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Harnessing big data for estimating the energy consumption and driving range of electric vehicles

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ABSTRACT

Analyzing the factors that affect the energy efficiency of vehicles is crucial to the overall improvement of the environmental efficiency of the transport sector, one of the top polluting sectors at the global level. This study analyses the energy consumption rate (ECR) and driving range of battery electric vehicles (BEVs) and provides insight into the factors that affect their energy consumption by harnessing big data from real-world driving. The analysis relied on four data sources: (i) driving patterns collected from 741 drivers over a two-year period; (ii) drivers' characteristics; (iii) road type; (iv) weather conditions. The results of the analysis measure the mean ECR of BEVs at 0.183 kW h/km, underline a 34% increase in ECR and a 25% decrease in driving range in the winter with respect to the summer, and suggest the electricity tariff for BEVs to be cost efficient with respect to conventional ones. Moreover, the results of the analysis show that driving speed, acceleration and temperature have non-linear effects on the ECR, while season and precipitation level have a strong linear effect. The econometric model of the ECR of BEVs suggests that the optimal driving speed is between 45 and 56 km/h and the ideal temperature from an energy efficiency perspective is 14 °C. Clearly, the performance of BEVs highly depends on the driving environment, the driving patterns, and the weather conditions, and the findings from this study enlighten the consumers to be more informed and manufacturers to be more aware about the actual utilization of BEVs.

1. Introduction

As the transport sector is one of the largest contributors of greenhouse gases at the global level (see, e.g., Alessandrini et al., 2012; Zahabi et al., 2014), there have been efforts by car manufacturers, car drivers and governments to improve fuel consumption efficiency, reduce pollution and limit dependence on fossil fuel. For example, some EU and US governments have set standards that limit the pollution level of cars and have used incentives and taxes to induce car manufacturers to produce, and car users to drive, fuel-efficient vehicles (Kono et al., 2008). Battery electric vehicles (BEVs) are considered as one alternative to curtail pollution from the transport sector and to reduce dependence on the scarce and highly pollutant petroleum since the electricity needed to charge BEVs can be obtained from renewable energy resources such as wind, solar power and hydro.

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However, the market penetration rate of BEVs is lethargic, mainly because of high purchase prices, limited recharging infrastructures, limited driving range coupled with long recharging times, uncertainties concerning driving range and battery life, and risk aversion behavior in adopting new technologies (see, e.g., Birrell et al., 2014; Egbue and Long, 2012; Kihm and Trommer, 2014). It is clear that uncertainty plays a significant role in the (non-)choice of BEVs, especially when thinking about the driving range and the refueling costs and time with respect to a conventional car. Uncertainty plays an even larger role when factoring in that customers have limited knowledge about the actual performances of BEVs and their sensitivity to driving environments, with this lack of knowledge adversely affecting the demand for BEV (Birrell et al., 2014; Jensen et al., 2013). Accordingly, providing insight into the factors that affect the energy consumption rate (ECR) and driving range of BEVs under different driving environments is very relevant to support on the one hand consumers in choosing appropriate vehicles that suit their needs and, on the other hand, manufacturers in distinguishing and targeting different customers depending on the driving environments that the customers live and travel in.

Insights into the factors that affect the ECR and information about the driving range of conventional cars have been provided extensively, as their fuel consumption is well-documented in both the theoretical literature (Mellios et al., 2011; Nam and Giannelli, 2005) and the empirical literature (Brundell-Freij and Ericsson, 2005; Ericsson, 2001; Hu et al., 2012). Existing studies showed that the fuel consumption rate of conventional cars is affected by road width (Brundell-Freij and Ericsson, 2005; Hu et al., 2012; Kono et al., 2008; Yao et al., 2007), road grade (Nam and Giannelli, 2005; Wang et al., 2008), traffic congestion and speed limits (Brundell-Freij and Ericsson, 2005), as well as by traffic information provided to drivers (Fotouhi et al., 2014; Kono et al., 2008). Existing studies also illustrated that driving patterns (in terms of speed and acceleration profiles) are the main factors affecting fuel consumption of conventional cars (El-Shawarby et al., 2005; Ericsson, 2001; Heide and Mohazzabi, 2013; Nesamani and Subramanian, 2006; Wang et al., 2008). Moreover, a number of studies have provided mathematical and technical detailed accounts of the effects of different car characteristics on the fuel consumption of conventional cars (see, e.g., Brundell-Freij and Ericsson, 2005; Heide and Mohazzabi, 2013; Nam and Giannelli, 2005; U.S.E.P.A., 2014). It should be noted that the effects of car features on fuel consumption are usually taken into account during the design of the vehicle by the manufacturers, and are usually made available to the consumers during the purchase of the vehicle (Ben-Chaim et al., 2013; Kono et al., 2008).

