**Public**

# Quantitative Driver Behavior Modelling for Active Safety Assessment Expansion (QUADRAE)


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# 1 Executive Summary

In-vehicle technologies are essential for vehicle safety. Throughout their development process, their benefits must be continuously assessed to ensure that the designs effectively address real-world problems. Thus, there is a need for fast, accurate methods for evaluating the safety impact of advanced driver assistance systems (ADAS) and automated vehicles (AV). Virtual (computational) simulation models of driver behaviors, grounded in knowledge of human behavior, cognitive science and real-traffic situations, are a key part of these methods.

This project, Quantitative Driver Behavior Modeling for Active Safety Assessment Expansion (QUADRAE), addresses two crucial components of the technology development process: driver models and simulation methodology. Together, they have provided the industrial partners with state-of-the-art tools for system development and testing, facilitating the development of innovative technologies to improve traffic safety.

The main objectives of the project were to:

- develop and validate models of driver behavior needed in current and future simulation tools for virtual testing of active safety and automation.
- carry out prioritized virtual tests to estimate the safety benefit of a system, tune system parameters, and explore potential outcomes in scenarios when the system is active.
- learn more about the best methods for performing virtual testing using driver models.

As a result of the project, the partners now have an established virtual simulation framework using Predictive Processing (PP) as a general paradigm for modeling driver behavior. The modeling, based on the latest knowledge and ideas about human behavior in driving, draws on extensive research using volunteer drivers as study participants. Data from both controlled experiments and naturalistic driving were used to develop and validate the models. These models are already being used by the industry partners as part of their virtual safety assessment toolchain, to develop advanced driver support systems. The data will continue to be used by the project partners in industry and academia to develop future driver models (which will, in turn, foster improved driver support systems).

QUADRAE has not only advanced the state of the art in the area of driver modeling but has also allowed the partners to remain at the forefront of international research in this field.
The project has generated many academic accomplishments. Participating researchers, as well as colleagues within their organizations, have developed unique competences. Further, two PhDs and one Licentiate in Engineering have been completed, and several students have written their MSc theses (connected to the project). Fifteen peer-reviewed papers have been published in international scientific journals and conferences, some of which have been highly appreciated by researchers in the field. One additional publication is still in review and another three are in preparation. Three internal reports have also been created for the partners to use in their current and future work.

The work in QUADRAE has centered around three areas:

- Safety-critical events in semi-automated driving
- Pre-crash scenarios with mainly lateral support
- Pre-crash scenarios with mainly longitudinal support

Driver behavior models for braking in critical events (rear-end and straight-crossing-path intersection scenarios) were established in QUADRAE. Substantial knowledge has been acquired about the complexity of modeling drivers' steering interventions in intersections and lane-change situations. Two other models were also developed: one simulates drivers' responses to different visual cues; the second, the impact that drivers' glances have on the response process in critical events.

A major focus throughout QUADRAE was establishing methodologies for virtual testing that will yield the best possible benefits of active safety systems and automation. The virtual assessment methods have been applied evaluating the potential impact of potential intersection brake technology on safety. Assessing the combined effects of the inclusion of different levels of automation in cars on highways and the change in driver glance behavior that the introduction of such systems may induce has also been done.

Although some changes to the original project plan have been made due to personnel and organizational changes during the project, the original objectives have been preserved. The time plan has also been revised, mainly due to the COVID-19 situation (particularly challenging over the last part of the project). Further, normal changes due to new insights into the research were made, while maintaining the original project deliverables.

The important steps taken in QUADRAE have established a strong foundation for future research in the area as well as providing models for the industries' safety assessment processes. QUADRIS, a new project starting up, will further increase our knowledge about modeling driver behavior and other components of the virtual simulation, as well as delivering state-of-the-art tools for use by the industry.

# 2 Summering

Den snabba utvecklingen av förarstödsystem och automatisering inom fordonsindustrin har resulterat i ett stort behov av virtuell testning för utveckling och utvärdering av dessa system, som ett led i fortsatt förbättrad trafiksäkerhet. En kritisk del för dessa virtuella tester är adekvata modeller av förarens beteende. Att modellera människans beteende matematisk är oerhört komplext. Grundlig kunskap behöver byggas inom flera områden för att stödja denna utveckling och göra den applicerbar i en innovativ industriell miljö och därmed driva trafiksäkerheten framåt. Förarmodellering som område är under kraftig utveckling globalt och att ligga i framkant inom detta område är viktigt för att vara konkurrenskraftig både från ett teknik och ett kompetensperspektiv.

Projektet QUADRAE (Quantitative Driver Behavior Modeling for Active Safety Assessment Expansion) syftar till att utveckla förarmodeller och virtuella metoder för utvärdering av aktiva säkerhetssystem. Dessa kommer sedan att användas inom industrin för att driva och leda utvecklingen av aktiva säkerhetssystem och automatisering, specifikt gällande möjligheten att effektivt kunna utvärdera tekniska trafiksäkerhetslösningar i utvecklingsprocessen.

De övergripande målen inom QUADRAE har varit att:

- Utveckla och validera modeller för förarbeteende för användning i virtuell testning av aktiva säkerhetssystem och fordonsautomation
- Inkludera modellerna i metoder för nyttoanalys, systemutveckling och/eller potential/utfalls analys
- Öka metodikkunskapen generellt inom virtuell testning

Ett konceptuellt ramverk för förarmodellering tagits fram och använts (baserat på Predictive Processing). Baserat på detta ramverk har ett antal unika förarmodeller för olika situationer tagits fram. Dessa modeller har implementerats och används. Flera av modellerna används redan som en del av trafiksäkerhetsutvärderingkedjan hos industripartners i QUADRAE. Modelleringen baseras på den senaste forskningen om förarbeteende och ett omfattande arbete inom QUADRAE har varit att ta fram experimentell data på förarbeteende i olika situationer. Denna datamängd ligger till grund för utveckling och validering av flera av de virtuella modellerna som levererats av projektet. Data från projektet används också för vidareutveckling av förarmodeller i andra projekt och hos QUADRAEs-parters, samt i något fall också direkt i utvecklingen av ny säkerhetsteknik hos projektets parter.

Projektet har generat unik kunskap och kompetens. Femton refereegranskade publikationer från projektet är redan publicerade i högt ansedda vetenskapliga tidskrifter. Flera av dessa publikationer har hyllats och citerats av internationellt ansedda forskare inom området förarmodellering. Ytterligare en publikation är under granskning och tre till håller på att sammanställas som ett resultat av projektet. Detta har hjälpt till att vidare etablera svensk forskning inom området förarmodellering i ett internationellt perspektiv. Tre interna rapporter som nu används av de deltagande organisationerna har också tagit fram. Kompetens hos medarbetare inom de deltagande organisationerna har också utvecklats vilket i sig bidragit till ökad konkurrenskraft. Två tekniska doktorer (PhD) samt en teknisk licentiat är ett direkt resultat av forskningen inom projektet. Vidare har flera studenter på magisternivå utbildats genom de examensarbeten som utförts inom projektet.

De forskningsfrågor som legat till grund för arbetet inom QUADRAE har varit inom områdena:
- Säkerhetskritiska händelser i semi-autonom körning
- Kritiska körscenarior med primärt lateralt förarstöd
- Kritiska körscenarior med primärt longitudinellt förarstöd

Som resultat och leverans från projektet finns nu förarmodeller kopplade till bromsning i kritiska körscenarior som kan leda till kollisioner bakifrån samt delar av en modell för kritiska situationer i korsningar (när man kör rakt fram och ett fordon kommer från sidan). Grunderna för en förarmodell med koppling till styrmanövrar i kritiska situationer som kan leda till avkörningsolyckor har utvecklats inom projektet. Dessutom har viktig kunskap om utmaningar i modellering av hur förare styr i kritiska situationer i korsningar samt när man byter fil byggts upp. Modellering av förares blickbeteende och hur förare reagerar på visuella stimuli har också utvecklats inom projektet.
Metodik för utvärdering och trafiksäkerhetspotentialberäkning av aktiva säkerhetssystem och autonom körning som inkluderar förarmodeller har också varit en viktig del i projektet. Exempel där metodiken applicerats i projektet har varit för ett teoretiskt autobromssystem i korsningar samt ett autonomt körscenario och för dessa har potentiell säkerhetseffekt beräknats.

