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Electric vehicles' energy consumption measurement and estimation

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ABSTRACT

Use of electric vehicles (EVs) has been viewed by many as a way to significantly reduce oil dependence, operate vehicles more efficiently, and reduce carbon emissions. Due to the potential benefits of EVs, the federal and local governments have allocated considerable funding and taken a number of legislative and regulatory steps to promote EV deployment and adoption. With this momentum, it is not difficult to see that in the near future EVs could gain a significant market penetration, particularly in densely populated urban areas with systemic air quality problems. We will soon face one of the biggest challenges: how to improve efficiency for EV transportation system? This research takes the first step in tackling this challenge by addressing a fundamental issue, i.e. how to measure and estimate EVs' energy consumption. In detail, this paper first presents a system which can collect in-use EV data and vehicle driving data. This system then has been installed in an EV conversion vehicle built in this research as a test vehicle. Approximately 5 months of EV data have been collected and these data have been used to analyze both EV performance and driver behaviors. The analysis shows that the EV is more efficient when driving on in-city routes than driving on freeway routes. Further investigation of this particular EV driver's route choice behavior indicates that the EV user tries to balance the trade-off between travel time and energy consumption. Although more data are needed in order to generalize this finding, this observation could be important and might bring changes to the traffic assignment for future transportation system with a significant share of EVs. Additionally, this research analyzes the relationships among the EV's power, the vehicle's velocity, acceleration, and the roadway grade. Based on the analysis results, this paper further proposes an analytical EV power estimation model. The evaluation results using the test vehicle show that the proposed model can successfully estimate EV's instantaneous power and trip energy consumption. Future research will focus on applying the proposed EV power estimation model to improve EVs' energy efficiency.

Introduction

The transportation system is fundamental to the health of the economic growth. However, the current transportation system is overwhelmingly powered by internal combustion engines (ICE) fueled by petroleum. This not only causes the world

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be dependent on the whims of the global oil market (Pound, 2012); but more importantly, has made the transportation sector the economy's largest source of greenhouse gas (GHG) emissions (Greene and Schafer, 2003). Because of projected shortage of crude oil and the urgent need of reducing GHG emissions, more and more talents and resources are now focusing on shaping a sustainable transportation system that can address the climate change challenge as well as reduce oil dependence (US DOT, 2010). Among many innovative technologies, electrification of passenger vehicles is viewed by many as one that could significantly reduce oil dependence, operate vehicles more efficiently, and reduce carbon emissions.

Electric vehicles (EVs) include both plug-in hybrid (PHEVs) and battery-powered electric vehicles (BEVs). PHEVs usually have a moderately sized energy storage system and an internal combustion engine to ensure most miles are electrified while retaining the range capability of today's ICE vehicles. BEVs are entirely battery dependent and provide complete petroleum displacement for certain vehicle sectors. This research mainly focuses on BEV (simplified as EV for the rest of the paper). EV adoption has a great potential to play a significant role in addressing both energy and environmental crises brought by the current transportation system. First, electricity can help meet future transportation needs. Take U.S. as an example, since the vast majority of electric generation resources are domestic, electric vehicles are viewed as an excellent way to diversify transportation fuels. Although some challenges remain in regard to cost and battery technology, the availability of domestic electricity is not an issue so long as vehicles are charged at night, when excess electric generating capacity is available (Pound, 2012). In addition, fueling EVs is far less expensive than fueling ICE vehicles. With the average price of residential electricity at approximately 11.5 cents per kilowatt hour, a vehicle that runs only on electricity can travel approximately 30 miles on about 80 cents of electricity – almost one fourth of the cost of driving a similarly equipped ICE vehicle at $3 a gallon for gasoline (Andersen, 2012). Second, electricity has a strong potential for GHG reduction. Electric vehicles themselves have zero emissions, although generating the electricity to power the vehicle is likely to create air pollution. If electricity is generated from the current U.S. average generation mix, EVs can reduce GHG emissions by about 33%, compared to today's ICE powered vehicles (US DOT, 2010). If we assume 56% light duty vehicle (LDV) penetration by 2050, this could provide a total reduction in transportation emissions of 26–30% (US DOT, 2010).

The huge potential benefits of EVs have already attracted significant interest and investment in EV technology. Since late 2010, more than 20 automakers have introduced BEVs or PHEVs. Within the United States, the government has allocated considerable stimulus funding to promote the use of alternative fuels (Skerlos and Winebrake, 2010). The American Recovery and Reinvestment Act (ARRA) of 2009 provided over $2 billion for electric vehicle and battery technologies, geared toward achieving a goal of one million electric vehicles on U.S. roads by 2015 (Canis et al., 2011). (A recent post suggests that this goal will not be reached until 2018 (Car Congress, 2012)) Many states also have committed themselves to promoting EVs. For example, California has taken a number of legislative and regulatory steps to promote electric vehicle deployment and adoption, such as the Zero Emission Vehicle and Low Carbon Fuel Standard regulatory programs and rebates for purchasing electric vehicles (Elkind, 2012). These actions demonstrate the state's commitment to promote electric vehicles. With this momentum, it is not difficult to see that in the near future EVs may gain significant market penetration, particularly in densely populated urban areas with systemic air quality problems. We will soon face one of the biggest challenges: How to improve efficiency for the whole EV transportation system? (Here the EV transportation system includes any EV related applications of technologies and policies to the planning, functional design, operation and management of facilities and infrastructure in order to provide for the safe, efficient, economical, and environmentally compatible movement of people and goods.)

The majority of current EV research is focused on how to overcome technical barriers such as battery technology limitations (Axsen et al., 2010) and charging infrastructure problems (Morrowa et al., 2008). Extensive research efforts and investments have been given to address these barriers (Deutsche Bank, 2009; Frade et al., 2010; He et al., 2013; Ip et al., 2010; Pan et al., 2010; Sioshansi, 2012; Sovacool and Hirsh, 2009; Sweda and klabjan, 2011). For example, according to a research conducted by Deutsche Bank (2009), over $7 billion was being invested in lithium-ion battery manufacturing to construct over 36 million kilowatt hour of battery production capacity which will be enough to power 15.0 million HEVs or 1.5 million EV. Many studies have also investigated the location problem of public charging stations. For example, Frade et al. (2010) formulated a maximum covering model to deploy a certain number of charging stations; Ip et al. (2010) applied a hierarchical clustering model to locate charging stations; Pan et al. (2010) developed a two-stage stochastic program to optimally set up PHEV battery swapping stations; Sweda and klabjan (2011) developed an agent-based decision support system for electric vehicle charging infrastructure deployment; and He et al. (2013) adopted a game theoretical approach to investigate the optimal deployment of public charging stations for PHEV.

However, very little research has been focused on how to improve the efficiency of the EV transportation system. People have yet to realize the importance of this question, partly because they have not foreseen the oncoming growth worldwide for EVs; but more importantly, due to lack of knowledge of electric vehicle performance and drivers' behaviors. We have yet to identify the unique features of both EVs and EV drivers that control energy consumption and efficiency. These unique features could fundamentally change our understanding of people's travel and driving behaviors and further impact the transportation system, our environment, and our society. This research begins to explore these features starting by investigating EVs' energy usage measurement and estimation.

Measuring and estimating EVs' electricity usage is an important requirement for the future improvement of energy efficiency of the EV transportation system. One of the most advanced features of an EV, compared to conventional ICE vehicles, is its ability to capture and store energy through the regenerative braking system (RBS) (Clegg, 1996; Xu et al., 2011; Zhang et al., 2008). RBS uses the electric motor to recharge the battery by applying negative torque to the drive wheels and