DC Fast as the Only Public Charging Option? Scenario Testing From GPS Tracked Vehicles

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ABSTRACT

Electric vehicle travel and DC Fast charging was simulated using travel information from 48 households in the Sacramento Area using gasoline capable vehicles. Ranges of 80, 100 and 120 miles were simulated to investigate the travel that could not be completed with home charging alone. DC fast charging was the only public infrastructure in the simulation in order to highlight its possible role in a future charging network. Between 8.3% and 3.4% of tours would require some public charging under different range and charging assumptions accounting for 45% and 30% of VMT respectively. By limiting the number of fast charges to 2 per tour, combined with level 2 charging at home, 27% to 7% of VMT could not be completed in an EV. The day of week and time of day charging would be needed suggested that there would be congestion at fast chargers near the weekend and around 5PM. The location of fast chargers needed was near home when vehicle range was 80 miles. The location of chargers shifted to the adjacent-region corridor when vehicle range increased 100 and 120 miles.

INTRODUCTION

Electric Vehicles are now available from major original equipment manufacturers (OEMs). An oft cited criticism of electric vehicles is their short range, and lack of electric charging infrastructure prompting several questions. Will the range be enough for consumers used to range of gasoline vehicles? If the range is insufficient, will charging infrastructure be able extend this range in a manner acceptable to consumers? There have been various studies looking at different aspects of the range and charging issues. However, little work has been done on the applicability of fast charging. Fast charging (approximately 20-30 minutes to charge) was not available to consumers in the rollout of electric vehicles in the 1990s (using level 2 requiring 4-8 hours to recharge), but now many vehicles are equipped to accept fast charging. There will be some fast charging available as part of Department Of Energy (DOE) funded charging installations, but the question remains as to what role fast charging can play in the future of electric vehicle transportation.

BACKGROUND

The demand for charging is derived from the demand for plug-in vehicles (PEVs) and from the travel patterns expected for these vehicles. Recent studies on the demand for charging are primarily focused on the aggregate demand for electricity and the energy and environmental impacts derived from PEVs [1,2,3,4,5].

Some have estimated the frequency charging may be needed using vehicle travel patterns. To obtain exact travel patterns, GPS tracked vehicles were used in several studies estimating the demand for charging. A study by Davies and Kurani[6], using the same data set used in this paper, examine the variation in plugging in a vehicle coupled driving patterns to determine the extent to which plugging in a vehicle affects emission and energy use. A study Gonder [7] used GPS traces of 227 vehicles for one day to simulate the energy consumption and the potential of PEVs. The Gonder study focuses on the impact of different vehicles and battery size but does not explore the need for charging or the demand for PEVs based on travel behavior. A longer time frame using GPS for a full year was used by Pearre et al. The study is based on a year of driving data from nearly 500 instrumented gasoline vehicles, and showed that 9 percent of the vehicles never exceeded 100 miles in a day. For those who are willing to make adaptations six times a year -- borrow a gasoline car, for example -- the 100-mile range would work for 32 percent of drivers [8]. The study also explores the question of how much range is required for a daily driving. This paper reveals the impact of long range relatively low frequency trips on total VMT but again does not explore how charging may address need and impact of charging infrastructure.

One suggested type of public charging infrastructure is DC fast charging, which will be the subject of this paper. On this subject the literature is largely silent, although plans for placing DC fast chargers are underway. For example, Ecotality™ will install 260 DC fast chargers in Arizona, Tennessee, California, Oregon, and Washington State aimed to serve the new Nissan Leaf™[9]. The research on the demand for DC fast charging is lagging behind the sales of PEVs capable of using these chargers. In Tokyo, the first city to install DC fast chargers, early somewhat anecdotal results suggest that these chargers allow longer EV trips both by charging the cars and also as a safety net that allows higher depletion of the battery between charging[10].

Additionally, there is evidence that consumers value the option to charge quickly. A study by Hidrue et al. [11] estimates that as battery charging time decreases from 10 hours to 10 minutes, consumers would pay an estimated $3,250 per hour. For driving range, consumers value each additional mile of range at about $75 per mile up to 200 miles, and $35 a mile from 200-300 miles.

METHODS

In order to estimate how DC fast charging could be used by customers, we studied travel patterns for 48 households that were tracked for approximately one month using a GPS logger. These survey subjects were part of a separate study on PHEVs conducted by UC Davis where a vehicle was loaned to a household for a period of time. Since these were blended PHEVs with no range limitation, travel was assumed to represent destinations respondents wanted to go to regardless of range considerations. Only travel data from these vehicles were used in this analysis, and no aspect of the special attributes of a PHEV was used. Since the vehicle was likely more efficient than any other vehicle available to the survey household, household travel might be higher in this month than in a typical month of travel. Conversely, since this was an unfamiliar vehicle, the vehicle may have been driven less by some households. Even so, the survey respondents were deliberately given little instruction on how to use the vehicle. They were simply told to drive it as they would any other vehicle in their fleet. The travel patterns can be seen in Figure 1.

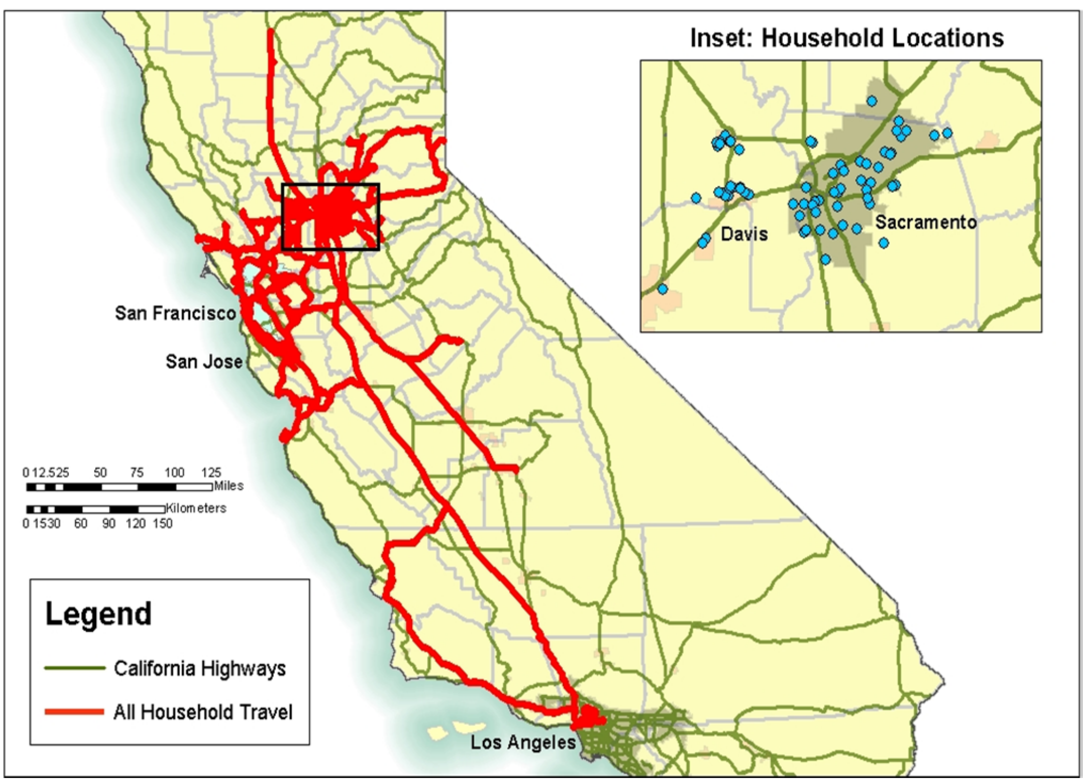

FIGURE 1 Map of survey respondent approximate locations and aggregate travel patterns

The total number of miles for all vehicles was 58,026 representing 1429 days of travel. This corresponds to an average of 15,294 miles per vehicle per year if this vehicle were driven similarly throughout the year. This compares to about 20,000 miles per year on average for a new vehicle in California[12], These travel characteristics can also be compared to a study by Pearre et al. [8] looking at the daily travel miles. The travel characteristics shown in Figure 2 appear to correspond well with, but appear slightly higher than those in a study by Pearre et al. who tracked 484 gasoline vehicles for a year. For example, it appears as though 83% of daily travel is less than 100 miles for the 4th quartile in Pearre et. al's study. In Figure 2, the approximately 81% of travel is less than 100 miles in the 4th quartile.

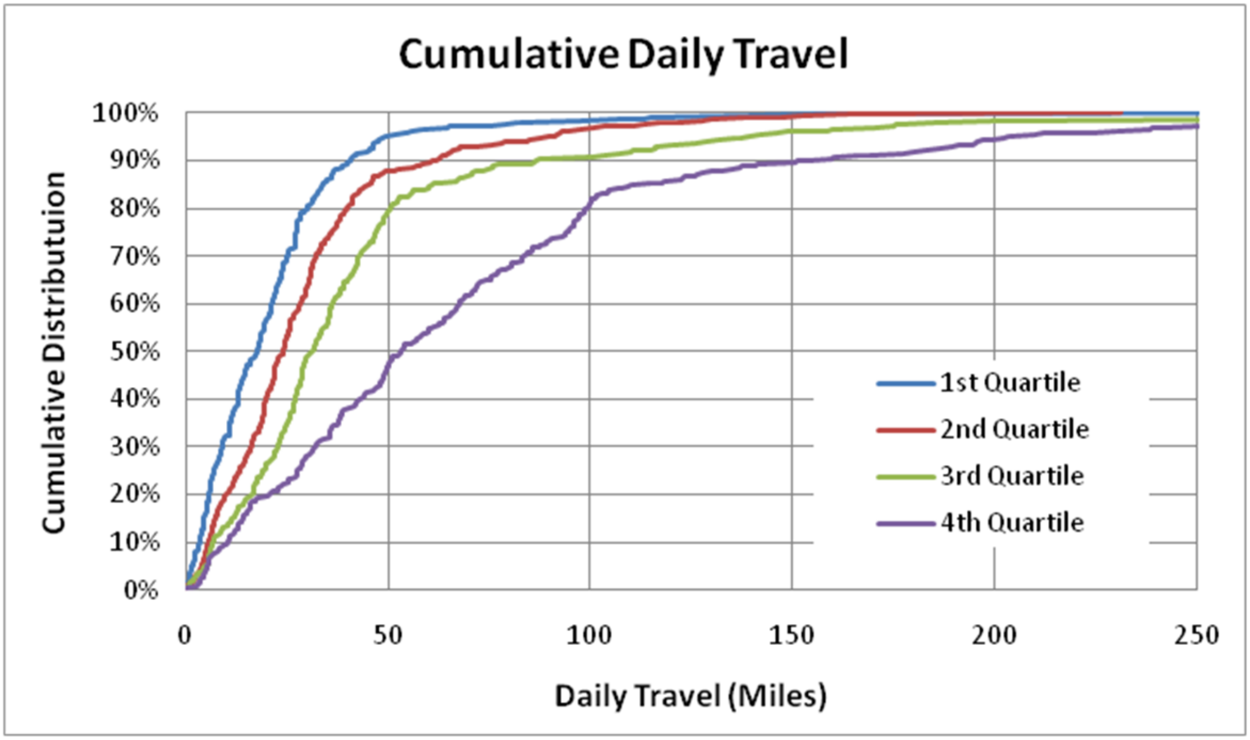

FIGURE 2 Cumulative daily travel miles by average daily travel quartiles. For example the 1st quartile represents the travel from one quarter of the households with the lowest average daily mileage.

Vehicle and Charger Simulation

The goal of the simulation was to estimate how travel in gasoline vehicles could have been completed in an electric vehicle. In reality we do not assume this travel in and electric vehicle would be completed in the exact same manner as occurred in a gasoline vehicle, but for the purposes of this analysis, we assume that this is the case. How drivers would adapt to the time and range constraints is reserved for future analyses, but the simulation detailed here estimates how it *could* be completed and how demand *could* be met with DC fast chargers as the only public charging option.

The data are in the format of GPS points showing the position of the vehicle at all times throughout the approximately 1 month survey period. Although there were many available attributes contained for each point including speed, temperature, pedal position etc., only location and distance traveled were used for this analysis. Some simulation could be done regarding speed of travel for the actual vehicles, but this aspect of the analysis was addressed by changing the range of the vehicles rather than simulating the increase or decrease in range due to individual driving style.

Vehicle Parameters

Three ranges were simulated: 80, 100, and 120 miles. The battery size for the 80 and 100 mile range simulation was 24kWh and was chosen to parallel a higher and lower estimate of efficiency for a vehicle such as a 2011 Nissan Leaf™[13]. The battery size for the 120 mile simulation was 28.8 kWh. In the simulation, the battery size has much less of an effect than the range estimates and only comes into play when estimating the time required to charge at home.

Charger parameters

The chargers in the simulation consisted of 3.3kW (level 2) at home and 64kW DC Fast chargers. However, each type of charger was used a different way in the simulation. Home chargers charged at the rate of 3.3kW based on the amount of time the vehicle spent at home. If a driver only stopped at home for one hour, the car could only gain a maximum of 3.3kWh of electricity or about 14 miles of range (assuming 24kWh resulted in 100 miles total range). Conversely, the fast charging was based only on the proximity of the vehicle to a fast charger along a travel route, not the time spent parked next to a simulated fast charger location. This was necessary since the actual gasoline based vehicles used in the simulation did not stop on their trips. Consequently, the DC fast charging stops had to be simulated. Lastly, DC fast chargers only charged the battery 80% state of charge (SOC) according to manufacturers limitations of rapidly putting energy into a battery[14].

Charging Scenarios

The location of the DC fast chargers was dealt with in two ways. In the unconstrained charger location scenario, alternately called the “perfect placement” scenario, the vehicle was allowed to use all of its range and when the vehicle reached zero range, it was returned to 80% SOC by a fast charger. The “location constrained” scenario was intended to simulate a more realistic driving situation in which some compromises had to be made when deciding where to charge and there was some safety buffer preventing drivers from getting to zero range. In the location constrained scenario, drivers had to choose from specific charging locations and were prohibited from falling below the 20% state of charge level except in the 120 mile range case. The 20% state of charge meant never falling below 16 miles of range with the 80 mile range vehicle, and 20 miles range with the 100 mile range case. This arbitrary distinction to consider the battery SOC more than simulated mileage left was made to capture the situation where drivers may pay more attention to the battery SOC since they have the option to slow down and drive more efficiently if the SOC gets low. For the 120 mile range case, the SOC was allowed to drop to 17% due to the larger battery size corresponding to 20 miles of range left. Drivers could skip chargers if they would reach the next charger without going below these SOC limits.

Charger Locations

The locations chosen for the fast chargers was not optimized for this simulation as the goal for this scenario was to highlight the tradeoff between “perfect placement” and some compromise in location of chargers. Fast charge locations were placed at the intersection of highways or along trans-regional (long-distance across many regions) corridors. Additionally, fast chargers were placed only to serve the travel from the survey subjects and were not placed at every intersection to every highway in the state. There were 105 fast chargers available to simulated vehicles. However, the simulation determined which of those chargers was used and in fact, several of the chargers were not needed by the simulated vehicles.

Tours

Most of the results are based on the "tour" as a unit of analysis. A tour as defined in this simulation is travel done away from home. As soon as a vehicle returns home, a new tour starts. An example of a tour and how the simulation works can be seen in Figure 3.

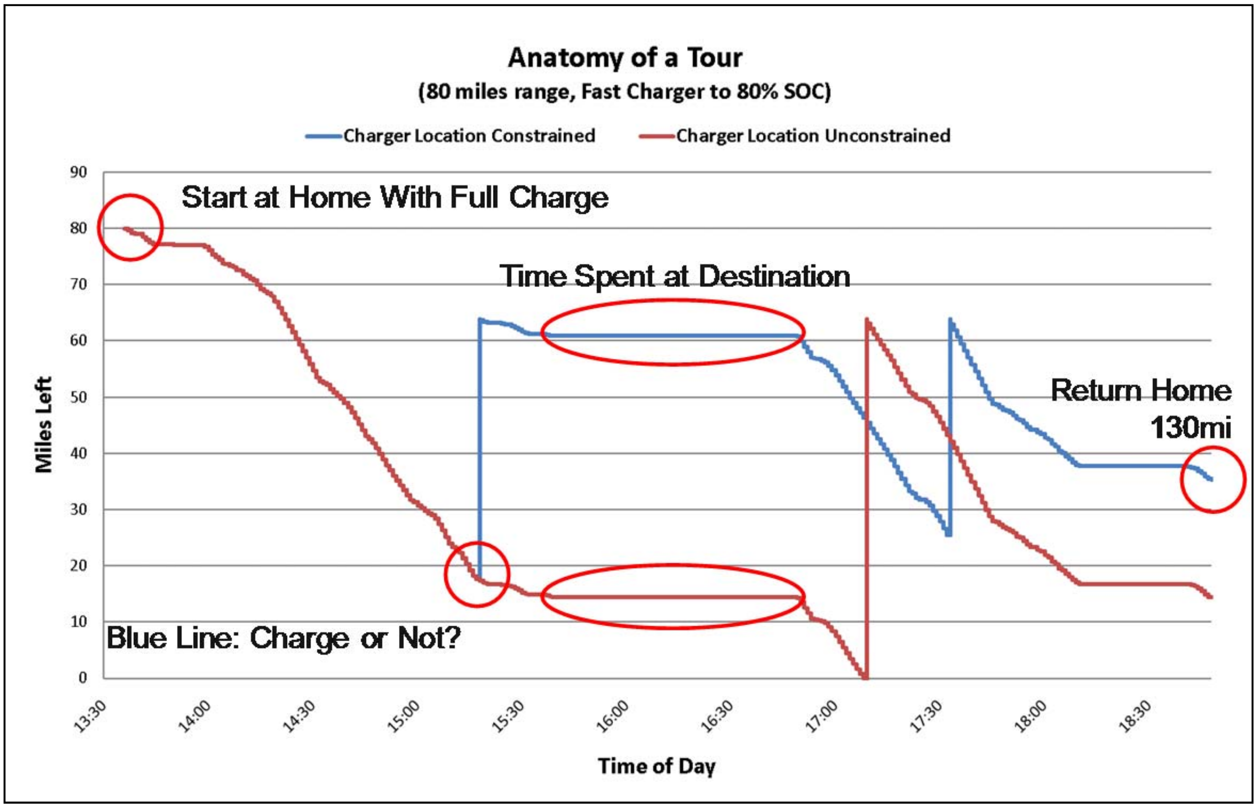

FIGURE 3 Closer examination of a tour. The red line and blue line represent two charging cases. When location is constrained and the battery is not allowed to drop below 20% SOC, more charging occurs on the same tour.

Figure 3 shows the case of a vehicle with 80 miles range completing a 130 mile tour under 2 different charging scenarios: location constrained and location unconstrained. In the location constrained scenario the vehicle is prohibited from going below 16 miles of range. When it reaches a fast charger the driver must "decide" to charge based on whether it will violate that rule before it reaches another charger. In the unconstrained case, the vehicle is allowed to reach zero miles left then is assumed to reach a charger at the perfect location and recharge to 80% SOC. Figure 3 also highlights the effects of constraining location to discrete locations. The constrained scenario requires two charges and the unconstrained scenario requires only one charge.

RESULTS

The results show that between 8.3% and 3.4% of tours would require charging of some sort under different range estimation and charging location scenarios (Figure 4). Even though only a small fraction of tours would require some away from home charging, the 8.3% indicated by the “Conservative Leaf estimate” accounted for 45% of VMT in the travel. However, 21% of the survey households would not have needed any infrastructure other than home charging even under the conservative Leaf estimate.

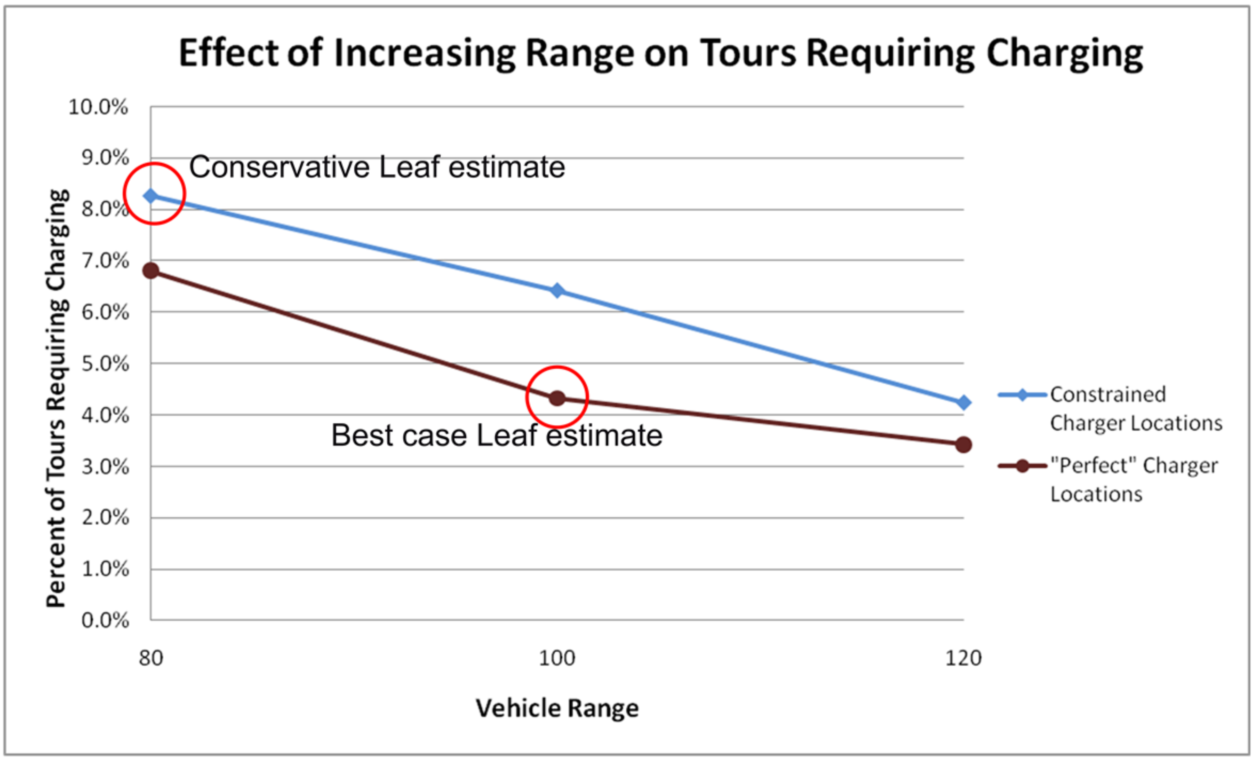

FIGURE 4 As range on the vehicle increases fewer tours need charging.

The “Conservative Leaf estimate” is meant to simulate a vehicle with 80 miles range, and the driver never wants to go below 20% SOC (16 miles left). The driver must also chose from discrete charging locations and hence may have to charge at sub-optimal locations. The “Best case Leaf estimate” simulates a vehicle with the same battery size as in the 80 mile range case, but the vehicle is more efficiently driven, the vehicle SOC is allowed to drop to zero, and the location of charging is optimal for all drivers. This shows that for the “same” vehicle, the results can vary widely based on assumptions and restrictions on charging location.

If the results are shown in terms of VMT we see a different perspective (Figure 5).

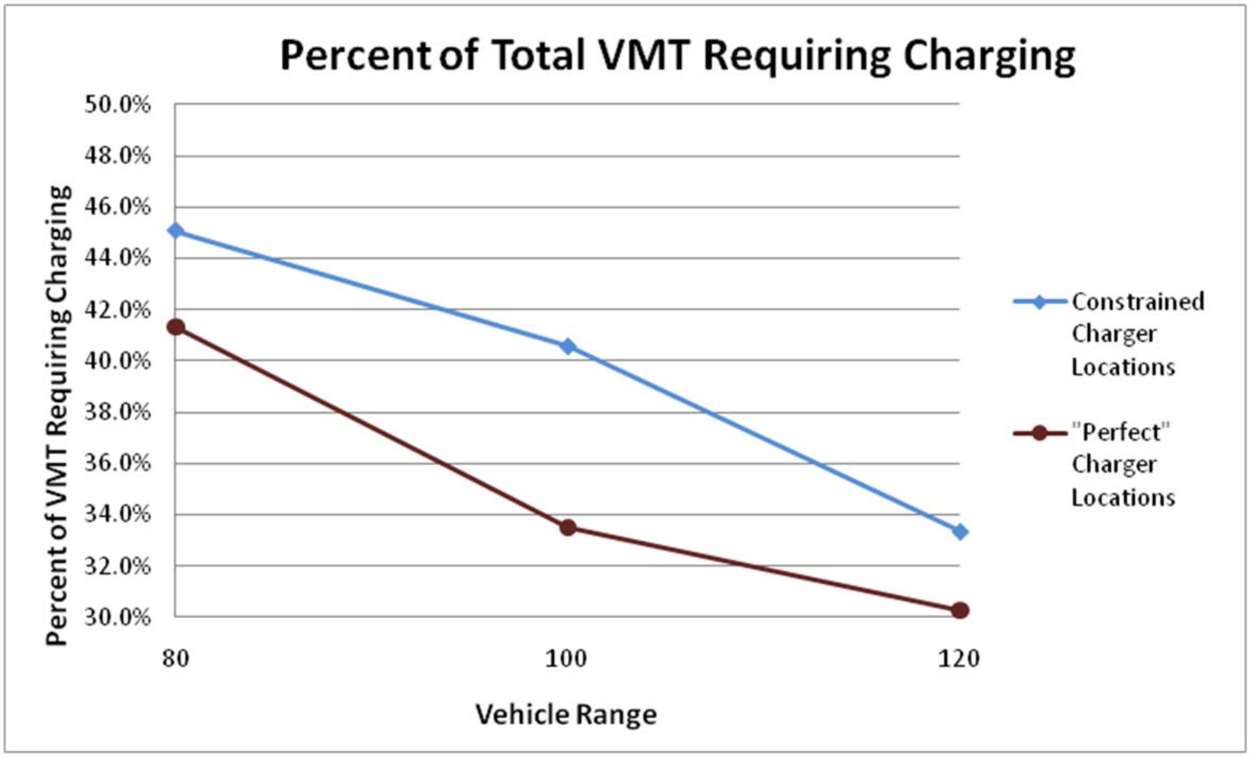

FIGURE 5 Travel that will require some charging in terms of VMT.

In the most conservative case 45% of VMT would require charging. Even with a range of 120 miles and allowing the battery SOC to drop to zero, approximately 30% of VMT would require some charging if attempted in an electric vehicle. Longer tours obviously account for a disproportionate amount of VMT.

Due to the time required to fast charge and battery limitations on the number of fast charges per day[14], not all tours may be attractive to consumers. We acknowledge that there are many permutations for charging including a mix of level 2 and level 1 and that overnight trips may afford the possibility for drivers on long tours to easily charge their vehicle without the need to use a fast charger. However, for the case of fast charging, we can impose a limit of two charges per tour in order to simulate the aversion to taking an electric vehicle on long tours, opting instead for some other means of transport. For example, A simulation of a 286 mile trip shown in Figure 6 shows that there is an approximate 2 hour time penalty for taking an EV versus a gasoline vehicle.

