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Optimal allocation for electric vehicle charging stations using Trip Success Ratio

Yassir A. Alhazmi [a,b,*], Haytham A. Mostafa [a], Magdy M.A. Salama [a]

[a] Department of Electrical and Computer Engineering, University of Waterloo, Waterloo, ON N2L 3G1, Canada
[b] Department of Electrical Engineering, Umm Alqura University, Makkah 21955, Saudi Arabia

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ABSTRACT

This paper proposes a new model for optimally allocating Plug–in Electric Vehicle (PEV) Charging Stations (CSs) in the network. The model considers Trip Success Ratio (TSR) in order to enhance CS accessibility for PEV drivers. Diversity of usage and different driving habits are considered in the presented model, as well as different trip types (In-city, Highway). The allocation model has two stages: modeling TSR to estimate Charging Station Service Range (CSSR), and the CS allocation stage. In the first stage, the service range of charging stations has been estimated using TSR with consideration of the uncertainty of trip distances (In-city, Highway) and the uncertainty in the Remaining Electric Range (RER) of PEVs. The estimated CSSR is utilized in the CS allocation stage in order to optimize the CS location set that covers the network with a certain guaranteed TSR level. The allocation problem has been formulated as the Maximum Covering Location Problem (MCLP) in order to make the optimal decision for allocating CSs in the network.

1. Introduction

Increasing oil prices and energy demand are significant challenges facing transportation sectors, as reliance on oil as the main source of energy has some negative influences that can affect those sectors. Environmentally, the transportation sector overall produces a large percentage of emitted carbon dioxide, causing greenhouse gas (GHG) emissions to greatly increase. According to the U.S. Greenhouse Gas Inventory Report 2011 [1], 30% of carbon dioxide emissions in the US come from the transportation sector. In Canada, 35% of energy demand is represented by the transportation sector, and it is the second-highest source of GHG emissions [2]. Therefore, meeting future transportation energy demands by finding alternative energy sources has gained much attention.

The availability of charging infrastructure is a crucial factor in increasing the adoption of PEVs. It is normally expected that PEVs will be recharged nightly at home [3], but the limited Electric Range (ER) of PEVs makes public charging a requirement for long-distance trips. Therefore, providing a public charging service as a complement to home charging will be an essential need. Electrical CSs will eventually be dispersed in the network, but inefficient planning for implementing charging infrastructure will hold back PEV adoption. Hence, the siting of the charging stations should be properly planned.

The planning approach for implementing charging infrastructure should be done with a view to meet users' and suppliers' needs. PEV users require access to CSs whenever they need them, accompanied with a high quality of service. Therefore, a lack of charging facilities due to siting them inappropriately or not at all will have a negative impact on drivers' convenience. The planning model should also enhance PEV drivers' accessibility to charging points by optimally choosing those points from the candidate sites in the network.

This work proposes an optimization model for allocating plug-in electric vehicle charging stations from a new perspective, which is PEV drivers' convenience. The main purpose of the study is to optimally choose from the available candidate sites the charging station set that best enhances the ratio of trips completed successfully, based on the Trip Success Ratio (TSR) level of all PEV trips. A PEV trip can be completed successfully if the electrical energy remaining in the PEV's battery is sufficient to allow the PEV to reach the destination; otherwise, the PEV battery has to be recharged on route in order to complete the trip successfully. As a result, optimally selected CS locations can guarantee a certain TSR level for PEV drivers' convenience.

* Corresponding author at: Department of Electrical and Computer Engineering, University of Waterloo, Waterloo, ON N2L 3G1, Canada.

E-mail addresses: yalhazmi@uwaterloo.ca, yahazmi@uqu.edu.sa (Y.A. Alhazmi), Halyatte@uwaterloo.ca (H.A. Mostafa), msalama@uwaterloo.ca (M.M.A. Salama).

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The proposed work consists of two stages: the first stage is modeling PEV trip behaviors, followed by modeling the electrical energy available in PEVs' batteries at the beginning of trips. Hence, Charging Station Service Range (CSSR), which is the area that can be covered by the charging station, will be estimated for each TSR level. The estimation process can be achieved by considering the randomness of PEV trip behaviors and the randomness of the electrical energy available in PEVs' batteries. The second stage is to choose the best CS set using the estimated CSSRs of the TSR levels from the first stage. The allocation optimization problem will be formulated as the Maximum Coverage Location Problem (MCLP), and the cutoff impedance of the MCLP will be the estimated CSSRs [4]. The presented model for allocating CSs will be in generic form, so it should be applicable for different transportation networks (In-city and Highway), and different case studies will be presented for different network layouts (In-city and Highway).

