Energy Conversion and Management 166 (2018) 545–555

Contents lists available at ScienceDirect

Energy Conversion and Management

journal homepage: www.elsevier.com/locate/enconman

The influence of accessory energy consumption on evaluation method of braking energy recovery contribution rate

Ning Li[a,b,c], Junzhi Zhang[c,b,*], Siyi Zhang[c], Xiaohui Hou[c], Yingshuai Liu[a,b]

[a] School of Mechanical and Vehicle, Beijing Institute of Technology, China
[b] Collaborative Innovation Center of Electric Vehicles in Beijing, China
[c] State Key Laboratory of Automotive Safety and Energy, Tsinghua University, China

ARTICLE INFO

Keywords:
Regenerative braking
Energy recovery contribution rate
Energy flow
Accessory system

ABSTRACT

This article discusses the influence of accessory energy consumption on evaluation method of braking energy recovery contribution rate. The energy flow model of three types of the electrified buses were firstly analyzed. Then, methodologies for the economic contribution rate of the brake energy recovery system including accessories and the system without accessories were proposed. The test method of the braking energy recovery efficiency was analyzed and proposed combining with the practical application. Vehicle tests were carried out under the China city bus typical driving cycle. The tests demonstrated that the effect of vehicle accessory system energy consumption on the braking energy recovery contribution rate is very little.

1. Introduction

Due to the concerns about environmental issues, along with the shortage of fossil oil energy, low-carbon technologies are therefore rapidly advancing. The increasingly serious environmental pollution requires vehicles to be more efficient and cleaner. Among the solutions for vehicle emission purification, electric driven vehicles including internal combustion HEVs, plug-in electric vehicles and fuel cell hybrid electric vehicles are developed by nearly every major manufacturer.

For the development of electric vehicles, regenerative braking is one of the key technology, because regenerative braking can improve the vehicle economy effectively by recovering braking energy [1–3]. According to the study, through the application of regenerative braking, vehicle economy can be increased by 15% [4].

In the existing study, vehicle manufacturers, parts manufacturers and researchers around the world have carried out many research and development in the regenerative braking system design and control. In [5], the electrically-driven intelligent brake system, which is composed of an electric motor and a ball screw, is applied in the Nissan Leaf electric vehicle. In [6], an electro hydraulic brake system is successfully developed by Toyota Corporation and applied to hybrid vehicles. In [7], three control strategies, namely the good-pedal-feel strategy, the maximum-regeneration-efficiency strategy, and the coordination strategy for regenerative braking system of an electrified passenger car are researched. In [8], a novel sliding mode control based high-precision hydraulic pressure feedback modulation is proposed, an open loop load pressure control based on the linear relationship between the pressure-drop and coil current in valve critical open equilibrium state is proposed. In [9], a direct comparison between high-speed flywheels and ultra capacitors functioning as a secondary energy storage is provided during regenerative braking on different road types. In [10], a novel transient fault tolerant approach for BBW systems is proposed to facilitate the realization of transient fault prevention, detection, and mitigation at both the node and system levels. In [11], a system-architecture is proposed for a brake-by-wire system with fail-operational capabilities. In [12], the control of an electro-hydraulic brake by wire system is presented, vehicle brake-by-wire systems is researched, a position-pressure map estimation algorithm is introduced.

For regenerative braking system, the key technology includes three important aspects: the system design, the brake control and the energy efficiency evaluation.

Compared with regenerative braking system design and control aspect, the research on the evaluation of the system is relatively few. In [13], analysis and simulation were applied to analyze the energy conversion efficiency of different HEV topology structures. In [14], a computationally efficient simulation model for estimating the energy consumption of EVs was presented. In [15], evaluation methods of contribution brought by regenerative braking to electric vehicle's energy efficiency improvement were discussed in this article. In [16], the evaluation methods of regenerative energy contribution were introduced, the energy flow of an electric vehicle was analyzed, tests were carried out on chassis dynamometer under typical driving cycles with

* Corresponding author at: State Key Laboratory of Automotive Safety and Energy, Tsinghua University, China.
E-mail address: jzhzhang@mail.tsinghua.edu.cn (J. Zhang).

https://doi.org/10.1016/j.enconman.2018.04.040
Received 20 November 2017; Received in revised form 10 April 2018; Accepted 10 April 2018
Available online 03 May 2018

three control strategies.

The existing research on traditional diesel engine bus was pointed out, the total energy consumption of the accessory system accounts for about 15% of the total fuel consumption, while for the hot weather and the cities near the equator, the proportion is greater, reaching about 50% [17,18]. Studies showed that the energy efficiency of an electric vehicle is more sensitive to the energy consumption of accessories compared to a conventional vehicle [19]. However, the impact of the accessory system on the brake energy recovery system has hardly been studied systematically, especially the practical methodologies for measuring the contribution of regenerative braking are rarely studied.

In [16], the energy flow of electric vehicle considering accessories's energy consumption was covered, but it only restricted to one type of vehicle and its measurement method were not related. In [20], impacts of accessories on energy efficiencies of different hybrid electric vehicle topologies were discussed, but impacts of accessories on brake energy regeneration system were not discussed. In [21], Teresa Donateo and some others used simulation analysis and real vehicle test to study the influence of air conditioning and radio operating conditions on the vehicle mileage, but the article mainly focused on vehicle test, the mechanism analysis of accessories on brake energy regeneration system were not introduced.

