Available online at www.sciencedirect.com

ScienceDirect

Transportation Research Procedia 70 (2023) 28–35

Transportation Research Procedia

www.elsevier.com/locate/procedia

8th International Electric Vehicle Conference (EVC 2023)

Efficient Regenerative Braking Strategy Aimed at Preserving Vehicle Stability by Preventing Wheel Locking

Giulia Sandrini [a,*], Marco Gadola [a], Daniel Chindamo [a], Paolo Magri [a]

[a]*Department of Mechanical and Industrial Engineering, University of Brescia, I-25123 Brescia, Italy*

Abstract

This paper presents a regenerative braking logic to be adopted on full electric vehicles with front, rear-drive or all-wheel drive with one motor for each axle, which aims at maximizing energy recovery under braking, avoiding wheel locking thus preventing vehicle instability. The logic implies the adoption of a brake-by-wire system i.e., the hydraulic braking system can be activated independently from the brake pedal. As a matter of fact, with the pedal pressed, the logic gives priority to the braking action of the electric motor(s) which acts as a generator, thus maximizing energy recovery, however taking into account various limitations, including the wheel locking limit, ensuring the stability of the vehicle. When the electric motor cannot satisfy the regenerative torque request, braking is integrated with the help of the hydraulic brakes, whose contribution aims to bring the braking towards a condition of optimal braking distribution. The front and rear hydraulic systems must therefore be independent of each other and controllable separately. This logic was tested via simulation, and it emerged that, on the WLTC driving cycle, the logic saved about 30% in consumption compared to the same vehicle without regenerative recovery, and about 23% compared to a logic commonly adopted on the market. On cycle US06, it saves about 24% and 19%, respectively.

Keywords: regenerative braking logic; electric vehicle; energy optimization; energy recovery; vehicle stability

1. Introduction

A strong limitation of full electric vehicles is the limited range compared to traditional internal combustion engine vehicles (Ehsani et al., 2018). For this reason, it is very important to manage energy on board the vehicle in the best possible way, minimizing consumption and maximizing energy recovery when braking. The adoption of a suitable regenerative braking logic is therefore essential for increasing the range of the electric vehicle without increasing the

* Corresponding author.
E-mail address: g.sandrini005@unibs.it

10.1016/j.trpro.2023.10.005

vehicle weight by increasing the capacity of the battery pack. This also results in a less severe environmental impact in the use and industrial phase of the vehicle (Cecchel et al., 2018; Sandrini et al., 2021a).

In this work a regenerative braking logic (called RB logic) is therefore presented, which aims at maximizing the use of the regenerative motor torque during braking, minimizing the action of traditional brakes which dissipate energy. The RB logic is a MATLAB/Simulink model that can be adopted on full electric vehicles with front, rear-drive or all-wheel drive with one motor for each axle, which aims at maximizing energy recovery under braking, avoiding wheel locking and the related vehicle instability. The RB logic was tested using VI-CarRealTime® software (by VI-Grade®) and the TEST model described in (Sandrini et al., 2021b) (for more detail see also (Daniel Chindamo et al., 2014; D. Chindamo et al., 2014)).

In the literature there are several papers that deal with regenerative braking logics, the goal of the RB logic is to combine its merits while avoiding its defects. In particular, some logics can occasionally lead to vehicle instability (Li et al., 2005); others always following the ideal curve for braking distribution, do not maximize energy recovery (Biao et al., 2021; Guo et al., 2008); in others various aspects are not considered (i.e., constraint factors (Li et al., 2007), vertical load variation on the axes (Kim et al., 2011; Ko et al., 2014), battery pack characteristics (Lian et al., 2013)).

Nomenclature

AWD	All-wheel-drive
$Crnt_{MAX}$	Maximum current which can currently be absorbed by the battery pack
$Crnt_{req}$	Recharge current required of the battery pack
F_{req}	Braking force required by the electric motor
FWD	Front-wheel-drive
$J_{in/mot}$	Sum of the moment of inertia of the motor and of the transmission after the motor reducer
J_{out}	Moment of inertia of the transmission before the motor reducer
J_{wheel}	Moment of inertia of the wheel
L1	Front left wheel
L2	Rear left wheel
RB	Regenerative Braking
R_{cable}	Resistance of the electric cables
RWD	Rear-wheel-drive
R_{wheel}	Nominal rolling radius of the wheels
TEST	Target-speed EV Simulation Tool
T_{mot}	Regenerative motor torque
T_{ref}	Reference torque
T_{req}	Required braking motor torque
US06	SFTP-US06 driving cycle, described in the “EPA Supplemental Federal Test Procedure”
$Volt$	Battery pack voltage
WLTC	Worldwide Harmonized Light-Duty Vehicles Test Cycle
η_{mot}	Electric efficiency of the motor
η_{trans}	General efficiency of the entire transmission
τ	Total transmission ratio
ω_{mot}	Angular speed of the motor
ω_{wheel}	Angular speed of the wheels

2. Methodology

The RB logic maximizes the energy recovery by giving priority to the action of the electric motor(s) during braking and then integrating the braking action with the traditional hydraulic system, taking into account various limitations (wheel lock limit, motor limitations, battery pack limitations) and ensuring the vehicle stability, according to the diagram presented in Fig. 1.

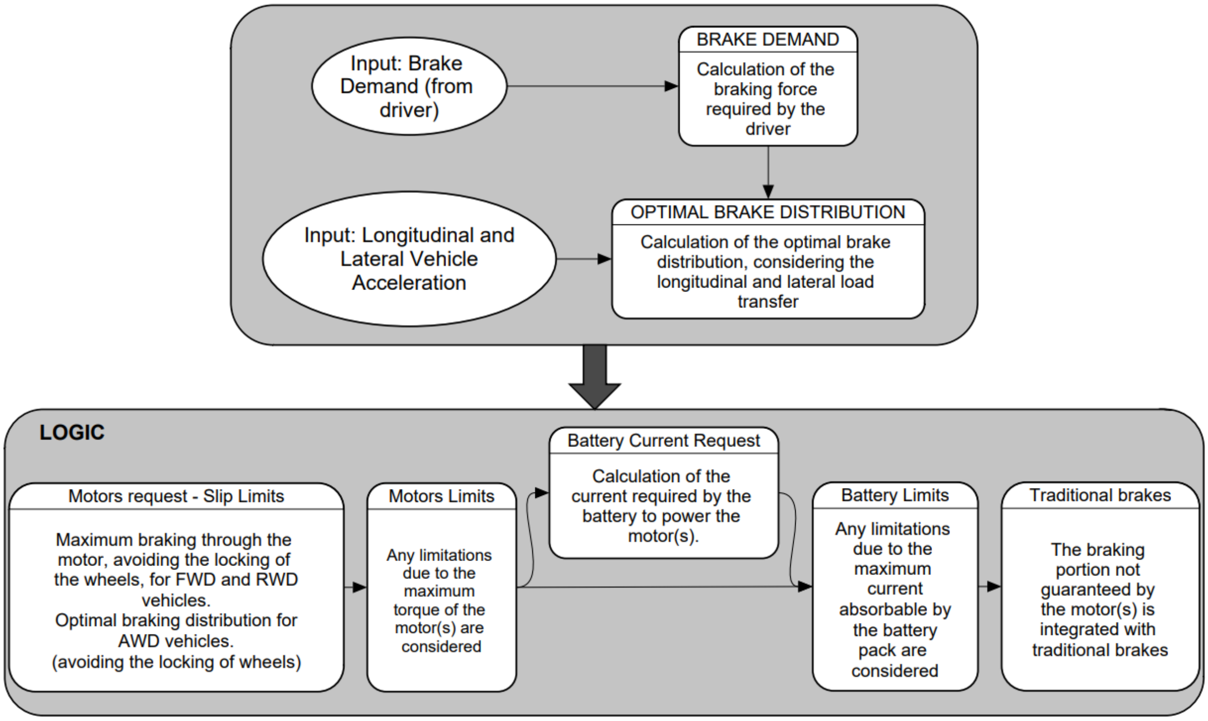

Fig. 1. Structure of the regenerative braking logic. For more calculation detail see paper (Sandrini et al., 2022).

