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Validation of a Bicycle Dynamics Assistance System Using Hardware–in–the–Loop Simulation

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ABSTRACT

This paper describes a Hardware-in-the-Loop (HiL) test bench developed at the UAS Pforzheim to aid in the model based design of a Braking Dynamics Assistance System. It uses a real world hydraulic bicycle brake in combination with an equation based bicycle model. The requirements originating from the model based design approach and their implications for the logical and technical design architecture of the test bench are discussed. The final hardware and software integration of the test bench are described. The HiL test bench facilitates the validation of the physical MiL simulation model also used in the research project. The controller developed with the validated MiL simulation model is able to achieve good results in HiL validation and later RCP testing.

Keywords: Bicycle Dynamics, Model Based Development, Hardware in the Loop Testing, Bicycle Safety, Pedelec.

1 INTRODUCTION

Overall road safety is improving. However, the decline in road fatalities is mostly caused by decreasing numbers for passenger car occupants. In comparison, safety for vulnerable road users (VRU - pedestrians, cyclist, and motorcyclists) is improving at a much slower rate. According to surveys done by the EU, 45% of traffic fatalities belong to this group [1], with cyclists bearing a disproportionately high risk. In Germany, cyclists cover 1/30 of traffic distance, but are victims of 1/8 of road fatalities [2]. The decline in fatalities for passenger car passengers is partly caused by the increased application of active safety systems. Starting with anti-lock braking in the 70s, passenger cars of today can be equipped with a large variety of active safety features, some even allowing for level 3 autonomous driving. In the EU, anti-lock braking for motorcycles is mandatory since 2017 as a first step to improve the safety of VRU.

Pedelecs currently undergo a huge growth in popularity, with a growth rate of 36% for 2018 in Germany, while the overall bicycle market is growing at less then 9% [3]. The electrification of bicycles facilitates the implementation of active safety systems for this group of VRU.

Research Project BikeSafe
The BikeSafe project was employed at the UAS Pforzheim with the goal of developing a prototype for a system providing anti-lock braking and rear wheel lift-off mitigation, called Braking Dynamics Assistance (BDA) [4]. For the rider, front wheel lock-up is generally much harder to control than rear wheel lock-up. Furthermore, modulation of the front wheel's braking torque can be used to prevent rear wheel lift-off. Therefore, pressure modulation of the hydraulic brake commonly found in pedelecs was chosen to accomplish the given task. For pressure modulation, a pumpless

system based on the Bosch motorcycle ABS 9.1M base unit was used. All simulations and tests are conducted as braking maneuvers. Acceleration up to the starting speed of the test is not considered in simulation and not recorded in real-world testing.

One challenge is the validation of the overall system over a wide range of parameter values such as mass of the driver, braking forces, initial speed, coeffient of friction between tyre and road, frame geometry etc. Real world experiments are not suitable as they are too dangerous, hardly reproducible and in particular only few parameter configurations could be tested. Hence, a Hardware-in-the-Loop (HiL) test stand was set up for system validation. HiL testing is a standard procedure in many areas such as in the automotive industry [5]. Yet hardly any usage for bicycle systems is reported.

Model Based Development

Braking dynamics assistance systems are common in the automotive industry. For the development, the V-model is employed as process framework using model based design as an integral methodology. In doing so, tools such as HiL testing are employed for system validation. One of targets of the BikeSafe project is to transfer this methodology to the development of bicycle safety systems.

Two different models for longitudinal dynamics for the bicycles dynamic behaviour were developed. The first is a detailed multi body system, comprising a simple rider model as well as the bicycle parts. It consists of 15 bodies and 19 joints with no friction. The bicycle tyres are modeled using Pacejkas magic formula. The hydraulic brake system model consists of brake lever, pistons, pipes, sensors, and fittings and is implemented using Simulink Simscape. The multi body system is described in [6] in detail. The second model is based on differential equations and is described in detail in [7]. It consists of four rigid bodies: rear frame with rider, the fork and the two wheels. The slip characteristic is represented via the approximation described in [8].

Hardware-in-the-Loop Simulation

Particularly in system testing, HiL simulation is an integral part of verification and validation. For the BDA, these tests ensure that the system achieves the goals of anti-lock braking and rear lift-off mitigation for a variety of parameter configurations, including such that are hard or even impossible to achieve by real world tests. Model in the loop (MiL) simulation is a predecessor step to HiL testing. In our research the main source of model errors is the simulation of the hydraulic brake, because a dependable simulation of the hydraulics system requires a sophisticated hydraulics model with a large number of hard to get parameters and will not run in real time on the target platform. Therefore, the HiL test bench combines the real hydraulic system used in the RCP bicycle (Magura MT-2 brake lever with MT-4 caliber) including the hydraulic unit (HU) as an actuator with the second simulation model of the bicycle. With this setup, the control algorithms can be tested with a real bicycle brake while the parameters of the driving situation still can be varied easily.

2 BRAKING DYNAMICS ASSISTANCE SYSTEM

The BDA serves two purposes, namely the prevention of a front wheel lock up and the avoidance of a vehicle nose over. Both functions operate independently. The front wheel lock up prevention requires front wheel speed (ω_f) and vehicle acceleration in logitudinal (x) direction (a_x) as inputs. The functional design follows the principal idea of an ABS known from the automotive industry (cf. [10]). The newly developed rear lift-off mitigation function relies on the pitch rate measured at the vehicle body. To distinguish a nose over motion from a sudden downward movement of the front wheel (e.g. when riding down a curb or rolling over a knoll) acceleration in z direction is also required. A detailed discussion of the BDA function can be found in [4] or [9].

3 MATERIAL AND METHODS

3.1 Requirements

The test bench is designed to be used for function development. Therefore, a smooth transition from HiL to real-world experiments using the method of rapid control prototyping (RCP) is indispensable. Hence, methodical and technical requirements have to be met. The methodical requirements are derived from the model based design approach:

1. Controller validation
   The HiL test bench must allow the same parameter variations as the MIL simulation, preferably using the same simulation model. Furthermore, the control algorithms should be transferable between MiL, HiL, and RCP.
2. Model validation
   Besides function development, the test bench should also be usable to validate the simulation models. On the one hand, the physical brake model used in the MiL simulation has to be validated using the HiL simulation. On the other hand, the simulation model used in HiL should be validated with the real-world experiments.

In order to conform to these methodical requirements, a set of technical requirements must be met. The same control unit has to be used in both HiL and RCP testing. Therefore the same interfaces as in the real vehicle must be provided for the control unit on the test bench. Tests executed with MiL simulation also have to be reproducible using the HiL test bench. To facilitate this, a Data Management Program (DMP) was developed. The work with DMP is illustrated in figure 1.

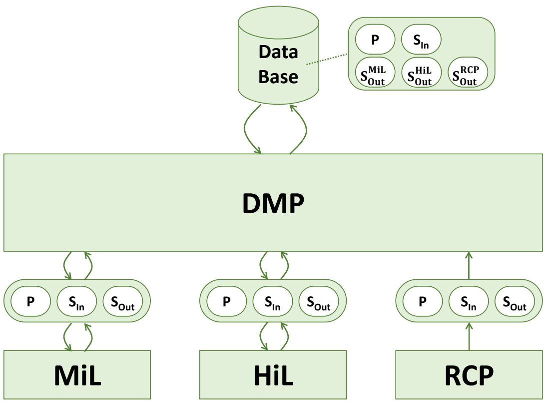

Figure 1: Structure of the Data Management Program.

When doing real-world experiments (in this case using RCP methodology) parameters (P) and input signals ($\mathrm{S_{In}}$) are determined by the experimental setup. This is indicated by the unidirectional arrows. The input values together with the resulting output signals ($\mathrm{S_{Out}}$) are stored in the data base as a data set. Similar handling applies for MiL and HiL setup except for the fact that P and $\mathrm{S_{In}}$ can be varied arbitrarily (indicated by pairs of arrows). When using an already existing experiment for MiL or HiL simulation DMP stores the additional output signals to the same data set to facilitate comparison (denoted by the superscript in the data set of the data base).

To cover a large amount of scenarios during function development the bicycle models have to be configurable with varying parameters. The varied parameters on the HiL are road surface properties, road slope, mass of the rider, frame size and initial velocity of the braking maneuver. For reproducible test results, the HiL system must provide the automatic actuation of the brake lever. In addition it should be possible to brake manually to provide the manual feedback when the system is engaged for subjective evaluation.

For real-time simulation the bicycle models also have to be computable and stable for fixed-time solvers as simulation on real-time platforms always runs with fixed step-times. The sensor signals and the connection to the HU must be provided and connected to the control unit. Relevant sensor values for the BDA function are actuation pressure, brake pressure, brake trigger, wheel speed of front and rear wheel as well as acceleration and rotation signals for all vehicle axes. These measurement values have to be captured and saved for further investigation and retracing of experiments.

3.2 Logical System Architecture

All functions needed to meet the mentioned requirements are structured in the **logical system architecture** of the HiL test bench. These functions are employed using real world components (such like signal generator, computer, and hardware installation). The functions of the logical architecture are then assigned to system components which leads to the **technical system architecture** of the bench, which also includes the interface definitions. The logical architecture of the test bench is shown in figure 2. All functions belonging to the (real time) control loop are enclosed by the red rectangle.

