Quantifying the (In)Convenience of Electric Vehicle Charging

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Introduction

A perceived barrier to widespread adoption of electric vehicles[1] (EVs) is the presumed inconvenience of charging them for personal transportation. Infrastructure for refueling internal combustion engine vehicles (ICEVs) is nearly ubiquitous, highly visible, and relatively easy and fast to use. On the other hand, even though progress towards expanding a diverse and accessible public charging network continues, EV charging stations are currently less available and accessible, not as publicly visible, and "refuel" vehicles at slower rates. We contend that charging infrastructure planning/operation that considers the consumer-centric concept of convenience will improve the acceptability of electrified transportation and ultimately sustain its economic viability.

At present, evidence suggests that publicly available charging infrastructure remains insufficient for many potential EV owners to achieve convenience parity relative to their ICEV experience. This situation hinders consideration of EV purchases for those who contemplate long-distance driving in their transportation mix. Further, the lack of multi-unit dwelling charging infrastructure constrains EV purchase for those other than single-family households. Similar situations apply to individuals living in rural or mountainous areas, and to those who do not work or have no access to workplace charging. In each of these cases, 100% electrification of personal vehicle fleets will be difficult to achieve if vehicle charging and operation are inconvenient.

With passage of the Infrastructure Investment and Jobs Act (IIJA) in November, 2021, the US will attempt to address charging inequity by investing approximately $5B over five years in a national EV charging network. Ultimately the near- and medium-term viability of EV ownership will depend on how these funds are deployed. Thus, it is critical to develop evaluation criteria and methods which go beyond geographic distribution and focus on the convenience and value of the driver-infrastructure interaction.

Defining Charging Convenience

We define convenience here as the absence of waste (time, money) experienced while operating a vehicle. Using this definition, we assert there are both well-documented inconveniences and conveniences associated with EV operation relative to ICEVs. Considering these together promotes a deeper understanding of how to approach charging infrastructure planning, and how best to communicate EV operation.

As defined, inconvenience is minimized when EV owners charge their vehicles while parked at locations having high driver utility, like home or work (Figure 1). Time-to-charge (dwell time) is generally not an issue because owners typically recharge their batteries overnight or leave them plugged in when not being driven. In this sense, EV owners have an advantage since ICEV owners cannot refuel at home/work and must make dedicated trips or detours for fueling. Still, as suggested above, there are situations in which charging at home/work is not possible, leading to reliance on publicly available charging locations in the same way that ICEV owners rely on publicly available refueling locations. Further, at-home charging, itself, can be inconvenient because, without access to a fast-charging unit, dwell time can be lengthy depending on the battery's current charge state. In some cases, the time required to charge an EV will be longer than the time the vehicle is parked. Hence, slower charging and shorter dwell times may constrain on-demand, full-range EV operation, forcing owners to pursue more inconvenient public charging alternatives.

Generally speaking, public charging convenience reflects the geographical availability/accessibility of a charging station and the time required to fully recharge the vehicle's battery. This has to do with charging sta-

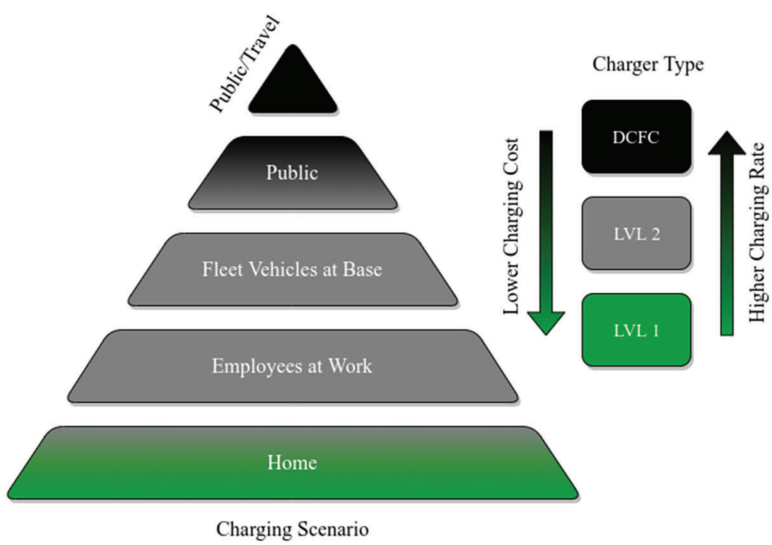

Figure 1. Charging activity pyramid. Modified composite of original graphic by T. Bohn, Argonne National Laboratory.

