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The design of electric vehicle charging network

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ABSTRACT

The promotion of Electric Vehicles (EVs) has become a key measure of the governments in their attempt to reduce greenhouse gas emissions. However, range anxiety is a big barrier for drivers to choose EVs over traditional vehicles. Installing more charging stations in appropriate locations can relieve EV drivers' range anxiety. To determine the locations of public charging stations, we propose two optimization models for two different charging modes - fast and slow charging, which aim at minimizing the total cost while satisfying certain coverage goal. Instead of using discrete points, we use geometric objects to represent charging demands. Importantly, to resolve the partial coverage problem (PCP) for networks, we extend the polygon overlay method to split the demands on the road network. After applying the models to Greater Toronto and Hamilton Area (GTHA) and to Downtown Toronto, we show that the proposed models are practical and effective in determining the locations of charging stations. Moreover, they can eliminate PCP and provide much more accurate results than the complementary partial coverage method (CP).

1. Introduction

Many countries around the world are drawing up plans to electrify their transportation systems in order to reduce greenhouse gas emission and to improve air quality in urban areas. The core of such plans is to promote the adoption of Electric Vehicles (EVs). However, range anxiety is one of the primary barriers for drivers to choose EVs over traditional Internal Combustion Engine (ICE) vehicles (Eberle and von Helmolt, 2010; Pollution Probe, 2015). Installing more EV charging stations is one of the strategies that can reduce range anxiety. This leads to a facility location problem: how many charging stations do we need and where are the best locations to install those charging stations? The answer of this problem depends on many factors, including the driving ranges of EVs and the cost of charging stations.

The driving range of EVs can vary greatly by model and manufacturer. Currently, the longest EV driving range is 424 km (2014 Tesla Model S) while the shortest range is 60 km (2013 Scion iQ EV). Most EVs have ranges between 100 km and 160 km (U.S. Department of Energy, 2014).

EVs are charged through Electric Vehicle Supply Equipment (EVSE). According to Community Energy Association (2013), there are three levels of EVSEs. Level 1 EVSE, with a cost less than $1000, typically takes 10–20 h to charge. The long charging time makes Level 1 chargers suitable only for home usage. Level 2 can be used for both commercial and home charging purposes. EVs will take 4–8 h to reach a full charge. Commercial Level 2 charging equipment costs between $3500 and $6000 for

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a single cord station while residential Level 2 charging equipment is much cheaper with a cost around $1000. Level 3 EVSE, also called fast charger, provides the fastest way of charging EVs and can achieve 50% charge in 10–15 min. It's also the most expensive EVSE with its cost ranging between $60,000 and $100,000.

Home, work and public charging are three common EV charging scenarios (National Renewable Energy Laboratory, 2014). Home charging is the dominant charging scenario. At least 70% of the electricity that EVs use is charged at home (National Renewable Energy Laboratory, 2014). Work charging happens at workplace where people park their EVs during working hours. Public charging usually occurs at public places such as shopping malls, hotels, restaurants, or public parking lots. Due to different charging times required for different levels of EVSEs, Level 1 and Level 2 EVSEs are suitable for home and work charging. Level 2 and Level 3 are suitable for public charging.

In this paper, we focus on the design of a network of public charging stations. We propose to locate the Level 2 & 3 charging stations based on different standards of ranges. For Level 2 charging stations, because it usually takes hours to fully charge an EV, the EVs are often charged at the parking spaces while the drivers are conducting some other activities, e.g., shopping or dining. Therefore, the drivers will look for charging stations within walking distance of the activity. Level 3 EVSE charges much faster, requiring about 30–60 min for a complete charge. Thus, it is appropriate for mid-trip charging where the drivers usually conduct longer distance driving and expect to charge the EVs fast (Community Energy Association, 2013). In this scenario, the drivers will look for charging stations within driving distance before the battery is depleted.

Most traditional facility location models assume that the demands come from discrete points (Miller, 1996). This approach can cause error when measuring the distance between the demand and the service facility, thus affecting the result of the facility locations (Miller, 1996; Chen et al., 2013; Frade et al., 2011; Xi et al., 2013). Moreover, models using point representation suffer from the partial coverage problem (PCP) and Modifiable Areal Unit Problem (MAUP), which will be introduced in Section 3. Recent studies (Murray, 2005; Alexandris and Giannikos, 2010; Cromley et al., 2012; Wei and Murray, 2014, 2015; Yin and Mu, 2015) use polygon overlay and other modeling methods to eliminate/alleviate these problems and investigate the operational and computational costs of these methods. We assume that the sources of demands are multi-dimensional geometric objects. We model the public Level 2 charging demand using Traffic Analysis Zones (TAZ) (polygons) and the public Level 3 charging demand using links of the traffic network (lines). We apply the polygon overlay approach to TAZ, and extend the polygon overlay approach to links of traffic network. Our approach is called geometric segmentation (GS) method.

The approach proposed in this paper may be used by city planners to plan the EV public charging infrastructures, by businesses to estimate how many charging stations they need to install to fulfill their customers, or by utility companies to estimate the impact of charging loads on the electricity grid.

To identify the optimal locations for EV charging stations, we propose the GS method which is a uniform framework for both Level 2 and Level 3 charging stations. Compared to previous similar studies on the locations of EV charging stations, this paper has three major innovations (Frade et al., 2011; Liu, 2012; Lee et al., 2014). Firstly, the proposed models focus on addressing range anxiety, i.e., making sure the charging stations are accessible to the largest possible number of EVs within allowed distances. Moreover, we discuss different definitions of range anxiety for both Level 2 and Level 3 charging stations. Secondly, we use polygon overlay techniques to avoid partial coverage, which can cause models to be inaccurate. We also extend the polygon overlay approach to the case of road networks. Thirdly, the proposed approach can be applied to Level 2 and Level 3 charging stations under a uniform framework, offering a more comprehensive solution strategy than existing models.

This paper is organized as follows. Section 2 reviews the literature of charging network design. Section 3 discusses the PCP and the two major approaches to address this problem - modeling (complementary partial coverage) and data transformation (polygon overlay). Section 4 describes the framework and mathematical formulation for fast charging stations (Level 3). Section 5 describes the framework and mathematical formulation for slow charging stations (Level 2). Finally, in Section 6, we apply the proposed model for Level 3 and Level 2 to the Greater Toronto and Hamilton Area (GTHA) and Downtown Toronto respectively, and conduct numerical studies to demonstrate the effectiveness of the proposed method. The paper is concluded in Section 7.

2. Literature review

Numerous efforts have been made to tackle the EV charging station location problem. In the remainder of this paper, we refer to Level 3 as fast charging and to Level 2 as slow charging.

A large number of models have been developed for fast charging stations (Ge et al., 2011; Chen et al., 2014; Hanabusa and Horiguchi, 2011; Lee et al., 2014; Lam et al., 2014). A fast charging station serves mid-trip charging needs, so that the charging demand is usually based on the number of EVs on the road and is closely related to EV users' traveling behavior. Traffic assignment is a common tool for modeling the EV drivers' behavior (Lam and Lo, 2004). Hanabusa and Horiguchi (2011) apply the stochastic user equilibrium method to estimate the traffic flow on the road network. The goal of their model is to minimize the system's total travel time and equalize the charging load among charging stations using entropy maximization. Their model focuses on the impact of charging stations on EV driver's route choice but doesn't address the accessibility of charging stations to EVs. Chen et al. (2014) also utilize user equilibrium traffic assignment method to model the traffic flows, however, no facility location optimization model is developed to determine the optimal locations of charging stations.