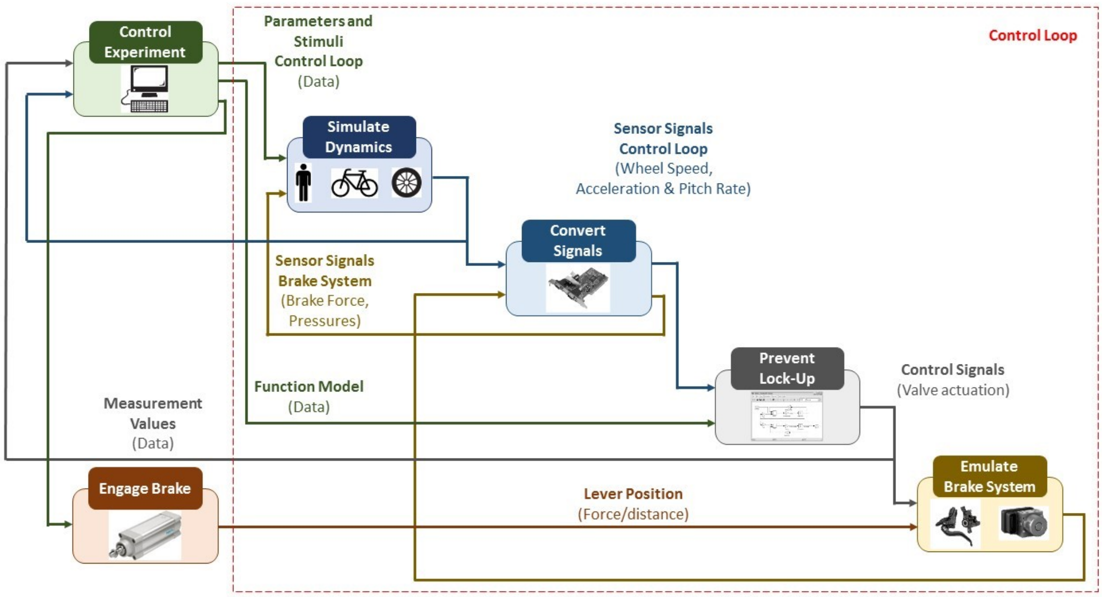

Figure 2: Logical Architecture of the HiL System.

Simulation of the bicycle dynamics is calculated within the function *Simulate Dynamics*. The model of the controlled system including bicycle, driver, tyres and road surface used for the HiL is the second model consisting of for rigid bodies. The driver is represented by a single mass point in this model. By setting parameters accordingly different drivers (mass and height), bicycle frames, and road surfaces can be simulated. Signals produced by the model are also recorded for validation purposes. Some of them need to be represented by real signals as required and real world signals need to be read in - in particular when interacting with the controller under test. This is done in the main function *Convert Signals*. The function *Emulate Brake System* represents the function of the hydraulic system. The function receives the control signals for the HU as an input along with the actuation of the brake lever (lever position). The output of the function are sensor signals measured at the brake system which comprise the brake force employed on the brake disc as well as hydraulic pressures. For function development in BikeSafe only the brake system of the front wheel is of relevance. The main function *Prevent Lock-Up* represents the controller to be developed and therefore closes the control loop. The inputs to this function are the sensor signals from the control loop. Signals for controlling the HU are emitted. The measurement signals of the experiment are recorded here. Generation of the parameters along with parameterisation of the bicycle model is handled by the main function *Control Experiment*. To control the experiment sub-functions for starting and stopping need to be employed. The model needs to be parameterised and stimuli have to be provided for each scenario under test. Resulting signals need to be stored for further evaluation. To compare experiments throughout the whole development process data is converted into comma separated values which are used project-wide, also in MiL and RCP experiments. Data is organised in the BikeSafe tool DMP discussed earlier.

3.3 Technical System Architecture

The Technical System Architecture depicted in figure 3 implements the functions of the logical architecture.

