EV EVERYWHERE OR EV ANYTIME? CO-LOCATING MULTIPLE DC FAST CHARGERS IMPROVES BOTH OPERATOR COST AND ACCESS RELIABILITY

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Abstract

This work examines the tradeoffs between maintaining availability of DC fast chargers, waiting times, station utilization, and cost per vehicle served. We built a queue model informed by the characteristics (e.g. charging rates, battery size, range) of current battery electric vehicles (BEVs) and available DC fast chargers to determine how we can expect costs, utilization and availability of chargers to change with respect to each other and find out what the costs are for maintaining satisfying availability for users. The model shows that for a charging station with few chargers, it is difficult to achieve cost-effective levels of utilization while maintaining reliable access for arriving vehicles. Large numbers of chargers per station make it possible to maintain a high reliability of access and a high utilization rate.

Keywords: BEV (battery electric vehicle), Fast charge, Reliability, Infrastructure, Business model

INTRODUCTION

Adoption of battery electric vehicles (BEVs) depends on many factors such as up-front cost, fuel cost, charging time, and the availability of charging infrastructure (*1*). Figure 1 illustrates that over 60% of initial BEV adopters charged more than once per day on average. Between this and the fact that not all drivers have access to home charging facilities (*2*) the necessity of public charging facilities is clear.

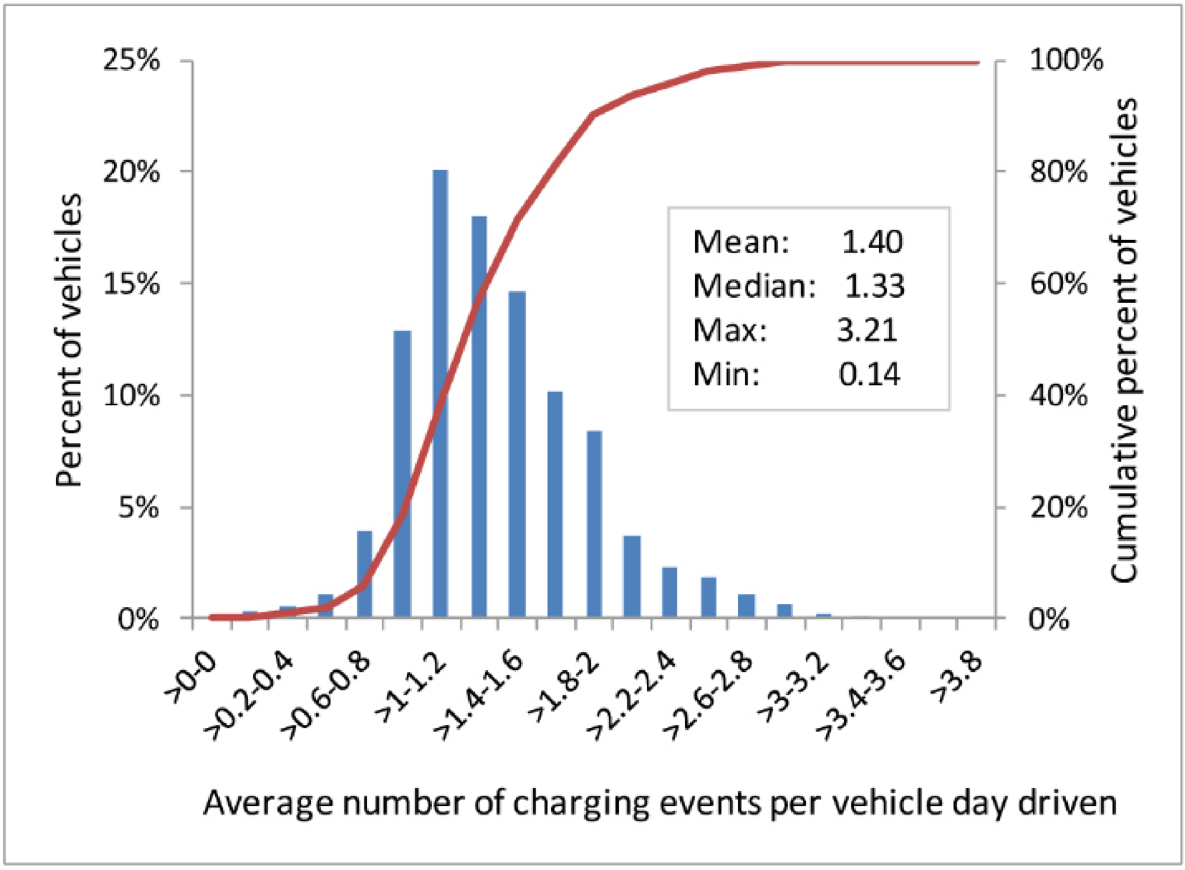

FIGURE 1 Distribution of daily average charging events across battery electric vehicles in the EV Project (*3*)

A key disincentive to the adoption of BEVs is range anxiety, defined as the fear of fully depleting BEV's battery in the middle of the trip, leaving the driver stranded or forced to make a lengthy stop for recharging. This can cause drivers to choose a gasoline vehicle over an electric vehicle, thus preventing BEVs from gaining a significant share of the vehicle market (*4*). Neubauer and Wood (*4*) noted that "Increased range anxiety was regularly shown to decrease vehicle utility" and concluded that additional access to recharging infrastructure would reduce the impact of range anxiety and investigation of refuelling infrastructure has the potential to improve vehicle utility considerably. Thorough reviews of related literature can be found in Hoen & Koetse (*1*) and Tanaka et al (*5*).

