



Article

Location-Allocation of Electric Vehicle Fast Chargers—Research and Practice [†]

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Abstract: This paper conducts a comparative analysis of academic research on location-allocation of electric vehicle fast chargers into the pattern of the actual fast-charger allocation in the United States. The work aims to highlight the gap between academic research and actual practice of charging-station placement and operation. It presents evidence that the node-serving approach is, in fact, applied in the actual location-allocation of fast charging stations. However, little evidence suggests that flow-capturing, which has been much more predominantly applied in research, is being applied in practice. The author argues that a large-scale location-allocation plan for public fast chargers should be formulated based on explicit consideration of stakeholders, the objective, practical constraints, and underlining assumptions.

Keywords: electric vehicle; fast chargers; location-allocation

1. Introduction

Location-allocation of electric vehicle (EV) fast chargers has received increasing attention in recent years in both academic research and business practices as the investment into public EV fast chargers by vehicle manufacturers and others has accelerated. For example, the United States has earmarked the most investments for EV charging infrastructure development in the next decade as Electrify America, a subsidiary of Volkswagen, is set to invest \$2 billion [1]. In the past decade, academic researchers around the world have produced an extraordinarily large—for such a seemingly niche subject matter—volume of articles on the location-allocation problems of EV fast chargers in a wide range of peer-reviewed journals, where their domains are interestingly often well beyond transportation. However, despite the sheer volume of the studies, the decision-making process for allocating public EV fast chargers in practice remains a challenging problem. In the real world, legal, physical, and financial constraints are much more complex and stricter than typically assumed in studies. Moreover, because academic studies of this nature typically do not elaborate on a myriad of assumptions implicitly made and justifications for them, it is extremely difficult for the reader to know under what specific conditions the findings stand. For those reasons and others, there is a vast discrepancy between the academic research on location-allocation of public EV fast chargers and the actual practice.

This paper, therefore, examines the inner workings and assumptions of some of the existing methodologies commonly used for a study of location-allocation of public EV chargers to highlight the gap between the academic research and practice. Section 2 covers the background of location-allocation of public EV fast chargers. Section 3 examines the inner working and assumptions of the methodologies that are typically applied in research. Section 4 describes the patterns of EV fast charger allocation observed in the United States. Section 5 discusses the discrepancy between the research on location-allocation of EV fast chargers and the practice. Finally, Section 6 addresses the limitations of the past research and proposes direction for future research.

2. Location-Allocation of EV Fast Chargers

The literature on EV charging stations has conventionally postulated that large scale systems of public EV charging stations will be required in the future [2–7].

Concurrently, a relevant question arose: “Where should we put charging stations?” In consequence, a large volume of articles on location-allocation of public charging stations appeared in peer-reviewed journals of a wide-range of domains in the past decade. This includes the studies that were done in a more generic context of fueling infrastructure, often referred to as “alternative fuel,” which seemingly includes electric, hydrogen, natural gas, or any fuel other than gasoline [8–13].

Although it has been frequently used in the literature, it is important to note that the use of the generic term “alternative fuel” is inappropriate in the location-allocation context. Each fuel type has its own unique characteristics in its physical properties, production, transferability, and accessibility; thus, a distinction must be made as to what alternative fuel station is under study. In other words, a different paradigm for location-allocation should be constituted for each type of fuel in accordance with its nature: An application of a universal paradigm for all fuel types is conceivably impossible. For example, [9] considered the p -median model, which minimizes the total distance between population and the closest facility, as a viable model to be applied in location-allocation of “alternative-fuel” stations. However, if the type of fuel under the study was electricity, allocating a refueling station as closely as possible to EV owners’ homes is not sensible because EV owners typically have access to charging at home and conceivably, their demand for public charging would be infinitesimal in areas near their homes.

Instead, location allocating of refueling stations must begin by specifying the type of fuel under the study. For public EV charging stations, it would be necessary to further specify the type of charging station (slow, fast, or extremely fast) because physical, legal, and financial requirements of a charging station are different depending on its size, power source requirement, and costs. A slow charger, which typically includes both Level 1 and Level 2 chargers, can be allocated with low equipment and installation costs as its size and electrical power requirement are not demanding. Level 1 charging can be done using an ordinary 120-V outlet. Level 2 charging requires a higher-output power source than Level 1 charging and will likely incur an installation cost, which is typically around \$1,000 in the United States [14]. Misallocation of a slow charger, which can result in low or no utilization, may not, therefore, produce serious repercussions; rigorous planning may not be necessary for the allocation. Because of its slow charging rate, however, allocation of a public slow charger is generally limited to places where users can accommodate long hours of charging—those places may include work sites, hotels, schools, and store parking lots. By contrast, a fast charger requires a much shorter charging duration and can potentially be allocated to a wider variety of places. However, unlike a slow charger, allocation of a fast charger involves high equipment cost and requires a large electrical power capacity and substantial engineering work for installation at the hosting site. Because installing a fast charger involves an immense sunk cost, location-allocation of a fast charger deserves much more rigorous planning to avoid misallocation. In this paper, the focus is placed on location-allocation of public EV fast chargers.

