

EV Everywhere or EV Anytime? Co-locating multiple DC fast chargers improves both operator cost and access reliability

Parasto Jabbari¹, Don MacKenzie

¹University of Washington, Box 352700 Seattle WA 98195, jabbari@uw.edu

Summary

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 EVs 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: EV (electric vehicle), fast charge, reliability, infrastructure, business model

1 Introduction

Adoption of electric vehicles (EVs) depends on many factors such as up-front cost, fuel cost, refuelling time, the availability of refuelling infrastructure [1]. Figure 1 illustrates that over 60% of the vehicles need to be charged more than once per day on average. By considering this fact and also the fact that not all of the EV users have access to home charging facility the necessity of public charging facilities cannot be denied.

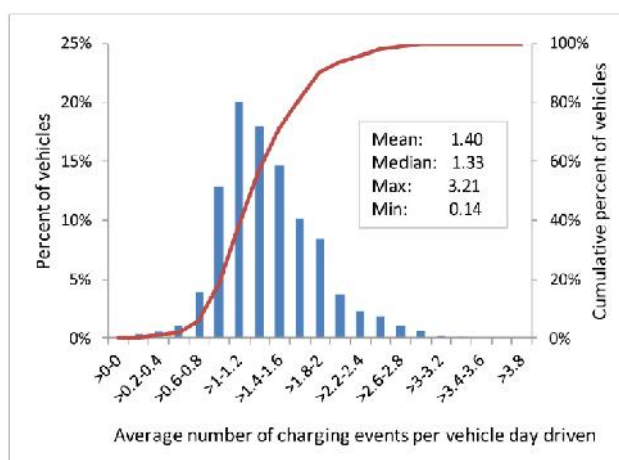


Figure 1. Distribution of daily average charging events across battery electric vehicles in the EV Project [2].

A key disincentive to the adoption of EVs is range anxiety, defined as the fear of fully depleting EV'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 EVs from gaining a significant share of the vehicle market [3]. Neubauer and Wood [3] 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 [4].

Fast chargers help to address charging time issues by reducing full charging time to around 30 minutes. Botsford and Szczepanek [5] concluded that the availability of DC fast chargers would increase adoption of BEVs considerably. Fontaine [6] calls fast charging infrastructure a "catalyst" for consumer acceptance of EVs. 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 [7].

Widespread deployment of public DC fast charging infrastructure is therefore necessary both to ensure that EVs can meet drivers' travel needs from a technical standpoint, and to increase consumers' willingness to adopt EVs. 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 an EV 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 [8] 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 EVs 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 EV market to the point where investments in DC fast charging infrastructure are financially viable.

2 Queue Model

Queueing Theory analyzes the relationship between the demand for specific service and the availability of that service for the users [9]. "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". 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 to have left the queueing 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).

There are three sets of information required to model a queueing system:

1. The user generating information (How frequently 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).

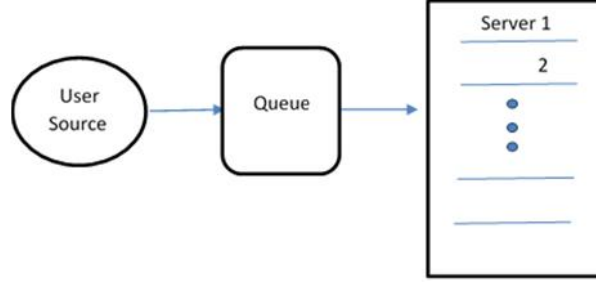


Figure 2. Scheme of Queue model

We assume that user's arrivals and departures follow a Poisson process, so the interarrival time and service time follow negative exponential distributions [10]. 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 become 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:

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

2.1 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 EVs 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 Leaf Nissan (typical EV), from 30% state to 80% state of charge, is around 25 minutes [11]. Here, we assume a charging time of 30 minutes. Also, most DC fast charging activity happens between 11 a.m. and 11 p.m. [11]. Therefore, we assume that stations are active for 12 hours per day.

