

# The Safety and Dynamic Performance of Blended Brake System on a Two-Speed DCT Based Battery Electric Vehicle

Jiageng Ruan, Paul Walker, Nong Zhang, and Guangzhong Xu  
University of Technology Sydney

## ABSTRACT

Regenerative braking has been widely accepted as a feasible option to extend the mileage of electric vehicles (EVs) by recapturing the vehicle's kinetic energy instead of dissipating it as heat during braking. The regenerative braking force provided by a generator is applied to the wheels in an entirely different manner compared to the traditional hydraulic-friction brake system. Drag torque and efficiency loss may be generated by transmitting the braking force from the motor, axles, differential and, specifically in this paper, a two-speed dual clutch transmission (DCT) to wheels. Additionally, motors in most battery EVs (BEVs) and hybrid electric vehicle (HEVs) are only connected to front or rear axle. Consequently, conventional hydraulic brake system is still necessary, but dynamic and supplement to motor brake, to meet particular brake requirement and keep vehicle stable and steerable during braking. Therefore, a complicated effect on the safety and performance of braking, mainly relating to tyre slips and locks, vehicle body bounces and braking distance will be applied by the blended brake system.

In this paper, the brake energy recovery potentials of typical driving cycles are presented. Relevant critical limitations are introduced to define the available brake force distribution range for front and rear axles. Then the distribution strategies are compared and analyzed to achieve a satisfied balance between braking performance, driving comfort and energy recovery rate. Next, the required motor brake force is tuned, according to the response time and efficiency loss in transfer process which obtained in testing bench. At last, solutions for some special cases are proposed, for instance, motor brake torque interruption when downshifting occurs on long downhill.

A credible conclusion is gained, through experimental validation of optimized brake force distribution strategy on a two-speed DCT based BEV testing rig, that the selected force distribution strategy help the blended brake system achieve a comfortable and safety braking during all driving conditions.

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## INTRODUCTION

Due to the great potential of reusable braking energy in daily driving, the blended brake system, which consists of electric and hydraulic brake, has been validated theoretically and experimentally to be effective on a battery electric vehicle (BEV) by a plethora of papers [1, 2, 3, 4]. Most of these researching mainly focus on the improvement of braking energy rate, nevertheless, lose the sight of safety issue that new blended brake system brings. Even the few papers focused on the performance of controllability and stability for a blended brake system, the massive strong brake required situations and the balance of braking performance and kinetic energy recovery ability are still out of scope [5,6].

More and more BEVs utilize a multi-speed transmission, e.g. Automatic Transmission (AT), Automated Manual Transmission (AMT) and Continuously Variable Transmission (CVT), to improve vehicle dynamic performance and extend one-charge driving range [7, 8, 9]. An advanced and simplified two-speed Dual Clutch Transmission (DCT) has been proven to be more efficient, at the

same time, help vehicle recapture more braking energy [10, 11, 12]. However, this new architecture of powertrain introduces more uncertainty to the blended brake system and needs some special designed algorithms to ensure a safety braking, in the meanwhile, recovery energy from braking as much as possible. The safety-oriented control algorithm applied on the conventional vehicles, e.g. Anti-lock Brake System (ABS), Electro Stability Program (ESP), should also be integrated to the blended brake system after some reasonable modifying [13,14]. Therefore, a completed strategy, which considers the braking performance, reliability, durability, cooperating with gearbox, interacting with driver assistance system (ABS, ESP, etc.), is badly needed.

The aim of this paper is to study, evaluate and finally supply a reliable and effective strategy for blended braking system in two speeds DCT based EV. A manually selected braking strategy is proposed in this paper to achieve the balance of driving experience and energy recovery ability, which comes along with automatically intervened top-priority control strategy. First of all, kinetic energy

recovery potential is calculated to evaluate the researching work for a more complex regenerative braking strategy. Then, individual pros and cons introduced by the two-speed DCT based front drive BEV, for instance, load transferred to motor connected axle and 'torque hold' in shifting, is discussed. Three different strategies are designed to recapture more braking energy, achieve the best brake performance and compromise between performance and energy. Next, a Matlab/Simulink® model is established to analyze the details of brake force distribution, wheel slip and kinetic energy recovery. Finally, strategies are tested in the electrified powertrain testing bench.