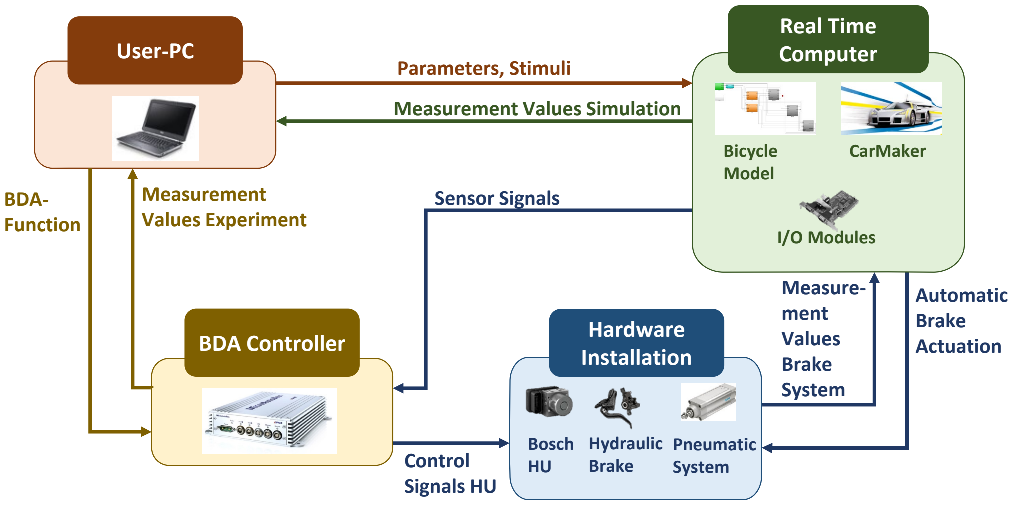

Figure 3: Technical Architecture of the HiL System.

The Real-Time Computer is an Xpack4 by IPG comprising a 32-bit Single-Board-Computer running Linux with Xenomai real-time modification. Simulation of the bicycle model is done by a fixed calculation step 4^{th} order Runge-Kutta solver with a step size of 1 ms. Software integration of the Simulink model is done using a block set maintained for IPG CarMaker. Tyre slip curves for a low, medium and high friction track are included in the model and can be selected via a separate parameter. Simulation starts with an initial speed (parameter) of the bicycle and stops when the velocity of the front wheel (speed-over-ground) is below 4 km/h (lock up prevention) or when the rear wheel is back on the ground (rear lift-off mitigation). The computer is extendible by several different I/O-Modules for generating and measuring the required signals.

In order to simulate the hall sensors for wheel speed measurement, two 7/14 mA current signals need to be generated. In BikeSafe impulse wheels with 60 teeth are employed. Analogue channels are used for the brake force sensor and the brake actuation. Finally, standard a CAN interface is used to simulate the signals of the pressure sensor at the front wheel brake (1 ms sample rate), brake and actuation pressure sensors (10ms each), and the 5D-sensors (5ms). The 5D-sensor (Bosch MM5.10) is used to measure acceleration in all three axes and pitch- and yaw-rate.

In BikeSafe the controlled system usually comprises the driver, vehicle, wheel and road. On the HiL test bench the control loop is divided into two parts. The hydraulic brake system is integrated as a real hardware installation whereas the rest of the vehicle including driver, road and tyre behaviour is being simulated. The Hardware-Installation implements the same hydraulic brake system of the front wheel as used in the experimental vehicle (depicted in figure 4. A hydraulic unit (HU) by Bosch is integrated to perform the brake interventionsaction , which are triggered by the BDA-Function. Within the brake system, there are two pressure sensors, one close to the brake lever and one close to the brake caliper. Those are not necessary for the BDA functionality but useful for validating the MiL simulation.

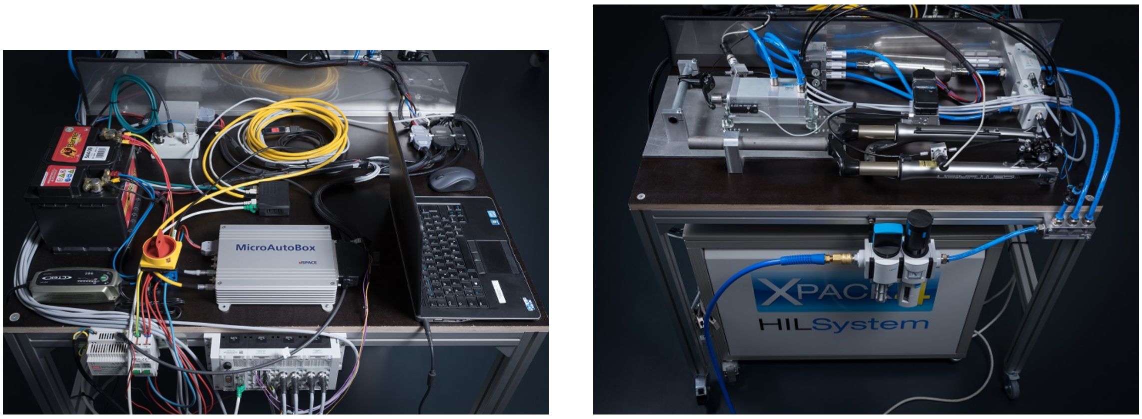

Figure 4: Hardware installation of the HiL test bench.
Left: Electric part of the HiL. The MAB in the centre implements the controller function.
Right: Installation of the hydraulic brake. The brake lever is mounted on a tube on the left side. The pneumatic cylinder can automatically actuate it while leaving enough room for manual actuation. The pneumatic system can be deactivated by the rotary switch at the front. The brake caliber is mounted on the bicycle fork and the force sensor is mounted between the braking pads.

On the HiL test bench actuation of the bicycle brake can be done in two ways, namely manually or automated. The brake lever is freely accessible on a tube so the user can actuate it manually. To enable automated actuation a pneumatic system was developed in cooperation with Festo AG. It is a hybrid system with two energy storages and two actuators. A pneumatic ADNM cylinder with two chambers and a SMAT positioning sensor is used as the actuator. Brake gradient can be adjusted by changing the used maximum pneumatic pressure. To avoid inducing damage to the brake system the displacment of the cylinder is controlled. After reaching the defined distance the pneumatic pressure is cut off to hold the brake lever at its current position. In that way behaviour of a human rider can be emulated. Automatic brake actuation is triggered by the real-time computer.

The brake caliper represents the boundary between simulated part and real-world part of the controlled system. A piezo sensor is mounted between the brake pads to measure brake force. The overall transmission ratio i_{total} is about 21. This transmission ratio includes the transmission from brake lever to master piston as well as from master piston to slave piston. The maximum actuation force is estimated to be about 200 N. This results in a one-sided clamping force of about 3780 N. The sensor employed (a PACEline CLP/7kN by HBM) covers a measurement range up to 7kN. This small-sized component (only 3 mm height) is mounted between the brake pads. The sensor's sensitivity is stated to be 4.3 pC/N. A charge amplifier (PACEline CMD600 by HBM) converts the sensor value to an analogue signal ranging from 0 V to 10 V. To cover the full measurement range the amplifiers range is set to 4.3 pC/N · 7 kN = 30.1 nC. The amplifier's output resolution is 12 Bit for the full range (-10 V to +10 V). Thus, resulting resolution of the force measurement is about $7\,\mathrm{kN}/2^{11} \approx 3,4\,\mathrm{N/Bit}$ which is precise enough for the model.

On the User-PC the project-own tool DMP is running to import and organize all measured data. An input mask of the tool is also used to generate parameter files. This mask is common to both HiL and RCP experiments. The simulation on the real-time computer is controlled using IPG software CarMaker 4.5.5/HIL. CarMaker allows for starting and stopping of the simulation as well as loading the bicycle model and parameters to the real-time computer. ControlDesk 5.1 by dSPACE is used to control the MicroAutoBox. Likewise the software provides starting and stopping of the BDA-function along with loading the function to the control system. The dSPACE MicroAutoBox II serves as the control system. Sensor signals from the hardware installation and from the real time computer are processed and control signals to the HU are generated. The control unit executes the BDA function and also records the simulation results.

4 RESULTS

The equation based bicycle model was validated in two steps. First the simulation model for MiL experiments was validated against the real-world experiments. In a second step the bicycle model on the real-time computer of the HiL test bench has been validated against the MiL simulation. Details on the results are presented in [9]. Figure 5 depicts an open loop experiment (i.e. the BDA function was not activated) executed on the HiL. As the front brake pressure is rapidly raised to about 100 bar by actuating the brake lever, the circumferential velocity of the front wheel is breaking down to zero. This means that the front wheel locks up and a critical situation occurrs. Thus, the critical situation of a front-wheel lock-up can be simulated using the HiL test bench as described before.

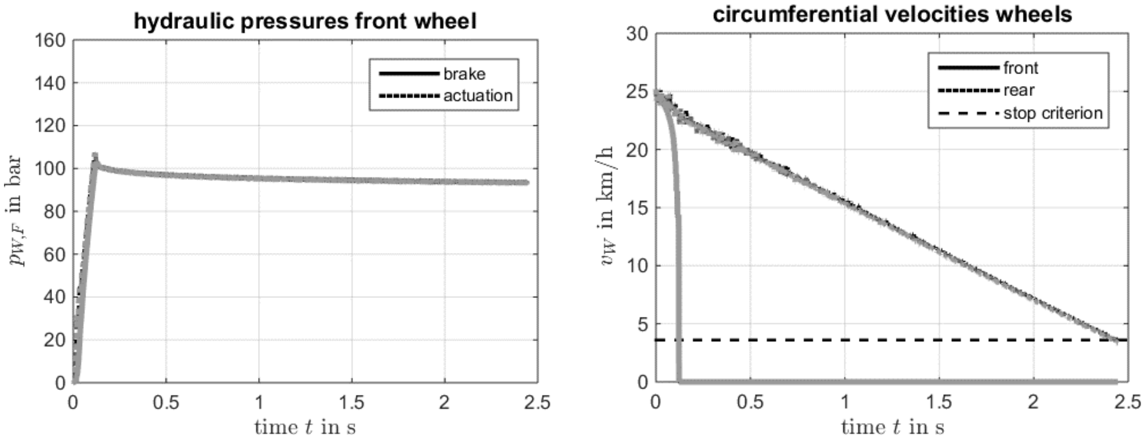

Figure 5: Experiment for validation of the HiL test bench. The left plot depicts pressure at lever and at brake. The right shows the circumferential wheel speed. Obviously the front wheel locks up upon brake actuation.

