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Driver Comfort Boundaries in Intersection Negotiation

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Content

FFI in short

FFI is a partnership between the Swedish government and automotive industry for joint funding of research, innovation and development concentrating on Climate & Environment and Safety. FFI has R&D activities worth approx. €100 million per year, of which half is governmental funding. The background to the investment is that development within road transportation and Swedish automotive industry has big impact for growth. FFI will contribute to the following main goals: Reducing the environmental impact of transport, reducing the number killed and injured in traffic and Strengthening international competitiveness. Currently

Executive summary

The project intended to provide a basis for requirements and methods for the design and verification of ADAS focusing on warnings at intersections that are based on when drivers would appreciate a warning.

DCBIN focus has been on situations which include two vehicles with crossing path at intersection. The project has mainly focused on LTAP/OD (Left Turn Across the Path/Opposite Direction) situations, but also considered LTAP/LD (Left Turn Across the Path/Lateral Direction) and SCP (Straight Crossing Path) situations as well. Intersection crashes is a major global road safety problem and although much has been done in terms of infrastructure design in many countries, such as roundabouts, ADAS must handle safety for the global market where traditional intersection layouts are still common.

The project aimed to analyze the drivers' decision making and threat analysis based on the "safe path of travel". This included analyzing drivers scanning behavior in relation to the intersection and the presence of other road users commonly referred to DVE (Driver, Vehicle, Environment) parameters.

Methodology and approach of the project included controlled on-road and test-track experiments (drivers driving specific routes/interactions under controlled circumstances) to analyze the drivers' eye movements and scan behavior in relation to the other vehicle crossing the path of the subject vehicle. Naturalistic driving data was used to build DVE models based on data from recorded vehicle signals and video. The models were refined and supplemented based on data collected during test-track experiments, which were designed to study a continuum of driving – from everyday safe driving to near-crash situations. This continuum was from the test-track experiments were compared to naturalistic driving data for the validation of results on the test track.

The project was carried out according to the above method and approach. However, it was decided to focus on the test track experiments, rather than controlled on-road trials with consideration to personal safety. A very extensive work was successfully conducted by the parties that included method development of experiments with the driver in the loop.

The main goal of this project was to quantify drivers comfort zone as defined by measures of closeness in time and space between the vehicles and the safety margins selected by the drivers during crossing path situations. Consequently, the comfort zones defines the boundaries of when drivers would accept warnings or not, which in turn informs the design of ADAS with high driver acceptance. The second goal was to further investigate the variability of driver behavior considering variations between driver, within driver, as well as the influence of driving context during intersection negotiations, in order to enable development of adaptive ADAS systems for intersections. A third goal was to further develop models that includes the driver, vehicle, and environment in intersection situations.

Comfort zones are defined for a number of different variations of DVE parameters in the LTAP/OD scenarios, in which the driver chooses to make a left turn before or after a car driving in the opposite direction at an intersection. A set of probabilistic connections between the driver and context have been developed to describe the drivers' comfort zones when turning left. Interpretation has been made for the relationship between driver, driving context in relation to the driver's decision making, threat analysis and scan behavior. Further development of driver models have been limited in DCBIN, with the understanding that these will best be implemented in the new FFI project QUADRAE, which is the continuation project to the FFI project QUADRA.

The results from the DCBIN project as well as cross-talk between DCBIN and other projects studying intersections has formed a foundation both for further research, as well as facilitated the development of products within the industry. The results have been used directly in product development and in the evaluation of ADAS systems.

Background

Crashes in intersections often occur at high speed, resulting in severe injuries or fatalities. Fatalities in intersections in accounted for approximately 21% of all traffic crash fatalities in 13 European Union countries, resulting in more than 65.500 persons were killed in traffic junctions between 1996 and 2005 (SafetyNET 2007). Out of a total of 1 643 000 intersection crashes in the US in 1998 (GES), 27% were Left Turn Across Path, Opposite Direction (LTAP/OD) crashes, 30% Straight Crossing Path (SCP), and 20% Left Turn Across Path, Lateral Direction (LTAP/LD), (Najm et al. 2001).

