Friction Losses During Slip Conditions in Regenerative Braking of Electric Vehicles

*Agung Prijo Budijono**
Department of Mechanical Engineering, Universitas Negeri Surabaya, Surabaya 60231
Doctoral Student, Institut Teknologi Sepuluh Nopember, Surabaya 60111
**agungbudijono@unesa.ac.id*

I. Nyoman Sutantra, Agus Sigit Pramono
Department of Mechanical Engineering,
Institut Teknologi Sepuluh Nopember, Surabaya 60111

ABSTRACT

The regenerative braking system (RBS) in electric vehicles (EVs) enhances its capability against internal combustion engines (ICE). Antilock braking system (ABS) is widely used in RBS because of its maneuverability and safety. One of the purposes of applying ABS is to avoid slippage. Slip on the braking process, especially hydraulic brakes, results in a difference in time to stop the wheels and the vehicle. It is avoided because it relies on friction between the tires and the road to stop transportation. Timing results showed that ABS with high frequency, above 30 Hz, tended to act like hydraulic brakes. Hydraulic brakes achieved the highest time difference, 8 seconds at 2250 rpm. It increased the distance of 350 m in slipping while the lowest time difference ABS 10 Hz owned, 0.1 seconds at the same rpm. Slips caused losses. These losses could be minimized with low-frequency ABS. It converted the friction between the wheels and the brakes into electrical energy instead of stopping the vehicle. As a result, the 10 Hz ABS had the highest potency stored despite the lowest performance.

Keywords: *Regenerative Braking; Electric Vehicles; Antilock Braking System; Friction Losses; Braking Process*

ISSN 1823-5514, eISSN 2550-164X

https://doi.org/10.24191/jmeche.v11i1.23591

Received for review: 2022-09-05
Accepted for publication: 2022-10-30
Published: 2022-11-15

Introduction

Electric vehicles (EVs) have become an alternative to internal combustion engines due to environmental and economic interests [1]. Barriers to EV development are power storage and scarce battery charging bays [2]. Besides that, it has many advantages, including high efficiency. It can recharge its power with a regenerative braking system (RBS) and regenerative suspension system (RSS) [3]. These systems occur dynamically when the vehicle is running on the road. Therefore, the coefficient of friction between the tire and the road also affects this process [4].

RBS can minimize one-third to one-half of vehicle energy lost due to braking [5]. Generally, the braking on EVs has two types of brakes, electric and friction [6]. They can be used in series or parallel control to get a fast response and high stability [7]. Several studies have used nonlinear modification models as their predictive control method to maximize braking energy recovery instead of ensuring braking stability [8]. Also, the motor for regenerative braking can be directly added to conventional braking to get greater efficiency and better energy recovery capacity of regenerative braking [9].

The parallel control on the RBS is similar to conventional braking, while the series control prioritizes regenerative braking before friction braking [10]. It refers to the distribution of friction between the front and rear axles with the regenerative force of the motor [11]. The ideal distribution curve becomes the reference for the distribution of these forces for braking stability [12]. The brake-by-wire system introduced in the EV has increased the efficiency and control response of the antilock braking system (ABS) [13]. It can also help to increase the braking torque, which is generally much higher than the torque that an electric motor can produce [14].

ABS has high safety and stability, so it is often used in the systems on both conventional and electric vehicles [15]. ABS can stop transportation quickly by setting wheel slip at the optimal value, resulting in maximum friction. All braking systems are reliable in road conditions with an ordinary coefficient of friction [16]. For slippery roads, the potential of the wheels being locked is very high, so an algorithm that regulates the pressure of the brake pistons is needed [17]. The ABS model-based algorithm (MBA) provides a wide piston frequency range so the designer can adjust it to the road friction coefficient [18].

Battery electric vehicle (BEV) is a common EV power source encountered today because the system is simple and easy to implement [19]. However, its power management strategy (PMS) is riskier than conventional vehicles because the power source is only from the battery [20]. Generally, BEVs contain a supercapacitor (SC) bank to overcome that problem and imitate a DC-DC converter as a regulator of energy discharge and recovery in RBS [21]. The size of the BEV depends on the EV's minimum mileage and power demand [22]. The thing that needs to be underlined is when the wheel rotation is low, the power generated by the RBS cannot be charged to the power source because the feedback energy is low [23].

