PUBLIC REPORT

QUADRA

Quantitative Driver Behaviour Modelling for Active Safety Assessment

Final report of the FFI QUADRA project

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Sammanfattning på svenska

Inom projektet FFI QUADRA har tydliga framsteg gjorts inom det vetenskapliga fältet *förarbeteendemodellering*. Målet med projektet var att skapa specifika förarbeteendemodeller för väldefinierade *användarfall*, där vart och ett inkluderade olika aktiva stödsystem för personbil och lastbil. Målet var att utveckla och använda förarbeteendemodeller för att simulera och förutsäga interaktioner mellan förare och stödsystem i kritiska situationer, och därigenom möjliggöra att med virtuella metoder utvärdera och vidareutveckla stödsystemen i fråga. Projektet har levt upp till dessa förväntningar, och överskridit dem på så vis att även andra, mer allmänna, fynd om förarbeteende har kunnat påvisas.

Executive summary

The QUADRA project was active 2010-2014, was sponsored by VINNOVA FFI and SAFER, and involved AB Volvo (project coordinator), Volvo Car Corporation, the Swedish National Road and Transport Research Institute (VTI), and Chalmers University of Technology. QUADRA has made significant contributions to the research field of driver behavior modeling. The aim of the project was to develop specific such driver models for some well-defined *use cases*, each involving different *active safety systems*. The intention was to utilize driver models in order to simulate and predict driver–system interaction behaviors in critical situations and therefore offer a new way of evaluating and further develop active safety systems in general. However, the results of the project exceeded the expectations due to additional novel findings regarding human control behavior in general. This text summarizes the most important findings, which are further discussed in the two appended PhD theses [12, 13].

In the beginning of the project, a review of existing driver models and their uses in critical situations were made [2]. It was found that there was a large variety of driver models and that these have been used for many different purposes. However, it was also found that models were typically not based on nor validated against relevant driver behavioral data. Furthermore, it was found that different driver models have rarely been compared to each other in actual simulation. These shortcomings were later specifically addressed within FFI QUADRA [8], and the results suggested that psychologically plausible models, rather than models based on control theory, tend to better describe human control behavior in critical traffic situations.

Probably the most well-spread[1] result made in connection with FFI QUADRA is a new theory of human steering [9], a theory which also gives an answer to an almost 70-years old mystery of human control [12]. The theory states that steering is carried out iteratively by the driver adding small well-defined steering corrections, where each correction follows the same pattern as is known from the *reaching* theory (see [12] for more details). Basically, each reaching movement is carried out as *open-loop* and has the same duration, independent of distance. The new theory of steering was validated against large amounts (over 1000 hours) of steering data[2], and it was found that 95% of all extracted (1.3 million) individual corrections in fact could be seen as reaching movements. The immediate implication of this discovery is that steering should not be seen as a linear continuous process, and that the shape of a given steering correction can be predicted before it is finalized. The theory was utilized and evaluated further when developing the *aim point correction model* [12], and the general idea of intermittent control has been incorporated into a general framework for driver control modeling [10].

To focus the modeling efforts in the project, specific use cases were defined, each targeting the driving behavior relevant for a particular active safety system. The active safety systems treated within FFI QUADRA were: (i) *forward collision warning* (FCW), (ii) *advanced emergency braking system* (AEBS), (iii) *electronic stability control* (ESC), and (iv) *emergency lane keeping aid* (eLKA). The first three systems can be found in production vehicles[3], and the last was of a more experimental character.

