

Regenerative Braking Control Enhancement for the Power Split Hybrid Architecture with the Utilization of Hardware-in-the-loop Simulations

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ABSTRACT

This study presents the utilization of the hardware-in-the-loop (HIL) approach for regenerative braking (regen) control enhancement efforts for the power split hybrid vehicle architecture. The HIL stand used in this study includes a production brake control module along with the hydraulic brake system, constituted of an accelerator/brake pedal assembly, electric vacuum booster and pump, brake hydraulic circuit and four brake calipers.

This work presents the validation of this HIL simulator with real vehicle data, during mild and heavy braking. Then by using the HIL approach, regen control is enhanced, specifically for two cases. The first case is the jerk in deceleration caused by the brake booster delay, during transitions from regen to friction braking. As an example, the case where the regen is ramped out at a low speed threshold, and the hydraulic braking ramped in, can be considered. During this transition, due to the communication delay and the delay associated with booster dynamics, the regen ramp out and hydraulic braking ramp in are not perfectly synchronized, which can cause a jerk in deceleration.

The second case considered is the jerk in deceleration when the regen torque is ramped out to zero during an ABS event. This causes a sudden loss in deceleration, again causing a jerk. By properly controlling regen torque in these two events, it is shown by real time simulation results that smoother deceleration can be delivered without causing vehicle instability.

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1. INTRODUCTION

Hardware-in-the-loop (HIL) method has been a corner stone for automotive control engineers in the last decade for control strategy development purposes. By using actual powertrain components in the simulation loop, it has been possible to go one step further in tuning the control strategies in real time, prior to vehicle testing. By means, HIL approach enabled control engineers to tune control strategies and see their effect on different vehicle components before going to the final step of applying them to the vehicle.

In this context, this study considers utilization of a HIL stand that includes the production brake module and the friction brake system for the powersplit hybrid architecture (Fusion hybrid, BEV, C-max). The powersplit hybrid architecture is shown in [Figure 1](#).

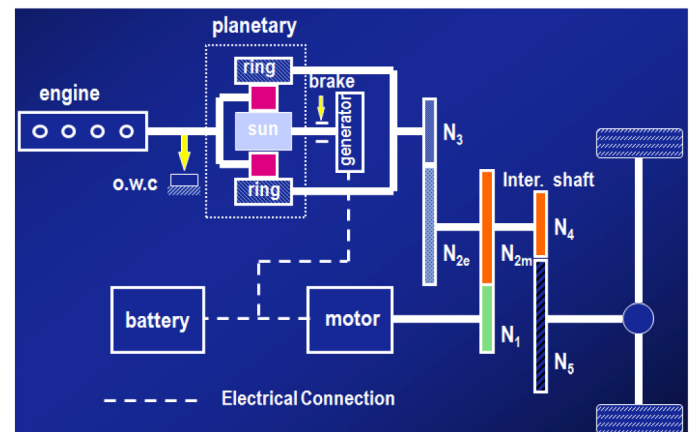


Figure 1. Overview of the powersplit hybrid architecture

The brake HIL stand is constituted of an accelerator/brake pedal assembly, electric vacuum booster and pump, brake hydraulic circuit and four brake calipers. The pressure at each corner is measured with pressure transducers and reported through analog lines to the DS 1005 processor with the DS 2210 I/O board [1]. dSpace HIL simulator in this setup represents the powertrain and vehicle dynamics models.

One of the key variables that are among the outputs of the model is the wheel speeds that are reported to the brake module for ABS and regen functionality. Apart from the wheel speeds, there is CAN communication set up between the module and dSpace, which involves many messages, some of which are driver torque requests, estimated torque at the wheel level, vehicle speed, etc. The stand is illustrated in Figure 2.

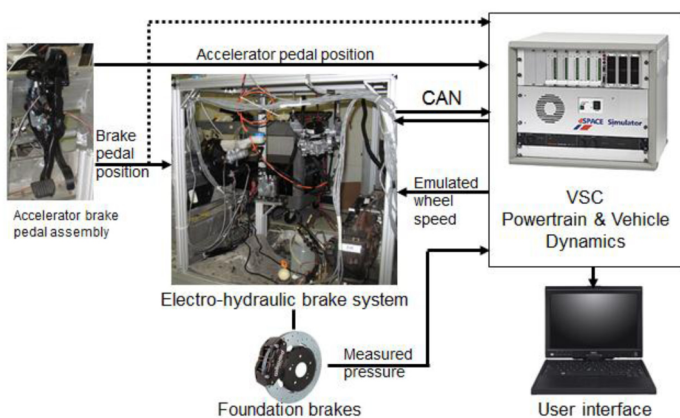


Figure 2. Overview of the brake HIL stand

This paper is divided into four main sections. In Section 2, the validation results of the model running in HIL are presented, by comparison with real vehicle data. In Section 3, the use of this stand in enhancement of the regen torque control strategy against booster delay compensation is given. In Section 4, the second example of enhanced regen torque control during an ABS event is presented. Both control strategies aim at achieving smoother deceleration trends without causing any vehicle instability. The paper is concluded in Section 5 with closing remarks.

2. HIL MODEL VALIDATION

Obviously the first requirement in using model based design for control development is the validity of the models used. As the control strategies presented in this study consider braking maneuvers, the validation was carried out during mild and heavy braking.

During braking maneuvers, it is important to use a reliable model that would capture not only vehicle dynamics variables such as tire slip, but also the driveline dynamics, as the presented control strategies in this study propose integrating regenerative braking torque with electro-hydraulic friction braking. Hence the motor output shaft and the half shafts are modeled as torsional spring damper elements, as illustrated in

Figure 3. The open differential on the other hand, is modeled as a two degree of freedom element considering the left and right half shaft speeds, ω_{dfl} and ω_{dfr} , respectively. The wheel dynamics take into account the non-linear tire faces, generated by the Pacejka tire coefficient. Details of the tire and the differential model can be found in [2].

The vehicle dynamics model takes into account two degrees of freedom, namely the longitudinal motion, and pitching, as straight line braking is considered, and no split- μ condition.

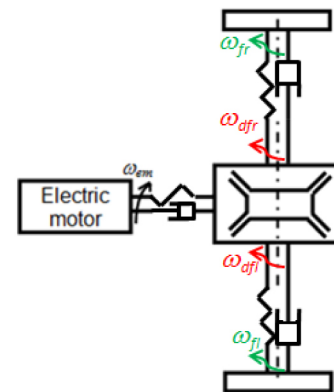


Figure 3. Overview of the driveline compliance model between the motor and the wheel

For the pitching, a half car model was associated, considering unsprung masses, and front and rear suspension stiffness and damping.

For the validation purpose, the driver inputs, namely the accelerator and brake pedal inputs, as measured in vehicle tests are directly fed into the simulator, and the outputs of the HIL stand are compared with the vehicle test results.

Figure 4 shows some crucial signals that were compared, for the first set of validation (all signals are not given here for brevity). These signals include brake pedal position (top left), measured front caliper pressure (top right), estimated powertrain torque, i.e. regen at wheel level (middle left), wheel and vehicle speed (middle right and bottom left, respectively) and the vehicle deceleration (bottom right).

This set of validation results include a step like input for the braking pedal as evident from the figures, after a fully released accelerator pedal, at around 70 kph vehicle speed. Therefore the braking request of the driver in these cases are the interpretation of the brake pedal position to brake torque, plus the anticipated compression braking due to released accelerator pedal.

The main observation from these figures is that there is a satisfactory overall match between the vehicle test data and the data collected from the HIL stand, especially for steady-state conditions.

Another observation is that the driver's braking demand is satisfied by both regen and conventional friction braking, the former being the prior source of braking as in the case of series regen braking strategy [3]. For instance in Figure 4a,

