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The dynamic performance and economic benefit of a blended braking system in a multi-speed battery electric vehicle

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HIGHLIGHTS

- Maximum braking energy recovery potentials of various cycles are reported.
- Braking strategies are proposed for performance, comfort and energy recovery.
- Braking force distributions and wheel slip ratios of different strategies are demonstrated.
- The performance of 'Eco' strategy is experimentally validated in HWFET and NEDC.
- The economic benefit of energy recovering is summarized, regarding to the fuel and maintenance cost saving.

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ABSTRACT

As motor-supplied braking torque is applied to the wheels in an entirely different way to hydraulic friction braking systems and it is usually only connected to one axle complicated effects such as wheel slip and locking, vehicle body bounce and braking distance variation will inevitability impact on the performance and safety of braking. The potential for braking energy recovery in typical driving cycles is presented to show its benefit in this study. A general predictive model is designed to analysis the economic and dynamic performance of blended braking systems, satisfying the relevant regulations/laws and critical limitations. Braking strategies for different purposes are proposed to achieve a balance between braking performance, driving comfort and energy recovery rate. Special measures are taken to avoid any effects of motor failure. All strategies are analyzed in detail for various braking events. Advanced driver assistance systems (ADAS), such as ABS and EBD, are properly integrated to work with the regenerative braking system (RBS) harmoniously. Different switching plans during braking are discussed. The braking energy recovery rates and brake force distribution details for different driving cycles are simulated. Results for two of the cycles in an 'Eco' mode are measured on a drive train test rig and found to agree with the simulated results to within approximately 10%. Reliable conclusions can thus be gained on the economic benefit and dynamic braking performance. The strategies proposed in this paper are shown to not only achieve comfortable and safe braking during all driving conditions, but also to significantly reduce cost in both the short and long term.

1. Introduction

The benefit of regenerative braking by blended braking systems, combining electric and friction brakes, has been theoretically and experimentally validated in many kinds of electric vehicle (EV), e.g., Battery Electric Vehicle (BEV) [1,2], fuel cell electric vehicle (FEV) [3], and hybrid electric vehicle (HEV) [4]. A plethora of similar papers can be found which focus on braking energy recovery improvement by optimizing strategies and studying the performance of braking system itself. Nian et al. used PID control and fuzzy logic in a brushless DC motor to realize regenerative braking and prolong driving range, ensuring the braking quality at the same time [5]. A vehicle lateral motion state based adaptive control strategy was proposed by Han and Park to guarantee the vehicle controllability and stability [6]. Electromechanical brake was integrated into regenerative braking to ensure braking force

Abbreviations: BEV, Battery Electric Vehicle; DCT, Dual Clutch Transmission; AT, Automatic Transmission; AMT, Automated Manual Transmission; CVT, Continuously Variable Transmission; VCU, Vehicle Control Unit; ABS, Anti-lock Brake System; EBD, electro control brake distribution; RBS, regenerative brake system; SOC, state of charge; MPC, mileage per cycle; CPK, consumed energy per km; RPK, recovered braking energy per km.

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distribution ratio follow an optimal curve, instead of a linear line [7]. According to the results from Gao et al., blended braking system structure plays an important role in energy recovery rate [8]. Zhang developed a regenerative braking system by utilizing as much as possible mature components, integrating cooperative regeneration with Anti-lock Braking System (ABS)/Traction Control System (TCS) functions, which provided system reliability, low development cost and risk at the same time [9]. Battery current balance during regenerative braking was investigated in [10] by experimental analysis in both used-defined and FTP-75 driving cycles.

However, the frequently mentioned energy recovering ability and braking performance, in the above studies, are just two of the key factors in blended braking system design, and are not mutually independent. The safety issues introduced by the addition of a brake-by-wire system, the braking performance affected by a combination strategy, the potential economic benefits, and the relationship of economic benefit and braking performance need to be considered as well. Specially testing maneuvers for blended braking system, which are often neglected by many studies, are required to validate the braking performance in all conditions [11,12]. The problems became more complicated when a multi-speed gearbox became popular on EVs, such as an Automatic Transmission (AT), Automated Manual Transmission (AMT) or Continuously Variable Transmission (CVT) is added to improve the dynamic performance and driving range, then additional problems of response delay and torque interruption are introduced [13–15]. These problems are of particular concern for the simplified two-speed Dual Clutch Transmission (DCT), which has been proven to be extremely suitable for EVs [16,17]. Additionally, safety-oriented driver assistance system, such as the Anti-lock Braking System (ABS) and Electronic Brake Force Distribution (EBD), should also be integrated into blended braking strategies properly to ensure their effectiveness [18,19]. At last, for any of these complicated powertrain architectures, specially designed braking algorithms are needed to ensure safe braking, while recapturing as much kinetic energy as possible.

In this paper, an optimized blended braking strategy with a manual/automatic switch over function is proposed to achieve the balance between braking performance and energy recovery ability. This demonstrates the energy recovering improvement based economic benefit. A comprehensive investigation of the energy recovery, safety issues, braking dynamic performance, and economic benefit of a multi-speed transmission based blended braking system is clearly addressed.

Based on the achievement and limitations of previous papers, a brief breakdown of the comprehensive researching work, regarding to the dynamic performance and economic benefit of braking energy recovering on multi-speed BEV, is presented in following parts:

1. The energy lost in conventional friction braking is reported to indicate the maximum potential gains from regenerative braking.
2. The strengths and weaknesses of blended braking in a two-speed DCT based front-drive BEV are discussed.
3. The advantage of load transfer to the motor-connected front axle during braking is examined, while the torque interruption in gear shifting presents a disadvantage.
4. Different strategies are designed to either recapture maximum braking energy, or achieve the best braking performance, or to compromise between energy recovery and braking performance.
5. A simulation model is established to analyze the details of braking force distribution, wheel slip, and kinetic energy recovery rates in various test conditions.
6. One of the strategies is validated experimentally on an electric powertrain test bench for city and highway driving cycles.
7. Finally, the economic benefit of blended braking systems with different strategies is evaluated, in terms of fuel cost, initial manufacturing cost and maintenance cost.
8. Superior dynamic performance and economic benefit are obtained than for the strategies used in another recent study [20].

Some of the above content has been presented in paper [21] by a subset of the authors. That content is included here for completeness, but the content is restructured and rewritten, and extended with the new results on the brake force distribution, dynamic performance and economic benefit analysis of energy recovering.

2. Maximum kinetic energy recovery

In EVs, regenerative braking captures the drop in the vehicle's kinetic energy, which in traditional Internal Combustion Engine (ICE) vehicles is lost as heat in friction brakes. However, the different working principles and the potential safety risks have been barriers to large-scale commercialization. To assess whether it is worth the extra cost of additional equipment and R&D to achieve a blended braking system for EVs, one must know the potential gain, i.e. how much energy is consumed by braking.

Fig. 1 shows the distributions of energy consumption in several typical driving cycles for a medium size passenger Battery Electric Vehicle (BEV), without regenerative braking. The results are based on the integral of driving energy consumption and energy lost in friction braking with respect to time. The dynamic energy consumption in driving of specification Table A1, i.e. rolling, aerodynamic drag and acceleration, is calculated by Eq. (1), which is the product of vehicle dynamic resistance and travel distance per computational step size. According to the target speed profile of cycles, the dynamic friction braking force is achieved in Simulink model, shown in Fig. 2. For city or hybrid cycles, the energy wasted in braking is very high, e.g., 39% in the California Unified Cycle (LA92) and 35% in Urban Driving Dynamometer Schedules (UDDS). In fact, the energy wasted can easily go over 50% during peak commuting times in congested cities. Even in the highway cycle Highway Fuel Economy Testing (HWFET), with less acceleration and deceleration events, the braking loss is still a considerable 15%. Though not all of the energy can be recaptured, these figures show the significant potential for a regenerative braking system (RBS) to extend driving range, thus saving energy use cost.

$$\Delta E_{driving} = (\mathrm{mg}C_R\cos\varphi + \mathrm{mg}\sin\varphi + \mathrm{C_D A u^2}/21.15 + \delta \mathrm{m d_u}/\mathrm{d_t}) \times \Delta x \tag{1}$$

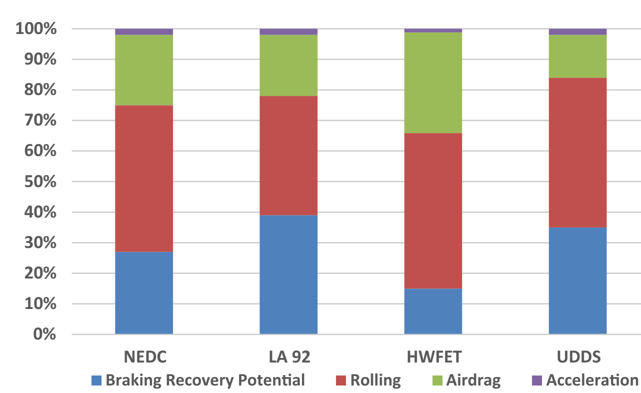

Fig. 1. Energy consumption distribution in driving cycles, with the energy lost in braking shown in blue. (For interpretation of the references to color in this figure legend, the reader is referred to the web version of this article.)