Vehicle in the Loop (VIL) –
A new simulator set-up for testing Advanced Driving Assistance Systems

Dipl.-Ing. Thomas Bock, Dr.-Ing. Markus Maurer, Prof. Dr.-Ing. Georg Färber

Thomas Bock, Audi AG, 85045 Ingolstadt

Dr. Markus Maurer, Audi AG, 85045 Ingolstadt

Prof. Georg Färber, Lehrstuhl für Realzeit-Computersysteme, Technische Universität München, Arcisstraße 21, 80290 München

Abstract

The Vehicle in the Loop test setup has been developed for the safe, reproducible and resources-saving test of driver assistance functions for support in critical traffic situations. This setup combines the advantages of driving simulators and a real test vehicle by incorporating it into a traffic simulation. While driving, the synthetic outside traffic is visualized to the driver realistically by means of an optical see through Head Mounted Display. Thanks to the Vehicle in the Loop test setup, motion sickness is avoided.

With the help of sensor models, driver assistance functions can react to synthetic outside traffic already in an early phase of development, and the function can thus be tested realistically and without danger for humans and machine.

Introduction

Systems to improve driver safety provide an essential criterion for customers when deciding on buying a new car. They become an increasingly important provider of turnover and return in the car industry [1]. While only little progress can still be achieved in the classical field of passive safety at a relatively high cost, there are significantly more potentials in the development of systems for active safety [2].
A current topic of research and development are the autonomous intervening assistance systems for collision avoidance (CA) or collision mitigation (CM). As such systems need to mesh with the driving dynamics of a vehicle partly without an explicit action of the driver very high standards are required regarding functional safety and reliability of the single systems as well as their interaction with already existing vehicle systems.
With the increased complexity of these systems there are new demands on the test and simulation tools which are used in system development until they are ready for production. With the established methods current and future assistance systems can often be tested only within limits or not at all.
The moment for triggering an automatic emergency braking justifiable at the moment lies within a very short time slot immediately before a collision [3]. That is why a reproducible and above all safe test for the test driver of such systems has proved to be very difficult so far.