## KINETIC ENERGY RECOVERY POTENTIAL

Braking energy recovery is regarded as one of the greatest improvement, which can help save money and energy, instead of wasted by heat in traditional Internal Combustion Engine (ICE) vehicle. However, due to the completely different working principles and routes, some potential risk will be introduced to vehicles. Therefore, more complicated strategies and equipment are needed. It is important to know how much energy is consumed by braking and if it is worth that spending extra money on additional equipment and R&D to achieve a satisfied brake system for BEVs. Fig.1 clearly shows the theoretical energy consumed by braking in several typical driving cycles. For city cycles or hybrid cycles, like LA92 Dynamometer Driving Schedule (LA92, Unified Driving Schedule), New Europe Driving Cycle (NEDC) or Urban Driving Dynamometer Schedules (UDDS), the energy wasted in braking accounts for more than 40%. Even in highway cycle, i.e. Highway Fuel Economy Testing (HWFET), relative fewer acceleration and deceleration, it takes over 20 %. Actually, the energy wasted in braking can easily go over 50% during daily peak time commuting driving, especially in metropolises. Even not all of them can be recaptured; RBS can significantly extend driving range, in other words, save your money.

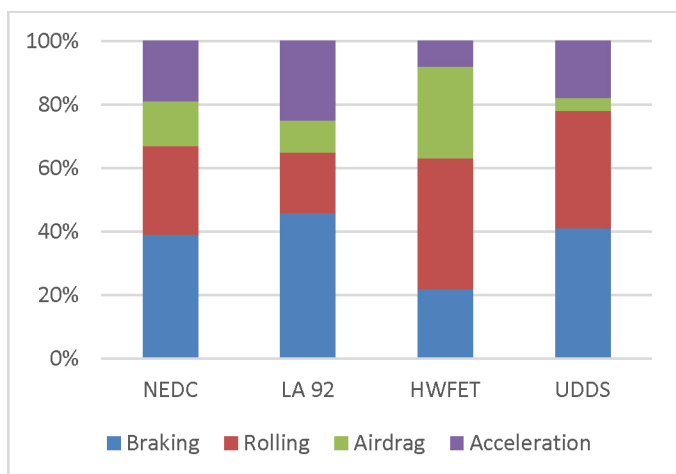


Figure 1. Energy Consumption Distribution in Driving Cycles

## Vehicle Specifications

The vehicle parameters used in this studying are shown in Table.1:

Table 1. Vehicle Specifications

| Parameters                  | Symbol              | Value     | Unit           |
|-----------------------------|---------------------|-----------|----------------|
| Battery Capacity            | C                   | 72        | Ah             |
| Motor Torque (Peak/Rate)    | $T_{peak}/T_{rate}$ | 300/150   | Nm             |
| Motor Power (Peak/Rate)     | $P_{peak}/P_{rate}$ | 125/45    | Kw             |
| Transmission Ratio          | $i_1/i_2$           | 2.15/1.46 |                |
| Main Reducer                | $i_g$               | 3.93      |                |
| Centre of Mass Height (CoM) |                     | 0.5       | m              |
| CoM to Front Wheel          |                     | 1.3       | m              |
| CoM to Rear Wheel           |                     | 1.5       | m              |
| Vehicle Mass                | m                   | 1850      | Kg             |
| Tyre Radius                 | r                   | 0.3125    | m              |
| Air Drag Coefficient        | $C_D$               | 0.28      |                |
| Road Friction Coefficient   | $\mu$               | 0.9       |                |
| Vehicle Front Area          | A                   | 2.2       | m <sup>2</sup> |

## POWERTRAIN TOPOLOGY

The advantages and details of two-speed DCT based BEV has been introduced [15]. In this paper, only braking relevant topics, which caused by this new DCT structure, are studied. Fig.2 is a schematic diagram that shows the principle of two-speed DCT based powertrain, on the top left, and the structure of testing bench.

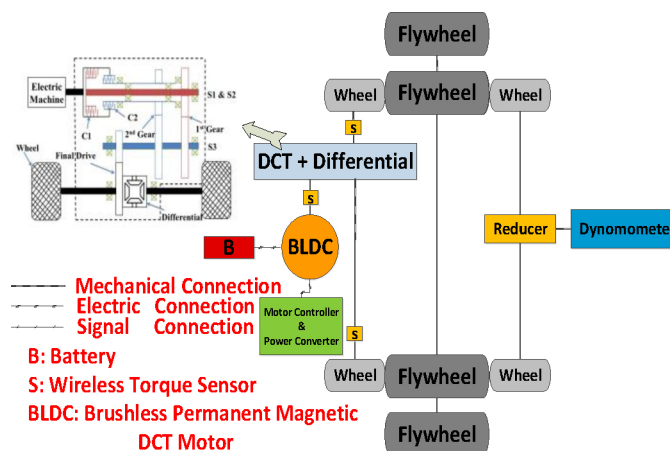


Figure 2. Two-Speed DCT based BEV Powertrain Structure

The front drive BEVs has lots of common merits same to the traditional ICE vehicles, such as cheaper and easier to build, a more capacious room. Furthermore, this structure provides an extra benefit for regenerative braking due to the load transfer in BEVs.

Load transfer is presented when vehicle is accelerating or decelerating, no matter it theoretically supposed to be a rigid vehicle or a vehicle has suspension system that would exhibit pitching or rolling of the body. The effect of pitching and rolling only adds small load transfer [16], in this paper, the vehicle is assumed to be a perfectly rigid body without suspension, considering the main target is safety and energy optimization. The dynamic adding weight during braking are expressed as Eq.1:

$$\Delta \text{Weight}_{\text{front}} = a \frac{h_g}{w} m \quad (1)$$

$a$  is the longitudinal deceleration,  $h_g$  is the height of mass center,  $w$  represents the wheelbase length and  $m$  stands for the vehicle mass. The ratio of normal force distributed on front and rear wheels at different deceleration are illustrated in Fig.3. Comparing to the static state, 1g deceleration will transfer almost 40% load from rear wheels to front ones. As shown in Eq.2, the normal load of wheel decides the maximum available friction torque on a certain road. Which means the limitation of wheel unlocked friction ability will increase during braking. And the regenerative brake from front-mounted motor can play a greater role in braking and energy recovery.

$$F_b = \mu F_R \quad (2)$$

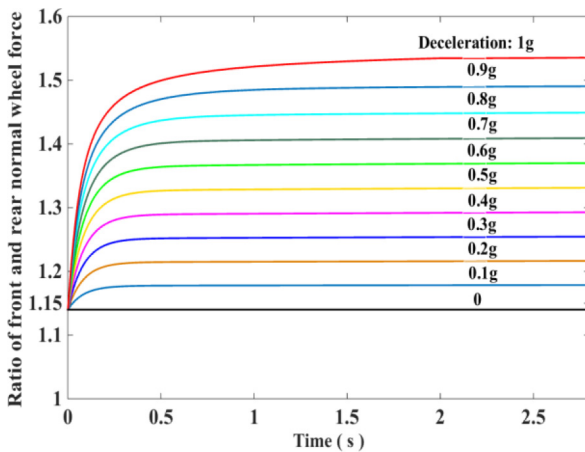


Figure 3. Wheel Normal Force Variation due to Dynamic Load Transfer

## SAFETY AND STABILITY DESIGN IN BLENDED BRAKE SYSTEM

The goal of automotive brake system design, no matter for conventional vehicle or BEVs, is to achieve a comfortable and reliable decelerating as the request of driver. And stop vehicle as soon as possible in emergency situation, meanwhile, maintaining dynamic stability and controllability.

On the longitudinal direction, the relative motion between tyre and road will turn from a mix of sliding and rolling to pure sliding, if the force applied on the wheel by caliper exceeds the maximum available friction force between tyres and ground (Eq.3). This phenomenon is also known as 'wheel lock'.

$$f_{\text{caliper}} > f_{\text{brake\_friction}} = mg\mu \quad (3)$$

$\mu$  is friction factor depending on road conditions and type of tyre. The motion of wheel in a normal driving vehicle consists of two parts, i.e. rolling and sliding, which causes a difference between the speeds of vehicle and wheel. The wheel slip ratios is defined as the difference between the rotational speed of the wheel and the translational velocity of the wheel center:

$$\lambda = \frac{\Delta v}{v} = \frac{\omega r_{\text{dyn}} - v}{v} \quad (4)$$

$\omega$  is wheel rotation speed;  $r_{\text{dyn}}$  is the dynamic radius of wheel, which is achieved indirectly by measuring the travel distance per rotation circle.  $\lambda$  is a value from 0 to 100% representing the motion of wheel from freely rolling to lock. The solid blue curve in Fig.4 shows friction factor ( $\mu$ ) varying according to longitudinal slip ratio ( $\lambda$ ) on dry asphalt pavement. The  $\mu$  drops significantly when vehicle riding on the wet and snow road, which are presented by solid and green dash curve in Fig.4. Moreover, a steering angle causes the friction factor to fall as well.