Figure 1: Three intersection crash types making up for more than 75% of intersection crashes (Najm et al. 2001).

Countermeasures addressing intersection crashes have traditionally been intersection design and passive safety measures. During the last 10 years, significant progress in sensing and other technologies has enabled new opportunities for Advanced Driver Assistance System (ADAS) in intersections – aiming at mitigating or avoiding intersection crashes by using in-vehicle technology. The projects INTERSAFE and INTERSAFE2 (Intersafe-Consortium 2008, Intersafe2-Consortium 2011) focused on technology development and functionality testing. There are also advances in infrastructure design, such as the roundabout deployment in Sweden, but these design approaches may not be suitable in all contexts and all countries. ADASs have a huge potential in reducing the number of intersection crashes, or mitigating their consequences. The ADASs may either be in-vehicle, cooperative by including communication between vehicles, or between infrastructure and vehicle. So far, the focus from an ADAS perspective has primarily been on technology, while there is limited knowledge about driver behavior and actions when entering and negotiating intersections in normal driving as well as in critical situations preceding crashes. Further understanding in these areas is crucial for the design and implementation of intersection ADASs, both from the perspective of system effectiveness at reducing harm and of system acceptance by drivers.

In 2009 partners from the Swedish Automotive industry finished the project IVSS Intersection Crashes: Analysis and Prevention. This was a first Swedish project that focused on understanding driver behavior in intersections and the causes of crashes and incidents related to driver behavior in intersections. The scope of the IVSS project was to (1) gather large amounts of data from a few intersections (site-based video tracking) and to analyze the observed vehicle interactions, (2) use a high-fidelity experimental vehicle for in-depth analysis of driver actions and attention (?) in relation to the environmental context for a few drivers in two intersections, and (3) implement the features of the chosen intersections and encroachments in driving simulators to study wellcomeness (or acceptance) of warnings and critical encroachments through the interactions between a confederate (experimenter controlled) vehicle and three participants (vehicles) being in the same driving simulator environment at the same time.

The IVSS Intersection project provides a basic foundation for setting thresholds for system activation for a specific scenario, an (embryonic) understanding of driver actions as a function of intersection driving scenarios, as well as information about driver

acceptance of warnings as a function of the indicator Post-Encroachment-Time (PET). PET is a "closeness to crash" indicator defined as the minimum temporal separation between a pair of vehicles on crossing paths. It is measured using the hypothetical rhombus formed by the intersection of the paths of two crossing vehicles. PET is the time between when the first vehicle leaves the rhombus and the second enters it.

While the IVSS Intersection project contributed significantly to the understanding of intersection negotiation and to the development of a set of tools, models and methodologies for analyzing intersections, it took only the first steps towards understanding the complex interactions and actions/reactions by and between Driver, Vehicle and Environment. A deeper understanding is needed to develop effective and accepted ADASs. In 2009, SAFER funded a project called Scenario based testing of pre-crash systems that focused on defining simple and typical intersection scenarios to be used for technical ADAS testing. This project provided a comprehensive review of intersection crash statistics (Sandin, 2009).

Comfort zones and their boundaries

Part of safe passage through intersections is the detection and avoidance of encroachment incidents and crashes. An encroachment occurs when another road user enters the future path of the host vehicle. In conceptualizing sources of threat from other road users, Gibson and Crooks (1938), proposed an "envelope" around the vehicle which they termed "the safe field of travel". Encroachments are violations of this field. An important part of safe passage through an intersection is the detection and avoidance of any encroachments.

Observations of actions taken to avoid encroachment may be the only way to ascertain where a point on the boundary of a driver's field of safe travel was at that time. From the driver perspective, as long as he/she stays within the field of safe travel he/she feels comfortable with the situation – the field of safe travel can thus be regarded as the driver's comfort zone. The comfort zone boundary is dynamic and a function of Driver, Vehicle and Environment parameters (DVE). In the intersection context, important DVEs include e.g. actions by the Driver (steering, braking, search strategies, secondary tasks), and the performance of the Vehicle and Environment (presence of, velocity, and position of other road users, as well as intersection design).

Driver Traits

Personality traits are characteristic behaviors and attitudes that are consistent (often to the point of being invariant) and long-lasting. Individual drivers vary in driving styles and comfort zone boundaries, and this is likely to be strongly influenced by differences in personality traits.

There are many widely accepted and applied descriptive models of personality traits such as the Big Five (Costa and McCrae 1992), the Driving Style Questionnaire (French et al. 1993), and the Manchester Driving Behavior Questionnaire (Lajunen and Summala 2003, Lajunen et al. 2004). In this project we collected questionnaire data from the participants to enable comparisons between measured data from experiments and driver traits elicited from the questionnaires.

Objective

The aim of this project has been to quantify drivers' comfort zones defined by measures of closeness in time and space between the vehicles, as well as the selected safety margins by drivers passing through intersections. This hasprovided thresholds for when the drivers would accept a warning or not, and consequently defined the boundaries for ADAS design. Between and within driver differences and invariants have been further related to driving context in the intersection negotiation, to enable future implementations of adaptive ADAS systems for intersections.

Project realization

4.1 Test track experiments

Four test-track experiments were conducted as part of the study. All studies addressed the LTAP/OD crash scenario, but with different configurations. Three of the studies focused on quantifying the turning drivers comfort-zone boundaries in the LTAP/OD interactions, but with different conditions for the turning driver: (A) free traffic flow (approaching the intersection with speed, without any lead vehicle), (B) starting from stand-still in gap situations and (C) approaching intersection at speed with lead vehicle present. The fourth (D) study evaluated drivers' reactions to an autonomous brake intervention. The first three studies (A-C) were conducted at the Vårgårda air field with a self-propelled balloon vehicle simulating an oncoming vehicle. In studies A-C there were two main conditions. In the first condition, the participants were instructed to turn in front of the oncoming vehicle (balloon car) only when it was safe and comfortable, as in everyday driving. In the second condition, the participants were instructed to turn as if they were in a hurry (e.g., late for a job interview). For each condition, the drivers performed a number of runs (i.e., passes through the intersection). The first four runs at 1, 2, 3, and 4 seconds predicted post encroachment time (PET; Figure 2) between the two vehicles. The predicted PETs were main independent variable. The predicted PET is defined as the PET given "typical" trajectory through the intersection. These trajectories were established as the average trajectories (for the oncoming and turning vehicle respectively) across of a set of pilot runs through the intersection. The predictive PET for each individual run was set by manipulating when the automated balloon vehicle started, in relation to when the

subject vehicles started (each having a deterministic approach trajectory to the intersection). Hereafter predicted PET is called SetPET.

These first four runs were performed to establish a starting point for an iterative procedure to manipulate the timing (based on the method 'method of adjustment' Gescheider (1997)). For example, if a driver did not turn at SetPETs of 1 or 2 seconds, but turned at 3 and 4 seconds, the next run would be a SetPET 0.4 s lower than 3 s (=2.6s). If the driver still turned, it was lowered by 0.4 s yet again (=2.2 s). If the driver then turned, this was considered the comfort zone boundary. The comfort-zone boundary was quantified in terms of the actual PET (the resulting PET for each individual drive through the intersection) and the maximum lateral acceleration at the comfort zone boundary. Similarly, in the second (hurried) condition, driver dread-zone boundary were quantified in the same to metrics. The dread-zone boundary is the equivalent to the comfort zone boundary, but a boundary which drivers would not pass, even with strong motivation. Correlation analysis was further performed between questionnaires items and measures of comfort zone boundaries (i.e., PET and maximum lateral acceleration for the different conditions).

There were, however, some differences in study design between studies A-C, in addition to the three different initial conditions (free flow, stand still with gap situations and lead-vehicle). In studies B and C an additional condition where drivers were instructed to perform a cognitive-load task were conducted. This was performed in order to study the effects of cognitive load on selected safety margins (the comfort-zone boundary), or (if the drivers failed to complete the cognitive task) the prioritization of the driving task over the cognitive task while turning. The cognitive load task used was the one-back test (Mehler, Reimer, & Dusek, 2011). Furthermore, in the first three studies, different methods of evaluating habituation effects were employed. This was evaluated since there was a concern that repeated runs would produce smaller safety margins. Study C included an eye-tracker to evaluate drivers' glance behaviors as they approached the intersection. This was particularly interesting since the lead-vehicle was obstructing the view of the oncoming balloon vehicle.

In the preparatory phase of study A, several other manipulations of the scenario were considered. These included: the presence/absence of a median barrier, varying speeds of the oncoming balloon car (the maximum possible speed was 50km/h), different intersection configurations, and finally including a straight-crossing-path (SCP) scenarios as well. However, the in-vehicle time for participants prohibited an extension of the study design for each of the three experiments (A-C). Experiment A started with a larger study design, but it had to be scaled back to participants spending more than four hours in the vehicle on the test-track.

The fourth experiment D was performed at ASTA Zero. In experiment D, an evaluation of a brake intervention by the left-turning vehicle was performed.

This study aimed to examine drivers' reaction and movement to an autonomous braking system in a LTAP/OD scenario.

A balloon car was placed in an oncoming left lane from the turning driver's point of view. The test leader explained the balloon car as a sight obstruction in the intersection, and that the test subject should imagine it standing still in the intersection waiting to make a left-turn itself. To simulate real world crashes in LTAP/OD intersections the participants were given a task to have their attention focused on the lane they made the left turn into. To accomplish this, another balloon car was placed about 15 meter into the lane they made the left turn into. The participants were instructed to turn as if a big gap situation emerged after the start signal, and regulate the acceleration so that they managed to stop the vehicle before the balloon car. This balloon car was supposed to simulate a car standing still right after the turn, as if there was a line of cars ahead.

The subjects first drove 6 left-turns without autonomous braking. On the 7th turn the autonomous braking was activated some meters after start from stand still. All subjects were unaware that the car would brake before it did it.

Simulator studies were also initially considered, but after a review of simulator studies in left-turn scenarios it was decided to not conduct simulator studies (and focus on test-track experiment) due to the very high rate of motion sickness in simulator turning scenarios.

The test-track experiments were highly weather dependent. In rain of heavy wind, the balloon vehicle performance became unpredictable. This, together with issues with the balloon vehicle itself, made all experiments much more time-consuming than expected.

4.2 On-road experiments

Early in the project a master thesis project was performed by two students in order to develop and evaluate a method for conducting a semi-controlled on-road experiment. The aim was to have participant drive a specific route several times. While doing so, a confederate oncoming car (driven by experimenters) were to get continuous feedback from a system. The system was developed in the DCBIN project, together with the students and consisted of a sensing and a car-infrastructure-car communication system. The system provided the confederate driver information about what speed to aim for to arrive in a specific intersection just in time for "normal" interaction with the participant's car – producing comfort-zone boundary situations. On-road pilot experiments were conducted in an intersection in Gothenburg. The experiments were successful but used only with in-project personnel as subjects in the pilot. Due to ethical concerns, the steering committee for the project decided not to pursue the on-road experiments to establish comfort zone boundaries. Instead, a larger focus was put on test-track experiments. However, the methodology for the on-road interaction generation is documented as a Master's thesis, and have also been submitted for publication as a scientific paper at a conference.

4.3 Analysis of naturalistic driving data

4.3.1 EuroFOT data

This project included analysis of the already existing euroFOT naturalistic driving data (NDD) with the aim to study drivers' normal interaction in intersections (comfort zone boundaries), and to identify critical events (e.g., near-crashes).

The EuroFOT NDD is Europe's largest (to date) set of data with everyday driving in real-traffic. In Sweden more than 200 drivers drove a total of 102 Volvo cars in the Göteborg area for approximately one year (2011-2012). All drivers were employees at Volvo cars. The aim of the original euroFOT-study was to evaluate safety benefits for a set of different active safety systems (e.g., forward collision warning, lane departure warning).

In DCBIN, however, the euroFOT data was analyzed without considering the active safety systems since they were expected to have a negligible effect on intersection negotiations. Instead the EuroFOT data was used to study driver behavior in everyday driving and comfort zone boundaries in, primarily, LTAP/OD scenarios. The procedure to do this was as follows: All left turns were identified automatically (using an algorithm including yaw-rate, yaw-angle and speed) in the entire EuroFOT database including Volvo cars. A total of approximately 11 million turns were identified. However, these included turns in parking lots, as well as artefacts of sensing issues. The 11 million turns were clustered on position based on GPS coordinates. That is, turns occurring in close proximity of each other were clustered together and were considered to be in the same intersection. This resulted in approximately 10 000 clusters in the Göteborg area where left turns had been performed. These were then sorted based on the number of passes through each intersection. The first 1000 of these were manually reviewed to match with a template intersection (rural left turn without traffic lights). First 90 candidates (out of the 1000) were identified as likely matches. This was then further reduced to 20 intersections with an infrastructure configuration similar to the template intersection. All left turn passes through these 20 intersections were then extracted from the EuroFOT database (approximately 100 000). Students were then set to manually review approximately 8000 of these left turn passes and annotate the presence of other road users (e.g., vehicles including direction of approach, pedestrians, bicyclists, motorcycles, no road users). Also weather and road condition were manually coded for the 8000 passes. As data on relative distances and speeds were not available for other road users it was not possible to automatically extract data to calculate for example PET or other safety margin metrics. Instead manual (visual) review was made of videos of LTAP/OD interactions to identify "close calls" (near-crashes) in a subset of the interactions. The estimate of normal driving or near-crash was made through basic human assessments rather than actual estimates of safety margins (as the tools to do make such estimates were not available at the time). Contrary to expectations, no situations were identified as "close calls" (near-crashes) in this subset. Instead of focusing the analysis on near-crashes, the data extracted for the subject vehicle were then analyzed with respect to, for example, approach speeds and longitudinal/lateral accelerations during the turns. As interaction dynamics turned out to be very different when a turning vehicle interacted with several oncoming vehicles, only situations where the turning vehicle turned in-front of one (and only one) oncoming vehicle with a predictive PET of less than 4.0 s were selected for further analysis. Surprisingly such interactions were very rare. The extreme diversity on

driver behavior as a function of context (presence, position, speed, acceleration of other road users) made the research aimed at developing generic (or even specific) models of intersection interactions difficult.

The drivers glance behavior in intersection negotiations when no other road users were present (using euroFOT data) were also analyzed. Specifically, we studied the intersection gaze release time (IRGT) defined as the last time drivers looked towards oncoming traffic (lane/road) before entering the path of the oncoming traffic (encroachment zone: See Figure 4 in Måluppfyllnadsdokument DCBIN). Initial results were disseminated at a scientific conference (Bärgman, Werneke, & Smith, 2013) and a second paper is in preparation.
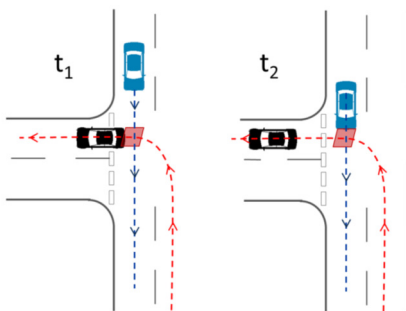

Figure 2: Showing the two moments in time used in the calculation of post encroachment time (PET) when one vehicle turns left in front of an oncoming vehicle with the right-of-way. The red "square" is the encroachment zone. PET=t_2-t_1.

A master thesis project was also conducted (Bardinet de Horna & Secondo, 2014) where two different models of normal driver behavior for intersection negotiation were implemented and assessed using a set of left turns (without oncoming vehicles) from naturalistic driving data (euroFOT) to set the parameters for the two models. The models did not take the decision making of turning before or after on oncoming vehicle into account, but instead only aimed to define the point of decision to turn (model based on Nobukawa (2011)), and the trajectory based on the concept of a near and a far-point for driver lane keeping (Salvucci & Gray, 2004).

The manual annotations made in DCBIN based on video from EuroFOT data are available for furthers studies.

4.3.2 SHRP2 data

SHRP2 is a large naturalistic driving study that included more than 2000 participants driving instrumented vehicles for about one year each. See http://onlinepubs.trb.org/onlinepubs/trnews/trnews282SHRP2nds.pdf for more details on the SHRP2-study. The SHRP2-data were analyzed in order to investigate characteristics and contributing factors to real world LTAP/OD crashes and near-crashes.

The SHRP2 dataset contains approximately 4000 near-crashes and crashes. The LTAP/OD cases where selected by using the following filtering criteria: 1) The variable *Event severity 1* where either categorized as a crash or a near-crash, 2) *Event nature 1* where categorized as one of five categories including "conflict with vehicle turning across another vehicle path". 3) *Relation to junction* where either categorized as intersection or intersection-related. 4) Finally, the combination of *V1 configuration + V2 configuration* where either 68+69 corresponding to LTAP/OD where the subject vehicle were turning, or 69+68 corresponding the LTAP/OD where the subject vehicle where going straight. This resulted in a dataset of 27 LTAP/OD cases where the subject vehicle was turning and 62 cases where the subject vehicle was going straight.

The data from the SHRP2 web site (https://insight.shrp2nds.us) were used for the analysis. This includes forward video, some of the most important filtered vehicle signals (e.g., speed, longitudinal acceleration, yaw rate) that were available for viewing, as well as several variables that were coded for each event (e.g., weather conditions, traffic control, secondary tasks, driver behaviors, timing of the drivers OOPs reaction). In addition to the existing variables, additional analysis of the forward video was performed in order to estimate the speed of the conflict vehicle as well as the timing and nature of visual obstructions. The analysis of visual obstructions from video considered 5 seconds prior to the proximity or impact time, type of object obstructing the view as well as position and direction of movement when the object was another non-conflict vehicle. A detailed analysis of speed and timing of visual obstructions was performed for all turning vehicles and was limited to 26 out of the 62 cases with straight going subject vehicles due to time constraints. Analysis of the data further included analysis of prevalence of a number of different factors, such as distraction and other types of driver behavior, as well the presence of a lead-vehicle turning left in front of the left-turning conflict vehicle, and what the proportion of standstills and moving left-turn vehicles were in the sample.

4.5 Tool development for research on intersection safety

Early in the project it was identified the need for a tool for extraction of data from forward video from intersection crashes, near-crashes and everyday driving. A master thesis project was conducted by two students with the aim to develop and evaluate a means of manually and semi-automatically extract information from video from low-quality, low-frequency video (Meng & Wang, 2016). This thesis was conducted as a collaboration between two departments at Chalmers University of Technology (The department of *Software Engineering, Computer Science and Engineering*, and the *vehicle safety* division at the department of *applied mechanics*). The tool was aimed to produce data for analysis based on forward video views recorded in the EuroFOT project as well as from Lytx event data recorders (see www.lytx.com), in order to extract subject vehicle speed, the speed and range to oncoming vehicles, as well as the position of the subject vehicle related to the intersection.

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Several other tools and methods were developed as part of the analysis efforts during the project. See below.

Results and deliverables

See the document " Måluppfyllelse – Driver Comfort Boundaries in Intersection Negotiation (DCBIN)" for a description of how tasks and results match the goals, aims and deliverables of DCBIN. Only a brief description of the type of results from the project is given here.

Main quantitative results of the project that can be/ are used in development of ADAS include:

a) Quantifications (mainly distributions) of comfort (and dread) zone boundaries in terms of post-encroachment time (PET) and lateral acceleration in LTAP/OD scenarios for three different driving configuration (approaching, standstill and approaching with lead vehicle), and with and without a secondary cognitive task. (Bärgman, 2017b; Bärgman, Smith, & Werneke, 2015)

b) Distributions of glance behavior metrics in both test-track and naturalistic driving data. Specifically to understand when drivers choose to not monitor potential oncoming vehicles any more. A new metric was defined to understand driver threat assessment in LTAP/OD situations. (Bärgman et al., 2013)

c) Distributions and time-series data of speed and acceleration through the approach and negotiation of the left-turn in LTAP/OD scenarios in naturalistic driving data and test track experiments.

d) Information on how different driving contexts (the presence of other road users) affect the speed profile when approaching an LTAP/OD

e) Verification that glance behavior (last glance on oncoming lane) is similar between test-track and on-road data. (Bärgman, 2017a)

f) Assessment of two models of driver behavior for turning left without oncoming traffic (master thesis) (Bardinet de Horna & Secondo, 2014)

g) Prevalence information for a set of factors in LTAP/OD crashes/near-crashes collected in the SHRP2 naturalistic driving study.

Results in terms of method developed in the project

a) A method to quantify driver comfort zone boundaries in a test-track environment.

b) A method to evaluate driver reactions to autonomous braking in intersections in a test-track environment.

c) A method to extract, annotate and analyze naturalistic driving data for position based analysis (i.e., intersections). (Bärgman et al., 2013)

d) A pilot study into method for quantifying the interaction between speed and lateral acceleration in LTAP/OD scenarios.
e) A method to produce unobtrusive encounters between a subject vehicle and a confederate vehicle in real traffic (master thesis) (Boda & Cantillo, 2013)
f) Furthered development of expert-assessment based methods to assess crash causation (in collaboration with other projects)
g) A method to combine sensor data with manual annotation based on video to extract the relative speed and distance on oncoming vehicles (master thesis).(Meng & Wang, 2016)

5.1 Delivery to FFI-goals

The project results have provided important results in several different dimensions of the FFI-goals, including:

• Collaboration between industry and academia has been strengthened, as well as between Autoliv and VCC – especially with respect to test-track test methods
• Understanding of driver comfort zone boundaries have enhanced the competence in driver behavior in everyday driving that is highly relevant both for industry and academia, as well as the development and evaluation of different levels of vehicle automation.
• Increased knowledge on driver behaviors though intersection in general (both in normal inactions as well as in critical situations) that provide a foundation for further development of in-vehicle systems, as well as for future research on intersection safety addressing the Vision Zero.
• The increased knowledge has also contributed to strengthening Sweden's role as a leader in traffic safety in general.
• In addition to methods developed and interpretation of results, key results include actual distributions of data and their relationship for use in development.
• Publications have furthered science (one journal article published, one journal article in preparation, one published conference article, one conference article submitted for publication, one conference article in preparation, and three master thesis reports)

Dissemination and publications

6.1 Knowledge and results dissemination

The project results may have an accelerated dissemination in the future work on developing consumer test methods for crossing scenarios in Euro NCAP. Knowledge dissemination will also be done via parallel FFI projects, as QUADRAE (driver modeling) and the A-Team (test method development).

6.2 Publications

Bardinet de Horna, P., & Secondo, F. (2014). *Evaluation of driver models for left turn across path manoeuvres.* (Masters thesis), Chalmers University of Technology, Göteborg, Sweden.

Boda, C.-n., & Cantillo, J. C. (2013). *Field assessment of driver decision making at intersections: A real-time wireless application to manipulate encroachment time.* (Master thesis), Chalmers University of Technology.

Bärgman, J. (2017a). The development and application of a novel metric for analysis of visual attention-selection in left turn across path / opposite direction (LTAP/ID) scenarios. *In preparation for submission to peer-reviewed conference*

Bärgman, J. (2017b). Quantifying drivers' comfort-zone and dread-zone boundaries in stands-still and moving-with-lead-vehicle LTAP/OD and moving. *In preparation for submission to scientific journal*

Bärgman, J., Smith, K., & Werneke, J. (2015). Quantifying drivers' comfort-zone and dread-zone boundaries in left turn across path/opposite direction (LTAP/OD) scenarios. *Transportation Research Part F: Traffic Psychology and Behaviour. 35*, 170-184. doi:10.1016/j.trf.2015.10.003

Bärgman, J., Werneke, J., & Smith, K. (2013). *A method for extracting data for quantification of comfort zone boundaries for intersection.* Paper presented at the 3rd International Conference on Driver Distraction & Inattention, Göteborg.

Engström, J., Werneke, J., Bärgman, J., Nguyen, N., & Cook, B. (2013). Analysis of the role of inattention in road crashes based on naturalistic on-board safety monitoring data. *Proceedings of the 3rd International Conference on Driver Distraction & Inattention.* Göteborg, Sweden. Retrieved from http://document.chalmers.se/download?docid=f3644f5c-4f33-45bb-ad19-88c7e5538a8b

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Mehler, B., Reimer, B., & Dusek, J. A. (2011). *MIT AgeLab Delayed Digit Recall Task (n-back).* Massachusetts Institute of Technology - Agelab. Cambridge, MA.

Meng, L., & Wang, Y. (2016). *Tool development and quantitative analysis for naturalistic Left Turn Across Path/Opposite direction (LTAP/OD) driving scenarios.* (Masters thesis), Chalmers University of Technology, Göteborg, Sweden. (ISSN 1652-8557).

Nobukawa, K. (2011). *A model based approach to the analysis of intersection conflicts and collision avoidance systems.* (PhD Thesis), The University of Michigan, Mechanical Engineering, Ann Arbor, MI. Retrieved from http://hdl.handle.net/2027.42/89791

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Conclusions and future research

The DCBIN project aimed to quantify driver comfort zone boundaries in left-turn across path / opposite direction (LTAP/OD) situations for the turning driver. The project has produced a set of such quantifications for different driving contexts. The project has also studied speed and decelerations during interaction between drivers in LTAP/OD negotiations as well as critical situations. Several tools and methods to study driver behavior have been developed. The DCBIN project has provided data and analysis results from four new test-track studies, analysis of the euroFOT and SHRP2 naturalistic driving studies, and a small on-road study.

Results show that drivers' behavior vary dependent on driving contexts – information that are used and will be used in the development of information, warning and intervention systems in future ADAS systems but also in future Autonomous Driving systems by VCC and Autoliv.The understanding of driver behavior in LTAP/OD interactions has been greatly increased for the three partners VCC, Volvo and Chalmers, both when considering system development and safety research.

Future research could expand the LTAP/OD crash scenario to other intersection crash scenarios in order to provide input to the development of safety products in industry. In addition, analysis of commercially collected naturalistic driving data could provide detailed insight into drivers behaviors in critical intersection situations (see https://www.youtube.com/watch?v=O9ch3DCBac0 and Engström, Werneke, Bärgman, Nguyen, and Cook (2013)) and further strengthen both research and industry towards the Vision Zero. Finally, automated vehicles will eventually take the leap to negotiate intersections. The work from DCBIN will help in this transition, but further analysis of comfort zones and accepted safety margins by drivers and occupants are likely needed.

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Participating parties and contact person

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