3. Methodologies Typically Applied in Research

The goal of location-allocation of public fast chargers is to provide fast charging service to EVs on a road network. Identifying the demand for fast charging is a challenging task because the demand cannot be observed and must somehow be estimated. In addition, the demand for charging is both spatially and temporarily dynamic: Demand for fast charging arises from moving vehicles. Although a myriad of methodologies can be applied, the two prominent demand estimation methods typically applied in research are node-serving and flow-capturing approaches. In a node-serving approach, demand for EV charging is assumed to arise from nodes of a road network. Examples of the objectives of this approach include maximizing the coverage of demand nodes [15] and minimizing the overall cost of charging stations [16,17]. The logic behind this approach is that stations should be installed in

such a way that the EV can reach the charging station without running out of power. A node-serving approach can work in a straightforward way in a virtual world in which a road network is simplified—a theoretical road network typically consists of origin node, destination node, and path (arc)—because the only variables that need to be considered are the distance between nodes and the driving range. The complexity of a node-serving problem depends on the level of abstraction of the road network under study: The more nodes a network has, the more charger locations to choose from. This also means that the applicability of a node-serving deployment in the real world depends on the degree of discrepancy between the real road network and the simplified counterpart: A high degree of abstraction will render the problem easy to solve but the resulting charging-station placement scheme may be too abstract for a practical application.

On the other hand, a flow-capturing approach assumes that demand arises from vehicle flow and a node covers (captures) the flow on all of the links for which it is an endpoint [18]. In the charger allocation problem, this means that a fast charger located at a node captures the assumed demand for charging from all links that end at that node. Unlike the node-serving approach, the flow-capturing approach, therefore, requires vehicle-flow data on each link. However, because detailed vehicle-flow data are costly and difficult to obtain, the vehicle flow is typically estimated from origin-destination data, which have higher availability. Traditionally, it is typically assumed that all flows between each origin-destination pair take the same path—which can be reasonably argued to be the shortest path. However, stochastic traffic flow assignment can also be used to allow deviation from the shortest path [9,19–23].

The concept of a flow-capturing approach does not, by itself, constitute a location-allocation problem. To produce the right answer to the question at hand, a flow-capturing problem must be formulated in accordance with the objective and constraints of the study. If there is a constraint on the number of charging stations that can be allocated, the maximal coverage approach may be used [16,22–26]. In this approach, the objective is set to allocate a given number of charging stations so as to maximize the flows captured. If the objective of the study is to capture all traffic, no constraint will be placed on the number of available charging stations to be allocated. Instead, a cost-minimization problem is formulated to minimize the number of facilities required to cover all demand; this formulation is referred to as the set covering [21,27–31].

In cases where detailed Global Positioning System (GPS) data from vehicles are available, locations of charging demand can be estimated using a proxy, such as dwell time [32,33]. However, GPS based data are rarely available for research purposes; thus, the applicability of this methodology is limited.

4. Location-Allocation of Fast Chargers in Practice

Having reviewed how academic research has been typically done, the patterns of actual location-allocation of public fast chargers in the United States were visually examined to see if they follow the patterns expected from the theoretical approaches. Location data for fast chargers were obtained from United States Department of Energy's Alternative Fuels Data Center. For the purpose of analysis, the data were segmented into two groups, Tesla Superchargers and CHAdeMO/Combo. Each subset of the data was plotted separately on a map of the United States (see Figures 1 and 2).

