Blended Antilock Braking System Control Method for All-Wheel Drive Electric Sport Utility Vehicle

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Abstract At least two different actuators work in cooperation in regenerative braking for electric and hybrid vehicles. Torque blending is an important area, which is responsible for better manoeuvrability, reduced braking distance, improved riding comfort, etc. In this paper, a control method for electric vehicle blended antilock braking system based on fuzzy logic is promoted. The principle prioritizes usage of electric motor actuators to maximize recuperation energy during deceleration process. Moreover, for supreme efficiency it considers the battery's state of charge for switching between electric motor and conventional electrohydraulic brakes. To demonstrate the functionality of the controller under changing dynamic conditions, a hardware-in-the-loop simulation with real electrohydraulic brakes test bed is utilized. In particular, the experiment is designed to exceed the state-of-charge threshold during braking operation, what leads to immediate switch between regenerative and friction brake modes.

1 Introduction

One of the advantageous features of the electric vehicles (EVs) is their ability to recuperate energy during a deceleration process. In EVs, friction braking (FB) cooperates with regenerative braking (RB), which opens a need to efficient torque control between two separate actuators (i.e. torque blending), which are characterized by different dynamics. In some cases, RB is simply not enough to achieve the requested

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braking torque; therefore, the FB system is activated in parallel or in series. In other cases, the battery conditions (e.g. temperature, battery's state of charge (SOC)) must be considered. For instance, when the battery is fully charged, the recuperation is no longer useful and even dangerous [1].

The SOC is a ratio of the remaining battery capacity to the fully charged one. It is one of the most important parameters in EVs. Its feature is used not only in battery management to estimate potential driving range before the next recharge but also in vehicle traction (e.g. hybrid EV) and braking (e.g. blended braking system) control strategies [1]. For example, to avoid electric battery overcharge, and consequent damage, the regeneration by electric motors is usually limited to a specific upper bound, 80–90% [2]. Therefore, the SOC must be always involved in a blended antilock braking system (ABS).

Nowadays, the fuzzy logic controllers (FLCs) are widely used in automotive engineering to solve various problems [3]. For instance, in [4], the effectiveness and strong robustness of a fuzzy sliding mode control over conventional proportional-integral-derivative (PID) and Mamdani's type FLC in energy recuperation for EV in simulation environment was demonstrated. The complexity of vehicle dynamics in deceleration process, especially during emergency braking, was not integrated in the study.

An FLC-based RB strategy integrated with series RB was developed in [5]. The FLC received the driver's force command, vehicle speed, battery's SOC and the temperature to determine distribution between FB and RB to improve energy recuperation efficiency. In [6], the FLC involved SOC and a ratio between the brake torque and the biggest brake torque to determine the factual FB and RB brake torques. An RB control strategy applying FLC was presented in [7]. The simulation results demonstrated that the developed method is able to recover energy and distribute power flow to maintain SOC around target value. A PID in combination with FLC ensured efficient RB strategy of the EV [8]. The SOC was taken as an input of the FLC. Despite impressive results, all these works only focused on the base brake case. The ABS function was not considered.

In [9], the authors applied genetic algorithm in EV stability control logic using RB of the rear wheels motor and FB of electrohydraulic brake (EHB). The simulation results showed that the optimal recuperation strategy is able to provide an increase in recuperation energy. However, neither SOC in torque allocation nor ABS performance were under investigation. The brake force distribution strategy for EVs based on estimation of tire–road friction coefficient was provided in [10]. The road condition estimation was also based on fuzzy theory. An efficient torque blending was demonstrated in [11]. The experiment was conducted on a real vehicle braking on low-friction road surface. In [12], the FLC was used to adjust braking torque between RB and FB. However, in these works torque blending or force distribution did not consider the SOC of a battery.

Scholars in [13] integrated sliding mode controller with FLC for an ABS control to maintain optimal wheel slip ratio deceleration. The SOC was reckoned in torque blending in this instant. However, the ABS controller inputed fixed slip ratio. Thus, wheel slip adaptability to various road conditions was not considered. Advanced control allocation with energy recuperation for EV was introduced in [14]. The authors also involved the battery's SOC. Both works did not study the situation when SOC exceeds its bound during braking manoeuvre.