tion density in the vehicle owner's accommodation region, the time/route necessary to travel to the nearest available charging location, and any time delay experienced when arriving at the charging location. Charging density can mean the existence of multiple charging ports at a specific location or the number of charging locations with at least one charging port in a particular geographic area. The owner's accommodation region is the typical space within which s/he travels during a week to shop, conduct personal business, etc. Individual itineraries within a given region will vary greatly, and different individuals will experience differing levels of convenience even in similar situations.

Dwell time is important when evaluating recharging convenience at public stations, and it depends on a number of technical factors, including charging port type, age and state of the vehicle's battery, and ambient temperature. For example, public stations equipped with direct current fast-charging (DCFC, or Level 3) ports provide faster charging than Level 2, but there are even different levels of DCFC chargers. Though the situation continues to improve, EV owners are not likely to be able to charge their vehicles today at any publicly-available station in the same time that it would take them to refuel a comparable ICEV at a gasoline/diesel pump (roughly 10 minutes, depending on tank size, pump speed, and amount of fuel remaining in-tank upon arrival).

As noted, an additional aspect of public charging convenience is the potential delay that can be experienced upon arriving at a charging location. Although improving, today EV owners do not typically have equivalent access to the same number of charging ports at a specific location as the number of pumps that IECV owners would encounter upon arriving to refuel at a gasoline station. While it is true that ICEV drivers do often have to wait in line, the time delay is typically short, as is the typical time to complete a transaction once refueling begins, resulting in fairly continuous flow of ICEVs in and out of a station. By comparison, EV owners may have to wait longer in line upon arrival because there are insufficient ports to serve demand and/or the charging time is longer, leading to a more constrained flow of vehicles in/out of the charging location. Further, the smaller number of charging ports at a specific site than a comparable number of fueling pumps at a gasoline station may increase the potential for EV owners to experience a charging port malfunction or lack of vehicle-to-port interoperability, resulting in a further time delay at that site or in transit to a different site. Due to the greater density of gasoline stations and the larger number of fueling pumps per station, an ICEV owner would likely experience a lesser degree of inconvenience than an EV owner in either situation.

A further question is whether cost is part of public charging convenience. At first blush, the temptation might be to consider cost differently. However, in the same sense that ICEV owners may choose to drive further to obtain cheaper fuel or opt for higher-priced fuel at a closer location when time or fuel level is critical, EV owners may choose to drive to charging locations where the cost-to-charge is less expensive. Unfortunately, charging stations do not typically post the price of electricity in the same way that gasoline stations post the daily fuel price. Additionally, many EV owners do not have a full appreciation of the actual cost-to-charge, nor can they easily translate between the cost of gasoline/diesel and electricity because of complexities in pricing structures. For example, some stations impose plug-in fees or other costs in addition to the actual electricity price to help defray infrastructure expense, whereas at others the cost-to-charge may be entirely free, or it may be hidden in the overall price paid.

Because the perception of convenience can be confounded by many interacting factors, perhaps a more direct way to consider convenience (noted above) is to explicitly view it as the lack/absence of inconvenience. For example, an EV owner is inconvenienced when required to deviate from a planned itinerary to charge the vehicle's battery, and such events become more inconvenient the longer the charging event. However, if the EV owner is only required to charge at locations where s/he would be present anyway, such as at home, work, or certain other "long dwell" destination types/events (shopping malls, movie theaters, etc.), then the owner would conceivably experience little or no time-based inconvenience. An EV owner can even be inconvenienced by at-home charging if dwell time limits that individual's ability to maintain a planned schedule, take advantage of unscheduled opportunities, or react to emergencies or other unplanned requirements (e.g., drive to an urgent care center). On whole, such inconvenience would typically be less than if home charging was not available at all. Further, individuals with high mileage commutes might invest in higher-rate charging at home or be incentivized to seek publicly available fast-charging; but this, too, could be considered an inconvenience from a cost perspective.

Community Charging Versus Corridor Charging

The type of charging discussed above is sometimes called community charging (local "gas station style"), as distinguished from corridor charging2 associated with individuals or families traveling longer distances away from their homes/workplaces (e.g., cross-country vacations). Many aspects of community charging convenience already identified apply equally to corridor charging but become somewhat more critical. Accessibility to charging stations is particularly route-sensitive for corridor travel. Whereas charging stations are regularly available along interstate and other major highways in populous regions (e.g., travel plazas), that is not necessarily true everywhere. Further, access may be restricted to drivers who belong to a specific charging network. For example, Tesla owners have access to a proprietary charging network in the US, but, currently, no one else can charge at these stations. Density of charging stations at a particular location is also an issue. Some restaurants and hotels provide fee-based charging stations for overnight guests, but most do not; and, if multiple EV owners happen to frequent the same establishment, there would likely not be enough to go around. Further, depending on the destination and route, drivers traveling cross-country may find themselves in mid-route or at end locations with no charging access at all, or they may experience malfunctioning equipment, thereby requiring emergency charging services. Despite these concerns, as EV ownership becomes more prolific, corridor charging will also become more accessible and convenient, certainly along major highways and thoroughfares.

Quantifying Charging Inconvenience

Because these same considerations help define the convenience of refueling ICEVs and EVs, it is instructive to consider the differential convenience associated with owning the two different vehicle types. Making the assumption that the convenience of refueling an ICEV forms the baseline understanding of transportation effort in the minds of most consumers,[3] the difference can be stated in terms of the inconvenience level experienced by EV owners relative to what they might otherwise encounter with an ICEV. The end goal is to establish a single metric with which to directly compare the in(convenience) of owning any type of vehicle as objectively as possible under a variety of operating scenarios.

Prior Work

The question of EV charging in(convenience) and its influences has not been widely studied. Using a Household Activity Pattern Problem model to estimate equivalent cost of delay for households pursuing theoretical itineraries, Kang & Recker[4] conclude that EV drivers who can charge at home on Level 2 chargers experience low levels of inconvenience in monetary terms. Tamor & Milačić[5] and Tamor et al.[6] define inconvenience in terms of the number of days per year that an EV has insufficient range to complete its itinerary. Using real itineraries and assuming at-home charging only, they conclude that EVs with a 120-mile range would be acceptable as one-to-one replacements for 90% of US vehicles and 60 miles would be sufficient for 90% of US households to own at least one EV. Roughly 65% of Americans live in owner-occupied detached dwellings[7] leaving 35% for whom nightly charging at home must be accommodated with non-dedicated charger/parking combinations. Dixon et al.[8] attempt to understand EV inconvenience for those with limited charging options by considering it both in terms of infeasible itineraries and delays to itineraries. Data were obtained from the UK National Travel Survey which collected week-long travel itineraries from almost 40,000 households. Assigning charges to type of destination (e.g., food shopping, entertainment), and assigning charging events via a scheduling heuristic, they found that around 95% of those who charge at home can achieve convenience parity with low-end EVs, but that the percentage is much lower for those who cannot. There are a number of limitations to the Dixon et al. approach, including several assumptions that may not be totally supportable; but the main one is the absence of a single metric of inconvenience. Zhou et al.[9] consider inconvenience in the interacting contexts of cost avoidance and time sensitivity as drivers attempt to accommodate an optimum schedule; and Greene et al.[10] discuss the value that public charging infrastructure imputes to EV owners by increasing their mobility and access, partially offsetting a perceived cost penalty attributable to vehicle range and dwell time.