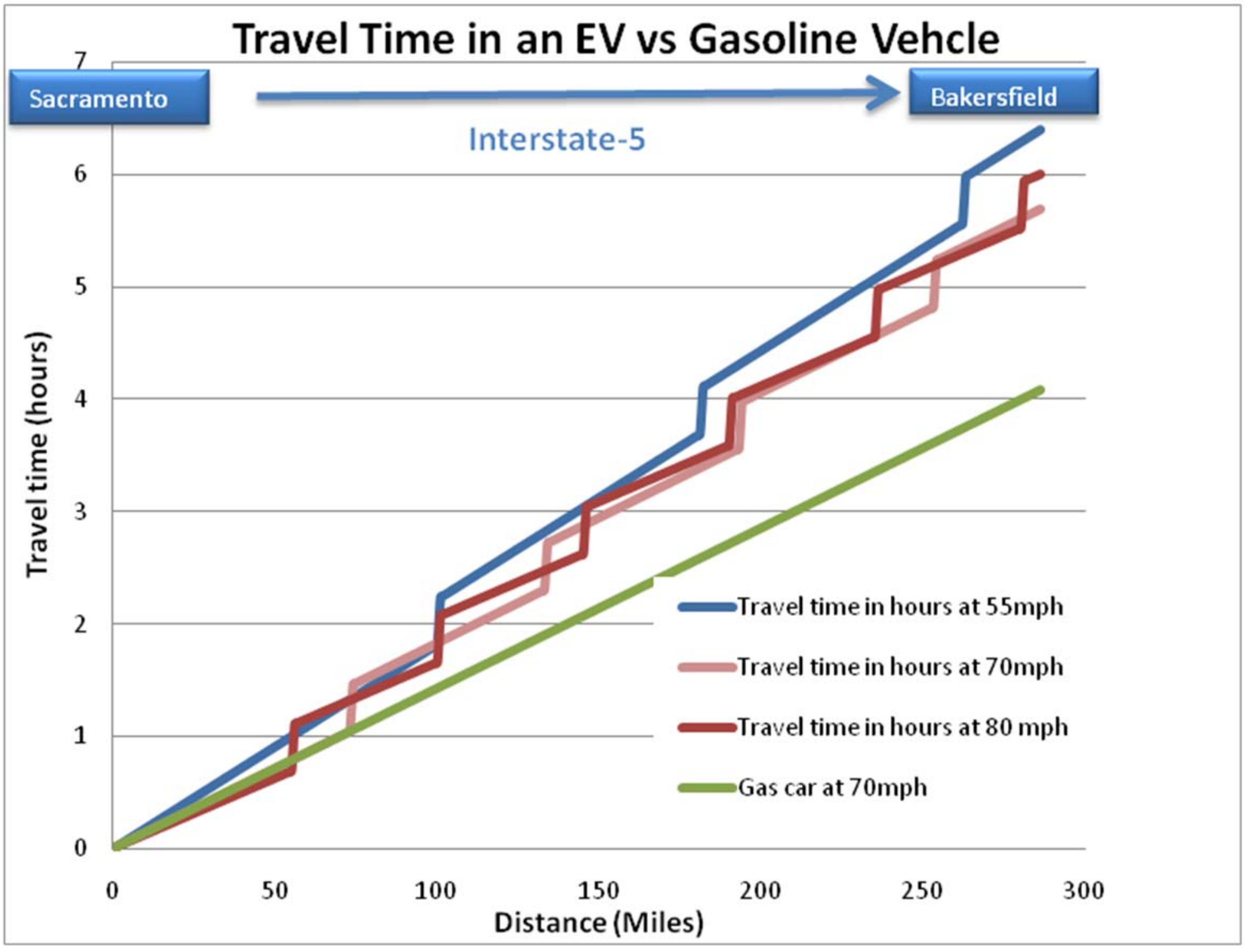

FIGURE 6 Time penalty for driving long distance in an EV. If an EV tries to match the speed of a gasoline vehicle, more charging is needed vs driving slower.

There are fewer charging events if the driver travels slowly, but the driving time is longer. Conversely, if the driver increases speeds, there are more charging events necessary resulting in arrival time similar to driving slower.

Because of the time penalty imposed upon a driver for longer trips, we study the effect of limiting the chargers per tour to two. Especially in the location constrained scenario, we see a drop in the percentage of tours that would be taken in an electric vehicle using these assumptions. 8.3% tours need some sort of charging, but only 5.5 percent of tours could be served with two or fewer fast charges. In terms of VMT, a more nuanced picture emerges when examining tours with only 1-2 fast charges (Figure 7).

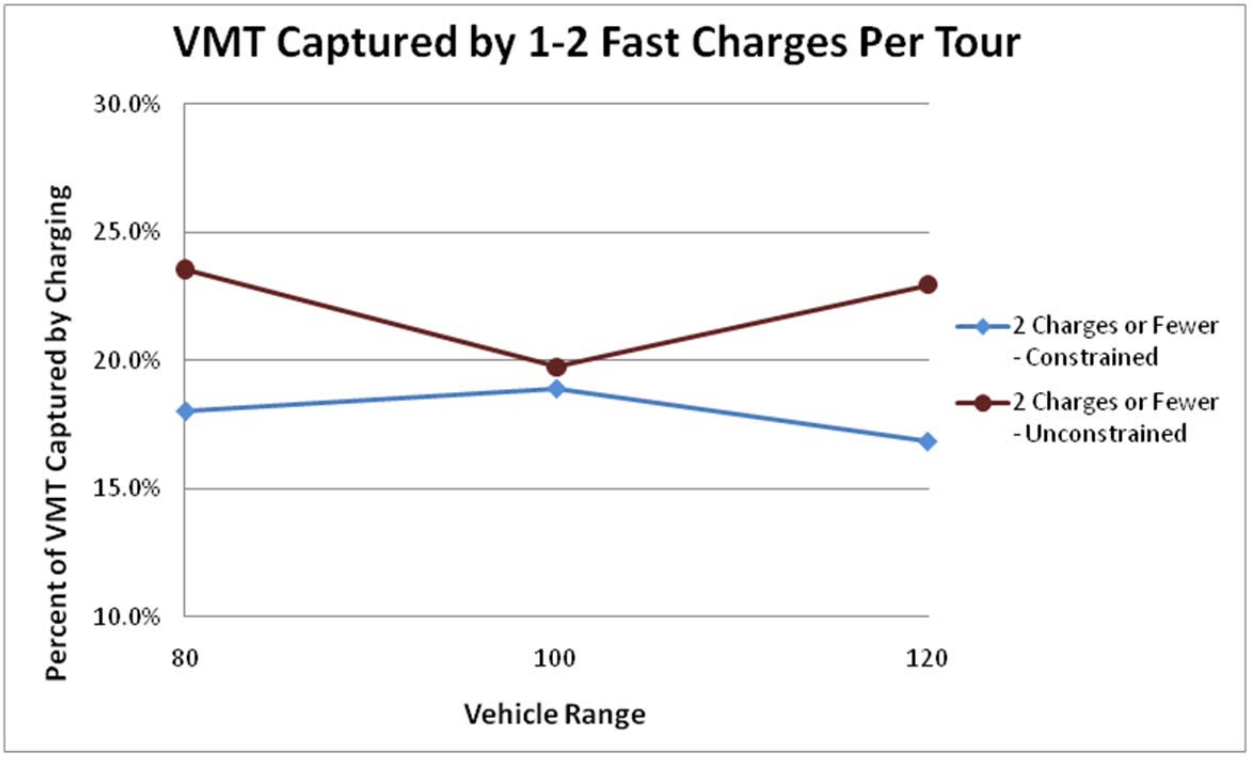

FIGURE 7 When focusing on VMT able to be captured by 1-2 charges per tour, a large proportion of VMT could be enabled by fast charging

By enabling tours requiring only 1-2 fast charges, between 17% and 24% of VMT could be captured. In the unconstrained scenario, more VMT is captured than in the constrained case because the tours requiring charging are on average longer, even though the total number of tours may be smaller in some cases. For the 120 mile range unconstrained case, 23% of VMT is captured by 1-2 charges leaving only 7% of total VMT uncaptured.

Time of Day and Day of Week Congestion

A challenging aspect of fast charging is that there is there is less opportunity to temporally shift demand. A driver may use fast charging en route to a destination and hence is less able to wait for when electricity would be cheaper, less congestion would be on the electrical grid, or would be cleaner. The paradigm for fast charging may be the need to meet demand when a driver arrives to charge. To investigate when drivers would show up, the day and time of each simulated charge event was recorded. An example of the temporal pattern of demand is shown in Figure 8.

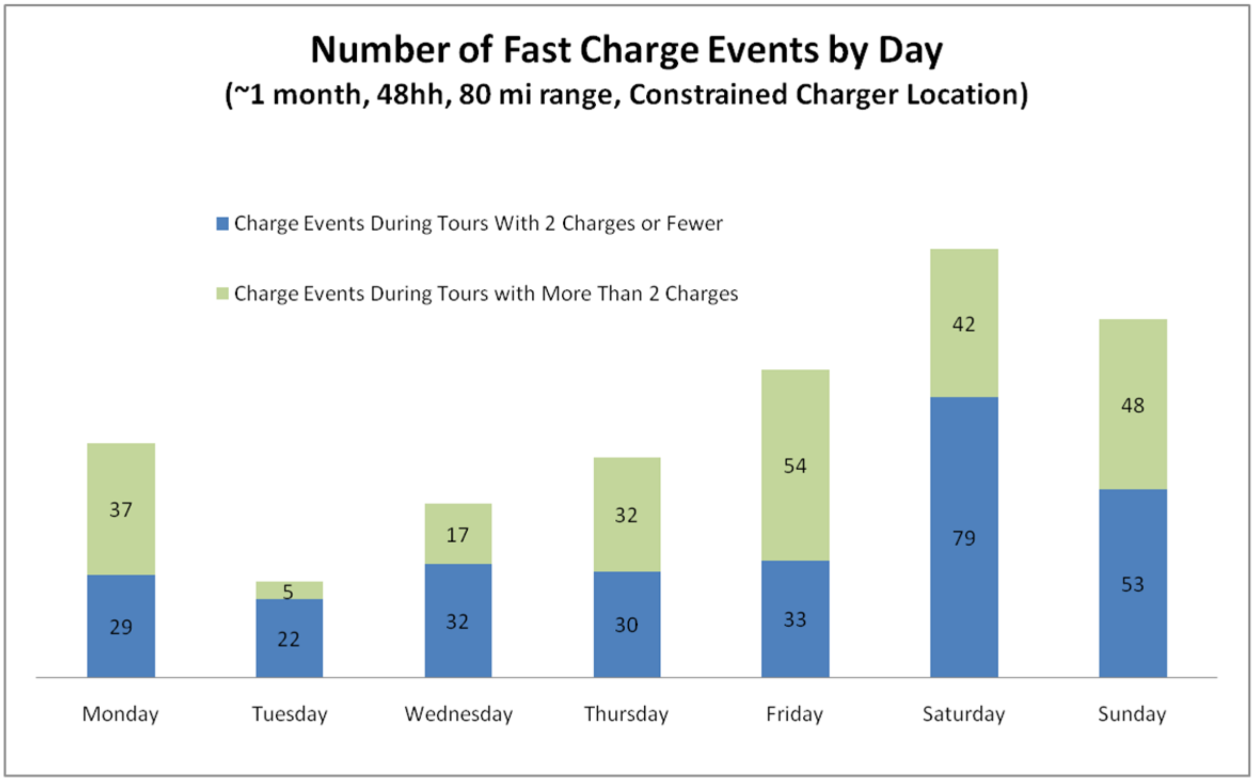

FIGURE 8 Longer tours are taken on or near the weekend prompting a need for fast charging in the simulation.

The results are broken down into charging for tours with two charges or fewer and for greater than two charges per tour. Although it is difficult to generalize from a sample of only 48 households, it appears as though there would be an increasing demand for fast charging near or during the weekend. Interestingly, a large proportion of the charging events on Friday appear to be for tours requiring more than 2 charges per tour. Although this requires more investigation, perhaps survey respondents are taking a longer weekend trip and this starts Friday. On the weekend, perhaps trips to regional medium distance destinations are taken.

The time of day that fast charging would be needed in the scenario also shows some patterns. An example from the 80 mile range constrained location case is shown in Figure 9.

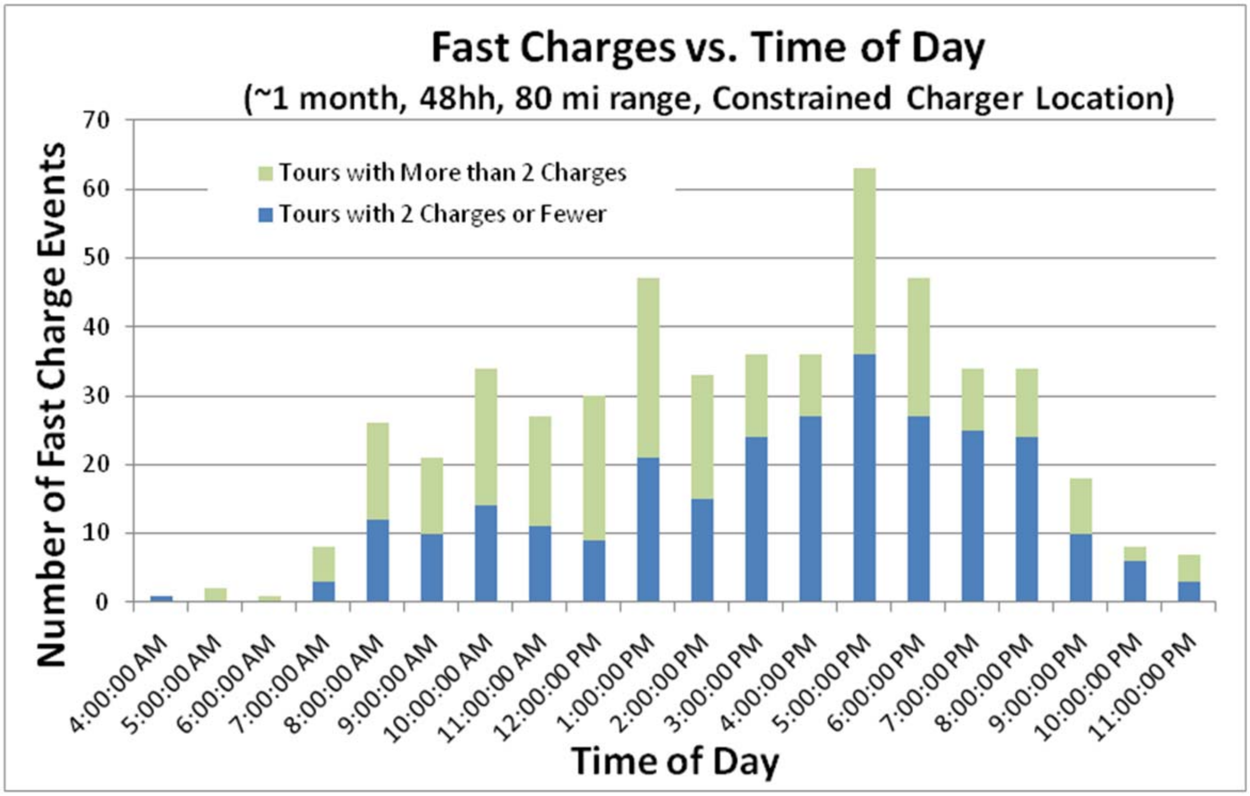

FIGURE 9 Fast charging would potentially be needed most in the afternoon. This has implications for congestion at chargers.

Demand for charging is higher closer to 5PM both before and after. This would indicate there might be some congestion at chargers during the afternoon. This could signal that more than one fast charger will be needed per site if peak demand is to be satisfied. Additionally, the relatively higher demand occurs in the simulation when the electrical grid is at higher loads. This may also have implications for criteria pollutant emissions from power plants since emissions per kWh generated are generally higher during times of higher grid loads[3].

Location of Demand

Following the 2 fast charges or fewer cutoff introduced earlier, we can examine the dynamics of charger location in relation to range. In Figures 10, 11, and 12 we see that as range increases in the constrained scenario, the location of simulated demand shifts from close to home to farther away.

