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Hardware-in-the-Loop Testing of a Hybrid Brake-by-Wire System for Electric Vehicles

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Abstract

Recent trends in automotive engineering, such as electrification and automatization, are opening chances as well as challenges due to the increased demand on new chassis components (e.g., drivetrain, brakes, steering, suspension, etc.) and control methods. This fast-growing market requires new methods to frontload as much efforts as possible to early design stages. The present article deals with a relevant case study on anti-lock braking system (ABS) design and tuning via hardware-in-the-loop (HIL) tests and rapid control prototyping (RCP) techniques on a hybrid brake-by-wire (BBW) system. Three types of wheel slip control algorithms are tested and benchmarked against each other. It was demonstrated that HIL simulations are suitable to develop vehicle subsystems and control strategies in a quite realistic manner even if the target vehicle or prototype is not available yet. Moreover, the benefits of continuous control approaches against classical rule-based wheel slip control were shown. In the article, aspects such as brake system architecture, control design, HIL testing environment, validation studies, and their analysis are further being discussed.

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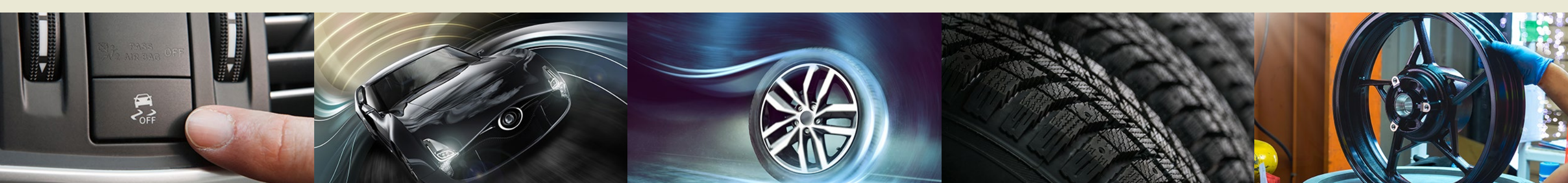


Introduction

The automotive sector is facing a paradigm change never known before. On the one hand, the outrunning reserves of fossil fuels and new climate-friendly policies are leading to an increased demand on alternative mobility solutions since many countries are limiting the release of vehicles with internal combustion engine (ICE). On the other hand, new vehicle and chassis designs—such as independent corner solutions for EV—are established, where more and more direct connections between driver and actuator are replaced by electronic components. These mechatronic systems, also called "X-by-Wire" systems, seem to become game-changers since they allow more efficient vehicle control with a higher operational speed for improving active safety, efficiency, and driving comfort [1].

Such a high impact is given by brake-by-wire (BBW) systems because new actuation concepts and more precise control on the calipers' clamping forces allow highly dynamic operation and enhances the functionality, e.g., by regenerative braking including regenerative anti-lock braking system (ABS), traction control (TC), electronic brake force distribution (EBD), or even electronic stability program (ESP) [2].

Moreover, a decoupled brake system architecture is beneficial for the use in electric vehicles for brake blending, where the driver's brake torque demand is divided and individually distributed between the electric machines and the friction brakes. Since the driver is not connected directly to the actuators, the pedal feeling can be freely adjusted, so that the blending stays unrecognized by the driver. Through blended operation of a BBW system in combination with a wheel-independent propulsion [e.g., in-wheel machines (IWMs)], remarkable improvements toward active safety, energy efficiency, fail-safety, and ride comfort can be achieved. Nevertheless, BBW systems have a limited use on serial vehicles yet due to the current maturity and the high impact of the systems on vehicle architecture.

For realization of BBW system, three main approaches are actually under development. Electrohydraulic brakes (EHBs) [3, 4, 5, 6] are predominantly being used now for BBW applications, due to the wide availability of components. In those systems, the driver's demand is detected by stroke sensors and then forwarded to an ECU. The ECU generates control signals for the actuators. Through the remaining hydraulic connection between the main cylinder and brake calipers, EHBs are fail-safe. Nevertheless, EHBs struggle with most of the disadvantages of conventional, hydraulic brake systems and low operational dynamics as compared to other types of mechatronic actuators that can be considered as disadvantage, e.g., for blended operation with highly dynamic IWMs.

Electromechanical brakes (EMBs) [7, 8, 9] allow faster actuation speeds and higher control dynamics, making them advantageous for electric vehicle applications. Moreover, absence of the brake fluid and hydraulic equipment makes the system integration (no pipes, no bleeding) easier and increases environmental friendliness. However, fully EMBs have strong functional safety requirements that should be considered already on early development stages. Even if the principle of EMBs offers technical advantages and the highest dynamics of the bespoken concepts, there is still a high demand for their further research and development due to the packaging and especially in the context of functional safety. Hence, hybrid systems as presented in [10, 11, 12] are the actual alternative combining partially higher dynamics of EMBs and also the fail-safety of EHBs in compliance with [13].

Besides the constructive aspects, there is still a lack in reliable control development and validation approaches for the vehicle motion control with BBWs as actuators. Especially different system dynamics and frequency ranges need to be considered for optimal blending and maximum energy recovery during controller design and tuning, but there is a limited number of studies in this regard. Mostly, rule-based methods are used in known applications because of their robust and real-time-capable performance. However, new mechatronic systems and the growing computational speed of embedded electronics also allow the usage of continuous control approaches, which are also more suitable by using BBW in the integrated vehicle motion control systems. In addition, remarkable progress for robust and real-time-capable control methods with the computational intelligence elements is also being observed [14].