Insights into the factors that affect the ECR of hybrid electric vehicles (HEVs) using both fuel and rechargeable batteries have been provided to a lesser extent. For example, winter has been related to a decrease of 20% in the fuel efficiency of HEVs, and their overall fuel economy with respect to conventional cars has been evaluated as possibly overweighed by the poor performance of HEVs in cold weather locations (Zahabi et al., 2014). Temperature has been found as relevant in other studies that have focused also on the driving environment (Alvarez and Weilenmann, 2012; Fontaras et al., 2008; Lohse-Busch et al., 2013), while the power ratio of HEV components and the applied control strategy of HEVs have been demonstrated analytically related to their ECR (Banjac et al., 2009).

Insights into the factors that influence the ECR of BEVs have been provided scarcely, mainly because of their recent market penetration. Most studies included technical analyses that investigated the effects of car components on the ECR (see, e.g., Duke et al., 2009) and analyses by car manufacturers and other stakeholders. Large differences were usually observed between the results of car manufacturers and the results observed in real-world (Huo et al., 2011), mainly because manufacturers test BEVs by performing a long and continue test drive from a fully charged battery to a completely flat battery, thus ignoring basic real-world energy expenditures such as the energy used to overcome the inertia force to propel a parked car and the energy used to cool down a car during each trip. A limited number of studies have focused on the ECR and the driving range of BEVs: the ECR of BEVs was evaluated by comparing the driving range reported by the manufacturer versus the actual driving range of drivers (Birrell et al., 2014); the ECR of BEVs was estimated by taking into account driving patterns and car features from GPS data, and in-city driving was deemed more energy efficient than freeway driving (Wu et al., 2015). However, these studies present limitations: (i) the study samples consisted respectively of one (Wu et al., 2015) and 11 drivers (Birrell et al., 2014), with obvious consequences on the possibility of generalizing any finding; (ii) the data collections did not cover the winter months, with obvious consequences on the possibility of analyzing the effect of cold temperature on the ECR of BEVs; (iii) the data analyses did not control for possible confounders, with obvious consequences on the possibility of assessing whether the ECR differences were caused by other factors.

As aforementioned, the uncertainty and the consequent anxiety about the driving range and the energy consumption of BEVs is one of the major barriers to their wider market penetration. It is therefore essential to provide insights into the actual ECR and driving range of BEVs under different driving environments as well as the factors that affect them while controlling for drivers' characteristics, weather variations, spatial areas, and road characteristics. The current study fills this gap by analyzing real-world data collected over a two-year period in Denmark, namely by addressing questions about the ECR of BEVs under various driving environments, the sensitivity of BEVs to speed and acceleration profiles, the optimal speed for the most energy efficient use of BEVs, the variability in the performances of BEVs with varying factors such as speed, wind, temperature, and location. Addressing these questions could help customers not only in reducing the uncertainty about energy consumption and driving range because of the provided information, but also in adopting optimal driving patterns for energy efficient driving.

Big data were used for providing answers to these questions, as more than a quarter of a million trips performed by 741 BEV drivers were analyzed in the current study. The data were collected over a two-year period between January 2012 and January 2014 by Clever A/S, an electric mobility operator in Denmark using three models of BEVs, namely Citroen C-Zero, Peugeot Ion and Mitsubishi iMiev. The data contained information for each trip about vehicle positioning (i.e., longitude, lat-