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A Hardware-in-the-Loop Facility for Integrated Vehicle Dynamics Control System Design and Validation

Amir Soltani*, Francis Assadian**

**Cranfield University, Cranfield, MK43 0AL, UK*
(Tel: +44-1234750111; e-mail: m.m.soltani@ cranfield.ac.uk)
***University of California, Davis, One Shields Ave., Ca 95616, USA*
(email: fassadian@ucdavis.edu)

Abstract: Due to the increased number and the complexity of the embedded systems in today's vehicle, there is ever increasing pressure to reduce the development cost and time to market of such systems. In recent years, Model based Development (MBD) is becoming a main stream in the development of automotive embedded systems, and Hardware-in-the-Loop (HiL) testing is one of the key steps toward the implementation of MBD approach. This paper presents the recent HiL facility that has been developed at Cranfield University. The HiL setup includes real steering and brake smart actuator, high fidelity validated vehicle model, complete rapid control prototyping tool chain, and driver-in-the-loop capability. The applications of HiL setup are including but not limited to: smart actuators system identification; rapid control development and early validation of standalone and/or integrated vehicle dynamics control systems. Furthermore, the facility can be employed for investigation on driver-vehicle interaction at the presence of standalone active steering and/or brake systems as well as various Advanced Driver Assist Systems (ADAS), such as lane keeping or adaptive cruise control systems. The capability of the HiL facility for validation of a several newly developed vehicle dynamics control systems is presented.

Keywords: Automotive Control, Integrated Vehicle Dynamics Control Systems, Rapid Control Prototyping, Control Validation, Model Based Development, Hardware in the Loop (HiL), Active Steering Control, Active Brake Control.

1. INTRODUCTION

As a result of the increased number and the capabilities of microprocessors, sensors and actuators that are being embedded in most of today's engineering systems (so called mechatronic systems), the functionalities, complexities and level of integration of these products have evolved considerably. Development of mechatronic systems is a complicated multidisciplinary task and often requires contribution from diverse technical disciplines. The use of Model Based Development (MBD) methodology together with the V-model development process is a well-accepted systematic development approach, (Nicolescu & Mosterman, 2010), where the product and process domains are considered (Aslaksen & Belcher, 1992). The V-model probably originates from system engineering and software development; however, this approach was adopted for mechatronic product development (Isermann R. , 2008; VDI 2206, 2004) as well as for development of automotive embedded systems (Nazareth & Siwy, 2013).

The V-model addresses tree main stages toward product development including *System Decomposition*, *System Implementation* and *System Integration* as shown schematically in Fig 1. (Holtmann, Meyer, & Meyer, 2011). It incorporates several seamless steps and feedback loops, starting from requirements definition and ending up with field tests and validation on the vehicle. These steps are called "Model in the Loop" (MiL), Software in the Loop" (SiL), "Processor in the Loop" (PiL), "Hardware in the Loop" (HiL), and prototype testing. These feedback loops are the key elements to reduce the development time and cost by ensuring that the Verification and Validation (V&V) are taking place in the early stages of development (Bringmann & Krämer, 2008). The objective is to test out the (embedded) System under Development (SUD), at its different levels of maturity, to ensure the system is designed correctly (i.e. meet the specifications) and also the customer requirements are satisfied.

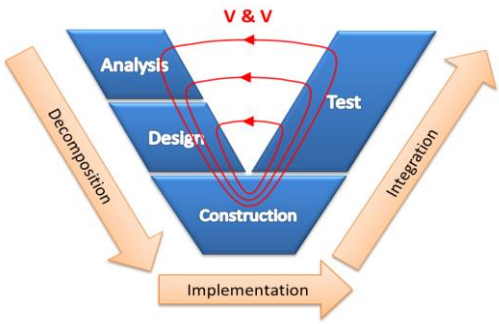

Fig. 1. The V-Model (Holtmann, Meyer, & Meyer, 2011)

2. THE PRINCIPAL OF HiL SIMULATION

To better realise the important role of the HiL simulation, it is essential to review the concept of Model Based Development (MBD) approach of the embedded control systems, in which, "*modelling*" of the physical system plays the central role in the development process. Modelling could be defined as an abstract mathematical description of a physical system (Bringmann & Krämer, 2008). In the MBD approach, the mathematical formulation of the system dynamics are modelled and represented graphically, within the modelling environment such as Matlab®/Simulink®/StateFlow®, in order to provide a common platform across different engineering disciplines, which lead to a simplified and more efficient design process (including control design process). Moreover, the low-level machine codes can be seamlessly generated from the models causing a dramatic reduction in time and cost required for system implementation and testing. The system dynamics include the (linear or non-linear) model of plant dynamics as well as the (linear or non-linear) models of sensors and actuators dynamics. The model development often involves several inevitable trade-offs between completeness and simplicity. As the construction of a model (especially for control design purpose) often involves several levels of simplification and abstraction, the outputs of the model deviate to a greater or lesser extent from the real values. Having concerns about the reliability of the simulation outputs, *fidelity* is defined as the measure of degree to which a model reproduces the state and behaviour of the real system. If a model includes sufficient fidelity, then the control performance can be evaluated through simulation and the risk and cost associated with experimental validation will be reduced considerably (Gerdes & Hedrick, 1999).

From a control design point of view, the model should be complete to ideally capture the fundamental dynamics of the system and remain simple enough to provide a basis for model based control development. This inevitable level of simplification means that there are some deviations exist between the real behaviour of the system and its virtual model. These may include (but not limited to):

- The simplified dynamics of the plant, actuators and/or sensors;
- The neglected nonlinearities (such as friction or backlash) in the plant and the actuators;
- The ignored delays and latencies on communication buses, such as CAN bus;
- The unmodelled external disturbances and noises exerted to the system.
- The difference between processing power and capacity of an off-line simulation computer (a PC, for example), a real-time control prototyping platform (dSPACE MicroAutoBox®, for example), and the final target processor (ECU);

The above mentioned differences mean that the performance of the final embedded product is not necessarily similar to the behaviour of the originally designed control system that was validated through off-line simulation. As the development of the product reach to some higher level of maturity within the left side of the V-model, it is necessary to validate the product in a more complex and realistic testing conditions, and to provide proper feedbacks for design correction. Although there are no definite agreement on the range and the definition of the validation tests within the context of MBD approach, but in general we can define the more common validation test as follow:

- The 'Model in the Loop' (MiL) stands for the off-line simulation and verification of the system models and controllers which are developed at different stages of the design process;
- The 'Software in the Loop' (SiL) is the real time simulation and verification of the software codes which are automatically generated from the developed models during the implantation phase and are executed on the prototyping ECU platforms (such as dSPACE MicroAutoBox®, ETAS, etc.);
- The 'Processor in the Loop' (PiL) is the real time simulation of the auto-generated software codes that are executed on the final target processor board (production ECU);
- And the 'Hardware in the loop' (HiL) simulation is defined as "a method in which one or more real components/sub-systems interact in a closed loop with components/sub-systems that are simulated in real time (real time dynamic models)" (Wältermann, 2009, April), as shown in Fig. 2.

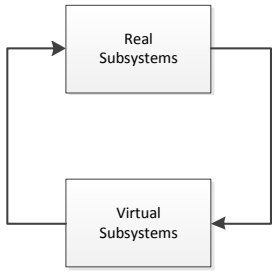

Fig. 2. Principal of a HiL Simulation

HiL system provides a fast, flexible and efficient means for verification of functional and non-functional aspects of the developed control systems (ECUs) in a real time environment in the presence of (actual and virtual) system dynamics (Mutz, Huhn, Goltz, & Kromke, 2003). The real part of the system consists mainly of one or more ECUs (controllers), and/or smart actuators and sensors which operate in a closed loop with components that are (mechanically and/or electrically) simulated in real time. If the simulated models reveal sufficient proximity to how the system behaves in reality, then the control performance can be evaluated through HiL testing with a high level of confidence and the risk and cost associated with experimental validation will reduce considerably. HiL systems are generally employed for validation of production ECUs for smart actuators (Hanselmann, 1996). However, integration of a HiL system with Rapid Control Prototyping (RCP) tools, such as dSPACE MicroAutoBox®, yields a suitable platform for control system development and validation in real time

environment (Abel & Bollig, A., 2006). The appplication of rapid control prototypimg for development of various chassis control systems including steering and brake have been presented in several liturratures, such as (Falcone, et al., 2007) and (Mutoh, et al., 2007).

3. THE CRANFIELD UNIVERSITY INTEGRATED STEERING & BRAKE HiL SIMULATOR

An integrated Steering and Brake HiL/RCP setup was designed and implemented at Cranfield University (Soltani, 2014). The systematic approach to design the Cranfield's integrated steering and brake HiL setup, and more importantly, its wide range of applications are explained in this paper.

3.1 Requirements

The HiL is intended to perform the following tasks:

- Rapid prototyping and control validation of the steering and/or brake control system.
- Functional and non-functional testing of the different stand-alone steering based active systems such as, Electro Hydraulic Assisted Power Steering (EHPAS), (EPAS), Active Front Steering (AFS), Steer by Wire (SBW); and also various steering based ADAS functions such as Lane Keeping and Lane Departure Warning systems.
- Functional and non-functional testing of the various stand-alone brake based active systems such as, Anti-Lock Brake System (ABS), Electronic Stability Program (ESP), Electro Hydraulic Brake (EHB), Brake by Wire (BBW), and also various brake based ADAS functions such as Collision Avoidance or Adaptive Cruise Control systems.
- Functional and non-functional testing of the integrated steering and brake active systems such as the customized IVCS system, as presented in (Soltani, 2014).

3.2 Specifications

To meet the requirements, the following specifications should be considered in the design of the HiL:

- Driver in the loop: Drive-vehicle interaction plays an important role in vehicle dynamics studies, especially in design of vehicle safety systems such as ESP or ADAS systems (Gietelink, et al., 2006). To achieve a realistic vehicle dynamics response, the HiL should include either a validated real time driver model and/or have means for real driver (steering, brake and gas) inputs, so called Driver in the Loop, or driving simulator setup (Chen & Ulsoy, 2001).
- Steering torque feedback: The EPAS works based on driver steering torque feedback (so called haptic feedback (Abbink & Mulder, 2010)). To be able to evaluate the performance of the EPAS control system it is essential to furnish the driver with an acceptable steering wheel torque feedback (Toffin, Reymond, Kemeny, & Droulez, 2007).
- Real OEM steering and brake systems: In order to validate the designed (steering and brake) control systems in a realistic environment, the effect of the real actuators dynamics, and their nonlinearities, such as friction, backlash and delays, as well as external disturbance and noises should be considered. By equipping the HiL with real OEM steering and brake systems, getting the closet results to reality are possible. To be able to receive real inputs from the driver, the steering wheel, brake and accelerator pedals should be equipped with the relevant sensors.
- Rapid control prototyping tool chains: Considering that the HiL is mainly developed for control prototyping and validation tasks; it is necessary to equip it with a fast, efficient and flexible means of deploying, calibrating and validating of the developed control systems in a real time environment. The HiL should be equipped with the proper rapid control prototyping (hardware and software) tool chains such as dSPACE MicroAutoBox, dSPACE Real Time Interfaces (RTI) Blocksets and Simulink® Coder™ (automatic code generation) .
- Validated models: To achieve reliable and validated test results, it is essential to employ validated high fidelity models for the simulated subsystems. Moreover, the models should be executed in a real time environment. Industry standard, off-the-shelf software such as CarMaker/HiL®, CarSim/HiL®, AVL CRUISE® are preferred as they provide validated results and facilitate straightforward data exchange among different parties in a joint project.
- Flexible yet strong structure: The mechanical structure of the HiL system should be properly designed to cope with a wide range of steering and brake system sizes and types. The HiL platform size should be appropriate to enable installing steering and brake of different (passenger) cars from different manufacturers and its mechanical structure should be as flexible as possible to allow modularity and to be fitted with different steering based active systems, such as EPAS, AFS, SBW; and/or different braking based active systems, such as ABS, ESP, EHB, BBW.

In addition, as the steering and brake systems are subject to tough real dynamic loads during their operations, it is required that the mechanical structure of the HiL is sufficiently robust to withstand high dynamic forces, especially from the steering system and actuators.

3.3 HiL Architecture

Architectural design is one of the most important stages in the systematic approach toward development of a HiL system. Recall that a HiL is a hybrid system that consists of real components/subsystems which work together with modelled (virtual) sub-systems to form a closed loop virtual reality environment. In the architectural design stage, the layout of the HiL system, in a high level of abstraction, is defined. More specifically, the main (real and virtual) elements of the system and their functionalities within the HiL platform are determined, and the boundaries and the interfaces between real and virtual components/sub-systems are specified. To design the architecture, one should consider the requirements and specifications together with engineering

trade-off between the system performance and available resources such as cost and time.

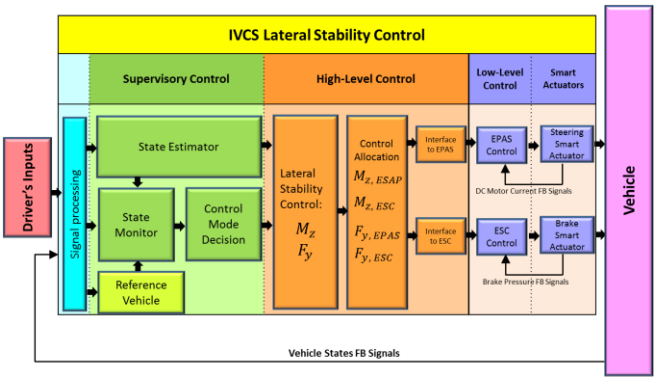

Fig. 3. Customised IVCS control structure

The HiL setup has been designed based on the customised IVCS control architecture for lateral vehicle dynamics control, as shown in Fig. 3. (Soltani, 2014). Considering the HiL requirements and specifications, as defined above, the proposed architecture for integrated steering and brake HiL/RCP setup is presented in Fig. 4. In this configuration, the real steering and brake smart actuator systems are linked to a virtual vehicle model. Here the existing steering and brake smart actuators are EPAS and EHB, respectively. It is, however, possible to employ different steering or brake active systems such as SBW, AFS, ABS, ESP, BBW and so on in this HiL.

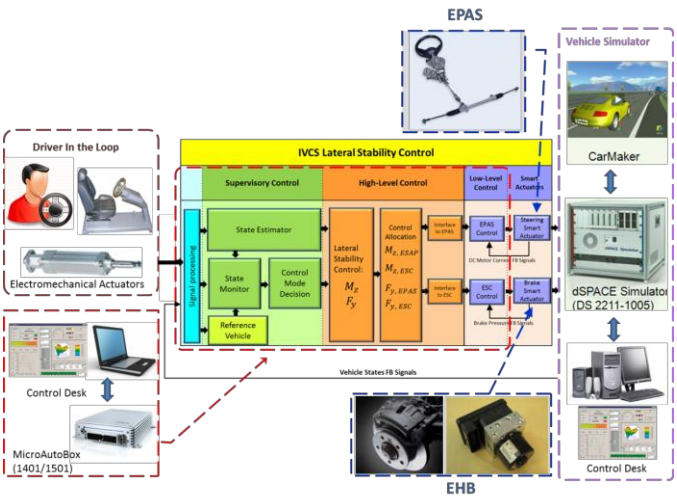

Fig. 4. The integrated steering & brake HiL architecture

The driver inputs to the system include the steering wheel (torque/angle), the brake and the gas pedals positions, based on the responses from a computer generated road scene which is projected in front. This forms a driver-in-the-loop (driving simulator) platform. The steering torque feedback to the driver is generated by the forces that are applied to the steering rack by means of two linear electric actuators, which are connected to both ends of the rack. The magnitude and direction of applied forces to the rack is calculated by the vehicle model and take the form of target values for the linear electric actuators controllers.

The real parts for brake system include: brake pedal, master cylinder, EHB valve modulation unit (or other stand-alone active brake systems), and a complete hydraulic line connected to each wheel brake callipers. In order to reduce the cost and the complexity of the HiL, the wheels do not rotate in this system. Therefore, the virtual parts of the brake systems are the wheel dynamics and the brake torque calculation, integrated with the high fidelity vehicle dynamics model. The brake torque at the wheels is estimated based on measuring the brake line hydraulic pressure by means of four pressure sensors connected to the end of the hydraulic line of each wheel. As there are no rotating wheels on the HiL, the wheel speed signals are provided by the vehicle simulator (virtual wheel speed sensor).

The vehicle simulator consists of the high fidelity vehicle model (here, CarMaker/HiL), which executes in a real time processor (here dSPACE Simulator, ds 2211-1005). It performs the numerical calculations and generates the required signals including vehicle dynamics states and wheel dynamics states. Concurrently, the designed control systems deployed and executed in the second real time processor (here dSPACE MicroAutoBox) as the rapid control prototype ECU. In this setup, the control systems which have been validated by HiL testing can be further tested in a real prototype vehicle, forthrightly. The prototype ECU receives signals from (real and virtual) sensors and generates command signals for steering and brake actuators. The communication between the vehicle simulator, the prototype ECU and the existing sensor and actuators is performed via various analogue, digital and CAN bus interfaces. The virtual vehicle could be driven either manually by real driver (steering, brake and gas) inputs or autonomously by receiving input from a high fidelity driver model that has been implemented in CarMaker/HiL software. A simplified schematic diagram of the HiL including its main elements and the feedback loops is shown in Fig. 5.

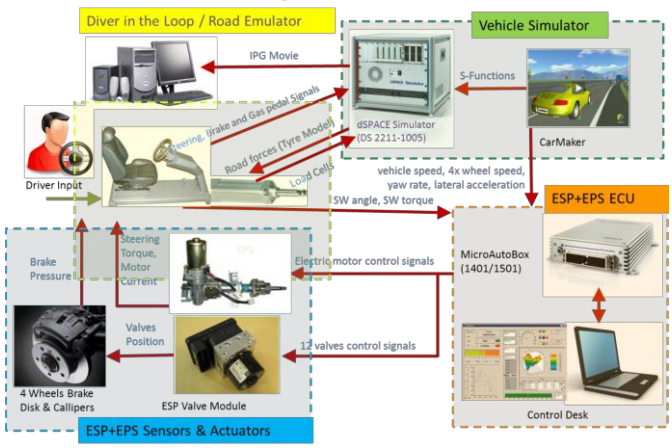

Fig. 5. The signal flows among several HiL components

To establish a communication between the HiL operator and all the existing active systems, several human machine interfaces are designed in the ControlDesk® environment to perform the following (real time) tasks: command and monitor the vehicle simulator (dSPACE Simulator)

operation; command and monitor the prototype ECU (dSPACE MicroAutoBox) operation; tune the designed control system parameters (RCP), and data acquisition and logging of the test results. A picture of the implemented HiL/RCP setup with the driver in the loop is shown in Fig. 6.

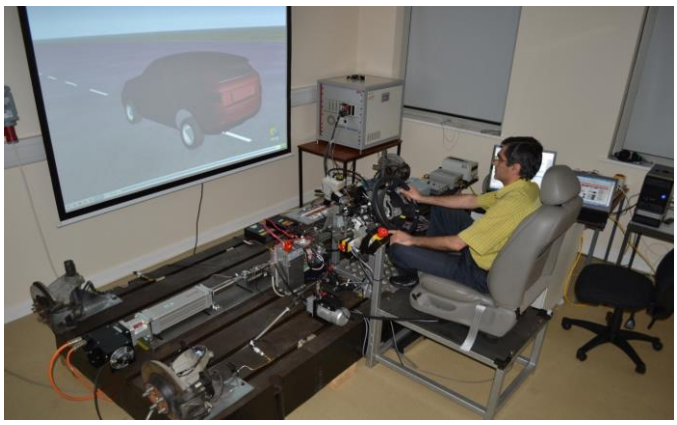

Fig. 6. Cranfield's HiL/RCP setup with the driver-in the-loop

4- THE CRANFIELD HiL APPLICATIONS

The Cranfield Integrated Steering and Brake HiL setup provides a wide range of control development, test and validation for various vehicle dynamics applications of prototyping and/or production systems. To name a few, the HiL Rig can be used for:

- Determination of dynamic characteristics of (steering or brake) smart actuators;
- Rapid control prototyping of standalone or integrated vehicle dynamics systems;
- Functional and Non-functional testing of vehicle dynamics active systems;

4.1 Dynamic characteristics of smart actuators

An Integrated Vehicle Dynamic System consists of several smart actuators such as active barking, active steering, active suspension in a coordinated manner. The HiL setup could be employed to determine the linear dynamics characteristics of the steering and brake based smart actuators, as well as their nonlinearities such as backlashes, frictions, and delays. The main application would be either estimation or validations of the model parameters that are normally employed in Model Based Development (MBD) of the control systems. This could be achieved through time based or frequency based analysis of the response of the actuator to standard inputs such as step, ramp, or sinusoidal inputs. An accurate dynamics representation of the system could be obtained by using advanced parameter estimation and validation tools such as Matlab/Simulink parameter estimation toolbox. An example of such study could be found in (Martínez, et al., 2014). A test result of Brake Caliper reponse subject to a step input is shown in Fig 7.

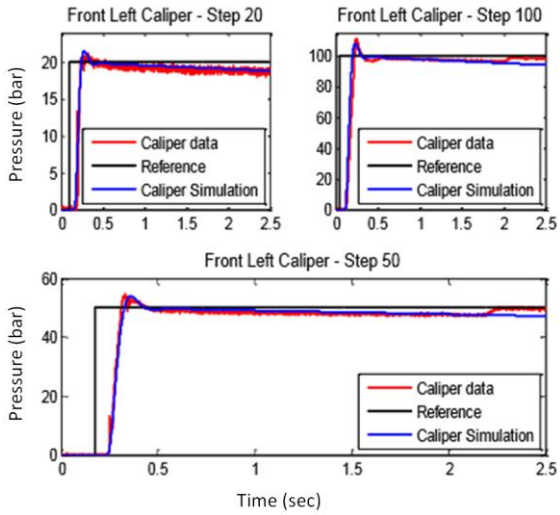

Fig 7. Brake Caliper Experimental and Simulation data (Martínez, et al., 2014)

4.2. Rapid control prototyping:

Having the real steering and brake actuators, the industry standard validated vehicle model, the latest Rapid Control Prototyping (RCP) tool chain, and the drive in the loop capability; the HiL provides an excellent and unique platform for the development and validation of various vehicle dynamics control systems in real time environment with the existence of the real control issues such as: actuator dynamics, nonlinearities, transport delays, CAN bus latency, etc. This will ensure that the behaviour of the designed control system in the lab environment exhibit a close proximity to what we can get in a real filed testing, with a considerably lower cost and much more flexibility.

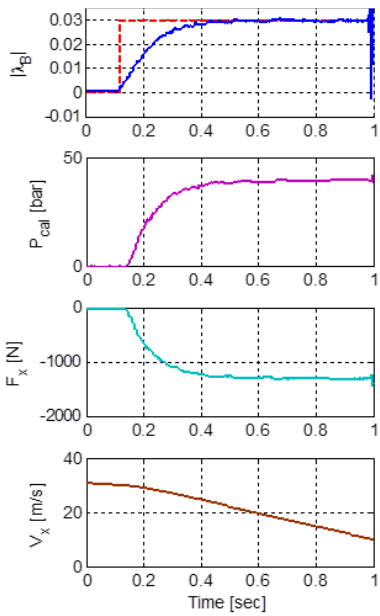

Figure 8: HiL test results for the closed loop slip control system (Soltani & Assadian, 2015)

The HiL setup can be employed for the development and validation of a wide range of system, from various low-level brake and/or steering active control systems, such as wheel slip controls (Soltani & Assadian, 2015), see Fig 8, to some specific functionality such as Torque Vectoring for conventional or electric vehicles (Claret, 2014), as well as high level integrated vehicle dynamics control structures such as the one proposed in (Soltani, 2014), as shown in Fig 9. The accuracy of the HiL results has been verified and confirmed by road testing of real vehicle.

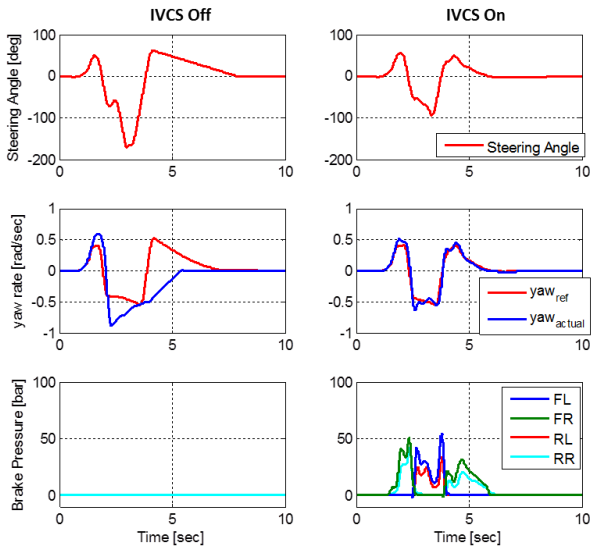

Fig 9. HiL test results of the Integrated Vehicle Dynamics Control System (IVCS) subject to VDA lane-change manoeuvre (Soltani, 2014)

4.3. Functional and Non-functional testing of vehicle dynamics active systems:

Thanks to flexible mechanical structure of the HiL, various OEM based steering and/or brake active systems can be fitted to the HiL. This gives the opportunity of employing the HiL as a validation tool for functional and/or non-functional testing of production ECUs and systems. The Hil setup could be employed as a significant tool for production sign-off and certification purposes, because of its capability to reproduce the test cases, and to repeat the same test scenarios for several times, and more importantly, its ability to deal with safety-critical applications.

As mentioned before, the HiL can work either autonomously or with driver input in the loop. In the former case, the HiL setup can be set to repeat hundreds of similar test cases autonomously, which is especially useful for robustness or failsafe validation and testing. And in the latter case there is an opportunity to have the response of the real driver which leads to a more realistic dynamic representation of the vehicle-driver control system. This feature is especially important in the design and validation of active safety systems, as well as ADAS system such as lane departure systems (Gietelink, et al., 2006).

5. CONCLUSIONS

The ever increasing of the number of ECUs and the growing complexity of the embedded systems in today's vehicles, Hardware-in-the-Loop (HiL) testing within the context of Model Based Development approach, is becoming an integral part of embedded control systems development process. In this paper, the recent integrated steering and brake HiL facility that has been developed at Cranfield University is presented. The HiL can be employed for rapid development and validation of steering and/or brake based standalone or integrated vehicle dynamics control systems. The HiL applications are including but not limited to: system parameter identification, functional and non-functional testing and early validation of the prototype and production systems. Furthermore, the facility can be employed for investigation of driver-vehicle interactions for active steering and/or brake systems as well as several Advanced Driver Assist Systems (ADAS). In this paper, we presented the capability of the facility for validation of a several newly developed vehicle dynamics control systems.

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