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# Distributed Local X-in-the-Loop Environment

## - A Tool for Electric Vehicle Systems Design -

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**ABSTRACT**: The paper describes methodology and corresponding environment for development, validation and testing of complex electric vehicle (EV) systems. The proposed approach is based on distribution of relevant design tasks between remotely working testing equipment with real-time (RT) data sharing and data exchange. The approach is demonstrated by the example of X-in-the-loop (XIL) environment uniting electric motor test setup, hardware-in-the-loop (HIL) platform with brake-by-wire system, and the brake dynamometer. The study introduces how this configuration of experimental tools can be used by designing the brake blending and control of an EV.

**KEY WORDS**: electric vehicle, X-in-the-loop, brake blending, in-wheel motor, brake-by-wire, hardware-in-the-loop, design methodology, experimental environment

## 1. INTRODUCTION

Many EV systems are composed from components and subsystems belonging to different physical domains, e.g. integrated regenerative and friction brakes. It sophisticates the design process in the case when the whole complex system has to be tested in a global experimental environment to address real-world conditions as much as possible. Limited availability of corresponding experimental equipment could lead to the fact that important operational factors and variables are estimated or derived from models. As a result, the test process can be not always sufficiently adequate to the real-world operation. An efficient solution in this regard can be obtained with modern communication technologies enabling connection and simultaneous real-time operation of experimental platforms from different domains and locations.

Despite the first attempts of connected experiments in automotive area are arisen about decade ago, only recently the web communications achieved the performance level, which is sufficient for real-time experiments on parallel testing devices (1), (2). The presented paper introduces the works contributing to this topic, which are advancing previous studies of authors on connected XIL technologies (3), (4). These works are concentrated on the development and utilization of distributed local XIL environment uniting several experimental platforms for testing different EV components.  Its operation is illustrated by the procedures of brake blending development.

## 2. X-IN-THE-LOOP ENVIRONMENT

### 2.1. Overall approach

The concept of XIL environment is shown on Fig. 1, where the highest layer represents the *application* (e.g. simulation process or testing facility). On the second level, the Functional Mock-Up Interface (FMI) can be used optional for mapping the exchanged signals. The communication protocol layer represents the transport communication protocol of the *application*. The last layer supports two gateway functionalities: (i) the translation of communication protocols and (ii) the routing and transportation of data in a network. The environment uses a Virtual Local Area Network (VLAN) for local communication and Virtual Private Network (VPN) for distributed systems.

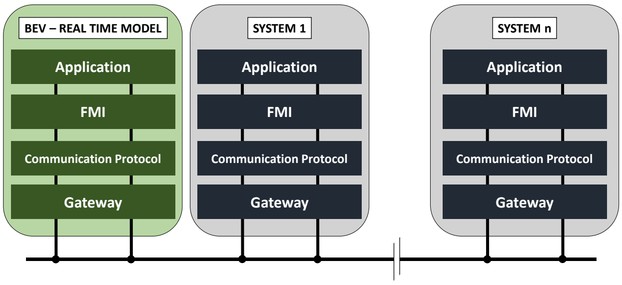

**Fig. 1: General XIL architecture.**

The proposed architecture supports plug and play over the RT simulation. Due to the modular structure of the full vehicle simulation, it is possible to substitute the virtual representation of a subsystem (electric motor) by its physical equivalent (e.g. test rig with EV powertrain).

### 2.2. Variant of distributed local XIL environment

For the purposes of this study, the architecture from Fig. 1 has been realized as shown on Fig. 2 to enable testing of EV brake system and powertrain.