In [15], the authors proposed the EV torque blending with recuperation capabilities taking into account the SOC. It was integrated with three types of controllers, namely PID, tabular, and FLC. In this paper, the attention is once again focused on the SOC's influence on the EV's blended ABS. To this aim, the intelligent FLC control method previously developed by the authors [16] was applied in the hardware-in-the-loop (HIL) simulation with real EHB system. The HIL testbed accompanied with a hardware delay is exploited to represent actual EHB dynamics, making the simulation experiment more valued for real-life application. The deceleration test is designed in a way that SOC reaches its maximum threshold in the middle of the braking process. Consequently, blended braking system rapidly switches from RB to FB.

In RB, the recovered energy is not stored directly in the battery, but in the ultracapacitor. From the latter, the recuperated energy is transmitted slowly to the battery or is used for vehicle acceleration. Thus, the SOC shall also consider the capacity of an ultracapacitor. Furthermore, the electronic power converters play an essential role in energy recuperation in EVs, as they are an intermediate connection between energy sources and motors. In this paper, it is assumed that the energy is transferred directly to the battery; thus, the SOC may surpass its maximum limit during the EV deceleration. However, the power electronics losses are neglected in the powertrain model. Nevertheless, possible consideration of the SOC of ultracapacitor in torque blending was also proposed by the authors in [15].

This paper is organized as follows. The next section (Sect. 2) stresses the HIL simulation environment together with vehicle modelling. Section 3 describes the blended ABS control method. In Sect. 4, the HIL simulation results are delivered. A brief conclusion is provided in Sect. 5.

2 Vehicle Model and Experimental Set-Up

2.1 Single-Wheel Model

A simplified schematic single-wheel brake diagram is presented in Fig. 1. The rolling resistance and lateral dynamics are neglected, because only the straight braking manoeuvre was studied in this work. The torque balance about a wheel axis is expressed as:

$$J_{\mathrm{W}}\dot{\omega}_{\mathrm{W}} = T_{\mathrm{d}} - r_{\mathrm{W}} \cdot F_x - T_{\mathrm{b}}, \tag{1}$$

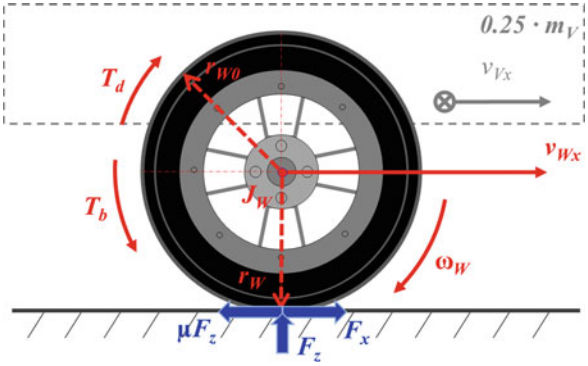

Fig. 1 A schematic drawing of a braked wheel for a single-wheel model

where J_w—moment of inertia of wheel; ω_W—angular velocity of wheel; T_b—braking torque; T_d—driving torque; r_w—radius of deformed tire; F_x—longitudinal force of tire.

A distinctive feature of the EV: its braking torque T_b is a summation of the RB T_{RB} and FB T_{FB} braking torques [16]:

$$T_b = T_{FB} + T_{RB}. \tag{2}$$

In practice, T_{RB} and T_{FB} are not measured by the sensors directly. They change proportionally to phase current of a switched reluctance motor (SRM) and line pressure of an EHB, accordingly. Those states are measured by on-board sensors available in modern vehicles. In this paper, the variables are represented as torques directly.

2.2 State Estimation

An essential characteristic of an ABS is tire–road friction coefficient μ. Straight direction braking manoeuvre neglects lateral dynamics; hence, μ is calculated as a ratio of longitudinal F_x and normal F_z forces:

$$\mu = \frac{F_x}{F_z}. \tag{3}$$

The proposed control method uses μ to understand the road surface under the tires of the EV. In this regard, μ is assumed to be proportional to the EV body deceleration rate [16]:

$$\mu^* = \frac{F_x}{F_z} = \frac{m_V \cdot a_{Vx}}{m_V \cdot g} = \frac{a_{Vx}}{g}, \tag{4}$$

where m_{V}—mass of vehicle; $a_{\mathrm{V}x}$—longitudinal acceleration of vehicle; g—gravitational acceleration.

The maximum vehicle deceleration achieved during the first period of heavy braking manoeuvre is related to road surface conditions and is used as the road recognizer in the proposed control method. The variable is expressed as μ^* [16].

Another important state for the control method is longitudinal wheel slip λ, which is estimated from vehicle $v_{\mathrm{V}x}$ and wheel $v_{\mathrm{W}x}$ longitudinal velocities:

$$\lambda = \frac{v_{\mathrm{W}x} - v_{\mathrm{V}x}}{v_{\mathrm{V}x}} \cdot 100\%. \tag{5}$$

Vehicle longitudinal velocity is derived from the vehicle body deceleration signal:

$$v_{\mathrm{V}x} = \int a_{\mathrm{V}x} \mathrm{d}t. \tag{6}$$

Wheel longitudinal speed is found as:

$$v_{\mathrm{W}x} = r_{\mathrm{W}} \cdot \omega_{\mathrm{W}}. \tag{7}$$

2.3 Electric Vehicle Model

The EV model is completed in IPG CarMaker® 6.0 (Germany) software. The 14 degrees-of-freedom model is interacted with MATLAB® from MathWorks, Inc. (USA), allowing users for rapid control algorithm development and testing. The software's integration in the HIL systems opens a great possibility for advance prototypes testing and concepts engineering, which sensitively saves development time and cost.

The sport utility EV model with all-wheel drive powertrain represents a vehicle under investigation. The specifications of the vehicle parameterizations are provided by the EV's manufacturer (e.g. mass, dimensions, electric propulsion system) or are collected experimentally (e.g. suspension, tire model).

Each of the four wheels is equipped with SRM. In-wheel motor transmission type is a two-stage reducer with helical gear and half-shaft. Considering the SRM's peak torque (i.e. 200 Nm at 800 V) together with overall SRM–gear ratio (i.e. 1:10.5), the maximum torque achieved on single wheel reaches 2100 Nm. The motor's behaviour is defined by the first-order transfer function. More information about vehicle model together with its parameters is available in [16].

The braking linings' coefficient of friction was modelled by means of a dynamic model, which was validated against data collected on the brake dynamometric test bed at Technische Universität Ilmenau (Germany). This model considers the influence of speed, pressure, and temperature on the brake linings' coefficient of friction [17].

The tire dynamics are approximated with Pacejka's "Magic Formula" with experimentally obtained coefficients. The tire–road model is a relevant element for the control method design. Particularly, it is important to know the most efficient workspace for the λ with various road surfaces. Deceleration with the optimal λ results in maximum braking manoeuvre efficiency that impacts the deceleration distance. Moreover, when the wheel slip is equal or smaller than its corresponding peak (so-called stable region), the EV presumes steerability. On the contrary, deceleration with the λ exceeding its optimal one (i.e. unstable zone) leads to wheels' lockage and lateral control aggravation. The ABS's task is to avoid wheel slip unstable region.

2.4 Electrohydraulic Brake System Test Bed

The EHB with control unit test bed (Fig. 2) was provided by Technische Universität Ilmenau. The test rig is developed by the ZF TRW Automotive GmbH (Germany). The EHB set-up is used in vehicle braking dynamics studies for reproduction of the real pressure dynamics of the brake circuit.