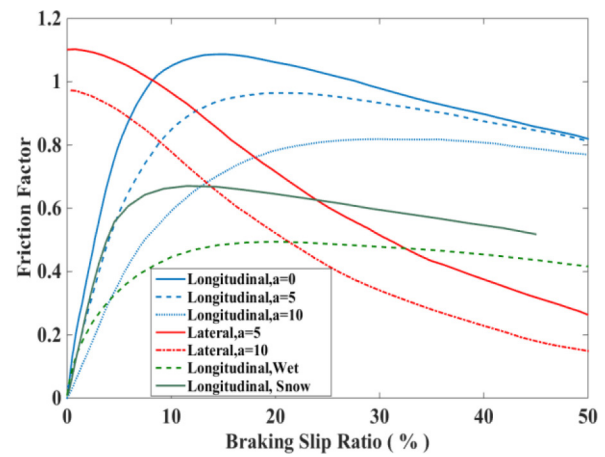


Figure 4. The Influence of Slip Ratio, Steering Angle and Road Condition on Friction Factor

The force on lateral direction of road-tyre contact surface directly affects the direction control ability of vehicle. Locked wheel cannot generate lateral force to offset the sideslip trend, when cornering or unintentional steering during emergency brake, resulting in unnecessary under-steering and uncontrollable over-steering. As shown in Fig.4, the lateral friction factor falls dramatically with longitudinal braking slip ratio increasing. Take the example of a wheel with 5° steering angle and 20% longitudinal slip ratio, the lateral friction factor only equals half of pure straight driving. When the longitudinal slip ratio goes up to 100% (Wheel lock), steering input has no result on yaw motion because the front tyres are saturated, and no lateral force can be generated. If it happens to the front wheel, the vehicle lost steering ability, however, there is no directional instability because "whenever the lateral movement of the front wheels occurs, a self-correcting moment due to the inertial force of the vehicle about the yaw center of the rear axle will be developed. Consequently, it tends to bring the vehicle back to a straight line path. On the contrast, if rear wheels are locked, they lose their capability to generate the required side forces and the rear end might start to slide sideways, losing directional stability. The omitted arrows on rear wheel and front wheels, in the 'Over-steering diagram' and 'Under-steering diagram' respectively of Fig.5, indicate the locked wheels and lost lateral force.

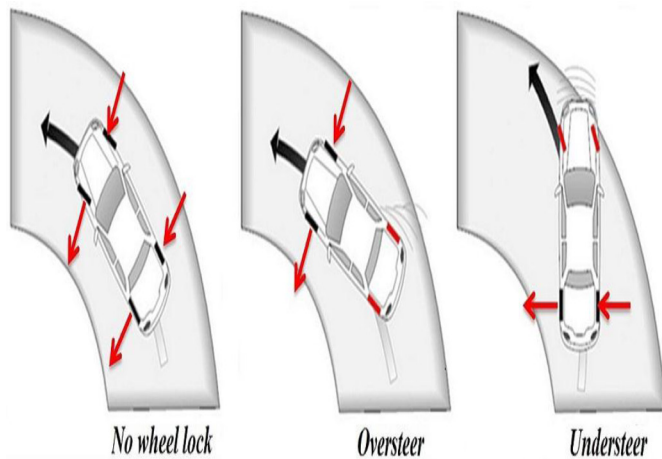


Figure 5. Over-steering and Under-steering when Wheels Lock

In traditional ICE vehicles, to ensure maximum brake force available and avoid slipping, lots of components and strategies are introduced into vehicle, e.g. Anti-lock Brake System (ABS), Electronic Stability Program (ESP), Electronic Brake Force Distribution (EBD) and Brake Assistance System (BAS). All the above functions rely on hydraulic actuators and work together. In brief, EBD supply appropriate force to help ESP effectively keep vehicle running at initial intended path, meanwhile, ABS ready to prevent any wheel lock. However, in the RBS, the strategies and intervention time of hydraulic brake system are changed, aiming at braking energy recovery.