This study tested the EV components using a DC motor as the power source and ABS as the RBS, the components as shown in Figure 1. ABS used the MBA to adjust the piston frequency from 10 to 50 Hz. The prototype also used conventional (hydraulic) brakes in addition to ABS and looked like remote-controlled toy car, as depicted in Figure 2. It ran on asphalt roads in dry conditions with a usual friction coefficient. The rotational speed of the vehicle wheels ranged from 500 to 2250 rpm. The braking pressure was set at 2 kg/mm^2, and the braking time was measured from the first braking applied until the vehicle came to a complete stop.

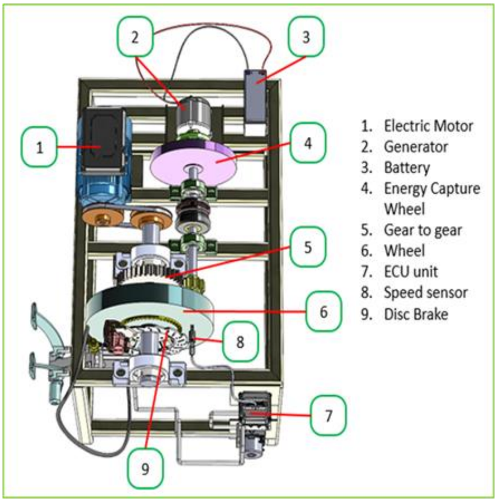


Figure 1: The vehicle components

Figure 2: The prototype

Methods

This study measured the reliability of ABS with a particular frequency range, which was applied as an RBS of an EV prototype. It ran on a dry asphalt road with straight paths. Once it reached a specific speed, the ABS worked to stop it. It was operated without a driver, and its measuring parameters were based on sensors installed, as illustrated in Figure 3.

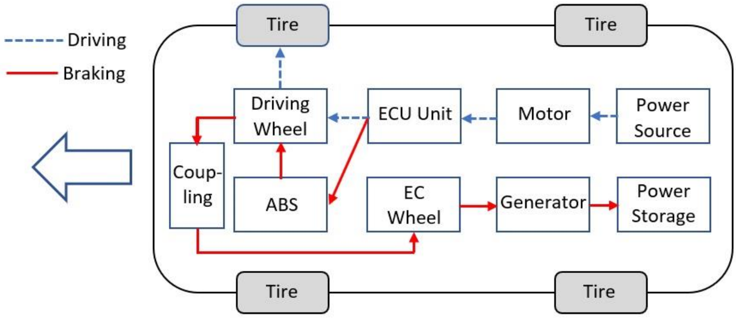


Figure 3: The vehicle configuration

The experiment measured motor rotation. It means the rotational speed of the vehicle's tires. Also, this study sized braking time, the time to stop the prototype, and the electric current generated by the generator due to regenerative braking. The axle transmission used a centrifugal clutch, as shown in Figure 4, to ensure that only the braking force rotated the EC wheel (ECW). The ECU unit regulated the motor power to turn the driving wheel (DW) until it reached the desired rotation, then turned off the motor and switched on the ABS. Power storage was distinguished from a power source, so the electric current generated by the generator can be read by the ammeter.

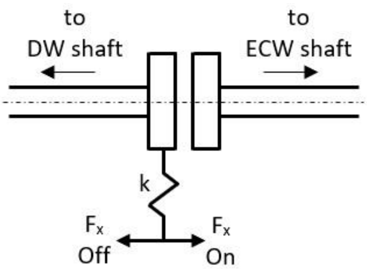


Figure 4: The centrifugal clutch

Dynamic model

Braking causes the forces on the tires, as described in Figure 5, to be in the opposite direction to the direction of the vehicle's speed to stop it. Factors that affect wheel rotation are tire-road friction, vehicle weight, and braking torque [24]. Vehicle and wheel dynamics models are

$$J\dot{\omega}_w = -T_e + RF_x \tag{1}$$

$$m\dot{v} = -F_x \tag{2}$$

$$F_x = \mu(\lambda)mg \tag{3}$$

$$T_t = RF_x \tag{4}$$

$$v = R\omega_v \tag{5}$$

$$\lambda = \frac{\omega_v - \omega_w}{\omega_v} \tag{6}$$

where J is the moment of inertia, T_e is the braking torque, R is the effective radius of the wheel, F_x is the longitudinal force of the tire, m is the total mass of one-quarter of the vehicle, g is the specific gravity, v is the longitudinal speed of the vehicle, ω_w is the angular speed of the wheels, ω_v is the angular speed of the vehicle, $\mu(\lambda)$ is the coefficient of longitudinal friction of the tire, λ is the wheel slip ratio, T_t is the torque due to ground friction.

