorithm were developed that included the driver intention model. The counterfactual simulation was carried out on artificial crash data and field data to understand the intention-based ADAS's performance and crash avoidance compared to a conventional system. The method focused on cars overtaking cyclists when an oncoming vehicle was present. **Results**: An operationalized definition of interaction was proposed to highlight the interaction between road users. The framework proposed uses UML diagrams to include interaction in the existing driver modeling approaches. The intention-based ADAS results showed that using the intention model, earlier warning or emergency braking intervention can be activated to avoid a potential rear-end collision with a cyclist without increasing more false activations than a conventional system. **Conclusion**: The approach used to integrate the driver intention model in developing an intention-based ADAS can improve the system's effectiveness without compromising its acceptance. The intention-based ADAS has implications towards reducing worldwide road fatalities and in achieving sustainable development goals and car assessment programs.

Keywords: Overtaking, Cyclist, Interaction, Driver intention, ADAS, Euro NCAP

Acknowledgments

Research was supported by the Modeling Interaction between Cyclists and Automobiles project (MICA, r.n. 2017-05522) and Modeling Interaction between Cyclists and Automobiles 2 project (MICA2, r.n. 2019-03082), funded jointly by the Swedish innovation agency Vinnova, the Swedish Energy Agency, the Swedish Transport Administration, and the Swedish vehicle industry through the strategic vehicle research and innovation (FFI) program. Part of the data was collected from the project "Drivers in Interaction with Vulnerable Road Users" (DIV), a collaboration between Toyota Motor Europe (Belgium), Autoliv, and Veoneer (both Swedish).

This work would not have been possible without the support of my supervisors Marco Dozza, Nils Lubbe, Tobias Aderum, and Ola Bostrom. A special thanks to Alessia Knauss. I want to thank all my colleagues at Veoneer Research and Vehicle safety at Chalmers, particularly Jordanka Kovaceva and Alexander Rasch, for all the exciting discussions. I would also like to thank Mark Rosenfeld for the language review and extend my gratitude to the reviewers of appended papers.

Thanks to my friends and family for all their love and support.

Lastly, Emilia, my love, thank you for your unconditional love and support.

Abbreviations

VRUs	- Vulnerable Road Users
ADAS	- Advanced Driver Assistance System
FCW	- Frontal Collision Warning
AEB	- Automated Emergency Braking
ESS	- Emergency Steering System
NCAP	- New Car Assessment Program
SDGs	- Sustainable Development Goals
UML	- Unified Modeling Language

Contents

1.Introduction

1.1.Global fatalities and injuries – From the present to the future

The number of motorized vehicles globally has seen a rapid growth, especially in low and middle-income countries. However, the rate of traffic fatalities relative to the size of the world population has stabilized from 2000 to 2016 [1]. In 2018, World Health Organization (WHO) reported that 1.35 million people have died due to road accidents in 2016, and roughly 50 million people were seriously injured [1]. Vulnerable Road Users (VRUs) – pedestrians, cyclists, and powered two-wheelers are disproportionately impacted relative to drivers or passengers in 4-wheeled vehicles and make up 54% of all road fatalities [1]. Cyclist fatalities in collisions with motorized vehicles make up 3% of the total fatalities in the world [1] and 7.8% of all fatalities in the European Union [2]. Reported cyclist fatalities have increased in Ireland and Norway between 2010 and 2018 [3]. However, the number of cyclist fatalities has decreased by 5.4% on average between 2010 and 2018 in the crash report from 34 countries [3]. The number of road fatalities is estimated to rise, and by 2060, 2.26 million people will die on the road if no additional measures are taken to reduce the number of fatalities [4].

The United Nations (UN) Sustainable Development Goals (SDGs) [5] adopted by all the member states in 2015 has set 17 goals to address aspects in need of urgent action in both developed and developing countries. The SDG 3, Good Health, and SDG 11, Sustainable Cities and Communities directly influence road traffic-related research. Target 3.6 relates to halving the number of fatalities on roads by 2020, and Target 11.2 relates to providing access to safe and sustainable transport for all by 2030. However, Target 3.6 of halving the road traffic fatalities by 2020 was not achieved despite the global plan of "Decade of Action for Road Safety" between 2011 and 2020. Based on the Stockholm Declaration of 2020, a push for a more substantial commitment by the UN member states, the targets were reiterated to achieve by 2030 [6].

The ways to reach SDG 3, Target 3.6 could be by improving road safety management, effective laws, improved infrastructure design, improved vehicle safety technologies [7], and to reach SDG 11, Target 11.2, are safe cities that are accessible and environmentally friendly to all road users. Cities are encouraged to provide bicycle lanes, design pedestrian-friendly pavements, and easily accessible public transport by more robust transport policies [7]. Furthermore, in the report Saving Lives Beyond 2020 [8], academic experts recommend different actions and responsibilities to reach the SDG goals. Recommendation number 3 – Modal Shift, recommends a greater emphasis on physical activities such as walking, cycling, public transport, and a cleaner, safer and affordable mode of transportation during urban and transport planning [8].

The WHO recommends a minimum of 150-300 minutes of moderate physical activity weekly [9]. Integrating cycling into daily routines is a good way of achieving that. There is much evidence of health benefits regarding cycling, such as increased cardiorespiratory fitness, improved cognitive function, and reduced risk of depression. The studies highlighting the health benefit were reviewed in the paper by Göteschi et al. [10] and Oja et al. [11]. Health benefits and environmental benefits to reduce climate change, cycling has seen a rise as a means of day to day travel. It has also given rise to cyclist-related fatalities. The rise in cyclist fatalities is attributed to infrastructure designs and perceived safety by the cyclist. A study by Graser et al. [12], in interviews with cyclists conducted in Vienna, showed that safety concerns are associated with traffic volume, confusing intersection design, cyclist lanes next to parked cars, and rail infrastructure. Similar results were also highlighted in [13].

1.2.Overtaking of cyclists by cars

A recent study on car-cyclist crashes using the crash databases from Sweden, Germany, and Hungary has shown that most fatalities occur when both cars and cyclists meet in longitudinal traffic [14]. In these scenarios, when both car and cyclist are traveling in the same direction, overtaking a cyclist becomes a challenging task, especially when there is an oncoming vehicle. Misjudging the speed and distance of an oncoming vehicle can reduce both longitudinal and lateral safety margins [15], possibly resulting in a crash [16]. Overtaking cyclists by cars has been previously studied using different datasets, field data [17], simulator data [18], naturalistic data [19], and data collected on a test track [20]. These studies detail the risk and parameters that influence cyclist overtaking. Specifically, the influence of an oncoming vehicle on the ego vehicle (i.e., “our” car) when overtaking has been highlighted in studies [17]–[19].

1.2.1.Phases of overtaking

Overtaking comprises different phases, for example, a three-phase classification based on fixed duration [21] or a five-phase classification based on the driver's intentions and actions [22]. Overtaking of a cyclist by cars has been classified to consist of four phases by Dozza et al. [17], who described this based on the field of safe travel [23]. Figure 1 details the different phases of overtaking a cyclist when an oncoming vehicle is present.

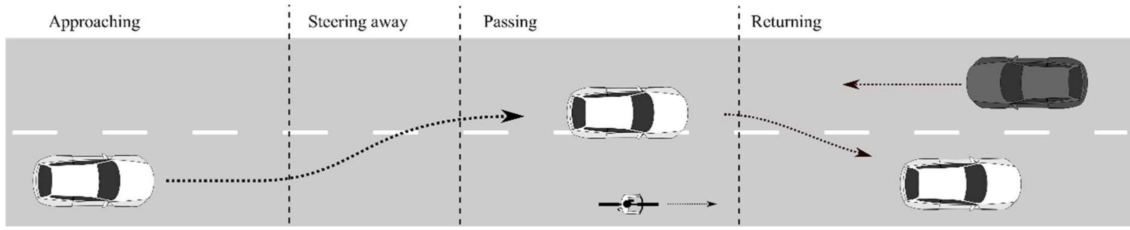

Figure 1: Overtaking phases as described in Dozza et al. [17]

1.2.2.Types of overtaking

The type of overtaking performed is based on the driver's comfort zone boundaries. Drivers can perform three types of overtaking [17], [24], flying overtaking, accelerative overtaking, or piggy backing. However, in this thesis, only flying and accelerative overtaking are considered. The flying overtake occurs when the ego vehicle steers to the adjacent lane (steer onset) and overtakes the cyclist before the oncoming vehicle has reached the cyclist. Accelerative overtake when the ego vehicle first brakes (brake onset) to let the oncoming vehicle pass and then overtakes the cyclist while reaccelerating to the initial speed [17], [20], [25].