Projektet har vidhållit och levererat mot de ursprungliga målsättningarna även om planen reviderats vid några tillfällen. Ändringarna i planen har företrädesvis varit kopplade till personal samt omorganisationer hos parter. Tidplanen har också ändrats och förlängts och det har varit kopplat till den exceptionella situationen kopplat till Corona pandemin. Adekvata anpassningar under projektets gång har också gjorts baserat på den kunskap som byggts över tid, dock med samma målsättning i form av leveranser.

QUADRAE har inte bara levererat ny unik kunskap utan också skapat förutsättningar för fortsatt viktig forskning inom området. QUADRIS-projektet som är under uppstart är ett sådant initiativ som kommer att fortsätta vidareutvecklingen och ge industriella parterna konkurrenskraftiga verktyg och kunskap framåt.

# 3 Background

As technologies for active safety and vehicle automation grow ever more complex, it becomes increasingly important to complement traditional methods for testing these systems with virtual tests based on computer simulations. The FFI QUADRA project (2010-2014) addressed this need, with a focus on driver behavior models. QUADRAE has gone beyond QUADRA by developing and validating driver models which provide more complete coverage of prioritized pre-crash scenarios and support systems. To create these more comprehensive models, QUADRAE focused on well-defined test cases, cooperating with industrial function developers and test engineers, and adopting proven models from psychology and neuroscience. Experiments with human drivers and state-of-the-art databases of actual crashes were used as input to the models. These tasks also contributed to achieving the overall goal of QUADRAE: to advance the general knowledge on how to do virtual testing of ADAS.

When we started QUADRAE, it was clear that there was no commonly agreed theoretic framework for driver modeling in the research community, or even among QUADRA partners. However, previous driver-behavior research had emphasized the importance of expectation and prediction (Endsley & Kiris, 1995; Hollnagel, et al., 2003; Rasmussen, 1985; Summala, 1988); these priorities formed the basis of the theoretical driver modeling framework in QUADRAE. Using this framework, the work on rear-end models in QUADRA and elsewhere (Markkula, G., 2014; Venkatraman et al., 2016) formed the basis for the QUADRAE rear-end modeling, while the work on the role of peripheral vision was inspired by, for example, Burns et al. (2000), Dukic et al. (2005), and Lamble et al. (1999). Also, during QUADRA and QUADRAE, there has been growing concern about the threat of off-path glances to road safety during driving (Dingus et al., 2006; Horrey & Wickens, 2007); increasingly, off-road glances are related to Human Machine Interfaces (HMIs), newly introduced vehicle automation technologies, or ubiquitous nomadic devices such as smart phones. This concern has triggered additional research (1) modeling visual glances (e.g., Liang et al., 2014); (2) assessing off-road-glances with respect to safety (Bärgman et al., 2017); and (3) understanding how different visual stimuli, e.g., in the peripheral vision, affect the driver's response (Lamble et al., 1999). This research has been a stepping-stone for QUADRAE. In addition, the driver modeling work in QUADRA on run-off-road conflicts (Benderius, 2014) was a natural starting point for QUADRAE, but with further anchoring in methods on, for example, clustering (Milligan & Cooper, 1987), for use in understanding the underlying problem. Further, driver behavior in intersections is a relatively uncharted research domain. Models that exist are often not anchored by actual driver perception and cognition but, instead, are based more on, for example, control theory—and are more data-driven than what we have aimed at in QUADRA and QUADRAE. That said, the models discussed so far have primarily assessed traditional advanced driver assistance systems (ADAS). However, the increasing application of vehicle automation (see SAE J3016, 2014, initial issue and following revisions) has created a need for models of driver behavior that assess how drivers react when the automation fails (see Seppelt & Lee, 2015, for a preliminary example of such models), considering the longitudinal and lateral control of the vehicle. Furthermore, the development of more complex HMIs (e.g., Mulder et al., 2012) has also called for the development of models that describe drivers' responses to vehicle-external stimuli (e.g., Benderius, 2014; Markkula et al., 2016). In summary, there has been a great deal of research on driver modeling prior to QUADRA which QUADRAE researchers have used as a starting point. However, in each of the research fields there were large gaps, gaps that QUADRAE set out to address.

# 4 Purpose, research questions and method

The main purpose of QUADRAE was to develop state-of-the-art, quantitative virtual models of driver behavior that can be used in test scenarios to evaluate existing (and proposed) active safety systems and automation. The scope of the project is critical scenarios from initial conflict to crash, as shown in Figure 1.

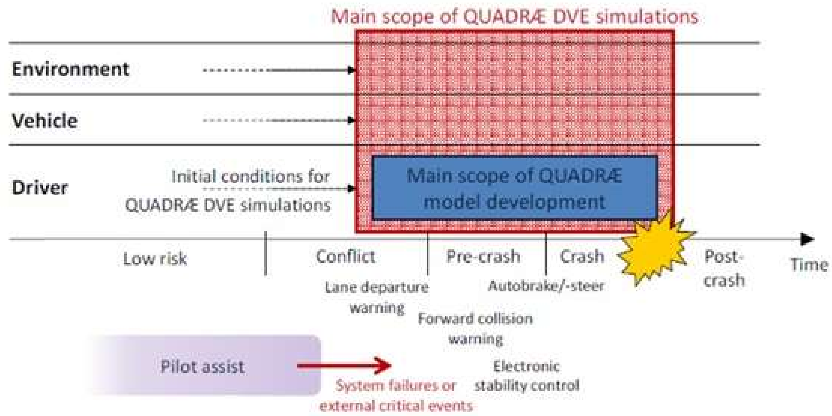


*Figure 1: Main scope of QUADRAE along a time line, illustrating approximate timing of support system interventions, and how routine operation of a pilot-assist system can transition into a safety-critical state due to system failures or external critical events.(DVE stands for Driver Vehicle Environment)*

The driver models developed in QUADRAE are intended to be part of the virtual safety assessment of ADAS and lower levels of automation. The models can be used in different ways within the assessment, including to generate baseline events/crashes and as response models with the system-under-test in the loop. The results can either be absolute, such as an estimate of the injury risk reduction or the number of avoided crashes with a certain system in place, or relative, such as whether one system is more effective than another.

## 4.1 Research questions

The questions guiding the methodology research in QUADRAE have emphasized modeling driver behavior, with the aim of enabling virtual testing to evaluate the performance and potential benefit of existing and future ADAS. Specifically, QUADRAE focuses on models that can help address the following three “expected benefit” research questions:

Safety-critical events in semi-automated driving (WP4)

1. **What is the outcome when a pilot assist function is suddenly disabled or encounters a critical situation?**

Pre-crash scenarios with mainly lateral support (WP5)

2. **What is the expected benefit of Emergency Manoeuvre Assist and Emergency Lane Keeping Assist?**

Pre-crash scenarios with mainly longitudinal support (WP6)

3. **What is the expected benefit of Collision Warning and Emergency Brake, and how should they be tuned?**

These three questions formulate the modeling and simulation efforts found in the project’s work packages (WPs) 4–6. Further input, such as test cases and driver behavior data as well as possible modeling frameworks, is required to deliver the objectives of the project (as shown in Figure 2). The different WPs must also be coordinated, to enable the partners involved to share the useful knowledge acquired. The benefit estimations for Automated Emergency Braking (AEB) and Forward Collision Warning (FCW) in car-to-car intersection crashes were carried out in WP6 using the framework, modeling, and virtual testing methods.