Next the BDA function is activated. Results obtained at the HiL are compared to MiL simulation runs. Figure 6 depicts the hydraulic pressure at the brake caliber for two experiments employing different actuation forces. One can observe the pressure drop due to the BDA function. The physical model used in the MiL simulation shows similar results to the measured pressure at the test bench. However, the high transient pressure drops off after opening the outlet valve are not modelled accurately in the MiL.

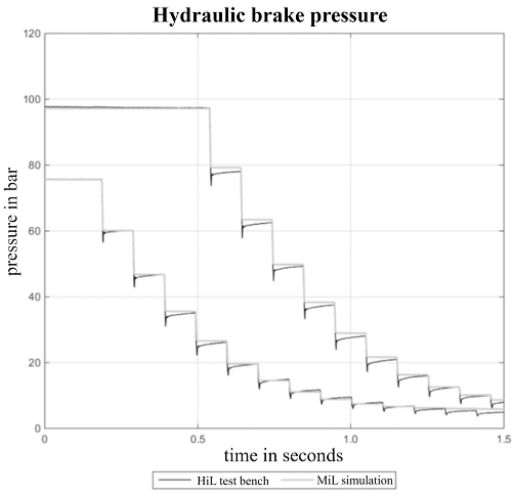

Figure 6: Comparison of HiL and MiL experiments. Hydraulic pressure at the brake caliber for two braking maneuvers with BDA intervention, starting at two different actuation pressures. The MiL simulation achieves similar pressure plateaus but is not able to accurately portray the drops in pressure after opening the outlet valve.

Figure 7 shows the hydraulic pressure at the front wheel and the circumferential speeds of both wheels. The control system also used in RCP testing is active and validated here. Employing the lock up prevention function makes exact repetitions of experiments harder as small deviations in initial pressure lead to significant changes. In the third experiment (light grey line), a lower initial actuation pressure leads to less drop of pressure upon system intervention. This results in a higher remaining pressure in the pumpless system. Hence, the stop criterion is reached ealier in this case.

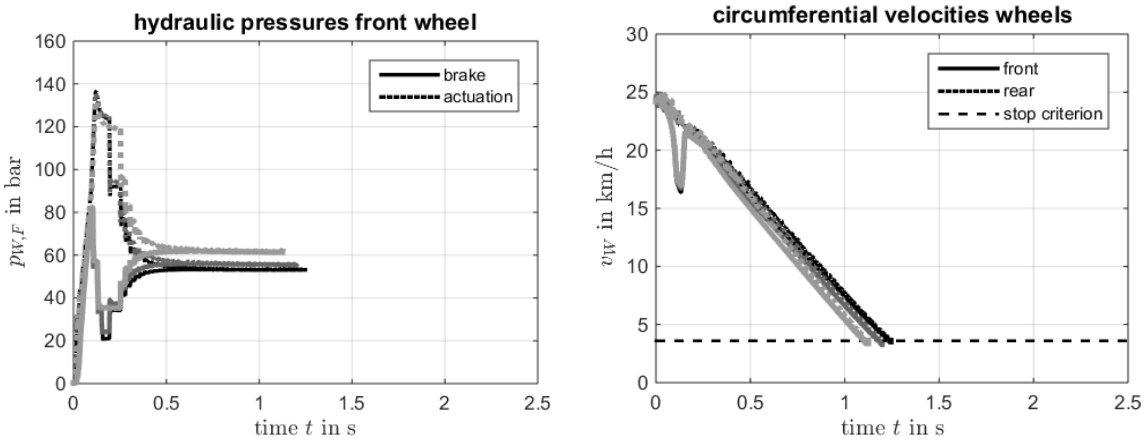

Figure 7: Three test runs (black, dark grey, and light grey lines) on the HiL test bench. The left figure depicts the pressure at the lever (dotted line) and at the caliper (normal line). The right figure shows the resulting circumferential speed of front (normal line) and rear (dotted line) wheel.

The wheel-speed graph shows that the control function is able to successfully prevent front wheel lock-up. Furthermore, the BDA function reduces the braking time from more than 2 seconds for the uncontrolled system (cf. figure 5) to about 1.2 seconds.

