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Electric vehicles' energy consumption estimation with real driving condition data

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ABSTRACT

The use of electric vehicles (EVs) is viewed as an attractive option to reduce CO_2 emissions and fuel consumption resulted from transport sector, but the popularization of EVs has been hindered by the cruising range limitation and the charging process inconvenience. Energy consumption characteristics analysis is the important foundation to study charging infrastructures locating, eco-driving behavior and energy saving route planning, which are helpful to extend EVs' cruising range. From a physical and statistical view, this paper aims to develop a systematic energy consumption estimation approach suitable for EV actual driving cycles. First, by employing the real second-by-second driving condition data collected on typical urban travel routes, the energy consumption characteristics analysis is carried out specific to the microscopic driving parameters (instantaneous speed and acceleration) and battery state of charge (SOC). Then, based on comprehensive consideration of the mechanical dynamics characteristics and electric machine system of the EVs, a set of energy consumption rate estimation models are established under different operation modes from a statistical perspective. Finally, the performance of proposed model is fully evaluated by comparing with a conventional energy consumption estimation method. The results show that the proposed modeling approach represents a significant accuracy improvement in the estimation of real-world energy consumption. Specifically, the model precision increases by 25.25% in decelerating mode compared to the conventional model, while slight improvement in accelerating and cruising mode with desirable goodness of fit.

Introduction

The development of electric vehicles (EVs) represents a potential partial solution to world-wide concerns related to energy security and environmental pollution, particularly from the transport sector by using a clean and renewable energy source (Gardner et al., 2013). However, their widespread adoption is hindered by limited range and inevitable charging procedure, as well as the relatively higher acquisition costs (Bühler et al., 2014). There are various ways to overcome these problems, most of them have been focused on the improvement of battery capacity (Masih-Tehrani et al., 2013), the design of gearing configurations (Wager et al., 2014), or the application of vehicle regenerative braking systems (RBS) (Clarke et al., 2010). Instead of concentrating on the development of new technologies for EV itself, many efforts have been devoted to

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the optimization of charging infrastructures layout (Chen et al., 2013) and energy efficient route planning (Rahman et al., 2013).

As the prerequisite of the aforementioned work, the existing research on energy analysis of EVs can be classified into four categories: (i) dynamic vehicle simulator approaches based on standardized driving cycles and complicated computer programs; (ii) computational intelligence methods, which build the relationship between energy consumption and microscopic driving parameters (instantaneous speed and acceleration) in the light of some intelligence-optimized algorithms; (iii) statistical models including different combinations of speed and acceleration levels using the chassis dynamometer test data; (iv) theoretical models established in accordance with the operating principles of powertrain system. However, the above research either has onerous calculations or depends on laboratory test data, the results cannot reflect the impact of the vehicle running status on energy consumption under real driving conditions.

Given the speedy development of intelligent transportation systems (ITS) technologies and the widespread use of microscopic traffic simulation models, this paper attempts to establish an actual microscopic energy analysis framework for EVs in order to estimate the real-world EVs' energy consumption in a simple and effective way. From a physical and statistical standpoint, this paper contributes to identify the EV energy consumption characteristics under actual driving cycles. Moreover, an improved modeling framework suitable for regenerative braking is proposed to enhance the accuracy of energy consumption estimation. Concretely, comparing with the conventional method, more influencing factors are included in this framework, and these factors at adjacent moments are considered with current energy consumption rate together under different operation modes.

The remainder of this paper is organized as follows: Section 'Literature review' reviews the previous work on the key factors of EV energy consumption and the development of energy analysis approaches. Section 'Study methods' presents the methodology. Based on the collected on-road instantaneous driving condition data, the energy consumption characteristics are comprehensively analyzed. Subsequently, a set of statistical energy consumption rate models are established considering both the inertial dynamics of EV and the efficiency of its powertrain together. The calibrated parameters and the model validation results are given and discussed by comparing with a conventional method in Section 'Results and discussion'. Finally, the concluding remarks of the present paper are provided in Section 'Conclusions'.

Literature review

To develop an energy consumption estimation model for EVs, it is essential to understand what factors influence EV energy consumption and their changing mechanisms. Lots of research has been conducted to explore the relationship between energy consumption and some factors from different perspectives, such as vehicle characteristics, road characteristics and traffic conditions.

Duarte et al. (2014) analyzed the influence of battery state of charge (SOC), an indicator of the amount of usable battery energy, on the energy consumption. A conclusion was drawn that the energy consumption was higher for lower SOC levels. Holdstock et al. (2012) studied the role of drivetrain topology in EV energy reduction. A significant increase was found in the performance of EVs when employing four-speed transmission system than single and double-speed variants. Yang et al. (2014) found that the energy consumption increased with the road tilt angle on uphill but decreased on downhill. It is worth noting that analyzing the energy consumption in the urban area is more meaningful due to the significant increase in energy consumption. Aiming at the urban area, Yao et al. (2013) established EV's energy consumption factor models for different road types. It was pointed out that the energy consumption factor varied with road type remarkably. Given that the instantaneous speed and acceleration are the leading indicators of traffic conditions which affect the energy use most significantly, Ahn et al. (2002) presented a variety of energy models as a function of the vehicle's instantaneous speed and acceleration levels. This opinion was also confirmed in the further work launched by Yao et al. (2014). Moreover, they emphasized that EV energy consumption was influenced by not only instantaneous speed and acceleration, but also operation modes.

Comparable studies have been published aiming to quantify such impacts on EV energy consumption. Xie et al. (2012) developed an integrated model for evaluating the impacts of alternative transportation fuels by incorporating a microscopic traffic simulation model PARAMICS and the emission model MOVES. The former model provided traffic information in detail, which were then used in the MOVES emission model for estimation of the corresponding emissions and fuel consumption. Nevertheless, the effects of energy-saving and emission-reduction relied on the simulated roadway traffic network. Shankar and Marco (2013) put forward a framework in which a neural network was used to classify both the road types and traffic congestion levels of the transport environment where the EV operated, and then the energy consumption was estimated over different road types. However, the energy consumption rate of the EV was calculated at the battery terminals, in which the external parameters, such as real-time battery terminals voltage and current, were unavailable under real-world driving conditions.

For the purpose of simplifying the calculation process and making it more useful in practice, the VT-Micro emissions model was adopted to predict the vehicle fuel consumption for various speed profiles in the work of Rakha and Kamalanathsharma (2011). The model was developed as a statistical model consisting of linear, quadratic and cubic combinations of speed and acceleration levels, but it mainly targeted at gasoline and diesel powered vehicles. Due to the completely different characteristics of the powertrain efficiency, Yao et al. (2014) validated the applicability of the VT-Micro model for EV further, and extended this model structure as follows: