Vehicle stability controller HiL validation on static simulator

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Abstract. In the automotive world, Hardware in the Loop (HiL) methodologies are used to speed up the design and calibration process of the various mechatronics components installed on the vehicle. Installing production parts on advanced driving simulator enables the performance assessment in realistic scenarios, including a test driver earlier in the design process. The scope of this work is to evaluate the effect of ABS and ESC system, replicating their influence on the steering wheel. A brake by wire production system has been installed on a static simulator, equipped with a EPSiL steering bench, capable of accurately replicate tie-rod forces on a production steering unit. Full brake, sine steer maneuvers have been carried out both on real vehicle and on virtual environment. The system showed its capabilities of replicating the same functionalities of the real vehicle, extending the static simulator potentialities to support the activities on calibration and test of vehicle systems.

1. Introduction
Tentative in order to achieve the objective of reducing the number and fatality of road accidents \cite{1} has made vehicle control and safety functionalities more complicated, making the urge for a faster yet reliable method of testing such components a current trends in the industry. For example, the Autonomous Emergency Braking (AEB) functionality has made the brake unit an active component, requiring a brake action even if the driver is not applying any force to the brake pedal \cite{2}.

Moreover, the search for higher vehicle efficiency is steering the market to more controllable and energy efficient brake by wire units, where the brake pedal is hydraulically disconnected from the calipers, and the oil is pressurized by the intervention of an active actuator \cite{3}.

The current development process of this type of units presents its challenges, given the intrinsic multi-domain specifications required \cite{2, 4}. To achieve the final design, of automotive mechatronic components and their functionalities usually requires that every step must be concluded with a test phase, defining that the design and its validation must be carried out at the same time and always before going further in the development. We refer to the graphical representation of this process as a "v-shape" \cite{5}. Various validation methodologies are available, depending on the design phase. Usually, a Model in the Loop (MiL) is firstly implemented. Given a basic but functionally-equivalent virtual model of the system in development, designers
can evaluate high-level specification and algorithms. Going further, with Software in the Loop the system in testing is the software of the unit, evaluating its programming and efficiency.

After this, a first physical prototype is available, and it’s used for Hardware in the Loop testing [6]. For example, a vehicle brake system, composed by actuator unit, brake pedal and calipers, is assembled outside the vehicle, and undergoes validation cycles in order to evaluate the functionality of both the physical part and the electronic control [7]. ABS, ESC logic are roughly calibrated during these tests [8, 9, 10], but a fine tuning phase is only assigned to real-vehicle testing with an human driver.

In order to include the driver earlier in the design loop, the use of driving simulators is increasing importance [11]. The aim of this work is to propose a methodology for brake by wire unit performance assessment that can serve as an intermediate validation phase between HiL test and real vehicle tests [12].

A commercial brake by wire unit has been installed on a static driving simulator, on which a steering bench is installed. This bench acts on the real steering system, which is totally installed on the sim, and it is able to accurately reproduce forces on tierods and consequently the steering torque; the system has proved itself capable in [13] to achieve the calibration of a prototype EPS, tuning the steering feeling with expert test drivers and subjective methodologies used in road vehicles. The brake system installation in this static simulator aims to reproduce the effect of ABS and ESC intervention on steering wheel torque, extending its accuracy.

A brief description of the static simulator and brake loop is introduced. Then, the validation methodology is presented: in order to assess if the unit has same behavior between real and simulator installation, several braking maneuvers are carried out, comparing the behavior during ABS and ESC intervention. Then, a full-brake maneuver is carried out on the simulator, comparing the performances of a commercial Model in the Loop and brake unit ABS functionality in terms of driver feedback on the steering wheel torque.

2. Real-time driving simulator setup
The experimental activity has been carried out on the static simulator, supplied by Meccanica 42, shown in figure 1. It is composed by three main parts: the real time simulator, the EPSiL steering bench, and the Braking unit, as in figure 2. The real time simulator comprehends a Concurrent-RT machine, which manages the simulation environment. This machine acquires the data coming from by the Human-Machine interface, interfaces it with the vehicle model, and sends a response to the force actuators guaranteeing the max delay of a millisecond (typical timestep for the simulation). This type of machine is necessary to use the Hardware in the Loop benches installed on the simulator.