Fast chargers help to address charging time issues by reducing charging time to around 30 minutes. Botsford and Szczepanek (*6*) concluded that the availability of DC fast chargers would increase adoption of BEVs considerably. Fontaine (*7*) calls fast charging infrastructure a "catalyst" for consumer acceptance of BEVs. A study of the usage of charging infrastructure in

Ireland has shown higher charge consumption values and charging frequency for fast charging infrastructure than standard ones (*8*).

Widespread deployment of public DC fast charging infrastructure therefore appears necessary both to ensure that BEVs can meet drivers' travel needs from a technical standpoint, and to increase consumers' willingness to adopt BEVs. Building charging infrastructure in more locations can help to address range anxiety, but is not sufficient to ensure reliable recharging access. Reliable charging access requires not only that chargers are deployed in enough locations, but also that a charger is available when a driver needs to use it.

Installing and operating DC fast chargers is expensive, and in order to justify these costs, DC fast chargers need to achieve a high rate of utilization. Work commissioned by the EV Project (*9*) explores the effects of utility demand charges on the costs of operating a DC fast charging, and how higher utilization could help to reduce those costs. On the other hand, to make BEVs appealing for users, the price of charging needs to be kept as low as possible, and reliable access to charging is a must. This sets up a fundamental tension: infrastructure developers would like to see infrastructure being utilized more of the time, but when a charger is in use, it is not available for other drivers.

In this paper, we study the interactions among utilization, availability and cost of DC fast charging infrastructure. We develop a queueing model to characterize the tradeoffs between utilization and availability of charging stations, and how these tradeoffs become less severe as the number of vehicles served increases. We also show that when we consider the need to maintain reliable access to charging, it becomes much more challenging to grow the BEV market to the point where investments in DC fast charging infrastructure are financially viable.

QUEUE MODEL

Queuing theory analyzes the relationship between the demand for specific service and the availability of that service for the users. "A *queueing system* is a generic model that comprises three elements: a user source, a queue, and a service facility that may consist of one or more identical servers in parallel" (*10*). The user source generates users who pass through the queue into the service facility. Each user spends a specific amount of time, ranging from zero to infinite in the queue. When the user has left the server and is no longer using it, we consider that user has left the queuing system. In the case of a DC fast charging station, the user source is BEV drivers who wish to charge, and the servers are DC fast chargers, of which there may be one or more at any given charging station (the service facility). Three sets of information are required to model a queueing system:

1. The user generating information (The time between when they arrive at the service facility)
2. The queue discipline (The order in which users enter the service facility)
3. The service process (The time needed for a server to service a user).

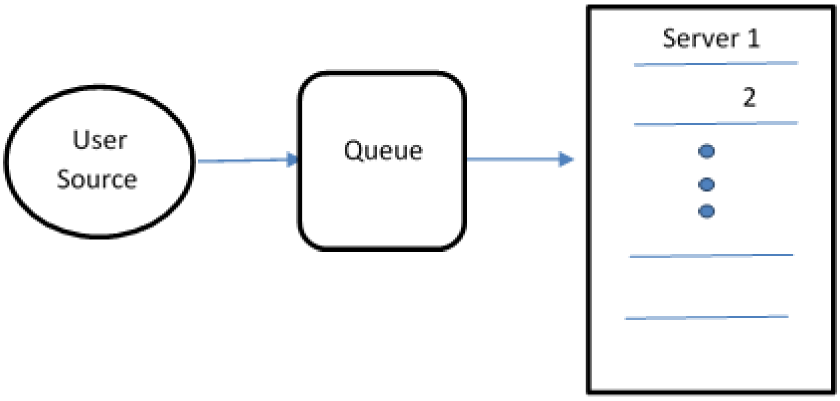

FIGURE 2 Scheme of queue model

We assume that users' arrivals and departures follow Poisson processes, so the interarrival time and service time follow negative exponential distributions (*11*). This is known as an M/M/m queue model in which the M's indicate Poisson arrivals and departures, and m represents the number of servers. The service times for each charger are assumed to be independently and identically negative exponential distributed. The queue discipline in this model is first come, first serve: when all the servers are busy, the user who has been waiting the longest will be assigned to the first server that becomes available.

The key outputs from our model are availability and utilization. We define utilization as the fraction of time that the chargers are in use. If the rate of arrivals of users is given by λ and μ is the average service rate for one server, then utilization ratio, ρ, is calculated as follows:

$$\rho = \frac{rate\ of\ user\ arrivals\ at\ the\ service\ facility}{total\ available\ rate\ of\ service} = \frac{\lambda}{m\mu} \qquad (1)$$

Assumptions

We define availability as the probability that at least one server would be available when a user arrives (so the user does not have to wait to charge). This is the probability of the queuing system being in a state less than *m*, where *m* is the number of servers.

To parameterize our model, we used typical characteristics of current BEVs and DC fast chargers. In this model, the inputs are the number of servers, charging time and arrival rate, and the outputs are utilization and availability.