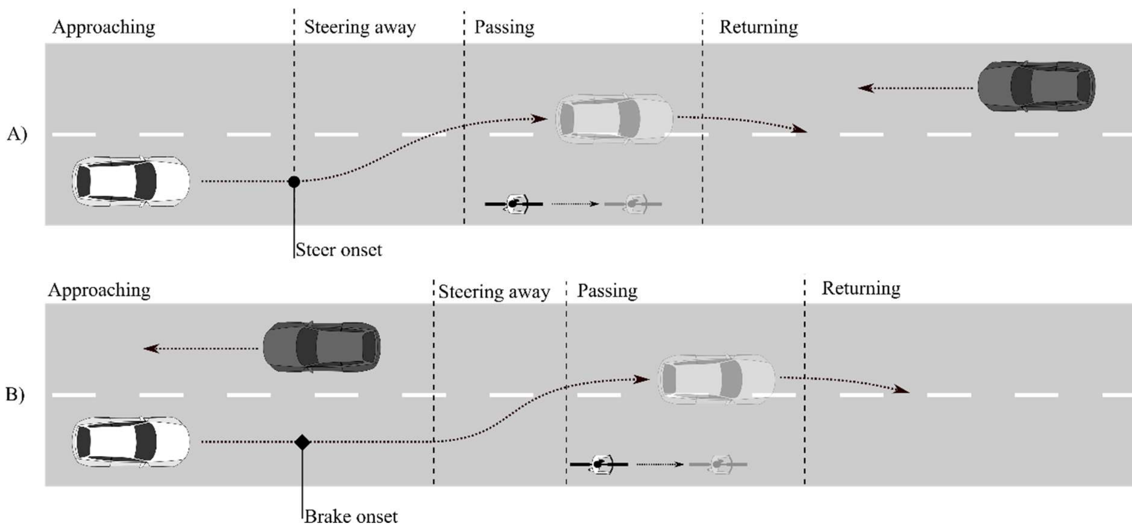

Figure 2: Types of overtaking quantified by driver A) steer onset for flying overtake and B) brake onset for accelerative overtake

There are several crash risks involved during the phases of overtaking, i.e., risk of rear-end collision with the cyclist in the approaching phase, head-on collision with the oncoming vehicle in the passing phase, sideswipe collisions with the cyclist in the passing and return phases. To ensure safe overtaking, it is essential to understand the parameters that influence the driver overtaking behavior and understand the crash risk associated with different overtaking strategies. Mathematical models that may help capture different driver behavior can be developed to understand and quantify the drivers.

1.3.Driver modeling

A driver model has been defined as "a comprehensive description of scientific knowledge about drivers" [26]. Driver models may be broadly defined as qualitative (typically considering subjective, human factors) or quantitative (typically considering objective, measurable factors). These models may play a crucial role in assessing a situation's perceived criticality (e.g., how close a driver feels to a rear-end collision). Different models are suitable for different scenarios. For instance, longitudinal control models [27], [28] would be particularly suitable for a rear-end situation, and lateral control models [29] for negotiating a curve.

1.3.1.Interaction among road users

When creating a model, driver behavior in complex situations such as overtaking, interaction among road users plays an important role, as highlighted by Dozza et al. [17]. Interaction among road users has been considered in both qualitative and quantitative modeling approaches. For example, an interaction may belong to all levels in the hierarchical model of driving tasks, distinguishing between tasks at the strategic, tactical, and operational levels

[30]. In quantitative driver models, interactions are often associated with crashes compared to normal driving scenarios [31].

1.3.2.Driver model in ADAS development

The most common cause of road fatalities is human errors [32], [33]. To reduce the errors and support drivers during complex driving situations, ADAS are being introduced. Driver models with interaction may help understand the perceived criticality of a situation (e.g., how close a driver feels to a rear-end collision) and improve the ADAS functionality. There has been an effort to include driver models in ADAS to predict road user behavior including creating interactive, probabilistic motion-models of other road users [34]; making set-based predictions about other road users [35], [36]; and combining trajectory planning of other road users with interaction prediction [37].

In complex situations, ADAS often use deterministic prediction approaches, which operate with limited information, potentially missing cues about other road users' intentions. Interactions can lead to driver expectations of future maneuvers not being matched by current ADAS, and in turn, to a driver's subjective hazard perception not reflected by the ADAS threat assessment [38]. Previous studies have shown that including driver models in ADAS development improves the systems' effectiveness [39], [40]. The interaction models that represent the interaction have been shown to improve existing ADAS, for example, by improving the system's ability to predict the ego vehicle's future trajectory or directly implementing in ADAS using the method described by Lefevre et al. [41] or reducing uncertainties in the probabilistic threat-assessment methods used in ADAS.

1.4.ADAS to address cyclist fatalities

ADAS such as FCW, cyclist AEB, and ESS are being introduced to the market to address the growing number of cyclist fatalities and support the driver in mitigating cyclist crashes. In a critical situation, a warning might be issued to alert the driver, and emergency braking or emergency steering is applied to mitigate the collision in a critical situation. The method used to assess the threat during a critical situation involves a wide range of approaches, ranging from simple vehicle kinematics, e.g., estimating time to collision (TTC) [42] or predict the minimum distance to the road-user ahead [43] or calculate the deceleration required to avoid a collision [44]. More sophisticated techniques involve, for example, logic-based approaches, which translate the requirements into logical sentences rather than specifying complex requirements (e.g., quantified differential dynamic logic [45]), or probabilistic assessments, which assign probabilities to different events and road-user actions [46].

The methods used to assess the threat, ADAS, must detect at all times objects in the range of the front of the vehicle. Forward-looking sensors such as cameras and radar installed in the vehicle can detect objects and other road users. The sensor can be used as standalone or in combination via sensor fusion to achieve high reliability and accuracy in detecting road users, even in adverse weather conditions and poor visibility.

For ADAS designed to prevent cyclist fatalities, it is essential to detect and classify the VRUs. Sensors' field-of-view (FOV) has been shown to influence the detection and tracking of objects. Effectiveness studies on intersection AEB showed that a wide FOV sensor (180°) substantially increased accident avoidance and injury mitigation rates compared with a 120° FOV sensor [47]. With wider FOV, new modulation schemes detect and classify objects in front of the vehicle with greater precision. However, concerning overtaking scenarios, a small overlap with the cyclist might be complicated, and small changes in steering adjustments can lead to different path predictions. Small overlap may also result in missed tracking by the single sensor; a network of radar sensors (as shown in s[48]) would improve the cyclist's tracking and detection. Multiple sensor setup could also give rise to a "hand over" problem when the object is tracked simultaneously over multiple time steps, giving rise to considerable uncertainty. A combination of missed detection, tracking, and limitations with path planning, ADAS may not be activated or are activated close to collision due to the high risk of false activations.

ADAS such as AEB and FCW are highly effective in mitigating car-to-car rear-end crashes [49], [50], and intersection crashes [51]. The effectiveness of VRU related AEB presented in Rosén reduced the cyclist fatalities up to 55% and severe injuries by up to 33% [52]. Furthermore, counterfactual simulation carried out by Kovaceva et al. [53] shows the recently proposed AEB and steering systems for car-to-cyclist scenarios has the potential to save up to 71-90% of crashes. For the same scenario, Char et al. [54] showed that FCW could reduce or mitigate 84% of crashes in the in-depth crash data from France and Germany. Char et al. [54] also highlighted that the drivers' reaction time to the type of FCW (audio, video, haptic) for car-to-cyclist scenarios influence crash avoidance.

However, ADAS are not perfect. A mismatched expectation between the system's functionality and the driver's expectations can lead to driver annoyance and prompt the driver to disable these systems [55]. The behavior of drivers disabling the system due to a perceived false warning was observed in the study by Reagen & McCartt [56]: where lane departure warning was turned on only for 32.8% of the time in all observed vehicles in the study.

1.5.Evaluation of ADAS

The effectiveness assessment of ADAS is of great interest for different stakeholders [57], vehicle manufacturers, safety system suppliers, and regulatory bodies. Independent NCAP organizations have a high interest in effectiveness estimates to verify whether their rating strategy matches real-life injuries. The assessment methods can be broadly classified into two broad categories: priori and posterior assessment.

1.5.1.A posterior assessment

A posterior or retrospectives assessment involves the assessment carried out on real-life data, e.g., naturalistic data, which gives an unbiased assessment of safety systems under evaluation. The retrospective assessment method involves evaluating the benefit with or without the ADAS. For example, effectiveness assessment of lane departure warnings based on insurance claim data by Isaksson-Hellman and Lindman [55], where cars with and without the lane departure warning systems were compared for the relevant crash scenario. Similarly, in a study by Cicchino, J. [50], a retrospective assessment was carried out of vehicles fitted with FCW and AEB on police-reported crash data.

1.3.2.A priori assessment

A priori or prospective assessment is carried out by utilizing different models and constraints that may not replicate reality. Prospective assessment is often carried out using different data, e.g., test track data, driving simulator, or virtual assessment. The virtual assessments may involve counterfactual computer simulations on real-world crash or near-crash data [58]–[60] under different assumptions. The driver, vehicle, and environment are modeled to analyze the reduction in the number of crashes or fatalities in simulations with the modeled new system compared to those without it.

1.3.2.1.Euro NCAP testing for ADAS for cyclist overtaking

Test protocols by the Euro New Car Assessment Program (Euro NCAP) for longitudinal scenario configuration, which evaluates both FCW and cyclist AEB, were introduced in 2018 [61]. In the scenario, FCW is evaluated for the configuration of 25% overlap between the car and cyclist in the longitudinal direction (CBLA-25), and AEB is evaluated for 50% overlap (CBLA-50) [61]. However, these assessments do not include an oncoming vehicle in the opposite lane; these testing protocols only evaluate the effectiveness of FCW and AEB in avoiding rear-end collision with the cyclist.

In longitudinal scenarios with a cyclist, steering control plays an important role; steering timing is influenced by the oncoming vehicle [18]. In critical situations, AES can be more efficient when avoiding collisions than AEB in critical situations [62], [63]. Systems such as Autonomous Emergency Steering (AES) have been proposed for preventing collision [64], [65]. Similar to AES, Emergency Steering Support (ESS) is being introduced and evaluated in Euro NCAP testing. ESS enhances the driver's steering action in a critical situation, attempting to avoid or mitigate a collision.

2.Aim and objectives

This licentiate work is based on a PhD plan which aims to provide scientific knowledge for ADAS development of the emergency braking system and emergency steering assistance to overtake a cyclist on a rural road safely. To achieve this aim, an operational framework was developed to understand and identify the possible interaction between road users while overtaking. Using the operational framework, a driver model with interaction has been used to develop threat assessment and decision-making algorithms for longitudinal support to reduce rear-end collision with a cyclist. Later lateral control, together with longitudinal control, will be implemented based on intention models to further advance scientific knowledge of ADAS development. The effectiveness of intention-based ADAS in reducing the number of cyclist fatalities during overtaking will be calculated. These steps were formulated into objectives listed below.

The objective of this licentiate was:

1. To develop a framework explaining how the interaction between road users may be considered in developing driver behavior models for collision avoidance systems.
2. To integrate driver intention in the threat assessment of automated emergency braking that supports the driver in the approaching phase of overtaking a cyclist when an oncoming vehicle is present.

Further objectives for the PhD are

3. To integrate driver intention in the threat assessment of automated emergency braking and emergency steering system that supports the driver in the approaching phase of overtaking a cyclist.
4. To integrate driver intention in the threat assessment of automated emergency braking and emergency steering assistance that support the driver in the passing and returning phase of overtaking a cyclist.
5. To assess the effectiveness of a driver intention-based threat assessment method for automated emergency braking and an emergency steering system in terms of crash avoidance and acceptance during a cyclist's overtaking.

The first two objectives and parts of the fifth are addressed in this licentiate thesis, while the remaining objectives will be addressed in later stages to achieve the PhD degree.

3.Methods

To fulfil the objectives of the thesis, to make overtaking of cyclists safer using driver intention-based ADAS, it becomes crucial to understand; a) interactions between road users during an overtaking scenario, b) how to define and operationalize interaction in driver modeling to be used in ADAS, c) the implementation of the interaction in ADAS to make overtaking safer. Identification and operationalization of the interaction in driver models involved evaluating all phases of overtaking. However, only the approaching phase was considered for the development of intention-based ADAS.

3.1.A framework to develop driver models with interactions for ADAS

To understand the interaction between road users and how they can be used in increasing the overall safety of overtaking, we needed a unified framework to combine quantitative and qualitative driver modeling approaches to develop interaction models. A framework based on Unified modeling language (UML), version 2.5.1 [66], would help identify the interaction between road users and operationalize the interaction definition. The motivation behind using UML to develop the framework was that it provides a tool to design, analyze and implement software-based systems along with modeling of such systems.

UML diagrams such as a) UML - Use case diagrams [66, Sec. UseCases], b) UML - State machine diagrams [66, Sec. StateMachines], c) UML - sequence diagrams [66, Sec. Sequence Diagrams] were used to identify the interaction between different road users for a chosen traffic scenario. Typically, these diagrams can be useful for demonstrating the chronology of actors' interactions, showing various ways the actors communicate to reach their goals. Case diagrams served as an initial step. In the overtaking scenario, the ego vehicle was considered the primary actor is initiating actions. Using the state machine diagrams combined with the use case diagram highlighted road users' transition from one state to another. The transitions were aligned with the existing driver behavior modeling frameworks.

The primary motivation in using UML diagrams was to use sequence diagrams to demonstrate the type of action and reaction the drivers and road users perform in a given scenario. These diagrams are usually used in software engineering to demonstrate the chronology of actors' interactions. Each road user in a sequence diagram is an actor represented by an object on a timeline. The timeline does not represent a literal measurement of time. The interactions of different actors are mapped sequentially. The mapping of actions helps in defining the interaction between road users.

Based on previous literature, interaction has a wide variety of definitions and is often described in the driver modeling frameworks implicitly. For example, interaction is defined as an interplay between different layers of hierarchical models. The unified framework using the UML diagrams benefit from having an explicit definition for interactions to be bundled together to assess the causality of driver's and other road users' actions during an overtaking scenario to maintain safety. A systematic literature review would give us different components to define interaction explicitly to operationalize it.

In this thesis work, an interaction was defined as,*" In traffic, interaction among road users is a cyclic process (including perception, planning, and action) that occurs when two or more road users share the infrastructure. Interaction is based on predictions and expectations and its main goal is to keep road users safe and comfortable while satisfying their need for mobility. Interaction may also serve to communicate one's intentions and to probe the intentions of others."*

3.2.Intention-based Advanced Driver Assistance Systems

When we look at the overtaking mechanism, previous work highlights the importance of the interaction between the oncoming vehicle and the cyclist. As defined in the interaction, intention and communication of intent between road users are part of the interaction. Different parameters in the approaching phase directly influence how drivers interact with other road users and can be used to determine the intention of overtaking.

Driver model by Rasch et al. [25] highlight that external parameters such as longitudinal distance between the driver and the bike, lateral distance between the oncoming vehicle and the bike, and longitudinal distance to the ego vehicle and oncoming vehicle can be used to predict the driver's intended overtaking strategy in the approaching phase. The strategy can be classified in terms of longitudinal control and later control to represent different overtaking types (flying and accelerative overtaking).

The main aim of ADAS, such as FCW and AEB, is to inform the driver by warning and emergency braking to avoid or mitigate a collision in critical situations. For intention-based ADAS for overtaking, the system's assessment algorithms should identify a threat and warn or intervene by braking to support the driver. The key assessment strategy of intention-based ADAS is the mismatch between the driver's current and predicted behavior.

In the approaching phase of overtaking, drivers' current behavior can be understood by obtaining the change in longitudinal control (brake pedal or accelerator pedal) and lateral control (Steering wheel) directly from the vehicle's control unit. The expected behavior of the driver's longitudinal and lateral control can be obtained from the driver model.

In the approaching phase, the driver's longitudinal control represents the driver's action to perform accelerative overtaking, where drivers start to slow down the vehicle by either starting to brake or varying the accelerator pedal to control the speed. Similarly, the driver's lateral control represents the flying overtaking, where drivers do not change the vehicle's speed but instead steer away to pass the cyclist. By comparing the driver's current behavior and expected behavior (from the driver model), the driver's intentions could be extracted. The assessment strategy highlights that the intention-based system becomes aware of human behavior and can identify any deviations from normal behavior using cumulative evidence that something may be wrong.

The basic principle of intention-based ADAS is highlighted in Figure 3. A mismatch between drivers' expected and current behavior constitutes a threat of rear-end collision with the cyclist, and the decision-making relies on a threshold-based strategy to either support the driver by issuing a warning or activation of emergency braking.

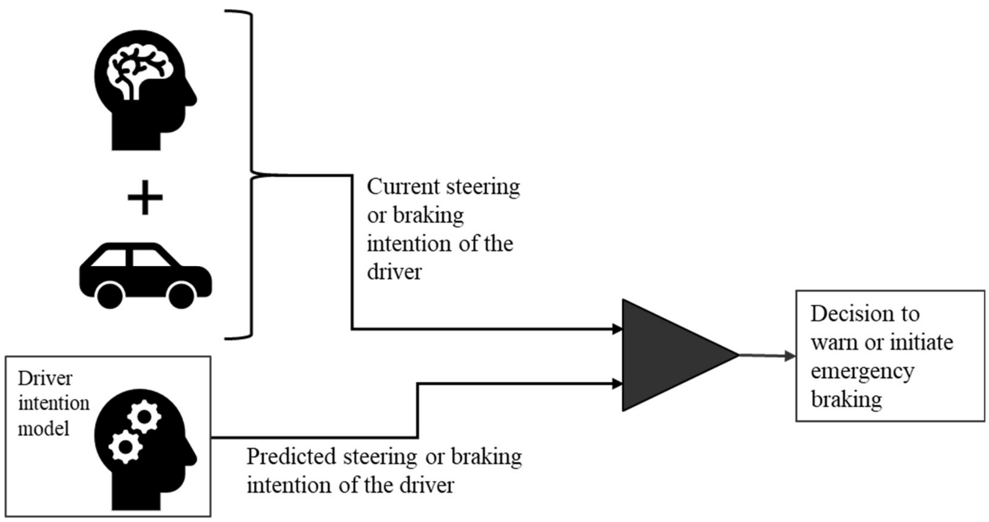

Figure 3: A novel method used to integrate the driver intention model in developing intention-based ADAS

3.3.Evaluating the intention-based ADAS

The evaluation plan for intention-based ADAS considered varying the activation threshold to evaluate the system's sensitivity, specificity, and acceptance. To evaluate the system, one can carry out either a prospective assessment or retrospective assessment. To carry out the retrospective analysis, the system under evaluation needs to have a high market penetration. If the system is not available or the system is still under development carrying out a retrospective assessment is difficult. Virtual simulations employed by a prospective assessment method are usually low-cost, and different parameters affecting the system's functionality can be easily tested in a relatively short time by carrying out virtual counterfactual simulations. Thus, a prospective assessment was carried out to evaluate the intention-based ADAS.

3.3.1.Counterfactual Simulations

Counterfactual simulations involve mathematical models of the driver, vehicle, safety systems, and environment. During the simulation, a safety system is modeled to analyze the reduction in the number of crashes or fatalities compared to those without it or against a modeled conventional system. The simulation included time-series data of the car, bicycle, and oncoming vehicle from different datasets available during the thesis work.

To understand the system's sensitivity and specificity in identifying the crash and the acceptance of the system. The system activation was classified based on the different definitions of the confusion matrix. The confusion matrix helps to quantify the performance of the system and driver acceptance. The counterfactual simulation was split into analyzing: a) reduction in the number of crashes and b) to estimate the true positive (TP) and false negative (FN) (using test track data), false positive (FP), and true negative (TN) activations (using field data).

3.3.2.Datasets

Test track data was collected and used to develop and evaluate the intention-based ADAS during the approaching phase of overtaking a cyclist. Data collected on the test track helps eliminate the variation between variables that may affect the performance of ADAS. Data was collected at the Vårgårda airfield, Vårgårda, Sweden, where participants overtook the cyclist. They were instructed to keep the vehicle speed of 70 km/h and variables a) time gap between ego vehicle and oncoming vehicle and b) cyclist overlap as a measure of lateral position was varied to create different overtaking conditions. The drivers overtaking behavior was collected using an instrumented vehicle. A dummy cyclist mounted on a high-speed platform (HSP, Figure 4) represented a cyclist traveling in a straight line and a balloon vehicle (Figure 4) representing the oncoming vehicle. The details of the test track experiment, exclusion criteria used, and demographics of the participants are presented in Rasch et al.[20].

Figure 4: Dummy cyclist mounted on HSP (left) and balloon car representing the oncoming vehicle (right)

In the absence of crash data, e.g., GIDAS [67], an artificial crash can be used as a substitute for evaluating the ADAS to capture the system's TP and FN performance. Test track data collected at the Vårgårda airfield were converted into artificial crashes. The crashes were created by taking away driver action to perform the overtaking, i.e., brake onset point for accelerative overtaking and the steer onset point for flying overtaking (Figure 2). This meant that that the ego car continued to go straight ahead until it collided with the bicycle.

The field data was used to evaluate the FP and TN performance of the intention-based ADAS. The data was collected in a naturalistic setting using an instrumented bike, which recorded the overtaking maneuvers performed by cars and trucks on the public road. The details of the study's data collection and findings are described in Dozza et al. [17]. For this study, the data were reduced to fit the scenario of cars overtaking bicycles on a straight rural road when an oncoming vehicle was present at a traveling speed greater than 60 km/h.

4.Summary of papers

Paper 1

Thalya, P., Kovaceva, J., Knauss, A., Lubbe, N., & Dozza, M. (2020). Modeling driver behavior in interactions with other road users. *Proceedings of 8th Transport Research Arena TRA 2020, April 27-30, 2020, Helsinki, Finland*, 1–16. Retrieved from https://psyarxiv.com/wu4z9/

Paper 2

Thalya, P., Lubbe, N., Knauss, A., and Dozza, M. "How can driver intention inform threat assessment for active safety ? A collision avoidance system to support cars,". Submitted to IEEE Intelligent Transportation Systems Transactions

Paper 1: Modeling driver behavior in interactions with other road users.

- **Introduction:**

  Advanced driver assistance systems (ADAS) aim to increase safety and comfort by supporting the driver in critical and non-critical situations. Deterministic methods used by ADAS often ignore the interaction between road users. Current ADAS may not match interactions that lead to driver expectations of future maneuvers and drivers' subjective hazard perception, which may not be reflected by the threat assessment used in ADAS.

- **Aim:**

  The aim of this paper was to propose a new operational framework for computationally modeled interactions among road users, where we introduced a definition for interaction among road users derived from existing literature and used this definition within the modeling framework.

- **Method:**

  In this study, a literature review was carried out to understand how interaction among road users was defined and incorporated within the existing driver modeling frameworks, both quantitative and qualitative driver models. Unified modeling language (UML) diagrams were used to operationalize the framework introduced in the paper, which included a new definition of interaction among road users. The UML diagrams were also used to exemplify the framework using a specific scenario, overtaking a cyclist by a car.

- **Discussion**:

  The paper highlighted the importance of the inclusion of interaction among road users in driver modeling frameworks. The steps proposed in this framework rely on the alignment of UML diagrams with existing driver modeling approaches; we also discuss how different data types, e.g., field tests, driving simulator experiments, and naturalistic data, can be used to verify the extent to which the potential interaction is plausible in different cultural setting and contexts. The discussion also focused on using driver models with interactions to improve the Automatic Emergency Braking system activations during the overtaking maneuver.

- **Conclusion**:

  In this paper, based on the literature review on interaction modeling, we proposed a new definition of interaction among road users. We proposed an operational framework to use the new definition of interaction, a four-step process based on ULM modeling and demonstrated the framework's usability using a scenario of a car overtaking a cyclist. We also highlight the possible improvement in an Automatic Emergency Braking system's effectiveness by using the explicit interaction models.

Paper 2: How can driver intention inform threat assessment for active safety? A collision avoidance system to support overtaking of a bicyclist

- **Introduction:**

  Overtaking a cyclist is a complex driving task. Failed overtaking maneuvers by drivers can lead to rear-end or sideswipe collisions with a cyclist. Collision avoidance systems, such as Forward Collision Warning (FCW) and Automatic Emergency Braking (AEB), can help reduce the severity of the risk of rear-end collisions during the approaching phase. Driver behavior models play a crucial role in assessing the perceived criticality of a situation, providing more adequate warnings and interventions, and evaluating the potential of new active safety systems.

- **Aim:**

  This paper aimed to address the research question: Can a driver intention model be used for earlier activation of a collision avoidance system (CAS) to improve crash avoidance in the approaching phase of a bicycle overtaking in the presence of an oncoming car, without increasing the number of false activations?

- **Method:**

  The study developed a threat assessment and decision-making algorithm of CAS by including the driver intention model developed by Rasch and Dozza (2020). Counterfactual simulations were carried out to create artificial crash data. Data from normal driving, i.e., field data, were used to calculate the activations and number of crashes avoided by the intention-based collision avoidance system (IntCAS) compared with a conventional CAS.

- **Results:**

  The results of the paper show that the intention-based system can be used to create a consent module for threat-assessment and decision-making algorithms that issue earlier but acceptable activation of CAS without increasing the number of false-positive activations compared to a conventional CAS. The results showed that IntCAS avoided 90% of all artificial crashes than 40% by conventional CAS by issuing an earlier warning. Similarly, earlier activation of AEB by IntCAS avoided 83% of artificial crashes compared to 53% by conventional CAS.

- **Discussion:**

  The paper discusses the implication of earlier warning or earlier activation of emergency braking in critical situations. The study highlights that earlier warnings help to bring a driver's attention back to the road sooner, and, in critical cases, earlier activation of the braking system may avoid the collision instead of just mitigating it. The study also discusses the novelty of evaluating the CAS using different data to complete the confusion matrix rather than focusing on true positive activations alone. The study also highlights driver intention-based models to include steering assistance to help the driver perform safe overtaking.

- **Conclusion**:

  In this paper, a novel approach was introduced to integrate the driver intention model into the threat assessment and decision-making for a new collision avoidance system. The counterfactual simulation results show that earlier warnings and braking interventions by IntCAS achieve higher crash avoidance compared to conventional systems without increasing the number of false activation for a car overtaking a cyclist in the approaching phase of overtaking. This paper also highlights the potential of an Emergency Steering System to help drivers during the steering away phase due to missed intervention by IntAEB during a critical situation.