Figures 1 and 2 show noticeably different location patterns between Tesla's Supercharger network and CHAdeMO/Combo chargers. In Figure 1, Tesla's Supercharger stations can be seen as a practical application of the node-serving approach in which most stations are placed with an approximately equal interval between them along interstate highways, connecting the East Coast and West Coast. However, it is also evident that highly urbanized areas, such as New York City and San Francisco, have a higher concentration of the chargers. Further investigation revealed that chargers concentrated in large cities were installed relatively recently, while no charger yet exists in the state of North Dakota. By contrast, Figure 2 shows a distinctly different location-allocation pattern of CHAdeMO/Combo chargers: The stations form disjoint clusters in major cities, rather than an interstate network, such as Tesla's Supercharger network. The exceptions to that are the chains of direct-current fast chargers

located along the Oregon Coast and on United States Interstate 5 (I-5), which runs through Washington, Oregon, and California. However, those chargers were installed specifically as a part of the Electric Highway project, a government-funded study to examine how station operators can be incentivized to sell electricity along the I-5 corridor [34]. The pattern depicted in Figure 2 certainly does not seem to be based on the node-serving principle.

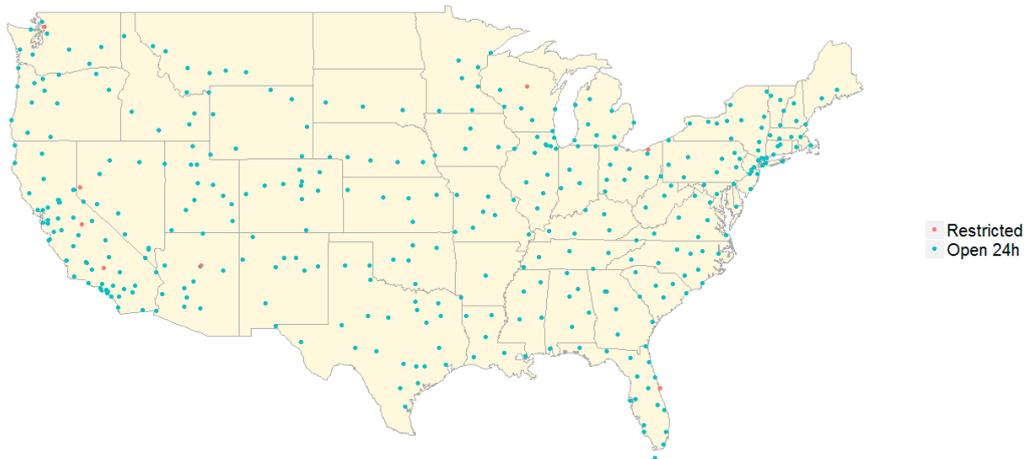


Figure 1. Tesla Superchargers network in the U.S.

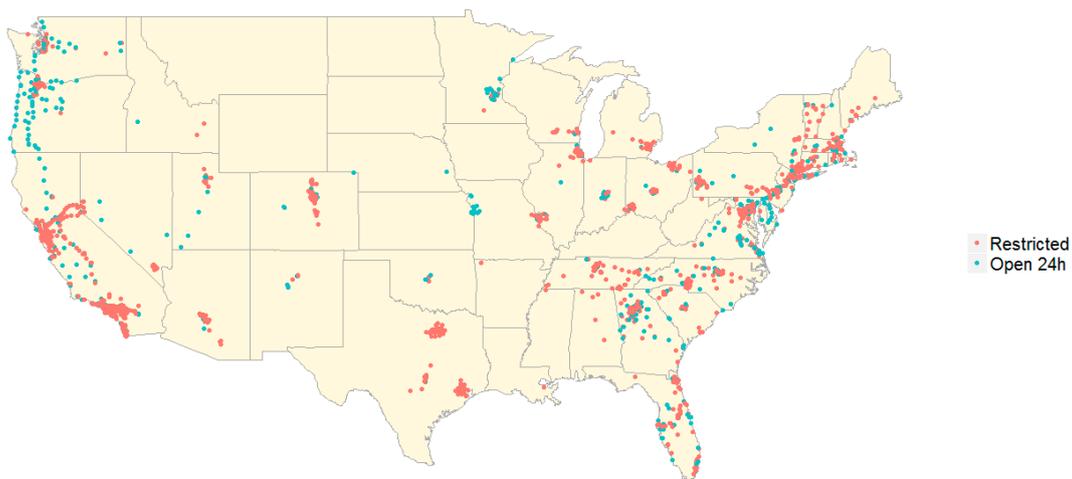


Figure 2. CHAdeMO/Combo in the U.S.

Location points in Figures 1 and 2 are color-coded to show the availability of chargers: The chargers that are available for use 24/7 are shown in blue, and those for which use is restricted are shown in red. Many of CHAdeMO/Combo chargers (1,187 out of 1,863) are not available for use 24/7, while most of Tesla's Superchargers are always available. The degree of restriction ranges from being limited to either business hours of the hosting business to being completely restricted to use by customers of the hosting business. The limited operational hours of charging stations highlight a distinction from today's gasoline stations.

5. Discussion

The last section showed evidence that the node-serving approach is, in fact, applied in the actual location-allocation of fast charging stations. However, little evidence suggests that the flow-capturing approach, which has been much more predominantly applied in research, is being applied in practice. It can be loosely argued that the pattern of CHAdeMO/Combo locations is related to flow-capturing in that chargers are placed in high-population areas where vehicle flows are high; however, that

connection may be a bit of stretch. It would perhaps be better argued that there is a natural relationship between the population and the number of chargers in an area as evident from both Figures 1 and 2.

An interesting discrepancy found in this study was that while studies assume that the demand is captured once a charger is allocated, in reality, the presence of a charger does not indicate its availability for use. This was found particularly true in CHAdeMO/Combo networks where chargers are owned and/or operated by many individuals. This indicates that it is difficult to assess the supply-demand relation of fast charging using static modeling because a charger's availability is not only spatially dependent but also temporal as a site owner can restrict the use of the charger for any given period of the day.

The discrepancy between research and practice of location-allocation of fast chargers can be attributed to many causes. However, one of the obvious facts is that many critical constraints in the real world are not accounted for in the mathematical problems typically formulated in past studies. This does not mean that all relevant information must be incorporated in mathematical programming because the costs of data collection and computation would quickly become too high for a practical purpose, especially when the scale of the area under study is large. Instead, it is important to examine the validity of the assumptions made in the study to see if the problem formulated is a reasonable abstraction of the actual problem.

In academic research, the researcher is free to decide, for each study, what the objective of location allocation of fast-chargers is and what constraints the objective is bounded by. This degree of freedom allows a vast variation in the problem formulation, and a slight deviation in the mathematical problem formulation from other studies by itself may justify the novelty of a study in academia. However, it is unclear if much progress has been made by the ever-increasing volume of the literature in terms of understanding how a location-allocation problem of fast-chargers should be formulated when the goal of the study is to produce a result that can be implemented in practice.

Past studies made many assumptions in the problem formulation rather implicitly despite those assumptions can critically limit the practicality of the results. The implicit nature of those assumptions makes it difficult for the reader to see under what conditions the results from the study can hold true. Therefore, to improve the practicality of the location-allocation plan, a new study must enumerate all critical assumptions made in the problem formulation. In particular, the following key aspects of the location-allocation problem must be elaborated. First, it must be clearly stated which location-allocation problem is under study. The quintessence of a study of the location-allocation is to make an allocation plan that has merit for an interested party—and a different party may have a different objective to achieve in a public fast charger allocation. The study, therefore, must clearly identify the party of interest for which the problem is solved. This leads to the next critical aspect of the problem formulation: A specification of the constraints the party is bounded by. For example, in past studies, it was typically assumed that a charger could be placed on any node in the road network. However, this obviously does not hold true in practice. A recommended site may be unavailable for hosting an EV fast charger for a number of reasons, such as the property value is too high, the site owner refuses to rent the property or host a charging station, the power required to operate a fast charger is not available, etc. The financial feasibility of the allocation plan, in particular, must be considered. Installing an EV fast charger involves an immense financial commitment with great uncertainty in the expected investment return. ChargePoint Express 200 CPE200, a 50-kW charger, is currently in the market for \$35,800 [35]. In addition, the installation of a fast charger can come with a high installation cost that is also highly variable depending on the nature of engineering work necessary [14]. Absent a careful consideration of the financial feasibility, a study may propose a large-scale installation of EV fast chargers that involves the financial risk most private or public entities cannot endure with ease. In that case, there is little merit in the proposed plan.

6. Conclusions

Many discrepancies were found between the approaches taken in the research on location-allocation of EV fast chargers and the actual location-allocation observed in the United States. The analysis conducted in this paper delineated some of the common assumptions made in research that may be too strong (or unrealistic) for results to be directly applied in the real world. In the past decade, academic researchers seemingly have provided “solutions” to location-allocation of EV fast chargers in predetermined contexts with arbitrary objectives. However, unfortunately, their problem formulations cannot be an adequate description of the actual location-allocation problem businesses (and any other relevant agent) face in practice.

To the best of the author’s knowledge, the issues described above have not been well discussed in academic research. This suggests that future research must pay closer attention at the complexity of fast-charger placement (that is, the stakeholders involved and financial, physical, and legal constraints) and place greater focus on the applicability of the methods and results in the real context. For starters, a new study must delineate (1) what the study was done for, (2) what variable was optimized on, (3) what constraints were considered, and (4) what assumptions were made on the objective and constraints.

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