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Battery capacity design for electric vehicles considering the diversity of daily vehicles miles traveled

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ABSTRACT

In this paper, we study battery capacity design for battery electric vehicles (BEVs). The core of such design problems is to find a good tradeoff between minimizing the capacity to reduce financial costs of drivers and increasing the capacity to satisfy daily travel demands. The major difficulty of such design problems lies in modeling the diversity of daily travel demands. Based on massive trip records of taxi drivers in Beijing, we find that the daily vehicle miles traveled (DVMT) of a driver (e.g., a taxi driver) may change significantly in different days. This investigation triggers us to propose a mixture distribution model to describe the diversity in DVMT for various driver in different days, rather than the widely employed single distribution model. To demonstrate the merit of this new model, we consider value-at-risk and mean-variance battery capacity design problems for BEV, with respect to conventional single and new mixture distribution models of DVMT. Testing results indicate that the mixture distribution model better leads to better solutions to satisfy various drivers.

1. Introduction

Electric vehicles (EV) become increasingly used in ground transportation (Tal et al., 2014), because EV can reduce the air pollution in urban regions as well as fuel costs of drivers, because of the low cost of electricity relative to that of the conventional fuel. It was reported in PG&E (2009) that more than 70% of carmakers were now developing battery electric vehicles (BEVs) or plug-in hybrid electric vehicles (PHEVs).

Current BEVs still have some shortcomings. As pointed out by Pearre et al. (2011), one major problem of a BEV was its shorter travel distance comparing to that of a gasoline vehicle. Meanwhile, the recharging of a BEV is more time-consuming compared with the refilling of a gasoline car. This problem prevents drivers who care about travel convenience from purchasing BEVs. One possible solution to this problem is to design an appropriate battery capacity for a BEV so that this capacity can cover daily travel distances of most drivers so that drivers only need to recharge their BEVs at home or workplaces. Clearly, the feasibility of this solution lies in an appropriate demand analysis and supply design.

On the demand side, researchers collected empirical driving data to investigate the energy consumption and charging patterns of drivers. For example, GPS equipment was installed on a number of BEVs and internal combustion engine vehicles

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(ICEVs) to collect the necessary information (e.g., timestamp, latitude, longitude and velocity) to determine energy consumption patterns (Greaves et al., 2013; Dong and Lin, 2014; Wu et al., 2015a, 2015b). Based on GPS data, vehicles' charging patterns and VMT between two consecutive charging were obtained and studied in Wu et al. (2015b), Dong and Lin (2014). Recently, the relationship between energy consumption and driving styles also received increasing interests (Tang et al., 2015a, 2015c; Li et al., 2015, 2016; Chen et al., 2016a, 2016b).

On the supply side, researchers analyzed the proper capacity of BEVs to satisfy daily vehicle miles traveled (DVMT) of most drivers.[1] For example, Pearre et al. (2011), Traut et al. (2012), Franke and Krems (2013), Greaves et al. (2013) had investigated whether the mile range of a certain type BEV can satisfy the current DVMT demand of the vehicle. Dong and Lin (2014) presented a probability model to describe the BEV feasibility. Lin (2014) developed an optimization framework to design BEVs, in which the objective reflected a trade-off between the battery's price and DVMT demand.

To balance the demand and supply to satisfy most drivers, most existing studies focused on modeling the diversity in DVMT and designing BEVs with respect to such diversity. There are three kinds of models for DVMT in existing approaches (Greene, 1985), summarized as follows:

The first kind of models assumes that DVMT is single-value. That is, such models assumed that DVMTs of drivers were the same and only the averaged value was used to characterize the DVMT of all drivers all the time.

The second kind of models assumes that DVMTs of drivers are different, but the DVMT of a driver is relatively constant for different days. Hence, such models use a single distribution to characterize the diversity of drivers (Liu et al., 2012; Tang et al., 2015b; Leng et al., 2016). However, empirical observations show that the DVMT of a driver can be significantly different from day to day. So, such models cannot fully describe the uncertainty in travel demands of drivers and are thus unable to accurately measure satisfaction degrees of different drivers.

The third kind of models aims to characterize both the diversity of DVMTs for different days and the diversity of DVMTs for different drivers (Pearre et al., 2011; Lin et al., 2012; Kontou et al., 2015; McCollum et al., 2016). For example, a special distribution model was proposed in Tamor and Milačić (2015a) and Tamor et al. (2015b). It assumes that the DVMT of a driver can be described by the mixture of a negative exponential distribution and a normal distribution. Moreover, the key parameters of this mixed distribution for different people can be described by a log-logistic distribution. This hybrid distribution model of DVMT were tested in several regions. However, we still do not know whether this hybrid model works for other regions.

To solve this problem, we propose a new mixture distribution model to describe the diversity of DVMTs for various drivers in different days. It is slightly different from the two-dimensional distribution models that had been proposed in Bhat and Eluru (2009), Chen et al. (2010) to characterize the uncertainty of traffic flow measures. Rather than consider two factors (drivers and days) in an equivalent and exchangeable position, this mixture distribution model can be viewed as a hierarchical distribution model, in which we first characterize drivers by their average daily vehicle miles traveled (ADVMT) and then further describe their diversities in different days.

Different from the parametric model proposed in Tamor and Milačić (2015a) and Tamor et al. (2015b) which has a fixed number of parameters to calibrate, this mixture distribution DVMT model is a non-parametric model which has some merits. First, its estimation process is quite straightforward and easy. Second, it makes no assumptions about the probability distributions of the variables being assessed and thus can be used to describe any kind of drivers in all regions.

Thus, it provides us a unique and convenient tool for further analysis. To demonstrate its benefit, we consider value-at-risk and mean-variance battery capacity design problems for taxi BEVs, with respect to conventional single and new mixture distribution models of DVMT. Noticing that municipal governments of many cities had enacted a series of regulations and policies to promote the development of new energy vehicles (Zou et al., 2016), we believe the design of taxi BEVs will attract increasing attentions. Tests indicate that the mixture distribution model better characterizes the diversity of taxi drivers and thus leads to better solutions to satisfy most of them.

To give a detailed presentation of our finding, the rest of this paper is organized as follows. Section 2 presents the mixture distribution model for DVMT. Section 3 presents optimization models to design a proper BEV capacity with respect to this new DVMT model. Section 4 provides some numerical tests based on taxis travel data collected in Beijing. The difference between single and mixture DVMT distributions based optimization models are highlighted. Finally, Section 5 concludes the paper. The nomenclature list of this paper can be found in Appendix A.

2. The mixture distribution DVMT model

In this paper, we assume that the DVMT of a driver in a particular day is a random variable. It follows a mixture distribution that is characterized by the kind of driver he/she belongs to and the associated DVMT distribution function of this kind of drivers. More precisely, suppose we have finite n kinds of drivers, where the proportion of the ith kind of drivers is p_i, $i = 1, \ldots, n$, satisfying

$$\sum_{i=1}^{n} p_i = 1 \qquad (1)$$

[1] We decide to keep the United States customary units, since most literatures that we cited in this field adopted the United States customary units.