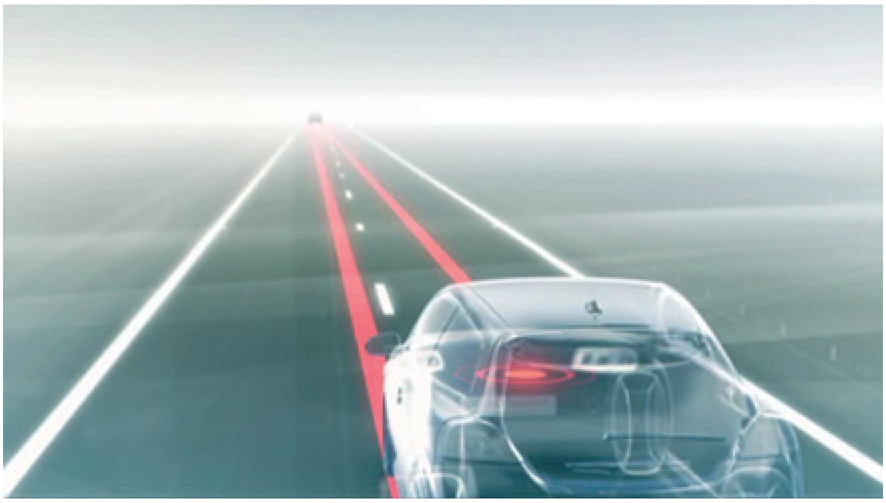
SPASS

Strengthen Performance Active Safety Simulator



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Preface

The *SPASS – Strengthen Performance Active Safety Simulator* project was initiated by Volvo Car Corporation (VCC) and has been performed as a close collaboration between VCC and the Swedish National Road and Transport Research Institute (VTI) within the competence centre *ViP Driving Simulation Centre* (www.vipsimulation.se).

SPASS was financed by the ViP centre, i.e. by ViP partners and the Swedish Governmental Agency for Innovation Systems (Vinnova). However, a part of the scenario development was carried out within the Quadra project, which is a project within the Swedish Strategic Vehicle Research and Innovation program (FFI).

The work described in this report comprised development of a conceptual test environment integrating a model-in-the-loop and hardware-in-the-loop simulator, an advanced driving simulator and a standard vehicle cabin. A case study was performed where the new test environment was utilized to evaluate an active safety system (an intervening emergency lane keeping assistance system, eLKA). Design of the test scenario, and realization of the eLKA function and the performance of the simulator car were key tasks in the study. The test environment was demonstrated to experts in the field who also assessed its capabilities as a tool for evaluating active safety systems.

Participants from VTI were Martin Fischer (project manager, now at Deutsches Zentrum für Luft- und Raumfahrt, DLR), Håkan Sehammar, Anders Andersson, Jonas Jansson, Anne Bolling, Fredrik Bruzelius and Bruno Augusto.

Participants from VCC were Mikael Ljung Aust, Martin Nilsson, Jonas Ekström, Urban Kristiansson, Annica Normén, Nenad Lazic and Kristoffer Mohn Lem.

Stefan Pettersson and Henrik Weiefors from Viktoriainstitutet participated in the project as consultants to VCC.

Gothenburg, July 2012

Martin Fischer

Quality review

Peer review was performed on 7 November 2012 by Jonny Vinter, SP. Mikael Ljung Aust has made alterations to the final manuscript of the report. The ViP Director Lena Nilsson examined and approved the report for publication on 27 December 2016.

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Abbreviations

DOF	Degrees of freedom
ECU	Engine control unit
eLKA	Emergency lane keeping assistance
ESC	Electronic stability control
HIL	Hardware-in-the-loop
LDW	Lane departure warning
LKA	Lane keeping assistance
MIL	Model-in-the-loop
POV	Principal other vehicle
RCP	Rapid control prototyping
SIL	Software-in-the-loop
Sim IV	VTI's advanced driving simulator in Gothenburg
sLKA	Safety lane keeping assistance
SV	Subject vehicle
VCC	Volvo Car Corporation
VTI	Swedish National Road and Transport Research Institute

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SPASS - Strengthen Performance Active Safety Simulator

by Martin Fischer[1], Mikael Ljung Aust[2], Håkan Sehammar[1], Martin Nilsson[2] and Mats Petersson[2]

[1]Swedish National Road and Transport Research Institute (VTI), [2]Volvo Car Corporation (VCC)

Executive summary

The aim of the SPASS project was to evaluate early development/rapid prototyping of new driver assistance systems by utilizing an advanced driving simulator in combination with a vehicle electrical architecture (including sensors, actuators and HMI). As a case study, the project demonstrated a novel active safety function which was rather well penetrated at Volvo Car Corporation (VCC), i.e. VCC had reference vehicles up and running.