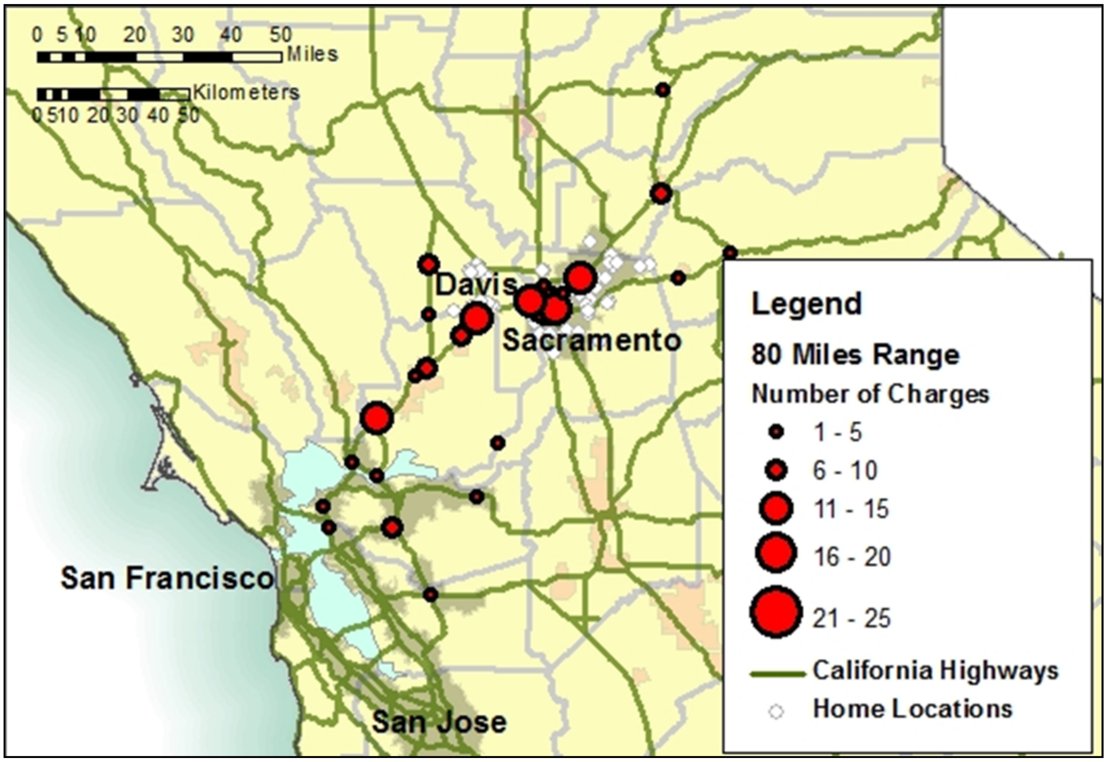

FIGURE 10 Charging using a simulated vehicle with 80 miles range, but not allowed to go below 20% SOC. Charging is demanded near home.

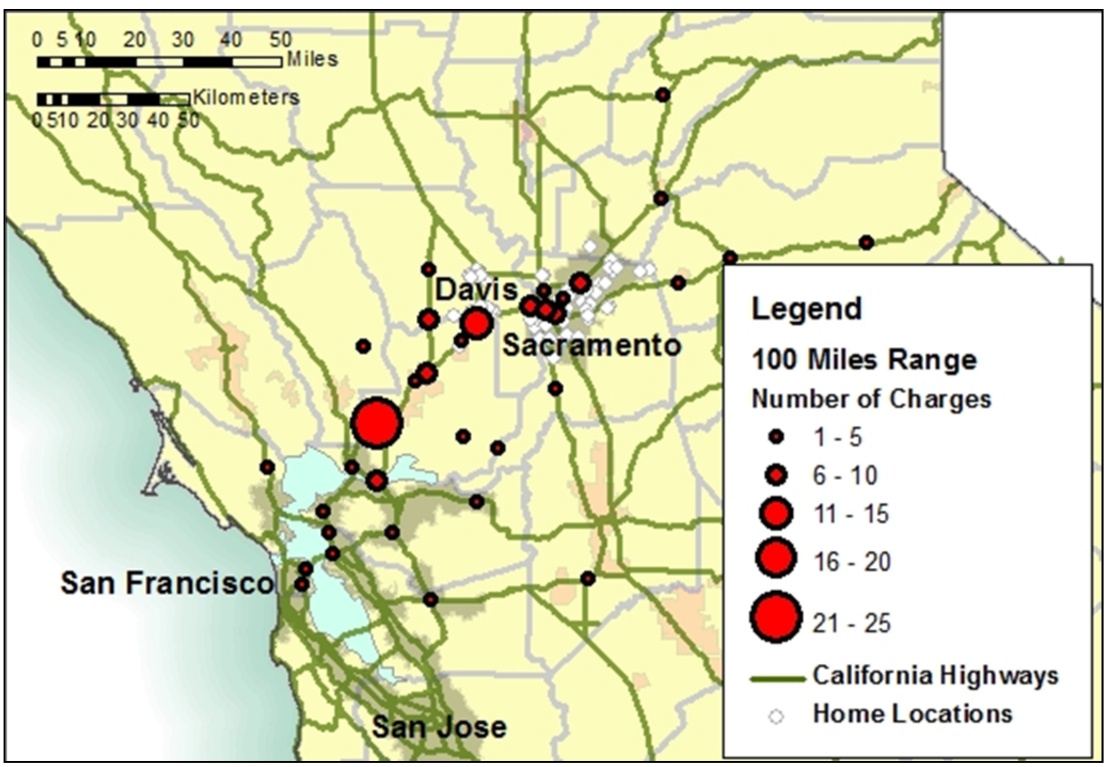

FIGURE 11 Charging using a simulated vehicle with 100 miles range, but not allowed to go below 20% SOC. Charging is demanded near home and the adjacent-region corridor.

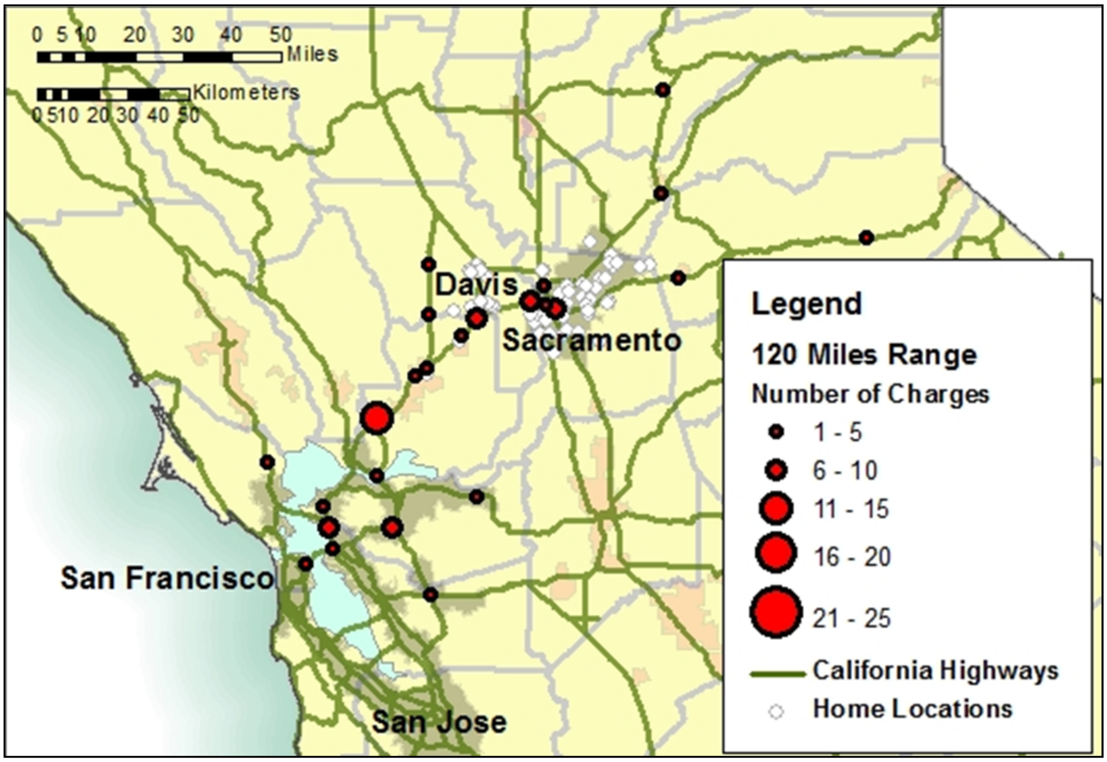

FIGURE 12 Charging using a simulated vehicle with 120 miles range, but not allowed to go below 20% SOC. Some charging is demanded near home, some on the adjacent-region corridor, and some near regional destinations.