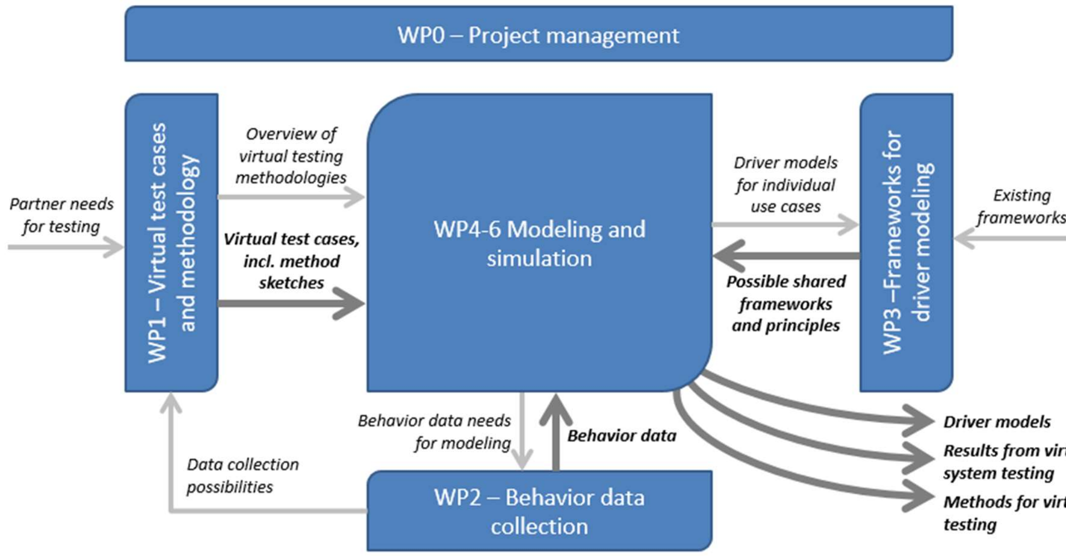


*Figure 2: Overview of project work packages (WPs).*

## 4.2 Use cases, driver behavior data, and framework

To support the overall objective to develop and validate models of driver behavior, a number of virtual test cases (each a function of the support system being addressed) were specified, together with some preliminary ideas about the most suitable simulation methodology. The test cases were characterized while taking into account the project's data collection possibilities. The defined cases were reviewed, and a summary was presented at an internal workshop. Slight refinements were made during the project.
To see if the differences in accident types could be represented by a small number of test scenarios, methodology-based work clustering was carried out. Methods for the scenarios corresponding to the accident types 'straight crossing path' (SCP), 'left turn across path, oncoming direction' (LTAP/OD), and 'left-turn across path, lateral direction' (LTAP/LD) were clustered together. This work was published in a journal paper (see Sander & Lubbe, 2018a) which used clustering methods to evaluate Intersection AEB. As a result of the authors' thorough analysis using various cluster methods and variable sets, it was concluded that it is not possible to reduce the diversity of intersection accidents into a set of test scenarios without compromising the ability to predict the real-life performance of Intersection AEB. Therefore, limited physical testing was suggested in order to facilitate the validation of more extensive virtual simulations.
A literature review of state-of-the-art methods for the virtual testing of active safety and automation was carried out (Deliverable D1.2: State-of-the-art methods for virtual testing of active safety and automation (2017, Sander U., Engström J., Piccinini G., Lindman M., Sandin J., Apoy C.). The resulting project report contains a review of existing models and describes what is needed to develop more advanced and validated models.

Several different databases of driver behavior data were created to provide input for the modeling and knowledge building within the project. As data collection is key for modeling and validation, the approaches used were constantly being improved as further knowledge was acquired. The following data collection studies were undertaken within the project:

- One study, using the VTI simulator SimIV, focused on reactions to silent failures, using a generic Adaptive Cruise Control function as a test case. The initial study, based on regaining control from a pilot assist system, was amended, to study the drivers' responses in the longitudinal direction only (i.e., braking) in detail.

- A small study was conducted to identify the looming cues that drivers use when judging whether a crossing vehicle is on a collision course.
- The VTI simulator was also used in a study of intersection scenarios. Although the original plan had been to use the test track at Autoliv, the complexity of the study required strict control of all involved vehicles to present the driver with the traffic conditions of interest. The simulator allowed the scope of the study to be expanded through the simulation of additional situations, which would have been unfeasible under real world conditions.
- After the intersection study was completed, a complementary study which integrated warnings was conducted using a similar setup (including the VTI simulator).
- A comprehensive study using the Volvo Cars simulator which assessed drivers' use of peripheral vision in the detection of, and response to, critical lead-vehicle deceleration events was also performed.
- In addition to the data collected in the project, we also re-used existing data from: GIDAS, SHADES, SHRP2, EuroFOT, UDrive, EyesOnRoad, and an internal VCC on-road data collection project.

After several internal seminars, an in-depth literature review, and discussions of the literature, Predictive Processing (PP) was identified as a very promising general framework (paradigm) for driver modeling, anchoring the modeling to current research on human behaviors. The main idea of PP is that humans continuously compare the predicted sensory inputs (expectations) with the actual sensory inputs received from the environment. The predicted inputs can be exteroceptive, interoceptive, or proprioceptive. According to the PP paradigm, the prediction error resulting from any mismatch is the relevant metric for developing driver models: when the prediction error has accumulated above some threshold, it can be cancelled through actions or changes to the predictions. In the context of driving, PP indicates that drivers might, for example, predict the movements of another vehicle and compare that prediction to real-world sensory information (i.e., visual inputs). That is, they might predict the expected looming (how fast the vehicle's size should be changing on their retinas) of an approaching vehicle and compare that to the actual looming. If there is a prediction error, the driver may take action, such as braking, or simply adjust the prediction. The driver models based on error accumulation in QUADRAE are all based on this paradigm.

# 5 Objective

The main objectives of the QUADRAE-project are to:
- develop and validate models of driver behavior needed in current and future simulation tools for virtual testing of active safety and automation.
- carry out prioritized virtual tests to estimate the safety benefit of a system, tune system parameters, and explore potential outcomes in scenarios when the system is active.
- learn more about the best methods for performing virtual testing using driver models.

To accomplish these objectives, QUADRAE specifies the behavioral phenomena that must be captured in the virtual test cases, gathers the human behavioral data, and identifies the virtual driver model candidates. These tasks are performed by determining which model(s) best reproduce(s) the human behavioral data (response process) while minimizing the number of parameters required to get adequate analysis results, thus supporting product development efficiency.

Modeling human behavior, specifically human driver behavior, is a challenge. Over the course of the project, new insights into methodologies and approaches led to adjustments in the different WPs.
In WP3, we initially started to work jointly through the available literature and paradigms on different frameworks for modeling driver behaviors. We produced much-cited publications (for

example, Markkula et al., 2016) that we then used as guide for the remaining modeling work. As we neared the project end, we revisited the work of WP3 and realized that our initial approach and assumptions had been quite good; they provided an overarching modeling framework that was based on the paradigm of Predictive Processing, implemented as an accumulation of prediction errors. Because we were satisfied with the initial work, instead of putting more effort into the framework, we chose to pursue more in-depth research on the individual research topics of WPs 4–6.

One of the objectives in the project (WP4) was to model drivers' behavior in pre-crash scenarios when the vehicle is in pilot assist mode (SAE automation level 2) and a reaction by the driver is urgently required. Two preliminary scenarios were targeted before the start of the project: a) *Pilot assist – missing control*: the control of the system is suddenly disabled due to sensor limitations, and the driver is required to take over control; b) *Pilot assist – critical rear-end conflicts:* similar to a) in that the system is suddenly disabled, but in addition the system encounters a critical rear-end situation caused by lead-vehicle braking. The first scenario aimed to assess drivers' steering responses in the absence of an intervention by the Pilot Assist (PA) while driving along a curve. The second scenario aimed to assess drivers' braking responses to a "silent failure" of Pilot Assist. Since the focus was on braking, and not steering, Adaptive Cruise Control (ACC) was selected, both because it exclusively regulates the longitudinal control of the vehicle and because drivers are more used to it than to PA. Moreover, this choice reduced the complexity of the experiment. Later in the project, an additional scenario (modeling drivers' responses to an automated truck changing lane in front of the subject vehicle) was added in WP4 to improve a previous model designed in the project. A driving simulator study involving about 40 participants was planned. However, the experiment could not be completed due to the onset of the Covid-19 pandemic and the withdrawal of the partner AB Volvo from the project.

The PhD student responsible for driver modeling in the run-off-road scenarios in WP5 completed his licentiate degree (Nilsson, 2017) and then decided to discontinue his PhD studies. The intent was that the PhD student working on WP6 would take over, but just as she finished that she went on parental leave for more than a year. As a result, this task was undermanned. Since it was intended that the parental-leave PhD student address this when she came back (April 2021), resources for this WP were shifted to other high-priority work in WPs 4 and 6.

Finally, we substantially extended the work in WP6. We conducted more research into understanding and modeling intersections and cut-in conflicts than was originally planned. We also performed research on how to assess the safety implications of the combination of safety systems of different automation levels and changes in eye-glance behaviors. These changes fit well with evolving industry needs, due to the introduction of new HMIs and higher levels of automation. Although these changes were not in the original proposal, they fit within its scope, and there was a clear industry need which became clearer over time.

Notably, the ongoing pandemic has been a challenge—not only in terms of our time plan, but also for some specific experimental setups. The time plan has been adjusted a couple of times. Experimental set-ups have either been adapted or delayed due to Covid-19.

# 6 Results and achievements

Two PhD dissertations and one Licentiate in Engineering based on the QUADRAE project have been completed, together with several theses at the Master level. In addition, one PhD student has acquired a solid foundation of knowledge as a result of participating in the project, to use as a basis for her continued work (in the FFI project QUADRIS). Fifteen peer-reviewed publications have been published in international scientific journals or conference proceedings, with another one currently in review. Three more are being prepared. In addition, three internal reports have been created for the partners' use.

The models and methodologies developed in QUADRAE are already being implemented and applied in the development processes by the project's industrial partners. In addition, the FFI project QUADRIS will continue the research into models of driver behavior for virtual simulations; however, it will focus more on driver reference models for the virtual assessment of vehicles with higher levels of automation and on other methodological aspects of virtual safety assessment (e.g., the generation and validation of baseline cases). Finally, it is likely that QUADRAE partners will be part of several consortia across different (January 2022) EC Horizon Europe calls related to driver modeling and safety benefit assessment.

## 6.1 Predictive processing framework

Predictive Processing (PP) constitutes the general framework for the QUADRAE modeling, anchoring the models to recent findings related to human cognition. The framework was presented in a peer-reviewed journal article (Engström el al., 2018) which currently has 32 citations in Scopus and a Field-Weighted Citation Impact of 3.85. Note that although PP, based on the concept of "free energy", is highly mathematically advanced, in QUADRAE we chose to adopt the overall idea of comparing predictions to actual sensory data, rather than its rather esoteric mathematical foundation. One implication of the choice of framework was that all models were developed with a) human visual perception and b) evidence accumulation (in terms of prediction errors) at the core. We also presented and discussed our work on the framework at the *Marcus Wallenberg International Symposium on Affective and Developmental Processes in Cognitive and Autonomous Systems – Augmenting Deep Learning using Neural Dynamics and Predictive Coding* (2019; May 6-7).

## 6.2 Modeling and simulating safety-critical events in semi-automated driving

The work conducted in WP4 focused on four main research areas: 1) modeling drivers' braking responses during failure of an ACC system (SAE automation level 1) in a rear-end critical scenario; 2) modeling drivers' steering responses during failure of a PA system (SAE automation level 2); 3) modeling drivers' responses to attentional demand in automated driving; 4) modeling drivers' braking responses to the lane change (cut-in) of an automated truck.
This research contributed to the completion of projects at the Doctoral and Master levels at Chalmers University of Technology: one PhD thesis (Morando et al., 2019a), three Master thesis projects (Floreano & Niro, 2018; Purushothaman & Manjunath, 2019; and Wörns, 2018), and one project within the Automotive Engineering Project course (Purushothaman et al., 2018). Four journal articles were also published in these research areas (Bianchi Piccinini et al., 2020; Morando et al., 2018; Morando et al., 2019b; Morando et al., 2020), further establishing our reputation in research in the global community.

***Modeling drivers' braking responses during failure of an ACC in a rear-end critical scenario.***

The primary aim of this research (Bianchi Piccinini et al., 2020) was to assess and model how drivers respond to a critical rear-end situation initiated by the braking of a lead vehicle; while the drivers are driving with ACC activated, the system has a silent failure. In this context, a silent failure is defined as a failure of the system which occurs without the driver being informed—by, for example, the HMI. An additional aim was to compare the resulting model of drivers' responses with a model of drivers' responses in a critical rear-end scenario while driving with Cruise Control (CC). This system automatically controls the speed of a motor vehicle, without taking over the full longitudinal control of the vehicle, as ACC does.
At first, we made á priori predictions about drivers' responses to these critical rear-end situations. The predictions originated from two models which were extensions of models designed within the QUADRAE project by Svärd et al. (2017). The two models built for creating the predictions were
1) Looming prediction model and
2) Lower gain model.

An innovative aspect of these models is that they assume that drivers react to unexpected looming rather than to looming per se.

A driving simulator study with 49 drivers was conducted on the VTI premises to assess drivers' responses in the scenarios under investigation. The participants were asked to drive in ACC and CC modes at 100 km/h and to follow a white van on a 2+1 Swedish road. During each drive (with either CC or ACC), the participants encountered six events with different lead vehicle decelerations, which were triggered on road sections with only one lane in the driving direction and a physical barrier on the left side. This design ensured that the participants would respond to the critical situation by braking rather than steering.

After assessing the data collected, we realized that the a priori predictions did not match the drivers' responses. Therefore, the models used for the predictions were fitted to the driving simulator data to yield better responses. The final kinematics-dependent computational driver models accurately predicted the brake responses to emergency rear-end situations occurring while driving with CC or ACC (in the latter case, during a silent failure). The models showed that:

- with increasing levels of kinematic criticality, drivers' braking responses significantly decrease, during driving with either CC or ACC.
- drivers' braking responses are significantly longer when they are driving with ACC than with CC.

More details about the research are provided in the 2020 publication by Bianchi Piccinini et al.

***Modeling drivers' steering responses during failure of a Pilot Assist system.***

This study, described in Purushothaman et al. (2018) and partly performed within the Automotive Engineering Project course, examined how drivers visually respond to silent failures of a PA while driving around a curve. The data for the study was collected from 14 participants at the AstaZero proving ground, with an instrumented vehicle provided by the Revere lab. The participants were required to drive in both manual and automated driving modes on a pre-defined route. The 'automated mode' was a Wizard-of-Oz setup; unknown to the participants, an experimenter in the rear seat was driving the vehicle with a joystick. While in this mode, the vehicle would drift out of the lane at certain points on the route, requiring the participants to take over the control of the vehicle. Although some technical difficulties with the eye tracker were experienced during data collection, the analyses clearly suggested that drivers act according to two different strategies: either the drivers trust the system and allow the vehicle to drift from the expected trajectory, or they do not trust it and respond immediately. Due to the limited number of participants and the exploratory nature of the study, further research is required on this topic. More data can be used to build driver models like the one developed in Bianchi Piccinini et al. (2020)—but with a focus on silent failures of the systems responsible for the lateral control of the vehicle.

***Modeling drivers' responses to attentional demand in automated driving.***

This research aimed to investigate how drivers' attention changes while driving an automated vehicle, with the purpose of improving the design of future automated systems.

The first study, described in Morando et al. (2018), used naturalistic driving data to create a reference model of drivers' glance behavior during manual and automated modes. The data used for the model were collected from 19 drivers within the FFI funded project "EyesOnRoad - an anti-distraction Field Operational Test". The drivers were provided with vehicles equipped with both ACC and Lane Keeping Aid (LKA). After a detailed filtering process to ensure the quality of the data, empirical probability density functions (PDFs) and empirical cumulative distribution functions (CDF) were created for both on-path and off-path glances, during manual and automated driving modes. (In the latter, the ACC and LKA are turned on and operational.) The results showed that drivers had longer glances in the automated mode, especially on-path glances (although a tendency was also shown for off-path glances). Overall, the study is unique, not only for the large amount of data collected in a naturalistic setting from eye trackers, but also for the thorough statistical representation of the data: the authors did not limit the results provided to the means and standard deviations. Rather, they presented the full distributions of on-path and off-path glances as well as a reference model of glance duration. The models from this study can be used in counterfactual simulations, to assess the safety benefits of automated driving and to support the future design of driver monitoring systems.

In the second study (Morando et al., 2019b), a reference model of visual time-sharing (VTS) behavior in manual and automated driving modes was developed. (In this case, driving is considered 'automated' when the ACC and LKA are turned on and operational). The dataset from the FFI funded project "EyesOnRoad - an anti-distraction Field Operational Test" was also used for this research. The VTS sequences, consisting of glance switching events between the forward path and other locations, were identified in the dataset using a previously established methodology. The sequences were extracted from the eye tracker and quantified using the following metrics: on-path and off-path glance distributions, total duration in seconds of each VTS sequence, the percent road center (PRC: percent of total glance time that glances were directed on-path), the proportion of on-path glances shorter than 1 s, and the proportion of off-path glances longer than 2 s. The metrics were modeled using a Bayesian approach; as with the first study, a full statistical representation of each metric's distribution was provided (mean and standard deviation alone comprise only a partial description). The resulting reference models show that driving in automated mode has minimal effect on VTS, although there was a tendency towards higher values of the metrics associated with off-path glances in automated mode compared to manual mode. The above-mentioned metrics also show negligible differences between the VTS sequences and routine driving sequences extracted from the previous study (Morando et al. (2018), although the PRC was lower for VTS compared to routine driving. Given the definition of VTS, this result is not surprising, but it is nonetheless noteworthy because it illustrates a possible use of the metric PRC: to distinguish between VTS and routine driving (for example, in future implementations of driver monitoring systems).

The third and last study (Morando et al., 2020) aimed to assess the driver's full visual-motor response process in critical situations when automated vehicles provide a warning to drivers. The study was conducted in the driving simulator of the Chair of Ergonomics at the Technical University of Munich, with 45 participants. While driving in automated mode (a combination of ACC and Lane Centering systems), the participants, who performed a secondary task while driving, experienced three different scenarios: a potentially critical rear-end situation with a lead vehicle, a potentially critical sideswipe situation with a side vehicle, and a false positive warning (when there was no actual threat from surrounding vehicles). In all three situations, the participants were given warnings to redirect their attention towards the threat.
The onset of the warning induced drivers to quickly divert their gaze from the tablet where the secondary task was performed and direct it on-path. All the drivers reacted to the critical situations with an avoidance maneuver—but, as expected, the glance movement occurred earlier than the motor responses (i.e., moving the feet to the pedal and the hands to the steering wheel). Overall, the glance location and the choice and timing of the evasive maneuver depended on the driving context and the previous critical situation experienced by the drivers. Rather than providing a single metric for the response process (e.g., take-over time), this research divided the overall response process into three components: visual (time from warning until glance away from tablet), motor (time from warning until movement of hand/foot), and intervention (time from warning until start of steering/braking) and estimated the distribution parameters for each component using Bayesian modeling. The resulting models can be used to design further studies investigating the response process to warnings or to improve current models of drivers' responses to warnings (implemented in counterfactual simulations).

***Modeling drivers' reactions to an automated truck changing lane ahead.***
The purpose of this research was to assess how drivers respond when a truck cuts in front of them in a simulation on a 2+1 Swedish road. The specific intention was to identify the comfort boundaries of the autonomous truck's lane changes for the participant drivers. The participants

were instructed to drive in the left lane (see Figure 3 for a representation of the participant's view).


*Figure 3: Representation in driving simulator of scenario with truck changing lanes.*

On some occasions while the participant was approaching the truck (ahead in right lane in Figure 3), it started a lane change, blocking the participant's lane.
After a preliminary study, a new simulation scenario was conducted, based on the original participants' feedback. In the new scenario, the initiation of the truck's lane change could be programmed as a function of either the distance between the two vehicles or the time to collision between them. The experience gained in the design of the driving simulator study and the pilot test with a small number of participants is very valuable input for future studies.

## 6.3 Modeling and simulating conflict situations

***Understanding run-off-road crashes.***
A cluster analysis of run-off-road crashes in the GIDAS crash database formed the basis for this research. The work was published as a peer-reviewed journal publication (Nilsson et al., 2018) with 10 Scopus citations and 1.43 as citation index. The results show that cluster analysis is a statistically sound method for analyzing in-depth, real-world crash data and organizing it according to the underlying data structure. The cluster analysis for the run-off-road use case highlighted scenarios relevant for the development of lane-keeping assistance systems. Since the crash data contain only limited information about driver behavior, additional analysis using another dataset would be necessary to further specify driver-related crash causation mechanisms.

In addition, research on neuromuscular models was performed to understand how steering maneuvers are executed—specifically, how the muscles in (mainly) the hands, arms, and back respond to signals from and send feedback to the driver's brain and spine. A steering model based on Benderius' work (Benderius, 2014) was developed, which covers three of the most prominent neuromuscular mechanisms associated with human steering behavior: (1) reaching, (2) holding (with and without load), and (3) the stretch reflex. All parts of the model take co-contraction of the agonist and antagonist muscles into account. Driver steering behavior in relation to two ADAS (evasive maneuver assist and LKA) will be analyzed (in upcoming projects) through simulations using this new neuromuscular model, after the model validation and parameter estimation have been completed. A scientific paper which includes a literature review of neuromuscular driver models and presents the current driver steering model is in preparation.

***Driver responses to critical rear-end conflicts***.

One component that is needed to develop computational driver models for use in virtual simulations is quantified driver responses to critical conflicts. There has been substantial work done in simulators and on test tracks studying driver responses to critical rear-end conflicts. However, prior to the research in QUADRAE, little work was performed analyzing driver responses to the unexpected rear-end conflicts that happen in everyday driving. A set of senior researchers in QUADRAE analyzed naturalistic driving data from two sources: SHRP2 naturalistic driving data and Lytx/DriveCam event data recorders with video. Crashes and near-crashes that included cars, trucks, or buses were analyzed. The timing of drivers' braking with respect to different perception metrics was studied. The remarkable results were published in Markkula et al. (2016). Until this publication, most driver behavior models used in virtual simulations were based on distributions of a simple reaction time after the onset of some event—typically when the lead vehicle in the conflict started braking (brake-light onset). (In fact, many models and researchers still are.) However, this paper, called "Farewell to brake reaction times", unequivocally demonstrated a dependence between situation urgency (with respect to the perceptual entity looming, tau) and brake reaction time. We also determined that if a driver looks back toward the road when the optically defined inverse time to collision (inverse tau) is less than 0.2, the braking response is fast (0.5s on average and ranging from 1.0 to 0.4s, decreasing as the situation gets more urgent). This paper has, to date, 51 citations in Scopus and a Field-Weighted Citation Impact of 4.97.
Subsequently, this study focused on the relation of brake and steering onsets to urgency for rear-end situations as well as other conflict types, both in the QUADRAE project and elsewhere. This research is ground-breaking because it directs the focus of driver modeling towards more plausible, human-oriented approaches; as a result, it is likely to increase the precision and accuracy of safety benefit assessments in industry and elsewhere.

***Modeling driver braking in rear-end situations.***
One of the prioritized scenarios in QUADRAE is the rear-end conflict. Longitudinal control between vehicles on highways and in stop-and-go traffic is, and will continue to be, an important aspect of avoiding collisions. Even though rear-end crashes seldom yield severe injuries or fatalities, they are very common. Based on the results regarding driver responses to critical situations and the framework prepared in QUADRAE, research was started to develop a driver model more advanced than traditional threshold-based models. The result was a first version of an accumulator model (based on Markkula, 2014 and Markkula et al., 2016) describing the driver's braking behavior in critical rear-end situations. The model applies intermittent brake adjustments to minimize the accumulated looming prediction error. Using hand-tuned parameters, the model was applied to simulated events based on the EuroNCAP rear-end scenarios. The outcome, in terms of brake initiation times and brake modulation (including jerk), accurately simulated the behavior observed in human drivers in similar situations, according to data from the SHRP2 naturalistic driving dataset. The work was primarily performed by a QUADRAE industry PhD student (Malin Svärd); this model was the seed for her continued work modeling braking in rear-end conflict scenarios. The peer-reviewed paper (Svärd et al., 2017) was presented at the Human Factors and Ergonomics Society 2017 Annual Meeting and has, to date, six citations in Scopus and a Field-Weighted Citation Impact of 2.4.

The industry PhD student's continued research on rear-end models focused on gaining a better understanding of whether (and if so, how) drivers use their peripheral vision to accumulate looming while looking away from the road just before a rear-end conflict. More specifically, while a driver is looking off-road, to what extent does the driver accumulate evidence for braking due to a rapidly approaching lead vehicle—and how does this accumulated evidence influence how soon the driver looks back towards the road and initiates braking? Two research streams were pursued.

The first stream was the modeling and parameter fitting of a set of accumulation model variants based on the original model (Svärd et al. 2017). Some variants were extended to handle looming input during off-road glances in different ways. Their performances were compared by fitting each variant to a set of crashes and near-crashes taken from the SHRP2 naturalistic driving data set, using a maximum likelihood approach and particle swarm optimization. The results, showing that drivers do indeed seem to use accumulation of looming of the lead vehicle even when their gaze is off-road, were presented in a peer-reviewed journal paper (Svärd et al., 2021a).