A Proposed Charging Inconvenience Metric

We seek to understand the technical combinations of vehicle and infrastructure characteristics that allow EVs to attain convenience parity with ICEVs apart from behavioral considerations. The objective is to develop a generally applicable method for predicting EV inconvenience which can be compared vehicle-to-vehicle and location-to-location.

Hence, a flexible metric of inconvenience is needed that can be evaluated for any vehicle. To operationalize this approach, it is necessary to shift from the notions of vehicle refueling and charging to the more comprehensive idea of vehicle "energizing." This redefinition allows for direct comparison of EVs and ICEVs traveling on the same itineraries/routes and, thus, the direct comparison of inconvenience between the two, regardless of trip length, dwell time, and location type.

In order to quantitatively evaluate inconvenience, a universal method for calculating energizing inconvenience is needed. As suggested above, inconvenience is essentially a function of time spent out-of-itinerary and money spent on energy. Because the relative importance of time and money is subjective and individualized, we propose to use the parsimonious expression in [1]:

$$S_{IC} = \beta_T T + \beta_C C, \qquad [1]$$

where is an inconvenience score, is a time multiplier, is a cost multiplier, and and are the time (minutes) added to the itinerary due to an energizing event and the actual energizing cost (dollars), respectively. Using direct comparisons can be made between vehicles with any sort of powertrain. A direct comparison in terms of S_{IC} should be made between best case scenarios for the vehicles involved in order to negate the effects of individual operator behavior. An estimate of globally optimal energizing behavior can then be generated using dynamic programming.

The optimization problem relies on the availability of known or simulated itineraries that identify the starting time (UTC code), ending time and location of each trip, total trip time and distance, and type of energizing location (home, work, or other). Using this formulation, the energizing event itself can be the primary trip purpose, or it can be embedded in sustained travel that continues after energizing is complete. Optimization also relies on technical parameters associated with specific vehicle models (standardized through simulation) to account for onboard energy storage capacity, average speed, and energy consumption under various driving conditions (city, highway, mixed). Relative to EVs, other important inputs include the likelihood of available charging ports at beginning and ending locations, port type (Level 2, DCFC), charging rapidity, and battery state-of-charge (SOC); and for IECVS, typical or average fueling time. Rabinowitz et al. provide additional details.[11]

Our approach has the following benefits: (1) it is location agnostic, (2) it leads to a single inconvenience score which does not depend on the vehicle powertrain type, and (3) by taking itinerary specifics into account, the generated results provide greater insight into EV charging inconvenience than simple geographical analysis.

Conclusion

Achieving convenience parity through public policy is difficult because there are multiple paths to consider, and the most efficient use of public funds must be ascertained. Our ultimate objective is to determine whether convenience parity can be achieved for those without access to chargers at home and whether such individuals are best served by public/destination chargers and DCFC stations. While more work is needed, results to date based on proprietary data indicate that: (1) from a time-only inconvenience perspective, parity can only realistically be achieved with home charging; and (2), in the absence of home charging, other parameters such as destination charging likelihood and in-route charging rapidity become important.

We note here the absence of publicly available data of sufficient quality and quantity on which to truly test our hypotheses, and conjecture that simulated or augmented data could be used to expand our research and knowledge. In addition, approaches other than dynamic programing, such as neural networks, could be used to develop alternative approaches for evaluating EV (in)convenience.

Footnotes

[1] Battery electric vehicles; plug-in hybrid electric vehicles.

[2] Sometimes referred to as destination charging; we make the distinction because a destination can be a convenience store a block away rather than a location several hours away.

[3] Crothers, B., 2021, Electric car fast charging vs gas: one wins on convenience. Forbes (October 29), https://www.forbes.com/sites/brookecrothers/2021/10/29/electric-car-fast-charging-vs-gas-one-wins-on-convenience/?sh=2266eb322c21.

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[7] Federal Reserve Economic Data (FRED), 2022, Homeownership rate in the United States. Federal Reserve Board of St. Louis, Economic Resources & Data (February 2), https://fred.stlouisfed.org/series/RHORUSQ156N.

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