The project used VTI's advanced driving simulator (Sim IV) in Gothenburg to establish a simulator platform for evaluation of driver-system interaction. The objective was to understand the capability of Sim IV when studying active safety functions requiring interaction between road infrastructure, sensors, electrical architecture, actuators and Human-Machine Interaction, and to understand how useful Sim IV is during the ordinary concept development phase at vehicle manufacturers.

Warning systems that act when the driver is on the way to unintentionally leave the lane are already available today. The next generation of systems will not only warn the driver but will actively contribute to the steering task. One such system is VCC's eLKA (emergency lane keeping assistance). As part of the SPASS project a scenario which lead to triggering of the eLKA function was developed and tested. The scenario consisted of rural road driving where drivers were distracted by means of a visual distraction task (reading numbers from a screen, placed at a relative large down angle relative to the view of the forward roadway) and then poured across the median towards an oncoming vehicle by introducing an additional steering angle in the simulated vehicle.

An integrated test environment for active safety functions has been developed and evaluated. VCC's emergency lane keeping assistance system (eLKA) has been used as test case in the evaluation, and the functioning of the eLKA has been validated and approved by experts at VCC.

Key features of the new integrated test environment are:

- Standardised interfaces between the driving simulator and the MIL and HIL vehicle simulator (Mozart), allowing flexibility in connecting different vehicle electrical architectures and systems.
- Flexibility in allocation and complexity of the models and controllers, allowing 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 evaluation of model-, software-, hardware- and driver-in-the-loop interaction in a realistic, safe and repeatable test environment.
- Easy integration and evaluation of new driver assistance systems at any stage of the development process.
- Possibility to apply fully repeatable system tests in potentially dangerous driving situations.
- Simplified test preparation, focusing on the driving scenario development as all system functionality is in place via the MIL and HIL simulator (Mozart).

1. Introduction

Warning systems that act when the driver is on the way to unintentionally leave the lane are already available today. The next generation systems will not only warn the driver but will actively contribute to the steering task. One such system is VCC's eLKA (emergency lane keeping assistance). The eLKA is designed to handle situations where a driver inadvertently is drifting into an adjacent lane, and there is a possibility of colliding with a vehicle in that lane. If this situation occurs and requisite conditions are fulfilled, including that a safe path exists in the original travel lane, the system provides an active steering intervention to move the host vehicle back into the original travel lane. The system relies on an on-board camera to detect the position of the host vehicle with respect to the road lane markings, and on a millimetre-wave radar to detect other vehicles in adjacent lanes (both oncoming and those being overtaken). The eLKA function is currently under development and will be tested in a simulated environment.

A scenario which will lead to the triggering of the eLKA function is rural road driving where drivers are distracted by means of a visual distraction task (reading numbers from a screen placed at a relative large down angle) and then "poured" across the median towards an oncoming vehicle by introducing an additional steering angle in the simulated vehicle. Such a scenario will be developed and tested in the SPASS project.

So far, most new active safety functions have been "productified" more or less as stand-alone add-on systems. This drives on-board cost and weight, and as a consequence the introduction of new functions (especially those requiring sensor data fusion) is delayed. A deeper integration of active safety functions into the electrical architecture may reduce time to market.

As most active safety functions until now have been developed and produced more or less as stand-alone add-on systems, the take rates are low. However, the trend is that these systems will become standard and thus become available to all drivers. 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 and cost, it can be expected that active safety functions will be more closely integrated with the existing electrical architecture of the vehicle in the future. Therefore, the complexity of functions, hardware and electrical architecture in future vehicles will increase.

Furthermore, new active safety functions during the next decade will strive to "be active earlier", i.e. warn and/or intervene at larger margins to imminent conflicts, compared to today's systems. The intention is to increase the interaction with the driver in due time before a potential collision. This interaction becomes more and more time critical during the journey from ordinary driving to a potential collision.

Thus, the complexity of active safety functions will increase significantly during the next decade. One way of accommodating this increased complexity, without losing development time, is to introduce rapid prototyping capability combined with functional simulations of 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.

With SPASS, the objective was to understand the capability of VTI's advanced driving simulator Sim IV for studying active safety functions requiring interaction between road infrastructure, sensors, electrical architecture, actuators and Human-Machine-Interaction. The objective was also to understand how useful Sim IV is during the ordinary concept development phase at vehicle manufacturers.

The first part of this report describes in detail the different components and overall features of the integrated test environment. The key features are summarised and put into the context of existing systems. The second part focuses on the proof-of-concept test-case. Thus, a prototypic active safety function is described as well as the developed test scenario. The scenario is an important part of the test procedure for active safety systems that interfere with the driver’s vehicle control tasks. Finally, the results are concluded.

2. Integrated test environment

An approach for easy and fast hardware-in-the-loop (HIL) and software-in-the-loop (SIL) 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)", developed by VCC and presented in Nilsson (2009).
- The new advanced research driving simulator (Sim IV), built and operated by VTI (Jansson, 2010).
- A standard Volvo XC60 vehicle cabin, modified in order to fit onto the simulator platform of Sim IV.

All three components are described in detail in the following sections.

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

2.1. The MIL and HIL simulator Mozart

The purpose of the Mozart simulator is to perform functional simulations of the controllers and other components that make up the vehicle's electrical architecture. The electrical system, not being constant during the development, is characterised by the current maturity of its various components, which in different development 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 engine control unit (ECU) or a rapid control prototyping (RCP) system), or to incorporate the software or model representation of controllers, and replicate its interfaces to other components in the network. This ability is essential to enable continuous 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. This set-up is similar to the standard MIL/HIL simulation techniques widely used in automotive control system development. But in Mozart the set-up is extended to include the whole network of controllers including their interaction with the environment, for example 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 RCP unit which interfaces with the rest of the vehicle’s control system in the same way as the production unit. The sensor stimuli, for example 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 an analogous manner to the RCP unit, sensor stimuli (for example vehicle speed and yaw rate), which are needed by the different controllers to provide correct system functionality, are provided via virtual sensor interfaces to the Mozart simulator. One exception to the hardware control unit implementation is the engine controller. Since the actual engine is missing for the test object, both the engine controller and the necessary plant models are implemented as virtual components in the Mozart simulator.

When 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. In a typical driving simulator these commands are determined by a generic propulsion model. In the Mozart simulator they are determined by the vehicle’s actual control units and detailed plant models. Thus, a challenge 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, the reading and feeding the electrical system with required data and the integration with the environment simulation of the driving simulator. Different testing scenarios will require different levels of fidelity of 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.

2.2. The simulator vehicle cabin

The vehicle cabin which was used in the simulator was from a Volvo XC60 (Figure 2). Although it was cut slightly behind the front seats, and wheels as well as engine and some other mechanical components were removed, the major part of the electrical system remained intact.

The vehicle cabin was equipped with an LCD display instead of the normal XC60 instrument panel. The display was chosen to fit perfectly into the original place of the normal panel. There are several benefits of using a programmable display since it gives the possibility to easily change the content of the information that is shown to the driver. Using a display also eases the integration of the cabin into the simulator environment since presentation of unwanted error signals can be avoided. Side-view and rear-view mirrors were also replaced by small LCD screens.

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

A force-feedback steering wheel was mounted and enabled feedback torque to the driver. A realistic tyre-to-road torque feedback is essential for the driver's ability to control the car and thus to use a similar steering strategy as in real driving. 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 shakers, Figure 2) were attached to the cabin floor. Based on amplified audio signals, vibrations up to 200 Hz could be excited.

Figure 2. XC60 vehicle cabin.

2.3. The advanced driving simulator Sim IV

VTI's simulator Sim IV[1] (Figure 3) is an advanced moving base driving simulator with inter-changeable cabins, located at VTI in 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 directions through a 5x5 m sled system. Sim IV is in operation since May 2011.

Nine Epson EB-410W projectors, with a resolution of 1280x800 pixels each, project the image (driving environment) on a cylindrical screen. The screen diameter varies between 1.8 m (to the left) and 3.1 m (to the right) and has 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).