2.1. EPSiL steering bench
The EPSiL steering bench integrates a complete steering system in a human in the loop driving simulator [14]. Two torque motors and transmission act directly on the tie-rods of a production steering system by the means of a rocker, accurately reproducing the kinematic movement of the suspension. With this architecture the rig can reproduce other components of the force beyond the forces on the xy plane, improving tracking performances between vehicle model and actual force. The tie-rods, equipped with loadcells, rack, EPS, steering column, and steering wheel are integrated in the system.
The described steering system layout replicates exactly the one of an actual vehicle model. In this way, steering bench is put into simulation loop, enhancing driving simulator experience and providing the perfect tool for steering feedback virtual development. In fact, through CAN connection, it is possible to change EPS tuning parameters and calibrate the system, while driver can assess the effect of each modification on multiple proving grounds. The unit proved itself capable of accurately reproduce real-vehicle tierod forces, resulting in the correct reproduction of the steering feeling [13].

2.2. Brake unit

A commercially available brake-by-wire system has been integrated on the simulator. The installation is described in figure 2. The stock brake plant is mounted on the simulator: the brake tubes, with the correct diameter and length, connects the electromechanical unit to the 4 stock brake calipers, which acts on the original brake discs. The brake pedal is directly integrated on the unit, and it acts as the main driver-machine interface.
The brake unit receives through the CAN communication line all the IMU signals that it usually receives on the car, simulated by the vehicle model on the real time computer. However, this unit needs the intelligent wheel speed sensors signal via a direct communication line [15, 16]. To overcome this problem, a wheel speed simulator has been implemented, which converts the signal of the wheel speed (sent via CAN from the RT machine) to the typical signal of the intelligent wheel speed sensors.

Lastly, 4 pressure sensors have been installed on the calipers, and their signals are sent back to the vehicle model via an EtherCAT measurement line, closing the loop, controlling the vehicle deceleration after a brake application by the driver. Brake unit and steering system belong to the same vehicle.

3. Methodology
The validation methodology is now presented. The goal is to have a simulator that can reproduce the vehicle behavior and driver feeling of the real scenario.

A previously validated vehicle model has been installed on the simulator, and adapted to the new control loop, given the brake unit presence. Then, the following set of maneuvers has been carried out by a driver on the simulator:

- Full brake
- Pulse brake
- Sine steer
- Brake in turn

To demonstrate the efficacy of the brake bench, the installed brake unit functionality must be coherent with the one of a vehicle during a real drive test. The same set of maneuvers has been carried out on an instrumented vehicle in a testing track. A tuning phase of the road parameters has been necessary to guarantee that the virtual and real results are comparable.

After this, a steering torque sensor has been installed on the simulator, and a maneuver with ABS intervention has been carried out, comparing a model ABS with the HiL ABS, to evaluate the effect of the brake unit on steering feeling.
3.1. Tuning

One of the main advantages to use a driving simulator is the possibility to consider the influence of various parameters on the driving test. For example, it is possible to modify the track adherence very easily, resulting in a faster evaluation of the control system in various different conditions, which is not possible or at least much more difficult to investigate on the real track.

However, track condition information is needed to correlate the behavior of the unit; the braking distance and the ABS intervention greatly depends on the track adherence. We decided to treat this value as our tuning parameter: without accurate information on the track condition, we compare the results of a full-brake maneuver from high speed to standstill in terms of braking distance. If this parameter is higher (or lower) in the simulated maneuver than the one in real-scenario, the adherence value is decreased (or increased), and the simulation re-run.

The resulting value of 0.85 is reasonable, given the fact that tests were carried out after a rainy day on a dry asphalt, reducing the available adherence. Once that the braking distance is comparable, we proceed with the evaluation of the remaining maneuvers.

4. Results

4.1. Full Brake

The first test is a full brake maneuver, from high speed to standstill. This is useful to evaluate the ABS control intervention. Starting from high speed, the driver applies full brake pedal. In figure 3 the time results are presented, in terms of longitudinal deceleration, wheel speed, brake corner and master cylinder pressure.

It is possible to spot a qualitative correlation of the latter signals between the two test environment. The major difference however emerges from the evaluation of the wheel speed: at lower speed, the signal oscillation has some noticeable differences. This behavior is caused by the tire model, which is unreliable when the braking moment causes large values of slip at lower speed. However, the results at speeds higher than 30km/h can be considered as valuable.

The KPI analysis that follows takes into account this limitation, excluding the results below this speed. Four indexes, which are maximum pressure, mean pressure, braking distance and deceleration on brake pressure ratio have been considered, and are shown in figure 4. The values have been scaled in respect to the real vehicle performance to easily compare in the same scale all the indexes; for this reason, the real test KPI has value one in all the following graphs. For all the four indexes, the error is always lower than 10% of the real test value.
4.2. Pulse Brake

The second test is a pulse brake, which consists in a repeated brake application of 3 seconds, followed by a brake release. The results are presented in figure 6. This is a dynamical maneuver, and we can see that the correlation is higher than the one derived by the first maneuver. This
is due to the higher speeds at which the brake momentum is applied, avoiding the numerical noise due to the inefficacy of the tire model, as already discussed.

