ABSTRACT:

Use of electric vehicles (EVs) has been viewed by many as a way to significantly reduce US 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 will 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 the entire EV system? This research takes the first step in tackling this challenge by addressing a fundamental issue, how to measure and estimate EVs' energy consumption. In detail, this paper first presents a system which can collect in-use EV data from both the battery system, including battery state of charge, pack current, pack voltage, pack power and vehicle driving data including velocity, acceleration, and vehicle position (latitude, longitude, and elevation). Then this system has been installed in an EV conversion vehicle built for this research. Approximately five 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 incity routes than driving on freeway routes. This has become one of the major reasons that EV driver prefers in-city routes over freeway routes. This research further analyses the relationships among the EV's power use, the vehicle's velocity, acceleration, and the roadway grade. This is done by categorizing data according to the specific ranges of velocity, acceleration, and roadway grade. In addition, through statistical analysis, we determined that the EV's power within a specific range of velocity, acceleration, and grade could be described as a normal distribution. Based on the analysis presented, this paper further proposes an analytical EV power estimation model using the fundamental theory of vehicle dynamics and basic relationships among power, force, torque, voltage, and current. This model has been evaluated using the test vehicle. The results show that this 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.

1. INTRODUCTION

The transportation system is fundamental to the health of the nation's economic growth. However, the current transportation system is overwhelmingly powered by internal combustion engines (ICE) fueled by petroleum. This not only causes the nation be dependent on the whims of the global oil market[15]; but more importantly, has made the transportation sector the economy's largest source of greenhouse gas (GHG) emissions[9]. Because of projected shortage of crude oil and the urgent need of reducing GHG emissions, more and more national 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[22]. Among many innovative technologies, electrification of passenger vehicles is viewed by many as one that could significantly reduce US 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 could play a significant role in addressing both energy and environmental crises brought by the current transportation system. First, electricity will help meet future U.S. transportation needs. 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[15]. In addition, fueling EVs is far less expensive than fueling ICE vehicles. With the national 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[1]. 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 percent, compared to today's ICE powered vehicles[22]. If we assume 56 percent light duty vehicle (LDV) penetration by 2050, this could provide a total reduction in transportation emissions of 26 to 30 percent[22].

The huge potential benefits of EVs have already generated 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 allocated considerable stimulus funding to promote the use of alternative fuels[18]. 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[3]. 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[6]. 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 system?

The majority of current EV research is focused on how to overcome technical barriers such as battery technology limitations[2] and charging infrastructure problems[13]. Extensive research efforts and investments have been given to address these barriers[5,7,10,11,14,17,19,20]. However, very little research has been focused on how to improve the efficiency of the EV system. People have yet to realize the importance of this question, partly because they haven't 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 the foundation for the future improvement of energy efficiency of the EV 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)[4,23,24]. RBS uses the electric motor to recharge the battery by applying negative torque to the drive wheels and converting kinetic energy to electrical energy. The use of RBS in EVs' fundamentally changes their energy consumption characteristics compared to ICE vehicles. For example, EVs are much more efficient when driving on interrupted urban routes than uninterrupted freeway[12]. This is in contrast to conventional ICE vehicles, which require much more energy in urban driving because of braking and thermal losses[8,16]. This characteristic could significantly change driving behaviors and travel behaviors in order to save energy. The unique characteristics of EVs needs to be carefully investigated; and the first requirement of this investigation is the ability to measure and estimate EVs' energy usage, which, as will be demonstrated in the paper, is a function of vehicle's velocity, acceleration, and roadway grade.

Fig. 1 Electric Vehicles and Batteries

Fig. 2 Data Collection System Architecture

Table 1: EV's Parameters to Calculate the Power Consumption Profile

Parameters	Values
Vehicle weight (including driver), m [kg]	1266
Rolling resistance coefficient, f_{rl}	0.006
Aerodynamic resistance coefficient, k [kg/m]	1.30
Product of armature constant and magnetic flux, $K = K_a.\phi_d [V.s]$	10.08
Resistance of motor (in general), r [Ω]	0.11
Radius of tire, R [m]	0.50
Transmission efficiency, η [%]	95

Based on the values in Table 1, we use Eq.11 to calculate instantaneous power. The control variables are EV's velocity, acceleration, and roadway grade. Vehicle velocity and acceleration time histories were taken directly from the data collection system. Elevation and grade information was manually collected from Google earth. With these input values as a function of time, we calculated EV power using Eq.11. We then compare this calculated power with the measured power. Fig.10 presents an example based on a trip on Dec. 03, 2012. As we can see from the figure, the purple line, which represents estimated EV power, closely follows the green line, which is the measured EV power. This shows the accuracy of our simple estimation model. We also include vehicle velocity and acceleration information indicated by light pink and light blue lines respectively as shown in the figure. Interestingly, we can see that the changes of power follow the trend of the change of acceleration closely.

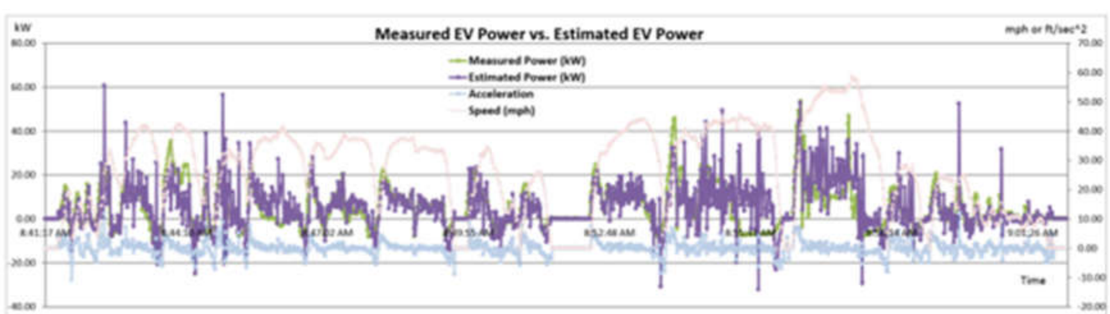

Fig. 3 Measured power vs. estimated power