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Design framework of large-scale one-way electric vehicle sharing systems: A continuum approximation model

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ABSTRACT

This paper proposes a Continuum Approximation (CA) model for design of a one-way Electrical Vehicle (EV) sharing system that serves a metropolitan area. This model determines the optimal EV sharing station locations and the corresponding EV fleet sizes to minimize the comprehensive system cost, including station construction investment, vehicle charging, transportation and vehicle balancing, under stochastic and dynamic trip demands. This is a very complex problem due to the NP-hard nature of location design, the large number of individual users, and the stochasticity and dynamics of generated trips. Further, the considerable charging time required by EVs distinguishes this problem from traditional car sharing problems where a vehicle is immediately available for pickup after being dropped at a station. We find that the CA approach can overcome these modeling challenges by decomposing the studied area into a number of small neighborhoods that each can be approximated by an Infinite Homogeneous Plane (IHP). We find that the system cost of an IHP is a unimodal function of the station service area size and can be efficiently solved in a sub-linear time by the bisection algorithm. Then integrating the solutions of all IHPs yields an approximate solution to the original heterogeneous area. With numerical experiments, we show that the CA solution is able to estimate the total system cost of the discrete counterpart solution efficiently with good accuracy, even for large-scale heterogeneous problems. This implies that the proposed CA approach is capable of providing a near-optimum solution to the comprehensive design of a practical large-scale EV sharing system. With this model, we also conduct sensitivity analysis to reveal insights into how cost components and system design vary with key parameter values. As far as the author's knowledge, this study is the first work that addresses design of an EV sharing system considering both longer-term location and fleet size planning and daily vehicle operations. The proposed CA model also extends the CA methodology literature from traditional location problems with stationary demand, single-facility based service to EV sharing problems considering dynamic demands, OD trips, and nonlinear vehicle charging times.

1. Introduction

The dominance of privately owned vehicles in North America, though providing incomparable mobility, flexibility and freedom to travel, imposes a huge challenge to sustainable transportation. The private auto mode constitutes over 83% of

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the total passenger trips in the US. Every year in the US, private vehicles are a major contributor to 17% household expenses on transportation, around 70% of the total petroleum consumption, and around 30% of greenhouse gas emission (Bureau of Transportation Statistics, 2014). In addition, personal vehicles, while being parked 23 h a day (Litman, 2007), account for around 688,000 acres of land (Jakle and Sculle, 2004) and 25% of urban surface occupancy,[1] and it further exacerbates the already congested urban traffic (Axhausen, Polak, Boltze, Puzicha, 1994). While public transit is able to overcome these defects, this mode is not utilized very well in many low-density areas in the US due to its disadvantages in mobility and accessibility (Sinha, 2003).

Car sharing is an alternative to private car ownership in that a group of people collectively own or use a number of spatially distributed vehicles (Cooper et al., 2000). Car sharing has been recognized as a missing link to sustainable transportation that integrates flexibility, mobility and accessibility from private vehicles and economy and sustainability from public transits (Britton, 2000). Over the past decade in North America, the number of shared vehicles have increased from under 700 to over 15,000, and the people who use this service have grown from 16,000 to over a million (Shaheen and Cohen, 2013). Successful businesses across the world include Zipcar (http://www.zipcar.com/) and JustShareIt (http://www.justshareit.com/) in the US, Autolib (https://www.autolib.eu/en/) in France, City Car Club (http://www.citycarclub.co.uk/) in the UK, Greenwheels (https://www.greenwheels.com) in the Netherlands, Stadtmobil (http://www.stadtmobil.de) in Germany, and Zoom (http://www.zoomcar.com/) in India. As this trend continues and car sharing evolves from a niche service to a major transportation mode with high spatial accessibility, car sharing holds promise for a future sustainable transportation system with high vehicle utilization rates, minimum land occupancy, significant cost savings, and substantial environmental and social benefits (Millard-Ball, 2005; Nobis, 2006).

The environmental and social benefits of car sharing can be further enhanced by using electric vehicles (EVs) (Green, 2009). EVs reduce our dependence on depletable fossil fuels, produce zero tailpipe emissions and thus bring minimum pollution to urban areas. Even considering the life-cycle emissions generated from the corresponding electricity plants, the overall impact to the air quality is much less than that from internal combustion engine (ICE) vehicles (Wang et al., 2005). The social and environmental benefits will be further magnified if renewable energy sources are used to power EVs. In addition, on the end user side, unit-distance cost of an EV is significantly lower than that of an ICE vehicle (Valdes-Dapena, 2008), and the fixed vehicle cost is steadily decreasing as the battery technologies evolve and massive production brings economies of scale (Vlasic, 2013). The adoption of EVs, though slow for private vehicles (e.g., due to range anxiety), is expected to become prevalent if EVs and car sharing can be well integrated (King et al., 2013).

Despite high expectations of the role of EV sharing in future transportation, there is not yet a comprehensive design framework on how to economically deploy an EV sharing system that is able to provide reliable service to stochastic trip demands in an urban area. This paper proposes a continuum approximation (CA) model for determining the optimal configuration of such an EV sharing system, including the location of car sharing stations and the corresponding vehicle inventories at these stations under stochastic demand and EV charging constraints. This optimal configuration shall minimize the total system life-time cost while ensuring the service reliability to stochastic one-way trip demands. We analyze the structure of the elemental cost function in the CA model and find an elegant unimodal property that ensures the superior computational performance. This enables us to solve its optimal value with a very fast sub-linear time bisection search algorithm. Numerical experiments show that this model can solve a large-scale problem instance to a near-optimum solution very efficiently. We apply this model to different city areas and draw interesting managerial insights into the optimal system design and the total system cost. Note that this paper studies car sharing without car-pooling (also known as ride sharing) and thus each vehicle only serves no more than one trip at a time.

2. Literature review

The proposed research is built upon existing studies on classic facility location problems, EV infrastructure planning, and car sharing system design. Daskin (1995) and Drezner (2002) provided comprehensive reviews of fundamental facility location problems (e.g., covering, median, center, fixed-charge location problems). In these fundamental models, each customer is basically assigned to one facility with an operational cost increasing with the distance between them, and the design goal is to determine the best locations to build facilities to balance the trade-off between facility investment and operational costs. These fundamental models have been extended to joint design with other system elements, e.g., commodity inventory at each facility (Chen et al., 2011; Shen et al., 2003), and they are particularly relevant to this study where the vehicle storage needs to be jointly determined with car sharing station location. A typical way to approach location problems is to discretize the space and solve the location design with integer programming (IP) techniques. However, location problems are in general NP-hard, and the IP approach may suffer from excessive computational burdens. To overcome this challenge, Daganzo and Newell (1986) developed a continuum approximation (CA) model that decomposes the complex location problem into a set of fairly simple homogeneous problems that each approximates a neighborhood of the original problem. CA can efficiently solve NP-hard network problems such as facility location (Carlsson et al., 2013; Cui et al., 2010; Li and Ouyang, 2010; Ouyang, 2006), vehicle routing (Langevin, 1996; Ouyang et al., 2014) and hub-and-spoke networks (Campbell, 1993a; Carlsson and Jia, 2013). It has been applied to air networks (Hall, 1989), one-to-many distribution (Campbell, 1993b),

[1] http://oldurbanist.blogspot.com/2011/12/we-are-25-looking-at-street-area.html.