[1] https://www.vti.se/en/research-areas/vtis-driving-simulators/

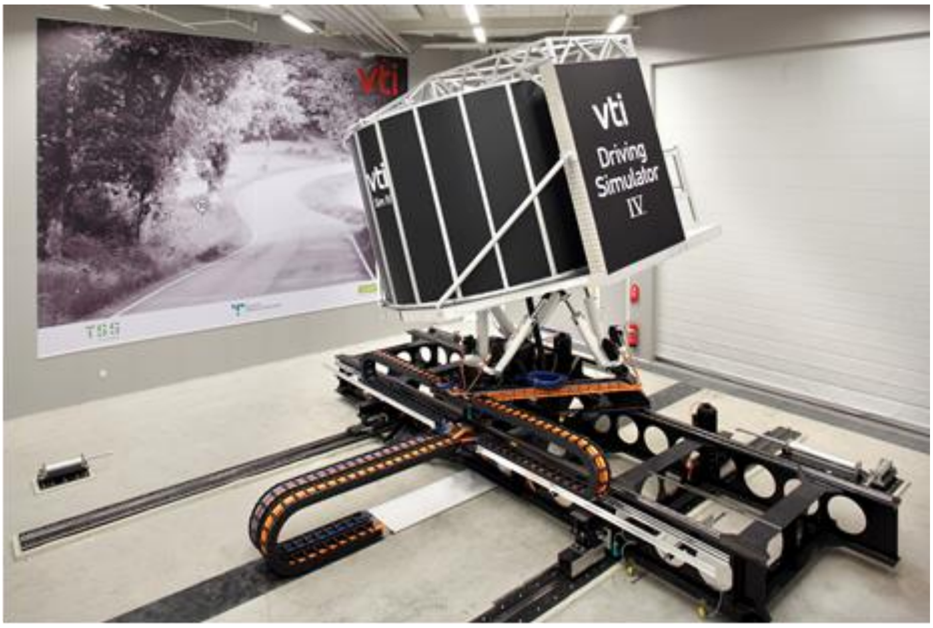

Figure 3. VTI Sim IV. (Photo: VTI/Hejdlösa Bilder).

The moving base is used to generate forces felt by the driver while driving. It consists of two parts: an XY-table providing large stroke linear motion in two directions and a hexapod providing 6-DOF motion capabilities within the stroke of the actuators. Table 1 and Table 2 show the performance of the two 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 directions to simulate long term accelerations such as driving in a curve or longitudinal acceleration and deceleration. The method used in Sim IV, for calculating how to present vehicle accelerations to the driver with a motion system, is called motion cueing. The strategy, which is used in Sim IV, is extensively described and discussed in Fischer et al. (2010). A major principle that all motion cueing implementations in VTI's simulators follow is to couple the movements of the lateral sled system directly to the vehicle's position on the road.

Currently, only a few advanced driving simulators with comparable systems exist (about 10-15 worldwide). Among them the two simulators with the biggest motion envelope are the National Advanced Driving Simulator (NADS) at the University of Iowa (Schwarz et al., 2003) and the Toyota driving simulators (Challen, 2008). Two simulators with similar motion envelopes are the University of Leeds Driving Simulator (UoLDS) (Jamson, 2007) and the Ultimate simulator at Renault (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).

2.4. The integrated test environment

In the integrated test environment (see also Figure 1), the Mozart simulator interfaces the existing electrical system of the vehicle mock-up and emulates any missing control units (for example the engine control). The driving simulator provides all necessary information about the environment, for example distance to other vehicles or the edge of the road, which usually would be provided by in-vehicle sensors. The interface is kept generic 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 require 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 report truly supports shortened lead times by allowing these activities to be performed in parallel to the system development, with quick turnaround times.

A general advantage of performing functional tests in simulated environments compared to performing them on the road is the repeatability of scenarios, which ensures 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 easily 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 early development phases. Hence, erroneous design or misleading features of a 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 past decade. HIL simulators with a focus on hardware testing of vehicle components (see for example Shidore et al., 2007) or vehicle control systems (see for example Svenson et al., 2009), and driving simulators mostly in the field of driving behaviour research (Nilsson, 1993). A growing area where both types of simulators are used is research and development on driver assistance applications, see Deng et al. (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 HIL simulation and advanced driving simulation is still unique, which 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.

3. Testing of active safety systems

The functionality of the integrated test environment 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 driver’s steering control task when there is risk of a frontal collision (Fischer, 2011). To set up 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 environment 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 performing autonomous steering intervention will be presented and discussed.

However, before going into these details it is important to point out that actively intervening systems have not been studied in driving simulators very often, with the exception of electronic stability control (ESC) (see for example 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 expected to act on given specific information. Examples of such studies include Curry et al. (2009), Engström et al. (2010), Hoffman et al. (2006) and Marshall et al. (2007).

In this study though, the assistance system is autonomous and intervening. Therefore, the key research question is not whether drivers act on given information, but rather to what extent they also try to do avoidance manoeuvres and what effect such interference with the intervening system’s action has on a situation outcome. This is essentially a new field of study within the evaluation of driver assistance systems.

3.1. 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 VCC. 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 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 to straighten up the car when the vehicle is about to leave the lane unintentionally and, if this is not enough to catch the driver’s attention, it vibrates the steering wheel while crossing the lane markings. This system is available on the market, for example in Volvo V40.

In addition to information about lane markings, the eLKA also takes radar-based 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, given that there are no obstacles in the original travel lane. The steering intervention can be anywhere between mild (like the sLKA) and quite forceful, depending on the threat assessment.

LDW, sLKA and eLKA have now all been released on the market. While at the time when this study was performed eLKA was still in a conceptual phase and was therefore chosen as an example for early development testing of a prototype system in our integrated test environment. The developed and used test scenario focuses on functional requirements of the eLKA only.

3.2. Lane keeping test scenario set-up

Given current sensor limits and the dynamic restraints on eLKA activation (particularly for lateral accelerations), an initial assumption was 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 departures.
- 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 eLKA function, the eLKA requirements and relevant crash statistics dictate that the scenario should start from normal driving on non-divided highways and rural roads with speeds at about 70 km/h or higher. Therefore, the scenario selected for implementation places the driver in a rural road driving situation with the conditions 90 km/h speed limit, daylight, no precipitation (i.e. 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.

3.2.1. The eLKA test scenario

The scenario is described using the coordinate systems displayed in Figure 4. The vehicle's accelerations and rotation velocities are given in a body-fixed coordinate system (x, y, Ψ) and the position of the vehicle on the road is described in a road-related coordinate system (r, s).

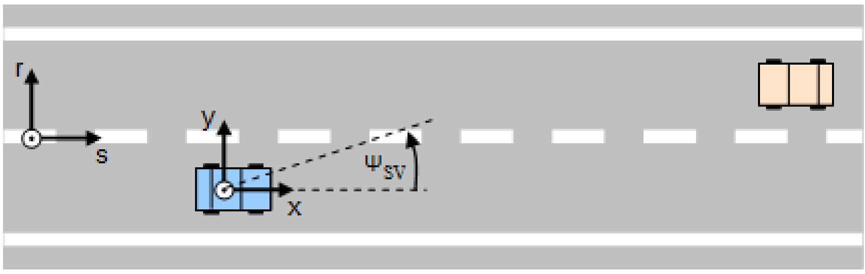

Figure 4. Coordinate systems used to describe the eLKA test scenario.

The driving scenario is illustrated in Figure 5, and the parameters used in each step of the scenario are described in Table 3. The subject vehicle (SV) initially travels in the right lane at a speed v_1 paced by the driver (and instructed to be 90 km/h).

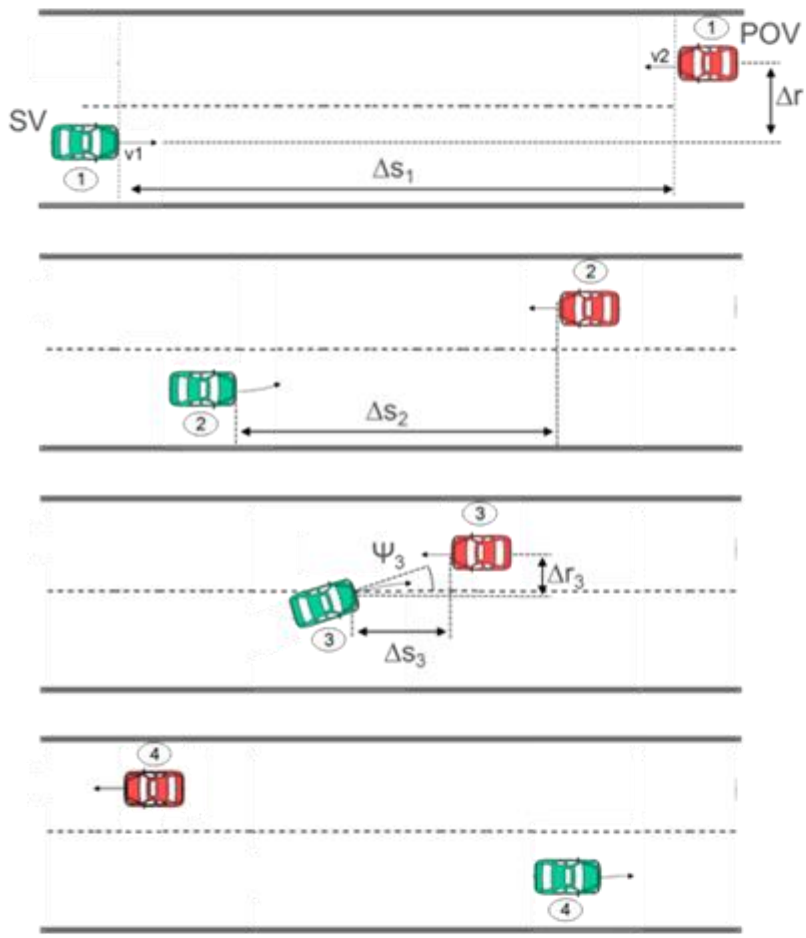

Figure 5. Course of the driving scenario for an eLKA intervention.

1. At scenario initiation at t_1, a principal other vehicle (POV) is instantiated at a distance of approximately 660 m (Δs_1) 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 speed of the SV so their combined relative speed becomes $v_{relative}$. Until they reach t_3, the POV speed is continuously adjusted to maintain $v_{relative}$ in the face of any changes in the SV speed. The lateral position of the POV stays at a constant distance from the middle line ($r_{pov,init}$).

2. At t_2, when there are 5 seconds (= $t_{start\_distraction}$) left before the critical distance between the two vehicles is reached, a visual distraction task (described in the following section) is initiated to make the driver visually distracted from the forward roadway for at least 2.8 seconds. The distraction task is first announced which takes about 2 seconds. After additional 0.5 seconds, when the driver should have started the distraction task, the yaw deviation necessary to move the SV across the median is initiated. The aim is to always trigger the eLKA intervention at similar lateral and longitudinal distances between SV and POV at t_3 (when d_{crit} is reached) for all repetitions of the scenario. To be able to fulfil this requirement, the speed of SV should be locked to its current speed at t_2. The yaw deviation function should be tuned such that the SV reaches the critical lateral distance Δr_{crit} at the specified critical longitudinal distance Δs_{crit}, which shall be within the sensor detection area and trigger an eLKA intervention.

3. After reaching the desired critical situation at t_3 the POV speed is 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. Ideal sensors without malfunctions or misleading signals are assumed for this scenario set-up.

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

To execute the described scenario, and thus to trigger the active safety system correctly, a lot of requirements must be fulfilled. The signals from lane and radar sensors have to contain correct and 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 real experiences in order to trigger realistic driver reactions to the system intervention. That means that all involved feedback systems (i.e. the graphics, sound system, force-feedback steering wheel and motion system) need to have appropriate performance characteristics (see Figure 7).

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 (from no response at all to violent avoidance steering) can be expected. Key dependent test variables therefore include magnitudes, durations and onset times of the driver's steering response. As these variables are measured through the driver's 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.

Table 3. Parameter specifications for the flow of events leading up to the intervention.

Parameter	Value
$v_{SV,x}$	Self-paced, but constrained between t_2 and t_3 to the speed reached at t_2
v_{rel}	180 km/h = 50 m/s
$\Delta s_{crit}\,(t_3)$	110 m (≤ 165 m sensor range!)
$t_{start\_distraction}$	5 s
$\Delta s_2\,(t_2)$	360 m = $\Delta s_{crit}\,(t_3) + t_{start\_distraction} \cdot v_{rel}$
$r_{pov,init}$	1.5 m
$r_{eLKA,trigger}$	0.8 m (distance to centre line threshold for an eLKA intervention)
Δr_{crit}	2.3 m = $r_{pov,init} + r_{eLKA,trigger}$
$T_{distract}$	5 s
$T_{yaw\_deviation}$	2.5 s

Variations of the Δs_{crit} and Δr_{crit} parameters turned out to be very effective in making the scenario more or less dangerous (from the driver's perspective).

3.2.2. Distraction task and yaw deviation function

To create the described eLKA situation the drivers were, from time to time, distracted by means of a visual task that consisted of reading numbers from a screen placed at a relative large down angle (see Figure 6). The task made the drivers visually distracted from the forward roadway. The drivers were prompted by a pre-recorded voice to read back a sequence of 6 numbers (randomised single digits between 1 and 9) appearing on the display. This took about 2 seconds. During the distraction task, each number was displayed for 0.3 seconds with 0.2 seconds of blank screen between numbers, creating a total task duration of 2.8 seconds. To motivate the drivers to complete the task they were told that their responses would be checked for correctness. The visual distraction task occurred on average once every 30 seconds of the driving, but always on straight road sections.

Figure 6. Position of the display presenting the visual distraction task (note that the picture is from another simulator than Sim IV). (Photo: Mikael Ljung Aust).

Ten to fifteen minutes into the driving session the main test scenario was triggered by "pouring" the vehicle across the median towards an oncoming vehicle. The pouring manoeuvre was done by introducing a steering angle in the simulated vehicle (Figure 5) in parallel to the distraction task. The steering angle was introduced without presenting a corresponding lateral acceleration in the motion system. Thus, the driver should not notice anything out of the ordinary until s/he looked up from the distraction task display. This method for introducing inadvertent lane departures was first used and explained by Kozak et al. (2006), and is described in more detail in Blommer et al. (2006).