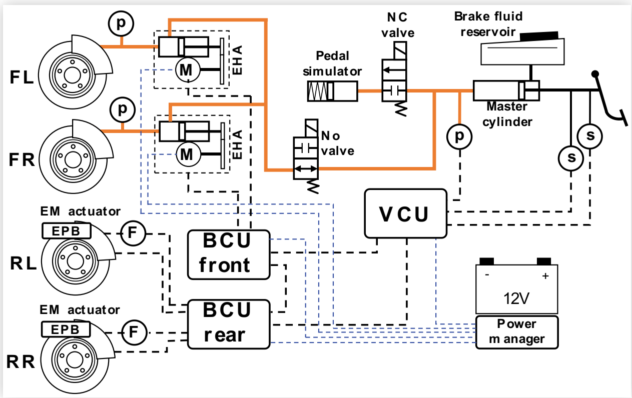
Due to the fact that the demand for more functionality of on-board systems is growing exponentially, innovative approaches for fast(er) control engineering are needed. Therefore, it is beneficial to shift tests of hard- and software to early development stages (frontloading) to save time and costs. Missing interfaces, sensors, subsystems up to whole vehicles can then be emulated in a virtual environment (e.g., vehicle dynamics simulations) via "X-in-the-loop" approach.

Studies on the benefits of X-in-the-loop simulations for active safety systems were already made in former publication for coupled [15, 16] and also BBW systems [14, 17, 18, 19, 20, 21]. Moreover, also other functions for electric vehicle (e.g., regenerative braking control) can be efficiently studied via hardware-in-the-loop (HIL) simulations [21, 22]. In this regard, the presented article introduces experimental investigations on an electric vehicle equipped with high-torque in-wheel propulsion and a hybrid BBW system featuring regenerative ABS and blending functionality. To solve the problem of fast, but also reliable controller development and parameter tuning under consideration of the actuators' dynamics and communication delays, the hardware-in-the-loop methodology has been used in this study.

Brake System and Control Architecture

As mentioned earlier, multiple design approaches and actuation possibilities for BBW systems are already well-established. The used hybrid system *Sensify*™ from Brembo S.p.A. contains a (wet) pedal simulator, EMBs with electronic parking brake

FIGURE 1 Simplified scheme of the used brake-by-wire system.

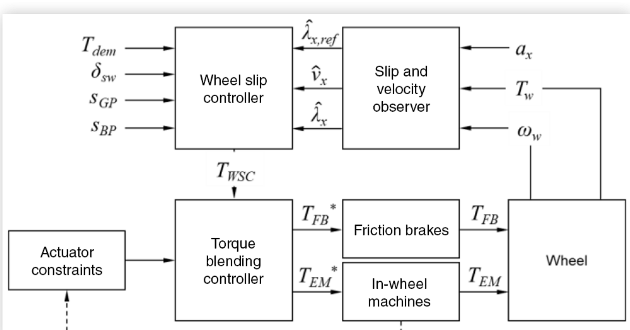


(EPB) device on the rear, and electrohydraulic actuators (EHAs) on the front axle. The maximum clamping forces are set to 47.7 kN for the front brakes and 23 kN for the rear brakes. This meets the requirement of stronger front brakes due to the shift of the dynamic wheel loads to the front corners during braking. The system is sketched in Figure 1.

Both axles are controlled by separate brake control units (BCUs), operating as "smart actuator," which means that they convert the external torque demand to pressure and force signals for the calipers. To fit the fail-safety requirements from [13] the system switches to hydraulic backup mode in case of power loss automatically, whereas the vehicle can still be decelerated with at least 0.25 g at a pedal force <500 N compliant to [23]. This is possible through the normally closed (NC) valve between master cylinder and pedal simulator as well as the normally open (NO) valve between master cylinder and EHAs.

For the presented case study, the ABS controller as well as the vehicle layout, introduced in [24, 25] and depicted in Figure 2, is used. Hatted values on Figure 2 declare estimated parameters. The block "wheel slip controller" corrects the torque demand (T_{dem}) by a reactive part to adapt it to the optimal wheel slip for maximum tire-road friction coefficient. The outcome is the corrected torque demand (T_{WSC}), which

FIGURE 2 Scheme of developed integrated controller structure.



gets forwarded to the "torque blending controller," where it is divided in a high-frequency part to be realized by the electric machines (T_{EM}^*) and a low-frequency part to be realized by the friction brakes (T_{FB}^*). The maximum motor torque is thereby limited by actuator constraints as the motor speed and temperature and other parameters, e.g., the state-of-charge of the high-voltage battery, which are considered by the so-called blending factor.

