ADVANCED DRIVING SIMULATORS AS A TOOL IN EARLY DEVELOPMENT PHASES OF NEW ACTIVE SAFETY FUNCTIONS

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ABSTRACT

This paper presents a platform for flexible hardware- and model-in-the-loop integration of driver assistance systems in a driving simulator environment. The new platform combines the capabilities of a full-scale vehicle electrical systems test environment with the driver interaction evaluation capabilities of an advanced driving simulator. This enables faster development cycles for driver assistance systems by allowing easy transition between simulation configurations used in the development process (e.g. Software-in-the-Loop and Hardware-in-the-Loop) and, crucially, includes the driving simulator as a key part in all stages of the process. The presented integrated test environment enables easy and fast adaptation to include different driver assistance systems of varying degrees of development maturity and functional integration in an advanced driving simulator. Generic interfaces guarantee flexibility and the architecture enables scalability of the development environment for new functions, ranging from desktop simulation to advanced driving simulators. In this integrated test facility even complex interactive full system tests of potential dangerous scenarios can be easily repeated. As an example a test scenario for a system with autonomous steer intervention will be presented and discussed.

Keywords: modelling and simulation, active safety system

INTRODUCTION

Most active safety functions have until now been developed and produced more or less as stand-alone add-on systems. However, the trend is that these systems will become standard. As the number of advanced support systems increases interaction between different modules becomes crucial. To achieve high performance interaction and to reduce on-board weight & cost, it can be expected that active safety functions in the future will have a much closer integration with the existing electric architecture of the vehicle. Thus the complexity of functions, hardware and electrical architecture in future vehicles will increase.

One way of accommodating this increased complexity without losing development time is to introduce rapid prototyping capability combined with functional simulations over the electrical architecture of new driver assistance systems in early development phases. This can be cost-efficiently achieved by utilizing an advanced driving simulator that incorporates a real vehicle's electrical architecture as well as modules which allow for integration of prototypical safety functions.

The first part of the paper describes in detail the different components and overall features of the integrated test environment. The main features will be summarised and put into the context of existing systems. The second part focuses on a proof-of-concept test-case. Thus a prototypic active safety function will be described as well as the developed test scenario, which is an important part of the test procedure for active safety systems which interfere with the driver's vehicle control tasks. Finally, the results are concluded and an outlook on planned activities is provided.

INTEGRATED TEST ENVIRONMENT

An approach for easy and fast hardware- and software-in-the-loop integration into a driving simulator environment is described in the following. The presented architecture enables faster development cycles for active safety systems and establishes a simulator platform for evaluation of driver-system-interactions. The integrated test environment is shown in Figure 1.

The three main components of this platform are the "Model-in the Loop (MIL) and Hardware-in-the-Loop (HIL) simulator for vehicles (Mozart)", explained in Nilsson (2009) and developed by Volvo Cars, a new research driving simulator (called Sim IV) built and operated by the Swedish National Road and Transport Research Institute, VTI (Jansson, 2008), and an original Volvo XC60 modified in order to fit onto the simulator platform of Sim IV. All three components will be described in detail within the following sections.