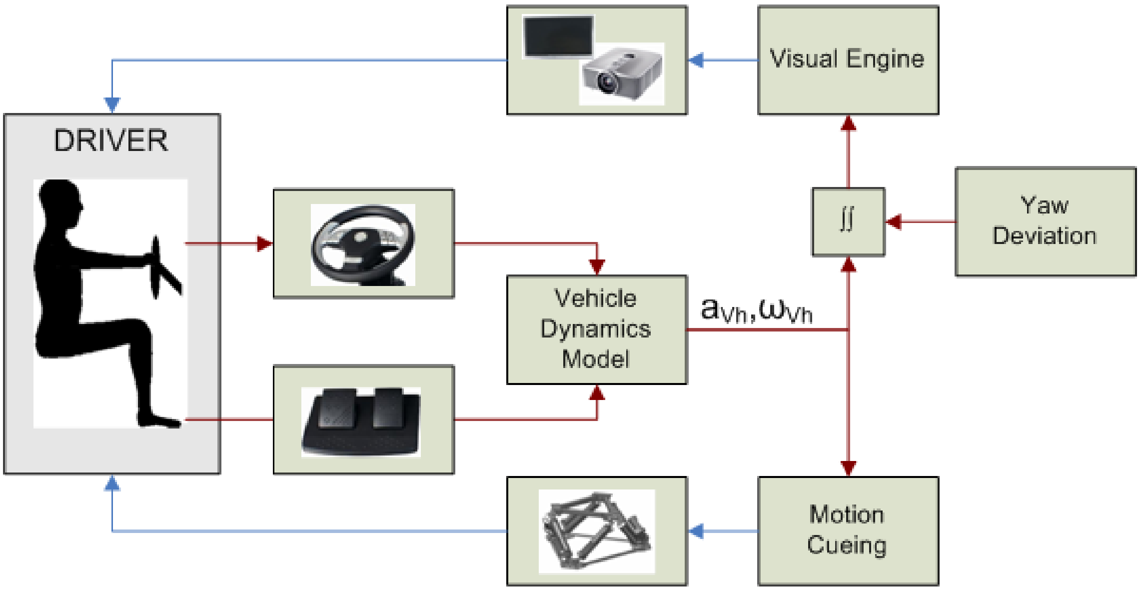

Figure 7. Driving feedback loop with interfering yaw deviation function.

As the chosen distraction task lasts for approximately 2.8 seconds, the yaw deviation function must bring the vehicle in a position close to the middle line within that time, reaching the heading angle $\Psi_{SV,\ crit}$.

The used yaw deviation function was calculated based on the sine-square function proposed by Blommer et al. (2006) with an additional term which takes into consideration the initial heading of the vehicle $\Psi_{SV,0}$:

$$\psi_{deviation}(t) = -\psi_{SV,0} \cdot \frac{t}{T_{\text{yaw\_deviaton}}} + \psi_{SV,crit} \cdot \sin^2\left(\frac{t}{T_{\text{yaw\_deviaton}}} \cdot \frac{\pi}{2}\right)$$

The lateral deviation can be calculated by

$$\Delta r_D = \int_{t2}^{t3} v_{SV,x}(t_2) \cdot \sin(\psi_{deviation}(t) + \psi_{SV,0})\, dt + r_{SV,0}$$

Before the event was triggered the drivers were free to choose their driving speed which results in varying initial lateral positions, initial headings and driving speeds. Those initial conditions can be taken into account when starting the event. However, with the aim to create the critical situation with a given critical lateral and longitudinal distance to the POV (see section above) either the duration of the deviation function $T_{yaw\_deviation}$ or the final heading $\Psi_{SV,\ crit}$ can be kept constant for every run, but not both parameters. Intensive testing showed that varying duration lead to larger perceivable differences in the events than varying heading angles. Thus, a constant duration of 2.5 seconds was chosen (see Table 3) and the critical heading angle was calculated using the following equation:

$$\psi_{SV,crit} = \frac{dr_0 - dr_{crit}}{p_{reg} \cdot v_{SV,x}(t_2) \cdot T_{dev}} \qquad \text{with } p_{reg} = 0.0087$$

where p_{reg} is a regression function parameter taking the influence of the initial speed into account.

As the distraction lasts for just about 3 seconds the yaw deviation function must be performed within this time, compared to 5 seconds in the original version by Blommer et al. (2006). Thus, the lateral acceleration caused by the function can reach higher values than those proposed in the original design (0.25 m/s^2). This has implications for the design of the motion cueing feedback during the distraction task. The chosen approach is described in the following section.

3.2.3. Motion cueing during distraction task

General motion cueing is described in detail in Fischer et al. (2010). For the presentation of the lateral acceleration the position of the car on the road is usually related to the position along the linear sled in lateral direction. During the testing of eLKA it became clear that this approach was not well applicable in combination with the chosen scenario. Due to the yaw deviation function, the car changes its position on the road while the driver is occupied with the distraction task. The change in lateral road position led to a movement of the sled system which could be noticed by the driver and led to steering interventions by the driver before the critical situation was reached. Even a counter-movement by the hexapod system could not mask the sled movement sufficiently.