The second research stream aimed to get a more detailed understanding of the role of the gaze offset angle when the driver looks off-road during a critical lead-vehicle event. To achieve this, the glance redirection on-road and brake onset times were studied for different gaze angles. In a driving simulator experiment, drivers were presented with a visual-manual secondary task (in this case, a game) to perform on a touch-sensitive monitor positioned at one of three different offset angles (away from the forward roadway): 12°, 40°, and 60°. At an unknown time, while the driver was interacting with the game, the lead vehicle braked hard, resulting in a strong looming onset. The analysis consisted of investigating at what time, and at what level of looming, the driver looked back at the roadway towards the threat, and how soon after that the driver initiated braking or steering to avoid a crash with the lead vehicle. The study was a between-groups design: the secondary task was displayed on a different monitor (i.e., a different offset angle) for each group. The impact of peripheral looming on driver braking and glance behavior was analyzed by comparing the response times as well as check glances, etc. between the three different groups. The results were quite surprising: there was no significant difference between the groups with respect to when the driver looked back at the road. However, the smaller the offset angle, the earlier (faster) the driver started braking to avoid the threat after looking back; that is, the time between looking back and braking decreased. Since this result is not what the research community was hypothesizing, it may have an impact on algorithms and metrics that use driver monitoring as part of ADAS. This work is published as a peer-reviewed journal article (Svärd et al., 2021b). As this paper has only recently been published, it does not yet have any citations, but we have received oral praise for it from one of the QUADRAE Advisory Board members.

***Understanding drivers' responses to cut-in scenarios.***
Late in the QUADRAE project we identified cut-in scenarios as a priority and started to analyze them using SHRP2 crash and near-crash data. Specifically, we studied the differences between different perceptual cues in simulations, across scenarios with and without cut-ins. Although the original intent was to use the analysis as a basis for further modeling, it was difficult to find significant relationships between the visual cues (e.g., different forms of looming, bearing angle, and bearing angle rate) and the driver's decision to brake for a vehicle that is cutting in ahead. Consequently, we were not, this late in the project, able to identify the relevant visual cues to include in an accumulation model to predict the onset of braking by a driver when another vehicle cuts in front. However, we initiated a MSc thesis on the topic, and two students implemented a traditional rear-end driver model. They then added both visual cue variables and cartesian variables (speeds and distances) and fit the model to SHRP2 near-crashes. Unfortunately, the performance of the fitted model was also in this study relatively poor (i.e., similar to the difficulties finding relationships between cues and driver actions, as described above). More research is needed to improve the computational modeling of brake onset in cut-in scenarios. This work resulted in a MSc thesis (Chau & Liu, 2021), but due to the lack of substantial modeling results in the analysis of visual cues, no further results were published on the topic.

***Modeling the driver response process in straight-crossing-path intersection conflicts.***
The application of AEB and FCW to intersection conflicts used a simple model of driver behavior assuming a distribution of response times after the FCW warning was given. However, more advanced models are needed in order to tune and assess an ADAS when the driver is in the loop (e.g., collision warning). QUADRAE took a two-step approach to the modeling. First, a simulator study identified which perceptual cues drivers use to judge whether a straight-crossing vehicle is a threat; second, an accumulation model for straight-crossing-path conflicts was created and

parameters were fit. The simulator experiment was a simple setup: a participant looked at a screen which displayed a scenario with the ego vehicle driving straight ahead and a principle other vehicle (POV) approaching the future path of the ego vehicle perpendicularly in a potential conflict. The participants were asked to press a button when they felt confident about their judgment of the situation playing out as a crash or a non-crash. Each participant got to view and respond to 14 different scenarios multiple times with both crash and non-crash timings: for each scenario, some visual cue was altered. Examples of visual cues were road texture, road markings, the speed of the POV, deceleration of the POV, and poles by the side of the road. The analysis compared the response times to those in a baseline scenario. The results showed, among other things, that texture matters a great deal, and that POV looming is a key variable. They also showed that visual cues such as equally spaced roadside poles are not used much to judge conflict timing. This study is being prepared for submission to the Accident Analysis & Prevention journal.

Based on the literature and the results from the first study, a VTI simulator experiment was set up. The goals were to investigate the driver's response process in straight-crossing-path (SCP) intersection conflicts and to use the output data for parameter fitting of an accumulator model for braking in such conflict situations. The results of the study show that drivers' brake reaction depends on the crash scenario: POV crossing in front of the ego vehicle vs POV crashing in the side of the ego vehicle. Interestingly, there were many no-braking reactions in the latter scenario, indicating a relationship between the decision to brake and the bearing angle. This factor was then taken into consideration in the modeling by improving on the accumulative looming model approach. The model's parameters were fitted using the data from the VTI simulator study. Results show that the braking response time depends on the overlap of the extension of the bearing angle rate between front and rear of the POV with parameterized triangle during the approach of the conflict. When the drivers in the simulator looked at the threat early, the brake response was late—leading to many crashes, even in situations with manageable reaction times (time-to-collision > 2 seconds). This finding implies great potential for improvement if active safety systems could communicate the level of urgency to the driver, rather than simply providing notice of the threat. While the braking model was established, the drivers' steering reaction, which can also prevent a crash in an SCP intersection conflict, was not always observed—and failed to show a clear structure. A conclusion from this work is that it is not obvious how to model the driver response process in straight-crossing-path conflicts. More work is needed, but QUADRAE has moved the research closer to a computational driver model that will be useful for virtual assessments. Descriptive statistics from the VTI study are being prepared for submission in a journal article to the Accident Analysis & Prevention journal. A separate paper based on the intersection modeling work is also planned.

Counterfactual simulations were run for the benefit assessment of braking assistance in intersection conflict scenarios. The simulations showed some potential for all situations in which the driver initializes braking. However, when the POV crashed into the side of the ego vehicle, in many cases the driver showed no braking reaction. To investigate whether a brake reaction could be prompted by a warning, a follow-up study was conducted. The setup was the same as in the original study, except a warning was introduced after the threat was visible but before the conflict. The aim was to investigate the ability of a warning to stimulate a braking response qualitatively as well as quantitively. Results showed that, compared to the original scenario without a warning, the number of cases with no braking reaction was reduced, as was the brake reaction time. However, most situations still resulted in a crash. The scenario was highly critical, but crashes were not unavoidable. A detailed study of the reactions showed a possible advantage of a multi-modal warning, as the reaction patterns indicate that the drivers' braking was triggered by the warning, not by the threat. This finding implies that warnings in SCP intersection conflicts have the potential to mitigate crashes; while the design of the warnings should be clearly linked to the threat, further research is to determine the ideal design(s).

## 6.4 Investigating the potential of ADAS in intersection collision scenarios

One of the objectives of QUADRAE was to carry out virtual assessments of prioritized scenarios. One group of such scenarios is car-to-car crossing path conflicts in intersections (e.g., left turn across path/opposite direction, LTAP/OD; and straight crossing path, SCP). This work focused on the evaluation and parameter assessment of automated braking when an impact is imminent. The results of this analysis allow the quantification of additional benefits of systems that warn the driver. An industry PhD student from Autoliv (Ulrich Sander) conducted three studies that utilized a framework for safety assessment (PREADICO) developed in previous work (Sander & Lubbe, 2016). The results of each study were published in peer-reviewed scientific journal articles.

The first study explored opportunities and limitations for intersection collision interventions (Sander, 2017). The main objective of the study was to investigate the effect of different algorithm and brake settings on the ability of Intersection AEB to prevent LTAP/OD crashes. We analyzed the capabilities of crash avoidance for both the turning vehicle and the one heading straight. The German In-depth Accident Study (GIDAS) and the GIDAS-based Pre-Crash Matrix (PCM) data were queried for LTAP/OD accidents. Pre-crash simulations using the vehicle trajectories in 384 LTAP/OD real-world accidents were conducted within the PRAEDICO assessment framework. The results show that nine out of ten collisions were caused by the driver of the turning vehicle. The reference simulations indicated that the AEB system in the turning vehicle has the potential to avoid approximately half of the collisions. In contrast, an AEB system in the vehicle going straight was less effective. Forward-looking sensing systems with expanded, state-of-the-art fields-of-view, designed for rear-end AEB interventions, were capable of addressing turning-across-path situations. System parameters were varied. This paper has, to date, 25 citations in Scopus, and a Field-Weighted Citation Impact of 3.01.

In the second study, the potential of clustering methods to define intersection test scenarios was evaluated (Sander & Lubbe, 2018a). We investigated whether clustering methods can be used to identify a small number of test scenarios sufficiently representative of the entire accident dataset to evaluate Intersection AEB. Accidents that were identified as similar to each other were re-simulated to reveal whether the AEB system performance in crash avoidance is homogeneous within each cluster. Data from GIDAS and PCM from 1999 to 2016 were analyzed by principal component methods to identify variables that account for the total relevant variances of the sample. Three different data clustering methods were applied to each of the accident types: two similarity-based approaches (Hierarchical Clustering and Partitioning Around Medoids) and one probability-based (Latent Class Clustering). The use of different sets of clustering variables resulted in substantially different numbers of clusters, although the stability of the resulting clusters increased when categorical variables were prioritized over continuous variables. None of the identified clusters had an average silhouette width of 0.7 or higher, indicating that the cluster grouping is partially random. This paper has, to date, 27 citations in Scopus, and a Field-Weighted Citation Impact of 3.12.