The vehicle model sends demanded braking pressure for each wheel to the EHB control unit. The dSPACE® (Germany) platform is utilized as an intermediate

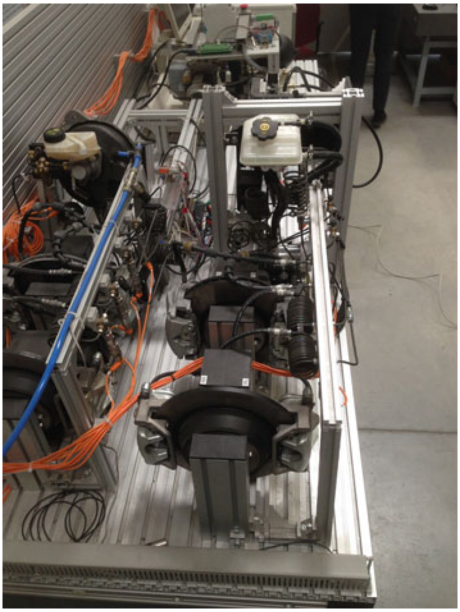

Fig. 2 Electrohydraulic brake system test bed

connection between the vehicle numerical model and the EHB. The requested braking pressure received from the vehicle model activates the valves that generate corresponding braking pressure between the wheels and the calipers. Finally, after measuring with the appropriate sensors, the line braking pressure on each wheel is returned to the vehicle model.

3 Blended Anti-lock Braking System Control Method

3.1 Control Method

The ABS control method supplies an appropriate braking torque to decelerate the vehicle with optimal wheel slip for each wheel. Different road surfaces are taken into account in control method design. A detailed description of control method and its design can be found in [16]. Only a brief introduction is presented here.

The control area network bus provides vehicle longitudinal deceleration together with wheel velocity (Fig. 3). In the next steps, applying Eqs. (4)–(7), two commanded variables, λ and μ^*, are obtained. They are used by the FLCs to generate the required torque for the actuators.

Two FLCs are designed separately for SRM and EHB control for each wheel. The fuzzy system accepts the information about vehicle body deceleration during the first step of heavy braking. Its maximum value is fed as a constant crisp input to the FLC to recognize road surface. This crisp input is uncertain. Hence, computational intelligence methods, such as a fuzzy set theory, are capable of dealing with such ill-defined and vague data. Thanks to the method's robustness, precise mathematical modelling may be avoided. The second input is wheel slip, which is used to decide whether to decrease or increase the requested torque $T^{(\mathrm{req})}$.

Both the FLC inputs have symmetrically dispersed over the whole universe of discourse triangular membership functions, five for λ and seven for μ^*. Overlapping membership functions ensure equal sensitivity of the inputs. The λ is bounded in [0 18] and μ^*—in [0 10]. Sugeno's inference method was exploited in this study. In Table 1, the rule base for the front and rear wheels in regenerative braking mode is provided. Considering the motor's peak torque limits, the output torque for the SRM has 11 linguistic values from 0 to 200 Nm. The T_{FB} is between 0 and 150 bar and has the same design principle as the RB (Table 1). The FLCs are designed based on the given tire model and the expert's knowledge concerning efficient plant control.

The modus ponens rules (**If** premise **Then** consequence) are the common expression of fuzzy input–output fit. As done in this work, the tabular representation is often acquired by trial and error. The main criterion for Table 1 design is to achieve wheel slip for each tire as close as possible to the optimal one. An example of input–output linguistic mapping is as follows: **If** wheel "*slip is 3% (S3)*" and road surface is "*Dry*", **Then** request from the SRM "*200*" Nm for the front wheels and "*120*"

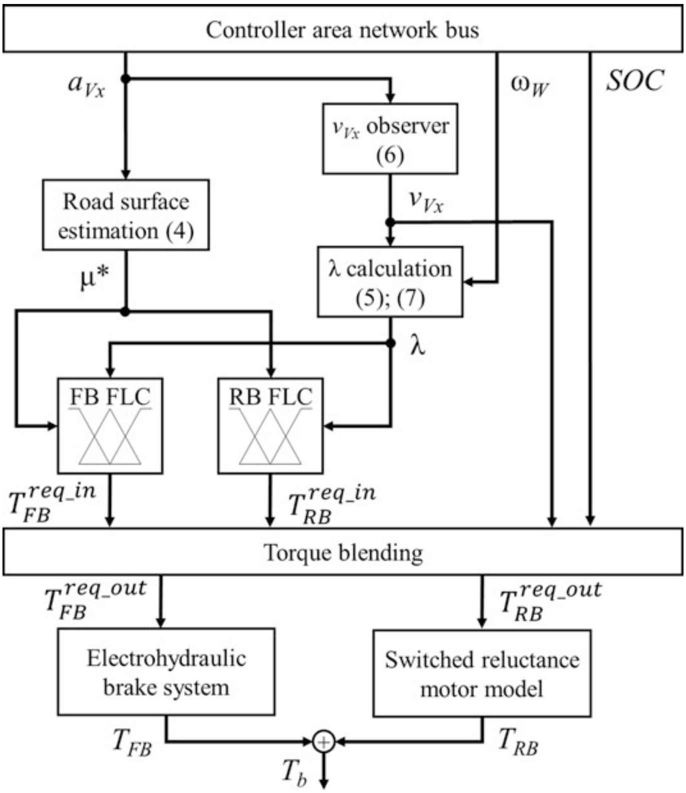

Fig. 3 Control block scheme for a single wheel of the EV: superscript req stands for “requested”; *RB FLC* regenerative braking fuzzy logic controller; *FB FLC* friction braking fuzzy logic controller

Table 1 FLC rule base for front/rear wheels in regenerative mode

T_{RB} (Nm)		μ^* Zero	Icy	Wet	Damp	Dry
λ (%)	S_0	60	80	160	200/120	200/140
	S_3	40	60	140	200/100	200/120
	S_6	20	40	120	200/80	200/100
	S_9	0	20	100	180/40	200/80
	S_{12}	0	0	60	160/20	200/40
	S_{15}	0	0	20	140/0	180/20
	S_{18}	0	0	0	120/0	160/0

Nm for the rear wheels. The final step is to translate the output linguistic variables back to crisp numbers. To achieve this, the center of gravity method is considered.

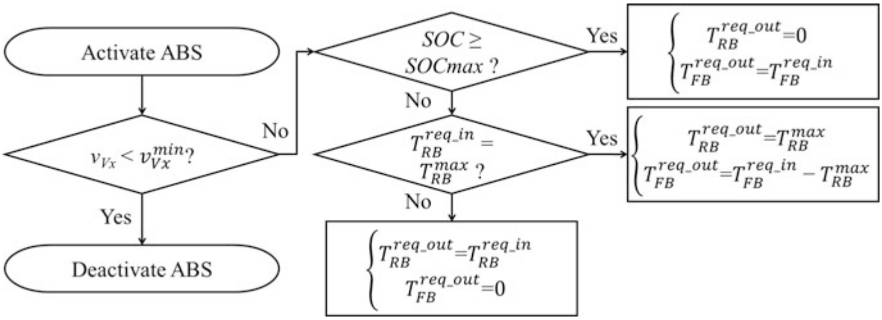

Fig. 4 Control flowchart of torque blending for a single wheel

3.2 Torque Blending

Torque blending is realized with simple logic rules. It requires several inputs, in particular, requested input RB and FB torques $T_{RB}^{req\_in}$ and $T_{FB}^{req\_in}$, vehicle longitudinal velocity v_{Vx}, and SOC of the battery SOC. Torque blending block outputs are requested RB torque $T_{RB}^{req\_out}$ for the SRM and requested FB torque $T_{FB}^{req\_out}$ for the EHB (Fig. 3). The approach flowchart is presented in Fig. 4. It is developed to prioritize the usage of the SRMs, yet without battery damage due to overcharge.

Firstly, the algorithm checks the velocity of the vehicle. When vehicle longitudinal speed is slower than a desired minimum threshold $v_{Vx}{}^{min}$ (typically 8–15 km/h), the ABS control is deactivated, because the distance travelled with very low speed with locked wheels is not critical.

Secondly, when the SOC reaches the maximum allowed threshold SOC_{max} (e.g. 90%), the braking switches to pure FB mode, where the torque for the SRM is equal to zero:

$$\begin{cases} T_{RB}^{req\_out} = 0 \\ T_{FB}^{req\_out} = T_{FB}^{req\_in} \end{cases}. \tag{8}$$

Thirdly, the blended ABS considers the SRM's peak performance. Specifically, when peak torque T_{RB}^{max} of the SRM is requested by the FLC, the block supplies the peak torque request to the SRM and calculates additional torque for the FB actuator to ensure optimal λ deceleration as:

$$\begin{cases} T_{RB}^{req\_out} = T_{RB}^{max} \\ T_{FB}^{req\_out} = T_{FB}^{req\_in} - T_{RB}^{max} \end{cases}. \tag{9}$$

Finally, when none of the previous conditions are true, the EV decelerates only with SRMs as the ABS actuators:

$$\begin{cases} T_{\mathrm{RB}}^{\mathrm{req\_out}} = T_{\mathrm{RB}}^{\mathrm{req\_in}} \\ T_{\mathrm{FB}}^{\mathrm{req\_out}} = 0 \end{cases}. \quad (10)$$

4 Results

The results of the EV heavy braking with activated ABS on a dry asphalt road ($\mu \approx 1$) is presented in Fig. 5. At the experiment time 3.5 s, the SOC of the EV's battery is assumed to exceed its upper bound. At this moment, the torque blending control is easily noticeable, because the EV switches from RB to pure FB mode. Energy recuperation is no longer conducted. The vehicle speed the wheels' speeds are presented in Fig. 5a.

Before the controller intervention, the wheels' slip rates grow due to exceeded torque requested by the driver (i.e. the braking pedal is instantly pressed to its maximum) (Fig. 5b). Nevertheless, after the ABS activation, the wheel slip rates drop down to their optimal values for a given road surface. The optimal slips for every wheel are also depicted.

In Fig. 5c, the road surface estimation method is scoped. At the beginning of the braking manoeuvre, the controller measures the maximum deceleration rate of the EV body. Its peak value is mapped with an appropriate road surface. The blue line symbolizes the crisp input for the estimation road conditions. The variable together with wheel slip is therefore processed by the FLC to estimate the relevant braking torques.

In Fig. 5d, braking torques for each in-wheel SRM of the EV are presented. Until the SOC makes an impact on blended ABS, it is seen that the SRM supplies its maximum available torque for the front wheels. As a result, the torque blending requests additional torque from the EHB (Fig. 5e) to lead λ as close as possible to their theoretical optimal values in accordance to Eq. (9). For the rear wheels, however, the generated torques by the SRMs (Fig. 5d) are enough to reach optimal rate. Thus, the FB torques are not required (Fig. 5e) as stated by Eq. (10).

When the SOC overshoot steps in (i.e. $t = 3.5$ s), the energy regeneration stops, and the SRMs are not used as braking actuators any more (Fig. 5d). Consequently, the RB torques for all wheels drop to zero. On the contrary, the system moves to the pure FB mode. Now, only the EHB's torques are applied to decelerate the transport (Fig. 5e), applying Eq. (8).

Moreover, the FB torques are not as smooth as RB ones. Furthermore, the optimal wheel slip achievability is not as precise as in the case when the SRMs affect vehicle deceleration (Fig. 5b). This phenomenon is mainly due to the EHB's significant delay as well as the plant complexity (i.e. the wheel tire's highly non-linear behaviour). It was also studied by the authors in the previous work [16].