In the present work, we discuss the effect of vehicle accessory system energy consumption on the braking energy recovery contribution rate. Three typical electrically driven buses, i.e. pure electric bus, fuel cell bus and hybrid bus are selected as the case-study objective. The energy flow of three kinds of electrically driven buses is firstly analyzed. Then, methodologies of the energy economy contribution is researched, the charge-discharge efficiency of the energy storage device and the energy consumption of the accessory system are taken into account in this method. The test method of the braking energy recovery efficiency is analyzed and proposed combining with the practical application. Real vehicle tests are carried out under typical driving cycles on electric bus and fuel cell bus respectively. The experimental results demonstrate that the effect of vehicle accessory system energy consumption on the braking energy recovery contribution rate is very little.

2. Energy flow analysis of three types of electric driven bus

2.1. Energy flow analysis of pure electric bus

Pure electric vehicles are electric vehicles powered by batteries and driven by electric motors instead of internal combustion engines. The electric vehicle system consists of three subsystems: energy subsystem, drive subsystem and auxiliary subsystem. The typical basic structure of the pure electric bus system is shown in Fig. 1.

In order to investigate the energy flow law of pure electric bus, the energy consumption and energy recovery are analyzed in the process of vehicle running, and the energy flow model of pure electric bus is established, as shown in Fig. 2.

The energy flow model includes several major modules of dynamic system which are the storage battery module, the drive motor module, the transmission system module, the accessory system module, the vehicle body module and the wheel module. The input end of the drive motor and the input terminal of the accessory system are on the output end of the battery, that is, the direct current bus. Among the variables in the diagram, E represents electric energy, W represents mechanical energy, η represents efficiency. Letter before underline represents the source of energy, *es* represents energy storage device, *reg* represents motor recovery energy, *mot* represents the mechanical energy generated by the electric motor. Letter after underline represents energy consumption, *drv* represents driving motor wheel energy, *as* represents the energy used by the accessory system. On the corner of variable energy′ represents the actual energy consumption of the system [15,20].

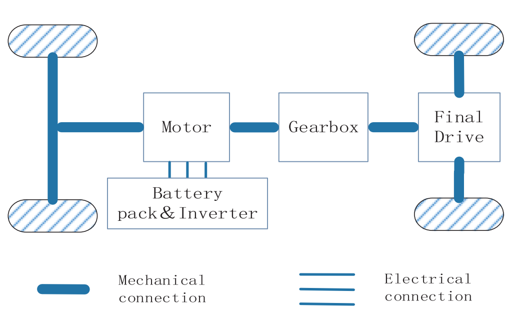

Fig. 1. Basic structure of pure electric bus.

2.1.1. Flow of electric energy on the direct current bus

When the vehicle runs in the driving state, the total energy output of the battery is divided into two parts, one part is consumed by the accessories, the other part is used to drive the motor, and then through the transmission system (clutch, reducer, transmission, etc.) is transmitted to the wheels, overcome the rolling resistance, air resistance, then the energy is converted to the kinetic energy of the vehicle. Since the pure electric bus has only one power source motor, the motor obtains the electric energy from the direct current bus, and the accessory system also obtains the driving energy from the direct current bus, then the total energy E_t output at the direct current bus is as follows:

$$E_t = E_{drv} + E_{as} \quad (1)$$

In formula, E_{drv} is the battery output electrical energy, which is used to drive the motor, E_{as} is the electrical energy obtained by the accessory system from the direct current bus.

When the vehicle is running in the process of feedback braking, the battery is in the state of charging, and the energy recovered by the motor is divided into two parts, some are stored in the battery for the next time, when the vehicle needs to be driven, and another part supplies the current accessory system. In the formula (1), the accessory system consumes energy E_{as} has two sources of energy:

$$E_{as} = E_{es\,as} + E_{reg\,as} \quad (2)$$

2.1.2. Transformation of electrical energy and mechanical energy

The total energy E_{drv} used to drive the motor passes through the motor and transmission system, and then the total energy W'_{drv} reaches at the wheel is:

$$W'_{drv} = \eta_{md}\eta_{td}\cdot E_{drv} \quad (3)$$

The η_{md} and η_{td} in the formula are the average efficiency of the motor and the average efficiency of the drive system in the driving state in the whole cycle.

Different pure electric bus have different transmission system configurations. For example, there is a traditional transmission system with multi gear drives and clutches, a single gear drive system without clutch demand, and a direct drive transmission system with two independent wheel hub motors. For different transmission systems, η_{td} is also different, which is defined as the ratio of the drive energy obtained at the wheel to the mechanical energy output at the motor output.

Similarly, in the feedback braking process, the motor recycling energy W'_{reg} is also through the transmission system and motor, converted to electric energy E_{reg} to the DC bus.

$$E_{reg} = \eta_{mb}\eta_{td}\cdot W'_{reg} \quad (4)$$

In the formula, η_{mb} and η_{td} are the average efficiency of the motor and the average efficiency of the transmission system in the braking state of the whole cycle.

2.1.3. Accessory energy consumption

In the pure electric bus, the most energy consuming accessories are