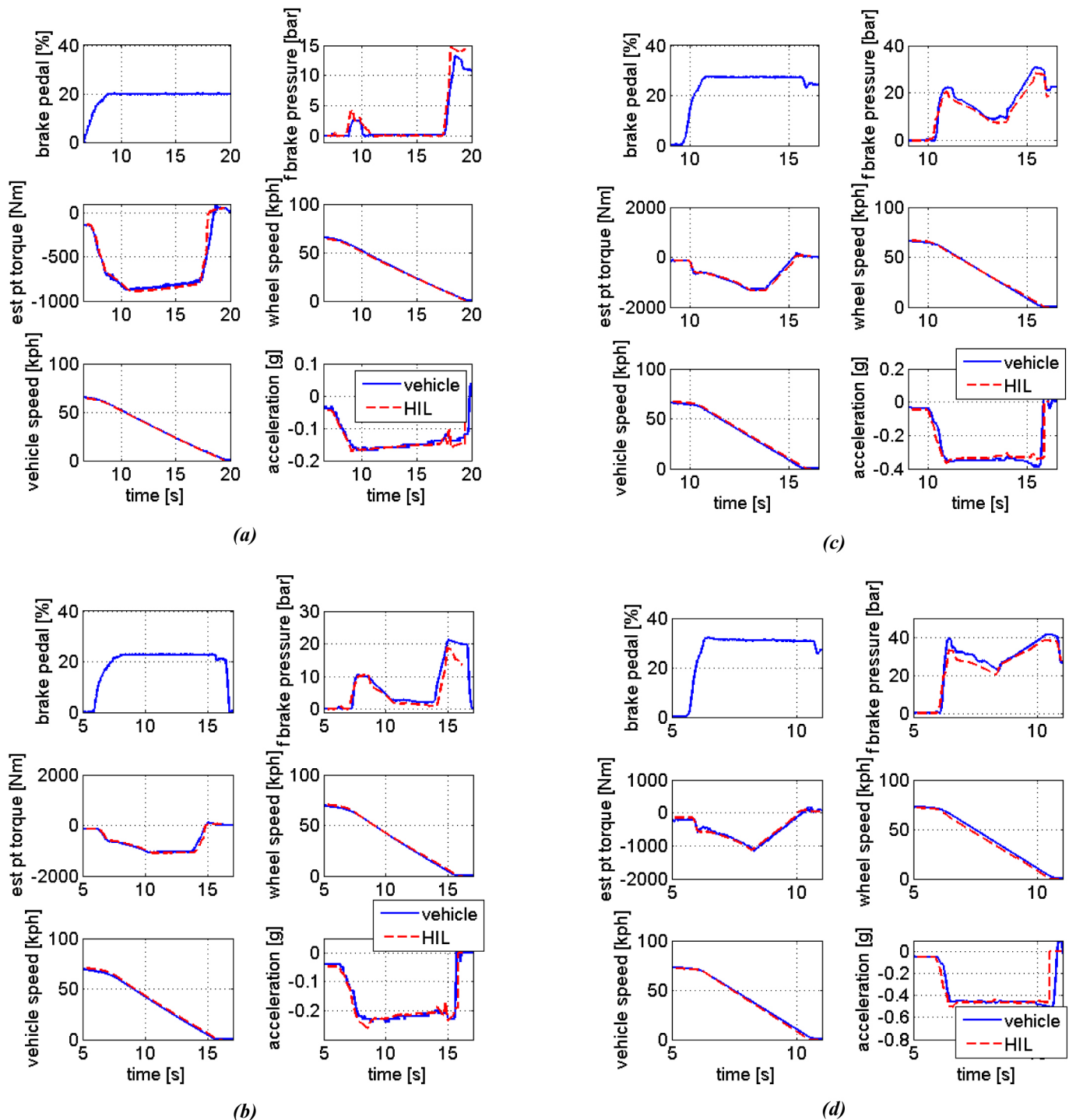


Figure 4. Model validation results for mild braking, with increasing brake pedal input from 20% in 4a to 32% in 4d. Brake pedal percentage, brake pressure, estimated powertrain torque at wheel level, wheel and vehicle speeds and deceleration are plotted.

almost all of the braking request of the driver is satisfied by regenerative braking torque, whereas the pressure rises shortly at around 9s where the regen limit is reached instantaneously.

As the brake pedal is increased in each test, the regenerative braking torque falls short in satisfying the

driver's braking request (due to its limitations depending on powertrain torque limits and vehicle dynamics constraints), and the magnitude of the hydraulic pressure built up, increases, as expected. The smoothness of transitions between the two sources of braking will be addressed in the next section.