Braking control strategies of modern hybrid and electric vehicles

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Abstract. Environmental issues and oil resource depletion have urged government and car manufacturers to reduce production of combustion engine vehicle and at same time give more attention to hybrid and electric vehicle (HEV/EV). Fortunately, we have seen these future cars on the road, for example, Nissan Leaf, Chevrolet Volt and Toyota Auris hybrid. To attract the buyers, these cars must have better efficient in term of equivalent litter per km. One way to achieve this goal, brake blending is incorporated to replace conventional brake system. This paper aims to investigate and compare the performance of such braking system using road test data. Recovered energy and driver comfort are two main aspect analyzed in aforementioned cars. Based on investigation detailed braking data on many driving conditions, it was found that different manufacturers employ different control strategies and have unique feature, respectively. Also, brake blending could cause driver confusion due to different pedal feeling experienced as in the combustion engine car.

1. Introduction
Surprisingly, electric vehicle had emerged in the market before internal combustion engine (ICE) vehicle in late 19th century. Due to low specific energy of batteries and advancement of ICE, the electric vehicle lost its market share for long time. In 2015, HEVs/EVs constituted less than 1% of vehicles on the road in US and China [1]. This indicates the campaign of fuel shortage and environmental issues has not managed to persuade people buying these modern cars. To regain the popularity again, the car makers should address both driver’s attitude and vehicle performance simultaneously since it deals with socio-technical problems [2]. It is understood that the buyers will choose the HEV/EV according to cost and performance, not environment come first. Especially for the EV, the price of lithium-ion battery pack is believed as the barrier to vehicle competitiveness. Egbue and Long urged the riches whose have environmental awareness are crucial elements to spread the benefits of the HEV/EV among the resistant consumers [3]. There is interesting comparison between 13 mid-size EV and ICE vehicles reported by Safari in terms of cost and performances and could assist potential buyers to make decision [4].

Electrification component of electric vehicle consists of battery pack, power electronic and electric motor. Nissan Leaf employs 80 kW permanent-magnet electric motor that can drive the car up to 140 km/h [5]. Its inverter power operates at high DC voltage 240-403 V and delivers 340 Arms current to the motor continuously. While the Nissan Leaf is battery electric vehicle (BEV), Chevrolet Volt is more advanced vehicle know as extended-range electric vehicle (EREV). Two motor EV drive (110 kW and 55 kW) enables the Volt to work in 4 different modes with 2 onboard energy source battery and the fuel [6]. Therefore, Chevrolet Volt have higher regenerative capability than Nissan Leaf.
In the previous works, detailed conventional braking system have been modeled using MATLAB/Simulink software [7]. For a given brake pedal force, the vehicle deceleration can be predicted and the energy loss can be calculated. Subsequently, advanced model for blended braking system in EV/HEV is created with MATLAB software as well. Verified models of electric powertrain and hydraulic braking system available in the Simulink are used to develop complete braking system [8]. The model was then validated with the experiment on Nissan Leaf and Toyota Auris hybrid and obtained good results. Ohtani et al. completely explained brake-by-wire employed in Nissan Leaf where the cylinder pressure is not generated by the drive, instead the electric motor [9]. Brake pedal travel is measured by the sensor and processed by electronic control unit. The brake demand is then divided into regenerative and mechanic portion which actuate the electric motor and electrohydraulic brakes.

2. Method
Unlike conventional braking system, Nissan Leaf adopt advanced technology in which there are two pistons located in the master cylinder. One is actuated by the driver and another by electric motor. Here, the electric motor amplifies the brake travel from the driver by increasing the master cylinder pressure. Figure 1 shows brake components of Nissan Leaf where many sensors are fitted to measure brake pedal force and travel, master cylinder pressure, front and rear caliper pressures, vehicle speed and battery current. There is a communication line between electric control brake and VDC (vehicle dynamic control) called CAN bus (controller area network). It is can be seen the brake pressure delivered by the master cylinder can be modulated by the VDC unit for each brake caliper in the wheel.

![Figure 1. Braking system of Nissan Leaf [10].](image)

3. Results and discussion

3.1. Nissan leaf
Define Figure 2 shows driving condition consisting acceleration followed by braking to access braking strategy. Here, the vehicle speed was 90 km/h when the driver started pressing the brake pedal at t=9.5 seconds. In short period of time 0.5 seconds, the pedal moves about 12 mm and then gradually increases to 17 mm in 1.75 seconds. As a result, the vehicle was decelerated to 60 km/h in 2.5 seconds. The brake pressures developed in master cylinder and front brake caliper from t=9 seconds to t=13 seconds are depicted in Figure 3. As can be seen, both curves are similar indicating the VDC unit was not involved in the braking. Interestingly, the pressure profile does not follow the steady increase of pedal travel as in conventional vehicle. The pressure raised from 0 to 30 bar in about 1.5 seconds and then declined to 25 bar at t=11 seconds before reaching back to 33 bar at t=11.75 seconds. This pressure response indicates that the motor acting as generator must compensate the different between demand and friction brake. Otherwise, the driver will notice the braking system in his/her car is faulted.
Figure 2. Vehicle speed and brake pedal travel of Nissan Leaf.

Figure 3. Pressure generated in master cylinder and acting in front wheel.

When the regenerative braking is performed, current flows from the electric motor through inverter and DC link. Therefore current profile is different in each of these terminals. In Figure 4, the traction portion of current is omitted to emphasis the charging current into battery. The current started entering the battery at \( t = 9.76 \) seconds and stopped at \( t = 12.03 \) seconds. But at this point, the pedal travel had not yet returned to zero and thus friction brake was still engaged. Trapezoidal rule of integration can be used to count the charges from into the battery and the result was 12.23 A*sec and nominal battery voltage of 364 V, charging energy was 1.24 Wh.

Figure 4. Battery charging current during regenerative braking of Nissan Leaf.
3.2. *Chevrolet Volt*

The initial speed of Volt was 90 km/h when the driver engaged the brake as shown in Figure 5, and fully stopped after 7.5 seconds. The driver brake demand constituted two parts, 10 mm for first 2 seconds and 7.5 mm afterward. As consequence, the slope of vehicle speed is observed to change $t=23$ seconds. From the figure, lower pedal travel results in lower vehicle deceleration.

![Figure 5. Vehicle speed and brake pedal travel of Chevrolet Volt.](image)

The master cylinder and front caliper pressures during braking are shown in Figure 6. Initially, they had similar responses and after reached steady value, caliper pressure was higher than master cylinder pressure. Rapid transition from one to another pedal travel position caused disturbance in the pressure response. From $t=23$ seconds to $t=27$ seconds, there were large fluctuation in the brake lines. This indicates that it is difficult to adjust the valves movement involved during fast response. After braking was requested by the driver, the electric motor functioned as generator and charged the battery as shown in Figure 7. The charging current reached maximum of 17 Ampere at $t=21$ seconds. Though the brake travel was still steady at 10 mm, the charging current was reduced to about 4 Ampere at $t=23$ seconds. As the end, total of 57 A*s charge was stored in the battery and recovered energy was 5.7 Wh with battery nominal voltage of 360.

![Figure 6. Brake pressure responses in steady condition and rapid change of demand.](image)
3.3. Toyota Auris

Compared with Nissan Leaf and Chevrolet Volt, Toyota Auris hybrid vehicle had lower initial speed in this test, that was 42 km/h and stopping time of 7 seconds. As shown in Figure 8, the driver engaged the brake at t=1 second and attained steady value of 18 mm at t=3.5 seconds. This relation between pedal travel and vehicle deceleration indicates that the Auris has larger brake effort since similar pedal travel generates smaller deceleration. Though the brake was applied at t=1 second, the pressure was not developed in brake calipers at same time. Figure 9 tells us that the pressure raised at t=3.5 seconds and exhibited fluctuations before gradually declined to 6 bar when the vehicle is stopped. Another fact is that the pressure at front wheels were not quite similar with the rear ones.

Figure 7. Battery charging current during regenerative braking of Chevrolet Volt.

Figure 8. Vehicle speed and brake pedal travel of Toyota Auris.

Figure 9. Pressure responses at front and rear calipers of Toyota Auris.
The Auris tries to maximize the recovered energy by only enabling the regenerative brake when the accelerator pedal is disengaged and brake pedal has not pressed yet. As demonstrated in Figure 10, since the beginning, the average charging current was maintained at 25 Ampere until t=5 seconds. At this time, the vehicle speed was 20 km/h but the Auris was able to increase the current up to 80 Ampere at very speed of 12 km/h. This is indeed excellent feature of Toyota Auris in optimizing the energy recuperation from braking condition. The amount of charge stored in the battery from this braking event was 220 A*s.

![Current generated during braking and stored in the battery of Toyota Auris.](image)

**Figure 10.** Current generated during braking and stored in the battery of Toyota Auris.

### 3.4. Brake pedal feeling

Beside improving energy efficiency using regenerative braking, car maker must ensure driver and passengers safety and comfort. The driver could be panic if he/she is unfamiliar with brake pedal feeling. When the brake is engaged, the driver pushes the brake pedal with amount of force and depends on mechanism in master cylinder, the piston will move to a distance. The problem is that distance varies from car to another car and creates uncomfortable. Ideally, the relation between pedal force and pedal travel is obtained from static characteristic in which a certain force is supplied to the pedal and steady state position of pedal is measured. However, in this paper, the characteristic is derived from dynamic response and scatter plot is used. For analysis purpose, some data are excluded from that plot.

Figure 11 shows the brake pedal characteristic of Nissan Leaf. From the rest, the driver must have supplied 20 N before the pedal started moving. After that, it was observed to slopes, one between 20 N to 40 N with gradient 0.6 mm/N and second was from 40 N to 160 N with gradient 0.125 mm/N. When the pedal was depressed below 30 N, the driver gradually reduces the force as the pedal travel down to 6 from 9 mm and then suddenly released the brake pedal.

Brake pedal of Chevrolet Volt exhibit interesting properties, there are two characteristic curves for increase pedal force increase and decrease as shown in Figure 12. Similar with Nissan Leaf, minimum force to move the pedal is 20 N. Small amount of force needed for pedal travel to 4 mm before linear relation between force and travel becomes linear with gradient of 0.1 mm/N. the upper side curve means that the driver slowly depressed the pedal indicated with smaller gradient compared with low pedal position. Start from position of 8 mm, the driver rapidly released the applied force while the vehicle was about to stop.
Figure 11. Brake pedal characteristic of Nissan Leaf.

Figure 12. Brake pedal characteristic of Chevrolet Volt.

4. Conclusion
Braking control strategies employed by modern HEV/EV have been investigated in this paper. The demand from driver is represented by pedal travel that is translated into brake pressure and motor torque to decelerate the vehicle. As the result, the brake pressure does not follow steady value of pedal travel but exhibits fast changing. Same condition is also observed in charging current to the battery produced by motor acting as generator. For driver comfort, both brake pedals of Nissan Leaf and Chevrolet Volt have similar characteristic in term of minimum force and gradient between force and travel.

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