The remainder of this paper is categorized into six sections. In Section 2, the related work that has been done on this topic will be investigated. Both the electrical and transportation literature on charging stations topic will be covered in this section. Modelling PEV trip behaviors and modeling the Remaining Electric Range (RER) of PEV battery will be presented in Section 3. In Section 4, the relationship between different CSSRs with different TSR levels is investigated with several battery capacities and types, as well as covering variety of battery combinations to describe these relationships. In Section 5, the CS allocation problem will be formulated as the MCLP, and the CSSRs will be utilized as cutoff impedances for the presented allocation model. The tradeoff between the available budget for implementing CSs in the network and different TSR levels will also be investigated in this section in order to obtain an optimal decision for CS locations. Different case studies on both In-city and Highway networks are covered in Section 6 to show that the presented model is in generic form and that it is applicable for different layouts. Finally, the major contributions of the present work will be discussed in Section 7.

2. Related work

In recent years, both in academia and industry, more attention has been paid to the optimal allocation of PEV charging stations. The placement of refueling and recharging stations has also been investigated recently in both electrical and transportation publications. Most of the existing research on the placement of electric charging stations has not considered the driver convenience issue as a perspective of locating the charging facilities. The diversity of the amount of energy available in PEV batteries during trips, also called the Remaining Electric Range (RER), is an essential parameter for users to switch to this new technology. The uncertainty of PEV RERs, which results from different PEV battery capacities as well as the diversity in State of Charge (SOC) levels at the beginning of each trip, has not been well addressed in previous research. Moreover, the diversity of travelers' habits, behaviors, and trip distances are not demonstrated well in the previous research, as well as the ability of charging station infrastructure to adequately meet PEV charging accessibility demand.

2.1. Previous work in the electrical field

Electrifying the transportation sector is projected to enhance energy efficiency. The key concern is with regard to the sufficiency and viability of the power infrastructure with large-scale PEV integration [5]. The diversity of travelers' habits, behaviors, trip distances, and the ability of charging station networks to cover the demand sufficiently are not well demonstrated in the previous electrical research on siting charging stations. A small number of studies have considered aspects related to the site selection of charging stations and the overall planning of a city's CS network [6–14].

The diversity of travel patterns and traffic flow aspects are not considered in [6–12], which may lead to locating charging stations at sites favorable for electrical utilities but not easy for drivers to access due to not including traffic flow aspects. In [13], the traffic flow and charging requirements are included as constraints in the model, but the diversity of trip mileages and the variety of PEV electric ranges are not considered. In [14], the planning strategy model maximizes the traffic flow to charging facilities and minimizes the investment and operation cost of the distribution system; however, the estimation of PEV demand is not considered in the model. Therefore, the proposed model will choose the minimum number of CSs in areas that have high levels of traffic flow; however, that number of CSs may not be adequate for the PEV demand, which leads to traffic network problems.

A study in [15] was done to look into the charging station placement from a new perspective of CS accessibility; however, the authors assumed that charging station service ranges are equal to the average of the electric ranges available in the market. This assumption is questionable due to the high diversity in the electric ranges of PEVs (80–300 km) which is not addressed in the model. In the model, if most PEV ranges are not concentrated in relation to the average battery capacity, the variations in ranges will have a real impact on the ratio of incomplete PEV trips.

2.2. Previous work in the transportation field

In recent transportation research on siting refueling stations [16–19], Flow–Refueling Location Models (FRLMs) have been developed to site Alternative Fuel Vehicle (AFV) stations for vehicles that need refueling during trips. FRLMs are an extended form of Flow–Capturing Location Models (FCLMs), which have been used for siting convenience stores [20]. FRLM formulation is obtained by adding vehicle travel range as a constraint. All trips from the same Origin–Destination (OD) pair have been assigned to one path in [16] or several detours in [17], but ignoring travelers' habits and behaviors will lead to inappropriate locations for CSs, especially In-city. Because the suitability of their model depends on the availability of trip destination data, the lack of PEV trip data will make their model inapplicable for locating PEV CSs In-city.

The diversity of vehicle ranges has not been considered in previous models [16–19]. In addition, in these models, they considered fixed battery capacities and did not consider different SOC levels during trips. The detours and alternative paths are assumed based only on a single scenario; however, considering different vehicle ranges – using different SOC levels and battery capacities – will accordingly change those detours and alternative paths. As a result, the number of PEV CSs planned in the system will be inadequate in an In-city network due to discounting the diversity of PEV RERs.

From the above discussion, it is observable that previous work on locating charging stations has some limitations, and that it has overlooked significant aspects that can affect the accuracy of the results. According to the authors' best knowledge, most of the previous electrical and transportation research has not considered various items, and these limitations can be summarized in the following: