Transportation Research Part D 46 (2016) 246–266

Contents lists available at ScienceDirect

Transportation Research Part D

journal homepage: www.elsevier.com/locate/trd

# Routing aspects of electric vehicle drivers and their effects on network performance

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ARTICLE INFO

*Article history:*

*Keywords:*
Electric vehicles
Route choice behavior
Range anxiety
Multi-class DUE problem
Network performance
Sensitivity analysis

ABSTRACT

This study investigates the routing aspects of battery electric vehicle (BEV) drivers and their effects on the overall traffic network performance. BEVs have unique characteristics such as range limitation, long battery recharging time, and recuperation of energy lost during the deceleration phase if equipped with regenerative braking system (RBS). In addition, the energy consumption rate per unit distance traveled is lower at moderate speed than at higher speed. This raises two interesting questions: (i) whether these characteristics of BEVs will lead to different route selection compared to conventional internal combustion engine vehicles (ICEVs), and (ii) whether such route selection implications of BEVs will affect the network performance. With the increasing market penetration of BEVs, these questions are becoming more important. This study formulates a multi-class dynamic user equilibrium (MCDUE) model to determine the equilibrium flows for mixed traffic consisting of BEVs and ICEVs. A simulation-based solution procedure is proposed for the MCDUE model. In the MCDUE model, BEVs select routes to minimize the generalized cost which includes route travel time, energy related costs and range anxiety cost, and ICEVs to minimize route travel time. Results from numerical experiments illustrate that BEV drivers select routes with lower speed to conserve and recuperate battery energy while ICEV drivers select shortest travel time routes. They also illustrate that the differences in route choice behavior of BEV and ICEV drivers can synergistically lead to reduction in total travel time and the network performance towards system optimum under certain conditions.



## Introduction

### *Background and motivation*

Electric vehicles have received considerable attention in the recent past with the promise of achieving reduced petroleum dependency, enhanced energy efficiency, and improved environmental sustainability. An electric vehicle (EV) uses a battery-powered electric motor for propulsion unlike an internal combustion engine vehicle (ICEV) which is powered by burning gasoline or diesel. Although the environmental sustainability of EVs is debated for the source of electricity generated for recharging the EV's battery, they have a clear advantage over ICEVs due to their efficiency. According to the U.S. Department

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http://dx.doi.org/10.1016/j.trd.2016.04.002
1361-9209/

of Energy (USDOE, 2014), it is estimated that only about 17–21% of the energy stored in the gas tank of an ICEV is converted to power at the wheels. The combustion engine alone loses 62.4% of the energy from fuel as heat. By contrast, EVs convert about 59–62% of the electrical energy from the grid to power at the wheels.

There are two main types of EVs in the market: plug-in hybrid electric vehicle (PHEV) and battery electric vehicle (BEV). PHEVs are equipped with both internal combustion engine and electric motor, and BEVs are equipped with only the electric motor. As a PHEV uses two drive-trains, typically its operating cost is higher than that of a BEV which uses single drive-train. There are unique characteristics currently associated with BEVs, including limited battery capacity and long recharging time that can be limiting for travel compared to ICEVs. Given the current battery technologies, a BEV typically has a driving range of around 80–100 miles with a full charge, depending on the vehicle type and battery size. Some premium BEVs, such as Tesla Model S, have a higher range of about 250–350 miles with the advancement of battery technology which is expected to improve further; however, they are significantly more expensive compared to typical EVs. The limited driving range of BEVs imposes an issue, known as the range anxiety, that is, the driver concerns that the vehicle will run out of battery power before reaching the destination (Tate et al., 2008). This issue is especially limiting for long trips where the travel distance is close to or beyond the driving range (Mock et al., 2010; Yu et al., 2011). This study focuses on BEVs rather than PHEVs as the purpose of this study is to capture range anxiety which is not applicable to PHEVs. A PHEV is similar to a BEV when operating on battery (if range anxiety is not a concern) and an ICEV when operating on gasoline or diesel.

Typically, a BEV spends 6–8 h (slow charging) to get fully charged, depending on the electrical charging equipment, charging schemes, and battery capacity (Botsford and Szczepanek, 2009). Fast charging technology is available, with 10 min charging for a range up to 100 miles. However, it requires special equipment in the power connector and is sparsely deployed in the public infrastructure. Even the "quick charge" facility available at public charging stations can take around 30 min to charge the battery up to 80% (USDOE, 2015). Furthermore, fast charging, including quick charging, can deteriorate the battery health and is not advisable on a regular basis (Rezvanizaniani et al., 2014). Another alternative to en route charging for long distance travel is battery swapping stations (BSS) where a depleted battery pack is quickly swapped with a recharged one. The success of BSS requires car manufacturers to follow certain battery standards, and even then can entail battery stock problem, especially in urban areas. These technological and logistical challenges make BSS impractical to implement (Senart et al., 2010). Therefore, BEV drivers currently, and in the near future, are expected to charge their vehicles through home-based overnight charging or workplace-based charging mechanisms most of the time.

The market share of EVs has increased significantly in recent years (Mock and Yang, 2014) and is likely to increase further in future, due to multiple incentives such as government subsidies, advancement in battery technology and public acceptance of EVs. Shepherd et al. (2012) investigate the effect of multiple factors such as subsidy, average vehicle life and emission rates on the market penetration of BEVs. Becker et al. (2009) predict that EVs, including both PHEVs and BEVs, could comprise 24% of the light-vehicle fleet in USA by 2030.

The increase in the market penetration of EVs, especially BEVs, will impact the traffic stream, which may imply new driving and route choice imperatives. BEVs are typically equipped with regenerative braking system (RBS) that can recuperate a part of the kinetic energy lost during the deceleration phase to recharge the battery. This is where braking energy that would otherwise be dissipated as heat is captured and restored in the battery. This can increase the driving range of a BEV. Studies show that in typical urban areas, the recuperation could increase range by about 20%, and often more in hilly areas (Artmeier et al., 2010). Due to the long battery recharging time, en route recharging is usually not an attractive option for BEVs currently, and thus energy-efficient driving and energy recuperation are important factors for BEV drivers. There are two important factors that can encourage a BEV driver to select an energy-efficient route rather than the traditional least travel time route: (i) reduce the operating cost, and (ii) improve the driving range. A BEV driver needs to pay for electricity to charge the battery. In addition, with every charge–discharge cycle, battery life degrades. Therefore, a BEV driver may prefer a route with extra travel time but with reduced energy consumption to decrease operating cost. Because the initial state-of-charge (SOC) of electric battery may not always be full before starting a trip, or the travel distance may be close to the driving range, some BEV drivers may face the dilemma of range anxiety because of the fear of running out of battery charge before completing the trip. In such a situation, a BEV driver may select a route with higher level of congestion to recuperate a part of kinetic energy lost to recharge the battery so as to improve the range. In addition, for BEVs, energy consumed per unit distance traveled is lower at moderate speed than at higher speed. This can further incentivize BEV drivers to select lower speed alternatives under range anxiety. The presence of BEVs in the traffic stream with the above characteristics of route choice raises two interesting questions: (i) whether the incentives in terms of energy savings and range improvement, and the range anxiety factor, can lead to different route selection by BEV drivers as compared to the ICEV drivers, and (ii) whether this difference in route choice behavior can affect network performance in terms of system travel time. These two questions form the motivation for this study.

## *Literature review*

Past studies related to EVs in the transportation domain can be broadly classified into four groups: EV energy consumption computation, EV energy-efficient routing, EV traffic assignment and facility location of charging stations.

In the context of EV energy consumption computation, electrochemical theory based models require battery-level data like voltage and current while the models using driving parameters such as speed and acceleration generally use basic principles of physics to estimate power consumption. Chan (2000) provides an overview of various electrochemical process