3 Business model

Here we want to 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%.

3.1 Costs

We based our 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.

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* [8]. 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 [8]. The energy charge is based on the amount of energy drawn, and is assumed to \$0.11 per kWh. Following the EV project [8], we assume that each vehicle's energy usage is 20 kWh per charging event.

3.2 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 two months of 2016. We use the 2015 Nissan Versa and 2015 Nissan Leaf as a basis of comparison. The Versa averages mile per gallon of 32.4, which works out to about \$0.06 per mile [12]. The Leaf on average consumes 0.3 kWh per mile [12]. 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.

4 Results

4.1 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 relation 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.

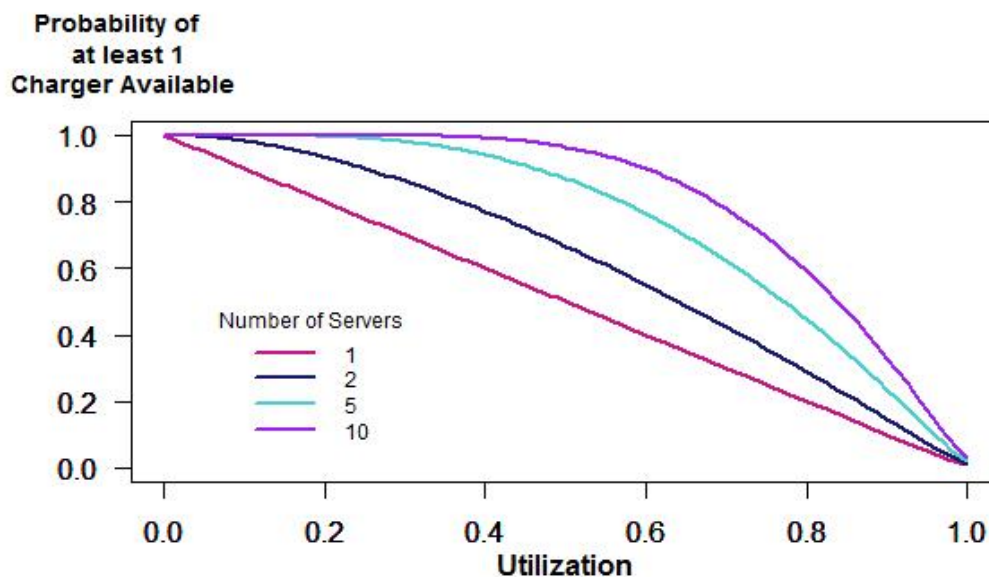


Figure 3. Effect of co-locating multiple servers on availability - utilization trade off

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, 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.

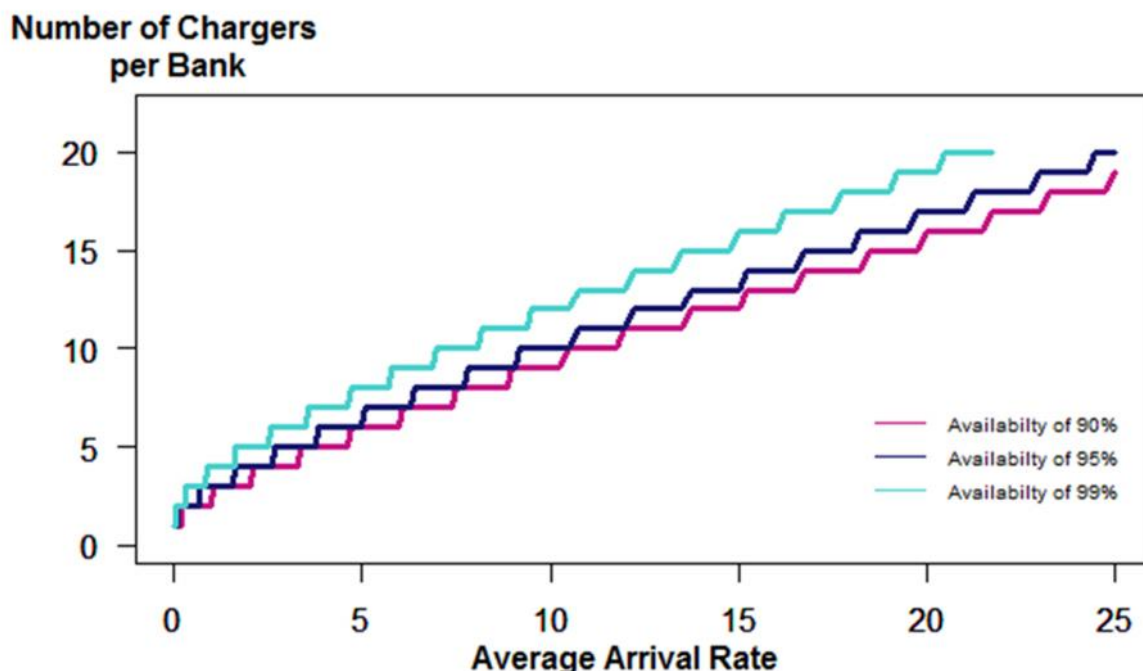


Figure 4. Effect of availability on number of chargers per bank as average arrival rate increases

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 relation between utilization rate and number of vehicles served per month, it can be seen that improving utilization rate demands great growth in EV fleet. Maintaining satisfactory availability therefore makes it harder to improve utilization rate.

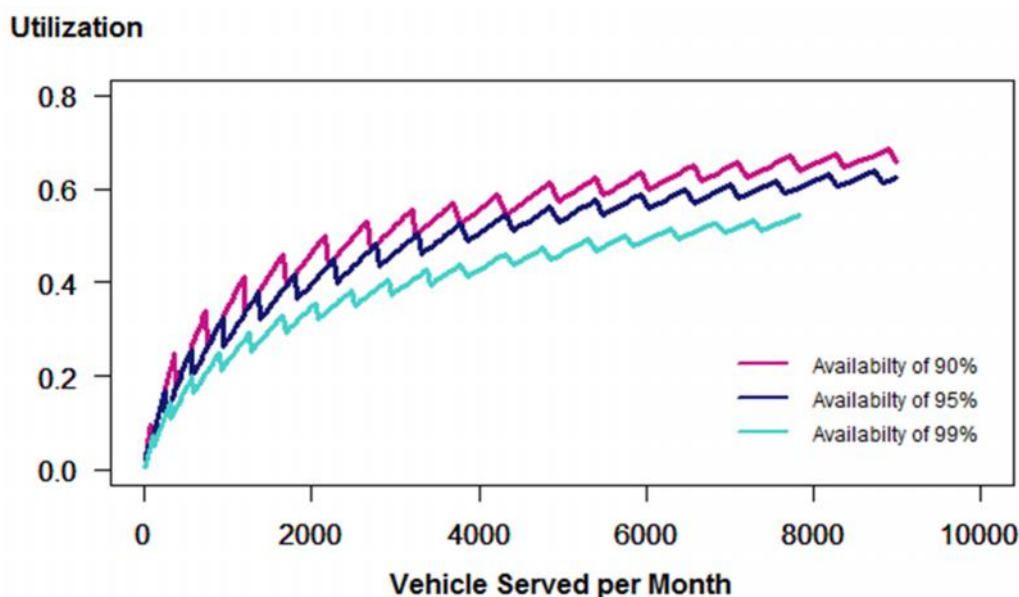


Figure 5. Effect of availability on utilization rate as number of vehicles served per month increase

4.2 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.