In Figure 10 with an 80 mile range, and the prohibition of going below 20% SOC, we see that much more fast charging is would be used within range of home and that the farthest destination is 74 miles away. The total number of fast charges was 126 for tours requiring 2 charges or less. In Figure 11 we see that fewer charges would be needed near home and that one particular charger situated between the Sacramento Region and the San Francisco Bay Area is the most heavily used in the simulation whereas the chargers in near home would be less frequently used. The total number of fast charges was 106. When the range of the vehicle is increased to 120 miles, fewer overall charges fell into the 1-2 charge per tour range at 71 charges. They were on average farther away.

DISCUSSION

We model a scenario in which all public charging is completed using fast chargers. Although the future public charging network will consist of primarily level 2 charging, not all charging can be served for all tours using level 2. Drivers will from time to time not be able to use level 2 charging for a variety of reasons: a driver may not find a spot to charge because the chargers are occupied where he or she parks, there are no public chargers near the destination or there is not enough time to charge while parked. In all these scenarios, level 2 charging will not be sufficient to complete a journey. Additionally, if a destination is beyond the range of an EV, fast charger would be needed. DC fast could provide a solution in all of these situations.

In our simulation, we find that when range is varied between 80 and 120 miles and the charging scenario has either perfect location or some compromise in location, between 3.5% and 8.3% of tours would require charging of some sort. This corresponds to 30% -45% of VMT. Although as much as 45% of VMT would require some public charging in order to complete all of the trips in the sample with an EV, the exact percentage of the VMT that customers would choose to attempt in an electric vehicle is unknown. Some have posited that fast charging could be the solution to serving these VMT. However, as suggested by the trans-regional simulation in Figure 6, we see there are large time penalties for driving long distances in an EV begging the question as to whether customers would even attempt driving an EV to far away destinations. Conversely, some tours would only require 1-2 fast charges to complete in an EV. As this could be reasonable in terms of time, we focus on how fast charging could address these tours. Through our simulation we find that up to 3.1%-8.3% of tours requiring charging would need 1-2 fast charges per tour. This accounts for 17% - 24% of VMT depending on the range and charging scenario.

We also find that the fast charging in the simulation does not happen evenly throughout the week or the time of day, portending possible congestion at chargers. The most popular days to charge would be Saturday and Sunday and the most popular time to charge would be 5 PM. Since shifting the time of fast charging is likely more difficult than for level 2 charging, congestion at fast chargers may occur, especially on the weekend and near 5PM. This has several implications. First, if demand is to be served, more fast chargers may be needed per location. Second, pricing may need to be increased during peak hours or peak days to encourage only those who really need to fast charge to do so. Third, if fast charging is demanded around 5PM, electricity with more emissions per kWh may have to be used decreasing the attractiveness of fast charging from an environmental perspective. Fourth, the time of day of demand may create strain on the grid during hot days. Some of these issues could increase the attractiveness of electricity storage near the DC fast charger whereby energy is stored during times when electricity emissions, prices, and electricity grid strain are comparatively lower.

Finally, the location of demand when we focus on tours requiring 1-2 charges shows some interesting patterns as the range of the vehicle in the simulation increases. When the range of the vehicle is 80 miles, factoring in not going below 20% SOC, a large portion of the demand may happen within range of home, reflecting one of two situations. First, a vehicle does not travel far away from home, but a long trip chain to several locations necessitates charging before returning home. Second, a vehicle may be just shy of returning home from a far away destination and needs to charge. In the first case, level 2 charging may be able to address some of these tours, provided level 2 charging is at the appropriate parking locations. However, as noted earlier, level 2 charging cannot be counted on in all situations making DC fast charging a viable option. In the second case, fast charging may truly be required to complete the tour. The maximum distance away from home for a destination was 74 miles.

As the range of the vehicle increases, many more adjacent-region tours are enabled with 1-2 fast charges per tour. Demand for charging goes down in one’s own region. For the 100 mile rage case where the SOC does not fall below 20%, a charger that is 30-50 miles away from driver’s homes appears particularly useful. However, more information is needed to generalize any charger distance metrics. This location was also the convergence of two interstates and so may be special in this respect. As the range of the vehicle increases to 120 miles, the overall number of simulated fast charging events decreases and the location of charging shifts farther away from home.

There are limitations in this analysis meaning that generalizing the results should be done with caution. Since we are taking a sample of people who are driving without the constraints of an EV many of the tours described in this simulation may not be taken in an EV at all. For example, we do not quantify the aversion to waiting approximately 20 minutes to charge. If an EV is not chosen for these longer trips then the simulated demand is inaccurate. Nor do we take into account that drivers who take longer trips on average may not even buy an EV, additionally making the demand reflected in this simulation inaccurate.

Another factor not dealt with in this analysis is public level 2 charging. In some cases, level 2 charging would be sufficient to complete the tours which exceeded vehicle range since the vehicle may be parked for the required amount of time to charge and complete a tour. Nor does this analysis single out overnight trips. Some of which could be served by even level 1 charging such as might be available at a friend's house.

Also, as suggested in the TEPCO study [10] the existence of fast charging may actually preclude its use in some cases. In the charging scenarios presented above, drivers did not use all of their range and always kept some range in reserve. The existence of fast chargers may encourage drivers to let their state of charge drop below 20% SOC simply because they have the assurance of being able to quickly charge if only a little bit more range is needed. This situation is not modeled in the simulations.

Finally, the charging scenarios presented here may be region specific. The Sacramento Region, although large, is not as large as the nearby San Francisco Bay Area. This may attract travel to the Bay Area, but if the same analysis were done in the Bay Area, would Bay Area drivers want to come to Sacramento in the same numbers? This dynamic is left for future analyses.

CONCLUSIONS

Although this paper only provides simulated demand for EV charging, the data upon which the simulation is based are actual driving patterns. Because these are actual data over 1 month, we can capture household travel which may include infrequent long trips or we can see that a no travel over a certain distance was taken. This enables us to more accurately describe how a travel could be completed with the aid of charging.

Despite some limitations, this analysis highlights the situation where public charging is not available where or when a driver needs it. It might not exist near where a driver parks, or the charger is occupied by another vehicle. Especially in the early years of EV infrastructure roll out, level 2 chargers won't be ubiquitous. The chance of being able to provide a charger in exactly the right parking spot 100% of the time seems unlikely. In these cases, the location and timing of demand shown in this paper will be applicable. For location, fast charging appears universally useful on adjacent-region corridors, and appears useful near home to varying degrees based on vehicle range. Around 20% of household VMT could be enabled for EVs assuming 1-2 fast charges per tour were acceptable.

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