The third study characterized avoided and residual SCP crashes as a function of Intersection AEB market penetration (Sander & Lubbe, 2018b). The main objective was to guide Intersection AEB implementation strategies in combination with technical specifications. We used a statistical model depending on the market penetration to define whether neither, one, or both vehicles were equipped with an Intersection AEB. Correspondingly, each crash was simulated with all possible equipment combinations. Intersection AEB was activated when neither of the conflict opponents could avoid the crash through reasonable braking or steering reactions. The results showed that crash avoidance is exponentially, not linearly, related to market penetration—with higher gains at low penetration rates and lower gains at higher rates. A 180° field-of-view sensor substantially increased accident avoidance and injury mitigation rates, compared to a 120° field-of-view sensor. Further, for the wider field-of-view sensor at 100 percent market penetration, about 80 percent of the accidents and 90 percent of the MAIS2+F injuries could be avoided. This paper has, to date, 12 citations in Scopus, and a Field-Weighted Citation Impact of 1.91.

The results of these three studies substantially support the Swedish automotive industry's leadership in the development of Intersection AEB, which as of this year has become part of the assessment protocol in Euro NCAP. Further, they deliver information to authorities on how to create strategies for reducing intersection crashes with moderate to fatal outcomes most effectively through AEB implementation—and, thus, how to establish a more sustainable traffic environment.

## 6.5 Studying the effect of glance behavior and the level of automation on safety

Drivers' off-road glances, which indicate that drivers do not have their eyes on the roadway/potential threats, have time after time been identified as a key contributing factor to crashes. The crash causation mechanism has been indirectly studied in QUADRAE (Markkula et al., 2016), but it has been more extensively studied in other literature. As the level of vehicle automation increases, ADAS and AV systems can help the driver in the driving task by avoiding crashes or mitigating their consequences. However, studies have shown that as the level of automation is increased, drivers' focus on the road—looking for threats and being ready to respond—is reduced. Traditionally, in analyses of driver glance behavior, the increased duration and frequency of glances off-road is considered to have a direct, negative impact on safety. However, when the increase in duration and frequency is due to the introduction of a safety system, e.g., ACC or higher levels of automation (when the driver is still expected to monitor the road), the traditional analysis is not valid; the added benefit of the safety system is not taken into consideration. In QUADRAE we performed a study that applied virtual simulations to SHRP2 naturalistic driving data conflicts and included glance behavior data from an internal VCC study on changes in glance behavior as a function of level of vehicles automation. We showed that the negative effect of more glances off-road was dwarfed by the positive effect of the safety systems. This research highlighted the importance of not assessing glance behavior in isolation, when the glance behavior change is due to some system that has a positive effect on safety: the combined effect must be assessed. This finding has implications for the assessment of all supervised automation (ADAS). We also showed how to use combined virtual simulations to determine the break-even point of the safety benefit of a system, with respect to how often the system fails. The work was presented at the Driver Distraction and Inattention Conference in 2018 (Bärgman and Victor, 2018), and a full peer-reviewed paper was subsequently accepted and published (Bärgman and Victor, 2020).

## 6.6 Contribution to the objectives of the FFI program

The very comprehensive work in QUADRAE follows the success of the previous project, QUADRA. The knowledge gained and models created contribute to the competitiveness of the industrial partners, as well as providing Sweden with a valuable edge in research regarding virtual testing, driver modeling, and traffic safety.

***Analysis, knowledge, and supporting technology.***
State-of-the-art methods and tools are prerequisites for future advanced driver assist technologies and autonomous vehicles. As active safety and autonomous systems in vehicles become more common, virtual tools are critical to help guide and drive the future development of these systems—in order to optimize their impact on road safety in different traffic environments. Research regarding the development of quantitative driver models and the refinement of virtual testing methods is key to high-quality safety systems since it allows us to assess and understand their effects in real traffic. QUADRAE is at the forefront; the deliverables from the project set the agenda, not only for the Swedish partners, but also globally, promoting Swedish research, knowledge, and innovative technology worldwide. Further, the results and deliverables from

QUADRAE are essential to drive the Swedish Vision Zero, as well as the UN goals, to help save lives on the roads in the future.

The research in traffic safety in Sweden, with its long-term commitment to collaboration by partners (industry, academia, and authorities) working towards the same objective, has proven very successful over the years; so also, within QUADRAE.

The contributions of QUADRAE are based on:

- meeting the automotive industry's need for highly advanced driver models that can be directly implemented in current and future active safety and autonomous systems using industrial simulation tools.
- deriving test cases from state-of-the-art, real-world data (from naturalistic driving (NDD), incidents, and crashes).
- applying scientific methodology to assess model validity using human behavioral data and grounding the driver models in psychological/neuroscientific knowledge.

The deliverables from QUADRAE include unique driver behavior models for braking as well as steering in certain critical events—even though modeling steering intervention proved to be more challenging than originally anticipated. Glance behavior and response have also been included in driver models. These models are of paramount importance for the virtual testing of future active safety and autonomous systems. In turn, virtual testing is the key to evaluating the potential benefits of such systems.

***Competence and research edge***

Within QUADRAE, researchers within industry and academia have made great strides in obtaining vital knowledge even beyond driver modeling and virtual testing. New findings in driver behavior research, applications in experimental test-setups, and combining data from different real-world data sources have led the partners to develop new competencies that will help them lead the industry forward, introducing life-saving active safety and autonomous driving technology. Jointly, the partners will help create a sustainable balance between automation and humans in future vehicle applications. The researchers directly involved in the project (as well as their colleagues in their respective organizations) have developed and further established their competence in this area. The project has already yielded two PhD dissertations, one Licentiate in Engineering, and several Master theses. The scientific publications delivered through the project, some of which have been ground-breaking, have contributed to spreading the knowledge gained. Hopefully, these accomplishments will lead to further research globally which will also benefit industry and academia in Sweden.

# 7 Dissemination and publications

## 7.1 Dissemination of knowledge and results

The dissemination of knowledge and results had five primary avenues. First and foremost was publication in scientific journals (15 published and 3 in preparation). The number of citations and field-weighted citation indices were, for the most part, substantially over average, with some exceptional publications (the top two received 51 and 32 citations, respectively, in only four years, with field-weighted citation indices above 3.5). The second was conferences (15 published and 3 in preparation), and the third was an international workshop (Bärgman, 2019). We also presented QUADRAE at a SAFER lunch meeting. Fifth and finally, some of the knowledge acquired in QUADRAE has been part of QUADRAE's partners' contributions to ongoing work on an ISO standard on methods for virtual simulations of ADAS and AD.

| Hur har/planeras projektresultatet att användas och spridas? | Markera med X | Kommentar |
|---|---|---|
| Öka kunskapen inom området | X | QUADRAE has to a very large extent increased knowledge in the area of driver modeling. |
| Föras vidare till andra avancerade tekniska utvecklingsprojekt | X | The work in QUADRAE is continuing in other projects. Specifically, in the newly awarded FFI project QUADRIS, and in the EC Marie Currie project SHAPE-IT. |
| Föras vidare till produktutvecklingsprojekt | X | Models from QUADRAE are already used in virtual assessment of production systems in industry. |
| Introduceras på marknaden | | Components of QUADRAE driver models are being included in the development of algorithms that reside in production vehicles. |
| Användas i utredningar/regelverk/ tillståndsärenden/ politiska beslut | | Not yet, but QUADRAE knowledge has been included in ISO work and we are promoting the work on combining assessment of driver behavior (glance behaviors) and different levels of vehicles automation when assessing safety. |

One of the PhD students completed his dissertation within the project, sharing the acquired knowledge on benefit estimation methodology and the specifications of advanced driver assistance systems. A paper on benefit estimation of automated braking systems in intersection was published (Sander, 2017).