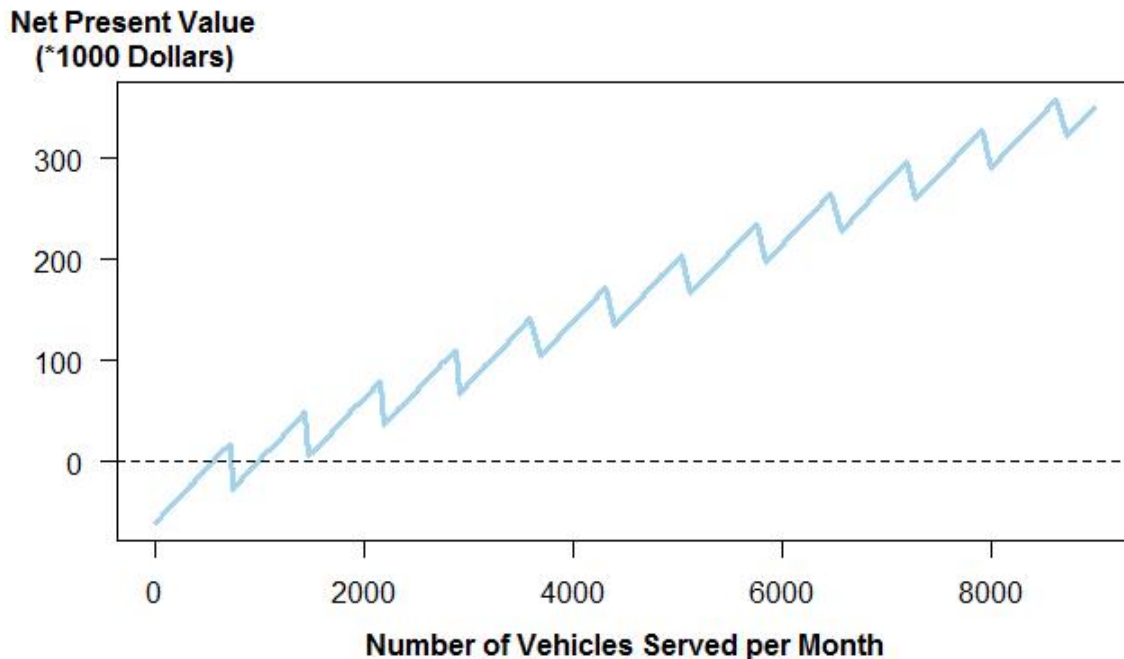


Figure 6. Impact of number of vehicles served per month on net present value when availability is not considered

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 EVs among vehicle purchasers. Therefore, Figure 6 does not represent a viable path to growing the EV 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 EV 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 much 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, for availability of more than 95% we can see a decreasing trend in net present value for the first 1800 vehicles. 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.

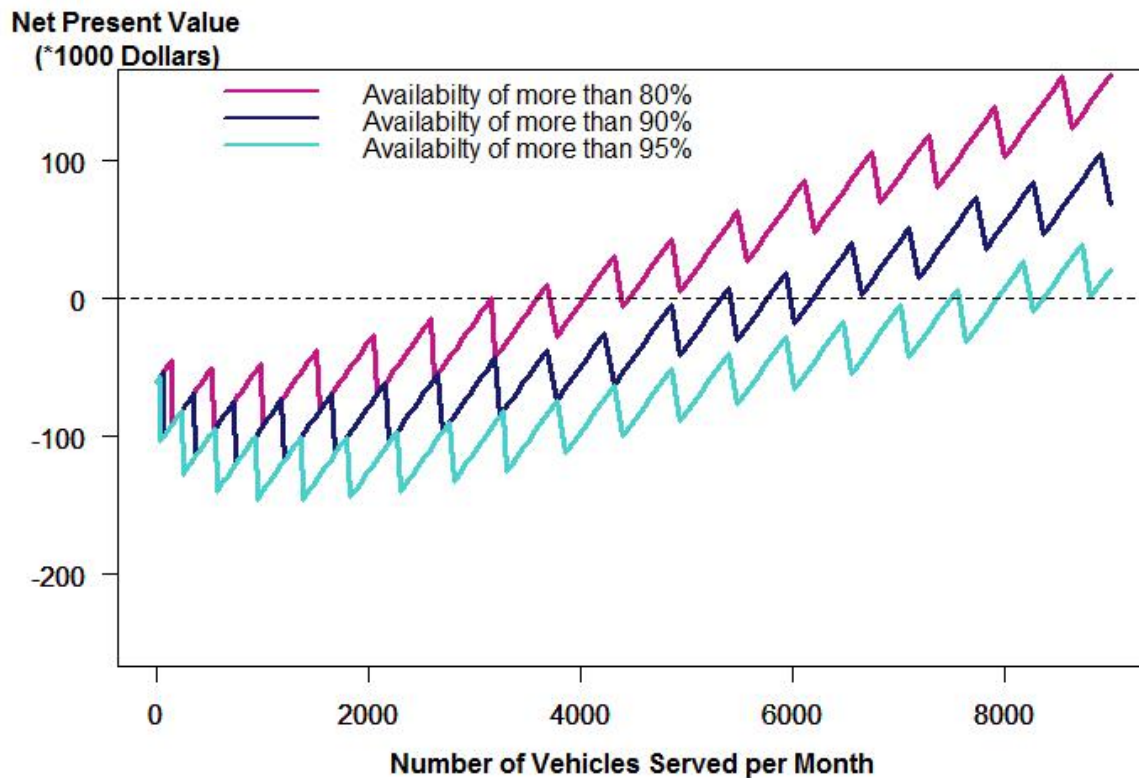


Figure 7. Effect of number of vehicles served per month on net present value for different levels of availability

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 EV owners.

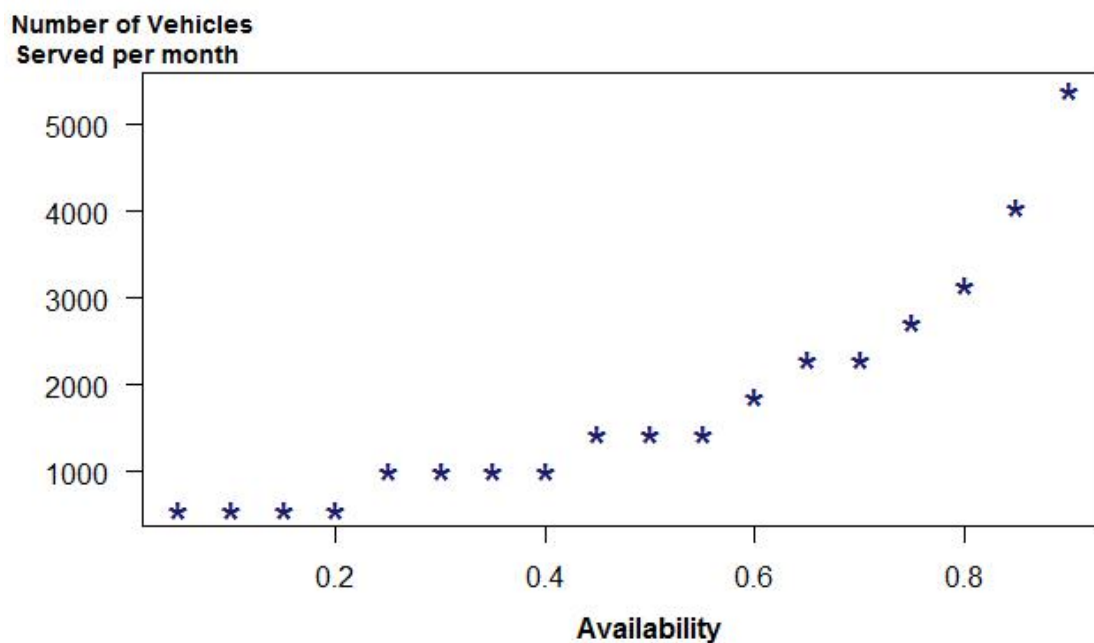


Figure 8. Minimum volume required to provide positive net present value, for each level of availability

5 Conclusion

One of the barriers on the way of adoption of EVs is range anxiety, the fear of running out of charge in the middle of the trip. To address this issue, public DC fast charging infrastructure is needed, since level 1 and level 2 chargers cannot deliver recharging times that are suitable for mid-trip recharging. DC fast chargers are expensive, and to be cost effective they need to have high utilization. In order to provide users with desirable 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 leads to low utilization of the chargers. However, as the EV market grows, both utilization and availability can be improved if larger numbers of DC fast chargers are co-located at stations.