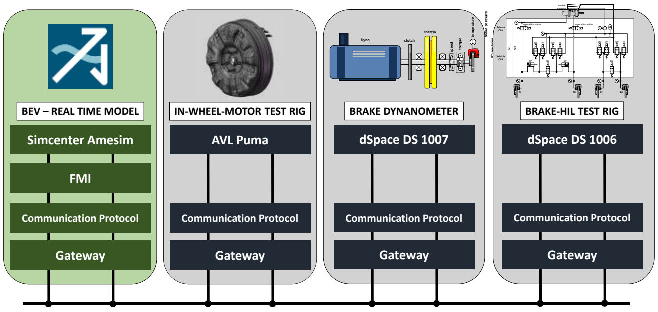

**Fig. 2: Mapped architecture for local XIL.**

This platform allows investigating the interaction of the friction brake and the electric generator for deceleration to realize the EV brake blending function. All test setups are situated within the campus area of TU Ilmenau and therefore connected by the local network. The RT vehicle simulation with an optional FMI layer communicates per UDP/IP protocol with three test setups: the powertrain test rig, the brake dynamometer, and the HIL test rig with installed brake-by-wire system. Each of them substitutes a different virtual subsystem by its physical equivalent. The test setups are equipped with AVL Puma or dSPACE systems.

## 3. IMPLEMENTATION CASE

The distributed local XIL environment, introduced in previous section, has been implemented as shown on Fig. 3 for the validation and testing of brake blending controller. In the Base Braking unit, the driver input is processed, and a total braking torque demand is calculated. The total braking torque demand is distributed to front and rear axle by the Brake Force Distribution unit. The Blending part is the central unit to be optimized with the help of the proposed XIL environment. The task is to distribute the brake torque demand per wheel through the in-wheel-motors (IWM) and friction brakes actuated by the electro-hydraulic brake system (EHB). The distribution strategy must be optimized depending on various parameters like velocity, driving situation, temperatures, state of charge (SOC) and brake demand.

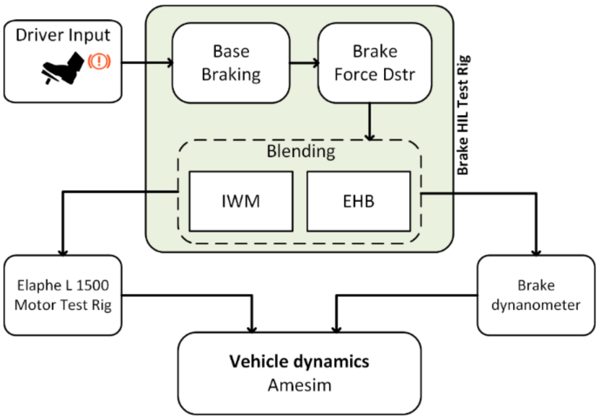

**Fig. 3: Integrated test platforms.**

The information form the controllers about the demanded brake torque and the brake pressure are correspondingly transmitted to the hardware test rigs: (i) the Elaphe L1500 IWM assembled on the AVL Dynospirit Powertrain test rig, and (ii) the combination from hydraulic HIL and brake dynamometer. The use of these real hardware systems ensures that the dynamic processes in all the components are reproduced as detailed as possible into the simulation environment. An observer structure is used to extrapolate the operation of one IWM and one friction brake to four combined systems, one per wheel. This will result in four calculated brake torques from each system, which are then used as an input to the vehicle dynamic simulation of the target vehicle in Simcenter Amesim.

## 4. TEST RESULTS

The brake blending control strategy impacts the electric energy balance, driving safety and comfort as well as braking performance. For the following experiments with the proposed test environment a number of scenarios is chosen to address the relevant indicators. In terms of electric energy balance the WLTP-cycle is defined to achieve comparable results. To investigate braking performance and driving safety, experiments were conducted in the straight line braking scenario under various boundary conditions.

All experiments were conducted in the proposed distributed XIL test environment.

### 4.1. Energy Consumption in WLTC

The WLTC represents driving under everyday conditions in 4 different sub-parts from low to extra-high speed. The energy consumption as well as the benefits achieved with a decent brake blending control can be assumed as an estimation for everyday usage of electric vehicles. Fig. 4 shows the velocity profile of the driving cycle and the accumulated energy consumption with and without regenerative braking.

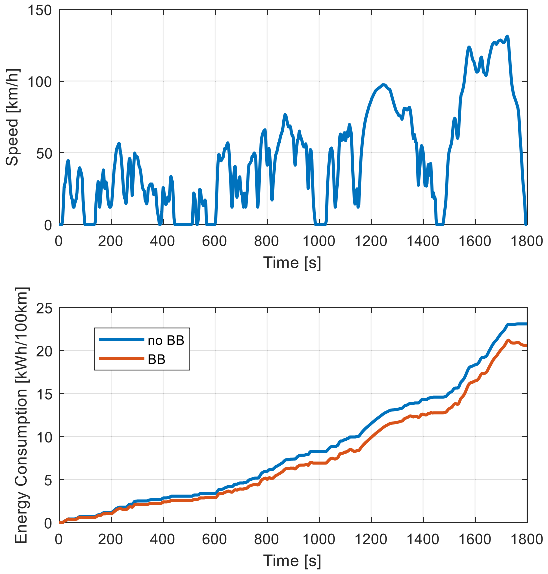

**Fig. 4: WLTC – Energy Consumption of powertrain with and without regenerative braking in XIL setup.**

The calculated energy consumption does only take the powertrain into account. Sub-components are not considered.

Reference is the energy consumption of four IWMs without regenerative braking. Accumulated consumption normalized to 100km is measured with 23.09 kWh/100km. Under active regenerative braking with a serial brake blending strategy the energy consumption is measured with 20.61 kWh/100km. This is a benefit of 10.74 % in powertrain energy consumption.

For a close look, Figure 5 shows a selected braking manoeuvre in WLTC. Initial speed of the brake manoeuvre shown is 130 km/h and the vehicle brakes to a standstill.

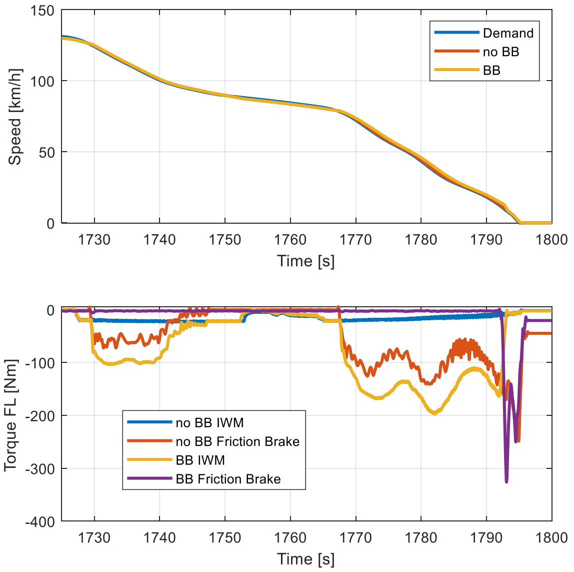

**Fig. 5: WLTC – Braking action from 130 km/h to standstill**

In the first part of the figure, it can be seen that the driver model can follow the speed specification almost identically in both cases, without and with regenerative braking. This can be expected due to the very small RMSE in speed demand tracking over the whole cycle (Table 1).

The lower diagram shows the distribution of the wheel torque between the in-wheel motor and friction brake system on the left front wheel. Without regenerative braking, the total braking torque is composed of the drag torque of the IWM (blue) and the braking torque of the friction brake (red).

If regenerative braking is activated, a major part of the braking is carried out purely regeneratively (1725 s - 1792 s). In second 1792, the lower speed limit for regenerative braking is exceeded. The brake blending controller therefore shifts the braking torque from the IWM (yellow) to the friction brake (purple).

The energy benefit of this braking action amounts to 0.146 kWh.

**Table 1: WLTC – comparison with and without Brake Blending**

| | **No Brake Blending** | **Brake Blending** |
|---|---|---|
| Energy consumption | 5.289 kWh | 4.743 kWh |
| Energy consumption per 100 km | 23.09 kWh/100 km | 20.61 kWh/100km |
| Max. long. acceleration | 1.7013 m/s² | 1.7087 m/s² |
| Max. long. deceleration | 3.9485 m/s² | 2.8495 m/s² |
| Speed tracking RMSE | 0.3538 m/s | 0.4361 m/s |

In terms of driving performance, both tests can be compared very well. No disadvantages due to regenerative braking could be demonstrated.

### 4.2. Straight Line Braking

The straight line braking maneuver represents a vehicle full stop from various initial speeds. The experiments were conducted with and without regenerative braking, with various initial speeds and brake pedal actuations. The results are evaluated in terms of braking performance and driving safety.

Figure 5 shows one experiment. In this case, the brakes were applied at 50 km/h with 75 % brake pedal position.

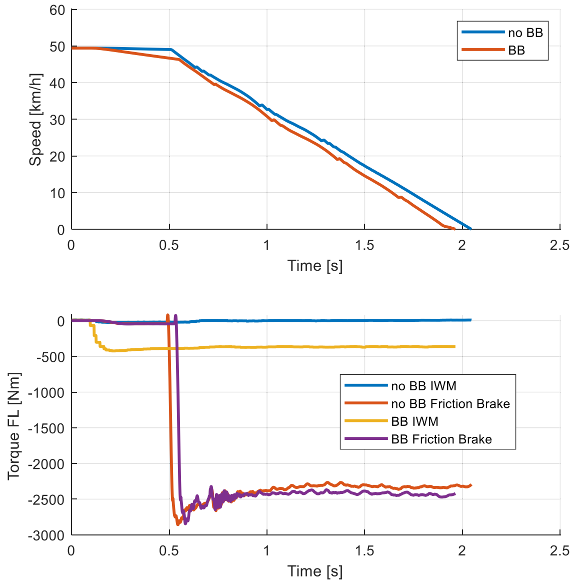

**Fig. 5: Straight line braking – 50 km/h, 75% brake pedal travel**

The scenario defines a brake pedal travel of 75 %. The total demanded brake torque calculated from this brake pedal travel is the same in both presented cases, without and with brake blending. However, in the speed diagram in Figure 5 can be noted that the vehicle with brake blending enabled stops in a shorter time after brake pedal actuation (- 4,4 %) and also in a shorter distance (- 6.3 %), also shown in Table 2. The reason for this is the faster response to a brake demand of the electric motors compared to the electro-hydraulic brake.

This process can be observed in the lower diagram of Figure 5. The measured torque applied to the front left wheel from IWM and friction brake is plotted. Like explained, the IWM brake torque (yellow) is applied to the wheel in simulation faster than the friction torques without (red) and with (purple) brake blending. Active regenerative braking therefore leads to a faster reaction of the vehicle to driver demands and due to this to a shorter braking distance. This improves the driving safety for passengers and pedestrians in case of an emergency stop. The regenerated energy in one braking action of the shown kind amounts to 6.826 Wh.

**Table 2: Straight line braking – braking with fully charged batteries and with active brake blending in XIL setup**

| | **No Brake Blending** | **Brake Blending** |
|---|---|---|
| Braking distance | 17.35 m | 16.26 m |
| Braking time | 2.05 s | 1.96 s |
| Mean deceleration | 6.72 m/s² | 7.00 m/s² |
| Regenerated electric energy | 0 Wh | 6.826 Wh |

## 5. CONCLUSION

The introduced methodology for validation and testing of EV systems can bring essential advantages through reduction of development time and related costs. The same approach can be also transferred to many tasks of EV systems design, e.g. development of integrated chassis control, driving comfort evaluation, and fail-safe studies.

The authors demonstrate an application of the shown methodology with investigations on the brake blending strategy. The required tests were successfully carried out in the XIL environment. The valid results prove that the proposed method is suitable for optimising and testing brake blending controllers using real components in HIL setups. This can significantly increase flexibility and efficiency in the development process. Component test benches for brake systems and drive systems, as shown in this use case, but also for any other component of an electric vehicle can be combined into a variable and geographically distributed development environment.

## ACKNOWLEDGMENT

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