Friction losses

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Friction losses during slip conditions in regenerative braking of electric vehicles

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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. Slip on the braking process results in a difference in time to stop the wheels and the vehicle. 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. ABS 10 Hz owned the lowest time difference, 0.1 seconds at the same rpm. Losses due to slip could be minimized with low-frequency ABS. It converts the friction between the wheels and the brakes into electrical energy instead of stopping the vehicle.

Keywords: *Regenerative braking; electric vehicles; antilock braking system; friction losses; braking process.*

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 [28]. Besides that, it has many advantages, including high efficiency. It can recharge its power with a regenerative braking system (RBS) and regenerative suspension

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system (RSS) [32]. 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 [10].

RBS can minimize one-third to one-half of vehicle energy lost due to braking [4]. Generally, the braking on EVs has two types of brakes, electric and friction [3]. They can be used in series or parallel control to get a fast response and high stability [2]. Several studies have used nonlinear modification models as their predictive control method to maximize braking energy recovery instead of ensuring braking stability [5]. 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 [11].

The parallel control on the RBS is similar to conventional braking, while the series control prioritizes regenerative braking before friction braking [19]. It refers to the distribution of friction between the front and rear axles with the regenerative force of the motor [17]. The ideal distribution curve becomes the reference for the distribution of these forces for braking stability [26]. The brake-by-wire system introduced in the EV has increased the efficiency and control response of the antilock braking system (ABS) [21]. It can also help to increase the braking torque, which is generally much higher than the torque that an electric motor can produce [20].

ABS has high safety and stability, so it is often used in the systems on both conventional and electric vehicles [34]. 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 [30]. 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 [22]. The ABS model-based algorithm (MBA) provides a wide piston frequency range so the designer can adjust it to the road friction coefficient [31].

Battery electric vehicle (BEV) is a common EV power source encountered today because the system is simple and easy to implement [24]. However, its power management strategy (PMS) is riskier because the power source is only from the battery [23]. 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 [29]. The size of the BEV depends on the EV's minimum mileage and power demand [8]. 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 [33].

This study tested the EV prototype using a DC motor as the power source and ABS as the RBS, 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. 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.

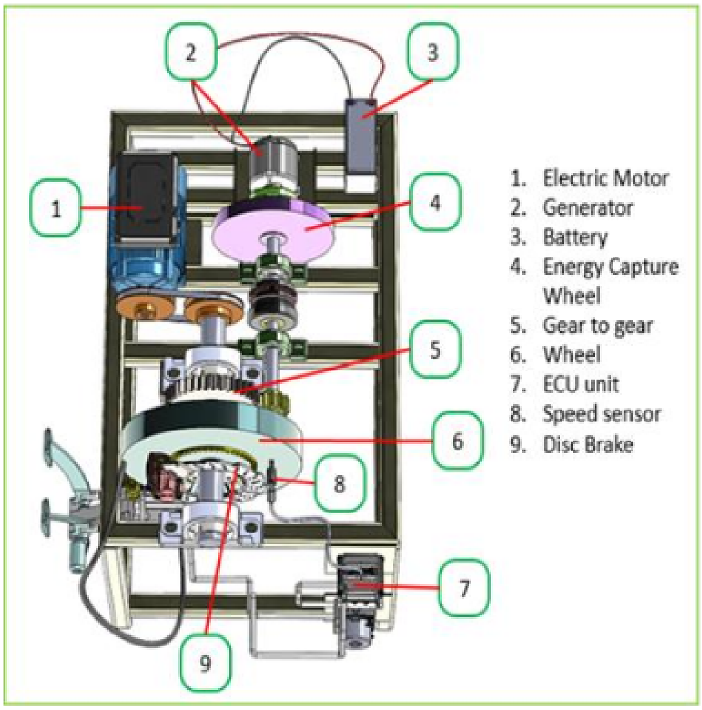


Figure 1: The vehicle components.

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 2.