In the present study, the focus lies on the optimization of wheel slip control techniques especially tailored for use in EV. Therefore, two continuous approaches—PI and ISM—are benchmarked against classical rule-based control as described in [26]. All controllers are designed for minimizing the wheel slip error λ_e, which is the difference between the actual wheel slip $\hat{\lambda}_x$ and the reference value $\hat{\lambda}_{x,ref}$.

$$\lambda_e = \hat{\lambda}_x - \hat{\lambda}_{x,ref} \quad \text{Eq. (1)}$$

The value of $\hat{\lambda}_x$ can be calculated with the wheel speed signal (ω_w), wheel radius (r_w), and the longitudinal velocity ($\hat{v}_x$), which is derived from the longitudinal acceleration sensor signal (a_x). To avoid inaccuracies during overlaid states of longitudinal and lateral motion (e.g., braking in a turn), the wheel slip observation gets inactive if the steering wheel angle (δ_{sw}) exceeds a predefined threshold.

$$\frac{\omega_w \cdot r_w - \hat{v}_x}{\hat{v}_x} = \begin{cases} \hat{\lambda}_x < 0 \ \text{ if } \ T_w < 0(\text{skid}) \\ \hat{\lambda}_x > 0 \ \text{ if } \ T_w > 0(\text{spin}) \end{cases} \quad \text{Eq. (2)}$$

Depending on the sign of the wheel torque (T_w), the control can operate in the ABS and the TC mode. The latter case is not investigated in this publication. For detection of a switching case, the information from the brake (s_{BP}) and gas pedal (s_{GP}) are taken into account. Moreover, the gradient of the position signal indicates a "service" or "emergency" brake situation.

The proposed PI controller with anti-windup follows the control law in Equation 3

$$u_{PI} = K_P \cdot \left(\lambda_e + \int_t \left[\frac{\lambda_e}{t_i} - t_a \cdot sat(u_{PI}) \right] dt \right), \quad \text{Eq. (3)}$$

where K_P is the proportional gain and t_i is the time constant of integral part. Additionally, t_a is the time constant of anti-windup part, which shall reduce the integral error, in case of a saturating input signal.

As for the ISM controller, the general control law is given by the following equation

$$u_{ISM} = u_{PI} - \int_\tau \frac{K_{ISM}\, sign(s) + u_{d,fit}}{\tau} dt, \quad \text{Eq. (4)}$$

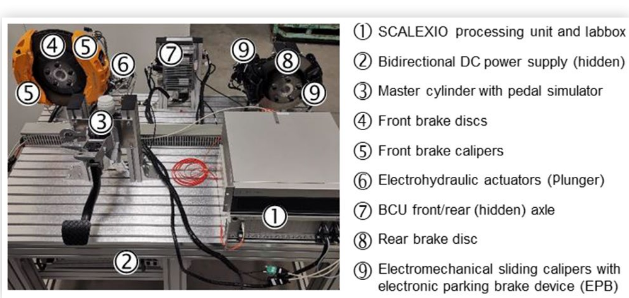
where $u_{d,filt}$ is the discontinuous control part, which is designed as the low-pass filter to reduce chattering. Further, K_{ISM} is the control gain, τ is the filter time constant, and s is the sliding variable, which depends on the wheel slip error and the reference wheel slip. These PI and ISM controllers are based on methods proposed in [29, 30].

Hardware-in-the-Loop Real-Time Environment

In this section, the HIL environment, used in this study, will be introduced. The methodology itself is already applied in different engineering disciplines for component development and validation. At its core lies the testing of real electronic devices (e.g., ECUs) in combination with a virtual vehicle (rest-bus simulation) for different purposes under real-world conditions. Adding other instances to the network and establishing a real-time-capable communication allows the user to build-up a decentralized testing environment as exemplary presented in [27, 28]. Therefore, HIL tests are advantageous for the development of electric vehicles with mechatronic components, where several systems can overtake multiple tasks at the same time and where parameter tuning can be very challenging due to, e.g., different system dynamics, latencies, and communication delays, which are hard to consider without the target components. For this reason, a new braking test bench (see Figure 3) was built-up and commissioned to enable HIL tests, containing the BBW system, a real-time processing device from dSPACE company, and a battery simulator. The different diameters of the brake discs (Front: 375 mm/Rear: 310 mm) are due to the requirement that the rear disc and actuator need to fit into the IWMs of the target vehicle. The harness is also identical to the target vehicle application to validate proper function.

The communication between the BCUs and the RT unit is done by 500 kBit-CAN and between the host and the RT unit by Gigabit-Ethernet. Through further Gigabit connection, the test bench can be connected to the internal VLAN to be part of the distributed X-in-the-loop environment at TU Ilmenau (see Figure 4). This environment allows to freely add other test benches and instances for different use cases. In the present case, only the BBW test bed will be used in combination with a virtual vehicle model, which is computed at a frequency of 1,000 Hz to ensure real-time capability. Due to the high dynamics of the electric machines that is nearly ten times higher than that of the brake system, the assumption is made that there are minor performance differences by using a model instead of real IWMs.

FIGURE 3 Test bed at TUIL with BBW system, RT hardware, and DC supply.



Experimental Investigations

Several straight-line braking maneuvers from 60 km/h to standstill under low (μ = 0.4), high (μ = 0.9), and split (μ = 0.4/0.9) friction conditions were performed in vehicle dynamics simulation software IPG CarMaker. The baseline vehicle model was experimentally validated in former investigations and enhanced by a new IWM-based powertrain model. The key parameters are included in Table 1.

For an objective evaluation of the tests, key performance indicators (KPIs) are defined and evaluated between the time point, at which braking is initiated ($t_0 = t(s_{BP} > s_{min})$), and the time point, at which the vehicle comes to standstill ($t_N = t(v_x < 0.1$ m/s)). The KPIs are explained next.

Braking Distance (Safety Criterion)

It defines the traveled distance during the braking maneuver.

$$s_{br} = s(t_N) - s(t_0) \qquad \text{Eq. (5)}$$

Mean Deceleration (Safety Criterion)

It defines the average value of the longitudinal acceleration during the braking maneuver.

$$a_{x,av.} = \frac{1}{N}\sum_{t=t_0}^{t_N} a_x(t) \qquad \text{Eq. (6)}$$

Yaw Rate (Stability Criterion)

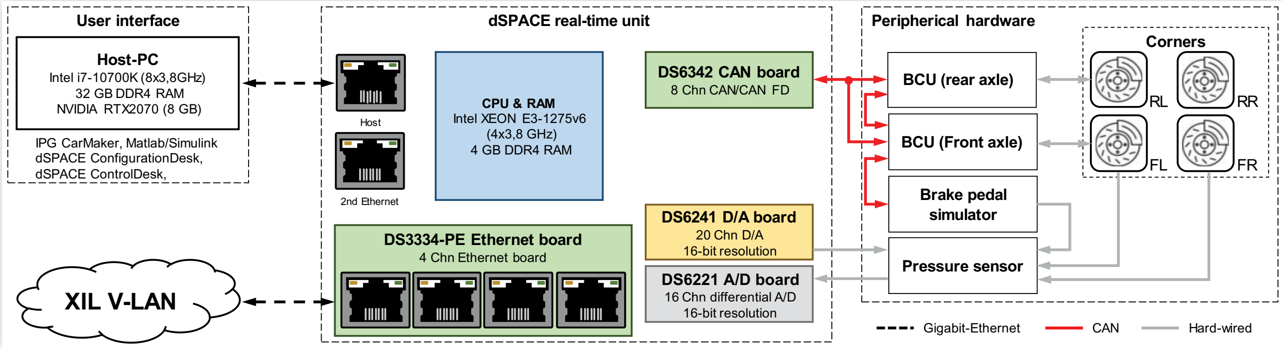
The yaw rate is the angle speed around the z-axis. For optimal performance, the vehicle must not yaw excessively during braking. This KPI is mainly relevant for the split-μ braking.

$$\dot{\psi}_{RMSE} = \sqrt{\frac{1}{N}\sum_{t=t_0}^{t_N}\left(\dot{\psi}(t) - \dot{\psi}_{ref}\right)^2} \qquad \text{Eq. (7)}$$

Vehicle Jerk (Comfort Criterion)

The jerk is the derivative of the longitudinal acceleration during braking and can deteriorate the ride comfort if there are heavy pulsations during ABS mode.

FIGURE 4 Schematic structure of the used testing environment.



$$j_{RMSE} = (\dot{a}_x)_{RMSE} = \sqrt{\frac{1}{N}\sum_{t=t_0}^{t_N}\left(\dot{a}_x(t) - \dot{a}_{x,ref}\right)^2} \quad \text{Eq. (8)}$$

Control Effort

The control effort is represented by the normalized integral of the absolute value of the control action (IACA).

$$\text{IACA} = \frac{1}{t_N - t_0}\int_{t=t_0}^{t_N} \left|\Delta T_{WSC}(t)\right| dt \quad \text{Eq. (9)}$$

Parameter Sensitivity Studies In the first step, the controllers' sensitivity to variation of control gains shall be analyzed, because even if the formerly used model of the BBW system was validated by the component supplier, it must be ensured that the actual controller tuning is not exciting any instable behavior of the system. Since it is not possible to show all the results achieved in the studies, only the most significant plots are outlined in Figures 5 to 7 for braking on low μ surface with active torque blending. The red bar depicts the initial controller tuning that was given by the MIL tests as reference for the further tests. It can be seen that both KPIs, the mean deceleration, and also the longitudinal jerk get beneficially influenced by higher gains for K_P and t_i. For the brake distance, higher gains are showing only minor effects, while lower gains are affecting a major performance degradation. Since the RMSE of the yaw rate is very low (<0.2 deg/s) for all configurations, this parameter gets neglected in the present case but is considered especially for the split μ maneuvers. The IACA for the IWMs is not showing any remarkable reaction to the parameter variation since their high dynamics allow very quick adaption of changing torque demands. More interesting is the IACA of the BBW system, since it reacts remarkably negative on low integration time constants (t_i). A reason therefore is that the controller can be excited, if the integration steps are too low, and—like in the present case—no derivative part is there to suppress this excitation. The excitation can only be mitigated by the anti-windup part, if it has a suitable time constant, too. In the present case, this was not the case.

As a benchmark, the ISM controller was analyzed too (see Figure 8). Contrary to the PI controller, the ISM does not show remarkable changes in its performance, if the gain K_{ISM} changes. This might be caused by the fact that it only affects the discontinuous part of the control, while the continuous part depends on the PI controller's tuning. Only some smaller improvements of the stability criterion seem to be possible for K_{ISM} = 200, 900, or 1000, but due the small amount, this KPI was neglected during evaluation. Moreover, further test on the controller with these parameters did not confirm the assumption.

From all the tests in the sensitivity analysis, the conclusion was drawn to adapt the control gains to the outcomes, means that all parameters of the PI controller get increased, while the gain K_{ISM} is kept constant at its former value.

Tuning Validation Tests Further tests were performed to validate the adapted tuning. To ensure statistic reliability, every configuration was simulated ten times. To evaluate ABS controls, a common indicator is given by *ABS Performance Index* (*API*) (see Equation 10) as the ratio of the average deceleration values (see Equation 6) in controlled and uncontrolled mode. For the present case, a Gaussian distribution is assumed, so the mean values of all ten test cases are used for calculation.

$$r_{ABS} = \frac{\bar{a}_{x,ABS}}{\bar{a}_{x,OFF}} \quad \text{Eq. (10)}$$

TABLE 1 Target vehicle parameters.

Vehicle curb weight	kg	2,500
Mass distribution front/rear	—	49:51
Wheelbase	mm	2,928
Tire dimensions	—	255/50 R20
Max. brake torque	Nm	4,000 (front)/1,600 (rear)
Max. motor torque	Nm	1,500

FIGURE 5 Sensitivity analysis of parameter K_P on μ = 0.4 road.

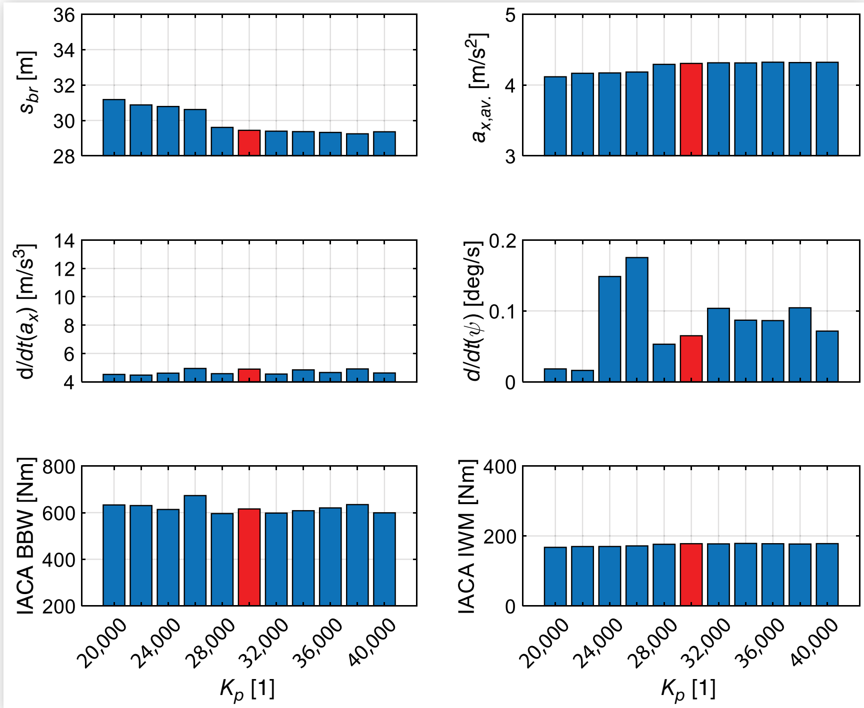


FIGURE 6 Sensitivity analysis of parameter t_i on μ = 0.4 road.

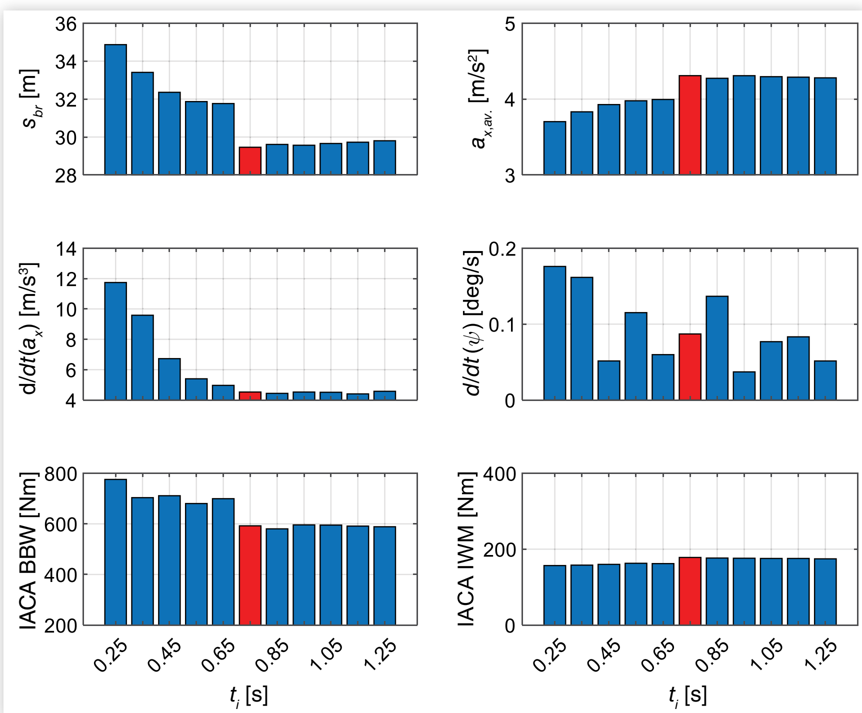


FIGURE 7 Sensitivity analysis of parameter t_a on μ = 0.4 road.

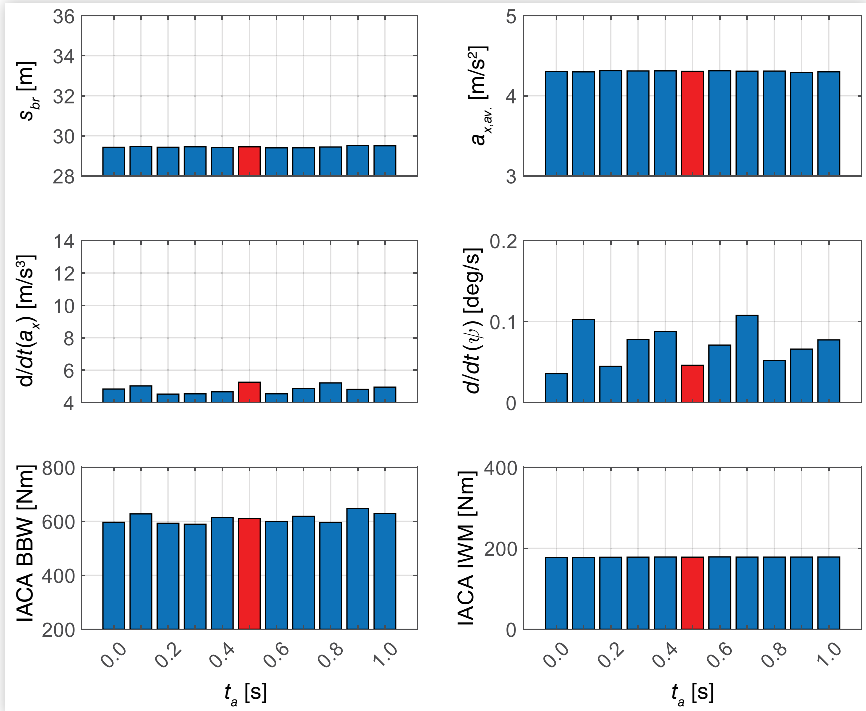


FIGURE 8 Sensitivity analysis of parameter K_{ISM} on μ = 0.4 road.

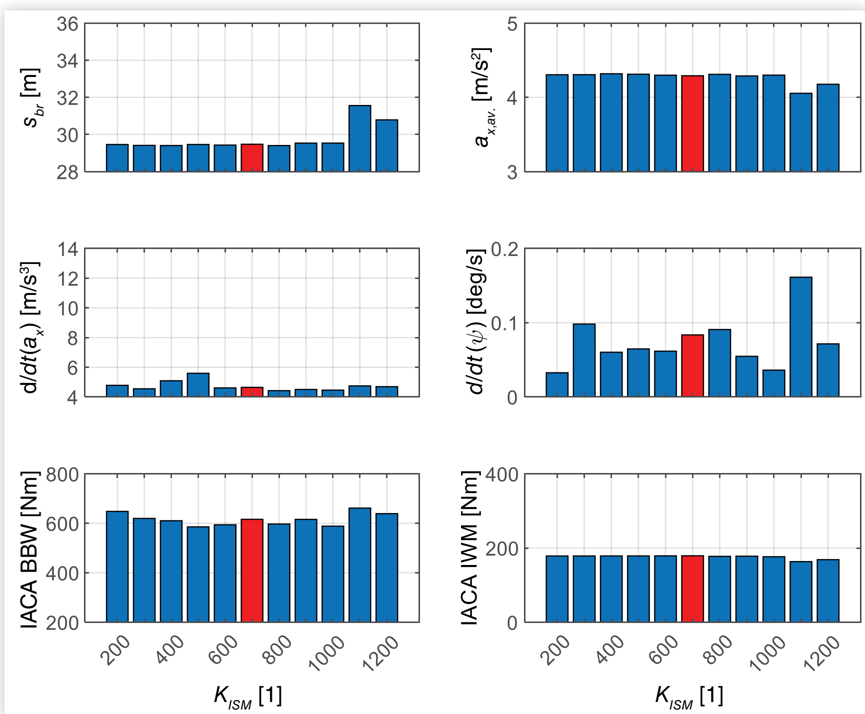


FIGURE 9 Results for API on low-, high-, and split-μ surface.

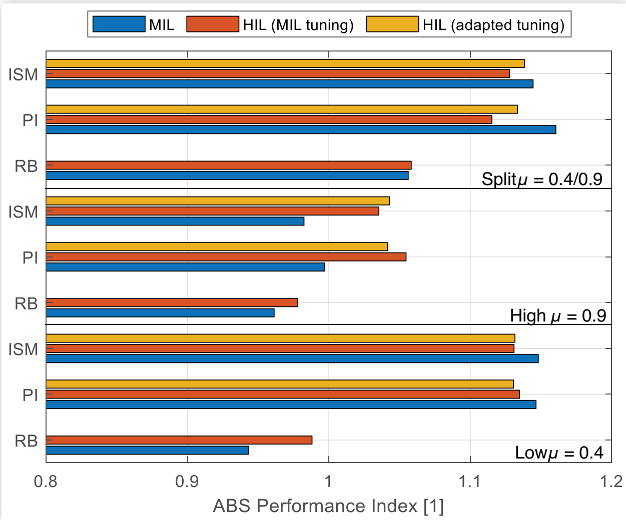


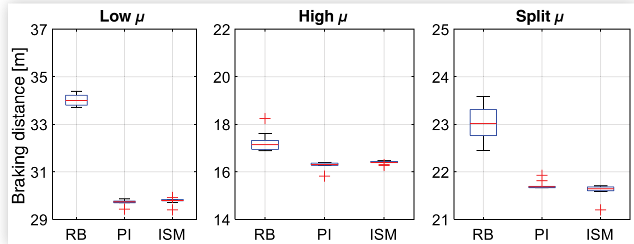
Figure 9 depicts the results in the investigated maneuvers. It shows the comparison between the MIL and the HIL simulations with unchanged and adapted gains. Since the tuning of the rule-based control was not changed during the experiments, there is no bar considering the new control gains. For the continuous approaches, the graphic shows a remarkable performance degradation especially for low and split μ conditions, if the old gains from the MIL experiments are used. By adapting the gains with the knowledge from the sensitivity analysis, this behavior was dissolved, so that the APIs in the HIL simulations are nearly equal to or better than the MIL results.

The differences can be explained with the differences between the MIL and HIL approaches: MIL is used in an early development stage in a virtual environment and normally without consideration of external (e.g., temperature, humidity) and internal (e.g., friction, wear, sensor noise) disturbances. As an example, Sensor noise can affect the control performance critically, but it has to be simulated in MIL tests.

Replacing the models by real target hardware in later development stages gives a more realistic and more reliable method of testing, since many parameters, which affect the results, are considered automatically through the use of hardware. Therefore, it might be necessary to adapt control gains to avoid performance degradation as seen from the results of the API calculation.

Since an evaluation based on the deceleration ratio is not expressive for aspects such as vehicle stability or other KPIs, additional parameters have to be considered. Figure 10 demonstrates the results for brake distance, where the rule-based control shows the highest amount and also the highest variance, while the PI and ISM controllers are characterized by less spreading. Moreover, the continuous approaches reduce the braking distance. Especially under low friction conditions, the average improvement is about 12.6% (PI) or 12.5% (ISM), respectively.

FIGURE 10 Boxplots of the braking distance for the different control methods.



Quite interesting are the results for vehicle stability criterion (yaw rate) under different friction conditions. Special focus lies on the results in the split μ maneuvers, because through the different friction coefficients on both sides the vehicle tends to turn around its z-axis. Under normal conditions and if the controller works properly, this yaw motion should be suppressed. Figure 11 shows the results for three control methods. As earlier, the rule-based controller keeps the vehicle on track, but at a medium-high yaw rate of 6.43 deg/s. By using continuous control approaches, this amount can be reduced by around 50% for split μ. Moreover, the deviation was decreased by 79.4% (PI) and 71% (ISM), respectively. The yaw rate analysis under low- and high-μ conditions is not relevant for this evaluation.

Besides safety and stability criterion, also the ride comfort shall be considered in the evaluation as well. Therefore, the longitudinal jerk is taken into account. Figure 12 shows the high potential of using continuous control approaches, especially on high μ the average jerk was reduced by 13.5% (PI) and 10.2% (ISM), respectively, which increases the ride comfort remarkably. For low μ, the results are showing even higher improvements with 20.9% (PI) and 19.3% (ISM). The experiments on split μ demonstrate less improvements, but for these conditions the vehicle stability shall be given more weight in the evaluation. For this background, the continuous approaches showed the best results as displayed in Figure 12.

Finally, the control effort for the BBW system shall be analyzed since it mainly influences the brake wear and also the energy consumption of the vehicle. Figure 13 gives an overview of the results for the implemented control methods: For low μ, the average IACA was decreased by 9.7% (PI) and

FIGURE 11 Boxplots of the yaw rate for the different control methods.

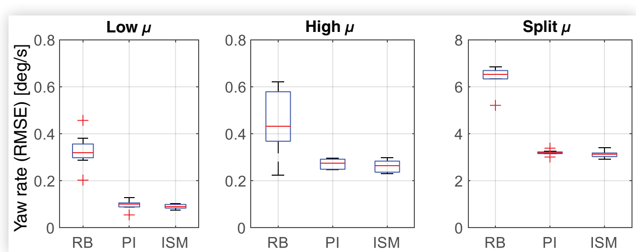


FIGURE 12 Boxplots of the longitudinal jerk for the different control methods.

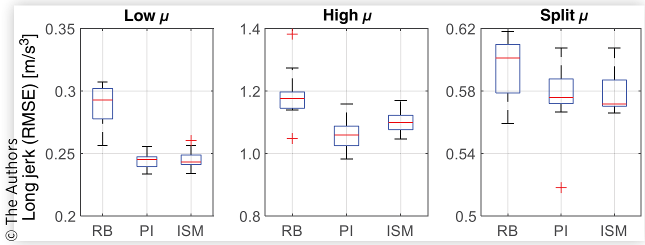
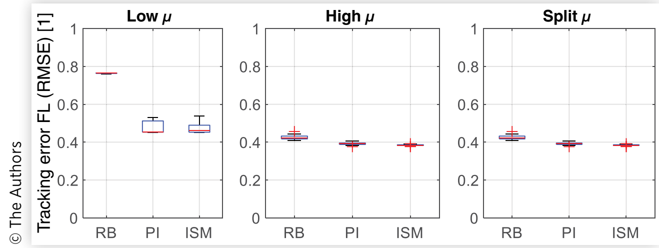


FIGURE 14 Boxplots of the wheel slip tracking error of front left corner for the different control methods.



11.3% (ISM), while for high μ the rule-based showed better performance.