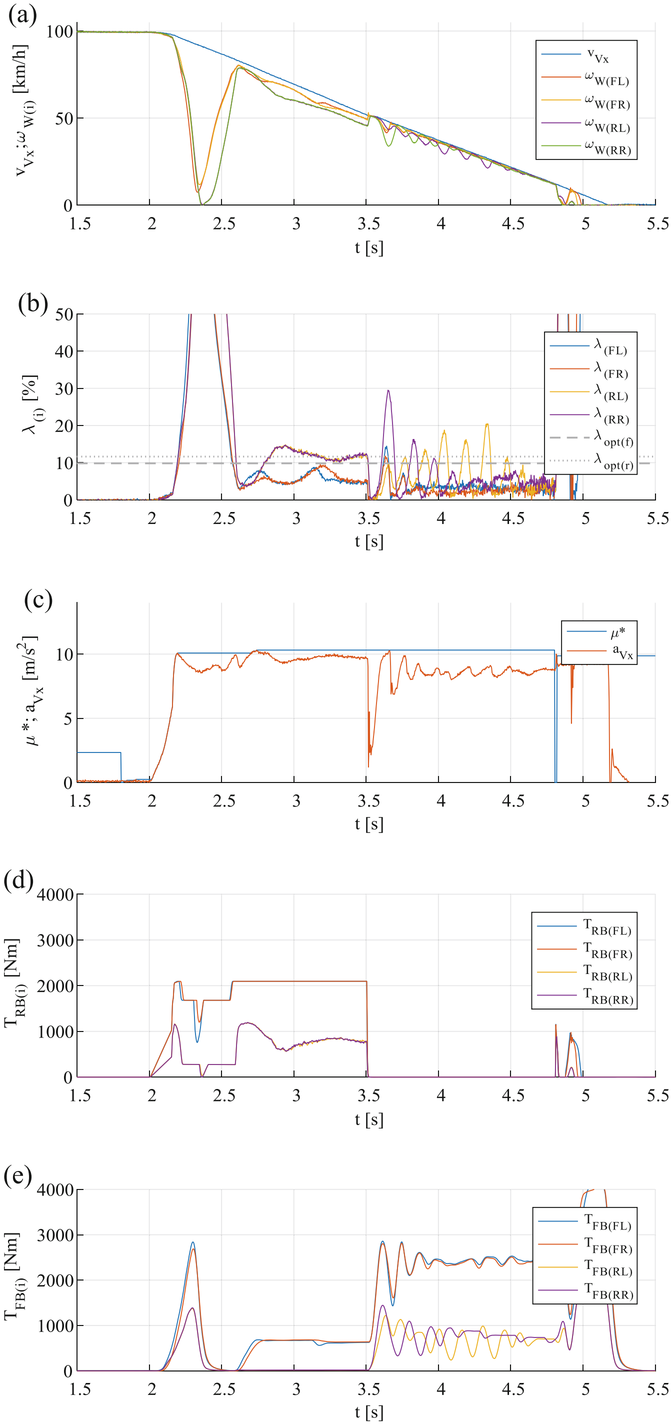

Fig. 5 Experimental results from vehicle braking on a high-μ ($\mu \approx 1$) road surface: (**a**) vehicle and wheels speeds; (**b**) wheels longitudinal slips; (**c**) road recognition with vehicle body deceleration rate (**d**) RB torques; (**e**) FB torques; (*FL* front left, *FR* front right, *RL* rear left, *RR* rear right)

The conclusion was made that, thanks to the electric drives' fast response, the control method accomplishes fast and more accurate control. As a result, the EV's RB braking affords noticeably more efficient EV deceleration performance under the ABS operation. It allows for vehicle stopping distance diminishment. However, the electric motors are not always fully available as the braking systems, as for instance in the case of deceleration on high-μ surfaces or in case with the exceeded SOC threshold.

5 Conclusions

In this paper, the blended ABS control method for all-wheel drive sport utility EV is described. The SOC and the requested torques from both actuators, namely in-wheel SRMs and EHB, are taken into consideration for providing a sufficient braking torque to presume maximum deceleration efficiency for every wheel independently. The efficiency is guaranteed by the optimal wheel slip ratio braking for each wheel. In combination with the intelligent FLC, the blended ABS control method provides high efficiency and robustness against varying road conditions and changing system states.

The proposed solution is verified against HIL simulation, in which the experimentally validated EV is coupled with EHB test bed, which provides real brakes dynamics followed by significant hardware delay. The presented experimental results are dedicated to heavy braking conditions on a high-μ road surface, during which the upper SOC threshold is achieved. As a result, the blended ABS switches from the RB mode to the pure FB, and the vehicle continues the deceleration process with optimal slip ratio without motors' impact and performance degradation.

Despite good optimal slip control for various road surfaces, the proposed FLC-based control method has several limitations. Firstly, the method depends on tire model, whose behaviour is also different for other types of vehicles characterized by different centres of gravity, masses, etc. Hence, for other vehicle and tire types, the control method must be slightly modified. Secondly, to design an FLC for complex control system, like ABS, an expert's multidisciplinary knowledge is essential.

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