In the FCW use case, the goal was to investigate and model the driver behavior relevant to rear-end crash situations as targeted by the FCW active safety system. From previous work it was found that a common hypothesis is that the FCW system directly triggers a braking response from the driver. However, in FFI QUADRA it was suggested that the driver does not automatically respond by braking, but rather shifting the attention towards the road. Evidence was found in naturalistic driving data that the actual braking response is instead triggered by the collision threat itself, in terms of *looming*. The looming in this case refers to the rate of which an object expands on the driver's retina, which relates to

1 So far published in over 100 newspapers world-wide, and also highlighted in Swedish radio and TV broadcasts.
2 The driving data were collected from driving simulator studies, test track studies, and from *field operational tests* (FOT).
3 In some cases, however, FFI QUADRA tested variations of systems that differed slightly from the systems found in production.

the relative speed of the object and, therefore, the specific kinematics of the scenario. Elsewhere, it has been shown that looming has an important role when triggering behaviors of animals and humans, and in FFI QUADRA it was further clarified how these concepts also play an important role in the driving task. Based on these findings, a driver model was developed and used in simulated lead-vehicle braking scenarios, for example useful for studying the effect of FCW system parameters on system benefit.

The AEBS use case was a continuation of the FCW use case, but in which also automatic braking from the vehicle was considered, and where the ultimate goal was to carry out *what-if simulations* of actual crashes; i.e. to estimate the effect that an AEBS system would have had on actual crashes, recorded with on-board logging equipment [13]. In terms of driver modeling, one important step forward here was the adoption, from psychology and neuroscience models, of the concept of *evidence accumulation*, to further improve on the reaction models developed in the FCW use case. It was shown that this phenomenon, whereby drivers accumulate evidence for the need of control action, up to a threshold at which action occurs, could account for some previously unexplained empirical data on drivers' brake reaction timing [10], as well as reaction timing in naturalistic rear-end crashes and near-crashes [13]. Also some specific suggestions were made for how to improve existing *what-if* simulation methodologies, adopting them better for use with crashes that have actually been recorded, as opposed to crashes that have been reconstructed from accident investigations [13]. However, full implementation of the envisioned what-if simulations could not be completed within the project.

In the ESC use case, the driver behavior when interacting with a heavy truck ESC system on a slippery road surface was studied. A large driving simulator[4] experiment was conducted involving 48 truck drivers [4]. In order to acquire more data by repeating unexpected scenarios, a new methodology for such repetition was designed and found to work well [4, 7, 13]. The results from the simulator study, together with the subsequent driver modeling, showed that heavy truck ESC will improve safety in unexpected critical maneuvering, something which has not been previously demonstrated [13]. Furthermore, by replicating the simulator study in computer simulation, the effect of individual driver behaviors on ESC impact could be studied in unprecedented detail [13]. A key behavioral finding was that drivers who attempt to cancel an ongoing skidding do so by chasing the rotating surroundings with the steering wheel, a behavior termed *yaw rate nulling* steering [8], and this finding motivated a patent application for an ESC system that could better handle severe skidding [6, 14].

In the eLKA use case, it was explored how a driver reacts to a sudden and unexpected torque applied to the steering wheel. A scenario was envisioned where an active safety system could avoid or mitigate an accident situation by turning the steering wheel automatically in order to steer away from an unintentional lane departure. For example, such departure could arise from the driver being distracted or drowsy. Several experiments were conducted in a driving simulator[5], and it was observed that drivers tend to resist any sudden and unexpected torque. The driving experience aspects were also tested further by carrying out similar tests with children and their parents[6] Based on close examination of the involved steering wheel torques and movements, as well as *electromyography* (EMG) measured from the drivers, it was found that the response arises from both the *stretch reflex* and an automatic *co-contraction* [12]. Both responses seem to be highly involuntary and effectively remove any applied torque. It was also noted that any *existing* driver model could not fully account for these observed behaviors. However, even though the behaviors were identified and thoroughly described no new mathematical model was defined within the FFI QUADRA project, partly because the envisioned active safety system was shown to be ineffective.

To conclude, the main insights gained from FFI QUADRA are that one may benefit from viewing driver behavior in critical situations from a neuroscience and psychology perspective, rather than in

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4 Here, the driving simulator used was the Sim II at VTI, Linköping.

5 The driving simulator used was the Sim IV at VTI, Göteborg.

6 As noticed in Swedish media in 2014, e.g. in Forsking & Framsteg and Mitt i Trafiken.

terms of optimal control theory. Furthermore, it was shown that computer simulation is a valuable tool when evaluating active safety systems. Finally, from the work carried out within the project, it is evident that the in-depth analysis of driver behavior required for designing a driver model can, in itself, lead to concrete ideas for how to improve active safety systems.

To address the needs for simulation-based evaluation in coming years, further model development is recommended, to be able to address a wider range of pre-crash scenarios and safety systems. Not the least, current development of increasingly automated vehicles could benefit greatly from simulation-based investigations of scenarios where the driver needs to resume control from the automation. In general, also further research on methodologies for simulation-based evaluation is recommended.

List of publications, in chronological order

[1] O. Benderius, G. Markkula, K. Wolff, and M. Wahde. A simulation environment for analysis and optimization of driver models. *Digital Human Modeling*. Springer, 2011, pp. 453–462.

[2] G. Markkula, O. Benderius, K. Wolff, and M. Wahde. A review of near-collision driver behavior models. *Human Factors: The Journal of the Human Factors and Ergonomics Society* **54.**6 (2012), 1117–1143.

[3] O. Benderius. *Driver modeling: Data collection, model analysis, and optimization*. Licentiate thesis. Chalmers University of Technology, 2012.

[4] G. Markkula, O. Benderius, K. Wolff, and M. Wahde. Effects of experience and electronic stability control on low friction collision avoidance in a truck driving simulator. *Accident Analysis & Prevention* **50** (2013), 1266–1277.

[5] G. Markkula. *Evaluating vehicle stability support systems by measuring, analyzing, and modeling driver behavior*. Licentiate thesis. Chalmers University of Technology, 2013.

[6] G. Markkula. *Vehicle control system and method for determining a desired yaw rate of a vehicle*. International patent application PCT/SE2013/000034. 2013.

[7] O. Benderius, G. Markkula, K. Wolff, and M. Wahde. Driver behaviour in unexpected critical events and in repeated exposures – a comparison. *European Transport Research Review* **6**.1 (2014), 51–60.

[8] G. Markkula, O. Benderius, and M. Wahde. Comparing and validating models of driver steering behaviour in collision avoidance and vehicle stabilisation. *Vehicle System Dynamics* **52**.12 (2014), 1658-1680.

[9] O. Benderius and G. Markkula. Evidence for a fundamental property of steering. *Proceedings of the Human Factors and Ergonomics Society Annual Meeting*. Vol. 58. 1. SAGE Publications. 2014, pp. 884–888.

[10] G. Markkula. Modeling driver control behavior in both routine and near-accident driving. *Proceedings of the Human Factors and Ergonomics Society Annual Meeting*. Vol. 58. 1. SAGE Publications. 2014, pp. 879-883.

[11] P. Nilsson, L. Laine, O. Benderius, and B. Jacobson. A Driver Model Using Optic Information for Longitudinal and Lateral Control of a Long Vehicle Combination. *Proceedings of the 17th International Conference on Intelligent Transportation Systems (ITSC).* IEEE. 2014, pp. 1456-1461

[12] O. Benderius. *Modelling driver steering and neuromuscular behaviour*. PhD thesis. Chalmers University of Technology, 2014.

[13] G. Markkula. *Driver behavior models for evaluating automotive active safety: From neural dynamics to vehicle dynamics*. PhD thesis. Chalmers University of Technology, 2015.

[14] G. Markkula, J. Eklöv, L. Laine, E. Wikenhed, and N. Fröjd. Improving yaw stability control in severe instabilities by means of a validated model of driver steering. Submitted.

Doctoral dissertations

Further details are available in the two PhD theses written during the project, appended hereafter in this report. Please note that for reasons of copyright, the full texts of the papers included in the theses have been removed here.