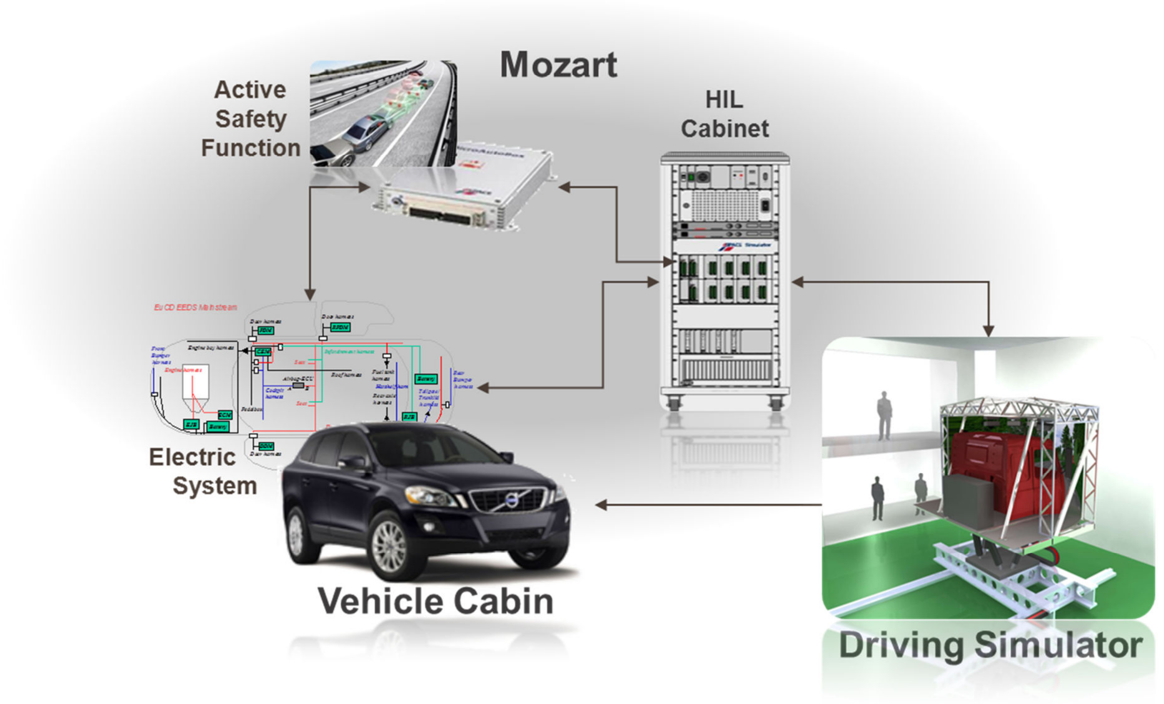

Figure 1 Integrated test environment for active safety functions utilizing an advanced driving simulator and the Mozart simulator.

The MIL and HIL simulator Mozart

The purpose of the Mozart simulator is to perform functional simulations over the controllers and other components that make up the vehicle electrical architecture. The electrical system, not being constant during the development, is characterised by the current maturity of its various components, which in different phases can be represented by models, software, hardware or any combination thereof.

To allow for functional simulation and integration of a system consisting of components of mixed maturity the Mozart simulator can for any specific controller be set up to either interface a hardware controller component (for example a production ECU or a rapid control prototyping system) or to incorporate the software or model representation of controllers and replicating its interfaces to other components in the network. This ability is essential to avoid having to hold off all integration testing until the very last component is finished.

In addition, most controllers require sensor stimuli in order to provide correct unit and system functionality. For this purpose the Mozart simulator contains plant models as well as sensor and actuator interfacing electronics that can generate any signal required by the electrical system, it being hardwired sensor signals, logical signals or replacement (bridging) signals. This setup is similar to the standard MIL/HIL simulation techniques widely used in automotive control system development, but is in Mozart extended to include the whole network of controllers and including their interaction with the environment, e.g. allowing for vehicle-to-vehicle and vehicle-to-infrastructure simulations.

In the scenario demonstrated in this paper a “new” control unit with driver assistance functionality is added to a rather mature system of vehicle controllers. Since production hardware for this component does not yet exist the functionality is implemented on a rapid control prototyping (RCP) unit which interfaces with the rest of the vehicle’s control system in the same way as the production unit. The sensor stimuli, e.g. inputs from camera and radar, which are required by the driver assistance system, are provided by the Mozart simulator which interfaces the RCP unit via so called virtual sensors.

The remaining electrical system of the vehicle consists for the most part of production level hardware control units. In a similar manner to the RCP unit, sensor stimuli which are needed by the different controllers in order to provide correct system functionality are provided via virtual sensor interfaces to the Mozart simulator (e.g. vehicle speed and yaw rate). One exception to the hardware control unit implementation is the engine controller. Since the actual engine is missing from the test object, both the engine controller and the necessary plant models are implemented as virtual components in the Mozart simulator.

In integrating Mozart with the driving simulator it is clear that the two environments share a lot of components. One example of this is the interpretation of driver acceleration and braking commands, which in a typical driving simulator is determined by a generic propulsion model, but in the Mozart simulator is determined by the vehicle’s actual control units and detailed plant models. Thus, one of the challenges in the set-up is to coordinate not only the electrical/logical integration of the prototype system, but also the integration of the plant models, reading and feeding the electrical system with required data, integration with the environment simulation of the driving simulator. Different testing scenarios will require different levels of fidelity from the Mozart system and in order to allow for flexibility and scalability of the test environment this integration issue is addressed by defining a set of standardised interfaces between the Mozart simulator and the driving simulator. This allows the integrated system to be run with different levels of electrical system complexity depending on the purpose of the specific test scenario.

The simulator vehicle cabin

The vehicle cabin which is used in the simulator is a Volvo XC60. Although it was cut slightly behind the front seats and wheels as well as engine and some other mechanical components where removed, the biggest part of the electrical system remained intact.

It is equipped with a LCD-display instead of the normal instrument panel. The display is chosen to fit perfectly into the original place of the normal panel. There are several benefits by using a programmable display since it gives the possibility to easily change the contents that are shown to the driver. Using a display also eases the integration of the cabin into the simulator environment since display of unwanted error signals can be avoided. Side and rear-view mirrors are also replaced by small LCD screens.

The sound system consists of a 6.1 surround system: two speakers at the front, two at the sides and two from the back plus a subwoofer. Additionally the original speakers of the car are used. This provides the opportunity to present directed sounds, e.g. from passing vehicles or warning sounds which shall be presented from a certain direction.

A force-feedback steering-wheel enables control over feedback torque to the driver. A realistic tyre-to-road torque feedback is essential for the drivers ability to control the car and thus to use a similar steer strategy as in reality. Further, simulated steering wheel vibrations can communicate important information about the current vehicle speed.

In order to introduce road and engine speed dependent vibrations into the chassis of the simulator vehicle cabin, low frequency audio transducers (so called shaker) have been attached to the cabin floor. Based on amplified audio signals, vibrations up to 200 Hz can be excited.

The advanced driving simulator Sim IV

VTI's simulator Sim IV is a moving base driving simulator with interchangeable cabins, located at VTI, Gothenburg, Sweden. The motion system, delivered by Bosch-Rexroth, combines the possibilities of a hexapod motion base with the extended motion envelope in x- and y-direction through a 5x5 m sled-system. Sim IV is in operation since May 2011.

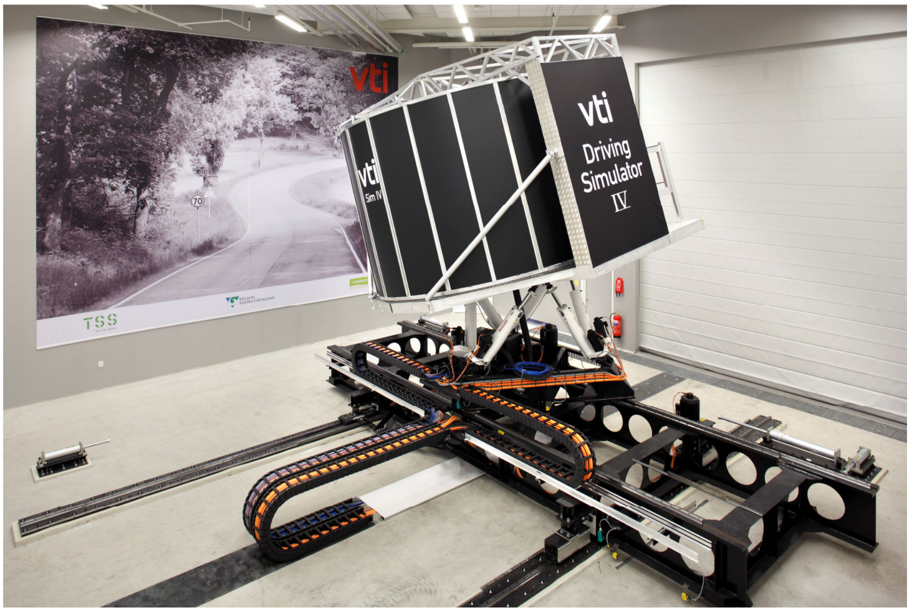

Figure 2 VTI Sim IV

9 Epson EB-410W projectors with a resolution of 1280x800 pixels each projects the image on a cylindrical screen with a diameter which varies between 1.8 (to the left) and 3.1 m (to the right) and a height of 2.5 m. The field of view is approximately 190×50 degrees. Automated edge blending and geometrical correction is provided by a state of the art system. The simulator also features rearward views through displays incorporated into the rear-view mirrors (right, left and centre).

The moving base is used to generate forces felt by the driver while driving. It consists of two parts a XY-table providing large stroke linear motion in two directions and a hexapod providing 6-DOF motion capabilities within the stroke of the actuators. The tables below show the performance of both motion systems.

Table 1 Hexapod performance

	Excursions	Velocity	Accelerations
Surge	-408 / +307 mm	+/- 0.80 m/s	+/- 6.5 m/s^2
Sway	-318 / +318 mm	+/- 0.80 m/s	+/- 6.0 m/s^2
Heave	-261 / +240 mm	+/- 0.60 m/s	+/- 6.0 m/s^2
Roll	-16.5 / +16.5 deg	+/- 40 deg/s	+/- 300 deg/s^2
Pitch	-15.5 / +16.0 deg	+/- 40 deg/s	+/- 300 deg/s^2
Yaw	-20.5 / +20.5 deg	+/- 50 deg/s	+/- 300 deg/s^2

Table 2 Sled system performance

	Excursions	Velocity	Accelerations
Surge	+/- 2.5 m	+/- 2 m/s	+/- 5 m/s^2
Sway	+/- 2.3 m	+/- 3 m/s	+/- 5 m/s^2

Sim IV is the only VTI simulator to provide large stroke linear motion in both the longitudinal and lateral direction simultaneously. The hexapod is used in the roll and pitch direction to simulate long term accelerations such as driving in a curve or longitudinal acceleration and deceleration.

The method for calculating how to present vehicle accelerations with a motion system to the driver is called motion cueing. The strategy which is used in Sim IV is extensively described and discussed in Fischer (2010). A major principle which all motion cueing implementations for VTI simulators follow is to couple the movements of the lateral sled system directly to the vehicle's position on the road.

Only a few advanced driving simulators with comparable systems currently exist (about 10-15 worldwide). Among them the two simulators with the biggest motion envelope: the NADS (Schwarz et al., 2003) and Toyota driving simulators (Challen, 2008), and a couple of simulators with similar motion envelopes, as the Leeds (Jamson, 2007) or the Ultimate simulator (Dagdelen et al., 2004). The simulator with the best performance characteristics is probably the new Daimler simulator which was taken into operation in 2010 (Zeeb, 2010).

The integrated system

In the integrated test environment, the Mozart simulator interfaces the existing electrical system of the vehicle mock-up and emulates any missing control units (e.g. the engine control). The driving simulator provides all necessary information about the environment (e.g. distance to other vehicles or the edge of the road) which usually would be provided by in-vehicle sensors. The interface is kept generic in order to guarantee utmost flexibility for the integration of new functions or even a replacement of the whole electrical architecture.

The integrated test environment extends the technical verification capabilities of the Mozart simulator into both early concept function evaluation and late system validation; areas which traditionally requires in-vehicle tests. While not being a full substitute for these types of testing it complements them by enabling testing which is both easily repeatable and safe. The integration as presented in this paper truly support shortened lead times by allowing these activities to be performed in parallel to the system development, with quick turnaround times. This is especially true when a model based design approach is used for the system development.

A general advantage of performing functional test in simulated environments compared to tests on the road is the repeatability of scenarios, which ensure comparability between different parameter settings, function designs or various test drivers. Even potential dangerous situations can be tested in a simulator without any harm to the driver or the car. This becomes more and more important as the focus of new safety functions slowly shifts from passive safety to active safety and thus the system activation moves closer to a possible crash event (i.e. crash avoidance instead of crash mitigation). A further trend in safety function development is to take over the vehicle control partly or completely which leads to increased interaction between the driver and the vehicle functions. It is thus valuable to have an indication of possible problems connected to this human-machine interaction already in early development phases. This can be realised more easy and cost-effective in a driving simulator.

Furthermore, scalability is an important feature for the usability of the test environment. That is to provide integration and interfacing options for new functionality without placing strong requirements on applicable hardware or software solutions for the development tools. This enables the developer to integrate the test facility into the regular development process already in in early development phases. Hence, erroneous design or misleading features of the new function can be detected much earlier which saves both time and money within the product development.

Both types of simulation environments, HIL simulators and advanced driving simulators, are more and more commonly used throughout the last decade: HIL simulators with a focus on hardware testing of vehicle components (e.g. Shidore et al., 2007) or vehicle control systems (e.g. Svenson et al., 2009), and driving simulators mostly in the area of driver behaviour research (Nilsson, 1993). A growing area where both types of simulators are used is research and development on driver assistance applications (Deng Lee and Annie Zhao, 2008 or Maruyama et al., 2011 for HIL simulation and Fors et al., 2010, Tomillo et al., 2008 or Simon, 2005 for driving simulation). Though, the combination of a HIL simulation and an advanced driving simulator is still unique. This makes the presented approach very interesting for future investigations of new applications with complex interactions between the human driver and vehicle safety or comfort functions.

ACTIVE SAFETY TESTING

The functionality of the integrated test facility is explained in the following by the example of an emergency lane keeping assistance system (eLKA). This next generation assistance system actively intervenes in the drivers steering control task when there is risk of a frontal collision Fischer (2011). To setup and tune this system correctly, exploration of driver-system-interactions is crucial and the opportunity to do that in early development phases saves time in the overall development process. Further, the usage of the described integrated test facility enables easily repeatable full system tests of potentially dangerous scenarios. To find a suitable test scenario in such an interactive set-up is a challenge itself. The wish to have the scenario as natural as possible, i.e. at the same time surprising for the driver and representative of situations where the system would intervene sets a lot of different requirements for the scenario design. A test scenario for a system with autonomous steer intervention will be presented and discussed.

Before going into these details however, it is important to point out that actively intervening systems have not been often studied in driving simulators, with the exception of ESC (e.g. Brown et al, 2009). Instead, driving simulator studies evaluating new driver assistance systems have typically focused on warning and information systems, where the driver is meant to act on certain information given. Examples of such studies include (Curry et al., 2009; Engström et al., 2010; Hoffman et al., 2006; Marshall et al., 2007), to name a few. In this study though, the assistance system is autonomous. The key research question is therefore not whether drivers act on information given, but rather to what extent they also try to do avoidance manoeuvres, and the effect such interference with the intervening system's actions has on situation outcome. This is essentially a new field of study within the evaluation of driver assistance systems.

Lane keeping assistance

In the following different types of lane keeping assistance (LKA) systems are shortly described. The terminology is based on how the different applications are specified at Volvo Cars. Currently, there are three different systems which interact with the driver regarding lateral vehicle control:

- Lane departure warning (LDW)
- Safety lane keeping assistance (sLKA)
- Emergency lane keeping assistance (eLKA)

The LDW assistant warns the driver both visually and acoustically when the car is accidently running over lane markings (i.e. without setting indicators). This system is already in production since 2008.

The sLKA corrects the current steering wheel angle in order to straighten up the car when the vehicle is about to leave the lane unintentionally, and, if this is not enough to catch the drivers attention, it vibrates the steering wheel while crossing the lane markings. Though, it never applies huge steer angles or fast steer interventions. This system is in a later development phase but not yet available on the market.

Additionally to information about lane markings, the eLKA takes as well radar- and video-based sensor information about other traffic participants into account. The eLKA is designed to handle a situation where a driver inadvertently is drifting into an adjacent lane, and there is a possibility for a collision with a vehicle in that lane. If this situation occurs, the system provides an active steering intervention to steer the host vehicle back into the original travel lane under requisite conditions, including the condition that a clear path exists in the original travel lane. The steer characteristic can be smooth (similar to the sLKA characteristic) or evasive, depending on assessed danger. Among the three listed systems, the eLKA is the one with the lowest level of maturity. This system is still in a conceptual phase and thus it was chosen as an example for early development test of prototype systems in a driving simulator environment. The given test scenario focuses on functional requirements of the eLKA only.

Test scenario set-up

Given current sensor limits and the dynamic restraints on eLKA activation (particularly for lateral accelerations), an initial assumption is that eLKA would have to start to intervene at approximately 2-3 seconds prior to a head-on collision during the traffic environment and speed conditions described below. In terms of road environment, eLKA requires two things:

- lines both to the left and to the right for the lane tracking camera to determine lane departure
- Straight road, or a curve with a radius of minimum 250 meters (~800 ft.), for the eLKA algorithm to work properly

In terms of a driving scenario to test the function in, the eLKA requirements and relevant crash statistics dictates that the scenario should start from normal driving on non-divided highways and rural roads with speeds at about 70 kph/45 mph or higher. The scenario selected for implementation therefore places the driver in a rural road driving situation with a 70 kph speed limit, with daylight conditions, no precipitation (dry surface), and a moderate density of ambient traffic (2-3 vehicles / minute) travelling in the opposite direction to the Subject Vehicle (SV). Subjects will be instructed to maintain the posted speed limit, but as this is difficult for some drivers in a driving simulator, a speed limiter was implemented with the maximum speed set to 80 kph to prevent excess speed.

In order to create a relevant eLKA situation, the drivers will from time to time be distracted by means of a visual task that consists of reading numbers from a screen placed at a relative large down angle (40-45 degrees). Each number is displayed for 0.3 seconds, with 0.2 seconds of blank screen in between numbers, creating a total task duration of 2.8 s. The task will re-occur approximately every 30 seconds during the drive, and to motivate drivers to complete the task, they will be told that their responses are checked for correctness. 15-20 minutes into the driving session, the main test scenario is then triggered by “pouring” the vehicle across the median towards an oncoming vehicle by introducing a steering angle in the simulated vehicle without presenting the corresponding lateral acceleration with the motion system. This is done in parallel to the distraction task, so the driver will not notice anything out of the ordinary until s/he looks up from the numbers display. This method for introducing inadvertent lane departures was first used and explained in Kozak et al. (2006), and is described in more detail in Blommer et al. (2006).

The proposed driving scenario is illustrated in Figure 3. The SV initially travels in the right lane at speed v_1, paced by the driver (instructed to be 70 km/h). Ideal sensors without malfunctions or misleading signals are assumed for this scenario set-up.

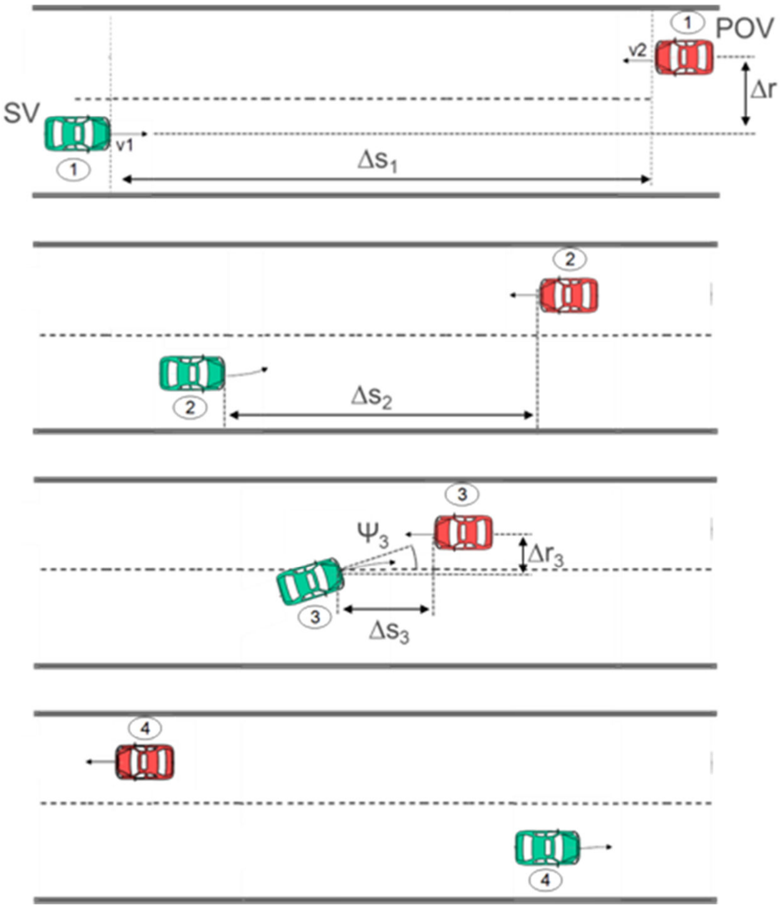

Figure 3 Course of the driving scenario for an eLKA intervention

1. At scenario initiation at t_1, a Principal Other Vehicle (POV) is instantiated at a distance of approximately 600 m from the SV in the opposite lane (if there is a vehicle in front of the POV in its direction of travel, the time gap to that vehicle should be at least 20 seconds (at posted speed limit). The POV begins to travel towards the SV with a speed that is coupled to the SV speed so their combined relative speed becomes $v_{relative}$. Until they reach t_3, the POV speed should be continously adjusted to maintain $v_{relative}$ in the face of any SV speed changes. In a similar way, the lateral position of the POV should be coupled to SV's lateral position such that their relative lateral distance remains exactly equal to the lanewidth.

2. At t_2, when SV and POV have a distance Δs_{start}, a visual distraction task as described above is initiated to make the driver visually distracted from the forward roadway for at least 2.8 seconds. At the same time, the yaw deviation necessary to move the SV across the median is initiated, such that heading angle, as well as relative lateral and longitudinal distances between SV and POV, will be the same at t_3 for all repetitions of the scenario. As the chosen distraction task last

for approximately 3 seconds, the yaw deviation function must bring the vehicle within that time into the desired position.

To be able to fulfil this requirement, the SV vehicle speed should be locked to its current speed at t_2. Based on the calculated lateral deviation Δr_D of the SV the lateral position of the POV is slowly changed from its lateral position at t_2 to a defined critical lateral distance Δr_{crit} at t_3.
The yaw deviation should be set so that the SV reaches the critical lateral distance Δr_{crit} relative to the POV with a heading angle of $\Psi_{SV,crit} = 5$ degrees at t_3, calculated to equal the point where the sensor detection area is reached and an eLKA intervention could take place. This point should be set so the intervention will avoid a collision with very small margin at a maximum lateral acceleration of lat_{max}.

3. As described, the heading angle, as well as relative lateral and longitudinal distances between SV and POV, will be the same at t_3 for all repetitions of the scenario. However, absolute later position and speed of the SV can vary, because the driver shall have full control over the SV before reaching t_2. After reaching the desired critical situation at t_3 the POV speed and lateral position is decoupled from SV, i.e. set to be constant from that time onwards. Depending on the current mode of the assistance function (off, Warning only, eLKA only, or warning + eLKA) the warning takes place and/or the eLKA intervention begins.

4. The driver reaction to the dangerous situation and, if applied, to system intervention can be observed. Subsequent, the SV continuous its travel and the scenario can be repeated in another road section, though without the same moment of surprise.

In order to execute the described scenario and thus to trigger the active safety system correctly, a lot of requirements have to be fulfilled. The signals from lane and radar sensors have to contain correct, realistic information about the virtual environment, drivers have to be successfully distracted and finally the visual, acoustic, haptic and vestibular feedbacks have to closely resemble the real experience in order to trigger realistic driver reactions to the system intervention. That means that all involved feedback systems (i.e. graphics, sound system, force-feedback steering-wheel and the motion system) need to have appropriate performance characteristics.

In terms of driver response measures, a key issue when testing a steering intervention is to understand the way in which drivers interact with the intervention. A wide range of driver responses (i.e. from no response to violent avoidance steering) can be expected. Key dependent test variables therefore include drivers steering response magnitudes, durations and onset times. As these are measured through drivers input to the steering wheel, it follows that one must have a way of separating the driver's and the function's steering torque input in the data logging.

CONCLUSIONS

A new concept of active safety test environment combining an advanced driving simulator with a vehicle level MIL and HIL simulator has been developed. The goal of the integrated simulation platform is to provide a testing environment for advanced driving assistance systems closely integrated in the vehicle electrical architecture. The concept is evaluated for a prototype driver assistance system – emergency lane keeping assistance – which is characterized by having close system-driver interaction and functionality distributed over several vehicle control units, implemented in production ECUs, as well as RCP units and MIL controllers. Thus, the proof-of-concept is demonstrated.

Summarising, the key features of the integrated test environment are:

- Standardised interfaces between the driving simulator and Mozart allows for flexibility in connecting different vehicle electrical architectures and systems
- Flexibility in allocation and complexity of the models and controllers allows for scalability of driving simulator testing, from a “simple” driver interaction system where generic vehicle models are used to testing with a full vehicle electrical system with detailed plant models
- Combination of two proven test platforms in order to include model-, software-, hardware- and driver-in-the-loop interaction evaluation in a realistic, safe and repeatable environment
- Easy integration and evaluation of new driver assistance systems at any stage of the development process
- Fully repeatable system tests in potential dangerous driving situation can be applied
- Eased test preparation: The focus can be on the driving scenario development as all system functionality is in place via the Mozart simulator

Following steps will be the practical validation of facility performance when doing extensive simulator experiments for function evaluation, further simplification of the integration process and comprehensive tests with various active safety functions. Among others, a study is planned for the fall of 2011, where potential differences in driver response given different function implementations will be studied. In particular, the study will assess whether the driver-function interaction increases or decreases if a visual-auditory warning is presented at the same time as the intervention starts, compared to doing the intervention only. Another possible improvement is the adaptation of the integrated test facility to a modular simulation architecture called SimArch (Vinter, 2010), developed within a recently finished national research project. This would enhance a couple of existing features even more, e. g. the scalability of simulation set-up and standardization of interfaces.

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