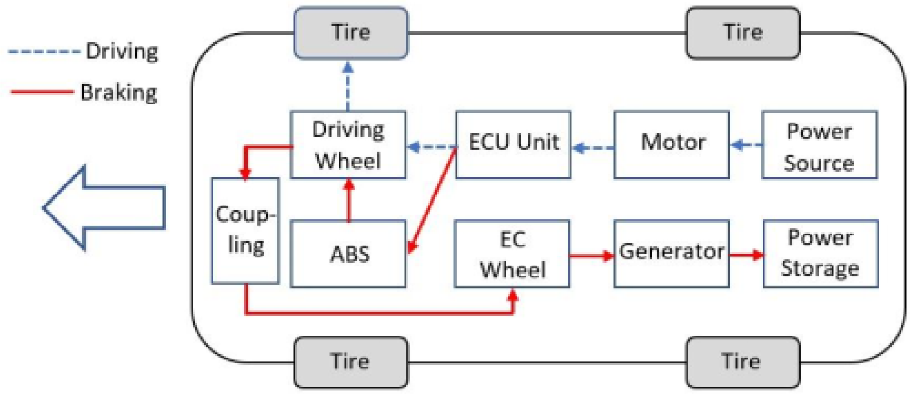


Figure 2: The vehicle configuration.

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 3, 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.

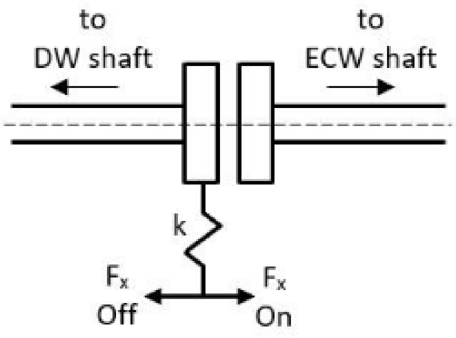


Figure 3: The centrifugal clutch.

Dynamic Model

Braking causes the forces on the tires, as described in Figure 4, 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 [14]. 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.

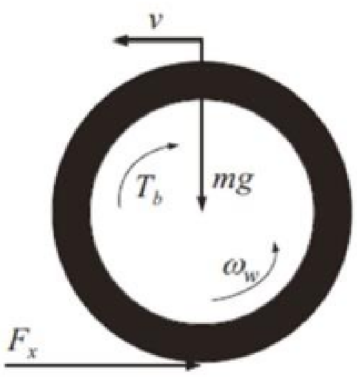


Figure 4: The wheel dynamic model.

The coefficient of longitudinal friction is a function of the slip ratio for various road conditions, as given in Figure 5. 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.

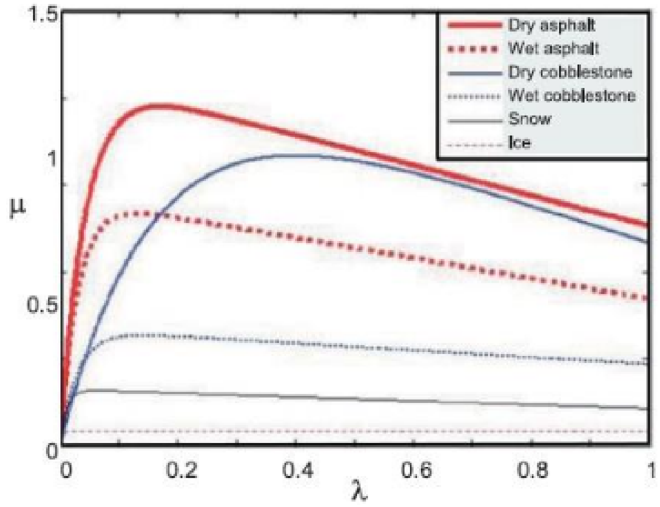


Figure 5: The friction coefficient of slip ratio function for various road conditions [25].

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

$$P_m = \frac{2\pi n_m T_m}{60} \qquad (7)$$

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.

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

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

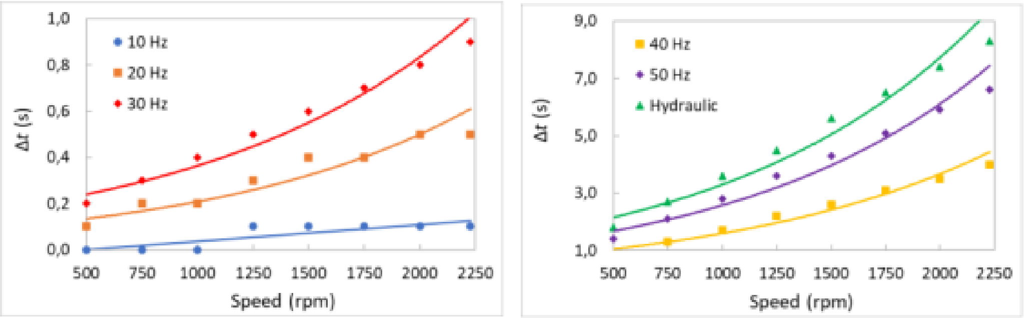
Where ε_{ind} is the induced emf in Volts, N is the number of windings, ϕ is the magnetic flux, t is the time, I_{ind} is the induced current in Ampere, and R is the resistance in Ω.

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

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. There was a difference in stopping time between the wheels and the prototype. Figure 6 shows this difference. 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.

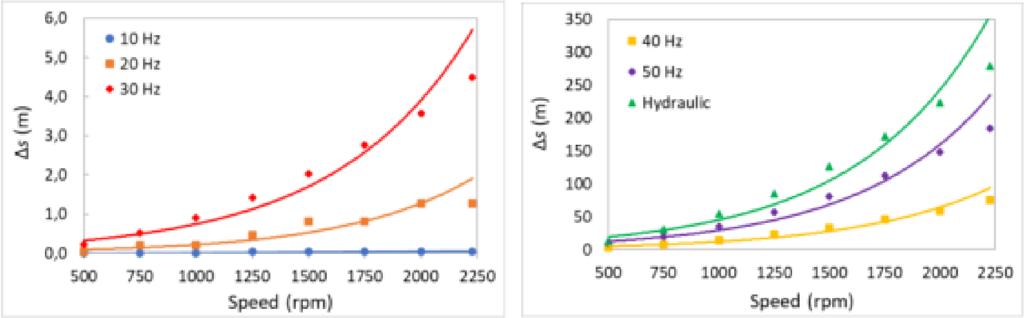


(a) (b)

Figure 6: The difference in braking time to stop the wheels and the vehicle: (a) lower frequency of ABS, (b) higher frequency of ABS and hydraulic.

ABS, with the lowest frequency, has the fewest time difference. It indicates that the ABS 10 Hz safety factor is very high because there is almost no slip at low speeds [6]. At high speeds above 1000 rpm, the time difference is 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 7 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.

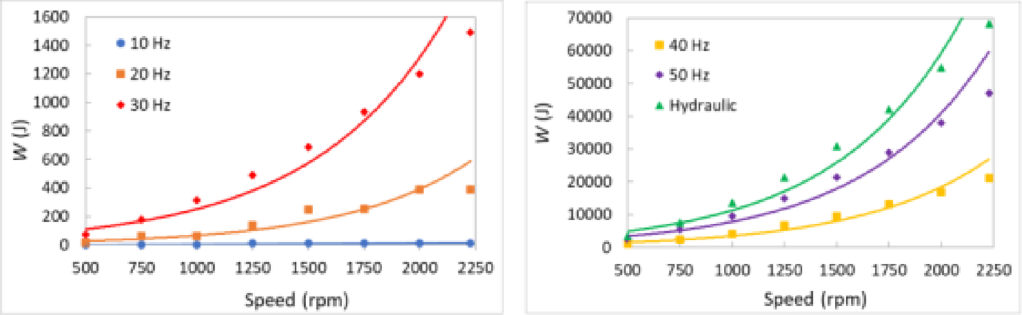


(a) (b)

Figure 7: 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 [12]. It operated on a maximum coefficient of friction, as shown in Figure 5. Hydraulics had the longest addition distance. It meant that hydraulic had the highest slip of all types of braking in this study [9].

The work of friction is the product of the friction force by the distance in Figure 7. This work was pure friction between the tires and the road without the wheel braking [13]. 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 [18]. Figure 8 describes the calculation of tire friction work.



(a) (b)

Figure 8: The work of friction between the tires and the road to stop the vehicle: (a) lower frequency of ABS, (b) higher frequency of ABS and hydraulic.

Hydraulics had an advantage in regenerative braking performance because the time to stop the wheels was the fastest [15]. The fastest time in turning the ECW will have given the highest induced emf [27]. Figure 9 illustrates the results of the performance calculation based on the measurement of the induced current in the generator.

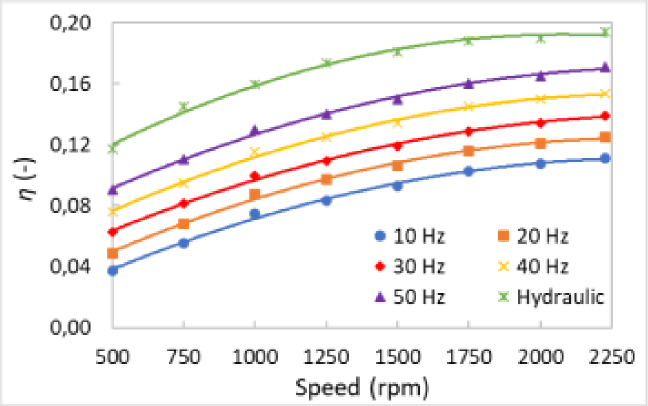


Figure 9: Regenerative braking performance.

The energy stored in batteries said otherwise. Hydraulics provided the lowest stored energy among other brakes [14]. The fastest time to stop the wheel caused the most change in kinetic energy to heat [7]. Figure 10 gives the results of the calculated energy stored by RBS.

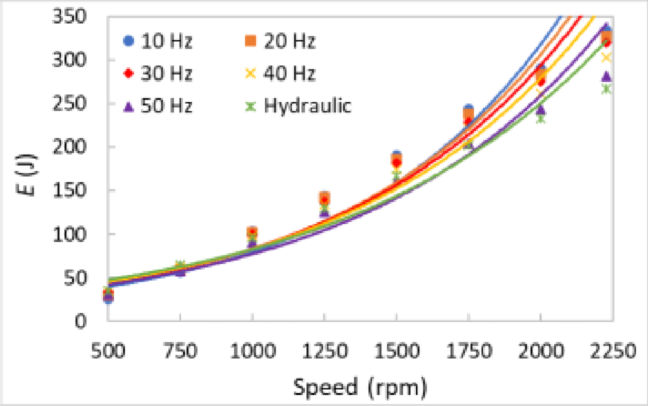
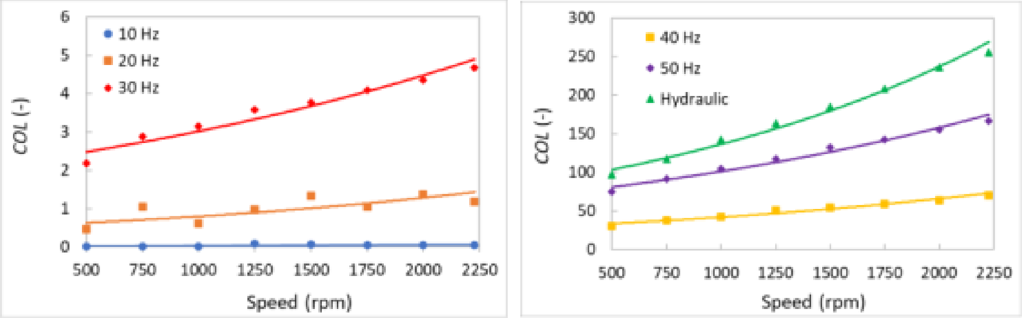


Figure 10: Energy stored from regenerative braking.

The coefficient of losses is the ratio between losses and stored energy. It will be zero when there are no losses at all. Figure 11 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 [16].



(a) (b)

Figure 11: Coefficient of losses (COL): (a) lower frequency of ABS, (b) higher frequency of ABS and hydraulic.

Conclusion

Many conventional vehicles apply ABS because of its safety and maneuverability during the braking process. High-frequency ABS made it close to hydraulic brake performance. During the braking process, there was a time difference between stopping the wheels and the vehicle. It caused an increase in the distance due to slip. Hydraulic brakes had the highest time difference. Meanwhile, ABS 10 Hz had the lowest time difference.

ABS 10 Hz provided friction loss due to low slip. Therefore, wheel friction in braking could be optimized in the regenerative braking process. As a result, it produced the highest stored energy compared to other braking systems.

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