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Impact of road gradient on energy consumption of electric vehicles

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ABSTRACT

We investigate the impact of road gradient on the electricity consumption of electric vehicles (EVs) by combining long-term GPS tracking data with digital elevation map (DEM) data for roads in Aichi prefecture, Japan. Eight regression models are constructed and analysed to compare the differences between linear and logarithmic forms of trip energy consumption, differences between considering the road gradient or not, and differences between considering the fixed effects of EVs or not. By categorizing gradients and assigning a percentage of the trip distance to each category, a significantly better model of electricity consumption can be achieved. The results of this study are a novel contribution toward understanding the challenges and benefits associated with downgrade braking on energy regeneration.

1. Introduction

Electric vehicles (EVs) are recognized as an environmentally efficient transportation mode with higher energy efficiency, especially in congested urban networks. However, a critical issue for EVs that has not yet been well addressed is range anxiety among drivers. To reduce range anxiety, accurate estimation of EV energy consumption is important so that, from a certain battery state of charge (SOC), the remaining range can be forecast under conditions where the urban road network and driving conditions present a complex environment. Experimental observations of EVs are necessary to help understand their energy consumption characteristics and energy efficiency.

In practice, substantial regional differences in driving patterns associated with road topography, traffic conditions, and other local characteristics are known to have an effect on the energy efficiency of Plug-in Hybrid Electric Vehicles (PHEVs) (Raykin et al., 2012). Distances driven and driving conditions are considered the main factors that account for differences in driving patterns. Of all the factors that affect driving conditions, the gradient of the road is considered one of the most significant influences on vehicle energy consumption (Cicero-Fernândez et al., 1997; Zhang and Frey, 2006; Boroujeni et al., 2013), however, quantitative analysis of the effect of road gradient on the consumption of EVs or PHEVs is rare.

Actually, for both PHEVs and EVs, regenerative braking energy is returned to the batteries, thus reducing overall energy consumption. Lorf et al. (2013) noticed that electric regenerative braking leads to lower energy consumption and lower emissions, but quantitative analysis of the influencing factors and modelling of regenerated energy is limited.

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It is a remarkable fact that road gradient has a certain impact on fuel economy, although EVs are less affected by road gradient compared to conventional vehicles (Fiori et al. 2016; Wyatt et al. 2014; Z. Sun et al., 2015). The results of the study by Travesset-Baro et al. (2015) also showed that the road gradient has a primary impact on fuel efficiency. However, the effect of the route gradients is neglected in many conventional studies, leading to relatively large estimation errors, due to the difficulty of directly measuring the road gradient and accuracy limitations of observed energy consumption (Levin et al., 2014).

In energy usage models, there is a gap in the understanding of the full effects of road gradient on energy consumption and regeneration because downward gradients are conventionally recognized as consuming/regenerating at similar rates for simplicity despite the gradients (Hyodo et al., 2013). The contribution of this paper is to fill the gap by investigating the effect of road gradient on vehicle energy consumption using long-term GPS tracking data collected from 68 EVs in Aichi prefecture, Japan and detailed digital elevation map (DEM) data for the roads. The following section reviews the state-of-the-art in the literature about estimating energy consumption. In Section 3, the dataset is described in detail. The general characteristics of electricity consumption on driving trips and the factors influencing it are described in Section 4, then Section 5 compares the goodness of fit and estimations for eight combination models. Lastly, conclusions are drawn and the direction of future study is discussed.

2. The literature on estimating EV energy consumption

Generally, the main factors that account for discrepancies between expected EV charge-depleting range and the real-world charge-depleting range experienced by drivers consist of driving pattern, such as speed (Vaz et al., 2015) and driving aggressiveness (Margarida and Marco, 2010), weather and temperature (Liu et al., in preparation), and traffic conditions. Moreover, using air conditioning can increase the energy consumption of a vehicle by approximately 20% on average (Javani et al., 2012). The energy requirements of heating, ventilation, and air conditioning (HVAC) systems have a close relationship with the local weather, solar loads, driving behaviour, etc. (Kambly and Bradley, 2014). To help determine the actual vehicle power output, driving behaviour can be monitored using a GPS receiver (Lorf et al., 2013) or estimated by simulation (Vieira da Rocha et al., 2013). However, as far as we know, there have been few large scale experimental explorations of EV energy consumption. This may be due to the numerous uncontrollable influential factors that may reduce the estimation accuracy in real experimental environments, such as ambient temperature issues (Wang et al., 2016) and the bounded rationality of the driver (Tang et al., 2015).

The automotive sector will be transformed by EVs, whose new and more energy efficient systems are set to change energy usage patterns (Kuhne, 2010). The energy efficiency of vehicles will benefit from regenerative braking systems (Åhman, 2001), which are widely used in the current generation of EVs. Lorf et al. (2013) stated that the energy saving potential of electric regenerative braking is significant for EVs, although quantitative analysis of electricity recovery using experimental data is still limited. The commonly used function of vehicle force to overcome gradient resistance (Eq. (1), Vaz et al., 2015) for estimating the instant power output due to road gradient is actually neglecting the effect of regenerative braking in downward gradients.

$$F_{hc} = m * g * \sin\theta \tag{1}$$

where F_{hc} is the hill climbing force, m is the vehicle mass (kg), g is gravitational force (9.8 m s^{-2}), and θ is the road gradient angle.

Braking is more frequent on routes with a downward gradient than on other routes, while upward gradients lead to increased energy consumption. Wyatt et al. (2014) demonstrated that the assumption of a flat road profile rather than one with gradients could result in considerable errors in estimating the real-world energy consumption and CO_2 emissions of conventional vehicles. In the case of EVs, intuition says that downward gradients may help reduce electricity consumption and vice versa, so road gradients are guaranteed to have a considerable impact on the maximum range and best route choice (Genikomsakis and Mitrentsis, 2017). Hu et al. (2016) proposed an optimal controller for a PHEV travelling on rolling terrain to reduce fuel consumption, the maximum potential benefit from the proposed controller is 8.9% on major arterials and 16.9% on collector roads. Most micro emission models proposed in past studies have already considered the effects of upward gradients, including in Ahn and Rakha (2013) and Rakha et al. (2004), but the regenerative braking energy delivered to EVs on downward gradients is seldom addressed due to a poor experimental environment and limited observational data. An exception is the study by Li et al. (2016), who conducted an experiment and proposed a braking downshift control strategy to address the energy efficiency of an electric vehicle during downward deceleration.

In terms of vehicle fuel consumption, models have been developed to estimate the energy required to overcome external resistance factors, which include rolling resistance, air friction, gradient resistance and acceleration resistance (Trigui et al., 2004; Hyodo et al., 2013). Another type of energy consumption model is based on the drive cycle (Vieira da Rocha et al., 2013) and vehicle specific power (VSP) function (Boroujeni and Frey, 2014); however, this relies on second-by-second observations of vehicle trajectory data, which is usually not available for large scale experimental studies.

Another issue for estimating the EV energy consumption is the errors from collected energy consumption information and from the observed six categories of influence factors summarized by Ahn et al. (2002). Specifically, the large difference in the observation particle size causes considerable issues, in which grade measurement errors and GPS errors (Hu et al., 2016), GPS