In figure 5 the KPI comparison is presented, and again the error is less than 10 percent. The indexes for this maneuver are the same as the previously described, given the similarity of the vehicle dynamics involved. The deceleration-pressure ratio has been excluded from the analysis because already assessed during the previous test.

![Pulse brake maneuver KPI comparison](image)

**Figure 5.** Pulse brake maneuver KPI comparison.

![Vehicle Test vs Simulator Test](image)

**Figure 6.** Pulse brake maneuver result.
4.3. Sine Steer
The third test is a sine steer in order to evaluate ESC intervention. A sine steer with frequency of 1Hz and amplitude 45 degrees has been carried out at 100 km/h. The results are presented in figure 7 and the chosen key performance indexes are shown in figure 8. These indexes are maximum brake pressure, sideslip angle, and yaw rate. Still, the error for the three KPI is less than 8%.

Figure 7. Sine steer maneuver result.

Figure 8. Sine steer maneuver KPI comparison.
4.4. Brake in Turn

The fourth and last test is a constant steer maneuver with the application of a full brake intervention with non-zero steering angle. The results and the KPI comparison are shown in figure 10 and 9.

The result of this maneuver are highly dependent on the tire model limitations, which introduces high wheel speed oscillation, excluding large quantities of data from the KPI analysis. The indexes for this maneuver are maximum brake pressure and sideslip angle, and the ratio between maximum yaw rate and steer angle. Again, the relative error is less than 10%.

![Brake in Turn KPI](image)

**Figure 9.** Brake in turn maneuver KPI comparison.
4.5. Driving feeling analysis

Given the good correlation attained during the previous maneuvers, our goal is to demonstrate the impact that the installation of the brake unit can have on the driver feeling.

A subjective comparison between driver feedback with and without the brake unit during the simulation has been carried out. The possible interfaces that the driver can have with the simulator are via steering wheel torque and pedal vibration. For this reason, a steering wheel sensor has been installed.

The same maneuver, a full brake event from the speed of 200km/h, is carried out on two different simulations; the first one has a model ABS system pre-installed on the vehicle model, which follows a longitudinal slip target, and the brake unit serves only as a brake pedal input for the simulation.

In the second, the brake unit is active, and the brake loop is closed on the caliper measured pressure. The time results are presented in figure 11.

The unit functioning is highlighted by a more realistic behavior and driver feeling: thanks to the high bandwidth of the steering bench, it is possible to observe higher frequencies of the steering wheel torque; this fidelity is demonstrated also with an higher frequency content of the steering wheel torque, as presented in figure 12.

![Vehicle Test](image1)

![Simulator Test](image2)

**Figure 10.** Brake in turn maneuver result.

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- [70x777]AIAS-2021
- [70x763]IOP Conf. Series: Materials Science and Engineering
- [284x763]1214 (2022) 012044
- [381x763]doi:10.1088/1757-899X/1214/1/012044
**Figure 11.** Model and HiL ABS comparison.

**Figure 12.** Steering torque frequency content comparison.
5. Conclusions
The validation process and the simulator setup has been presented. The test campaign results, summed up with the Key performances indexes, show that a good correlation between the unit behavior in the simulated and real scenario. Thanks to low error value between the KPI's, typically lower than 10%, we can affirm that this type of installation accurately reproduces the brake unit influence on the vehicle dynamics, thus allowing for reduced development time and cost of a commercial brake by wire unit; an higher number of driving scenarios can be investigated without the constraints typical for a real-world test campaign.

Moreover, this installation allows for a more immersive simulation environment, reproducing the correct driving feeling on this type of simulator where both the complete production steering and brake system are installed. Lastly, it is possible to compare the stock stability control performances with custom ones in a complete virtual environment.

It will also be possible to investigate the Advanced Driver Assistance System (ADAS) unit functionalities on the simulator, continuing the extension of driving scenarios that can be covered, as seen in [17]. Thanks to this, all the brake unit functionalities will be reproduced on the simulator, allowing for a complete and integrated testing of the product in a virtual environment, speeding up the development process.

Abbreviations
The following abbreviations are used in this manuscript:

- ABS  Anti-lock Braking System
- ADAS  Advanced Driver Assistance System
- AEB  Autonomous Emergency Braking
- ASIL  Automotive Safety Integrity Level
- BW  By-Wire
- BBW  Brake-By-Wire
- CAN  Controller Area Network
- ESP  Electronic Stability Program
- EPS  Electric Power Steering
- EPSiL  EPS in the Loop
- ESC  Electronic Stability Control
- HiL  Hardware in the Loop
- IMU  Inertial Measurement Unit
- KPI  Key Performance Index
- RT  Real Time
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