5.Discussion

This chapter discusses the two completed objectives of the licentiate degree. First, the discussion focuses on the method used to integrate the driver's intention in developing intention-based ADAS to improve the system's acceptance and crash avoidance in preventing cyclist fatalities. Furthermore, intention-based ADAS's effect on reducing cyclist fatalities in the future and contribution towards achieving SDGs targets. Second, the implication of interaction definition and interaction modeling framework in developing future driver models involving VRUs. This chapter concludes with the implication of the research work presented here on developing new active safety systems to address car-cyclist fatalities and Euro NCAP testing protocol.

5.1.The implication of intention-based ADAS

The intention-based ADAS, as described in *Paper 2,* deviates from the more conventional setup for ADAS, which relies on kinematic-based thresholds such as TTC or avoidance-based activation within driver comfort limits, without taking driver intention into account [39], [64], [68]. The intention-based threat assessment algorithm relied on the mismatch between the driver's current actions and predicted intention from the driver model. Following this approach, the new ADAS has an early but acceptable intervention strategy to avoid rear-end crashes with the cyclist. Based on the driver reaction model and driver comfort braking profile used in *Paper 2,* results show that earlier warnings and interventions by intention-based ADAS avoided more crashes compared to the later warnings and interventions from conventional ADAS. This result is in line with a previous study [69], which highlights that earlier warnings can reduce collision severity more than late warnings.

However, basing a safety-critical system on a mismatch between expected and actual actions alone may not be enough. Instead, the intention-based system was developed as a complementary module, which creates a necessary (yet insufficient) condition for system activation. The complementary module can be used as a "*Consent Module*," which collects evidence of variation in driver behavior, in turn, drivers intention, and complement that with a kinematic-based avoidance strategy to acceptably intervene in a critical situation.

The inclusion of a driver model with interaction could push the development of personalized ADAS. For example, drivers behave differently depending on the context and changing environment [70]. Factors such as changes in the curve of the road during overtaking or changes in other parameters (e.g., weather conditions)—or changes in the scenario itself—could influence driver behavior, including the choice of overtaking strategy. Rather than developing systems individually tailored to a specific scenario or changing context or variation within drivers, a solution could be to develop systems that have to deal with self-adaptive systems. One of the most recognized means of achieving a self-adaptive system is feedback loops [71], [72].

In the overtaking scenario, a self-adaptive system would collect personalized data on overtaking and, over time, be able to predict the driver's reaction (e.g., by updating the driver model for different overtaking scenarios, like a curved street). A self-adaptative strategy would enable ADAS to determine appropriate thresholds and update them in real-time: ADAS could adapt the warning strategy (visual, audio-visual warning), as driver reaction may vary depending on the strategy [73]. Personalization of ADAS could help determine the appropriate intervention strategy based on driver preference and acceptance and the situation's criticality.

5.2.Reduction of VRUs fatalities

The potential safety benefit of the intention-based ADAS in terms of injury risk curve is still being evaluated. Results of intention-based ADAS in *Paper 2* show that intention-based FCW has the potential to avoid 90% of crashes compared to 40% by the conventional FCW. Similarly, intention-based AEB avoided 83% of crashes compared to 53% by conventional AEB. A study by Kovaceva et al. [53] highlighted that intention-based FCW could reduce the majority of the collisions and provided larger safety benefits than baseline FCW. The study also highlighted the potential reduction in the number of severe injuries by 94% and slight injuries by 84%.

The estimated injury reduction can estimate the potential reduction in fatalities by 2060 based on WHO estimates [74]. A study by Lubbe et al. [75] estimates the remaining fatalities in the world after applying various ADAS function's estimated effectiveness. The study estimates that in 2060 114 000 cyclist fatalities would remain and not be addressed by any of the current ADAS on the market. By assuming a) 100% implementation rate for intention-based ADAS, b) all remaining fatalities are rear-end situations, and could be addressed by intention-based AEB. By applying the estimated benefit of 83%, cyclist fatalities can further reduced to 19 380 fatalities in the year 2060. Thus achieving the overall reduction in cyclist fatalities by 86%.

However, the estimated reduction in fatalities is based on various assumptions. The development of the system is based on the data collected in Sweden with Swedish drivers. Due to variations in driving styles, infrastructure designs, and variation in interaction between drivers and cyclists, the reduction in cyclist fatalities could vary when the intention-based ADAS is applied globally, which is outside the scope of this PhD. More research is needed to understand an intention-based system's implication in reducing cyclist-related fatalities and other VRUs groups, pedestrians, powered two-wheelers, and eScooters.

5.3. Acceptance of intention-based ADAS

As with all driving scenarios, drivers' actions in overtaking are tightly linked to how drivers perceive the environment. The driver's intent to overtake the cyclist and the driver's interaction with the oncoming vehicle are linked to being safe. The interaction identified in the UML framework using a sequence diagram plays a vital role in determining the driver's behavior and maintaining safety. Actions such as an increase in engine noise, turning on the turn indicator, or moving to the other lane by ego vehicle or oncoming vehicle slowing down to let overtaking occur, indicate to the systems what the driver in the ego vehicle intends to do. Corresponding interactions can be bundled together to enrich driver models so that ADAS interventions can be more effective and highly acceptable.

The results presented in *Paper 2* show that intention-based ADAS avoided more crashes by earlier intervention. However, this raises some concerns about the acceptability of the intention-based system to drivers. In our work, the earlier activations of ADAS were deliberately designed to be outside a driver's comfort zone (because the driver model is based on the driver's comfort zone), so drivers would accept them. The driver's acceptance of earlier warnings was also highlighted in a study on car-to-car FCW [62], which reported that drivers preferred earlier activations of FCW.

5.4. Towards reaching sustainability goals

The research work presented in this thesis focused on preventing fatalities with ADAS in vehicles. However, intention-based ADAS not only focused on preventing driver/passengers fatalities but also cyclist fatalities. The work presented in both papers focused on all the road users involved in overtaking scenario. The interaction between road users helps in promoting the overall perceived safety by the cyclist. The higher safety benefit of intention-based FCW is highlighted in the study by Kovaceva et al. [53]. Intention-based systems can help achieve the SDGs target 3.6 of halving the number of fatalities by 2030. However, the potential benefit is highly dependent on the implementation rate of an intention-based system.

The intention-based ADAS presented in *Paper 2* showed that increased acceptance of the system by the driver could also improve cycling safety. The improved safety could help promote cycling as a mode of transport, thus achieving SDGs target 11.2, providing a safe and sustainable mode of transport. The observed benefit was highlighted for overtaking of a cyclist on rural roads. The implementation and benefit of intention-based ADAS in the city environment have yet to be evaluated. Overall, improved safety of the cyclist and potential interaction that could be used both with road users and the infrastructure could improve the city and transport planning.

5.5. The implication of interaction modeling

Modeling driver behavior is an essential part of traffic safety research and is often used to represent the driver's understanding of their surroundings. Often the interaction among road users are overlooked—or driver modeling frameworks fail to implement these interactions. The interaction definition that was developed gathered different schools of thought and existing interaction definitions under one roof. The interaction definition introduced in *Paper 1* relates the aspects of perception, planning, and action components of the driver modeling framework to being safe, comfortable, and communication of intent. For example, road users communicate non-verbally to show their intentions and ensure a smooth interaction [76], [77].

The exemplification of the interaction definition and interaction in the driver modeling framework shows that the driver's actions during an overtaking can be linked to how they perceive the environment. The driver's communication of intent highlights different types of overtaking they can perform that can be linked to safe and comfortable overtaking. The safe and comfortable overtaking performed by the drivers also considers the comfort of the cyclist.

In the UML framework proposed in *Paper 1*, other road users are treated as independent actors whose communication and actions can influence the driver's behavior. Using UML diagrams, it was demonstrated that the various ways that actors can communicate and interact during an overtaking scenario. The potential interaction identified between the road users in the overtaking scenarios gave an indication of how they can be operationalized within the existing driver modeling frameworks. However, due to a lack of experimental data to identify the possible interactions, the framework was not validated.

The practical implication of including interaction in driver modeling approach was highlighted in work by Rasch & Dozza [78], where interaction between ego car and an oncoming vehicle, and with the cyclist was converted into quantifiable safety metrics which were used to predict the drivers' expected behavior of braking to slow down to perform accelerative or steering away to perform flying overtake.

5.6.Data and Counterfactual simulations

Different types of data were used in this thesis, prominently the test track data and field data. However, more data is needed to carry out more detailed analysis to either validate the results of the thesis or develop the system introduced or to identify the interaction between road users in a given scenario or quantify the system's real-world system performance.

The UML framework presented in *Paper 1¸* demonstrated that we could categorize drivers' actions based on our definition of interaction. However, the overtaking data used to demonstrate the framework's usability and interaction between road users involved were limited. As interaction and intention among road users play a crucial role in developing driver models and intention-based systems, more data is needed. Data from field tests, driving simulator experiments, and naturalistic data can be used to identify the potential interactions between road users.

The prospective assessment method used in this thesis helps to understand the parameters that influence the system design (understand the activation threshold) and its effectiveness. The virtual simulation carried to quantify intention-based ADAS's effectiveness relied on both assumptions made during the simulation and the type of data used. The analysis covered the system's effectiveness in crash avoidance and understanding the driver's acceptance of the system using a confusion matrix. Definition in the confusion matrix was used to visualize a system's performance by showing how the system performs in different conditions than ground truth data. The confusion matrix constructed in *Paper 2* helped a) to visualize the performance of intention-based ADAS and b) possible improvement of intention-based ADAS over conventional systems.

Based on our reviews, very few studies have evaluated a system performance using a *complete* confusion matrix; instead, many previous studies focused on the true positive rate. By evaluating the system using the complete confusion matrix, *Paper 2* highlighted the intention-based system performance in all four possibilities, i.e., true positive rate, false positive rate, true negative rate, and false negative rate.

The simulation carried out to evaluate the intention-based system used different datasets. In *Paper 2*, artificial crashes created from test track data were used to evaluate the true positive and false negative performance of ADAS, and Field data were used to evaluate the false positive and true negative performance of ADAS. However, these datasets were very limited, and several assumptions were made for them to be usable. Especially when it comes to the evaluation of the False positive rate, a larger and more diverse dataset (both test track data and field data used was collected in Sweden and driven by Swedish drivers) would help in the more accurate evaluation and comparison of the performance of an intention-based system compared to a conventional system. Not only that, the field data was collected from the cyclist perspective, and trajectories were extracted using several assumptions. However, this data lacks critical events for it to be used to calculate the system's true positive performance.

The counterfactual simulation is highly dependent on driver reaction time and braking profile to estimate the number of crashes avoided [53], [58], [79], [80]. The research work thus far focused on both FCW and AEB as a part of intention-based ADAS. The effectiveness of FCW is highly dependent on driver reaction and driver action in relation to the warning. A basic reaction model and comfort braking profile for the driver was used in the counterfactual simulation. The crash avoidance results might differ if a different driver reaction and different braking profiles were used.

5.7.Euro NCAP testing protocol

When we look at the Euro NCAP rating for a system in longitudinal scenarios with the cyclist, the current testing protocol evaluates both FCW and AEB for different test configurations. For car speeds between 50-80 kmph with 25% overlap with the cyclist, FCW is evaluated. For car speeds between 20-60 kmph with 50% overlap with the cyclist, AEB is tested. The test protocol's main aim is to evaluate the system's performance in avoiding the potential rear-end collision with the cyclist. In all testing protocols, the oncoming vehicle is not considered.

The current test procedure used for system evaluation may not be suitable to test the intention-based ADAS as the activation times are regulated by distance to the oncoming vehicle and evaluates the potential of head-on crash risk with the oncoming vehicle. As presented in this thesis and previous work on overtaking cyclists, oncoming vehicles play an essential role in crash causation and driver intention. The results of Paper 2 highlighting the earlier warning when the oncoming vehicle is present indicates that the Euro NCAP protocol should include the oncoming vehicle for future testing of an active safety system during longitudinal scenario with a cyclist.

Assuming the presence of an oncoming vehicle, under the current test protocol of Euro NCAP, both intention-based FCW and AEB would achieve full scores. However, NCAP tests are often done on production systems (or systems close to being on the market). The potential of intention-based ADAS is still being evaluated and researched.

5.8.Limitations

As with any studies, the work presented here has limitations associated with data, assumptions made in developing the intention-based systems, and counterfactual simulation. The framework used to develop the driver model with interaction presented in *Paper 1* looked at all phases of overtaking maneuvers by the car with an oncoming vehicle present. However, the intention-based ADAS covered in *Paper 2* was limited to the approaching phase of overtaking when an oncoming vehicle was present. Furthermore, the integration of interaction in ADAS only covered the intentions, the driver, and the reaction and Communication between road users in relation to driver intention was not part of the intention-based ADAS.

The vehicle trajectories extracted from the field data assumed that the cyclist was traveling in a straight line, keeping the same lateral distance to the car recorded at the beginning of the approaching phase of the overtaking. The oncoming vehicle was assumed to be traveling in a straight line. The test track data was collected using a dummy cyclist and a balloon vehicle on a straight airfield with perfect visibility. These assumptions made both the extraction of data from the field data and test track data look artificial. The test track data and the field data only involved Swedish drivers, and data were collected in Sweden.

When artificial crash data were used in the counterfactual simulation, all drivers were assumed to react to the warning by braking. As the oncoming vehicle was present in the opposite lane, steering to avoid the collision was not considered an option in the system development. This is one of the significant limitations of our study, as the previous research [64], [81]–[83] has shown that, at higher speeds, steering is more effective than braking at avoiding the collision. The sensitivity analysis using driver responses was not carried out in the work presented.

The datasets used for the evaluation of intention-based ADAS covered were limited. The evaluation carried out on field data to capture the system's FP performance was carried out virtually, assuming a perfect sensor setup. Based on the limitation presented in *Paper 2*, the analysis only covered the ego vehicle traveling at 70 kmph. More data and a variety of data are needed to quantify the FP rate of the intention-based ADAS. Based on the assumptions made, virtual simulation carried out in this thesis can only give a rough estimate of the system's effectiveness. To develop a production system, prototypes of the system should be tested and evaluated in a controlled environment rather than in a virtual setting. The validity of the models used in the virtual simulation contributes significantly to the simulation results.

5.9.Future work

This work proposed a framework and developed intention-based ADAS, which was evaluated using both field and test track data. The counterfactual simulation could be extended in the future using crash databases and large naturalistic studies to further understand the safety benefit and acceptance of the intention-based system. The counterfactual simulation carried out in *Paper 2* was based on simple vehicle dynamics models with longitudinal control and assuming perfect sensing by the sensors. Future work may involve understanding the effect of sensing and developing vehicle dynamics models to evaluate the vehicle's lateral control.

The intention-based ADAS developed in *Paper 2* looked at collision warning and emergency braking as an intervention strategy. However, steering to avoid the collision by the driver and steering intervention systems such as ESS and AES were not considered. Future development of ADAS will consider the possibility of steering intervention and the combination of warning and braking intervention. Furthermore, ADAS was implemented in the approaching phase of overtaking when an oncoming vehicle was present. Future implementation could be extended to other phases of overtaking, steering-away, passing, and returning phases to address sideswipe and head-on collision risks. Future research will involve the extent to which steering assistance may improve overtaking safety and may involve developing different threat assessments to evaluate the types of steering support required for the safe overtaking of a cyclist in all phases.

The limitations involved in the evaluation and dataset show that we need more varied data to test the system's functionality and calculate the safety benefit—for example, more speed variation on the ego vehicle and more variation in the overtaking conditions. The work carried out in the thesis only covered the theoretical aspect of including interaction in ADAS; before such a system is introduced in the market, an engineering solution needs to be implemented and tested in a controlled environment to understand the feasibility of producing such a system. Large-scale acceptance and an FP evaluation need to be carried out to ensure the safety standard.

6.Conclusions

This thesis highlights the potential safety gains of interaction modeling and operationalization of the driver models with interaction to be used in the development of ADAS. A new definition for interactions among road users (including communication and probing of other road users' intent) proposed in *Paper 1* helps unify the driver modeling frameworks with interaction and ADAS development frameworks. The results contributed to fulfilling the first objective of the PhD. The framework laid the foundation to develop a driver intention model to be used in ADAS, where the question "can the driver intention model be used to improve the ADAS's effectiveness and acceptance during overtaking scenarios?" was tested.

Paper 2 aimed to address the second objective of the PhD, to support the driver in the approaching phase of overtaking a cyclist. The driver model that captured the interaction between the road users in the approaching phase was used to develop a novel method for assessing the threat and decision-making to prevent a rear-end collision with the cyclist. As hypothesized in *Paper 1*, the results highlighted that earlier warnings and earlier braking interventions by the intention-based ADAS indeed have higher effectiveness in preventing rear-end crashes. However, the higher effectiveness does not come at the cost of increased false alarms and reduced acceptance. The evaluation carried out combined different datasets to evaluate the entire contingency table and proving that the driver intention model can indeed be used as a "*Consent module.*" This thesis also highlights that in combination with FCW and AEB, the steering support system ESS or AES may potentially further increase intention-based ADAS's effectiveness.

While this thesis's main focus was to develop ADAS to address crash risks in the approaching phase of overtaking using interaction models, future work should include an intention-based steering support system as a part of intention-based ADAS and capturing both longitudinal and lateral support to the driver in all phases of overtaking.

Bibliography

[1] WHO, *Global status report on road safety 2018*. 2018.

[2] European Road Safety Observatory, “Traffic Safety Basic Facts 2017 - Cyclist,” 2017.

[3] “Road Safety Annual Report 2020,” 2020.

[4] World Health Organization, “World Health Organization. Global Health Estimates Summary Tables: Deaths by Cause, Age and Sex by various regional grouping. 2013,” 2013. [Online]. Available: http://www.who.int/healthinfo/global_burden_disease/en/.

[5] United Nations, “Goals @ Sdgs.Un.Org,” *United nations sustainable development goals*. 2020.

[6] “Stockholm Declaration - Third Global Ministerial Conference on Road Safety: Achieving Global Goals 2030,” 2020.

[7] UNECE, “Road Safety for All,” 2019.

[8] Swedish Transport Administration, “Saving Lives Beyond 2020: The Next Steps,” 2020.

[9] WHO, *WHO Guidelines on physical activity and sedentary behaviour*. 2020.

[10] T. Götschi, J. Garrard, and B. Giles-Corti, “Cycling as a Part of Daily Life: A Review of Health Perspectives,” *Transp. Rev.*, vol. 36, no. 1, pp. 45–71, 2016.

[11] P. Oja *et al.*, “Health benefits of cycling: A systematic review,” *Scand. J. Med. Sci. Sport.*, vol. 21, no. 4, pp. 496–509, 2011.

[12] A. Graser, M. Aleksa, M. Straub, P. Saleh, S. Wittmann, and G. Lenz, “Safety of Urban Cycling: A Study on Perceived and Actual Dangers,” in *Transport Research Arena 2014*, no. April, 2014, pp. 145–159.

[13] S. M. Balogh, “Perceived safety of cyclists - The role of road attributes,” 2017.

[14] M. Wisch *et al.*, “Car-to-cyclist crashes in Europe and derivation of use cases as basis for test scenarios of next generation advanced driver assistance systems – results from PROSPECT,” *Enhanc. Saf. Veh. Conf.*, no. January, pp. 1–15, 2017.

[15] P. Vassilis, N. Dimitris, P. Evangelia, and M. Nicolas, “The effects of changes in the traffic scene during overtaking,” *Accid. Anal. Prev.*, vol. 79, pp. 126–132, 2015.

[16] D. D. Clarke, P. J. Ward, and J. Jones, “Processes and countermeasures in overtaking road accidents,” *Ergonomics*, vol. 42, no. 6, pp. 846–867, 1999.

[17] M. Dozza, R. Schindler, G. Bianchi-Piccinini, and J. Karlsson, “How do drivers overtake cyclists?,” *Accid. Anal. Prev.*, vol. 88, pp. 29–36, 2016.

[18] G. F. Bianchi Piccinini, C. Moretto, H. Zhou, and M. Itoh, “Influence of oncoming traffic on drivers' overtaking of cyclists,” *Transp. Res. Part F Traffic Psychol. Behav.*, vol. 59, pp. 378–388, 2018.

[19] J. Kovaceva, G. Nero, J. Bärgman, and M. Dozza, “Drivers overtaking cyclists in the real-world: Evidence from a naturalistic driving study,” *Saf. Sci.*, no. December 2017, 2018.

[20] A. Rasch, C.-N. Boda, P. Thalya, T. Aderum, A. Knauss, and M. Dozza, “How do oncoming traffic and cyclist lane position influence cyclist overtaking by drivers?,” *Accid. Anal. Prev.*, vol. 142, no. July 2020, 2020.

[21] K.-H. Chuang, C.-C. Hsu, C.-H. Lai, J.-L. Doong, and M.-C. Jeng, “The use of a quasi-naturalistic riding method to investigate bicyclists' behaviors when motorists pass,” *Accid. Anal. Prev.*, vol. 56, pp. 32–41,

2013.

[22] G. Hegeman, K. Brookhuis, and S. Hoogendoorn, “Opportunities of advanced driver assistance systems towards overtaking,” *Eur. J. Transp. Infrastruct. Res.*, vol. 5, no. 4, pp. 281–296, 2005.

[23] J. Gibson J and L. Crooks E, “the American of Psychology,” *Am. J. Psychol.*, vol. 51, no. 3, pp. 453–471, 1938.

[24] T. M. Matson and T. Forbes, “Overtaking and passing requirements as determined from a moving vehicle,” *Highw. Res. Board Proc.*, vol. 18, pp. 100–112, Mar. 1938.

[25] A. Rasch and M. Dozza, “Modeling Drivers’ Strategy When Overtaking Cyclists in the Presence of Oncoming Traffic,” *IEEE Trans. Intell. Transp. Syst. Model.*, pp. 1–10, 2020.

[26] D. Cody and T. Gordon, “TRB Workshop on Driver Models: A Step Towards a Comprehensive Model of Driving?,” in *Modelling Driver Behaviour in Automotive Environments*, London: Springer London, 2007, pp. 26–42.

[27] O. Lappi and C. Mole, “Visuomotor control, eye movements, and steering: A unified approach for incorporating feedback, feedforward, and internal models,” *Psychol. Bull.*, vol. 144, no. 10, pp. 981–1001, 2018.

[28] D. N. Lee, “A theory of visual control of braking based on information about TTC.pdf,” vol. 5, no. 1974, pp. 437–459, 1976.

[29] D. D. Salvucci and R. Gray, “A two-point visual control model of steering,” *Perception*, vol. 33, no. 10, pp. 1233–1248, 2004.

[30] J. A. Michon, “A Critical View of Driver Behavior Models: What Do We Know, What Should We Do?,” in *Human Behavior and Traffic Safety*, L. Evans and R. C. Schwing, Eds. Boston, MA: Springer US, 1985, pp. 485–524.

[31] R. Elvik, “A review of game-theoretic models of road user behaviour,” *Accid. Anal. Prev.*, vol. 62, pp. 388–396, 2014.

[32] D. J. Fagnant and K. Kockelman, “Preparing a nation for autonomous vehicles: Opportunities, barriers and policy recommendations,” *Transp. Res. Part A Policy Pract.*, vol. 77, pp. 167–181, 2015.

[33] E. Fraedrich, S. Beiker, and B. Lenz, “Transition pathways to fully automated driving and its implications for the sociotechnical system of automobility,” *Eur. J. Futur. Res.*, vol. 3, no. 1, 2015.

[34] C. Hubmann, J. Schulz, M. Becker, D. Althoff, and C. Stiller, “Automated Driving in Uncertain Environments: Planning With Interaction and Uncertain Maneuver Prediction,” *IEEE Trans. Intell. Veh.*, vol. 3, no. 1, pp. 5–17, Mar. 2018.

[35] M. Koschi and M. Althoff, “Interaction-aware occupancy prediction of road vehicles,” *IEEE Conf. Intell. Transp. Syst. Proceedings, ITSC*, vol. 2018-March, pp. 1–8, 2018.

[36] M. Althoff and S. Magdici, “Set-Based Prediction of Traffic Participants on Arbitrary Road Networks,” *IEEE Trans. Intell. Veh.*, vol. 1, no. 2, pp. 187–202, 2016.

[37] J. R. Ziehn, M. Ruf, D. Willersinn, B. Rosenhahn, J. Beyerer, and H. Gotzig, “A tractable interaction model for trajectory planning in automated driving,” in *2016 IEEE 19th International Conference on Intelligent Transportation Systems (ITSC)*, 2016, pp. 1410–1417.

[38] C. Kaß, G. J. Schmidt, and W. Kunde, “Towards an Assistance Strategy That Reduces Unnecessary Collision Alarms: An Examination of the Driver’s Perceived Need for Assistance,” *J. Exp. Psychol.*

Appl., 2018.

[39] M. Brännström, E. Coelingh, and J. Sjoberg, "Model-Based Threat Assessment for Avoiding Arbitrary Vehicle Collisions," *IEEE Trans. Intell. Transp. Syst.*, vol. 11, no. 3, pp. 658–669, Sep. 2010.

[40] M. Ljung Aust and J. Engström, "A conceptual framework for requirement specification and evaluation of active safety functions," *Theor. Issues Ergon. Sci.*, vol. 12, no. 1, pp. 44–65, Jan. 2011.

[41] S. Lefevre, C. Laugier, and J. Ibanez-Guzman, "Evaluating risk at road intersections by detecting conflicting intentions," *IEEE Int. Conf. Intell. Robot. Syst.*, pp. 4841–4846, 2012.

[42] B.-C. Chen, C.-W. Shih, and Y. Lin, "Design of Forward Collision Warning System using Estimated Relative Acceleration and Velocity Vector." SAE International, 2014.

[43] A. Polychronopoulos, M. Tsogas, A. Amditis, U. Scheunert, L. Andreone, and F. Tango, "Dynamic situation and threat assessment for collision warning systems: The EUCLIDE approach," *IEEE Intell. Veh. Symp. Proc.*, pp. 636–641, 2004.

[44] J. Hillenbrand, A. M. Spieker, and K. Kroschel, "A multilevel collision mitigation approach - Its situation assessment, decision making, and performance tradeoffs," *IEEE Trans. Intell. Transp. Syst.*, vol. 7, no. 4, pp. 528–540, 2006.

[45] S. M. Loos, A. Platzer, and L. Nistor, "Adaptive cruise control: Hybrid, distributed, and now formally verified," *Lect. Notes Comput. Sci. (including Subser. Lect. Notes Artif. Intell. Lect. Notes Bioinformatics)*, vol. 6664 LNCS, pp. 42–56, 2011.

[46] J. Dahl, G. Rodrigues de Campos, C. Olsson, and J. Fredriksson, "Collision Avoidance: A Literature Review on Threat-Assessment Techniques," *IEEE Trans. Intell. Veh.*, vol. PP, no. c, pp. 1–1, 2018.

[47] U. Sander and N. Lubbe, "Market penetration of intersection AEB: Characterizing avoided and residual straight crossing path accidents," *Accid. Anal. Prev.*, vol. 115, pp. 178–188, 2018.

[48] M. Kunert, F. Flohr, D. Gavrila, and A. Koch, "PROSPECT - Obstacle detection, VRU classification and tracking," 2016.

[49] B. Fildes *et al.*, "Effectiveness of low speed autonomous emergency braking in real-world rear-end crashes," *Accid. Anal. Prev.*, vol. 81, pp. 24–29, 2015.

[50] J. B. Cicchino, "Effectiveness of forward collision warning and autonomous emergency braking systems in reducing front-to-rear crash rates," *Accid. Anal. Prev.*, vol. 99, pp. 142–152, 2017.

[51] U. Sander, "Opportunities and limitations for intersection collision intervention—A study of real world 'left turn across path' accidents," *Accid. Anal. Prev.*, vol. 99, pp. 342–355, 2017.

[52] E. Rosén, "Autonomous Emergency Braking for Vulnerable Road Users," *Proc. IRCOBI Conf.*, pp. 618–627, 2013.

[53] J. Kovaceva, J. Bärgman, and M. Dozza, "Safety benefit assessment of a new collision warning system for car-to-cyclist overtaking scenario (Submitted)," pp. 1–19, 2020.

[54] F. Char, T. Serre, S. Compigne, and P. Puente Guillen, "Car-to-cyclist forward collision warning effectiveness evaluation: a parametric analysis on reconstructed real accident cases," *Int. J. Crashworthiness*, vol. 0, no. 0, pp. 1–10, 2020.

[55] M. Ljung Aust and S. Dombrovski, "Understanding and Improving Driver Compliance With Safety System," *23th Int. Tech. Conf. Enhanc. Saf. Veh.*, pp. 1–7, 2013.

[56] I. J. Reagan and A. T. McCartt, "Observed activation status of lane departure warning and forward

collision warning of Honda vehicles at dealership service centers," *Traffic Inj. Prev.*, vol. 17, no. 8, pp. 827–832, 2016.

[57] Y. Page *et al.*, "a Comprehensive and Harmonized Method for Assessing the Effectiveness of," in *The 24th International Technical Conference on the Enhanced Safety of Vehicles (ESV)*, 2015, pp. 1–12.

[58] J. Bärgman, C. N. Boda, and M. Dozza, "Counterfactual simulations applied to SHRP2 crashes: The effect of driver behavior models on safety benefit estimations of intelligent safety systems," *Accid. Anal. Prev.*, vol. 102, pp. 165–180, 2017.

[59] U. Sander, *Predicting Safety Benefits of Automated Emergency Braking at Intersections Virtual simulations based on real-world accident data*. 2018.

[60] J. Kovaceva, A. Bálint, R. Schindler, and A. Schneider, "Safety benefit assessment of autonomous emergency braking and steering systems for the protection of cyclists and pedestrians based on a combination of computer simulation and real-world test results," *Accid. Anal. Prev.*, vol. 136, no. October 2019, p. 105352, 2020.

[61] Euro NCAP, "Test Protocol - AEB VRU systems," 2020.

[62] N. Moshchuk, S. K. Chen, C. Zagorski, and A. Chatterjee, "Optimal braking and steering control for active safety," *IEEE Conf. Intell. Transp. Syst. Proceedings, ITSC*, vol. 2, no. 1, pp. 1741–1746, 2012.

[63] T. Dang *et al.*, "Handbook of intelligent vehicles," in *Handbook of Intelligent Vehicles*, vol. 1–2, 2012, pp. 1–1599.

[64] M. Brännström, E. Coelingh, and J. Sjöberg, "Decision-making on when to brake and when to steer to avoid a collision," *Int. J. Veh. Saf.*, vol. 7, no. 1, p. 87, 2014.

[65] U. Sander and N. Lubbe, "Prediction of Accident Evolution by Diversification of Influence Factors in Computer Simulation : Opportunities for Driver Warnings in Intersection Accidents," *Akt. Sicherheit und Autom. Fahr. - Methodenentwicklung im Expert.*, p. 29, 2016.

[66] Object Management Group (OMG), "Unified Modeling Language (UML) specification V2.5.1," no. December. p. 796, 2017.

[67] GIDAS, "GIDAS Methodology." [Online]. Available: https://www.gidas.org/en/about-gidas/gidas-methodik/.

[68] N. Kaempchen, B. Schiele, and K. Dietmayer, "Situation Assessment of an Autonomous Emergency Brake for Arbitrary Vehicle-to-Vehicle Collision Scenarios," *IEEE Trans. Intell. Transp. Syst.*, vol. 10, no. 4, pp. 678–687, Dec. 2009.

[69] J. D. Lee, D. V McGehee, T. L. Brown, and M. L. Reyes, "Collision warning timing, driver distraction, and driver response to imminent rear-end collisions in a high-fidelity driving simulator.," *Hum. Factors*, vol. 44, no. 2, pp. 314–334, 2002.

[70] J. D. Lee *et al.*, "'Distraction detection and mitigation through driver feedback: Appendices,' DOT HS 811 547B, 2013," 2013.

[71] J. O. Kephart and D. M. Chess, "The vision of autonomic computing," *Computer (Long. Beach. Calif).*, vol. 36, no. 1, 2003.

[72] S. Dobson *et al.*, "A survey of autonomic communications," *ACM Trans. Auton. Adapt. Syst.*, vol. 1, no. 2, pp. 223–259, 2006.

[73] J. Lylykangas, V. Surakka, K. Salminen, A. Farooq, and R. Raisamo, "Responses to visual, tactile and

visual-tactile forward collision warnings while gaze on and off the road," *Transp. Res. Part F Traffic Psychol. Behav.*, vol. 40, pp. 68–77, 2016.

[74] WHO, "World Health Organization (2018). Projections of mortality and causes of death, 2017-2060," 2018.

[75] N. Lubbe, P. Thalya, P. Puthan, and O. Boström, "Global Road Traffic Fatality Estimate for 2060: The Effect of Increased Vehicle Automation," in *IRCOBI Asia*, 2020, pp. 3–6.

[76] S. Kitazaki and N. J. Myhre, "Effects of non-verbal communication cues on decisions and confidence of drivers at an uncontrolled intersection," *8th Int. Driv. Symp. Hum. Factors Driv. Assessment, Training, Veh. Des.*, no. July, pp. 113–119, 2012.

[77] A. J. Schramm, A. Rakotonirainy, and N. L. Haworth, "How much does disregard of road rules contribute to bicycle-vehicle collisions?," *Cent. Accid. Res. Road Saf. - Qld (CARRS-Q); Fac. Heal. Inst. Heal. Biomed. Innov.*, 2008.

[78] A. Rasch and M. Dozza, "Modeling drivers' strategy when overtaking cyclists in the presence of oncoming traffic," 2020.

[79] S. H. Haus, R. Sherony, and H. C. Gabler, "Estimated benefit of automated emergency braking systems for vehicle–pedestrian crashes in the United States," *Traffic Inj. Prev.*, vol. 20, no. sup1, pp. S171–S176, Jun. 2019.

[80] K. D. Kusano and H. C. Gabler, "Safety benefits of forward collision warning, brake assist, and autonomous braking systems in rear-end collisions," *IEEE Trans. Intell. Transp. Syst.*, vol. 13, no. 4, pp. 1546–1555, 2012.

[81] A. Eckert, M. Sevenich, and P. E. Rieth, "Emergency Steer & Brake Assist – a Systematic Approach for System Integration of Two Complementary Driver Assistance Systems," *Enhanc. Saf. Veh.*, pp. 1–9, 2011.

[82] M. Schorn, "Quer- und Längsregelung eines Personenkraftwagens für ein Fahrerassistenzsystem zur Unfallvermeidung," 2007.

[83] M. Sieber, K. H. Siedersberger, A. Siegel, and B. Farber, "Automatic Emergency Steering with Distracted Drivers: Effects of Intervention Design," *IEEE Conf. Intell. Transp. Syst. Proceedings, ITSC*, vol. 2015-Octob, pp. 2040–2045, 2015.