Researchers in the EV Project reported that charging time for a Nissan Leaf (a popular BEV), from 30% to 80% state of charge, is around 25 minutes (*12*). Here, we assume a charging time of 30 minutes. Also, most DC fast charging activity happens between 11 a.m. and 11 p.m. (*12*). Therefore, we assume that stations are active for 12 hours per day.

BUSINESS MODEL

We develop an illustrative application of how the results of the queue model and consideration of charger availability can be incorporated into a business case analysis. We explore how number of vehicles served per month impacts the attractiveness of an investment in a DC fast charging station, as measured by the net present value of the project. In order to do so, we assume a project life of 10 years and a discount rate of 15%. The results are sensitive to assumptions, of course, but the point is to illustrate the general direction and magnitude of the effect that maintaining reliable access has on profitability.

Costs

We based our capital and maintenance cost estimates on BMW's recent installations of DC fast chargers in Seattle. We assumed that cost of purchasing each charger is $7000, with an installation cost of $2000 for the first charger and $1000 for each additional charger at the same site. We also assume $300 for shipping and handling per server. These costs are incurred at the beginning of the project. We assume maintenance costs of $1700 per charger per year, incurred annually. Finally, we assume 9.6% for tax on these costs. These costs are much lower than many other contemporary cost estimates, and are probably optimistic in the context of high-power DCFC installations along a highway corridor. This only reinforces our point that it is very difficult to get to the point where selling electricity through a DCFC station is an attractive investment.

Other important costs are those charged by the electric utility, which include meter charges, demand charges and energy charges. A meter charge is meant to cover the costs of maintaining lines, reading meters, billing and similar costs, and it is assumed to be $200 per month per *charging station* (*9, 13*). A demand charge is a fee proportional to a facility's maximum power draw over the course of a month. Here, we assume a demand charge of $600 per month per charger (*9*). The energy charge is based on the amount of energy drawn, and is assumed to $0.11 per kWh. Following the EV project (*9*), we assume that each vehicle's energy usage is 20 kWh per charging event.

Revenues

We assume that a charging station operator bills based on energy charged, with a price per kWh determined from the distance-equivalent price for gasoline. This is based on an assumption that to keep BEVs competitive with conventional vehicles, the cost for fast charging should not exceed the cost of gasoline on a per-mile basis. We assume that the price of one gallon of gasoline is $2.00, which is close to the U.S. average reported by the Energy Information Administration for the first half of 2016. We use the 2015 Nissan Versa and 2015 Nissan Leaf as a basis of comparison. The Versa averages 32.4 miles per gallon, which works out to about $0.06 per mile (*14*). The Leaf on average consumes 0.3 kWh per mile (*14*). In order to keep the per-mile energy cost of the Leaf less than that of the Versa, a charging station operator should not charge more than $0.20 per kWh.

In addition to billing for energy, there are other potential revenue sources that could be result for a DCFC station operator, through activities such as partnerships and sponsorships, energy premiums and value added services (*13*). As we will see, such revenue sources are probably crucial to making the economics of DCFC stations viable in the near term.

RESULTS

Queue Model

We begin by presenting the tradeoff between utilization and availability in charging station operations, and how this changes as more servers are added to the system. When there is only one server in the system, there is a direct linear tradeoff between utilization and availability. If a charging station has only one charger, and it is utilized 30% of the time, then it is (of course) only available 70% of the time. However, when multiple servers are available in the same system, higher levels of utilization can be realized while maintaining a given level of availability for users (and vice versa). Figure 3 illustrates the relationship of utilization and availability and how number of servers impact this relation. By adding more servers, it is possible to improve both utilization and availability: achieving a win-win situation for both the operator and the users.

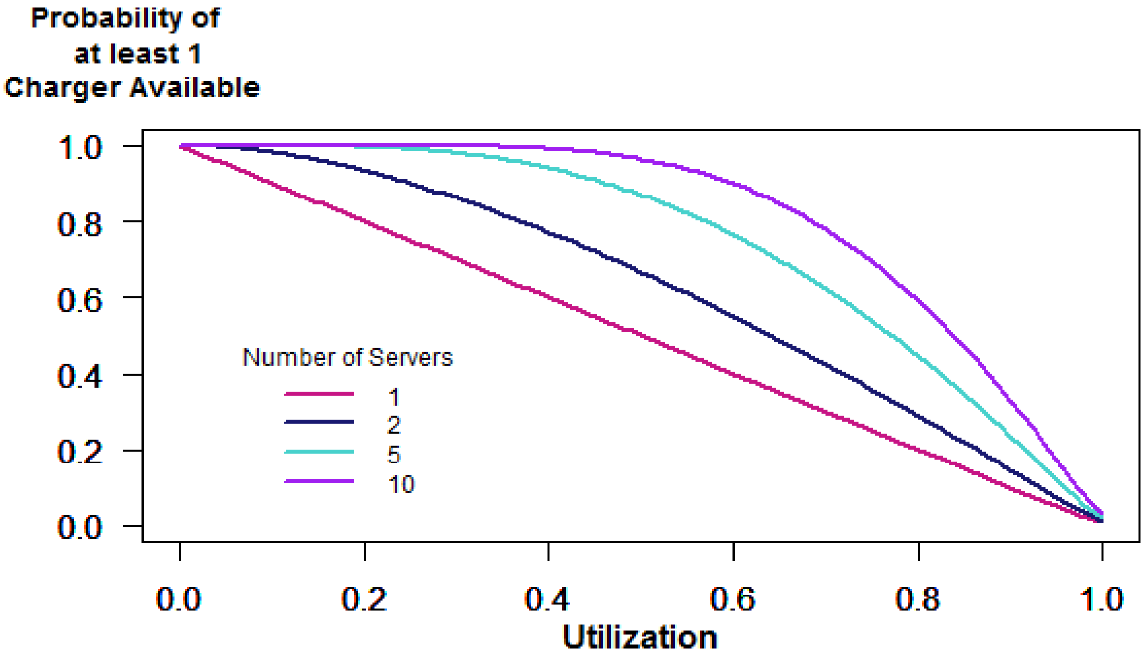

FIGURE 3 Effect of co-locating multiple servers on availability - utilization trade off

Next, we determined how many servers were required to maintain a certain minimum level of availability as the number of vehicles served increases. We assumed that there is some threshold level of availability that we wish to maintain. For example, we might want to ensure that a vehicle arriving at a random time would find a charger available with 90%, 95% or 99% probability. Figure 4 illustrates the relationship between average arrival rate, number of chargers per station, and the probability of at least one charger being available at a random time. For a given average arrival rate, a higher target availability level means more chargers are needed at each station. Also, as average arrival rate increases, more chargers are needed to maintain a given level of availability. The flat “steps” in Figure 4 reflect the fact that a given number of chargers can maintain a target level of availability for a range of arrival rates, but when the arrival rate exceeds that range, another charger must be added. A final important feature of Figure 4 is that the required number of chargers increases less than linearly with the arrival rate, with each additional charger adding a larger increment to the allowable arrival rate (i.e. the “width” of the steps increases as arrival rate increases).

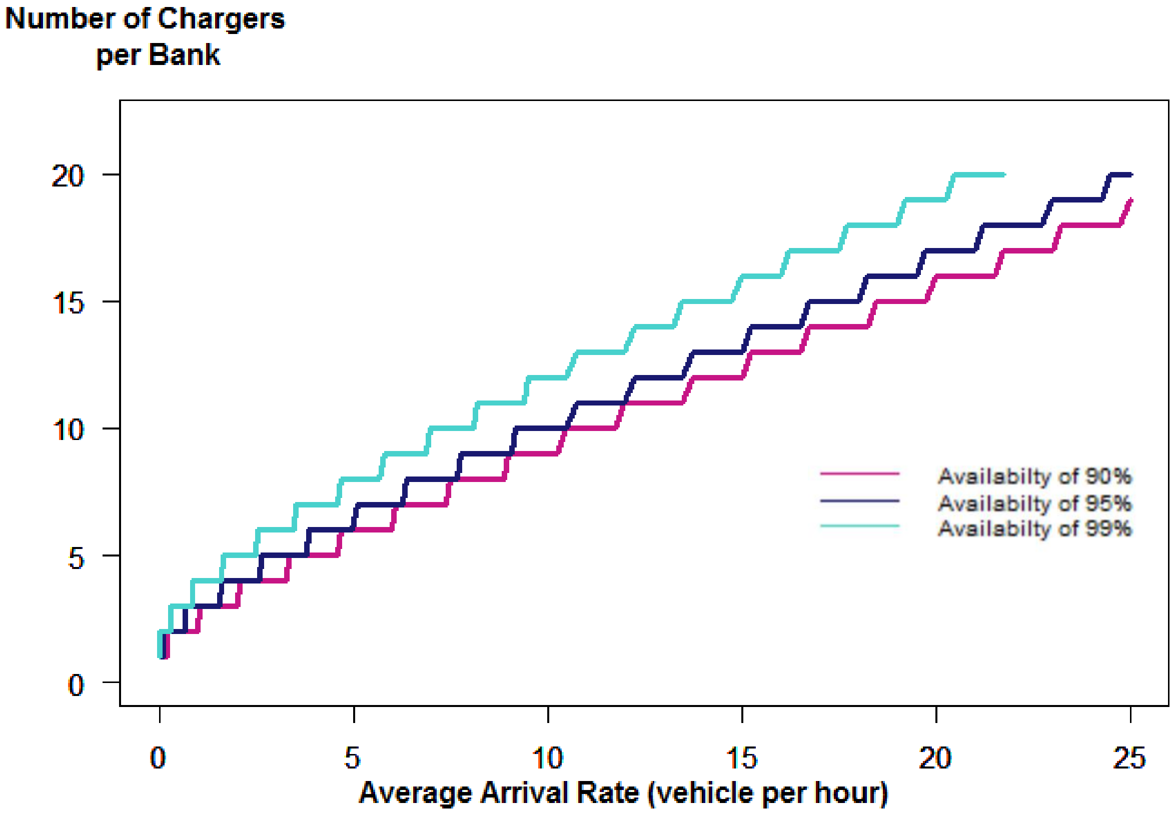

FIGURE 4 Effect of availability on number of chargers per bank as average arrival rate increases

Figure 5 plots the utilization rate of chargers as a function of the monthly number of vehicles served by a charging station. The "sawtooth" pattern in utilization results from adding more chargers: each time a new charger is added to a charging station to maintain availability, the overall utilization of chargers at that station drops. Generally, however, as the market grows, more plugs are needed but each plug has higher utilization. Yet it can be seen that to achieve 30-50% of utilization, more than 2000 vehicles need to be served per month. Also, based on the relationship between utilization rate and number of vehicles served per month, it can be seen that improving utilization rate demands great growth in the BEV fleet. Maintaining satisfactory availability therefore makes it harder to improve utilization rate.

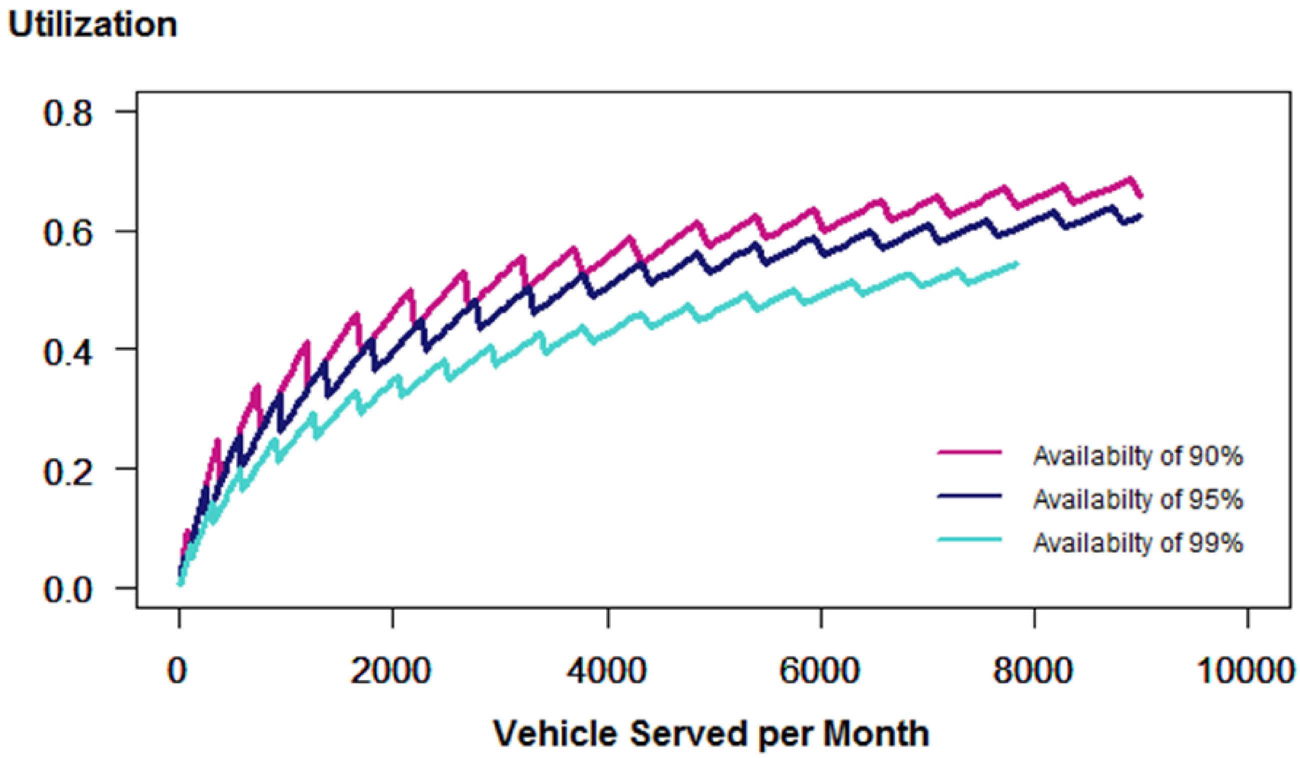

FIGURE 5 Effect of availability on utilization rate as number of vehicles served per month increasea

Business Model

We begin with a simplistic model that does not consider reliability of access (availability) for a charging station. We assume that each charge takes an average of 30 minutes, and the charging station is active for 12 hours per day, so each server can serve 24 vehicles per day. Under these assumptions, the net present value increases rapidly with the number of vehicles served, as shown in Figure 6. Net present value increases as more vehicles are served, up to the point that capacity is saturated, and another charger must be added.

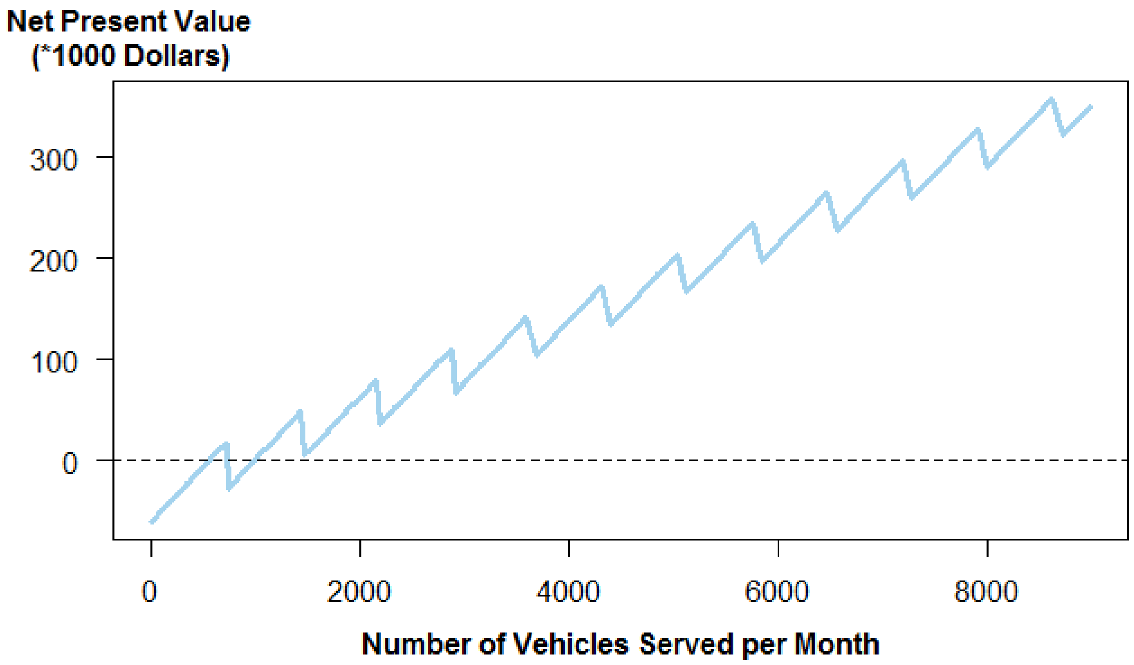

FIGURE 6 Impact of number of vehicles served per month on net present value when availability is not considered

However, this is not realistic. Since people arrive at the stations randomly, some of them would have to wait in queue for a long time. This inconvenience and inadequacy of service for the users would cause them to not come back again, while unreliable fast charging access would also likely curtail demand for BEVs among vehicle purchasers. Therefore, Figure 6 does not represent a viable path to growing the PEV market or profitably deploying infrastructure.

Figure 7 illustrates the effect of maintaining reliable access to chargers. To maintain availability, more servers need to be added as the BEV fleet grows, well before capacity is fully utilized. Once again, the sawtooth pattern in the plot is caused by adding servers each time availability drops below the specified target level. It can be seen that up to a point, adding more vehicles to the system actually decreases net present value. This is because the cost of adding servers to the system to maintain availability is higher than the revenue earned. The higher the target availability level, the more significant this effect is. For example, for an availability of more than 80%, the decrease in net present value is almost negligible. However, if we want to maintain availability of more than 95% we can see a decreasing trend in net present value for the first 1800 vehicles per month. This is because the cost of adding a server is greater than the incremental revenue from the additional customers. As demand gets sufficiently large (above 4000-8000 vehicles per month, depending on the target availability level), the net present value becomes positive. However, the high costs of fast charging stations and the need to maintain reliable access create a “valley of death” for fast charging market growth.

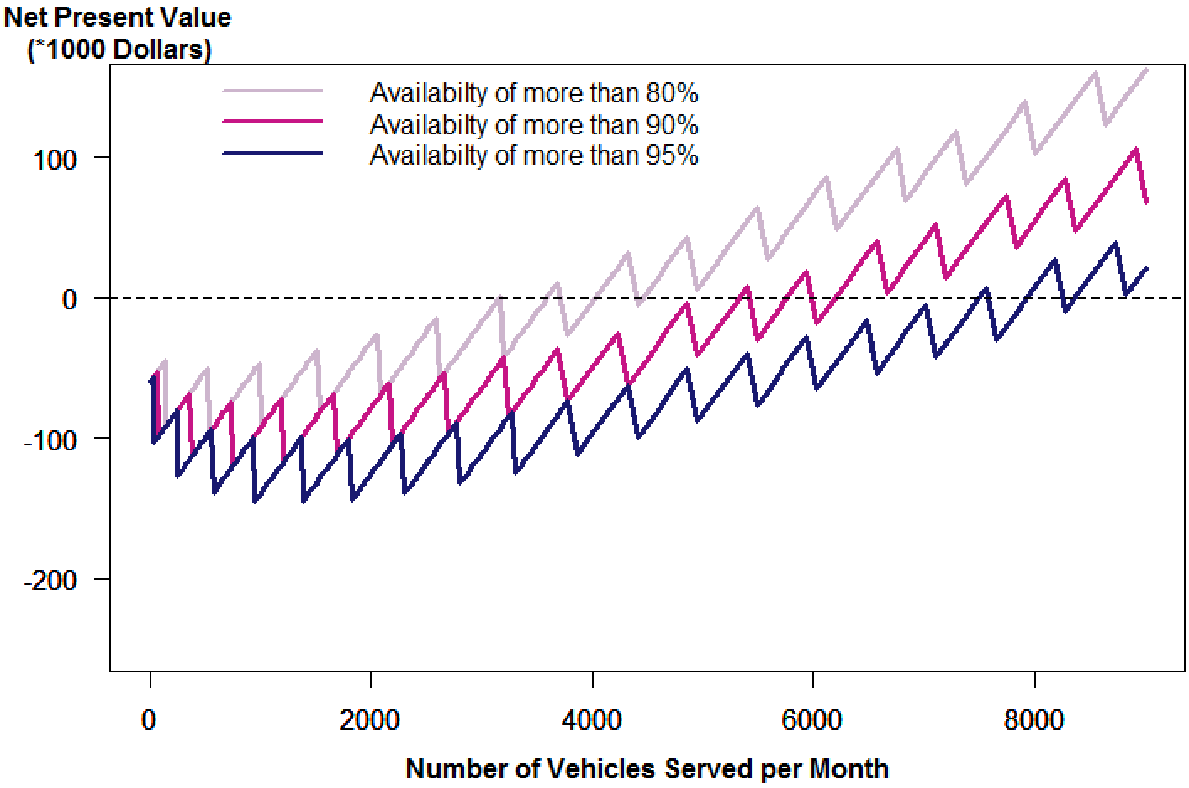

FIGURE 7 Effect of number of vehicles served per month on net present value for different levels of availability

Figure 8 shows the breakeven number of vehicles that must be served (that is, the minimum number of monthly vehicles served that will generate a positive net present value), as a function of the target availability level. It suggests that the breakeven number of charges per month is very sensitive to the required level of availability, particularly at high levels of availability. This suggests that more research should be done to identify precisely what an acceptable level of availability is for current and prospective BEV owners.

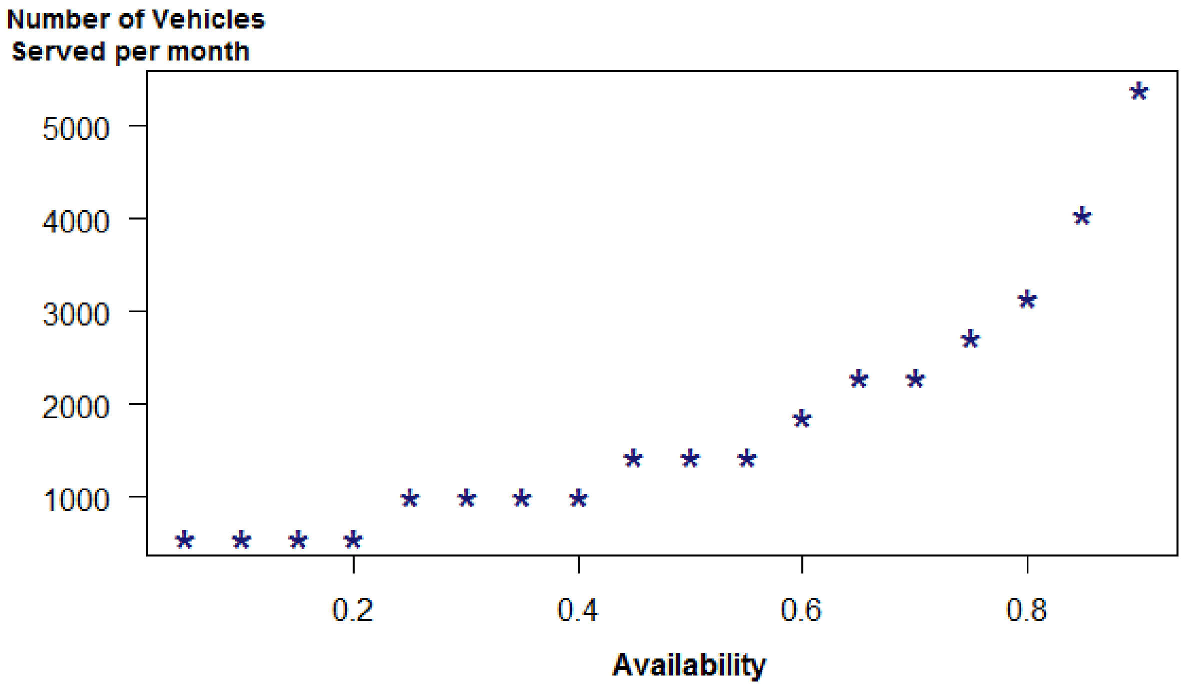

FIGURE 8 Minimum volume required to provide positive net present value, for each level of availability

CONCLUSIONS

DC fast chargers have high capital and fixed costs, so to be cost effective they need to have high utilization. In order to provide users with reliable service and reduce their range anxiety, a satisfactory level of charger availability should be maintained. Installing an excess of DC fast chargers is one way to ensure availability, but it leads to low utilization of the chargers if the demand does not increase. However, as the BEV market grows, both utilization and availability can be improved if larger numbers of DC fast chargers are co-located at stations.

Our findings illustrate how the need to maintain reliable access limits the degree of utilization that we can get out of charging stations in the near term. This suggests that it will be even harder than previously thought to reach the stage where there is clear business case for DC fast charging.

Decision makers can use this model to estimate the number chargers per station required to balance the availability of chargers and utilization rate in order to provide satisfying service for users and beneficial business for operators. Also, this model demonstrates how growing the fleet of BEVs can lead to more affordable cost of charging for users and higher utilization rates for stations' operators.

As discussed in business model section, in order to provide higher quality of service for users, more vehicles need to be served so that costs and revenue break even and investors earn their money back and profit. Even though our specific assumptions are debatable, the qualitative impact of considering the reliability vs utilization tradefoff will remain; maintaining more reliable access will mean lower NPV. For example, to maintain availability of 80% and more, more than 5000 vehicles need to be served per month for the specific station in order to achieve a positive net present value over 10 years. Let's see how many BEVs the fleet need to have in order to serve the customers adequately and provide a return to the investors. The following diagram from Greene (*15*) indicates that if percentage of stations offering an alternative fuel drops below 25%, the probability of choosing a car with that alternative fuel drops precipitously.

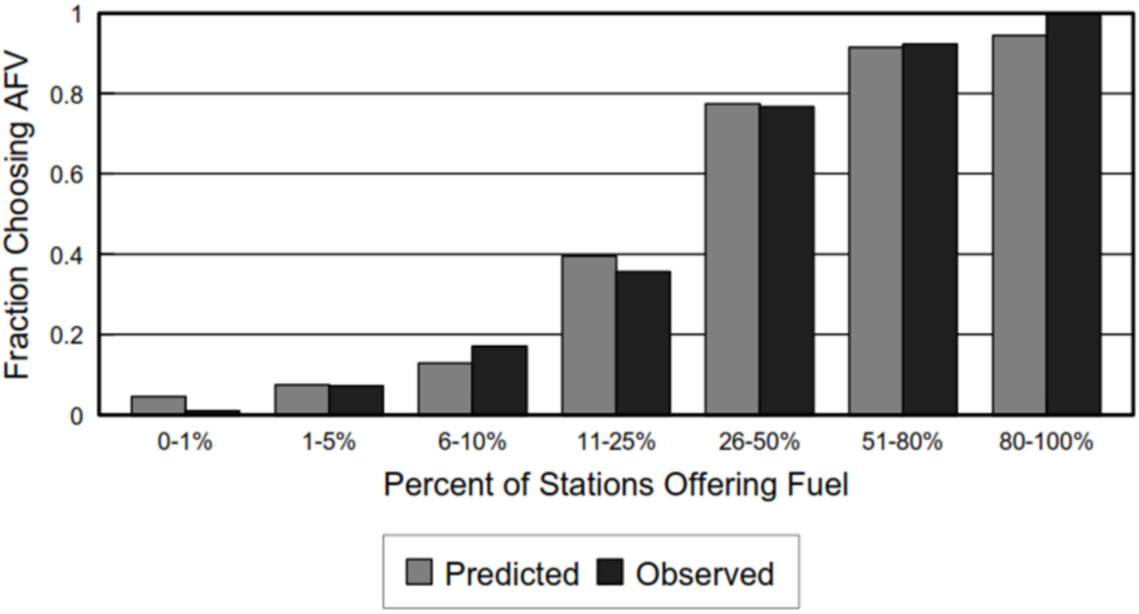

FIGURE 9 Cumulative frequency fit of exponential fuel availability model of alternative fuel engine choice (*15*)

Setting the number of DC fast charging stations equal to 25% of the number of gas stations in the U.S. implies 42,000 fast charging stations (*14*). If station operators are to ensure that 80% of arriving BEV owners do not need to wait to charge (i.e. availability of 80%), about 4000 vehicles per station per month will be required in order to break even. If we assume that BEVs average one fast charge every 3 days (10 per month), then we would need around 17 million BEVs in the U.S. in order to ensure availability of 80% for drivers and an attractive investment for infrastructure developers. The situation can get even more challenging. As technology advances, the range of electric vehicles is expected to increase, and people would need to charge their vehicles less frequently.

There are several ways that these challenges might be addressed. For one, instead of focusing on the probability of zero waiting time, it might be useful to find out what would be the acceptable range of waiting time for users. This can help operators achieve better utilization without impacting quality of service dramatically.

Second, greater use of information technology, such as connected vehicles and reservable charging stations, could help to increase utilization while maintaining a good experience for drivers. Relatedly, we should aim to have chargers be compatible with all BEVs, either through mandating a single charging standard or ensuring that equipment is compatible with multiple standards. Failure to do so effectively reduces the number of chargers available, leading to lower reliability and less attractive investments.

As demonstrated in our business model analysis, capital costs of charging stations and utility demand charges are important components of total costs. By lowering these costs, investing in DC fast charging stations would become more appealing for operators. Providing subsidies for purchasing charging equipment is one way that can positively impact the capital cost, but would be extremely expensive to deploy at large scale. Also, as BEV fleet grows more chargers will be produced, which could lead to cost reductions through learning over time (*16*). However, some believe that these costs would not be strongly affected by scale since chargers mainly consist of less sophisticated electronics and standard commodities for the body, which are less sensitive to scale (*17*).

Finally, government and public utility companies can work on reducing utility demand charges. Even if it this cost reduction took place for a limited period of time until BEV fleet grows to the point that investors earn their money back, it could work as incentive and motivator for private sector investment.

We recommend that future work investigate how the utility of BEVs to current and prospective adopters depends on waiting times for fast charging, in order to establish appropriate targets for availability and waiting times. In addition, more sophisticated queuing models should be developed to capture the dynamic (not just steady state) operations of DCFC stations, while incorporating more realistic distributions of arrival and service times.

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