The Scientific Advisory Board (SAB) consisted of Associate professor Erwin Boer (Delft University of Technology and University of Leeds; Scopus h-index: 27), Professor Gregor Schöner (Ruhr-University Bochum; Scopus h-index: 57), Professor John Lee (University of *Wisconsin-Madison;* Scopus h-index: 19*)*, Professor John Wann (*Royal Holloway*, University of London; Scopus h-index: 36) and Professor Timothy Gordon (University of Lincoln; Scopus h-index: 19). All the members of the SAB are leading researchers on topics related to the QUADRAE project. In addition to his university appointments, Erwin Boer is the founder of Entropy Control, Inc.; he has been deeply involved in the development of human-machine technologies for driver support systems and autonomous and cooperative vehicles. Gregor Schöner, who is also the Director of the Institute of Neuroinformatics at the Ruhr-University Bochum, is interested in understanding how embodied and situated nervous systems develop cognition, and how to use theoretical principles to develop autonomous robots. John Lee, who leads the Cognitive Systems Laboratory at University of Wisconsin-Madison, has extensive expertise in cognitive engineering and focuses his research on human-machine systems, using conceptual and computational models of human-technology interaction as the basis. John Wann leads the Action Research Labs at the Royal Holloway and his research focuses on human movement in complex environments and during the performance of highly skilled actions, including steering a vehicle and judging a vehicle's speed. Timothy Gordon, who is also Head of School of Engineering in College of Science at University of Lincoln, has extensive experience in vehicle dynamics and control, including the safe travel of automated vehicles, driver modeling, and safety system evaluation.

## 7.2 Publications

The following is a list of the deliverables from the project. An "academic" reference list (ordered by author names) can be found at the end of the document.

**WP1**

D1.1 & 1b Use Cases documented in QUADRAE web fora

D1.2 Internal report: Sander, U., Engström, J., Piccinini, G., Lindman, M., Sandin, J., Apoy, C. (2017), State-of-the-art methods for virtual testing of active safety and automation. Project report.

D1.2 Sander, U., & Lubbe, N. (2018b). The potential of clustering methods to define intersection test scenarios: Assessing real-life performance of AEB. *Accident Analysis and Prevention*, *113*, 1–11. https://doi.org/10.1016/j.aap.2018.01.010

**WP3**

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D6.4 Streubel, T., Bärgman, J., Lehtonen, L. (in preparation) Driver response to critical conflict situations in intersections: A simulator study. Submission planned winter 2021/2022. Target journal: Accident Analysis & Prevention

# 8 Conclusions and Future Research

Modeling driver behavior in critical situations is challenging for several different reasons. Firstly, there is a need to know how drivers act in critical situations in the real world—when they are driving in their everyday lives and unexpected situations unfold. Driver responses may be very different from responses in simulators or on test-tracks. The partners in QUADRAE have a great deal of experience working with Naturalistic Driving Data (NDD), which QUADRAE has used extensively. Several of the scientific publications from QUADRAE use novel approaches to study unique NDD, producing much-cited papers on driver responses in critical situations in the real world.

The second challenge is identifying the (perceptual) cues that the drivers use to acquire information about surrounding traffic in relation to their own vehicle and understanding the response process that follows the "gathering" of such cues: how drivers act on what cues. In computational driver modeling, these cues must be incorporated into mathematical expressions to capture how humans transform the cues into actions in a way that can be simulated in a computer.

A third challenge is to design and conduct experiments that empirically study the details of the drivers' response process. These response-process experiments can then be used to complement the study of NDD in the development and parameter fitting of driver behavior models. QUADRAE designed its experiments with input from the literature, partner experience, and the revered members of the QUADRAE scientific advisory board.

Finally, the fourth and overarching challenge is which overall modeling framework to use. There are several schools of thought with differing paradigms describing how to conceptualize the modeling of driver behavior. These schools range from purely control-theoretic approaches, which aim to capture the underlying mechanisms of human behavior, to modeling the human as a network of neurons. In QUADRAE, the focus was to develop models based on the underlying mechanisms that guide driver behavior.

In the global scientific arena of driver behavior modeling, there are several initiatives addressing driver modeling. In the new EC program Horizon Europe, there is even a specific call for the development of behavioral models for virtual simulations of connected and automated vehicles (HORIZON-CL5-2022-D6-01-03 "Human behavioral model to assess the performance of CCAM solutions compared to human driven vehicles"); there is also a separate call for methods dealing with the use of virtual simulations for safety assessment (HORIZON-CL5-2022-D6-01-06 "Predictive safety assessment framework"). QUADRA and QUADRAE have positioned their partners very well for these calls. It should, however, also be noted that that much of the work related to modeling driver behavior for use as part of automated vehicle systems and in virtual safety benefit assessment is conducted "behind closed doors" in the automotive industry (e.g., Helmer et al, and Waymo, 2020), making it even more important that projects such as QUADRA and QUADRAE are conducted to ensure that the automotive industry in Sweden is at the forefront of driver modeling and methods for virtual safety assessment.

The Swedish vehicle industry has a long history of leading the development of safety technologies that significantly help reduce injuries and fatalities on our roads. This success has been largely due to the unique collaborative research culture nurtured in Sweden, where partners from academia, the government, and industry create ground-breaking science relating to knowledge, methods, and tools through joint effort. Such collaborative research and way of working that others look at with envy has proven very successful and has been confirmed in the open innovation management research that was performed using SAFER as the case study (contact https://www.saferresearch.com/ for more details). Moreover, this collaborative culture will enable continued safety technology development, ensuring that the Swedish industry can stay at the forefront of global competition.

The development of future advanced driver assist technologies and autonomous vehicles requires state-of-the-art methods and tools; overall, QUADRAE has made significant contributions in this regard.

Within QUADRAE, driver behavior models for braking in critical events (in rear-end and straight-crossing-path intersection scenarios) have been established. Driver models of steering in run-off-road incidents have also been further developed, whilst significant knowledge has been acquired regarding the complexity of modeling driver steering interventions, in intersections as well as in lane-change situations. Models for drivers' response and glance behavior have also been developed. They are now being used and developed by the industry to develop active safety and automation.

Substantial work has also been performed in QUADRAE to establish methodologies for virtual testing that will yield the best possible benefits of active safety systems and automation. For example, when evaluating the possible effects of intersection brake technology in a supervised automated driving scenario, it was concluded the support system and the change in driver glance behavior need both to be considered.

The methodological framework is also being used and further explored within industry as well as academia. QUADRAE has not only increased knowledge about the framework per se, but, more significantly, has also increased the knowledge for its partners through the details found in the comprehensive experimental studies of driver behavior. This shared knowledge pool will enable even more advanced models of driver behavior in the future.

A unique competence has been developed that will improve global competitiveness, within both industry and academia.

***Future research.***

QUADRA and QUADRAE have made huge leaps forward in the understanding of driver behavior in critical situations, resulting in several models and methods for use in virtual safety assessment. However, the work does not stop there. The recently granted FFI project QUADRIS continues in the footsteps of QUADRA and QUADRAE, although the focus of QUADRIS is a bit different. QUADRIS focuses more on the need to assess the safety performance of higher levels of automation. Recent work (e.g., Waymo, 2020, and Rothoff et al., 2019) has shown one promising approach: developing reference models of driver behavior to be used as benchmarks against which the automated vehicle performance is compared. In QUADRIS, one PhD student will develop these models, which should respond to critical situations with the timing and amplitude of an experienced, good, attentive driver. A second stream of research in QUADRIS, different from that in QUADRA and QUADRAE, is pursuing the methodological aspects of generating synthetic events to be used in virtual simulations. The events must be reasonable approximations of what may happen (now or in the future) in traffic. Finally, QUADRIS also continues one of the research streams of QUADRAE: the development of a driver response model for run-off-road crashes. A PhD student starting in QUADRAE will continue this work in QUADRIS.

In addition to QUADRIS, there is a new EC call in Horizon Europe that specifically targets the development of driver behavior models specifically, with focus on connected and automated vehicles (HORIZON-CL5-2022-D6-01-03 “Human behavioural model to assess the performance of CCAM solutions compared to human driven vehicles”). There is also an EC call on methods dealing with the use of virtual simulations for safety assessment (HORIZON-CL5-2022-D6-01-06 “Predictive safety assessment framework”). QUADRAE partners, as well as the entire Swedish automotive industry, are well positioned to join future consortia for these calls, as a result of the knowledge acquired during the project. Hence, they will be able to continue to contribute to the development of high-quality models of driver behavior, as well as other aspects of virtual simulation methodologies.

# 9 Contributing partners and contacts

The project partners are Volvo Cars, Volvo Group, Veoneer, VTI and Chalmers University of Technology with the main participants throughout the project:

**Chalmers**:
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