These results can be explained by the difference between the rule-based and continuous wheel slip control principles: While the PI and ISM controller tracks the optimal wheel slip for the current friction conditions, the rule-based method uses a wider range of acceptable wheel slip to cover more scenarios at once. Since the wheel slip rises quite fast on high μ, the continuous tracking of the optimal wheel slip takes a lot more effort than rule-based control. Complementing these results, Figures 14 and 15 show that an average wheel slip tracking for the continuous approaches works better than for the rule-based control with a 7.8% (PI) and 10.1% (ISM) less tracking error for the front left (FL) corner. Through the high dynamics of the IWMs, the improvements for the rear right (RR) corner are even higher with 17% (PI) and 16.6% (ISM) less tracking error compared to the rule-based control. It has also been observed that the control effort shows the highest improvement on split μ road, where the average value decreases by 19% (PI) and 17.6% (ISM), while the average tracking error shows no remarkable improvement.

Summary/Conclusions

The present article introduced experimental studies on a hybrid BBW system following the HIL methodology. As case study, an integrated braking controller, featuring ABS and torque blending, was used. Moreover, two approaches for continuous wheel slip control were benchmarked against each other and against a classical rule-based controller. Contrary to the authors' former publication (see [24]) the simulation model was now replaced by the real target brake system using HIL simulations. The advantage of this approach is, that impacts of nonideal circumstances (e.g., system and actuator dynamics, temperature, pipe lengths, communication delays, latencies, compressibility of brake fluid and pads, etc.) become visible and can be considered in the parameter tuning. Even if this publication did not deal with the separate investigation of all those influences in particular, the results showed that there is a performance degradation in case of improper tuning through MIL tests only. To resolve this, decision was made to adapt the control gains for achieving better control performance.

Therefore, a parameter sensitivity analysis was done in the first step to investigate the influence of varying control gains on the overall performance of the controller and to identify instable configurations. It was shown that for PI control especially the integration time has the highest impact on the results, because quite low time constants are leading to a system excitation, while middle or high gains might have beneficial impacts. Similar behavior was identified for the proportional gain. For the ISM controller, the variation of the gain K_{ISM} showed no remarkable impact on the performance, so the decision was made to keep the parameters from the MIL tuning.

To validate the new tuning, multiple simulation-based straight-line braking maneuvers were performed under different friction conditions on the HIL test bench. Within those tests, former results with regard to the benefits of continuous wheel slip control were confirmed. In the present case, the controller reduced the braking distance by ca. 12% and

FIGURE 13 Boxplots of the BBW IACA for the different control methods.

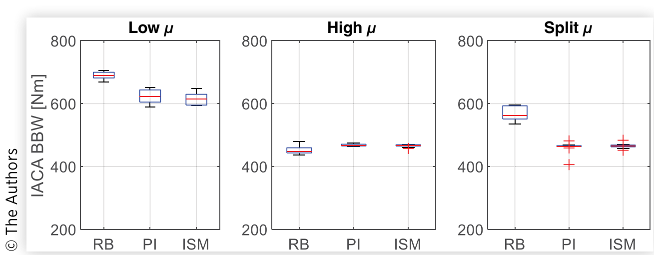
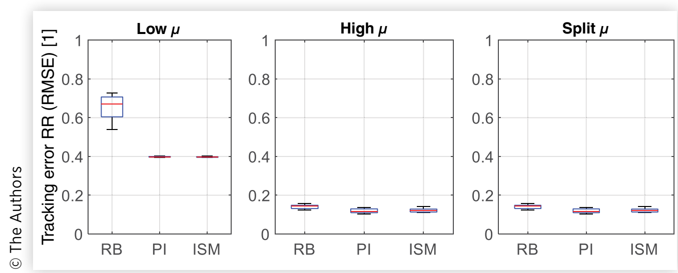


FIGURE 15 Boxplots of the wheel slip tracking error of rear right for the different control methods.



the yaw rate by over 50% and improved ride comfort through 11%-16% less longitudinal jerk. Especially under split μ conditions, the benchmark showed remarkable improvements toward vehicle stability.

Even if these studies had a lot of output, some open points are left. The experiments were only done at one initial speed, so future work shall include experiments with other speeds for improved reliability. Moreover, robustness should be confirmed through experiments on road with randomly placed friction patches. Alternatively, there can be experiments with spontaneously changing friction conditions during the brake maneuver.

The tests in this publication still used a model for the IWMs. This model should be replaced by a real-time-capable connection between the brake system and in-wheel test bench to investigate the impacts of the actuators' different frequency ranges and to ensure that the control gains are not affecting the dynamics due to instable poles.

Finally, the controller should be tested on the target vehicle to validate/revise the results achieved so far under real conditions, with special interest on other influences, which were not considered yet, e.g., brake temperature, pad wear, inhomogeneous friction conditions, and the like. Besides the use case of anti-lock-braking and brake blending, also other use cases, e.g., fail-safety studies are quite interesting. Those investigations are under final experiments and planned for future publications.

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Definitions/Abbreviations

API - ABS Performance Index

BBW - Brake-by-Wire

BCU - Brake Control Unit

CAN - Controller Area Network

EHB - Electrohydraulic Brake

EMB - Electromechanical Brake

IACA - Normalized Integral of the Absolute Value of the Control Action

ISM - Integral Sliding Mode

IWM - In-Wheel Machine

PI - Proportional-Integrate

RMSE - Root-Mean Square Error

VLAN - Virtual Local Area Network

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