Transportation Research Part B 57 (2013) 172–190

Contents lists available at ScienceDirect

Transportation Research Part B

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

A corridor-centric approach to planning electric vehicle charging infrastructure

Yu (Marco) Nie [*], Mehrnaz Ghamami

Department of Civil and Environmental Engineering, Northwestern University, 2145 Sheridan Road, Evanston 60208, United States

ARTICLE INFO

Article history:
Received 29 January 2013
Received in revised form 14 August 2013
Accepted 16 August 2013

Keywords:
Electric vehicles
Corridor
Battery swapping
Charging station
Level of service

ABSTRACT

The transition to electric vehicles (EV) faces two major barriers. On one hand, EV batteries are still expensive and limited by range, owing to the lack of technology breakthrough. On the other hand, the underdeveloped supporting infrastructure, particularly the lack of fast refueling facilities, makes EVs unsuitable for medium and long distance travel. The primary purpose of this study is to better understand these hurdles and to develop strategies to overcome them. To this end, a conceptual optimization model is proposed to analyze travel by EVs along a long corridor. The objective of the model is to select the battery size and charging capacity (in terms of both the charging power at each station and the number of stations needed along the corridor) to meet a given level of service in such a way that the total social cost is minimized. Two extensions of the base model are also considered. The first relaxes the assumption that the charging power at the stations is a continuous variable. The second variant considers battery swapping as an alternative to charging. Our analysis suggests that (1) the current paradigm of charging facility development that focuses on level 2 charging delivers poor level of service for long distance travel; (2) the level 3 charging method is necessary not only to achieve a reasonable level of service, but also to minimize the social cost; (3) investing on battery technology to reduce battery cost is likely to have larger impacts on reducing the charging cost; and (4) battery swapping promises high level of service, but it may not be socially optimal for a modest level of service, especially when the costs of constructing swapping and charging stations are close.

1. Introduction

1.1. Background

Transportation accounts for over 60% of all petroleum consumed in the US, of which 60% must be imported (NRS, 2010). While the world has witnessed a remarkably stable increase in oil production and consumption for a long period of time, the trend is clearly unsustainable (Energy Information Administration, 2007). Without alternative sources of energy, the price of petroleum is likely to rise at an ever-increasing pace and with greater volatility, to which those countries heavily dependent on imported oil are especially vulnerable (NRS, 2010). An oil-dependent transportation industry is not only a concern for energy security, it also creates major environmental problems (United Nations Climate Change Secretariat, 2006). In

---

[*] Corresponding author. Tel.: +1 847 467 0502.
E-mail address: y-nie@northwestern.edu (Yu (Marco) Nie).

0191-2615/$ - see front matter © 2013 Elsevier Ltd. All rights reserved.
http://dx.doi.org/10.1016/j.trb.2013.08.010

2005, transportation is responsible for roughly 23% of the world's carbon dioxide (CO2) emissions, a major greenhouse gas linked to global climate change (Ohnishi, 2008). Data also suggest that between 1990 and 2006 the growth in transportation GHG emissions represented almost 50% of the total growth (Cambridge Systematics, 2009). Transition to alternative fuel vehicles can effectively reduce oil use, and is widely considered an important ingredient in the solution to these grand challenges of our time, namely energy security, climate change and sustainable development (Ohnishi, 2008; NRS, 2010). Of particular interest to this study is plug-in electric vehicles (PEV) or battery electric vehicles (BEV), which will be simply referred to as electric vehicles hereafter.

Electric vehicles have a few notable advantages compared to conventional internal combustion engine (ICE) automobiles and other alternative fuel vehicles (e.g. hybrid vehicle). For one thing, electric vehicles are more energy efficient (Romm, 2006). Eberhard and Tarpenning (2006) show that the well-to-wheel efficiency of electric cars is around 1.15 kilo meter per million Joule (km/mJ). The same study estimates an efficiency of 0.56 km/mJ for the celebrated hybrid model, Toyota Prius, and much lower rates for conventional ICE cars (Toyota Camry, for example, is rated at 0.28 km/mJ). Second, because electric cars have zero emission at the point of operation, they contribute significantly to the reduction of local air pollution. Electric cars also help reduce greenhouse emissions (Samaras and Meisterling, 2008). A recent study (Crist, 2012) estimates a four-door electric Sedan could save up to 17 tone of CO2 in its lifetime compared to an ICE vehicle equipped with improved diesel engine technology.

PHEVs and EVs sales are appraised to be approximately 50,000 vehicle by 2015, which accounts for 0.3% of all cars sales (Newman, 2010). President Obama has promised to make the US "become the first country to have one million electric vehicles on the road by 2015".[1] Accordingly, the US government has pledged $2.4 billion in federal grants to further development of EVs (Canis, 2011). Still, the great promises of electric cars are crippled by the lack of enabling infrastructure and technology breakthrough. Electric vehicles are still considerably more expensive than ICE vehicles, largely due to the cost of battery packs that is still over €10,000 on average according to recent estimates (Crist, 2012). Another major hurdle is the so-called range anxiety, which has to do with the drivers' fear of batteries running out power en-route. Range anxiety is closely related drivers' refueling behavior in general, as shown by Kitamura and Sperling (1987). For EV drivers, the range anxiety is much more of a concern, mainly due to the limited range of the current batteries and the lack of public and private charging infrastructure.

1.2. Literature review

Overcoming the above barriers demands an EV charging network that is optimally configured to meet the needs of current and future EV fleets. A widely adopted approach to this design problem aims at locating charging facilities near the urban activity centers of EV owners (e.g. home, shopping malls and workplaces) so as to maximize the overall accessibility. Typically underlying this approach are various set covering or P-median facility location models (Dashora et al., 2010, e.g.; Frade et al., 2011; Chen et al., 2013; Sweda and Klabjan, 2011). Variants of this approach also address the interactions with power grids and route/destination choices (He et al., 2013) and the location of battery swapping stations (Pan et al., 2010). Most existing studies along this direction do not focus on long distance trips (more than 100 miles round trip) traditionally made using passenger cars, even though charging seems much more important for these trips than those near home (see Acknowledgements).

Flow capturing facility location models (FCLM) are better suited to tackle long-distance travel. Unlike the traditional facility location models which assume point demands (Daskin, 1952), flow capturing models assume that the demands are given in the form of origin–destination (O–D) flows. Hodgson (1990) proposes the first FCLM that seeks to locate a given number of facilities so as to intercept as much O–D flows as possible. Kuby and Lim (2005) applies the FCLM in the context of refueling problem for range-limited vehicles. In their flow refueling location model (FRLM), an O–D flow is "captured" only if vehicles never run out of fuel along their designated travel path. The objective of FRLM is to locate p refueling facilities to maximize the total vehicle flows refueled. Kuby and Lim (2007) extend FRLM so that facilities can be located along the arcs of the network, and later, Lim and Kuby (2010) proposes a few efficient heuristic algorithms for solving the FRLM problems. The refueling station location problem studied in Wang and Lin (2009) also considers O–D demands. Yet, instead of trying to maximize flow being captured, their model minimizes the total facility cost while ensuring all flows are properly served according to a "refueling logic". Later, Wang and Wang (2010) proposes a hybrid version of the refueling station location problem, along the line of Hodgson and Rosing (1992), which considers both point and O–D demands. Recently, Mak et al. (2013) studies a robust location problem of battery swapping stations. Similar to Wang and Lin (2009), their model attempts to minimize the total cost (or maximize the chance of meeting an investment-to-return goal) and embeds a recharging logic to ensure that all demands are served by swapping stations. Moreover, Mak et al. (2013) consider the capacity limits at the swapping stations and demand uncertainty.

The modeling approach adopted in this paper employs an embedded refueling logic. Yet, the main tradeoff concerned herein arises from the interdependence between the cost of building recharging infrastructure and manufacturing batteries, as elaborated below. We also explicitly consider the level of services experienced by EV users in the form of extra time spent on recharging batteries in their journey.

---

[1] Energy Speech Fact Sheet. http://www.barackobama.com/pdf/factsheet_energy_speech_080308.pdf.