Hence, a more classical frequency-split approach was used even for the lateral acceleration feedback. As the driving did not include demanding slalom or fast lane change manoeuvres, the frequency-split approach worked as fine as the road-related algorithm, with the advantage that it was not reacting to the yaw deviation function with any motion feedback.

3.3. SPASS demonstration activities

The SPASS demonstration activity was performed in the integrated test environment as described in section 2.

3.3.1. Validation

The key aspect addressed in the performed demonstration activity was to ensure a realistic eLKA intervention. The algorithm used was implemented on a D-space box (see section 2) and was provided by the eLKA developers. Nevertheless, appropriate functioning of the eLKA had to be ascertained. As the function had never been tested in a real vehicle before, a real reference was lacking. However, engineers involved in the development of eLKA were testing the design scenario and acknowledged that the steering intervention was according to the desired behaviour of their function.

3.3.2. Demonstration

When all technical details had been sorted out, the final step of the project was to demonstrate the implementation to a number of key people at VCC. “Key” is here used in the sense that simulator-based prototype evaluation might be, or become, part of the daily work that these people are leading and supervising. The demonstration activity was jointly hosted by VCC and VTI. Nineteen VCC employees participated in the activity, normally two at a time. The demonstration schedule is depicted in Figure 8.

Schedule Guest 1		**Schedule Guest 2**	
Introduktion			
Sim IV	SPASS demo	***VCC***	Tool Chain
	General demo		Function Development
VCC	Tool Chain	***Sim IV***	SPASS demo
	Function Development		General demo
Summary / Feedback / Discussion			

Figure 8. One hour demonstration activity schedule for two participants at a time.

During the introductory session, the project outline and the main project goals were described and the ViP competence centre was presented.

The possibilities and advantages gained by integrating Sim IV into VCC’s tool chain were explained and the future role of advanced driving simulators in the function development process was discussed during the VCC session.

The Sim IV session took place in the simulator and included a presentation of the project results and a general demonstration of the simulator’s capabilities. In the first part the participants were told to drive as they do in real traffic, not knowing that the designed eLKA event was to be triggered during their driving session. After the first unexpected event the nature of the scenario was revealed to the participants and they could experience the same event a few more times, now knowing what would happen to them. In the final part, the presentations and the demonstration were concluded and a brief discussion took place to get a first feedback.

The overall feedback from those participating in the demonstration activity was positive, with some more or less detailed suggestions for important improvements of the simulation environment (for example concerning steering feedback and vibration feedback). The ideas and improvement demands were summarised in the framework of a separate workshop, listing future initiatives concerning for example driving experience, common environment description, modularity and scalability of the software, distributed simulation, and sensor integration.

4. Conclusions

In the SPASS project 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 test environment for advanced driver assistance systems closely integrated in the vehicle electrical architecture. The concept was evaluated using a prototype driver assistance system, emergency lane keeping assistance (eLKA). The eLKA function is characterized by having a 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 was demonstrated.

In summary, the key features of the integrated test environment are:

- Standardised interfaces between the driving simulator and the MIL and HIL vehicle simulator (Mozart), allowing flexibility in connecting different vehicle electrical architectures and systems.
- Flexibility in allocation and complexity of the models and controllers, allowing 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 evaluation of model-, software-, hardware- and driver-in-the-loop interaction in a realistic, safe and repeatable test environment.
- Easy integration and evaluation of new driver assistance systems at any stage of the development process.
- Possibility to apply fully repeatable system tests in potential dangerous driving situations.
- Simplified test preparation, focusing on the driving scenario development as all system functionality is in place via the MIL and HIL simulator (Mozart).

Future work 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.

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Appendix A - Dissemination of results from the SPASS project

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ViP

Driving Simulation Centre

ViP is a joint initiative for development and application of driving simulator methodology with a focus on the interaction between humans and technology (driver and vehicle and/or traffic environment). ViP aims at unifying the extended but distributed Swedish competence in the field of transport related real-time simulation by building and using a common simulator platform for extended co-operation, competence development and knowledge transfer. Thereby strengthen Swedish competitiveness and support prospective and efficient (costs, lead times) innovation and product development by enabling to explore and assess future vehicle and infrastructure solutions already today.

Centre of Excellence at VTI funded by Vinnova and ViP partners

VTI, Scania, Volvo Trucks, Volvo Cars, Swedish Transport Administration, Dynagraph, Empir, HiQ, SmartEye, Swedish Road Marking Association

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