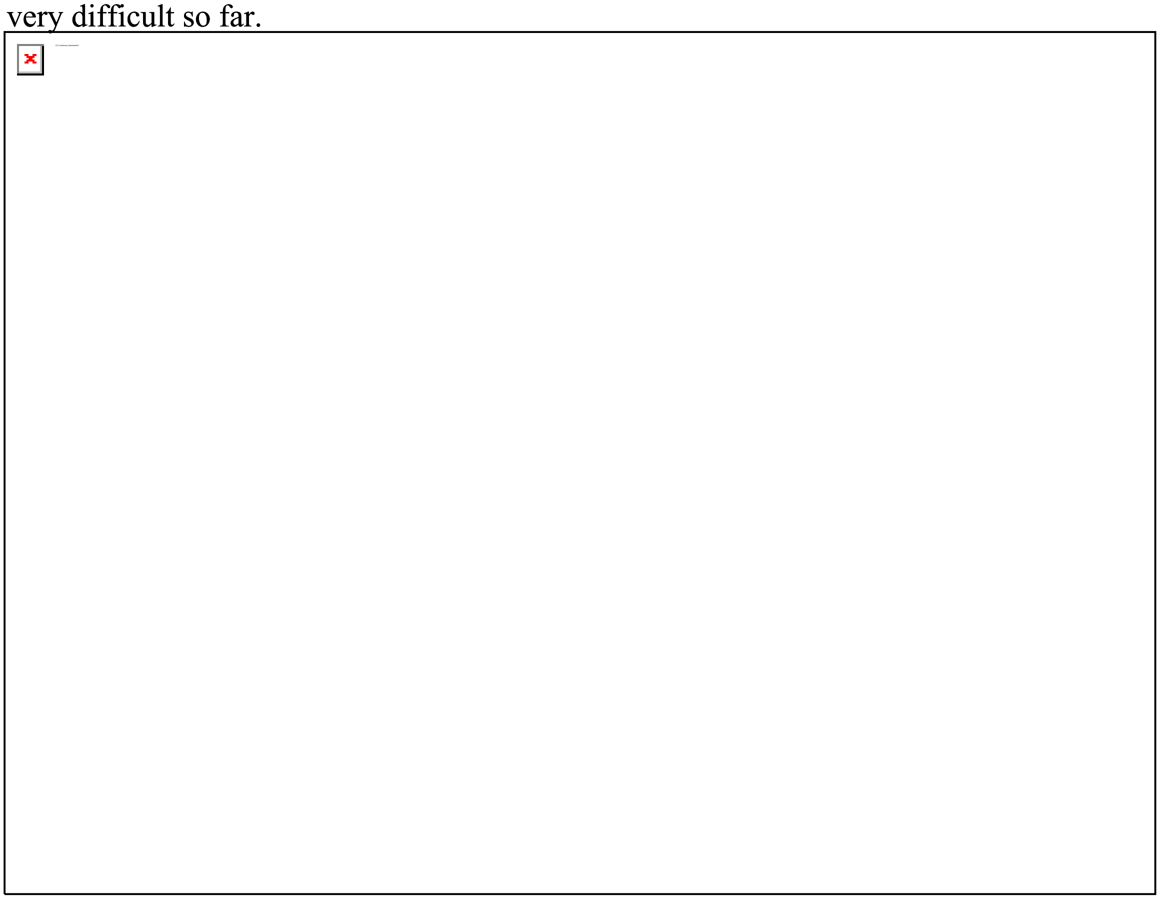

Fig. 1: Development Trends of the ACC to a Collision Mitigation System

State of the Art

Driver assistance systems especially for safety critical situations demand a test in real and/or synthetic traffic.
The current state of the art are driving simulators, traffic flow simulations and test vehicles, which collide with substitutes such as foam cubes. The test tools available at the moment fulfill the demands for a realistic, reproducible, safe and at the same time resources-saving test environment only within limits. A detailed description of current test methods is given in [4].

Vehicle in the Loop

From the test methods for collision mitigation systems discussed here, it is clear that alternatives for testing are needed. Like driving simulators they must offer a test environment that is safe, reproducible and resources -saving. But even complex moving systems are limited in the reproduction of the real dynamics of a vehicle. The idea of the Vehicle in the Loop test setup is therefore to combine the test vehicle with a synthetic test environment, and thus gain the advantages of both methods.

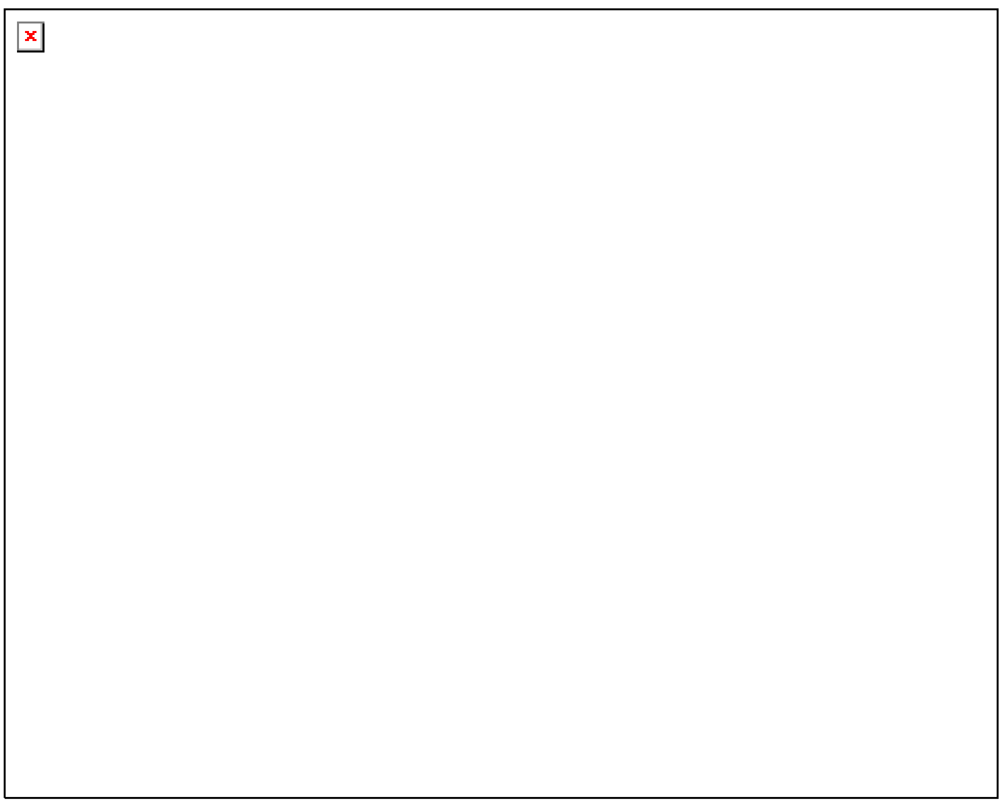

Fig. 2: Vehicle in the Loop – Linking a simulator and a test vehicle
(HMD: Head Mounted Display)

The vehicle in the loop (VIL) configuration facilitates a testing of the function of driver assistance systems directly in a vehicle which however does not move in real traffic, but on open spaces or blocked off roads and resorts to synthetic sensor dates of a partly simulated environment. Special advantages arise with safety assistance systems like an emergency brake function: Because of a virtual vehicle ahead, also triggers of the system that did not occur can be analyzed safely and reproducibly.

Functional Architecture of the Vehicle in the Loop

Fig. 3 shows the functional architecture of the Vehicle in the Loop test setup. The data of the position and orientation of the ego vehicle and the driver's head are transferred to a traffic simulation software online. In addition, the exact course of the road used (here AUDI AG test field) has to be stored in a track library in advance and also be transferred to the traffic simulation software. From the input data the traffic simulation calculates the position and orientation of the ego vehicle on the road used and the position data of the synthetic outside traffic. The traffic situation is visualized to the drivers by means of an optical see through Head Mounted Display depending on their head position and orientation. With the help of sensor models, which receive the position and orientation data of the synthetic traffic and the ego vehicle as input data from the traffic simulation, the input data for the driver assistance system are created. For example, an automatic emergency braking because of a simulated vehicle has effects on the driver-vehicle-environment loop. By reading in new position and situation data of the ego vehicle and the driver's head, the vehicle in the loop is closed.

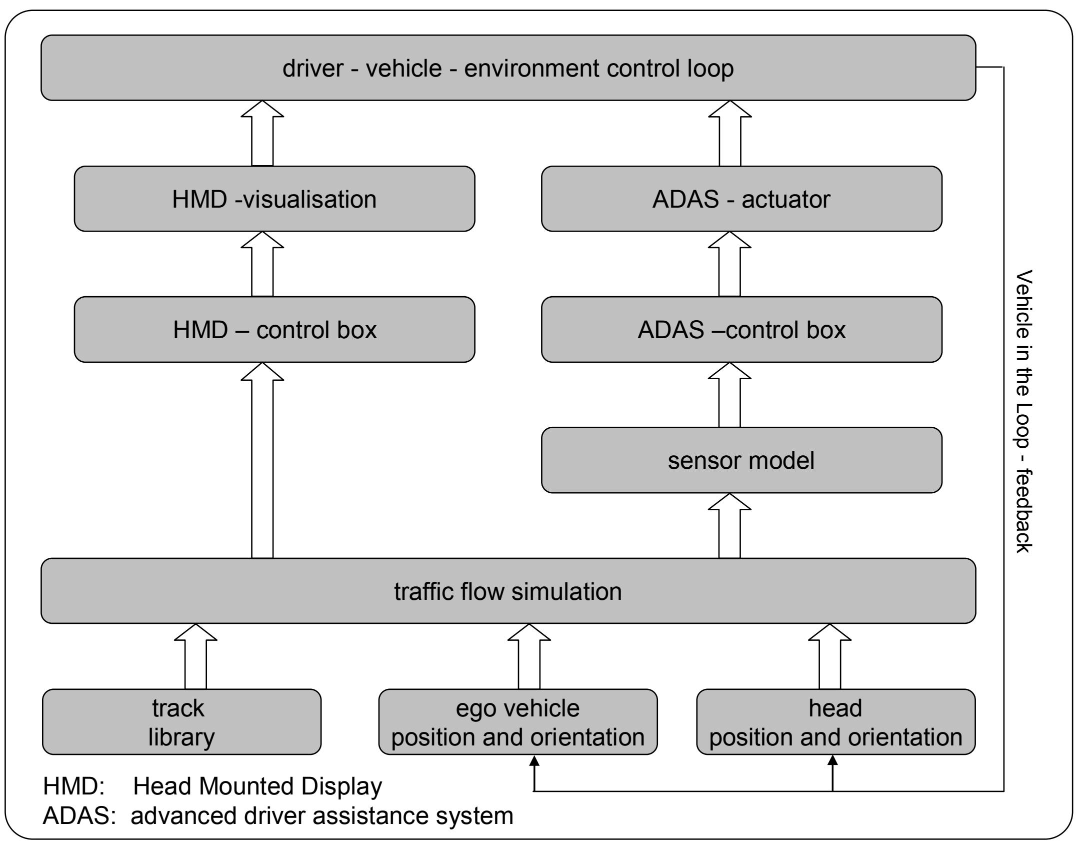

Fig 3: Functional architecture of the Vehicle in the Loop

System architecture/configuration of the vehicle in the loop

The next figure shows the system configuration of the vehicle in the loop test setup. The usage of these parts are described in the following sections.

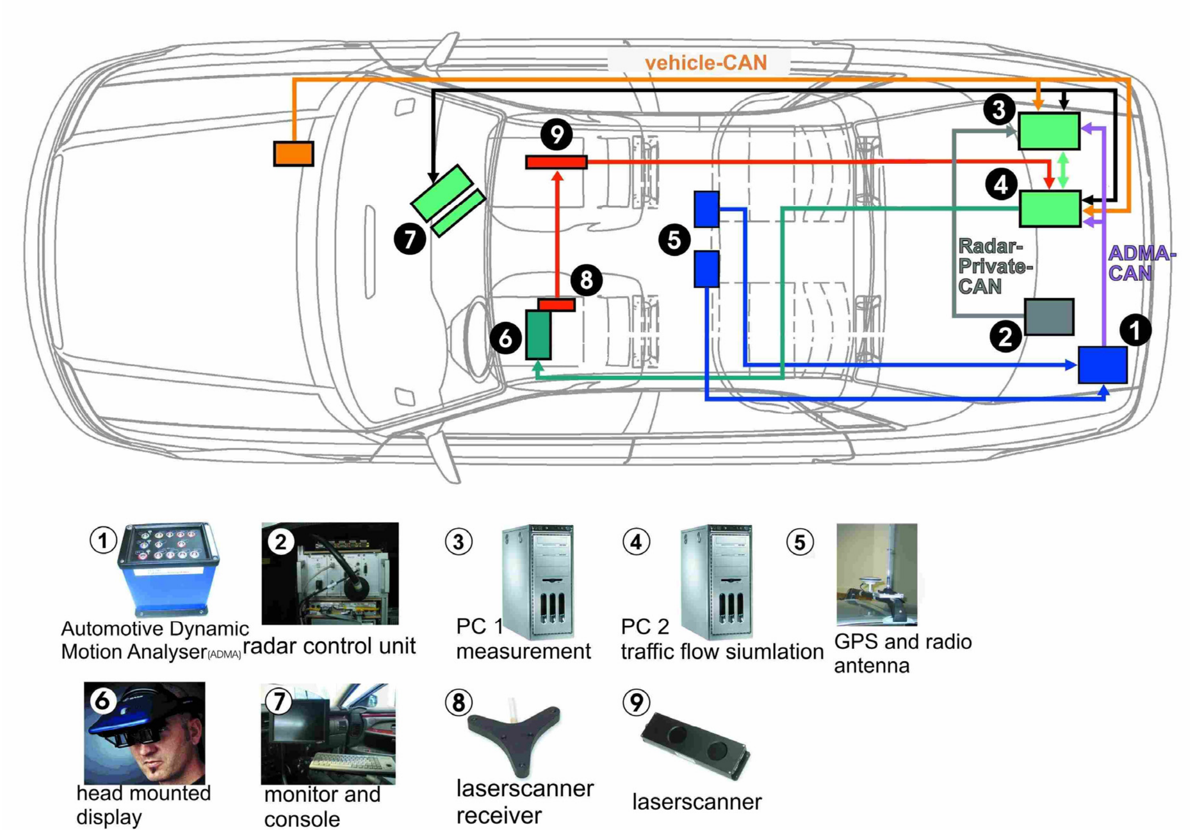

Fig. 4: System architecture of the Vehicle in the Loop

Traffic simulation and visualization

The traffic simulation and visualization of the company Vires Simulationstechnologie GmbH is integrated on a Intel® Pentium® D 3,2 GHz processor PC with a 12V connection in the trunk of the test vehicle (see Figure 4, no. 4). Beforehand, the location coordinates were recorded with DPGS (see Figure 4, no. 1 and 5) and the exact road routing of the Audi AG test field was stored in a data base. For this task, the road description format OpenDRIVE® was used. OpenDRIVE® is a data format to describe the physical road properties and road network for use in driving simulators [5].

The traffic simulation is designed in such a way that it facilitates the creation of reproducible lane change, braking and acceleration maneuvers of the simulated outside traffic. The triggers for these maneuvers can be activated either relatively to other traffic participants (and thus also to the ego vehicle) or by crossing an absolute location position. The synthetic traffic can also move on autonomously, using a model of the longitudinal and lateral dynamics of a normal driver.

Positioning the test vehicle in the traffic simulation

To represent the correct road section in the traffic simulation, the position of the ego vehicle on the AUDI AG test field must be determined exactly. Therefore a high-precise strapped down motion analyzer with a DGPS connection is used (see Figure 4, no. 1 and 5). By additionally comparing the data with DGPS, the exactness of the location determination is increased from approx. ±1m to approx. ±1cm. If either the number of the visible satellites goes down or the radio signal to the ego vehicle for the DGPS correction data breaks off, the position of the ego vehicle is continued to be determined by the high-precise strapped down motion analyzer. All signals on vehicle position and driving states are recorded on a separate CAN Bus and are thus available for the simulation.

Integrating the driver with Augmented Reality

The simulated traffic is visualized with the AddVisor™ 150 optical see through Head Mounted Display (HMD) of SAAB (cf. Figure 5). It is also connected to the simulation processor through a S-Video interface.

The drivers are not able to perceive the complete vehicle environment as it is present in the simulation, but are limited to their own visual field. Thus the visualization has to be limited to this natural visual field which keeps changing with the drivers' head position. Only the corresponding detail of the environment simulation is to be shown in the HMD.

The quality of the Vehicle in the Loop test setup depends decisively on the exact superposition of this real visual field and the corresponding simulated traffic presented to the driver. The essential data on the position and the orientation of the drivers' head are collected by the Head tracker System Laser-BIRD of the Ascension Technology Corporation (cf. Figure 5). The system consists of a laser scanner and a sensor module (see Figure 4, no. 8 and 9). The sensor module is fixed onto the HMD holder which again is placed on the moving drivers' head.

The simulation calculates an eye point from the received data of the Head tracker and the strapped down motion analyzer. Departing from this eye point the traffic scene is visualized in the HMD.

To enable the driver of the ego vehicle to interpret the visualized traffic scene three-dimensionally, the Virtual Image Distance of the HMD was fixed to 10m as monocular clues for depth perception (e.g. relative height in the image, linear perspective representation of the image size, overlap) dominate for larger distances [6]. Also larger distances to the outside traffic can be presented credibly with these clues for depth perception.

Fig. 5: HMD and headtracker integrated at the Vehicle in the Loop

In Figure 6 an Augmented Reality representation is shown, where the test vehicle of the Vehicle in the Loop test setup follows a synthetic vehicle on the AUDI AG test field. To make this photo, a camera filming the scene during the drive was integrated in the HMD.
In addition to the synthetic outside traffic, the synthetic lanes of the track can be seen. The representation of the lanes has been helpful to evaluate the correct positioning and orientation of the test vehicle and driver's head. If the synthetic lanes overlap the real lanes, a correct representation of the entire synthetic scene is granted. In the following development phases the synthetic lanes will no longer be represented as the driver can get his orientation from the real lanes.

Fig. 6: Augmented reality demonstration of the Vehicle in the Loop

Radar Sensor Model

The Vehicle in the Loop test setup is used for the development of driver assistance systems based on environment sensors. Obviously real sensors cannot detect objects of a virtual traffic environment. Therefore sensor models for reproducing the sensor functionality become necessary. In a first step, a radar sensor model is implemented. The behavior of real radar sensors is mapped by reproducing the physical context in a C/C++ software model. To facilitate the independent development of the sensor models from the Vehicle in the Loop test setup, the sensor models and the actual driver assistance functions run on another PC which is also integrated into the trunk of the ego vehicle (see Fig. 4:, no. 3). Both computers are permanently linked via an Ethernet (UDP - User Datagram Protocol) connection. They communicate according to a defined protocol in which, among other things, the position and state data of the simulated outside traffic are transferred from the simulation processor. As the sensor model functions on the basis of ideal outside traffic position data from the traffic simulation, the typical disturbance input and measurement uncertainties of real sensors additionally had to be evaluated statistically and integrated into the sensor model accordingly. Especially the perception range, the x/y deviation and the separation possibility were recorded each for various radar targets (cars, lorries, motor cycles) and modeled on mathematical error equations. As „ground truth“ reference to the radar signals tape measures and a laser distance meter (precision of measurement ±3mm) were used. A detailed deduction of the error functions for cars, lorries and motor cycles is given in [7].

Validation of the Vehicle in the Loop

The traffic simulation in the Vehicle in the Loop test setup includes the simulated outside traffic (cars, lorries, motor cycles) and lane markings. Both simulation objects (vehicles and markings) can be presented and used separately as well as in combination. The remaining objects to be perceived by the driver, e.g. road, houses, horizon etc., are real in the Vehicle in the Loop test setup. Therefore only the perception of the simulated traffic, the lane markings and the interaction of the simulation and the real vehicle dynamics have to be validated. This can be done in a study comparing the driving behavior in real traffic to the driving behavior in simulated traffic and showing possible differences.

It is the object of the validation to check whether the Vehicle in the Loop setup can be used as a tool for development engineers. Many systems supporting longitudinal and lateral guidance (Adaptive Cruise Control, Automatic Emergency Brake, Lane Departure Warning, Lane Change Assist etc.) are based on the interaction with the road traffic. Besides technical measurement data, the driver’s subjective perception plays a decisive part here.

A standard to be set for the Vehicle in the Loop test setup is therefore that the driver perceives the traffic as realistically as possible. The necessary degree of reality is determined, among other things, by the estimation of the distance to the simulated traffic and the perception of relative speeds and accelerations. These standards are checked on the basis of two data sources. One is a questionnaire on the subjective perception of the simulated traffic and the interaction between the simulation and the dynamic properties. Then, new insights can be gained by comparing driver reactions to simulated and real traffic in defined driving maneuvers (traffic situations). For this objective data of both drives (real / simulated traffic) are recorded and compared.

Test setup

To even out the differences in the driving behavior of the test drivers all over the study, it was divided into drives with real and virtual vehicles ahead the differences between a test driver's objective measurement data derived from real and virtual drive were examined.
The test setup for determining the necessary virtual objective data was the vehicle in the loop (cf. chapter III). All objective test parameter of the ego vehicle and the virtual vehicles were recorded by the traffic simulation software.
For the tests with a real vehicle ahead its exact position and objective driving state data needed to be ascertained. For an exact determination of its position, the real vehicle ahead was thus equipped with a DGPS system which was identical to the one in the vehicle in the loop. A WLAN system transferred the vehicle data of the vehicle ahead to the vehicle in the loop car.

Driving maneuvers and test hypotheses

Below all driving maneuvers of the study are listed with a short description (table 1).

Driving maneuver	Description	Recorded Values
A1	Approaching a standing obstacle comfortably from 80 km/h	Distance at braking and standstill, deceleration when approaching comfortably
A2	Approaching a standing obstacle with emergency braking from 80 km/h	Distance at braking and standstill, deceleration when approaching with an emergency braking
B1	Approaching a preceeding vehicle quickly and following it, speed differential 40 km/h	Distance at braking, deceleration and distance of following at a high speed differential
C1	Sudden cutting in, speed differential 30 km/h, distance 40m	Deceleration and time of reaction to a suddenly appearing obstacle
C2	Collision, emergency braking of the vehicle ahead at a distance of about 30m, speed 80 km/h	Deceleration and time of reaction to an emergency braking of the vehicle ahead
D1	Following a vehicle, and the vehicle ahead accelerating from 40 km/h to 70 km/h	Time of reaction and acceleration when the vehicle ahead changes the speed
D2	Following a vehicle, and the vehicle ahead changing the lane	Time of reaction to a lane change of the vehicle ahead

Table 1: Driving Maneuvers

With these driving maneuvers the following hypotheses are checked:

Driving maneuver	Null hypothesis	Alternative hypothesis	Mean of the determined values		Significance according to t-test
			real	virtual	
A1	The distance of standstill behind the real and virtual standing vehicle respectively is the same.	The distance of standstill behind the real and virtual standing vehicle respectively is different.	5m (s=3m)	8,62m (s=3m)	p = 0,25 *
A2	When approaching the real and virtual vehicle respectively, braking starts at the same distance.	When approaching the real and virtual vehicle respectively, braking starts at a different distance.	41m (s=9m)	42m (s=12m)	p=0,84 *
	The distance of standstill behind the real and virtual standing vehicle respectively is the same.	The distance of standstill behind the real and virtual standing vehicle respectively is different.	11m (s=6m)	10m (s=9m)	p=0,66 *
B1	Both in real and virtual traffic deceleration starts at the same distance to the vehicle ahead.	Both in real and virtual traffic deceleration starts at a different distance to the vehicle ahead.	58m (s=15m)	58m (s=25m)	p=0,94 *
	When approaching in real and virtual traffic decelerating is the same.	When approaching in real and virtual traffic decelerating is different	58% linear; 42% stepped braking	52% linear; 48% stepped braking	p=0,57 *
	The maintained average distance to the real vehicle is the same as to the virtual vehicle.	The maintained average distance to the real vehicle is not the same as to the virtual vehicle.	16m (s=4m)	17m (s=6m)	p=0,44 *
C1	The time of reaction to the suddenly cutting in real / virtual vehicle is the same.	The time of reaction to the suddenly cutting in real / virtual vehicle is different	0,9s	1,7s	p= 0,0
	The decelerations to the suddenly cutting in real / virtual vehicle are simelar.	The decelerations to the suddenly cutting in real / virtual vehicle are different.	-4m/s² (s=2m/s²)	-8m/s² (s=2m/s²)	p=0,0
C2	Comparison with values published [9],[10],[11]				
D1	The times of reaction to the accelerating vehicle ahead are the same in real and virtual traffic.	The times of reaction to the accelerating vehicle ahead are different in real and virtual traffic.	1,7s (s=0,6s)	2,5s (s=1,4s)	p=0,0
D2	The drivers need the same amount of time until they note the lane change of the vehicle ahead.	The drivers do not need the same amount of time until they note the lane change of the vehicle ahead.	1,4s (s=0,5s)	5,2s (s=2,1s)	p=0,0

Table 2: Driving maneuvers with the hypotheses to be checked
(s= standard deviation; * = postulated significance level of p=0,2 reached)

Interference Statistics

The evaluation of this study's measurement data was oriented to confirming the null hypothesis. The question was whether the test drivers' driving behavior in the tests with a virtual vehicle ahead was similar to their behavior in the tests with a real vehicle ahead.

As it is the aim in this study to reject the alternative hypothesis in favor of the null hypothesis (test for equality), the error probability α is set at a lower limit of 20%. α and β- errors are mutually dependent. Therefore it is assumed that, with an α-error level of 20 %, the β-error is below the 5% significance limit. If this is given, the null hypothesis can be confirmed, and the alternative hypothesis rejected. [8].

It is of interest whether the test drivers behave differently in real / virtual drives. To test the hypotheses a two-sided significance test (two sample t-test) is to be conducted. The t-test is a considerably robust test method for mean comparison. It is sufficient if the values of the variables have a approximately normal distribution.
On a random basis the normal distribution was checked with the Kolmogorov-Smirnov test, giving positive results without exception. Therefore a normal distribution of the variables is assumed below.

Test evaluation

Below the results of the statistical evaluation of the driving tests are summarized briefly.

Approaching a standing/moving vehicle (A1/A2/B1):

The test drivers were able to recognize the virtual standing vehicle and approach it comfortably with a relative velocity of 80 km/h (A1). Also a target braking (target distance to vehicle after braking should be 0m) because of the virtual vehicle was possible (A2). The virtual lane, which was visualized on the wide asphalt area in these tests with a virtual vehicle ahead, was perceived by all drivers.
The emergency braking (A2) started at the same point in time in the real and virtual tests. Also all drivers braked with maximum deceleration.
When approaching a virtual vehicle ahead (B1), all drivers perceived it as a moving road user. They were able to approach the vehicle and react to it. The braking distance at which the test drivers reacted to the vehicle ahead in virtual and real traffic was nearly the same. Decelerating and braking force when approaching were comparable in the real and virtual test. Following the virtual vehicle was no problem for the test drivers. Once the virtual vehicle ahead was approached, a steady distance was maintained comparable to the one in the real test. Thus the Vehicle in the Loop test setup is very suitable for the simulation of approaching a standing or moving vehicle.

Sudden cutting in and collision (C1/C2):

The virtual vehicle cutting in (C1) was perceived at a later point in time than the real one by the test drivers. Still the majority of the drivers reacted to the vehicle cutting in suddenly by drawing aside or by braking-
The test drivers reacted to the vehicles cutting in later because of perception difficulties ("jumping vehicles", indicators modeled too small and not bright enough). In these critical, unexpected traffic situations there is a difference in perception of a mean of 0,84s (Δ time of reaction) between the Vehicle in the Loop drive and the drive with the real vehicle ahead. As the drivers perceived the vehicle cutting in later and the time to collision was thus decreased, they had to brake more severely to avoid the collision with the virtual vehicle. The fact that, in spite of perception at a later point in time, the drivers still avoided the collision with the virtual vehicle points to a realistic perception of the criticality of the traffic situation.

The later perception of the virtual vehicle cutting in may be explained by the fact that this driving test was conducted against direct sunlight. This leads to the reduced contrast of the virtual vehicle.

In addition, this driving maneuver was conducted on a very uneven lane (bumps, potholes). This results in a relative movement of the HMD to the eyes of the driver. This has the effect of a jumping/vibrating perception of the virtual outside traffic. And, thus, assigning the lane of the virtual outside traffic becomes difficult.
So, there is the need to repeat the maneuver again on a road with no/less bumps and at days with cloudy weather (for better contrast at the HMD) to see, whether the reaction difference depends on perception problems or on other still unknown problems with the VIL.
In the test “collision” (C2, only virtual), the time of reaction of 0,95s to the virtual vehicle ahead braking suddenly was almost comparable to the published values of driver’s time of reaction in such driving situations. This shows that the drivers were able to assess correctly the distance in an emergency braking from 80 km/h and the maximum deceleration of the vehicle ahead.

Acceleration of the vehicle ahead (D1):

The changing acceleration of the virtual vehicle ahead was perceived with more difficulties by the drivers than that of the real vehicle. This can be seen from the longer times of reaction by 0.8 seconds in the virtual tests.
There is further need to do research on the reasons why there is a difference at the times of reaction. One reason might be possible perception differences that may be responsible for the poor test result with a virtual vehicle ahead.
The test drivers told us (with the questionnaire) that they were a bit surprised about the unusually quick acceleration of the virtual vehicle. Because of that another reason for the poor test results might be that the drivers perceived the changing speed correctly, but they were so surprised by the unusually quick acceleration of the virtual vehicle that they reacted late. Apart from that, the drivers told us they were not motivated to accelerate equally hard because of the narrow curves where the test was conducted.

Lane change of the vehicle ahead (D2):

Subjectively and objectively, the test drivers had more difficulties to follow a virtual vehicle ahead in a lane change. The times of reaction to the lane change of the virtual vehicle were markedly longer than the times of reaction in the real test (time differential 3.8s). The distance to the vehicle ahead is decisive for a sufficient time of reaction, as there are difficulties to assign the lane of virtual vehicles far ahead. For many test persons the big distance of following made perceiving the indicators difficult as they had been modeled too small and not bright enough.
In addition, bumps produced again a “jumping” presentation of the virtual outside traffic in this test (see above driving test “sudden cutting in”). This makes the assignment of the lane difficult.

Summary

To sum up, the Vehicle in the Loop test setup appears suitable as a future development tool. The simulation of the outside traffic by the VIL and correspondingly the driving

experience in the virtual tests is very realistic. The test drivers showed a similar driving behavior in the drives with a virtual vehicle ahead as in the real tests. They can well imagine to work with the VIL as a development tool and are convinced that critical driving maneuvers can be represented realistically.
A short training phase of about 15 minutes was sufficient to become acquainted with the Vehicle in the Loop system. When operating this system often, the user gets quickly accustomed to the built-in measurement instruments and to wearing the HMD.

On the one hand the VIL is a milestone for the simulation of driver assistance systems because of the better test possibility than in driving simulators of maneuvers with emergency brakes of the own car (cf. A2) and emergency brakes of cars driving ahead (C2).
On the other hand further work has to be done to improve the perception of virtual cars driving ahead especially on sunny days and to find the exact reasons for the “jumping cars” at uneven lanes.

References

[1] Oertel, Klaus - "Zukunftsmarkt Assistenzsysteme" - Automotive Electronics + Systems, Carl Hanser Verlag , Vol.11/12 - 2004, Seite 22-24.
[2] Kompaß, Klaus - "Integration Aktiver und Passiver Sicherheit - mehr Fahrerlebnis und besserer Insassenschutz", Baika Kooperationsforum Fahrerassistenzsysteme, April 2005.
[3] Kopischke, Stephan - "Entwicklung einer Notbremsfunktion mit Rapid Prototyping Methoden", Dissertation, Technische Universität Carolo - Wilhelmina zu Braunschweig, 2000.
[4] Bock, Thomas, Siedersberger, Karl-Heinz; Zavrel Martin; Breu Alexander, “Simulations- und Testumgebung für Fahrerassistenzsysteme - Vehicle in the Loop“, Technischer Bericht, Erprobung und Simulation in der Fahrzeugentwicklung - Mess- und Versuchstechnik, VDI-Berichte 1900, 2005.
[5] http://www.opendrive.org, Stand Mai 2006.
[6] Oehme, Olaf, “Ergonomische Untersuchung von kopfbasierten Displays für Anwendungen der erweiterten Realität in Produktion und Service”, Dissertation, RWTH Aachen, 2004.
[7] Meyer, Marcel, “Entwicklung und Implementierung eines Sensormodells für Radarsensorik”, Diplomarbeit, Lehrstuhl für Realzeit-Computersysteme, TU München, 2006.
[8] Bortz, Jürgen, Statistik für Human- und Sozialwissenschaftler, Heidelberg, Springer Medizin Verlag, 2005.
[9] Zobel, Robert; Achmus, Stefanie, Unfallanalyse zur automatischen Notbremsung, Wolfsburg, Volkswagen AG 1999.
[10] Cohen, A.S., The latency of simple reaction on highways: A field study, Public Health Reviews, page 291-310, 1987.
[11] Derichs, Hans, Vergleich statistischer Auswerteverfahren der experimentell ermittelten Reaktionszeiten von PKW-Fahrern im Straßenverkehr, Fachhochschule Köln, master thesis 1998.