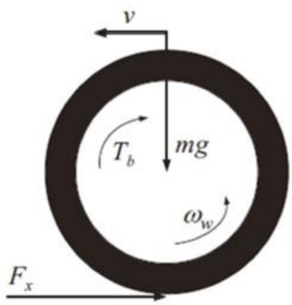


Figure 5: The wheel dynamic model

The coefficient of longitudinal friction is a function of the slip ratio for various road conditions, as given in Figure 6. Its value increases with an increasing slip ratio until it reaches a maximum point, then decreases slowly. The peak point of the coefficient of friction depends on the road conditions. It is also the optimal value of the slip ratio.

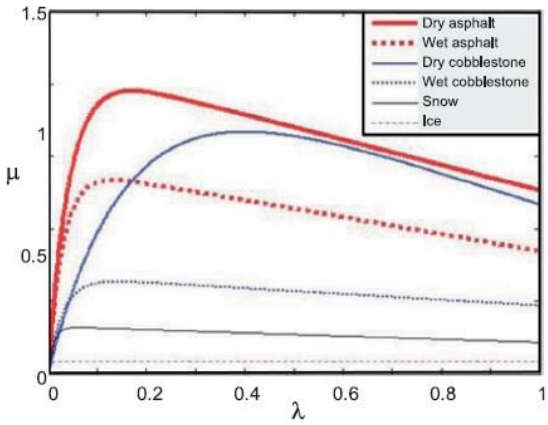


Figure 6: The friction coefficient of slip ratio function for various road conditions [25]

Figure 6 shows the maximum friction coefficient obtained at about 20% slip ratio. ABS works in this range. At slip ratios above 20%, the coefficient of friction decreases. It means a slip occurs, as displayed in Figure 7. The frequency variation in ABS and hydraulic brakes will indicate the range of slip ratios in which they operate.

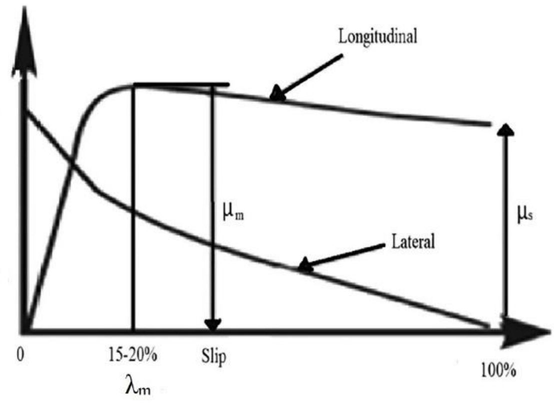


Figure 7: ABS working area at maximum friction coefficient (μ_m) and maximum slip ratio (λ_m) [5]

Powertrain

DC motor

The prototype used a DC motor as a drive. Table 1 shows the specifications where the power source was a battery. The relationship between power and motor rotational speed is;

$$P_m = \frac{2\pi n_m T_m}{60} \tag{7}$$

where P_m is motor power in Watts, n_m is motor speed in rpm, and T_m is motor torque in N.m.

Table 1: Motor specifications

Parameter	Value	Unit
Voltage	48	Volt
Power	350	Watt
Current	9.4	Ampere
Load (max)	350	kg
Torque	1.5–7.5	N.m
Speed	500–2750	rpm
Ratio	1:5	–

DC generator

The generator converted the ECW rotational kinetic energy into electricity, which will be stored in the battery. Table 2 provides the specifications installed on the prototype. The emf and the resulting industrial electric current are given by Equations 8 and 9, respectively.