Our findings show that the need to maintain reliability of access limits the degree of utilization that we can get out of charging stations in the near term. This means 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 fleet of EVs can lead to more affordable cost of charging for users and higher utilization rate 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 investigators earn their money back and profit. For example, by maintaining 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 EVs the fleet need to have in order to serve the customers adequately and benefit the investigators. The following diagram from Greene [13] 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.

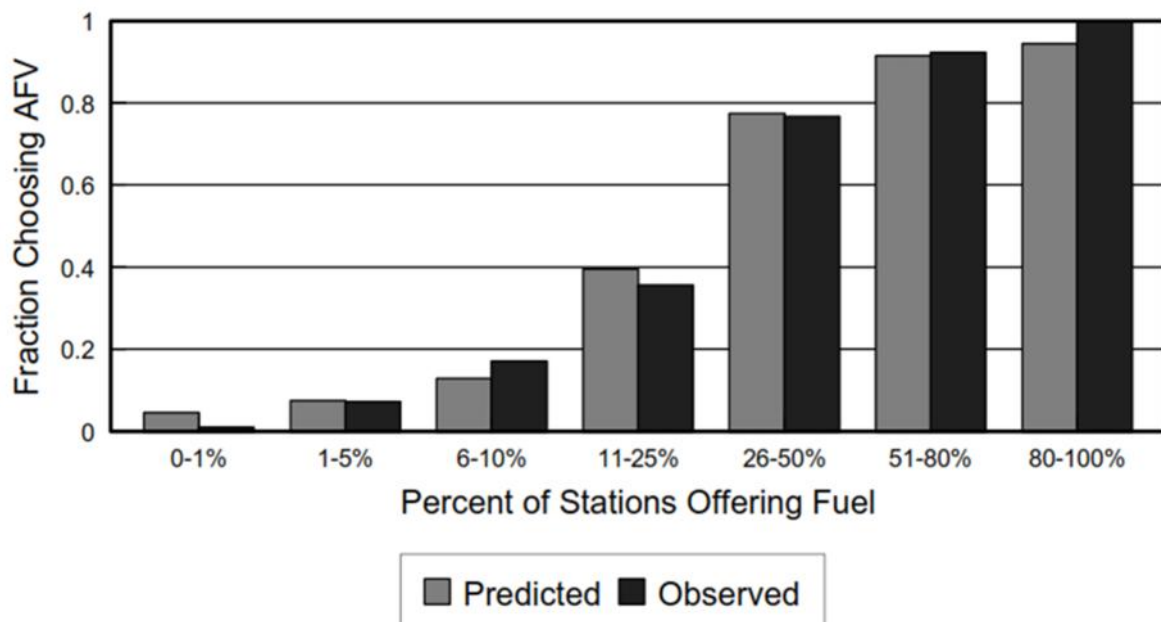


Figure 9. Cumulative frequency fit of exponential fuel availability model of alternative fuel engine choice [13]

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 [12]. If station operators are to ensure that 80% of arriving EV 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 EVs average one fast charge every 3 days (10 per month), then we

would need around 17 million EVs 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 tougher. As technology advances, the range of electric vehicles is expected to increase, and people would need to charge their vehicles less frequently. If EV owners charged just once every 3 weeks (1.5 times per month), on average, more than 100 million EVs would need to be on the roads before DC fast charging stations would make an attractive investment while ensuring 80% availability for drivers.

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 achieving better utilization without impacting quality of service dramatically. Additionally, 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.

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 EV fleet grows more chargers will be produced, which could lead to cost reductions through learning over time [14]. 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 [15].

Also, government and public utility companies can work on reducing demand charges. Even if it this cost reduction take place for a limited period of time until EV fleet grows to the point that investigators earn their money back, it could work as incentive and motivator for private sector. The EV project [8] identify several methods for operators in order to control their demand charges. However, before implementing such methods, their impact on quality of service and customer experience needs to be examined.

References

- [1] A. Hoen, and M.J. Koetse, *A choice experiment on alternative fuel vehicle preferences of private car owners in the Netherlands*, Transportation Research Part A: Policy and Practice, 61(2014), 199-215.
- [2] J. Smart, and S. Schey, *Battery electric vehicle driving and charging behavior observed early in the EV project*, SAE Int. J. Altern. Powertrains 1.1 (2012): 27-33.
- [3] J. Neubauer, and E. Wood, *The impact of range anxiety and home, workplace, and public charging infrastructure on simulated battery electric vehicle lifetime utility*, Journal of Power Sources 257 (2014): 12-20.
- [4] M. Tanaka, T. Ida, K. Murakami, and L. Friedman, *Consumers' willingness to pay for alternative fuel vehicles: A comparative discrete choice analysis between the US and Japan*, Transportation Research Part A: Policy and Practice 70 (2014): 194-209.
- [5] C. Botsford, and A. Szczepanek, *Fast charging vs. slow charging: Pros and cons for the new age of electric vehicles*, In International Battery Hybrid Fuel Cell Electric Vehicle Symposium (2009).
- [6] P. J. Fontaine, "Shortening the path to energy independence: a policy agenda to commercialize battery-electric vehicles." The Electricity Journal 21, no. 6 (2008): 22-42.
- [7] P. Morrissey, P. Weldon, and M. O'Mahony. *Future standard and fast charging infrastructure planning: An analysis of electric vehicle charging behavior*, Energy Policy 89 (2016): 257-270.
- [8] J. Wishart, *Lessons Learned - DC Fast charge – Demand Charge Reduction*, The EV Project, Electric Transportation Engineering Corporation, 2012
- [9] R.C. Larson, and A.R. Odoni, *Urban operations research*, ISBN 978-0975914632, Massachusetts, Dynamic Ideas, 2007
- [10] F. Schneider, Frank, U. Thonemann, and D. Klabjan, *Optimization of Battery Charging and Purchasing at Electric Vehicle Battery Swap Stations*, Working Paper (2013).
- [11] The EV Project: *Characterize the demand and energy characteristics of direct current fast chargers*, <http://www.avt.inl.gov/>, June (2015)
- [12] Fuel Economy, <https://www.fueleconomy.gov/>
- [13] D. L. Greene, *Survey evidence on the importance of fuel availability to the choice of alternative fuels and vehicles*. Energy Studies Review 8.3 (1998).
- [14] D. Chang, et al., *Financial Viability of Non-Residential Electric Vehicle Charging Stations*, Luskin Center for Innovation: Los Angeles, CA, (2012).
- [15] A. Wiederer, and R.Philip, *Policy options for electric vehicle charging infrastructure in C40 cities*, Master Thesis, Harvard Kennedy School, (2010).

Authors



Parasto Jabbari is a Master's student in Transportation Engineering at the University of Washington in Seattle. She is working as a research assistant under the supervision of Professor Don MacKenzie in the Sustainable Transportation Lab. Her research includes vehicle electrification, vehicle automation and their impacts on public policy. She received her Bachelor's degree in Civil Engineering from Sharif University of Technology, Tehran, Iran in 2015, and previously worked as undergraduate teaching and research assistant.



Don MacKenzie is an assistant professor of Civil & Environmental Engineering at the University of Washington in Seattle. His research addresses the travel and charging behaviour of electric vehicle owners, the environmental and social equity implications of shared-use transportation services, and the effects of vehicle automation on energy demand. He holds a PhD in Engineering Systems from MIT, and previously worked as a researcher on technical and policy issues spanning fuel cells, biofuels, and efficiency technologies in both the private and non-profit sectors.