The HiL test bench was used for integration test of the system for two reasons. Firstly, it makes use of all sensor signals as on the test carrier and secondly, the hydraulically actuated brake and the hydraulic unit for pressure modulation are identical to the one on the test vehicle. The verification of the interaction of sensors and function showed no abnormalities since errors were already eliminated during module and software integration tests performed earlier with measured data recorded in the driving test. The only modification necessary was with respect to the adaptation of the computing priorities of the sensor signals in the functional model. The highest priority was assigned to the processing of the speed sensor on the front wheel on the basis of hardware interrupts, followed by the inertial sensor system of the bicycle assembly, the calculation of the control algorithms and the actuation of the actuators.

The experiments depicted in 7 show that the control function developed in MiL simulation also passes the HiL test with the real brake hardware. Moreover, the HiL testbench allows for fast variation of parameters. To cover a wide range of possible variations a catalogue of maneuvers was developed based on a reference experiment. Parameters such as initial speed, road surface (i.e. coefficient of friction), payload, actuation pressure etc. are modified one at a time compared to the reference value.

Three quantitative requirements of the BDA anti lock-up function were defined to assess system validation. The *braking distance* is the distances travalled after start of the maneuver until the bicycle comes to stop. The *lock-up duration* is the total time at which the front wheel speed is zero while the bicycle still moves. And finally the *lock-up time* is the time from initial brake actuation to zero front wheel speed (in case of open loop) or (in case of closed loop) to the first control intervention of the BDA.

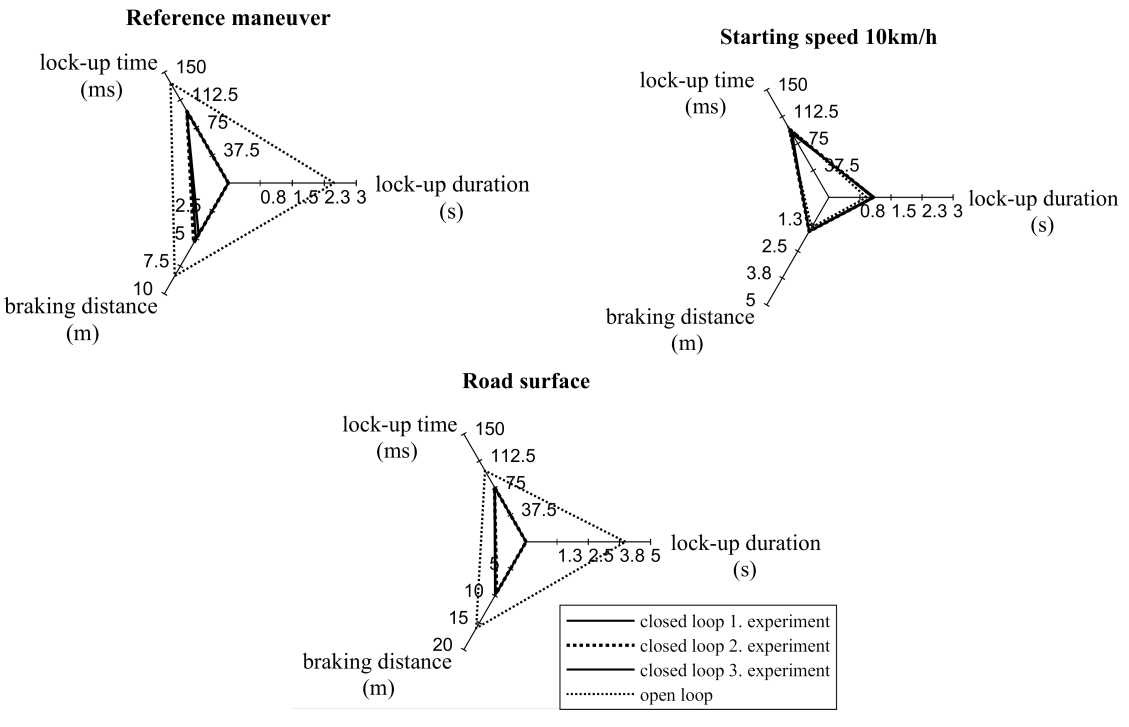

Figure 8: Results of three tests of the anti lock-up function with varying parameters (reference, lower initial speed, and low friction surface).

All parameter variations defined in the virtual driving situation catalogue in [9] (except for the variation of the payload) have been tested on the HiL. As an example the results of three different configurations are displayed as network diagrams in figure 8. As a reference the behaviour of the open loop system (i.e. no BDA function employed) is also depicted.

The network diagram of the reference drive maneuver with an initial speed of 25 km/h shows that the lock-up time and the braking distance in the closed control loop are smaller than in the open loop control. In addition, the lock-up duration with the anti-lock function active is zero. In sum, all requirements are fulfilled. At an initial speed of 10 km/h, the anti-lock function is not able to fulfill its function and the front wheel is locking up. Due to signal propagation delays and signal processing times the collapsing of the front wheel velocity is recognized later than on MiL. The variation of the friction coefficient represents a particular difficult case for braking assistant systems, as the wheels lock-up faster (see lock-up times for the open loop configuration in figure 8) and take a longer time to regain speed and therefore traction after brake pressure reduction. The traction coefficients where changed from slippery to very slippery (coefficient of adhesion from 0.7 to 0.5, coefficient of friction from 0.4 to 0.3). The control function is still able to completely prevent lock up and significantly improves the braking distance. Apart from the strong speed dependency of the BDA, which is to be tested in the driving test, the function shows satisfactory results and fulfills the requirements regarding lock-up time, lock-up duration and braking distance in five of seven driving situations.

In the same way tests were executed for the rear wheel lift-off mitigation function. The results of three tests with the reference configuration are shown in figure 9. Rear wheel lift off is observed as one can see in the pitch rate. Using that signal the BDA function estimates the pitch angle using a window integral value. When the critical situation is detected (by observing the front wheel acceleration) the pressure first is held (depicted by status '2' of the HU in the lower right figure). Only when the critical values for pitch rate and pitch angle are reached pressure is lowered by opening the respective valve (HU status '1'). As a consequence the rear wheel returns to the ground as can be seen in pitch anlge and rate.

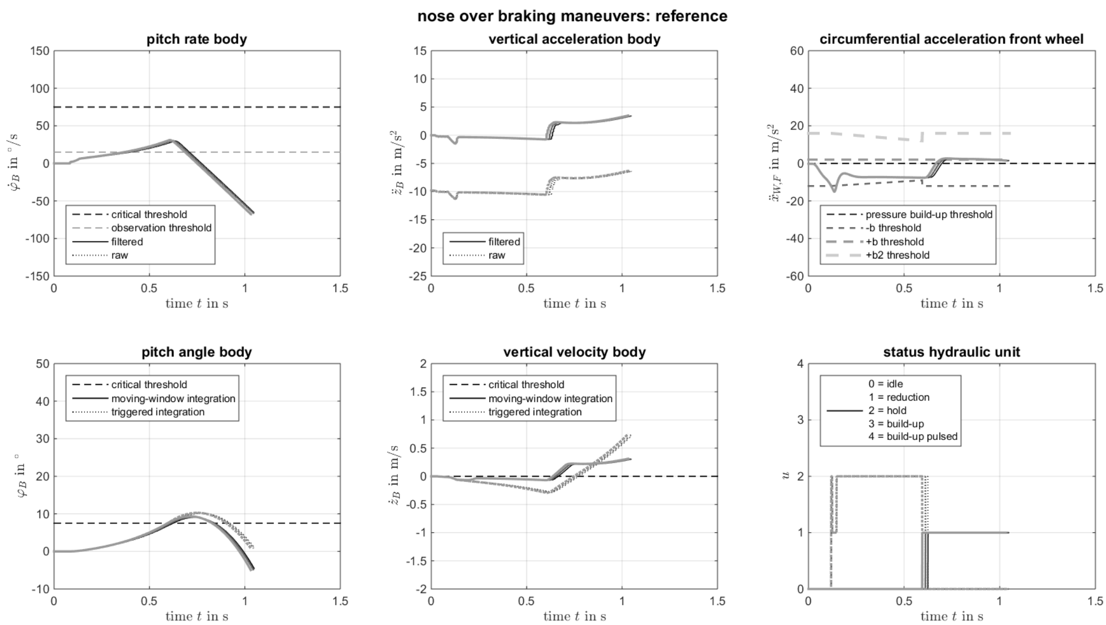

Figure 9: Three test runs (black, dark grey, and light grey lines) on the HiL test bench for the lift-off mitigation function. Vertical acceleartion is filtered. Hence, the constant gravitational acceleration is eliminated.

5 DISCUSSION

In developing a BDA system in the project *BikeSafe* the HiL test bench served as a powerful tool for system validation. In particular, artifacts such as models and test cases already developed for MiL experiments could be used (nearly) as is. Installing the hydraulic sub system as real hardware proved to be a helpful step towards real world behaviour. Using the HiL test stand parameters of the BDA were tuned to get a stable function over a wide range of parameter variations. After system tests at the HiL were passed successfully the BDA function was employed at the test vehicle. Real world experiments confirmed the results of the HiL validation. Both sub functions (anti lock-up and lift-off mitigation) satisfied the requirements. It is worth noting that the issued identified at the HiL with the anti lock-up function at low initial speed (10 km/h) did also occur in real world tests but at a lower speed.

6 ACKNOWLEDGEMENTS

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