Table 2: Generator specifications

Parameter	Value	Unit
Voltage	24	Volt
Power	250	Watt
Current	16.4	Ampere
Load (max)	350	kg
Speed rate	2700	rpm

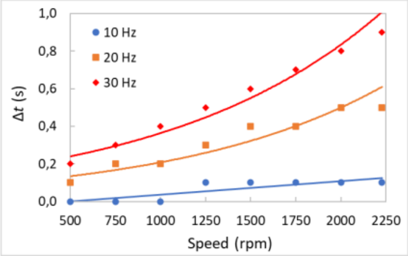
$$\varepsilon_{ind} = -N\frac{d\phi}{dt} \tag{8}$$

$$I_{ind} = \frac{\varepsilon_{ind}}{R} \tag{9}$$

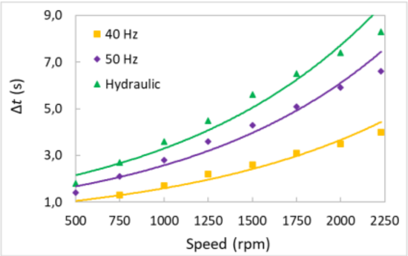
where ε_{ind} is the induced emf in Volts, N is the number of windings, ϕ is the magnetic flux, t is the time, I_{ind} is the induced current in Ampere, and R is the resistance in Ω.

Results and Discussion

This study used two stopwatches to measure braking time. A stopwatch was attached with a sensor on the wheel. It told the wheel stop time. Another stopwatch held by the researchers measured the braking time until the vehicle came to a complete stop. The vehicle lights would turn on when the motor turned off. It marked the beginning of the stopping time and braking time. Figure 8 shows the difference between these times. The piston frequency range in ABS produced two groups of discussion, the dominance of ABS and hydraulics. The lower frequency tended to be dominated by ABS.



(a)

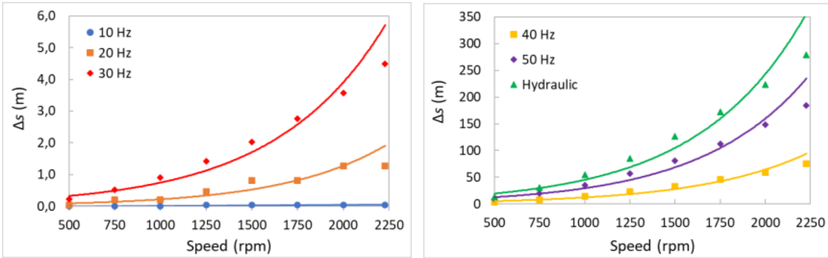


(b)

Figure 8: The difference between the stopping time to stop the wheels and the braking time to stop the vehicle: (a) lower frequency of ABS, (b) higher frequency of ABS and hydraulic

ABS, with the lowest frequency, had the fewest time difference. It indicated that the ABS 10 Hz safety factor was very high because there was almost no slip at low speeds [26]. At high speeds above 1000 rpm, the time difference of ABS 10 Hz was only 0.1 seconds. Therefore, conventional vehicles often use this ABS.

The difference in stopping time caused an increase in the distance to stop the vehicle. Figure 9 provides the results of calculating the difference in length to stop the wheels and the prototype. It was the role of friction between the tires and the road. The smaller the coefficient of friction, the further the distance increases.

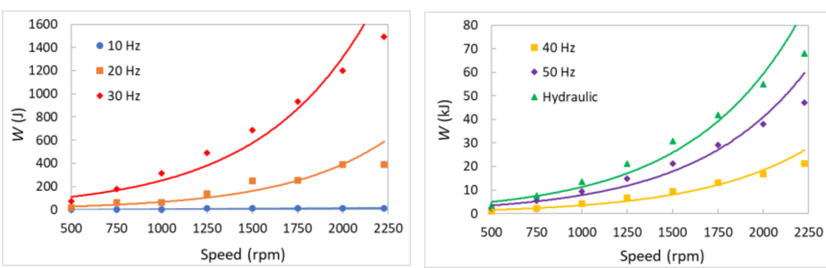


(a) (b)

Figure 9: Distance addition stopping the vehicle: (a) lower frequency of ABS, (b) higher frequency of ABS and hydraulic

ABS 10 Hz had the lowest distance difference, less than 1 meter, even at high speeds [27]. It operated on a maximum coefficient of friction, as shown in Figure 7. Hydraulics had the longest addition distance. It meant that hydraulic had the highest slip of all types of braking in this study [28].

A significant difference in distance occurs in the ABS 30 Hz and ABS 40 Hz. ABS 30 Hz and ABS 40 Hz have a distance of 5 m and 50 m at 2250 rpm, respectively. It is due to the time difference between the stopping time and the braking time of these variations, which are also significantly different. The addition of distance is a function of the square of the difference in time. The comparison of the time difference between ABS 30 Hz and ABS 40 Hz at 2250 rpm was 1/3, so the ratio of the addition of the distance between the two was 1/9.