When the deceleration intention is detected from brake pedal, motor begins to provide brake torque on front wheels; meanwhile, pressure is established in the rear hydraulic actuator to decelerate rear wheels. The force distribution between front and rear wheels is decided by Eco strategy, which aims at recovering energy as much as possible if the brake intention is moderate. EBD distribute more brake force on the front wheel to offset the load transfer, shown in Fig.3, and avoid rear wheels locking. When vehicle is loaded with passengers or goods, EBD detects it and redistributes more brake force on rear wheels to utilize the increased available friction force. (Shown in Fig.6) The variation of force on front and rear wheels, which is usually supplied by hydraulic system, can be provided by motor at the viewpoint of energy recovery. The brake force on front vehicle is provided by motor until it exceeds the rotation speed based maximum available torque, then, hydraulic-mechanical brake supplies the rest of required torque (Fig.6-1). When sensors detect added load, the previous distribution strategy is kept at the viewpoint of energy recovery, instead of increasing rear brake force and reducing front brake force immediately, at the cost of a longer stop distance (Fig.6-2B). However, this only happens in moderate braking ( $a < 0.3g$ ). Stop distance becomes the top concern when detected braking intention going stronger ( $a > 0.3g$ ). Brake force distribution is rebalanced to take full advantage of load transfer. Rear mechanical brake force is increased, at the same time, reduce front mechanical brake and keep motor brake, or reduce motor brake if no mechanical brake on front wheels. The detail procedures are described in the flowchart (Fig.7).

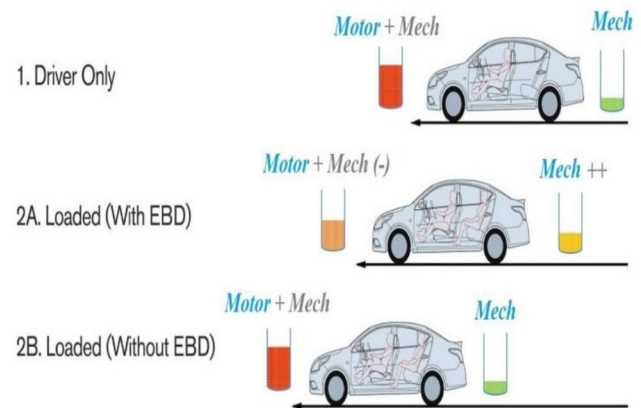


Figure 6. RBS Cooperate with EBD

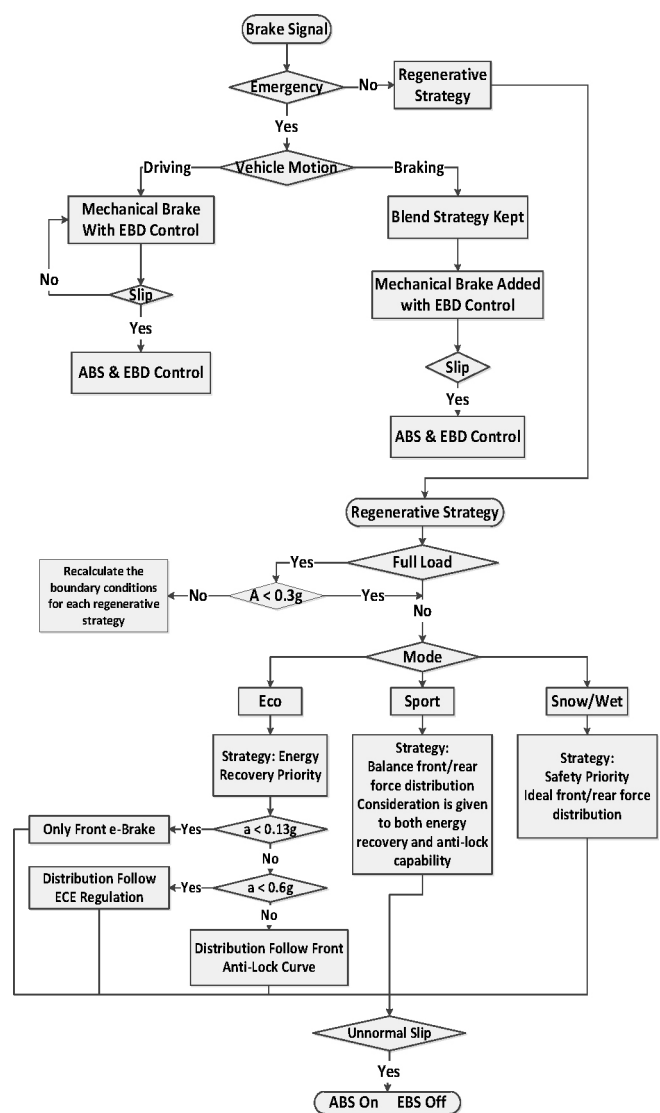


Figure 7. The Cooperation of RBS, EBD and ABS

ABS gets involved in EBD when emergency brake is activated. ABS reduces the pressure in the hydraulic brake actuator of the wheel that tending to lock. However, there are two different preconditions for the blended brake system when ABS works: