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Mechanism analysis and evaluation methodology of regenerative braking contribution to energy efficiency improvement of electrified vehicles

Chen Lv, Junzhi Zhang *, Yutong Li, Ye Yuan

State Key Laboratory of Automotive Safety and Energy, Tsinghua University, China

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ABSTRACT

This article discusses the mechanism and evaluation methods of contribution brought by regenerative braking to electric vehicle's energy efficiency improvement. The energy flow of an electric vehicle considering the braking energy regeneration was analyzed. Then, methodologies for measuring the contribution made by regenerative brake to vehicle energy efficiency improvement were introduced. Based on the energy flow analyzed, two different evaluation parameters were proposed. Vehicle tests were carried out on chassis dynamometer under typical driving cycles with three different control strategies. The experimental results the difference between the proposed two evaluation parameters, and demonstrated the feasibility and effectiveness of the evaluation methodologies proposed.

1. Introduction

With the rising concern in a global scale environmental issue, automobiles are required to be cleaner and more efficient [1]. In automotive domain, a lot of technologies have been researched and developed in order to save energy. In [2], optimal control based algorithms were developed for energy management of automotive power systems. In [3], the applicability of alternative fuel in a compression ignition engine was discussed. In [4], methods to improve efficiency of four stroke, spark ignition engines at part load were studied. In [5], design methods for vehicle light-weighting are researched.

Among these proposed solutions, electrified vehicles, including battery electric vehicles (BEVs), hybrid electric vehicles (HEVs), plug-in hybrid electric vehicles (PHEVs), and fuel cell electric vehicles (FCEVs), are very promising, due to the high-efficiency powertrain energy conversion and the reduced/zero emission. Moreover, the featured regenerative braking system (RBS) provides an ability to recover the vehicle's kinetic energy during deceleration, improving the fuel economy significantly. Studies show that in urban driving situations, about one third to one half of the energy of the power plant is discarded to the atmosphere in the form of heat by a conventional braking system during deceleration [6]. And this discarded energy is originally in the form of kinetic energy or energy of motion [7]. Therefore, it is aesthetically pleasing, environmentally satisfying and motivating to investigate methods for the recapture of this wasted kinetic energy [8].

From a practical point of view, recapture of the vehicle kinetic energy is feasibly done by converting that energy to either heat, mechanical or electrical energy format.

The kinetic energy recovery system (KERS), which is in the form of a rotating flywheel, has been applied in Formula 1 racing cars as an energy-saving and power increasing feature [9]. The hydraulic regenerative braking, which features in high power density and energy conversion efficiency, has been applied in heavy vehicles [10]. Control strategies of hydraulic regenerative brake were also studied [11]. However, the low energy density of the hydraulic accumulator makes it difficult to fully utilize the regeneration potential. Making a trade-off between performance and cost, the electro-mechanical RBS becomes the most popular choice in all kinds of vehicles [12]. It recaptures vehicle's kinetic energy during decelerations, improving vehicle's energy efficiency significantly [13]. Especially for all types of electrified vehicles in automotive domain, which are born with at least one electric motor, the electro-mechanical RBS have become a standard equipment [14].

For regenerative braking system, there are three important topics, namely the system design, blended brake control, and energy efficiency evaluation, which are worthwhile researching.

* Corresponding author.
E-mail address: jzhzhang@mail.tsinghua.edu.cn (J. Zhang).

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Nomenclature

a	acceleration of vehicle
A	frontal area of the vehicle
C_D	coefficient of air resistance
E_{drive}	energy consumption of a vehicle without regenerative braking
E^*_{drive}	energy consumption of a vehicle with regenerative braking
E_{regen}	regenerative braking energy
$E_{\text{bat\_in}}$	input energy at battery I/O port
$E_{\text{bat\_out}}$	output energy at battery I/O port
$E_{\text{mot\_out}}$	output energy of the electric motor
$E_{\text{mot\_in}}$	input energy of the electric motor
$E^*_{\text{bat\_out\_drv}}$	output energy of battery during driving situations considering energy consumption of accessories
$E^*_{\text{bat\_in\_brk}}$	input energy of battery during braking considering accessories' energy consumption
$E^*_{\text{bat\_out}}$	output energy of battery during the whole operating cycle in a regen vehicle considering accessories' energy consumption
$E_{\text{regen\_on}}$	energy consumption of vehicle with regenerative braking under a certain amount of driving range
$E_{\text{regen\_off}}$	energy consumption of vehicle without regenerative braking under a certain amount of driving range
ΔE_{drive}	reduced energy by regenerative brake
$\Delta E_{\text{bat\_out}}$	reduced energy consumption of battery in a regen vehicle considering accessories' energy consumption
E_0	a certain amount of energy utilization
f	rolling resistance coefficient
I_{bat}	current at the battery I/O port
M	motor torque
P_{drive}	required power at driven wheels
P_{regen}	regenerative braking power at driven wheels
$S_{\text{regen\_on}}$	driving range of an electric vehicle with regenerative braking under a certain amount of energy utilization
$S_{\text{regen\_off}}$	driving range of an electric vehicle without regenerative braking under a certain amount of energy utilization
S_0	a certain amount of driving range
u	real-time vehicle velocity
U_{bat}	voltage at the battery I/O port
ξ	conversion coefficient of rotational mass of powertrain
δ	regenerative braking contribution to energy utilization reduction of vehicle
δ'	regenerative braking when measurement point is at battery I/O port
δ''	regenerative braking contribution when measurement point is at electric motor
δ'''	regenerative braking contribution considering the accessories' energy consumption
δ_S	contribution ratio to driving range extension
δ_E	contribution ratio to energy consumption reduction
ω	angular speed of the electric motor
η_{fd}	efficiency of final drive unit
η_{g}	efficiency of gearbox
η_{gen}	generation efficiency of the motor
η_{m}	motor efficiency
η_{charge}	charging efficiency of the battery
$\eta_{\text{discharge}}$	discharging efficiency of the battery when measurement point is at the electric motor
η_{acc}	operation efficiency of accessories
η_{regen}	energy efficiency of vehicle with regenerative braking
$\eta_{\text{non-regen}}$	energy efficiency of vehicle without regenerative braking

Abbreviations

BEV	battery electric vehicle
DC	direct current
ECE	European Union Urban Driving Cycle
EUDC	Extra Urban Driving Cycle
FCEV	fuel cell hybrid electric vehicle
HEV	hybrid electric vehicle
KERS	kinetic energy recovery system
NEDC	New European Drive Cycle
RBS	regenerative braking system
regen	regenerative braking
non-regen	no regenerative braking
SOC	state of charge

In the existing studies, automakers, parts manufacturers, and researchers worldwide have carried out a series of research and development in system design and control. In [15], Toyota developed an electro hydraulic brake system and implemented successfully in commercialized HEV. In [16], the electrically-driven intelligent brake system, which features an electrically driven motor and a ball screw, was developed by Hitachi and applied in the Nissan Leaf electric car. In [17], a powertrain equipped with an energy regeneration system was design. In [18], the ultracapacitor can recover the regenerative energy was studied. In regenerative braking control, present research mainly concentrates on the cooperation between regenerative braking and friction braking. In [13], a new regenerative braking control strategy for rear-driven electrified minivans was designed. In [19], a control strategy coordinating the regenerative brake and the pneumatic brake was proposed, in order to recapture the braking energy and improve the fuel economy for fuel cell city bus. To improve the blended brake control performance further, a novel control method based on on–off solenoid valves was proposed in [20].

However, unlike the two aspects mentioned above, studies on evaluation of regenerative braking energy efficiency, especially the evaluation of contribution to the energy efficiency improvement on vehicle level, have seldom been reported. In [8], potential for passenger car energy recovery was discussed, but it only targeted the system being in the form of a rotating flywheel. In [21], only the potential reduction in fuel consumption enabled by regenerative braking was introduced, however, the real contribution and its measurement method were not mentioned. In [6], a contribution rate was proposed to evaluate the fuel economy of the vehicle improved by regenerative brake, but the mechanism analysis and practical implementation methods were not discussed in detail.

In the present work, we discuss the evaluation of contribution brought by regenerative braking to electric vehicle's energy efficiency improvement. The most typical configuration of electrified vehicle, i.e. a pure electric passenger car equipped with a central electric motor at the front axle, is selected as the case-study objective. The energy flow on vehicle level with the regenerative braking energy being taken into consideration is firstly analyzed and compared with the vehicle without a regenerative brake. Then, methodologies for practically measuring the contribution made by regenerative brake to vehicle energy efficiency improvement are introduced, and two different evaluation parameters are proposed. Real vehicle tests are carried out on chassis dynamometer under typical driving cycles with different control strategies. The experimental results demonstrate the feasibility and effectiveness of the evaluation methodologies proposed.