(a) (b)

Figure 10: The friction work between the tires and the road to stop the vehicle; (a) lower frequency of ABS, (b) higher frequency of ABS and hydraulic

The friction work was the product of the friction force by the distance in Figure 9. This work was pure friction between the tires and the road without the wheel braking [29]. This work was a disadvantage because the vehicle was supposed to be stopped by braking the wheels, and the optimum frictional energy from braking was utilized by regenerative braking [30]. Figure 10 describes the calculation of tire friction work.

Hydraulics had an advantage in regenerative braking performance because the time to stop the wheels was the fastest [31]. The fastest time in turning the ECW will have given the highest induced emf [32]. Figure 11 illustrates the results of the performance calculation based on the measurement of the induced current in the generator.

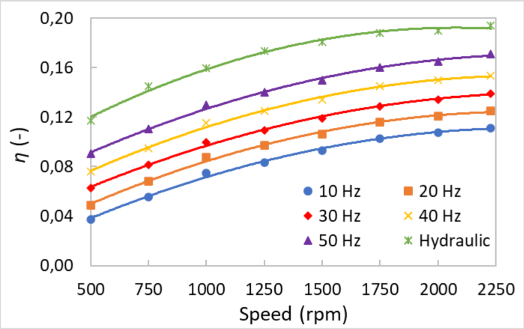


Figure 11: Regenerative braking performance

The energy stored in batteries said otherwise. Hydraulics provided the lowest stored energy among other brakes [24]. The fastest time to stop the wheel caused the most change in kinetic energy to heat [33]. Figure 12 gives the results of the calculated energy stored by RBS.

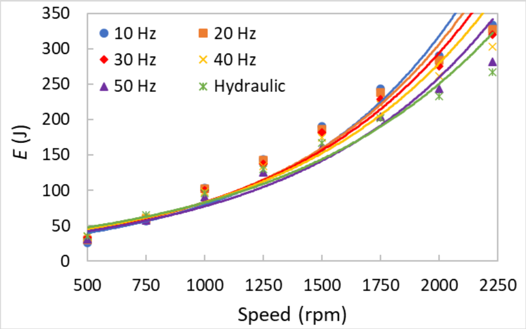
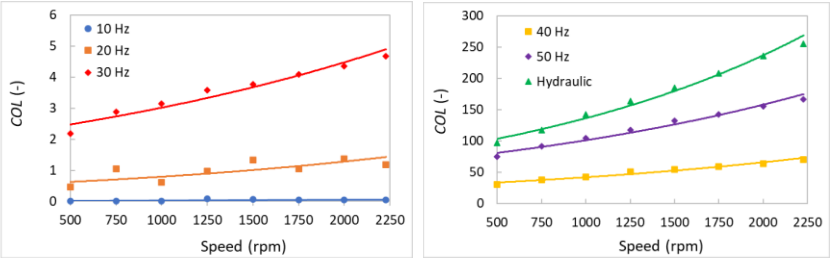


Figure 12: Energy stored from regenerative braking

The coefficient of losses is the ratio between losses and stored energy. It will be zero when there are no losses at all. Figure 13 is the result of the calculation of the coefficient of losses. ABS 10 Hz had the lowest coefficient of losses, which means it is good at EV energy management [34].



(a) (b)

Figure 13: Coefficient of losses (COL); (a) lower frequency of ABS, (b) higher frequency of ABS and hydraulic

Conclusion

EVs dominate vehicles on the road because of the efficiency they offer. This efficiency is due to the regenerative energy applied to EVs, one of which is RBS. People know ABS as a braking system that has high reliability. The application of ABS using the MBA method on RBS is needed to determine its performance and reliability. ABS minimizes slippage during braking. It is in contrast to the principle of hydraulic brakes (conventional), where the main goal is to stop the wheel spinning. There is a time difference between the wheels stop turning with the vehicle stops moving on the hydraulic brakes. It calls slip that only depends on the friction between the wheels and the road. High slip causes losses due to long friction. It causes a high coefficient of losses (COL). Although the hydraulic brake had the highest losses, it had the highest performance because it could stop the wheel rotation the fastest. It caused the highest induced current in the generator. However, ABS 10 Hz had the highest stored energy because it had the longest stopping time. It made the conversion of mechanical energy into electricity more optimal. The combined performance of RBS with regenerative shock breaker system (RSS) on EVs can be the future work of this research. The application of RSS suggests that the test track is not always straight, and the test results will be more optimal. When the vehicle turns, the value between RBS and RSS will increase or decrease. It will be a catchy discussion.

References

[1] M. Bahrami, H. Mokhtari, A. Dindar, “Energy regeneration technique for electric vehicles driven by a brushless DC motor,” *IET Power Electron.*, vol. 12, no. 13, pp. 3397 – 3402, 2019.

[2] G. Wager, J. Whale and T. Braunl, “Performance evaluation of regenerative braking systems,” *Proc IMechE Part D: J. Automobile Engineering*, vol. 232, no. 10, pp. 1414 – 1427, 2017.

[3] S. Xu, X. Zhao, N. Yang and Z. Bai, “Control strategy of braking energy recovery for range-extended electric commercial vehicles by considering braking intention recognition and electro-pneumatic braking compensation,” *Energy Technology*, vol. 8, no. 9, pp. 2000407, 2020.

[4] N. M. Jamadar and H. T. Jadhav, “A review on braking control and optimization techniques for electric vehicle,” *Proc. IMechE Part D: J. Automobile Engineering*, vol. 235, no. 9, pp. 2371 – 2382, 2021.

[5] M. N. Elghitany, F. Tolba, A. M. Abdelkader, “Low vehicle speeds regenerative anti-lock braking system,” *Ain Shams Engineering Journal*,vol. 13, pp. 101570, 2022.

[6] J. El-bakkouri, H. Ouadi, A. Saad, “Adaptive neuro fuzzy inference system based controller for electric vehicle's hybrid ABS braking,” *IFAC PapersOnLine*, vol. 55, no. 12, pp. 371 – 376, 2022.

[7] J. Bian and B. Qiu, “Effect of road gradient on regenerative braking energy in a pure electric vehicle,” *Proc. ImechE Part D: J. Automobile Engineering*, vol. 232, no. 13, pp 1736 – 1746, 2017.

[8] J. Feng, “Brake energy recovery system for electric vehicle,” *International Journal of Ambient Energy*, vol. 43, no. 1, pp. 942 – 945, 2022.

[9] F. Ji, Y. Pan, Y. Zhou, F. Du, Q. Zhang and G. Li, “Energy recovery based on pedal situation for regenerative braking system of electric vehicle,” *Vehicle System Dynamics*, vol. 58, no. 1, pp. 144 – 173, 2020.

[10] P. Mei, H. R. Karimi, S. Yang, B. Xu, C. Huang, “An adaptive fuzzy sliding-mode control for regenerative braking system of electric vehicles,” *Int. J. Adapt. Control Signal Process*, vol. 36, no. 2, pp. 391 – 410, 2022.

[11] S. Li, B. Yu and X. Feng, “Research on braking energy recovery strategy of electric vehicle based on ECE regulation and I curve,” *Science Progress*, vol. 103, no. 1, pp. 1 – 17, 2020.

[12] C. Sun, L. Chu, J. Guo, D. Shi, T. Li and Y. Jiang, “Research on adaptive cruise control strategy of pure electric vehicle with braking energy recovery,” *Advances in Mechanical Engineering*, vol. 9, no. 11, pp. 1 – 12, 2017.

[13] S. Rajendran, S. K. Spurgeon, G. Tsampardoukas, R. Hampson, “Estimation of road frictional force and wheel slip for effective antilock braking system (ABS) control,” *Int. J. Robust Nonlinear Control*, vol. 29, no. 3, pp. 736 – 765, 2019.

[14] E. Quintero-Manríquez, E. N. Sanchez, M. E. Antonio-Toledo, F. Muñoz, "Neural control of an induction motor with regenerative braking as electric vehicle architecture," *Engineering Applications of Artificial Intelligence*, vol. 104, pp. 104275, 2021.
[15] Y. Zhu, H. Wu and C. Zhen, "Regenerative braking control under sliding braking condition of electric vehicles with switched reluctance motor drive system," *Energy*, vol. 230, pp. 120901, 2021.
[16] Z. Wei, J. Xu and D. Halim, "Braking force control strategy for electric vehicles with load variation and wheel slip considerations," *IET Electr. Syst. Transp.*, vol. 7, no. 1, pp. 41 – 47, 2017.
[17] S. Saha and S. M. Amrr, "Design of slip-based traction control system for EV and validation using co-simulation between Adams and Matlab/Simulink," *Simulation*, vol. 96, no. 6, pp. 537 – 549, 2020.
[18] D. Wu, B. Zhu, D. Tan, N. Zhang and J. Gu, "Multi-objective optimization strategy of adaptive cruise control considering regenerative energy," *Proc IMechE Part D: J Automobile Engineering*, vol. 233, no. 14, pp. 1 – 16, 2019.
[19] R. S. Sankarkumar and R. Natarajan, "Energy management techniques and topologies for hybrid energy storage system powered electric vehicles: An overview," *Int. Trans. Electr. Energ. Syst.*, vol. 31, pp. e12819, 2021.
[20] H. Saleeb, K. Sayed, A. Kassem, R. Mostafa, "Power management strategy for battery electric vehicles," *IET Elect. Syst. Transp.*, vol. 9, no. 2, pp. 65 – 74, 2019.
[21] W. Wang, Y. Li, M. Shi and Y. Song, "Optimization and control of battery-flywheel compound energy storage system during an electric vehicle braking," *Energy*, vol. 226, pp. 120404, 2021.
[22] A. Geetha and C. Subramani, "A comprehensive review on energy management strategies of hybrid energy storage system for electric vehicles," *International Journal of Energy Research*, vol. 41, no. 13, pp. 1817 – 1834, 2017.
[23] Q-Y. Zhang and J. Huang, "Research on regenerative braking energy recovery system of electric vehicles," *Journal of Interdisciplinary Mathematics*, vol. 21, no. 5, pp. 1321 – 1326, 2018.
[24] W. Li, H. Du, W. Li, "Driver intention based coordinate control of regenerative and plugging braking for electric vehicles with in- wheel PMSMs," *IET Intell. Transp. Syst.*, vol. 12, no. 10, pp. 1300 – 1311, 2018.
[25] S. Seyedtabaii and A. Velayati, "Adaptive optimal slip ratio estimator for effective braking on a non-uniform condition road," *Automatika*, vol. 60, no. 4, pp. 413 – 421, 2019.
[26] N. Feng, J. Yong and Z. Zhan, "A direct multiple shooting method to improve vehicle handling and stability for four hub-wheel-drive electric vehicle during regenerative braking," *Proc. IMechE Part D: J. Automobile Engineering*, vol. 234, no. 4, pp. 1047 – 1056, 2019.

[27] H. Koylu and E. Tursal, "Experimental study on braking and stability performance during low speed braking with ABS under critical road conditions," Engineering Science and Technology, an International Journal, vol. 24, no. 5, pp. 1224 – 1238, 2021.
[28] Y. He, C. Lu, J. Shen and C. Yuan, "A second-order slip model for constraint backstepping control of antilock braking system based on Burckhardt's model," *International Journal of modelling and Simulation*, vol. 40, no. 2, pp. 130 – 142, 2020.
[29] C. S. N. Kumar and S. C. Subramanian, "Brake force sharing to improve lateral stability while regenerative braking in a turn," *Proc. IMechE Part D: J. Automobile Engineering*, vol. 233, no. 3, pp. 531 – 547, 2017.
[30] C-L. Lin, M-Y. Yang, E-P. Chen, Y-C. Chen, W-C. Yu, "Antilock braking control system for electric vehicles," *J. Eng.*, vol. 2018, no. 2, pp. 60 – 67, 2018.
[31] Y. Li, H. Deng, X. Xu, W. Wang, "Modelling and testing of in-wheel motor drive intelligent electric vehicles based on co-simulation with Carsim/Simulink," *IET Intell. Transp. Syst.*, vol. 13, no. 1, pp. 115 – 123, 2019.
[32] D. Sun, J. Zhang, C. He and J. Han, "Dual mode regenerative braking control strategy of electric vehicle based on active disturbance rejection control," *Proc IMechE Part D: J. Automobile Engineering*, vol. 235, no. 6, pp. 1483 – 1496, 2021.
[33] L. Gang and Y. Zhi, "Energy saving control based on motor efficiency map for vehicles with four-wheel independently driven in-wheel motors," *Advances in Mechanical Engineering*, vol. 10, no. 8, pp. 1 – 18, 2018.
[34] L. Li, X. Ping, J. Shi, X. Wang, X. Wu, "Energy recovery strategy for regenerative braking system of intelligent four-wheel independent drive electric vehicles," *IET Intell. Transp. Syst.*, vol.15, no. 1, pp. 119 – 131, 2021.