Model inputs are the brake demand, the longitudinal vehicle deceleration, the lateral vehicle acceleration, the vehicle speed, the angular velocity of the wheels and of the motors, the battery voltage, the maximum charging current of the battery pack. The RB logic, from these inputs, starting from the brake demand imposed by the driver, calculates the following outputs: the front and rear brake pressure, and the front and rear motor torque.

On the front and rear wheel drive vehicle, the RB logic gives priority to the braking action of the electric motor which acts as a generator, thus maximizing energy recovery, however taking into account the above-mentioned limitations. When the electric motor cannot satisfy the regenerative torque request, due to limitations of the motor itself or due to the locking limitation of the drive axle wheels, braking is integrated with the hydraulic brakes, whose contribution aims to bring the braking towards a condition of optimal braking distribution.

In the case of an all-wheel drive vehicle, the regenerative torque will be distributed between the two motors in such a way as to satisfy the optimal braking distribution, in the event that this does not clash with the possibility of maximizing energy recovery, otherwise the braking torque bias will be moved towards an axle, always avoiding the instability of the vehicle.

For its operation, the logic implies a brake pedal independent of the traditional hydraulic braking system and a front and a rear hydraulic system independent of each other and controllable separately.

2.1. Calculation process

This paper will show the structure, summarized in Fig. 1, of a regenerative logic (RB logic) that aims at maximizing energy recovery under braking while avoiding vehicle instability. The objective of this article is to provide guidelines for implementing a similar logic, thus providing useful information on what limitations and aspects to consider in order to maximize regeneration while avoiding wheel locking. Therefore, not all the equations of logic will be presented in detail, only some for-example purposes. The rest, in case of need to replicate the logic, are still available in (Sandrini et al., 2022).

2.1.1. Brake demand, optimal braking distribution, tire-adhesion limits, and motor limitation

The Simulink model of the RB logic receives the brake signal (from 0 to 1) as input, proportional to the force that the driver imposes on the brake pedal. The braking force request (discharged to the ground) is defined as the product between the brake signal and the maximum braking force that the front and rear hydraulic systems together can discharge to the ground. The latter force is calculated starting from the constant input data relating to the hydraulic system: the maximum pressure that can be generated inside master cylinders, the total areas of the brake pistons in the calipers, the dynamic coefficients of friction between the brake pads and brake discs, the average radii of application of the braking force on the discs and the nominal rolling radii of the wheels.

The RB logic also calculates the optimal brake distribution between the front and rear axle, taking into account the load on the axles, considering the load transfer (both longitudinal and lateral) and the road friction coefficient and so calculating the maximum front and rear braking force that avoid wheel locking. The reference loads on the front and rear axles are calculated considering the inside wheel when cornering, taking into account the longitudinal and lateral vehicle acceleration, the vehicle mass, the front and rear sprung and unsprung mass of the vehicle, the wheelbase, the front and rear tracks of the vehicle, the center of gravity height, the height of the front and rear roll center, the longitudinal distance between each axles and the center of gravity of the vehicle, the stiffness of the suspension springs, the stiffness of the anti-roll barsFare clic o toccare qui per immettere il testo..

If the vehicle is front-wheel drive or rear-wheel drive, the braking force required by the electric motor (F_{req}) is set as the minimum between the total braking force required by the driver and the maximum total front or rear, respectively, braking force that avoid wheel locking multiplied by a safety coefficient. The required braking motor torque (T_{req}) is then calculated, via equation (1).

$$T_{req} = \left[\frac{F_{req} \cdot R_{wheel} + (2 \cdot J_{wheel} + J_{out}) \cdot \dfrac{\Delta(\omega_{wheel})}{\Delta t}}{\tau} + (J_{in/mot}) \cdot \frac{\Delta(\omega_{mot})}{\Delta t} \right] \cdot \eta_{trans} \tag{1}$$

In particular, with reference to the axle considered, front for the front-wheel drive vehicle and rear for the rear-wheel drive one, R_{wheel} is the nominal rolling radius of the wheels, τ is the total transmission ratio, J_{wheel} is the moment of inertia of the wheel, J_{out} is the moment of inertia of the transmission before the motor reducer, $J_{in/mot}$ is the sum of the moment of inertia of the motor and of the transmission after the motor reducer, η_{trans} is the general efficiency of the entire transmission, ω_{wheel} is the angular speed of the wheels and ω_{mot} is the angular speed of the motor.

Instead, if the vehicle is all-wheel drive, the total braking force required by the driver is distributed between the front and rear respecting the optimal braking distribution. Then, the braking forces required from the front and rear motor are imposed as the minimum between the corresponding total braking force requested by the driver and the corresponding maximum total braking force that avoid wheel locking multiplied by a safety coefficient. Finally, the same calculation approach adopted for the front and rear-wheel drive vehicle, equation (1), is used for the calculation of the motor torques for the all-wheel drive vehicle.

The motor torques thus calculated, for all three types of vehicles, are compared with the maximum regenerative motor torques available, considering the torque curve of each motor on board. From this point on, the RB logic will adopt the minimum value, front and rear, between the motor torque previously calculated and the maximum available, as the reference motor torque (T_{ref}).

2.1.2. Battery current request and battery limitation

Therefore, considering the reference torques T_{ref} of the electric motor(s) calculated so far and the relative angular speed(s), it is possible, knowing the electric efficiency of the motor(s) (η_{mot}) and the resistance of the electric cables (R_{cable}, to calculate the power dissipated due to the Joule effect), to calculate the recharge current required of the battery pack $Crnt_{req}$, also taking into account the voltage ($Volt$) of the pack itself, as in equation (2). In the case of all-wheel drive vehicles, the equation (2) is used to calculate the current relating to both motors and the total required current will therefore be given by the sum of the two calculated currents.

$$Crnt_{req} = \frac{\left(T_{ref} \cdot \omega_{mot}\right) - R_{cable} \cdot \left(\frac{T_{ref} \cdot \omega_{mot}}{Volt}\right)^2}{Volt} \cdot \eta_{mot} \tag{2}$$

Then, the RB logic checks whether the current that the motors must send to the battery does not exceed the maximum current ($Crnt_{MAX}$) which can currently be absorbed by the battery pack. If this limitation is not respected, it is necessary to limit the regenerative motor torque(s), in such a way that the motor, or the motors send to the battery pack exactly the maximum current that the latter is able to accept at the input. Conversely, the regenerative motor torques calculated so far will be the front and rear input torques for motor control.

In the case of a purely front or rear wheel drive vehicle, the limited regenerative motor torque (T_{mot}), which will be the input torque for motor control, is calculated via equation (3), considering the maximum current allowable ($Crnt_{MAX}$).

$$T_{mot} = \frac{Volt \cdot Crnt_{MAX} + R_{cable} \cdot {Crnt_{MAX}}^2}{\eta_{mot} \cdot \omega_{mot}} \tag{3}$$

On the other hand, in the case of all-wheel drive vehicles, the maximum power that can be absorbed by the battery pack ($Volt \cdot Crnt_{MAX}$), is divided between the front and rear motors through the optimal braking distribution. By adding the power dissipated due to the Joule effect to the power associated with the front motor, and dividing the whole by the motor efficiency and by the angular speed of the motor itself, it is possible to obtain the new limited front regenerative motor torque, with a calculation process analogous to that presented in equation (3). At this point of the logic, a further check is carried out: it is verified that this limited front motor torque is not greater than the corresponding reference front motor torque (T_{ref}) calculated previously. If the condition is verified, it is not necessary to make changes to the new calculated torque, otherwise, the latter is set equal to T_{ref} related to the front motor. Furthermore, in the latter case, it is necessary to recalculate the input power to the battery associated with the rear motor, as the product between the battery voltage and the difference between the maximum input current ($Crnt_{MAX}$) and the current that the front motor supplies to the battery pack itself. The latter current must be recalculated considering the new front regenerative motor torque equal to T_{ref} and using equation (2). Now, considering this new power associated with the rear electric motor it is possible to calculate the new rear motor torque. Again, a further check is carried out: it is verified that this new rear motor torque is not greater than the reference rear motor torque (T_{ref}) calculated previously. If the condition is verified, it is not necessary to make changes to the new calculated torque and it will be the input torque for rear motor control. Furthermore, it is no longer necessary to make changes to the front limited motor torque, which will therefore be the input torque for front motor control. Otherwise, if the condition is not verified, the torque control of the rear motor is set equal to T_{ref} (previously calculated for the rear motor) and it is necessary to recalculate the regenerative front motor torque. To do this, it is necessary to calculate the current that the rear motor sends to the battery. At this point, by subtracting this current from $Crnt_{MAX}$, and always considering the losses due to the Joule effect, it is possible to obtain the electrical input power to the battery associated with the front motor. Finally, by dividing the latter power by the efficiency and the angular speed of the front motor, it is possible to calculate the regenerative torque to be used as control of the front motor.

2.1.3. Traditional brakes

Finally, the RB logic therefore calculates the pressure in the front and rear master cylinders of the brake system in such a way that the total force discharged to the ground by the brakes and motor(s) is equal to the force required, associated with the brake signal. Furthermore, integration of the braking with the hydraulic system is distributed between the front and rear axles in such a way as to pursue the optimal braking distribution as much as possible, to guarantee vehicle stability (in particular, in conditions close to the road-tire adhesion limit).

3. Results and Discussion

For validation tests, three full electric compact cars, with front, rear and all-wheel drive, were taken as reference. The three vehicles has the same characteristics of weight (1548 kg), wheelbase (2.577 m), front (1.506 m) and rear (1.477 m) track, center of gravity height (0.564 m), frontal area of the vehicle (3.23 m^2), drag coefficient (0.32), front (0.299 m) and rear (0.301 m) rolling radius, total transmission ratio (3.7), power absorbed by vehicle accessories (1500 W), braking system (maximum front pressure of 9.75 MPa and rear of 5.25 MPa), suspension system and the same battery pack (42 kWh nominal capacity). The front and rear-wheel drive vehicle's motor has a maximum power of 87 kW and a maximum torque of 220 Nm, the all-wheel drive vehicle's motors a maximum of 43.5 kW and 110 Nm. For more vehicles detail see (Sandrini et al., 2022).

The simulation tests carried out with VI-CarRealTime have shown that the RB logic does not compromise the original stability of the vehicle (see (Sandrini et al., 2022) for the straightline panic brake and braking in turn tests), while from the simulation carried out through the TEST model described in (Sandrini et al., 2022, 2021b; Zecchi et al., 2022) it emerged that, on the WLTC driving cycle, for front, rear and all-wheel drive vehicles, the logic saved between 29.5 and 30.3% in consumption compared to the same vehicle without regenerative recovery, and 22.6–23.5% compared to a logic commonly adopted on the market (Sandrini et al., 2021b). On cycle US06, it saves 23.9–24.4% and 19.0–19.5%, respectively. The RB logic performs better in terms of energy savings on relatively mild cycles (WLTC) compared to more intense cycles (US06), there is dependence on the driving cycle adopted (Chindamo and Gadola, 2018) (Table 1).

Table 1. Consumption on the WLTC (class 3b) and on US06 driving cycles (Sandrini et al., 2022). FWD: front-wheel drive vehicle. RWD: rear-wheel drive vehicle. AWD: all-wheel drive vehicle.

Type of Vehicle	Regenerative Braking Logic	Energy Consumption [kWh]		Specific Energy Consumption [kWh/(100 km)]	
		WLTC	US06	WLTC	US06
FWD	RB logic	4.12	3.00	17.73	23.67
	No brake recovery	5.92	3.97	25.43	31.33
	Benchmark logic (Sandrini et al., 2021b)	5.39	3.73	23.16	29.42
RWD	RB logic	4.12	3.00	17.72	23.68
	No brake recovery	5.92	3.97	25.43	31.32
	Benchmark logic (Sandrini et al., 2021b)	5.39	3.73	23.16	29.43
AWD	RB logic	4.17	3.02	17.92	23.84
	No brake recovery	5.92	3.97	25.44	31.34
	Benchmark logic (Sandrini et al., 2021b)	5.39	3.73	23.17	29.44

Fig. 2 show the results of a straight braking tests performed with VI-CarRealTime®. In these tests the three reference vehicles (front, rear and all-wheel drive), equipped with RB logic, start from 108 km/h and brake gradually to zero speed, with a ramp up time of 10 s to bring the brake demand from 0 to 1, in a road with a unitary road friction coefficient.

The objective of the straight braking test is not to validate the stability of the vehicle, but to show the operating principle of the logic, i.e. how and when the regenerative drive torque and braking by the traditional hydraulic system intervene. Conversely, the stability of the vehicle was correctly validated through further tests performed with VI-CarRealTime: panic brake tests and braking in turn tests. In fact, the latter tests, omitted from the paper for space reasons, showed that the behavior of the vehicle in terms of stability remains that of the same reference vehicle, but without regenerative recovery. The logic therefore does not make any worse in this sense, in fact it take into account various aspects, such as the maximum forces that can be discharged to the ground instant by instant and the wheel locking limits.

From Fig. 2 it can be seen how, during braking, the braking action of the motor(s) first intervenes and, subsequently, the latter is integrated by the action of the hydraulic systems of traditional brakes.

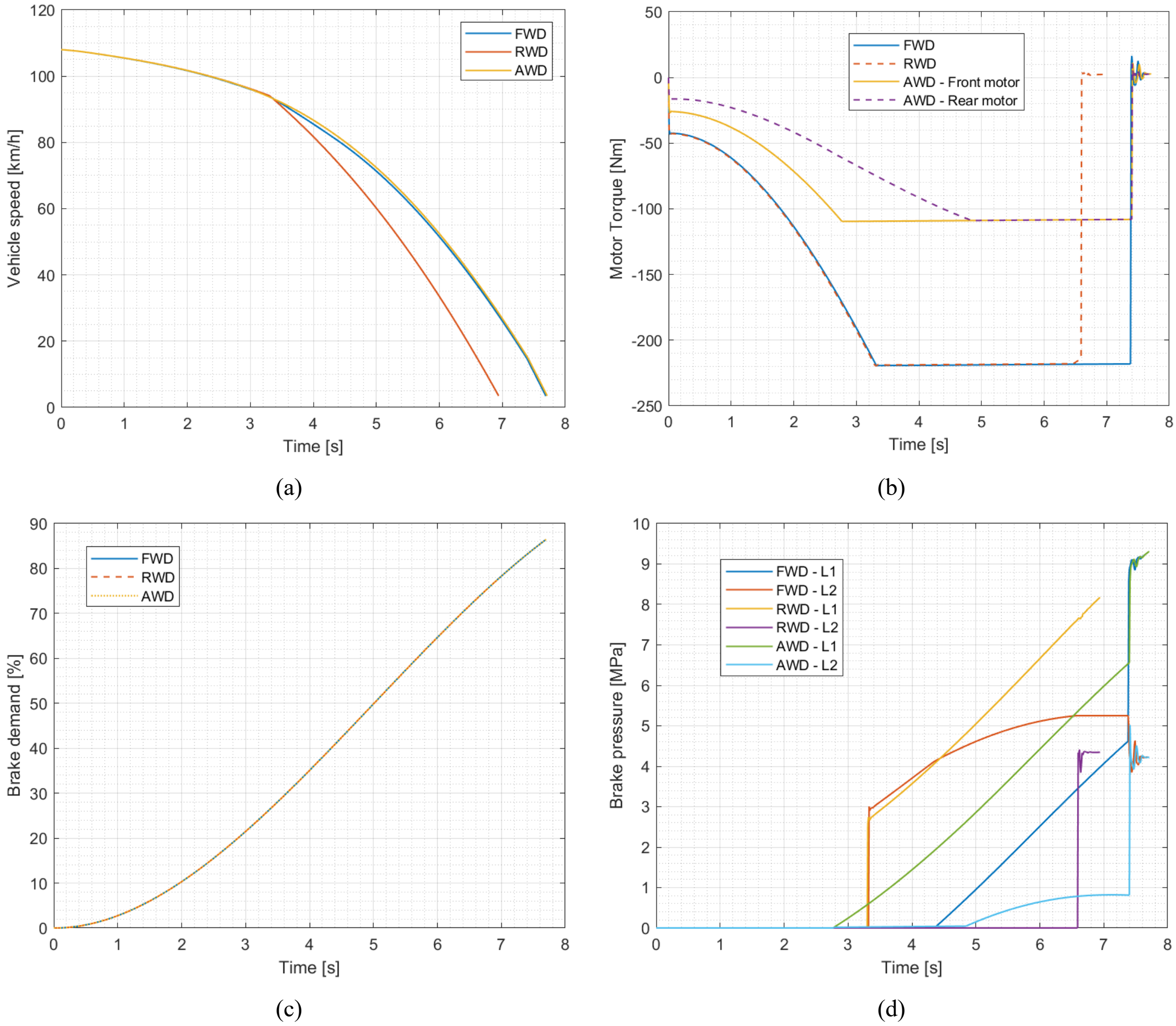

Fig. 2. Straight braking tests on front (FWD), rear (RWD) and all (AWD) wheel drive vehicles equipped with RB logic (operating above 15 km/h) (Sandrini et al., 2022). (a) Vehicle speed; (b) motor torque; (c) brake demand; (d) brake pressure at the front left wheel (L1) and at the rear left wheel (L2).

4. Conclusion

The RB logic aims at maximizing energy recovery, giving priority during braking to the electric motors which act as generators, avoiding vehicle instability and bringing the system into optimal braking distribution condition by approaching this latter condition.

Validation using VI-CarRealTime has shown that the adoption of the logic described here does not lead to a worsening of vehicle performance from the point of view of the vehicle stability. In fact, this logic, considering various aspects, including the weight distribution, the maximum braking forces that can be discharged to the ground and the grip limits between the tires and the ground, aims to prevent the wheels locking when braking. In particular, RB logic gives priority to regeneration during braking, compared to the use of hydraulic brakes, but the only regenerative motor torque, according to logic, must never be sufficient to lock the wheels. Therefore, as the grip limits are approached, the action of the traditional braking system intervenes more and more, integrating braking and bringing the system closer to the optimal braking condition. In limit conditions as regards stability, it will therefore be the action of the hydraulic brakes that supplies the excess force which will lead to blocking, but with optimal braking distribution. The locking of the wheels will therefore take place in a similar way to the case of a vehicle without regenerative recovery.

From the simulation on the reference vehicles, it emerged that, on the WLTC driving cycle, the logic saved about 30% in consumption compared to the same vehicle without regenerative recovery, and about 23% compared to a logic commonly adopted on the market. On cycle US06, it saves about 24% and 19%, respectively. Therefore, considering that the vehicles on the market are already equipped with a regenerative braking logic, it is possible to state that, thanks to this logic proposed in this paper, it is possible to obtain energy savings of around 20%, which varies according to the vehicle and the driving cycle considered.

References

Biao, J., Xiangwen, Z., Yangxiong, W., Wenchao, H., 2021. Regenerative Braking Control Strategy of Electric Vehicles Based on Braking Stability Requirements. International Journal of Automotive Technology 22, 465–473. https://doi.org/10.1007/s12239-021-0043-1

Cecchel, S., Chindamo, D., Collotta, M., Cornacchia, G., Panvini, A., Tomasoni, G., Gadola, M., 2018. Lightweighting in light commercial vehicles: cradle-to-grave life cycle assessment of a safety-relevant component. Int J Life Cycle Assess 23, 2043–2054. https://doi.org/10.1007/s11367-017-1433-5

Chindamo, Daniel, Economou, J.T., Gadola, M., Knowles, K., 2014. A neurofuzzy-controlled power management strategy for a series hybrid electric vehicle. Proceedings of the Institution of Mechanical Engineers, Part D: Journal of Automobile Engineering 228, 1034–1050. https://doi.org/10.1177/0954407014522777

Chindamo, D., Gadola, M., 2018. What is the Most Representative Standard Driving Cycle to Estimate Diesel Emissions of a Light Commercial Vehicle? IFAC-PapersOnLine 51, 73–78. https://doi.org/10.1016/j.ifacol.2018.06.213

Chindamo, D., Gadola, M., Romano, M., 2014. Simulation tool for optimization and performance prediction of a generic hybrid electric series powertrain. International Journal of Automotive Technology 15, 135–144. https://doi.org/10.1007/s12239-014-0015-9

Ehsani, M., Gao, Y., Longo, S., Ebrahimi, K., 2018. Modern Electric, Hybrid Electric, and Fuel Cell Vehicles. CRC Press, Taylor & Francis Group, Boca Raton, FL, USA, pp. 1–11.

Guo, J., Wang, J., Cao, B., 2008. Brake-Force Distribution Strategy for Electric Vehicle Based on Maximum Energy Recovery. Hsi-An Chiao Tung Ta Hsueh/Journal of Xi'an Jiaotong University 42, 607–611.

Kim, J., Ko, S., Lee, G., Yeo, H., Kim, P., Kim, H., 2011. Development of co-operative control algorithm for parallel HEV with electric booster brake during regenerative braking, in: 2011 IEEE Vehicle Power and Propulsion Conference, VPPC 2011. https://doi.org/10.1109/VPPC.2011.6043151

Ko, J.W., Ko, S.Y., Kim, I.S., Hyun, D.Y., Kim, H.S., 2014. Co-operative control for regenerative braking and friction braking to increase energy recovery without wheel lock. International Journal of Automotive Technology 15, 253–262. https://doi.org/10.1007/s12239-014-0026-6

Li, P., Jin, D.F., Luo, Y.G., 2005. Regenerative braking control strategy for a mild HEV. Automotive Engineering 27, 570–574. https://doi.org/10.1007/s12239–021–0043–1

Li, Y.F., Tian, Y.T., Hu, L.L., Yin, C., 2007. A study on control algorithm of regenerative braking for EV/HEV. Automotive Engineering 29, 1059–1063.

Lian, Y.-F., Tian, Y.-T., Hu, L.-L., Yin, C., 2013. A new braking force distribution strategy for electric vehicle based on regenerative braking strength continuity. J Cent South Univ 20, 3481–3489. https://doi.org/10.1007/s11771-013-1872-5

Sandrini, G., Chindamo, D., Gadola, M., 2022. Regenerative Braking Logic That Maximizes Energy Recovery Ensuring the Vehicle Stability. Energies (Basel) 15, 5846. https://doi.org/10.3390/en15165846

Sandrini, G., Có, B., Tomasoni, G., Gadola, M., Chindamo, D., 2021a. The Environmental Performance of Traction Batteries for Electric Vehicles from a Life Cycle Perspective. Environmental and Climate Technologies 25. https://doi.org/10.2478/rtuect-2021-0053

Sandrini, G., Gadola, M., Chindamo, D., 2021b. Longitudinal dynamics simulation tool for hybrid apu and full electric vehicle. Energies (Basel) 14. https://doi.org/10.3390/en14041207

Zecchi, L., Sandrini, G., Gadola, M., Chindamo, D., 2022. Modeling of a Hybrid Fuel Cell Powertrain with Power Split Logic for Onboard Energy Management Using a Longitudinal Dynamics Simulation Tool. Energies (Basel) 15, 6228. https://doi.org/10.3390/en15176228