

Electric Vehicle Driving, Charging, and Load Shape Analysis

A Deep Dive Into Where, When, and How Much Salt River Project (SRP) Electric Vehicle Customers Charge

2018 TECHNICAL REPORT

Electric Vehicle Driving, Charging, and Load Shape Analysis

A Deep Dive Into Where, When, and How Much Salt
River Project (SRP) Electric Vehicle Customers
Charge

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Final Report, July 2018

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ABSTRACT

Understanding when, where, and how much drivers charge allows utilities to adjust their load projections to include additional load from increased electric vehicle (EV) adoption. This report presents the results of a vehicle tracking study conducted in the Salt River Project (SRP) service territory June 2016 through January 2018. Through use of vehicle data logging devices, 100 EVs (both battery and plug-in hybrid EVs) were tracked during driving and charging events to acquire minute-level, high-resolution data; once the data were checked for integrity, 70 vehicles were included in the study. During charging events, voltage, current, GPS location, and state of charge (SOC) were collected. During drive events, additional data were collected such as mileage. Specifically examined were the charging differences between major EV model types: the Nissan LEAF, Chevy Volt, and Tesla.

Summary energy statistics included total yearly kilowatt-hours (kWh) and whether charging occurred at home, at work, or in a public location. On average, vehicles used 2,700–3,300 kWh per year, with 80% of charging occurring at home. Kilowatt-hour usage was higher for Teslas and lower for Nissan LEAFs and Chevy Volts.

Load shapes for weekends and weekdays as well as for different rate structures were generated. More than half of the vehicles enrolled in the study were enrolled in a time-of-use (TOU) rate. For these customers, the TOU rate was very effective in shifting peak load into the nighttime and early morning hours.

When using only meter data, only one vehicle charging location can be monitored. By placing data loggers on the vehicles themselves, both driving data and charging information can be gathered, regardless of where charging occurs. This method provides a better estimate of total charging for future EV grid projections.

Keywords

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Kilowatt-hour (kWh)

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Charging power

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Plug-in hybrid electric vehicle (PHEV)

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PRIMARY AUDIENCE: Distribution planning, substation planning, service planning, asset management, customer care, procurement, energy supply, generation, and electric transportation personnel

SECONDARY AUDIENCE: Automotive manufacturers and city planners

KEY RESEARCH QUESTION

Insights into when, where, and how much drivers charge allows utilities to adjust their load projections to include additional load from increased electric vehicle (EV) adoption. Understanding how these EV customers react to price signals through time-of-use (TOU) rates is also important in understanding how this load could potentially be shifted to times when utilities have excess grid capacity.

RESEARCH OVERVIEW

This report presents the results of a vehicle tracking study conducted in the Salt River Project (SRP) service territory June 2016 through January 2018. Data loggers were placed in approximately 100 EVs over the 18-month time period to collect information on vehicle voltage, current, and power during driving and charging events. Once filtered, data from 70 vehicles were then aggregated to show the combined grid load, whether drivers were charging at home, at work, or in a public charging location. Specifically examined were the charging differences between major EV model types: the Nissan LEAF, Chevy Volt, and Tesla.

KEY FINDINGS

- EVs use approximately 2,700–3,300 kWh per year.
- Utility TOU rates are very effective in shifting peak loads.
- While DC Fast charging comprised less than 3% of the total energy used in the study, DC Fast charging was the cause of most of the peaks in the total project load.
- Approximately 81% of charging occurred at home, while only ~3% of charging occurred in public charging locations.
- The majority of charging occurred at Level 2 (74.0%), followed by Level 1 (23.4%) and DC Fast charging (2.5%).

WHY THIS MATTERS

This project provides baseline information on EV charging characteristics to understand utility revenue opportunities as well as potential grid load impacts. The project also documents the effects of a TOU rate on EV charging behavior, a key tool that utilities can use to help shape grid load.

HOW TO APPLY RESULTS

While there have been attempts to understand and document EV driver behavior, many efforts fall short. Tracking studies that document utility advanced metering infrastructure (AMI) meter data miss the charging that occurs away from the base meter. Studies that use survey methods to log EV driver behavior often miss the mark because people generally cannot answer questions accurately on how much they drive (and charge). Finally, many studies track conventional vehicles and are then modified to adapt to an EV perspective, which requires far too many assumptions. The deep dive presented in this report addresses issues regarding minute-level, high-resolution data and tracking of vehicle movement from home to work as well as on road trips. The quality and resolution of the data allow not only for summary level statistics for drives and charges but also for time-series analysis of load data, which is usually only available with meter data.

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1

ELECTRIC VEHICLE MARKET OVERVIEW

As of March 2018, 813,000 electric vehicles (EVs) have been sold in the United States. March was the highest selling month to date with a total of 26,373 EVs sold, 35% of which were Prius Prime vehicles. As shown in Figure 1-1, since June 2015, battery EVs (BEVs) have outsold plug-in hybrid EVs (PHEVs), but the ratio of the two remains close to 50%. Approximately half of the EV sales in the United States are in California.

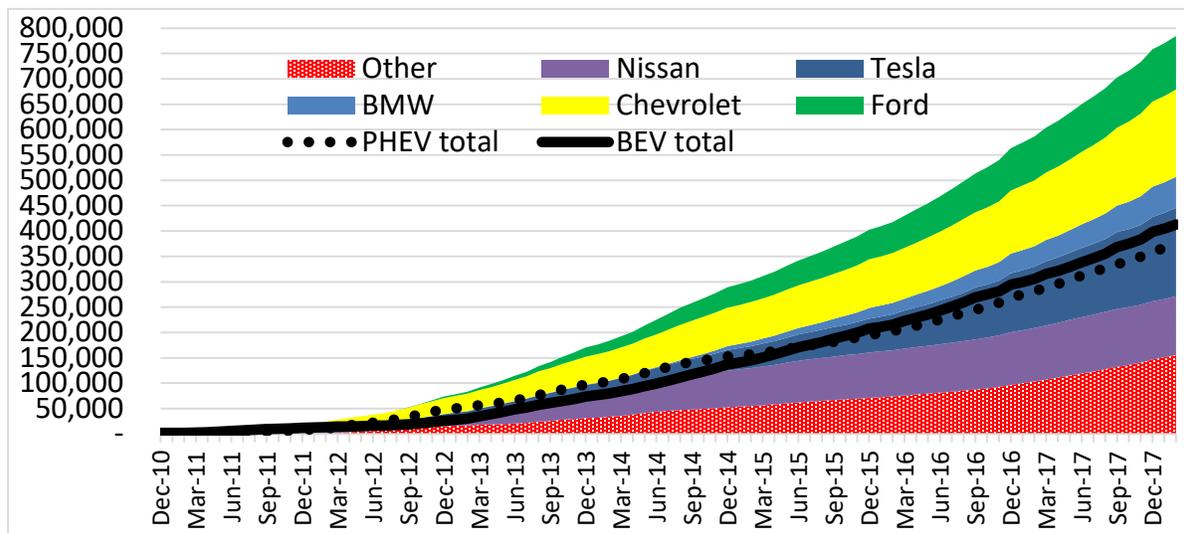


Figure 1-1
EV sales in the United States through the end of March 2018

At present, there are 45 EVs available for purchase on the market. While the EV market started primarily with smaller city cars, this is beginning to change; by 2022, 30% of the projected vehicle models will be SUV/crossovers, which is the best-selling vehicle segment currently, as illustrated in Figure 1-2.

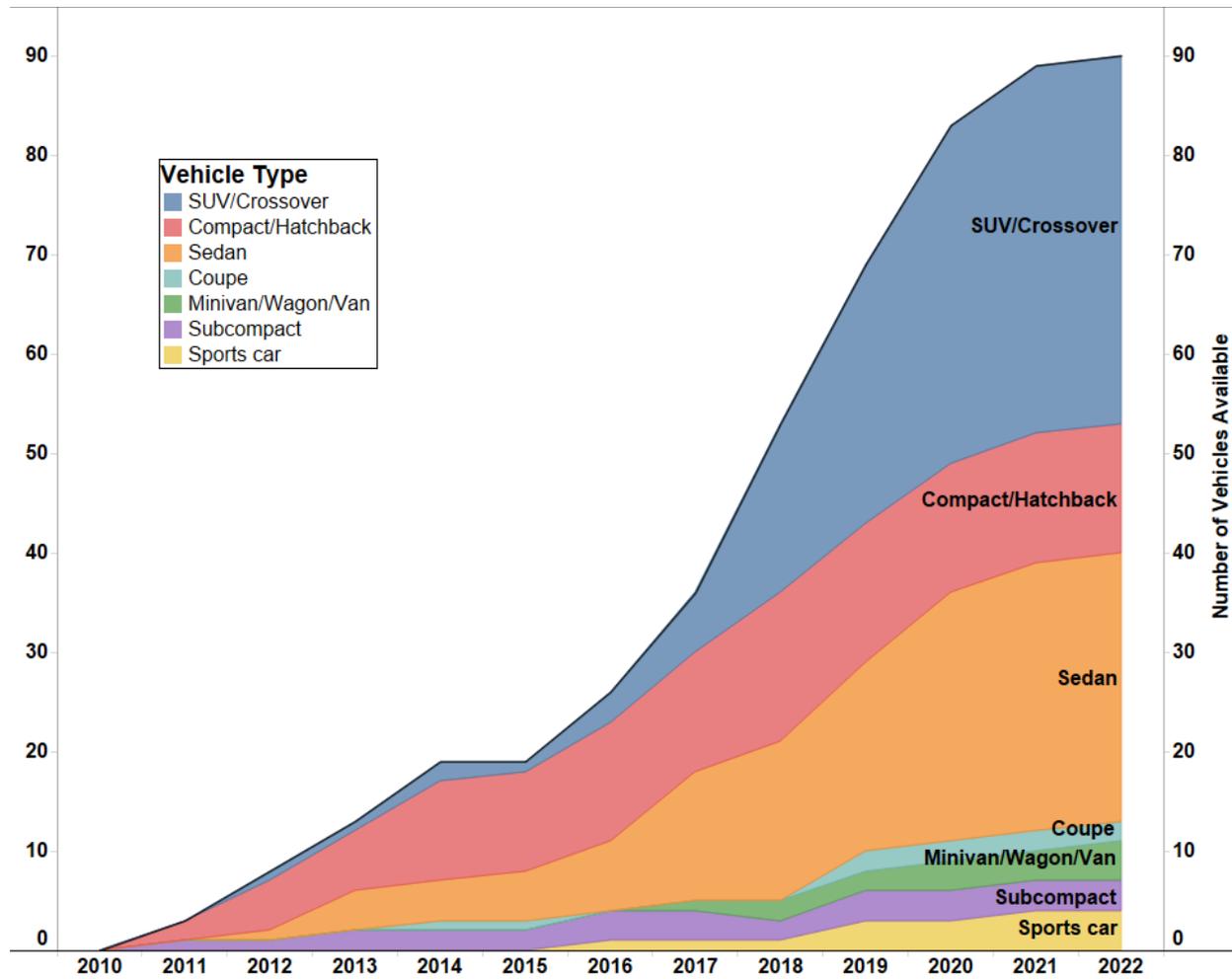


Figure 1-2
Number of both BEVs and PHEVs available each year out to 2022, with colors indicating the vehicle model type

Other factors are also increasing the EV adoption rate. First, there are more longer range and affordable BEVs on the market. Figure 1-3 removes PHEVs from the analysis and shows only BEVs, which will total approximately 45 EV types by 2022. The figure also includes a line showing the average electric range each year. The range continues to increase each year, with a corresponding decrease in battery prices over time.

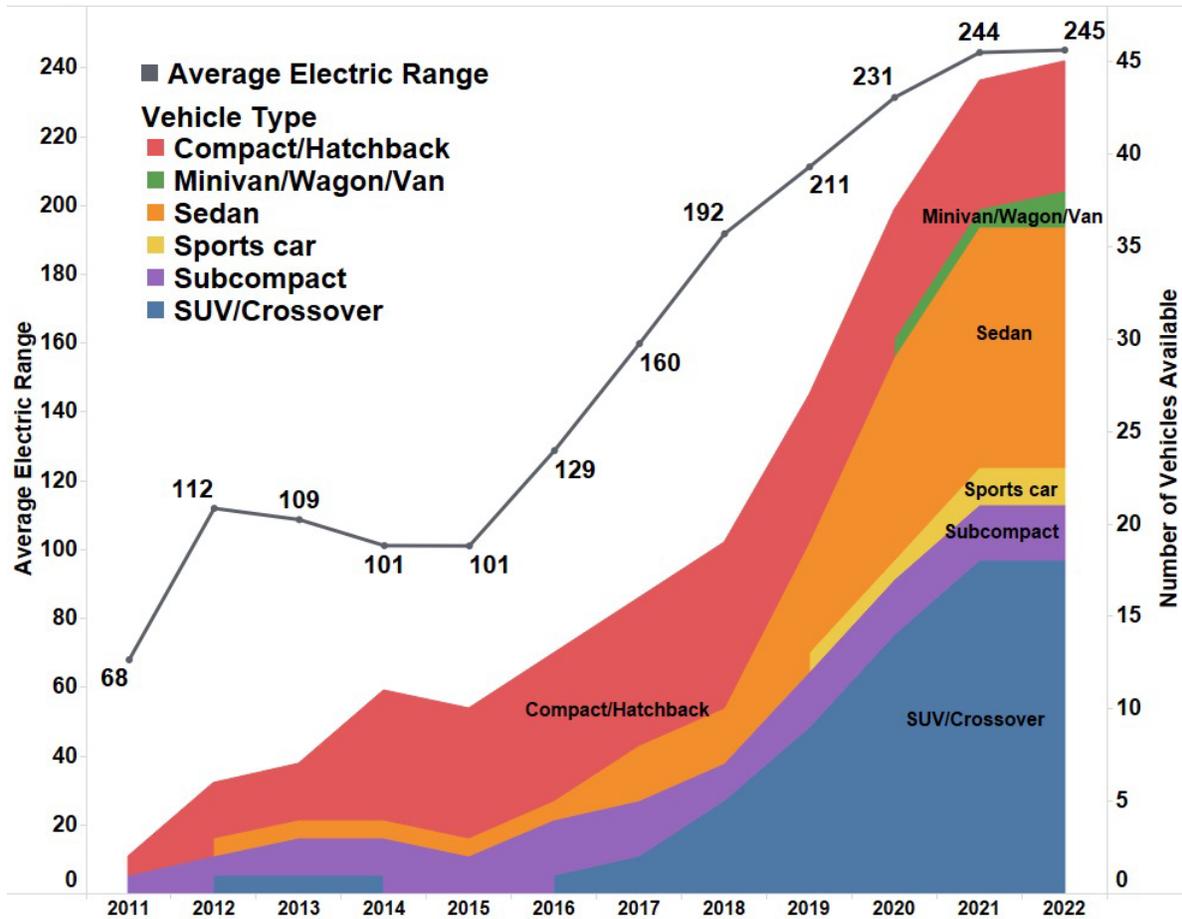


Figure 1-3
Number of BEVs available each year out to 2022, with the black line showing the average electric range of the vehicles each year

As shown in Figure 1-4, charging power is increasing as well. While it can be argued that charging an EV is more similar to charging a cell phone than a conventional gasoline-powered vehicle, the time it takes to charge an EV is approaching that of a conventional vehicle. At a power of 350 kW (a charging power that is projected to be available by 2020), a BEV can fully charge in under 10 minutes. Currently, the fastest charging vehicle, the Tesla, can charge at 125 kW. The results of the study presented here are very important in that they help explain how often EV drivers use DC Fast charging as it can cause a significant peak on the utility grid.

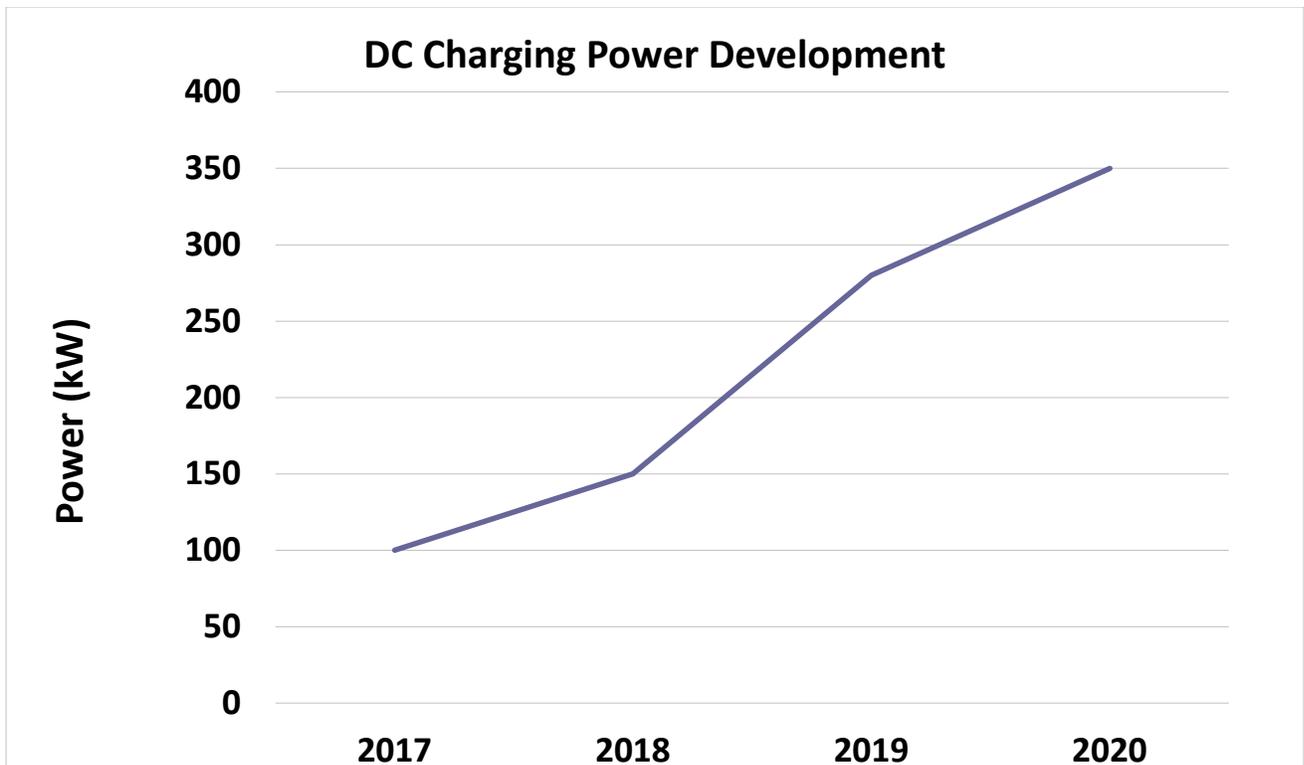


Figure 1-4
EV charging power over time

Currently on the market are two low-cost, long-range BEVs, the Tesla Model 3 and the Chevy Bolt. While Tesla received 400,000 pre-orders for its Model 3 in a one-month time period in 2017, the company is currently limited by manufacturing constraints. The Chevy Bolt hit the market in late 2016 and has had steady sales since its release. It remains to be seen whether the Tesla preorder customers are patient enough to wait for their vehicles or will opt for another electric vehicle on the market.

An Arizona Perspective

As of April 1, 2018, there were approximately 12,000 EVs in Arizona. There has been a recent uptick in vehicle sales as of 2018, as shown in Figure 1-5. A significant portion of these sales is the Tesla Model 3 (a total of 258 have been sold in the first three months of 2018 compared to only 90 Chevy Bolts). However, it must be noted that while the number of EVs selling each month is increasing, EVs still remain only 1.4% of total vehicle sales in the state.

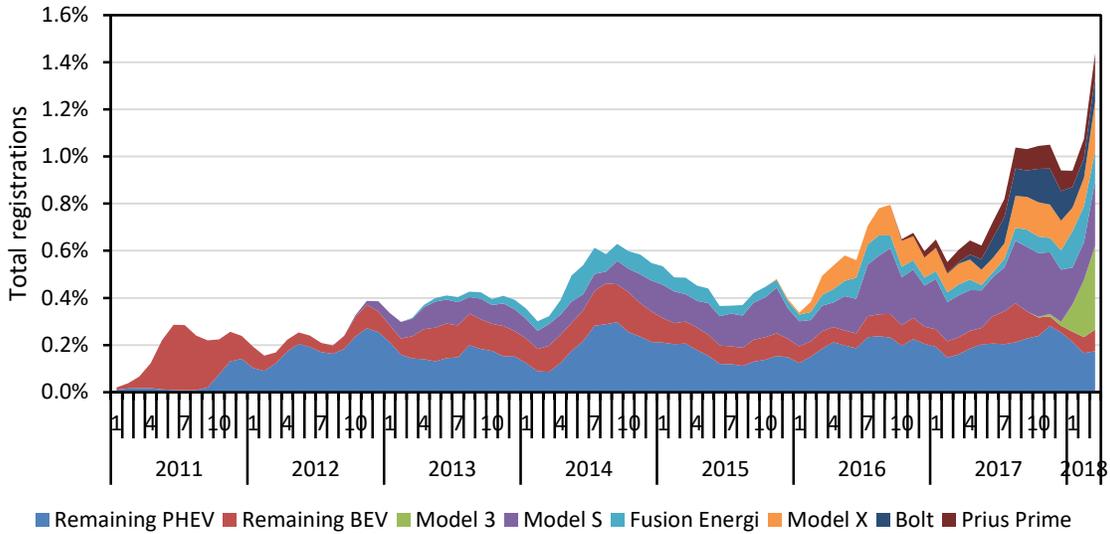


Figure 1-5
Monthly market share of EVs in Arizona (EPRI analysis)

As shown in Figure 1-6, Salt River Project (SRP) territory encompasses approximately half of all EV sales in Arizona (approximately 6,000 as of the end of March 2018).

Annual registrations by vehicle

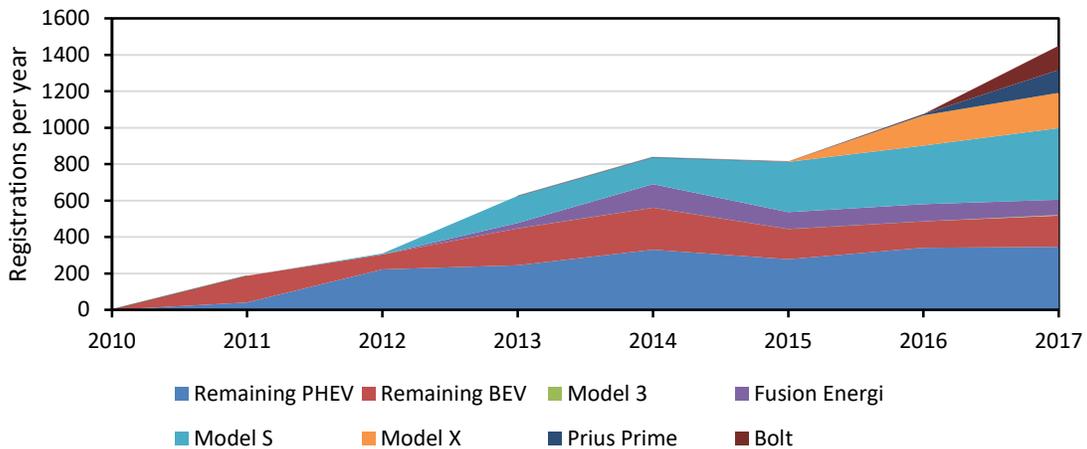


Figure 1-6
Annual registrations by vehicle in SRP service territory

Figure 1-7 illustrates the total number of vehicle sales for the first quarter of 2018. While the Bolt and the Tesla Model 3 are often considered to be competing vehicles in terms of range and price, in SRP territory, the Model 3 is more successful even given the aforementioned manufacturing constraints. When the Tesla Model S, Model X, and Model 3 are grouped together, they total just under 50% of all sales.

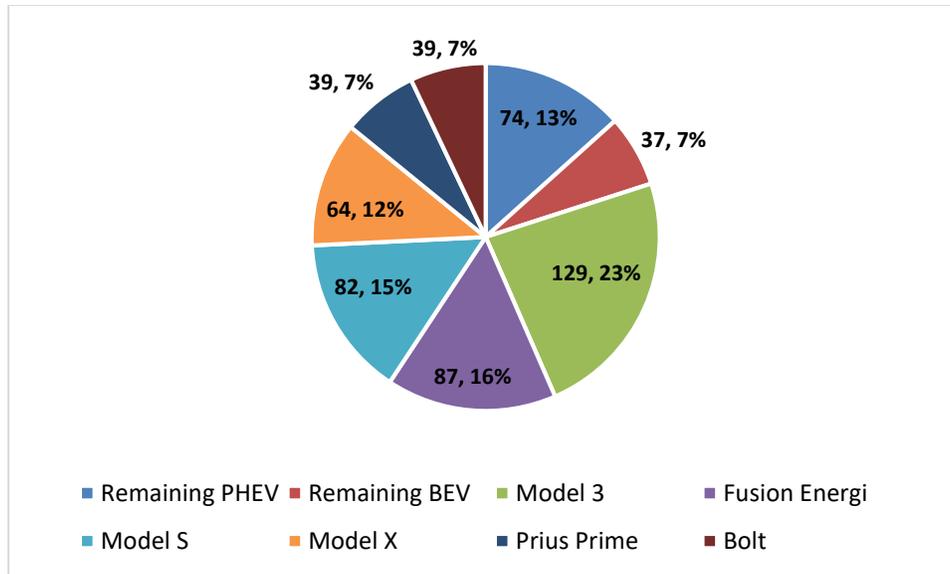


Figure 1-7
EV sales in the first quarter of 2018 denoted by vehicle model

Charging Infrastructure

Figure 1-8 shows the cumulative number of connectors over time in Arizona colored by connector type. The majority of connectors are Level 2 (J1772), which usually deliver AC power at 3–7 kW. While the Tesla Model S/X/3 *can* use slower charging connectors, there are a total of 220 DC Fast charging connectors in the State, of which approximately 75% are Tesla Superchargers.

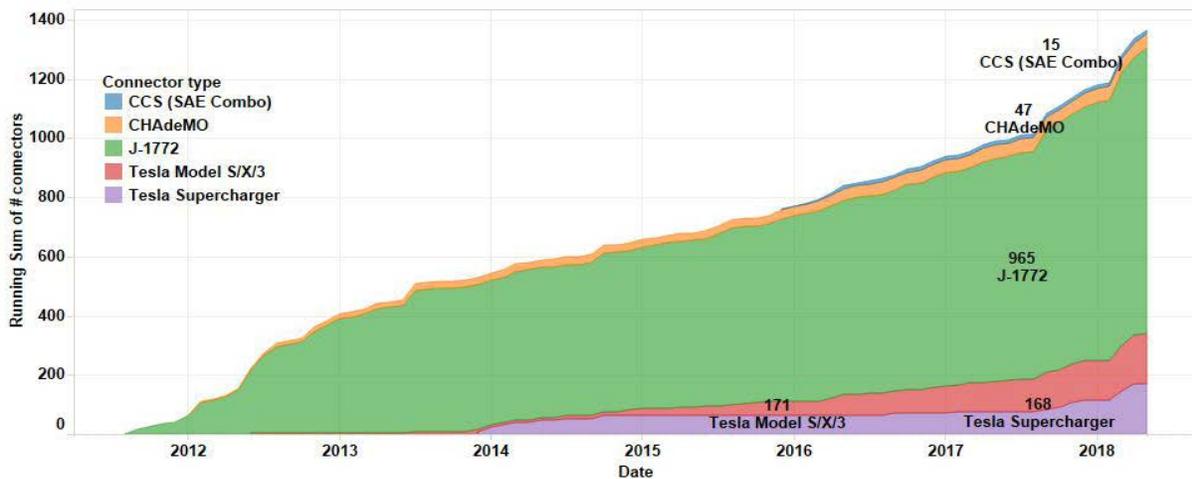


Figure 1-8
Number of public connectors over time in Arizona colored by connector type¹

¹ Data are made available through PlugShare—a crowd-sourced EV charging location app.

As shown in Figure 1-9, given the limited number of CCS and CHAdeMO connectors outside of the Phoenix area, it would be expected that longer road trips would be limited to Teslas as there is not a charging network supporting the other vehicle types. Data from this study indicates that, for a small sample size, this assumption is true. Teslas in this study drove much further than other vehicle types. Whether this driving pattern is influenced by the charging infrastructure or is simply because Teslas have a larger battery is unknown.

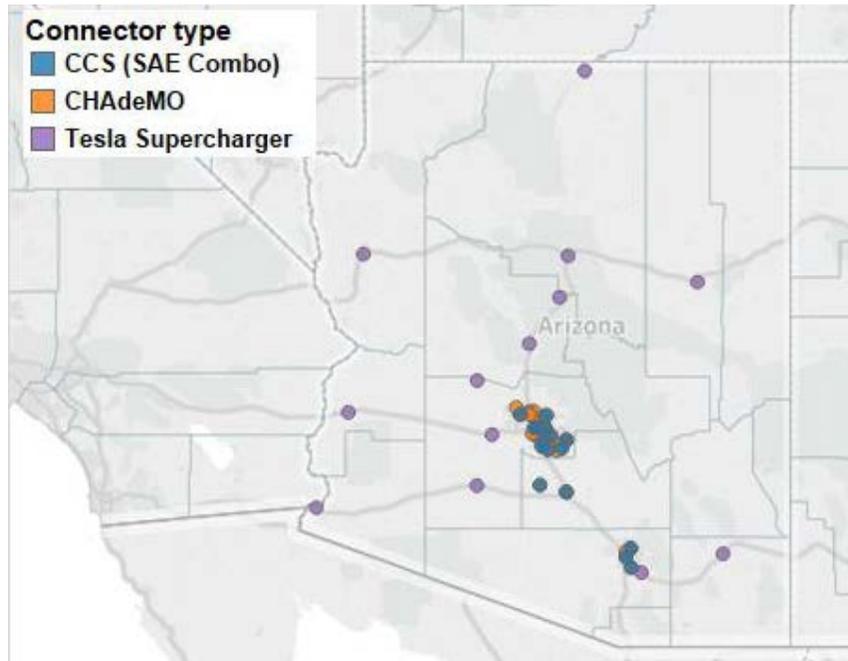


Figure 1-9
DC Fast charging locations colored by connector type. Note that more than one connector may be available at each location.

2

GENERAL PROJECT OVERVIEW

In order to understand how EV owners charge, data loggers were installed in more than 100 vehicles over an 18-month time period from June 2016 through January 2018. While 100 vehicles were enrolled at some point during the study, after filtering the study participants for data quality and consistent vehicle use, 70 vehicles were used for the detailed analysis in this report (more details can be found in Section 3 of this report).

The percentage breakdown of each vehicle model is shown in Figure 2-1. The two largest vehicle groups are Chevy Volts (32.9% of the study with 23 vehicles) and Nissan LEAFs (44.3% of the study with 31 vehicles) followed by six Teslas (both X and S models). The percentages of models in the study do not reflect the current model percentages in Arizona, and any future EV projection analysis must be weighted to reflect the current mix of vehicles in Arizona.

The majority of vehicles were enrolled in the study between June and December 2016. The total number of vehicles enrolled at any one time was variable as some vehicles dropped out and new ones were recruited and enrolled. Figure 2-1 shows the number of vehicles as well as the vehicle model enrolled at any one time during the study. A group of Teslas were enrolled towards the end of the study. The Tesla data, while incomplete, have been preliminarily included in this analysis as Teslas are representative of vehicles with large batteries and fast charging. In fact, SRP has chosen to continue monitoring the Teslas in order to acquire a full year of data.

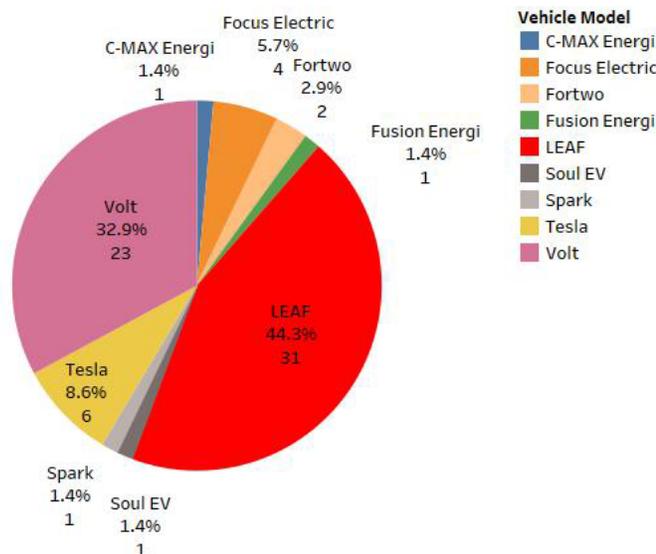


Figure 2-1
Vehicle model representation in the study shows the total number of each vehicle model as well as the percent of the total number of vehicles in the study. This does not reflect how long each vehicle was enrolled in the study.

While the total number of vehicles (as well as the vehicle types) changed over time, as shown in Figure 2-2, all kilowatt information used in the calculations was normalized by the total number of vehicles reporting at any one time. Thus, the average statistics are valid over the course of the study.

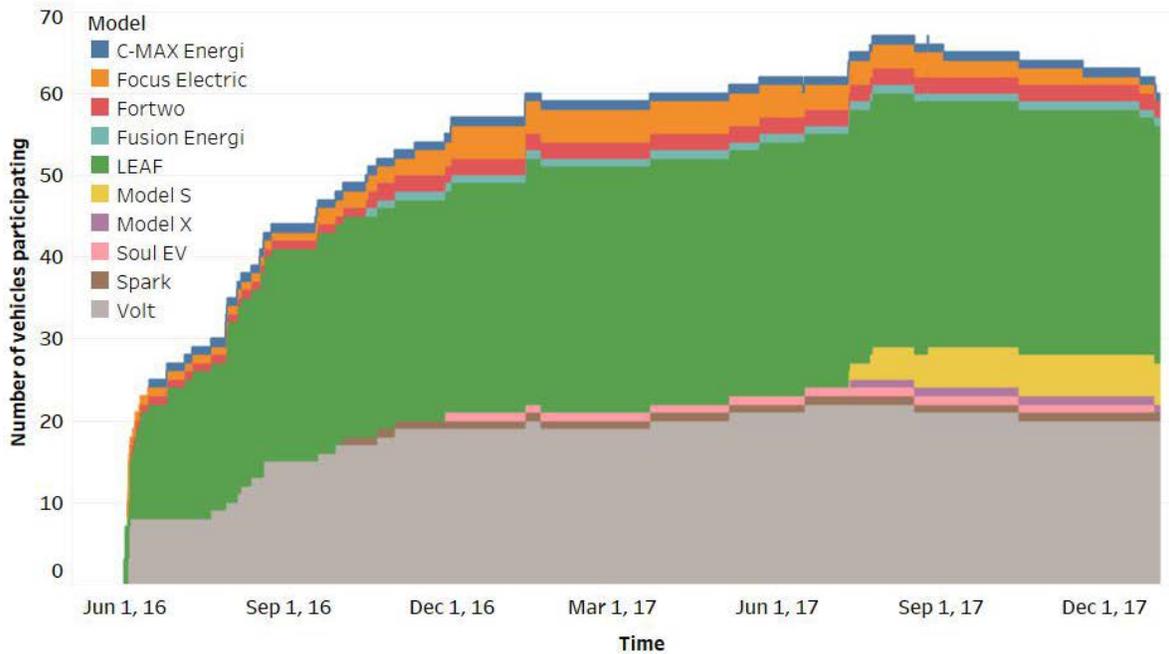


Figure 2-2
Vehicles enrolled in the study over time from June 1, 2016, through January 1, 2018, with color-coding by vehicle model

Table 2-1 shows the high-level data. There were 34,506 charges resulting in a total of 187,818 kWh used. Nearly 1 million miles were tallied over the course of approximately 100,000 drives. When looking at the gross calculations and dividing the total number of kilowatt-hours by the total number of charges, on average, 5.44 kWh were used per charge. Dividing the total number of miles by the total number of drives reveals that an average drive was approximately 8.6 miles long.

Table 2-1
Total number of charges, kWh, drives, and miles driven during the study

Total Number of Charges	Total kWh	Total Number of Drives	Total Number of Miles
34,506	187,818	106,449	915,864

The remainder of the report, which presents results of the vehicle tracking study conducted in the SRP service territory, is divided into four main sections. Section 3, Data, addresses data handling, filtering, and formatting. Section 4, Driving Statistics, examines event-level driving statistics and how they vary by vehicle model. Section 5, Charging Statistics, evaluates event-level charging statistics and how they vary by charge level as well as by vehicle model. Section 6, Charging Load Shapes, considers the load of the vehicles broken down in a number of different ways—from vehicle model to rate plan.

3 DATA

Data for this project were obtained using FleetCarma devices at minute-level resolution. For each minute, a number of different measurements were recorded, as shown in Table 3-1. The type of measurements reported depended on whether the vehicle was charging or driving as well as on the vehicle model.

Table 3-1
Table showing what is reported in the raw data

Measurement	Available for Drive or Charge Conditions?	Comment
Timestamp	Both	Minute resolution
GPS latitude + longitude	Both	Accuracy out to three decimal places—approximately ± 100 meters
Battery current (A)	Both	Reported as positive or negative values depending on the vehicle model, and whether the vehicle was driving or charging
Battery voltage (V)	Both	Except Prius and i3, which did not report during charging events
Battery state of charge (SOC) (%)	Both	Except Prius and i3, which did not report during charging events
Temperature	Both	Outside air temperature
Vehicle speed	Drive	
Is charging/driving?	Both	This measurement, which identifies whether the vehicle is charging or driving, is only available in the newer data loggers.

Soon after generation, the data for this project were delivered to EPRI through a secure FTP site. The data were then processed two different ways, as event summary information and kilowatts over time. In the case of event summary data, for each event whether a drive or a charge, the summary statistics are recorded. For charging events, the summary statistics include the following: time of start and end of charge, total kilowatt-hours charged, maximum kilowatts reached during the charge, and GPS information. For the drive events, similar start time and stop time information is recorded together with specific driving statistics such as miles driven, maximum speed, and gasoline used (if vehicle is a PHEV).

The kilowatts over time data format tracks kilowatts during charging events and allows the addition of load for each vehicle enrolled. Since 15-min resolution is the preferable resolution for utility planning work, for each 15-min segment, average kilowatts, maximum kilowatts, and the standard deviation of the kilowatts were documented. The maximum and standard deviation data were recorded in order to assess the variability within the 15-min segment. For a DC Fast charging event, one 15-min segment may have power from 110 kW to 80 kW that would not be captured fully by stating an average of 95 kW. This can be contrasted with a Level 2 charging event that may experience variability from 6.6 kW to 6.5 kW, where an average of 6.5 kW is more representative of what occurred during the 15-min segment.

Data Quality and Filtering

The data span from June 1, 2016, through December 31, 2017. The original number of vehicles enrolled in the study to some capacity numbered 100 vehicles. While summary information is available for all these vehicles (the number of drives and number of charges), unfortunately, minute-level information during charging is not available for a few of these vehicles, namely, the Prius plug-in and the BMW i3; therefore, they were not included in the study.

To examine the variability in how active vehicles were over the length of the study, the percentage of active days was calculated as follows:

$$\% \text{ active} = \frac{\text{Number of active driving days}}{\text{Total number of days in the study}}$$

A histogram of this calculation is illustrated in Figure 3-1, which shows a wide range of active days. The majority of drivers (over 60%) were active more than 80% of the days that they were part of the study. The histogram curve tails off at 60% active. The drivers below 60% active were either taking extended vacations of over two months duration or were simply not using their vehicles very much. For this data analysis, any vehicle that had an average percent active value less than 60% was not included in the analysis; this filter removed 14 vehicles.

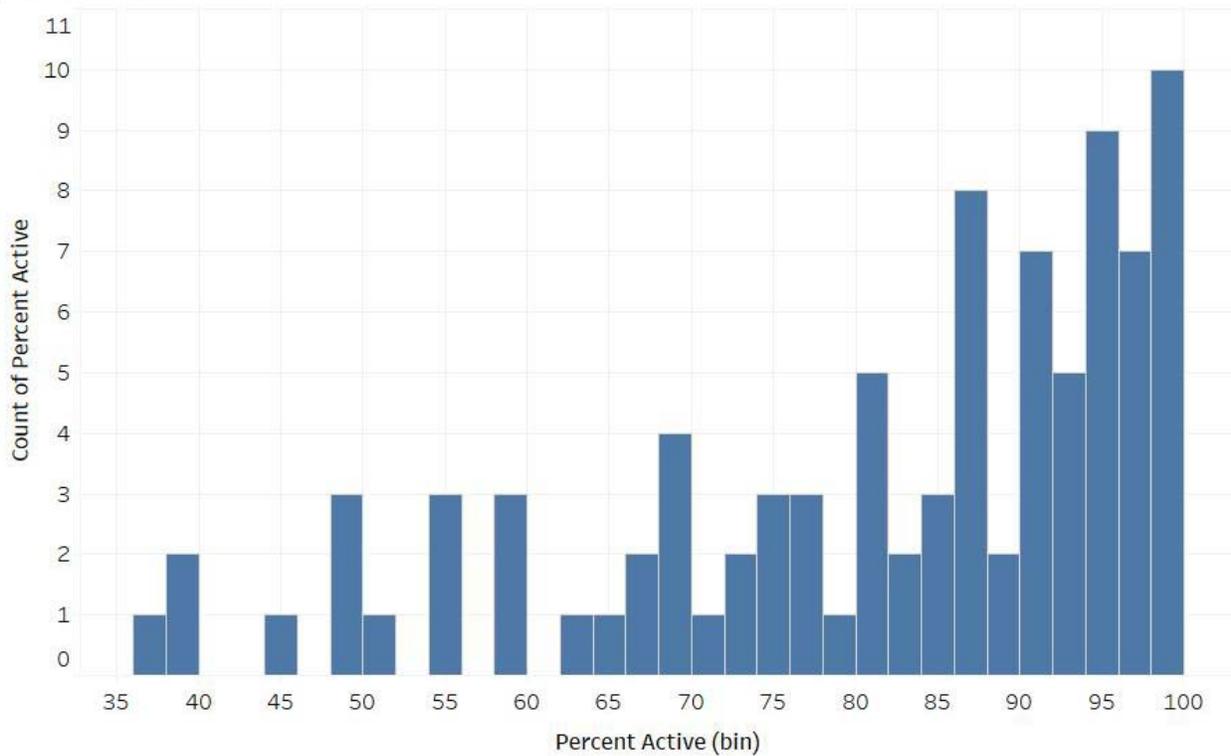


Figure 3-1
Histogram of the percent active for all vehicles enrolled in the study

In addition to the percent active driving filter, some of the initial vehicles enrolled either dropped out before being in the study a month, removed the loggers from their cars, or in the case of one Tesla, did not have their system updated to be able to record good data. One vehicle, for example, a Mitsubishi i-MiEV, did not log data clean enough for use in the analysis. Once all the problematic vehicles were removed, 70 vehicles were available for detailed analysis.

4

DRIVING STATISTICS

As mentioned in the introduction, just over 100,000 drives were logged by the vehicles analyzed in the study, totaling ~915,000 miles. This section examines the event-level statistics associated with the drives.

Table 4-1 shows what percentage of the miles traveled are attributed to each vehicle model. As one might expect, since the largest portion of the vehicles were LEAFs and Volts, they logged most of the miles (50% and 35%, respectively). Of the PHEVs, the Volt logged the greatest number of electric miles at 83%.

Table 4-1
Percentage of miles attributed to each vehicle

Vehicle Type	Model	% of Total Miles Traveled	Average Trip Distance (Miles)	Number of Trips	Total Miles Logged	% of Miles Electric
BEV	Bolt EV	1%	5.6	1,282	7,228	100%
	Focus EV	4%	6.2	5,150	31,828	100%
	Smart Fortwo Electric Drive	1%	4.1	1,125	4,577	100%
	LEAF	50%	8.0	55,167	439,401	100%
	Soul EV	2%	13.7	1,010	13,831	100%
	Spark EV	1%	7.8	1,015	7,885	100%
	Tesla	4%	9.2	3,676	33,833	100%
PHEV	C-MAX Energi	2%	16.3	948	15,414	40%
	Fusion Energi	2%	11.1	1,686	18,721	68%
	Volt	35%	9.9	31,338	309,879	83%

While Table 4-1 shows the average trip distance for each vehicle model, looking at the trip distribution is helpful to see what percentage of trips are within each mileage range. Figure 4-1 shows the histogram distribution of all drives in the study over all vehicles. Approximately 50% of the trips were 5 miles or under, and 99% of the trips were 45 miles or under. Figure 4-2 and Figure 4-3 show the histograms for the Nissan LEAF and Chevrolet Volt, respectively, which represent the different characteristics of BEVs and PHEVs. Figure 4-4 shows the histogram for the Tesla models. While there is significantly less data for the Teslas, the existing data show an interesting representation of the behavior of long-distance BEVs.

While LEAFs had, on average, shorter drives when compared to Volts, the cumulative distribution between the two vehicles is very similar. For example approximately 95% of drives were less than 20 miles in a LEAF, whereas approximately 92% of drives were less than 20 miles in a Volt.

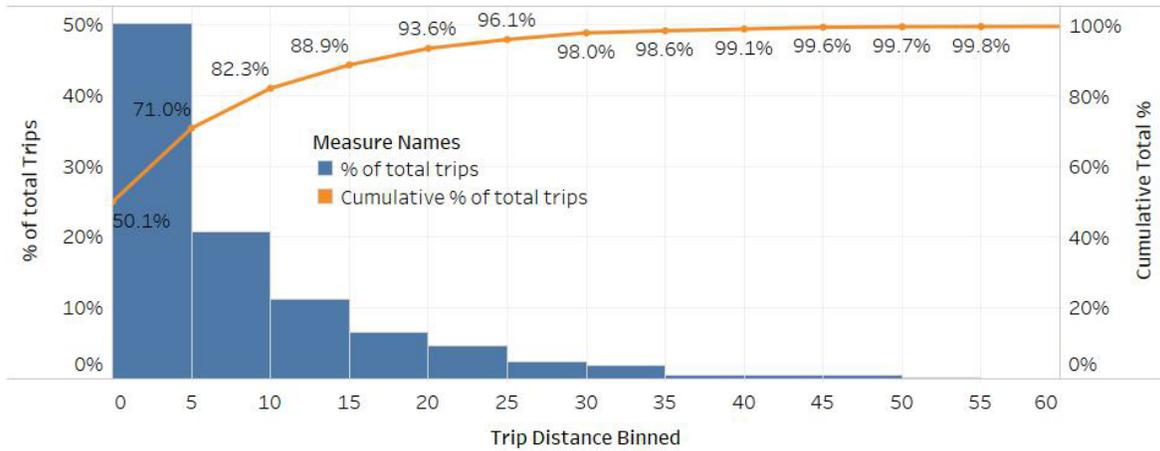


Figure 4-1
Histogram of all drives binned by trip length along with a cumulative distribution

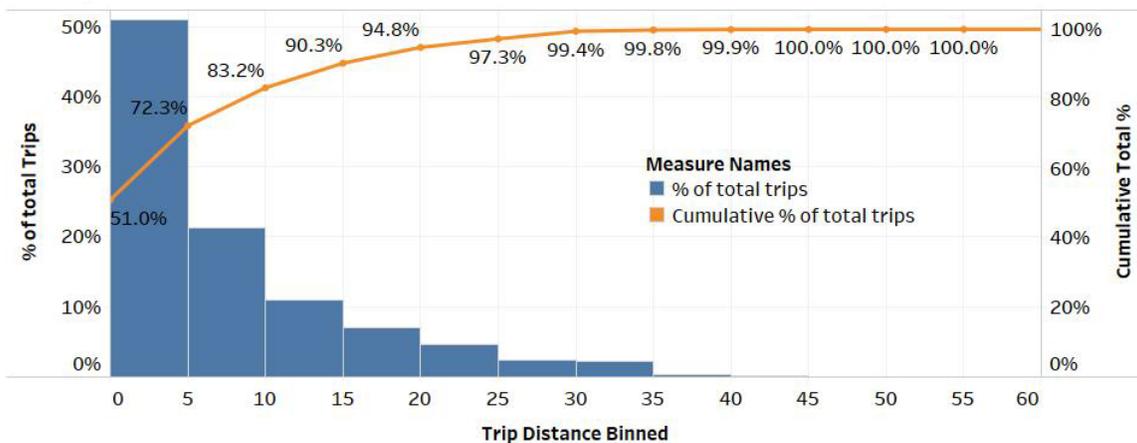


Figure 4-2
Histogram of all LEAF drives in the study along with a cumulative distribution

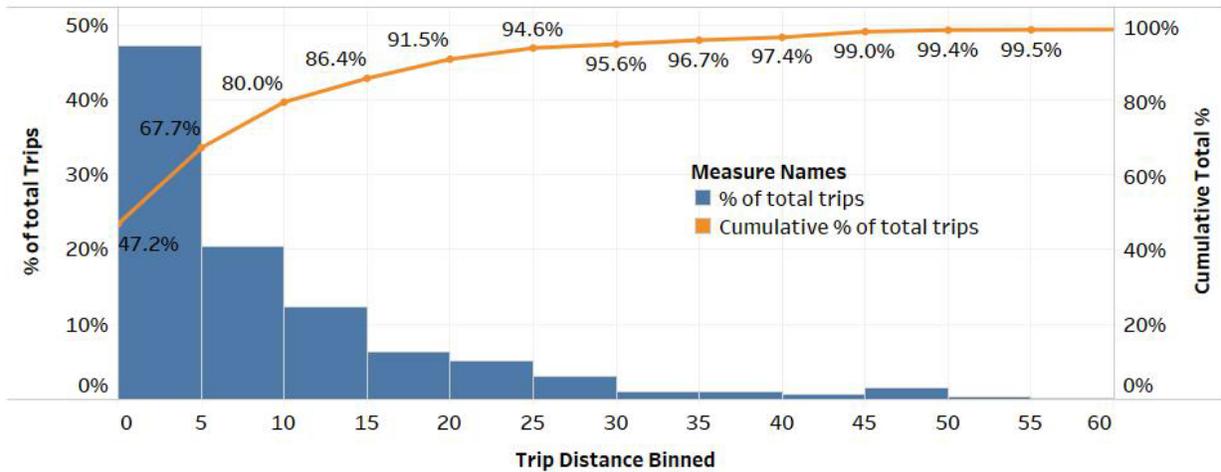


Figure 4-3
Histogram of all Volt drives in the study along with cumulative total

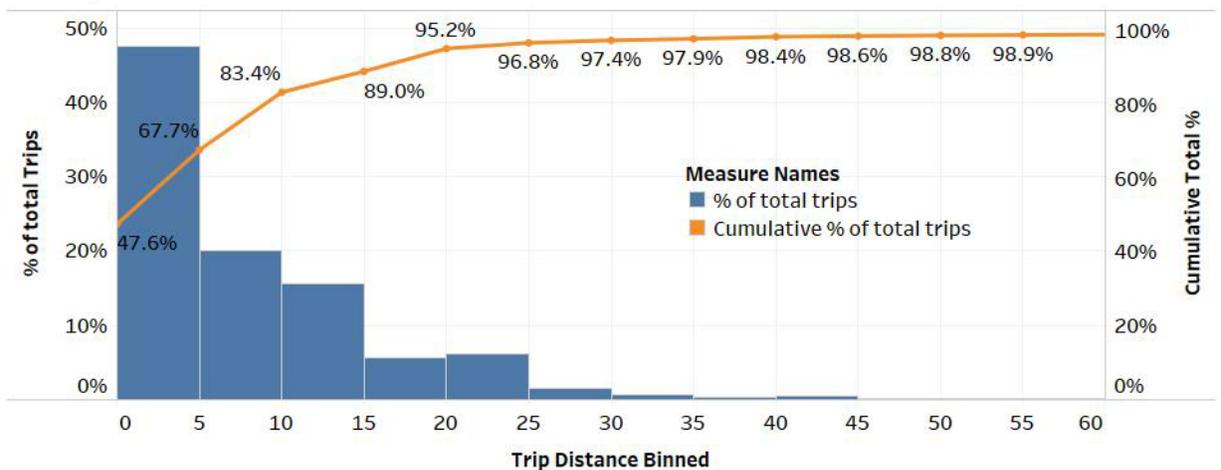


Figure 4-4
Histogram of all Tesla drives in the study along with a cumulative distribution. Note that these Teslas only enrolled in the study in July; therefore, a year’s worth of data were not available to generate this plot.

Table 4-2 shows a summary of the histograms for LEAFs, Volts, and Teslas. While Teslas are able to travel much further on one charge than LEAFs, 99% of Tesla trips are less than 65 miles. It would be interesting to compare these statistics to conventional vehicles and determine how they differ. Clearly, in these statistics, the range of the car could be limiting trip length, but how much that range changes the miles that drivers would travel in a conventional vehicle is unknown. It could be that for any trips of over 100 miles, drivers use a conventional vehicle, thus removing the uncertainty of finding a charger from their trip planning. Combining the mileage from all vehicles in a household would shed light on how miles are distributed between vehicles and would help determine if households actually needed a longer-range vehicle.

Table 4-2
Histogram summary of LEAFs, Volts, and Teslas

Vehicle Model	50% of Cumulative Total (Miles)	99% of Cumulative Total (Miles)
LEAF	<5 miles	<35 miles
Volt	<10 miles	<50 miles
Tesla	<10 miles	<65 miles

Table 4-3 shows the percent of miles driven on either battery power or gasoline power by PHEVs. Data from the Ford C-MAX Energi and Fusion Energi are shown here for illustrative purposes only as there was only one vehicle of each type available for analysis. The Volts operated approximately 83% of the time on battery power and consumed a total of 1,500 gallons of gasoline during the study.

Table 4-3
PHEV miles driven in charge-sustaining mode (using gasoline) or charge-depleting mode (using battery). Note that there was only one Ford C-MAX Energi and one Fusion Energi used in this analysis.

Vehicle Model	Total Miles Driven	Charge Depleting Miles	% of Total Miles Charge Depleting	Charge Sustaining Miles	% of Total Miles Charge Sustaining	Fuel Consumed (Gallons)
C-MAX Energi	15,414.0	6,155.9	40%	9,258.2	60%	197.4
Fusion Energi	18,721.1	12,685.1	68%	6,036.4	32%	142.5
Volt	309,879.2	258,127.3	83%	51,751.5	17%	1,508.0

Figure 4-5 shows the yearly mileage from each vehicle. The median mileage over all vehicles is 11,113 miles with a 95% confidence interval ranging from 9,848–12,379 miles. There is significant variability among the LEAFs and the Volts. The Volts have a slightly higher median mileage of 12,025 miles (95% confidence interval ranging from 9,203–14,847 miles), while the LEAF has a median of 10,235 miles (95% confidence interval ranging from 8,686–11,783 miles). Teslas had a much smaller sample size, with a higher median of 14,624 miles; however, the 95% confidence interval was much larger from 11,086–18,162 miles.

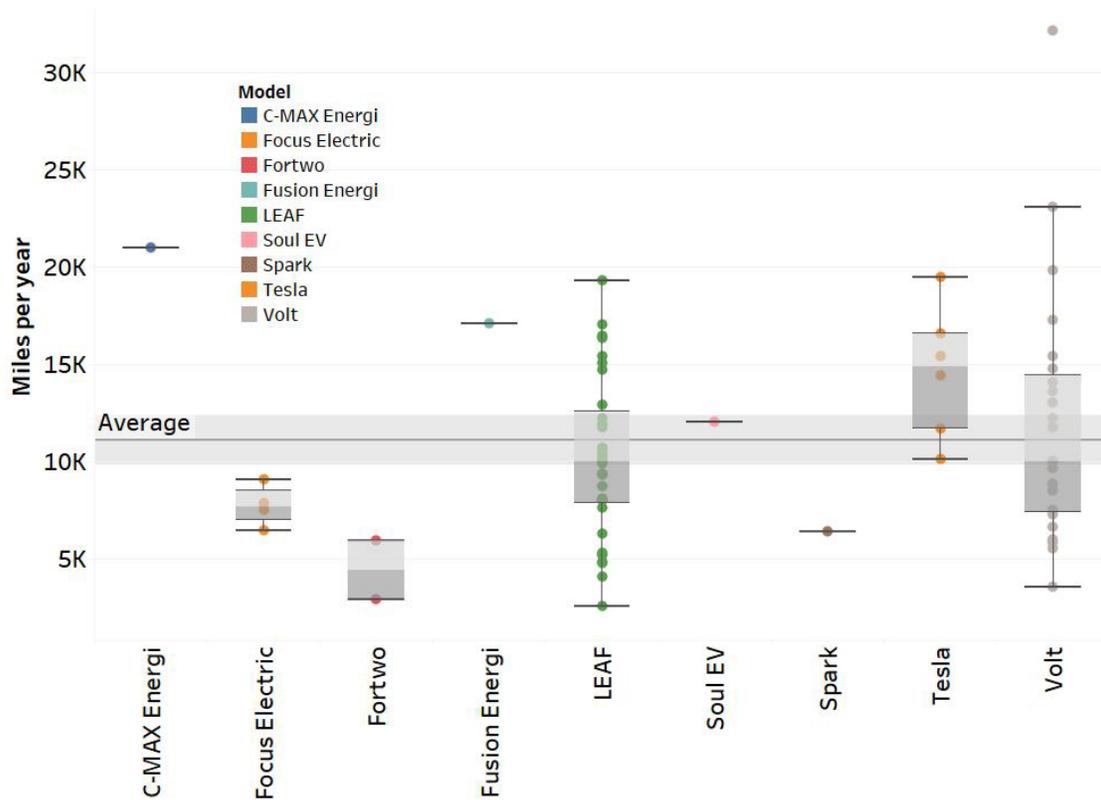


Figure 4-5
Miles per year driven by each vehicle in the study grouped by vehicle model. A study-wide average is shown as well as a box plot for each vehicle type highlighting the data between the first and third quartiles (or one standard deviation from the median).

Generally, it is believed that EVs are driven approximately 3–4 miles/kWh, but this can vary by trip depending on driver habits as well as the ambient temperature, which can affect battery chemistry and the auxiliary power needed for air conditioning and heating. Figure 4-6 shows the average kilowatt-hours/year colored by vehicle type, BEV or PHEV.

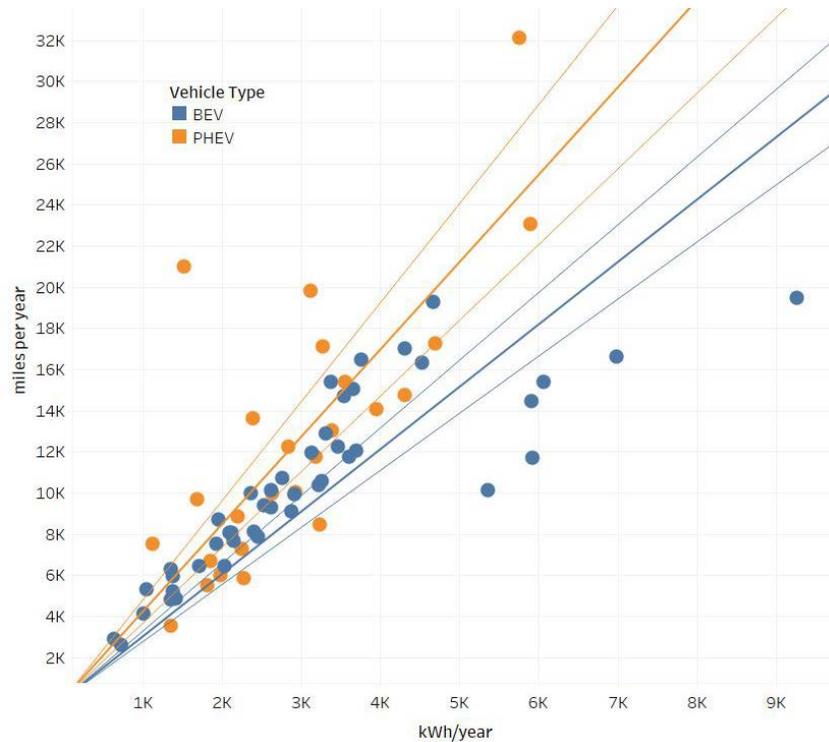


Figure 4-6
Kilowatt-hours/year plotted against miles/year for each vehicle in the study, with colors indicating whether the vehicle is a PHEV or a BEV. A best-fit line has been fitted to both PHEVs and BEVs to obtain a slope indicating miles/kWh, including charging from AC and DC sources.

A best-fit line has been fit for both the PHEVs and BEVs. PHEVs can be driven a greater distance per kilowatt-hour because they also use energy from gasoline. The increase in slope of the PHEVs over the BEVs is due to the fact that gasoline is supplementing the driving range in some cases. For BEVs, the slope of the line is 3.0 meaning that, on average for every kilowatt-hour used, the vehicle travels just over 3 miles. For the PHEVs, the slope of the line is 4.2 miles/kWh. The slopes (or coefficients) provided here can be used to correlate between miles/year and potential kilowatt-hour usage. It is important to note that the Volt, which had the highest proportion of PHEVs in the study, has a longer range than the other types of PHEVs. These statistics, therefore, will reflect more electric miles than may be traveled with shorter range PHEVs. Table 4-4 shows the average yearly kilowatt-hours by the top three vehicle types as well as the average yearly mileage. While a year’s worth of data are not available for the Teslas, the statistics have been provided here for illustrative purposes; SRP is continuing to monitor the Teslas for an entire year.

Table 4-4
Average yearly kilowatt-hour totals divided by LEAF, Volt, Tesla, and all others grouped together

Model	Average Yearly Mileage	Miles/kWh	Average Yearly kWh
LEAF	10,235	3.8	2,693
Volt	12,025	4.1	2,933
Tesla	14,625	2.2	6,648
Total	11,113	3.4	3,269

To examine the effects of temperature on vehicle range, each vehicle trip is plotted in Figure 4-7. To achieve a better comparison between PHEVs and BEVs, only PHEV drives that did not consume gasoline were included. The colors highlight the ambient temperature grouping during the trip. A best-fit line was fit to the data for each of the temperature groupings. The slope of the line becomes more horizontal indicating that more energy is used per mile.

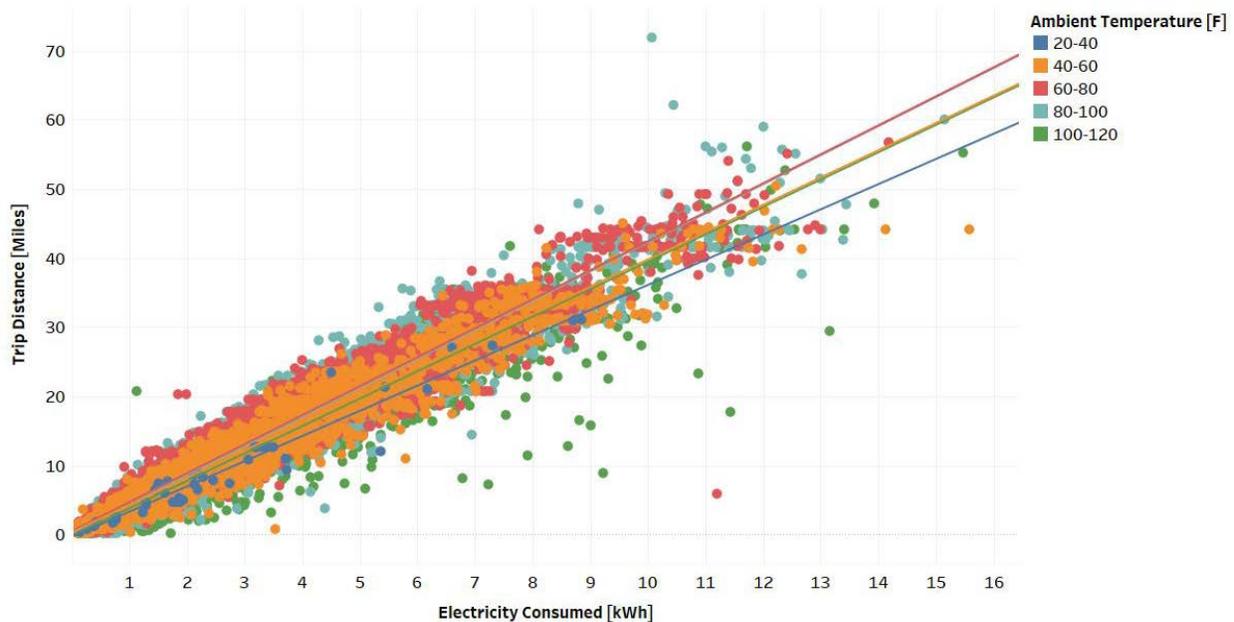


Figure 4-7
Kilowatt-hour and trip distance is shown for each drive taken in the study. The ambient temperature for each vehicle is indicated by color. A best-fit line has been fit for each 20° temperature range.

Table 4-5 shows the slope, p-value, and R-squared value of each line fit. The p-value is the probability that the observed result happened by chance. A p-value of less than 0.05 indicates that the fit is significant. The R-squared value is an indication of the spread of points in relation to the line fit. An R-squared value of 0 means that there is no correlation between the data points and the proposed fit, while an R-squared value of 1 means that the line perfectly fits all of the data. All line fits show a significant p-value and a high R-squared value indicating that the linear fits are good fits to the data.

Table 4-5
Slope, P value, and R-squared value for all lines fit to the kilowatt-hour and miles data in Figure 4-7

Temperature Range (°F)	Slope	p-Value	R-Squared Value
20–40	3.6	<.0001	0.93
40–60	3.9	<.0001	0.95
60–80	4.2	<.0001	0.94
80–100	4.2	<.0001	0.93
100–120	3.9	<.0001	0.92

Table 4-5 shows that the most efficient temperature is between 60–100°F. Most likely this is caused by the fact that at those outside temperatures, a significant amount of air conditioning or heating is not needed. Conversely, when temperatures are cooler or hotter than this, drivers are using more of the auxiliary systems in the vehicle to make the drive more comfortable (heating or cooling). Later analysis will show that while temperature does have an impact on the vehicle efficiency, the charging power level and time of charging impacts load shapes more dramatically; thus, the temperature variability between months does not alter load shapes significantly.

Figure 4-8 shows the temperature variability over the year. While most of the average monthly temperatures fall between 60–100°F, there are many data points that fall outside of this range when energy efficiency decreases.

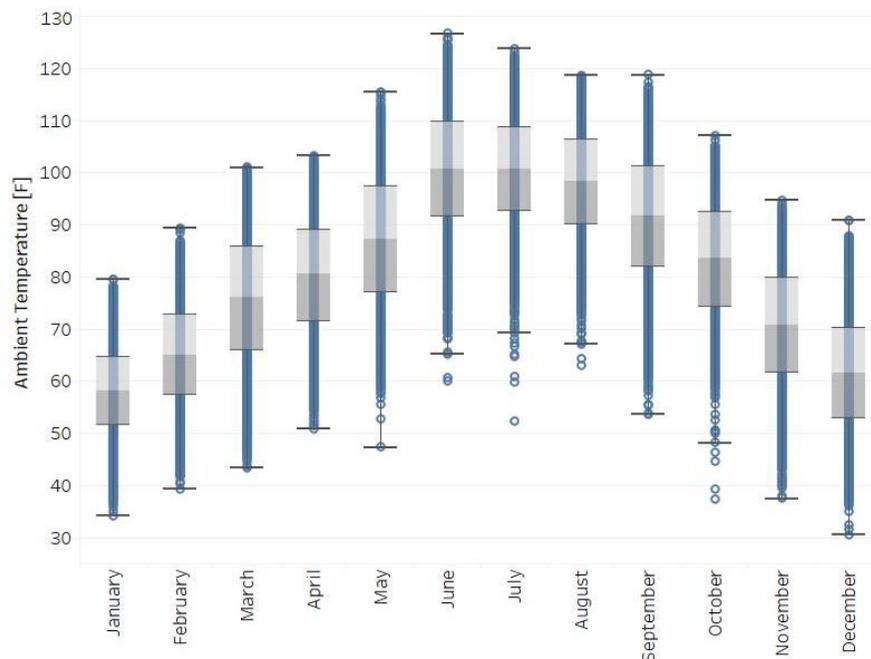


Figure 4-8
Ambient temperature for each drive over the length of the study grouped by month. Box plots have been fit to each month’s data showing the median and one standard deviation from the median.

To understand how drivers charge between drives, the SOC at the start of each drive can be examined. Figure 4-9 shows that only 18% of drives start with an SOC of 50% or less.

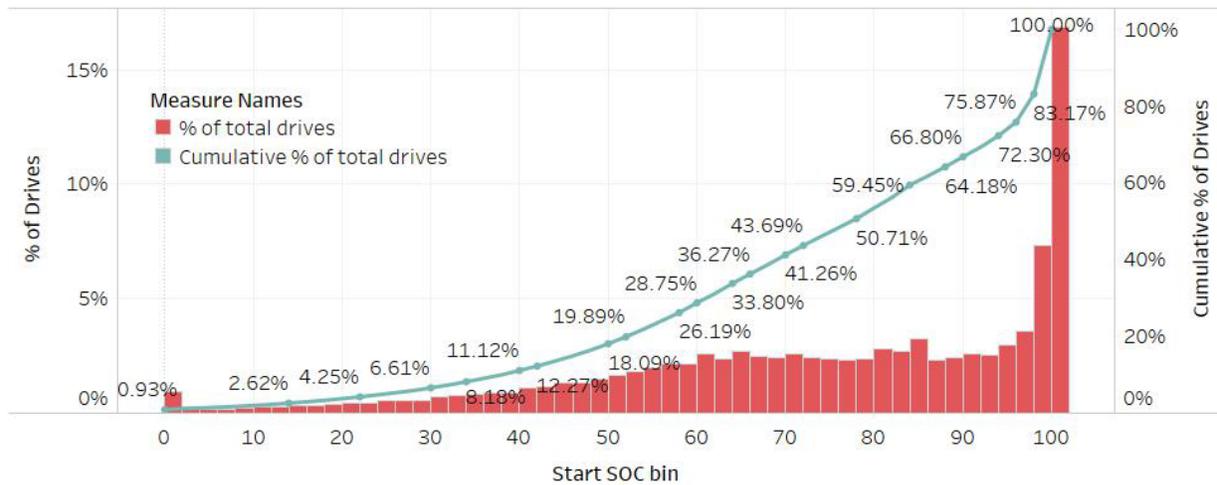


Figure 4-9
Histogram and cumulative distribution of drive start SOC for all drives in the study

Figure 4-10 shows a significant distribution change when only PHEVs are examined in the same type of plot. In PHEVs, 25% of drives start with an SOC of 50% or less, meaning more drives start with less energy. Because PHEVs have a backup engine, drivers are less worried about running out of fuel.

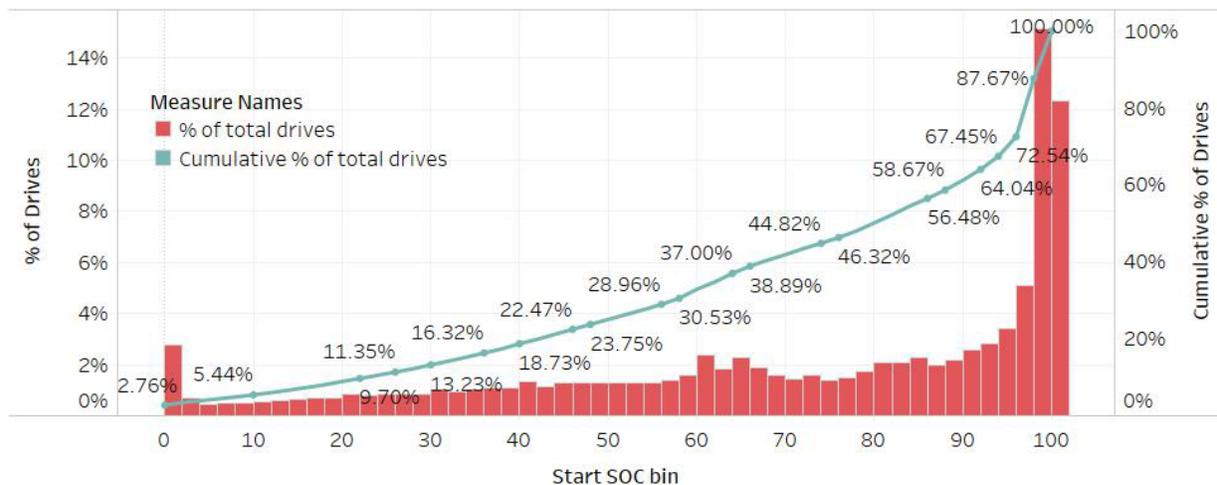


Figure 4-10
Histogram and cumulative distribution of all PHEV drives in the study

If just the BEVs are isolated, as in Figure 4-11, then the distribution shifts again, but in the other direction. Only 15% of drives start with an SOC of less than 50%, and 55% of drives start with an SOC of less than 80%, which conversely means that 45% of drives have a starting SOC of more than 80%—almost half. Nearly 20% of drives start with an SOC of 98–100%. These data show that, in general, BEV drivers start their drives with a fuller battery charge than those of

their PHEV counterparts. This outcome could be due to range anxiety or charging anxiety (the ability to locate a charger that works and is available) or simply to the fact that drivers who purchase BEVs tend to have reliable and convenient charging as well as shorter daily driving ranges and therefore feel more comfortable purchasing a BEV.

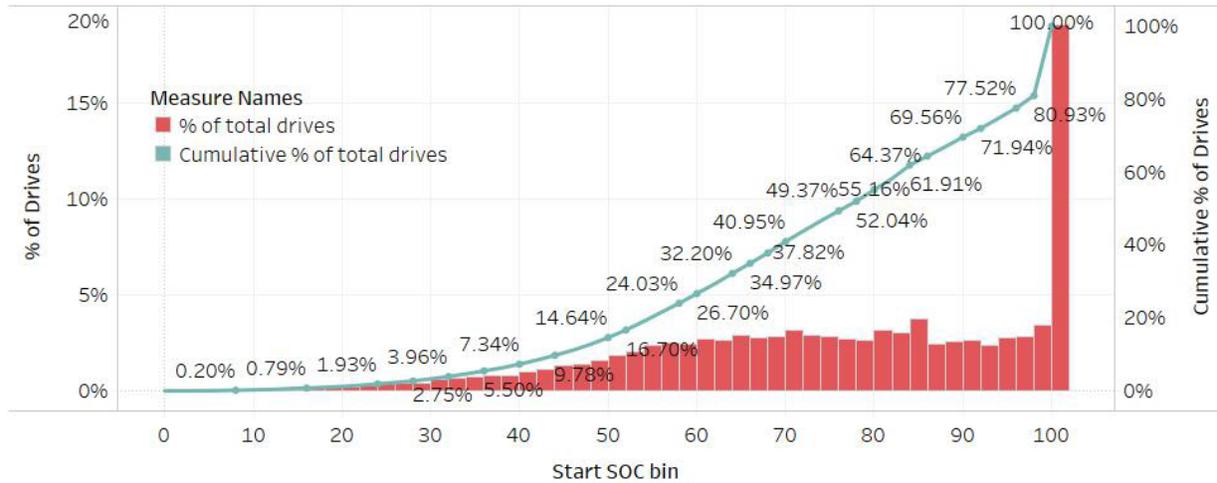


Figure 4-11
Histogram and cumulative distribution of all BEV drives during the study

5

CHARGING STATISTICS

Charging information is divided into two sections. The first section examines event-level information that contains summary information about the charges such as average length and average energy used. The second section evaluates the charging data in a time-series format where kilowatt usage is examined over time. This data format allows analysis of load shapes. As stated in the beginning of the analysis, there were approximately 35,000 charges in the study totaling 187,000 kWh and occurring at 395 different locations.

One objective of the study was to determine where charging was occurring. To meet this objective, GPS information from each charge was examined. When the GPS location of one charge event was located more than 100 meters from another location, then it was defined as a different location. While this seems like a large distance between locations, this threshold was chosen for two reasons. One was to co-locate charging areas where the chargers are spread a wide distance apart such as a workplace charging parking lot, and the other is due to the accuracy of GPS reporting.

Figure 5-1 shows all the unique charging locations colored by the location type (home, work, public, or other). When examining the location of the drive events on a similar map, longer road trips can be seen, but charging did not occur on these trips as they were taken in PHEVs.

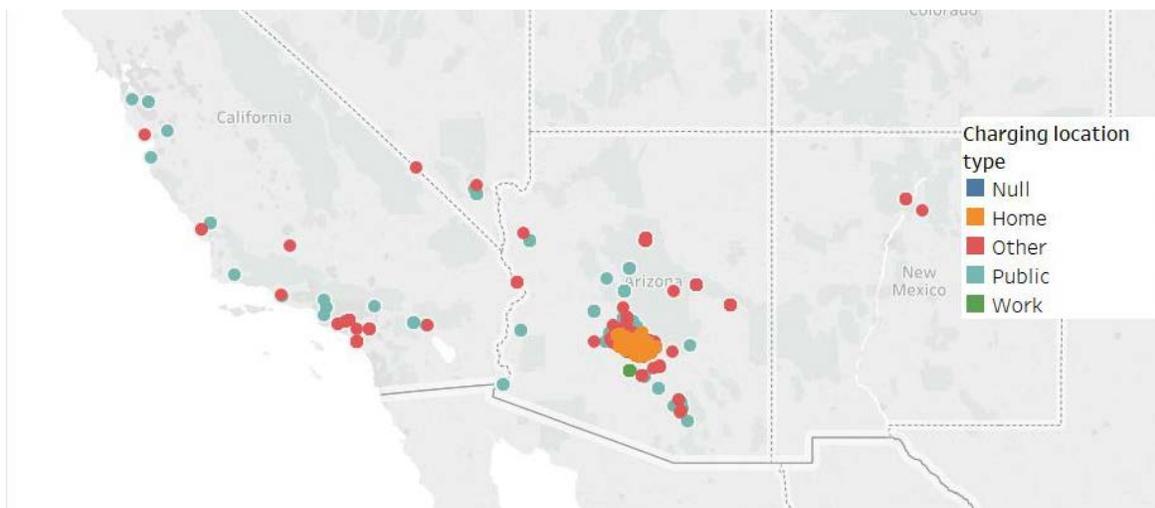


Figure 5-1
Map of all the charging locations used in the study colored by location type. A location ID of “Null” is not shown in this map but is indicative of charging events that occurred where GPS location was not provided for reasons unknown.

To shed further light on which vehicles were taking these road trips, an additional map in Figure 5-2 shows the same charging location IDs but colored by vehicle model (or in the case of Model X or S just by Tesla's brown color).

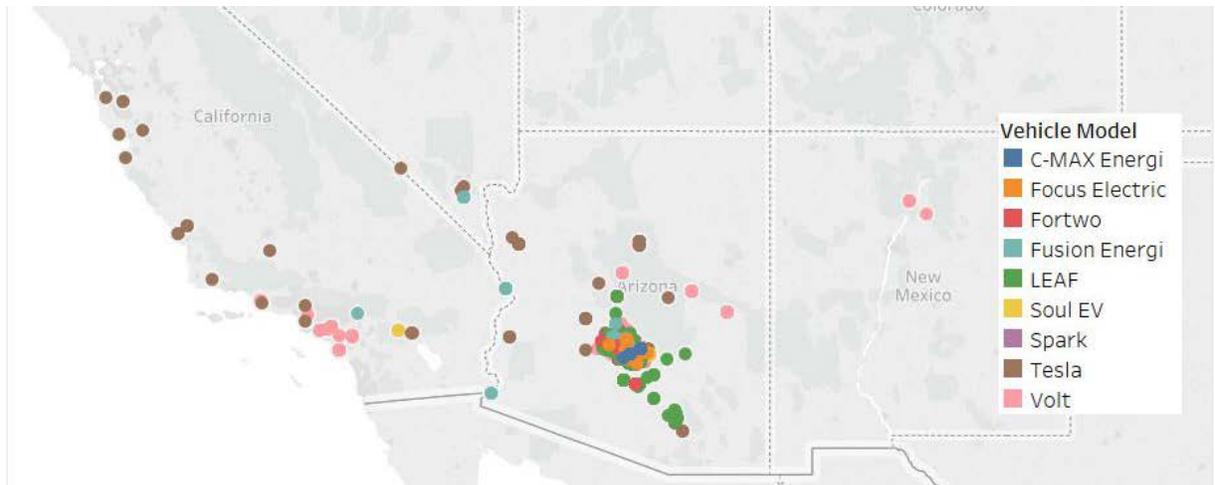


Figure 5-2
Map of charging locations throughout the study colored by model type. Where multiple vehicle types use a charging location, the color shown is the most recent vehicle model charge.

This figure points to the fact that Teslas are taking the longest road trips of the BEVs primarily due to the fact that there is a good, free, DC Fast charging network that easily enables long distance travel with a little planning.

A final map is shown in Figure 5-3 highlighting the total kilowatt-hours charged at each location. This map is zoomed in as the size of the dots for road-tripping charges are very small since they are often only used once. The majority of the charging, ~81%, took place at home, represented by the largest circles on the map.

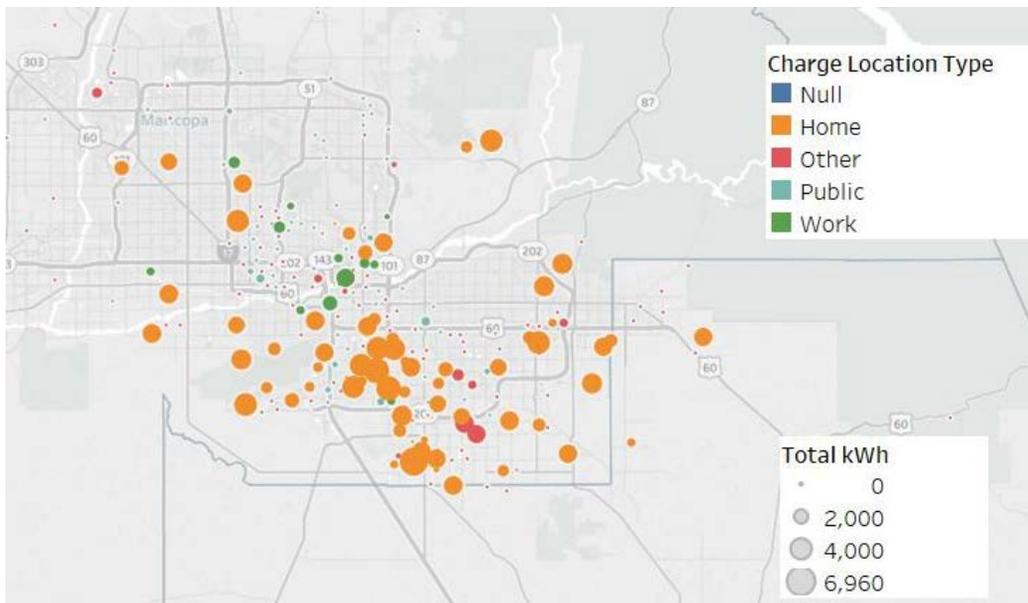


Figure 5-3
Zoomed in map showing charging station colored by station type. The size of the marker is indicative of the total kilowatt-hours charged at a particular location over the length of the study.

For identification of home locations, EPRI worked with SRP to provide the GPS locations of each charging station. SRP then correlated those locations with the addresses of the drivers in the study and identified those locations as home or not. For the public charging locations, EPRI correlated the GPS locations of the study with that of the PlugShare database to determine whether they were at a public location. Finally, a charging location was deemed a workplace location if there were at least 50 charges at this location, 90% of the charges took place during the week, and all the charges occurred between 7 a.m. and 8 p.m. It is possible given the many flexible workplace hours and locations that these strict rules eliminated some workplace charges; however, without more information, no definite identifications could be made. Perhaps in the future it would be possible to gather and identify workplace locations of the study participants in order to help with charging location classification.

Since the vehicles in this study were not restricted only to charging in the SRP service area, some of the charging statistics are from outside of the SRP area. Using a map provided by SRP of its service territory, all of the charging locations were also tagged with whether or not they were in SRP territory.

Figure 5-4 shows the breakdown of kilowatt-hours over the study divided by whether the charging occurred in or out of the SRP service territory. Overall about 5–7% of the kilowatt-hours logged over the study were outside of SRP service territory.

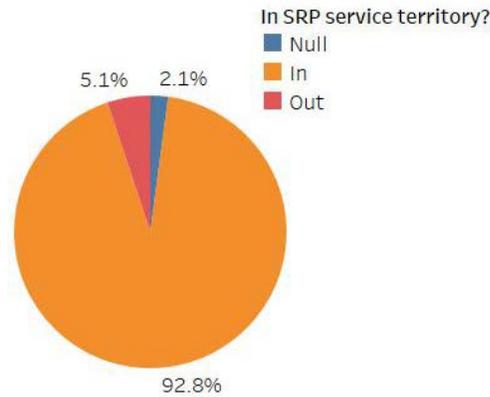


Figure 5-4
Percent of total kilowatt-hours charged in and out of SRP service territory. The “Null” value indicates that charging took place without GPS information being provided; therefore, the location of this charging is unknown.

Table 5-1 shows the percentage of total kilowatt-hours for each charging location. Approximately 2.1% of the energy charged was outside of SRP service territory.

Table 5-1
Percent of total kilowatt-hours for each charging location

Location ID	Percent of total kWh
NULL	2.11%
Home	81.08%
Other	7.08%
Public	3.18%
Work	6.55%

Figure 5-5 shows the breakdown of charging level by number of events as well as by total kilowatt-hours charged. As could be expected, for both Level 2 and DC Fast charging, the number of events equals a smaller percentage of the total (left pie) than the percentage of the total kilowatt-hours (right pie) as more energy is transferred per session than with Level 1 charging. The opposite is true for Level 1 charging. While 32% of the charge sessions are at Level 1, they account for only 27% of the energy used in the study.

Proportions based on number of charging events Proportions based on total kWh used

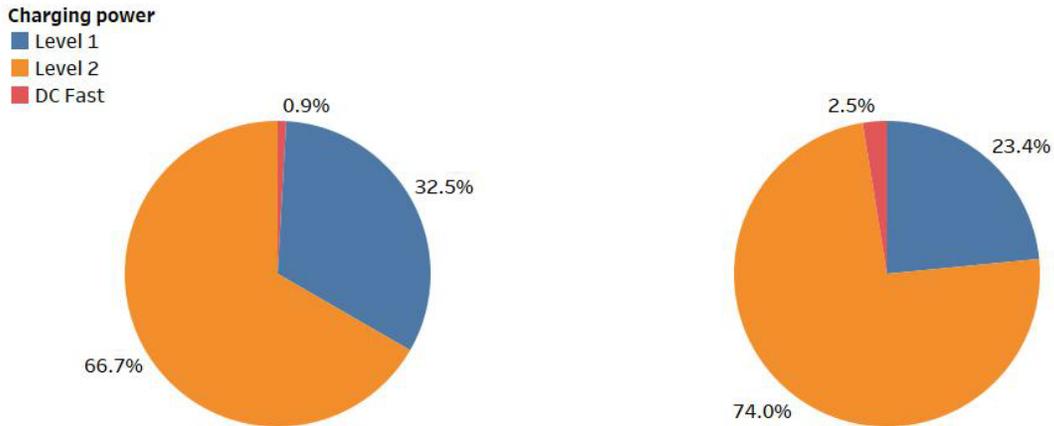


Figure 5-5
Left: Percentage of charging events that are either DC Fast, Level 2, or Level 1 charging.
Right: Percent of total kilowatt-hours that are either DC Fast, Level 2, or Level 1 charging.

Table 5-2 explores how these percentages are broken down by vehicle type showing that while all vehicles use Level 2 charging over Level 1 and DC Fast charging, the extent depends on the vehicle type. Volts use Level 1 the most, which makes sense as they have the shortest electric range and are not DC Fast charging capable. Teslas show the largest percentage out of all the vehicles for Level 2; however, LEAFs are not far behind. As might be expected, Teslas use DC Fast charging the most, which is probably influenced by the fact that the Supercharging network is free and reliable. It will be interesting to see how this behavior shifts as Tesla is no longer going to include free charging with vehicle purchases moving forward.

Table 5-2
Charging level percentages by event and by kilowatt-hours for all vehicles as well as by LEAF, Volt, and Tesla vehicles

Power Level	Level 1		Level 2		DC Fast Charging	
	By Event	By kWh	By Event	By kWh	By Event	By kWh
All vehicles	32.5%	23.4%	66.7%	74.0%	0.9%	2.5%
LEAF	21.8%	16.4%	76.6%	81.9%	1.5%	1.7%
Volt	39.3%	40.2%	60.7%	59.8%	NA	NA
Tesla	2.4%	1.6%	90.5%	87.5%	7.2%	10.9%

Table 5-3 shows the charging information differently. Rather than highlighting the percent of energy used for each charging power, it shows, on average, the number of charges each month or, in the case of DC Fast charging, per year. While there were not many vehicles enrolled in the study outside of the LEAF, Tesla, and Volt models, the other vehicle types have been listed here for illustrative purposes. This information is helpful when evaluating what kind of charging

infrastructure is appropriate to support EVs, especially EVs that are located in apartment buildings and may rely more on the public charging infrastructure. For example, when looking at DC Fast charging usage, Teslas used DC Fast charging approximately 22 times per year, so it might be expected that each Tesla added to a service territory would add 22 more visits to the surrounding fast charging infrastructure.

Table 5-3
Average number of times each model type uses each type of charging power. The Level 1 and Level 2 charging is on a per month basis, while the DC Fast charging is on a yearly basis. The total days logged is total number of days logged over multiple vehicles for the length of the study. LEAFs and Volts are in bold as they have the largest number of vehicles from which to generate statistics.

Vehicle Model	Total Days Logged	Average # of Level 1 Charges/ Month	Average # of Level 2 Charges/ Month	Average # of DC Fast Charges/ Year
C-MAX Energi	563	28.35	4.42	0.00
Focus Electric	1,510	23.72	11.11	0.00
Smart Fortwo	1,020	13.00	0.32	0.36
Fusion Energi	444	15.68	43.04	0.00
LEAF	16,064	7.08	21.01	4.82
Soul EV	420	6.36	22.07	1.74
Spark	458	27.90	25.61	0.00
Tesla	967	1.77	25.56	21.89
Volt	10,517	41.12	25.30	0.00

In the driving section, histograms showing the SOC at the beginning of each drive were examined. Here, the SOC at the beginning of *each charge* is provided. While looking at the SOC at the beginning of each charge does not shed any light on the total load shapes that may result from combining a number of vehicles, it does give an idea of when people plug in. Do they wait until their battery is at 20%? Or do they often plug in at 50%? What cannot be explained from the histograms below is whether drivers were plugging in their EVs because they felt the need to charge based on their driving patterns or if there was just an available charger near where they were parking and they decided to plug in when they did not really require a charge. Figure 5-6 shows a histogram of the SOC at the beginning of charge for PHEVs over the length of the study. This shows that a significant number of charges start with an SOC of 0–10%. Without consequences of running the battery down to 0%, this is an acceptable option for these drivers. Only about 33% of drives start with an SOC between 50% and 100%.

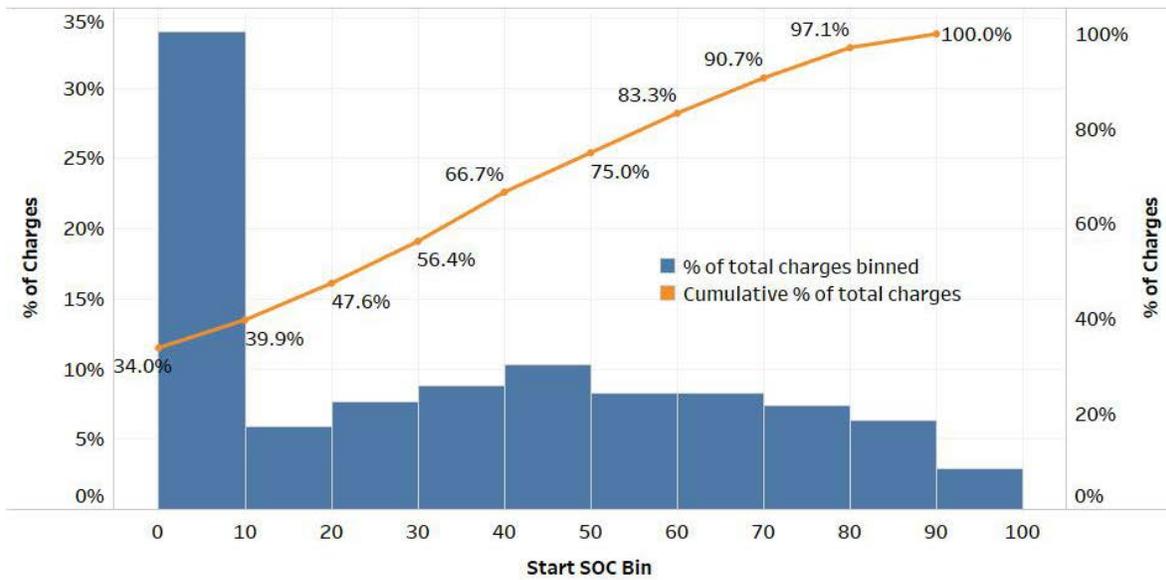


Figure 5-6
Histogram of the starting SOC for all charges for PHEVs, also showing a cumulative line

This curve differs greatly from the BEV-only SOC start curve shown in Figure 5-7, where only 3.5% of the charges start between 0% and 10 % SOC. In the case of BEVs, 50% of the charges start with an SOC of 50% or more.

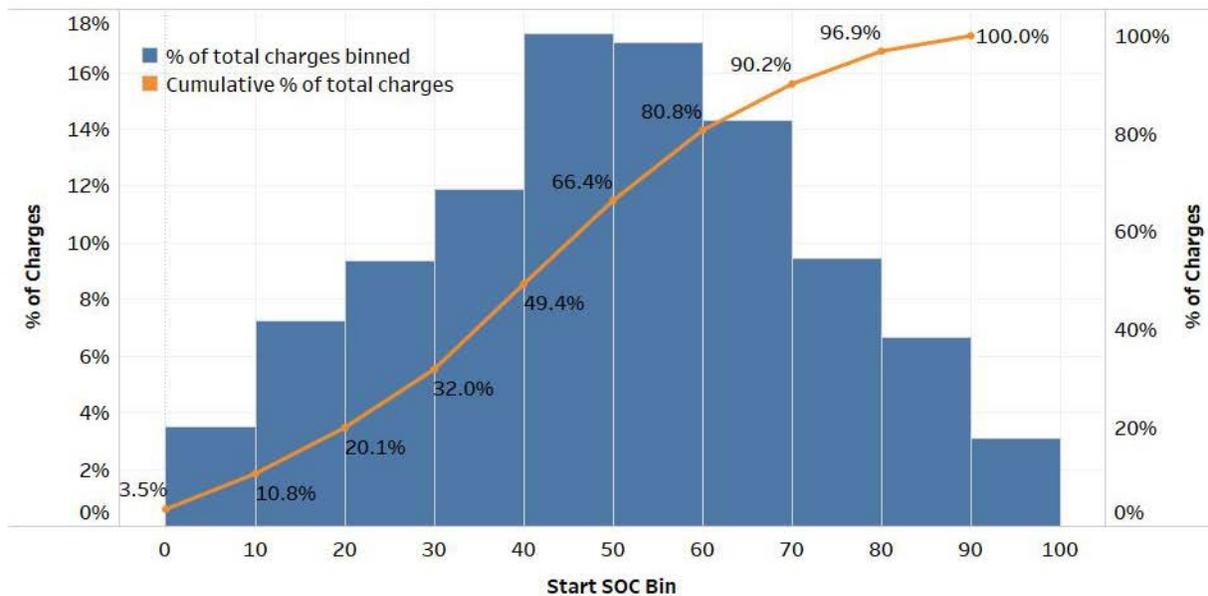


Figure 5-7
Histogram of the start SOC for all BEV charges for the length of the study, also showing a cumulative distribution

What cannot be inferred from these driver tendencies is how they will change with longer range BEVs and with a better charging infrastructure network. Will drivers feel more comfortable running their batteries down knowing that more options are available when they *do* need to charge? Will they wait longer between charging at work or at home because their battery only needs to be charged every few days? Without the ability to control for each of these features, the influence of each one on consumer behavior is unknown, and it is likely that their influence varies across regions. As charging infrastructure improves and EV batteries become longer range, monitoring the changes in driver trends will be important to help plan for the utility grid infrastructure needed to support them.

6

CHARGING LOAD SHAPES

One of the main objectives of this study was to determine what the load shape of an average EV looks like. When and how fast are vehicles charging? Is charging behavior naturally variable, or are EVs all charged at approximately the same time and therefore cause a kilowatt spike? This section examines in detail the total load over the study as well as the kilowatt-hours used.

Kilowatt-Hour Load

Figure 6-1 shows the kilowatt load over the entire study for the 70 vehicles included in this analysis. This figure shows the sum of the average kilowatts used for each 15-min period over the study and plots it over time. On average, once the majority of the vehicles were enrolled, the sum of power ranged from 20–60 or 70 kW, with spikes of up to 120 kW. There is an increase in the kilowatts used from July 2017 onwards due to a number of Teslas (both Model S and X) enrolled in the study at that time. The potential extremes that could be expected from this type of figure would be the time when no vehicle was charging resulting in 0 kW usage, or all vehicles were charging at their fastest charge rate (DC Fast) at the same time. In reality, while 0 kW happens occasionally, the other maximum extreme does not occur.

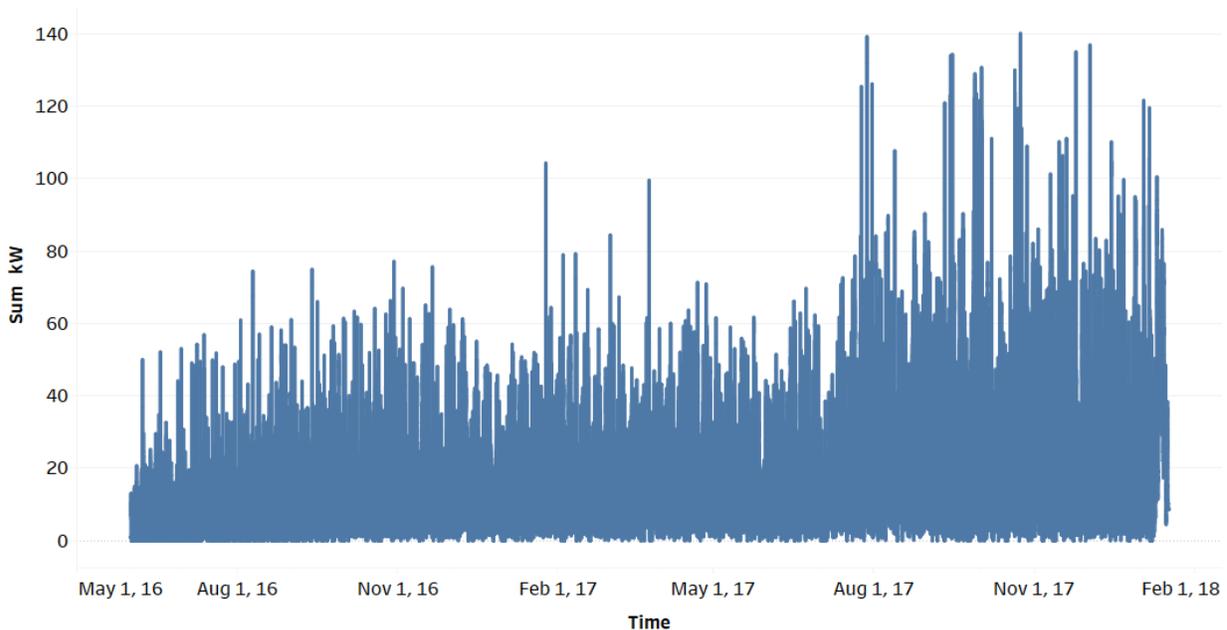


Figure 6-1
The sum of the maximum kilowatt usage over all vehicles over the length of the study, with an increase as of July 2018 as a number of Teslas joined the study

If the above plot is normalized by the number of vehicles enrolled in the study at each point in time, then the trend does not increase. There are still some data spikes, but the magnitude is reduced, as shown in Figure 6-2.

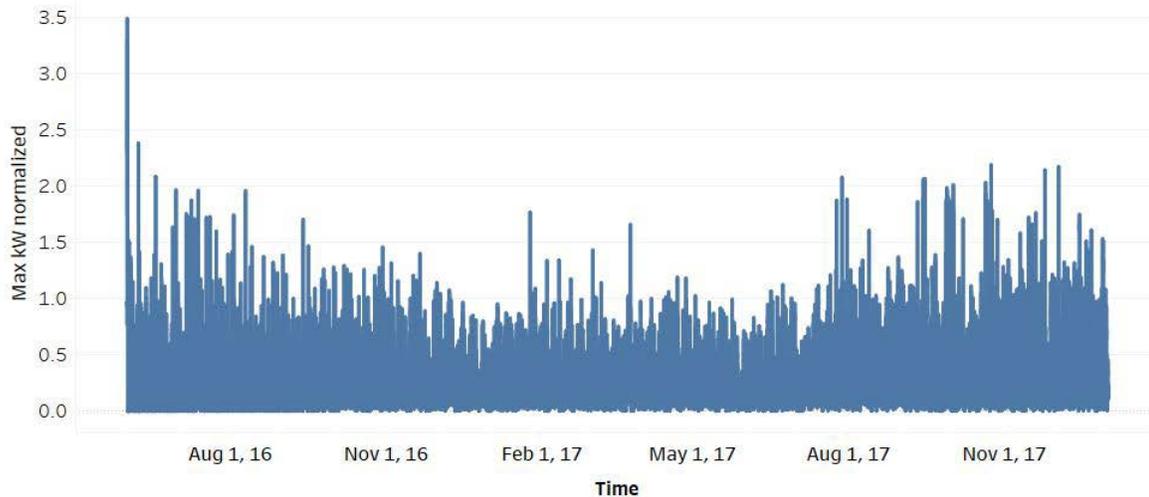


Figure 6-2
Sum of the maximum kilowatts over all vehicles over the length of the study, with each point in time normalized by the number of vehicles reporting at that time

Figure 6-3 shows a histogram distribution of the maximum kilowatt readings over the length of the study for each 15-min period. While vehicles were enrolling over the length of the study (including a number of Teslas for the last third), it is apparent that the large spikes shown in Figure 6-1 are not that common. In fact, more than 50% of the time, the sum of the kilowatts was less than 15 kW over a 70-vehicle fleet. Examination of the other end of the plot shows a total of 80 kW usage occurred only 1% of the time.

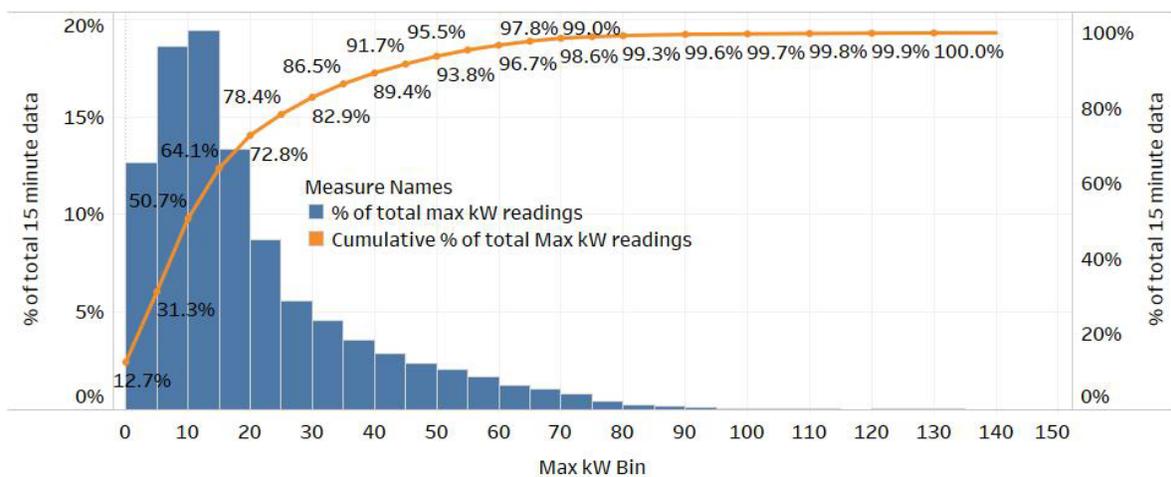


Figure 6-3
Histogram of the maximum kilowatts for each 15-min period for all vehicles over the length of the study, with a cumulative distribution also shown

So what is causing these spikes during the study? Is it just that many vehicles happen to charge at the same time, or is there just one Tesla charging at a Supercharger? Figure 6-4 shows the maximum kilowatts for each 15-min segment and number of vehicles charging at that time. The first important point is that while data were collected from 70 vehicles for analysis, the maximum number of vehicles logging data in the study *at any one time* totaled 65, and the maximum number of vehicles charging at the same time was 31 (about half of what could have been charging). What can also be seen is that while the lower bound of the number of vehicles charging at the same time increases with the maximum kilowatts, the upper bound is not dependent on the total number of vehicles charging simultaneously. In fact, peaks of 120–140 kW occur when there are 0–10 vehicles.

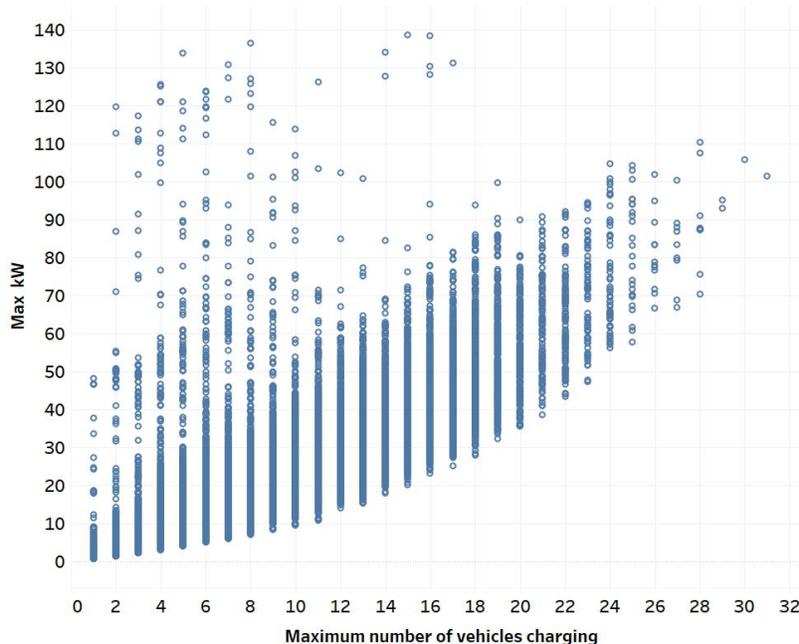


Figure 6-4
Maximum kilowatts at each 15-min time period vs. the number of vehicles reporting kilowatt usage greater than 0

Single Day Examples

The following section shows three days in detail to understand the cause of some of the kilowatt spikes. For each day chosen, there are three different panels shown. Each panel illustrates the same total kilowatt usage during that day, in this case the maximum kilowatts reached in each 15-min period. The top panel coloring shows the vehicle types contributing to the load at each hour. The middle panel shows the type of location where the charging occurred, and the final panel shows whether or not charging was in SRP territory.

January 24, 2017

On January 24, 2017, a peak of approximately 100 kW was reached, as shown by Figure 6-5, due to a combination of four Volt and three LEAF vehicles charging at the same time. The contribution of the four Volts totaled approximately 6 kW; however, the LEAFs were charging at a much faster rate than the Volts. Their contribution was a total of 90.69 kW (35.54 + 18.70 +

36.45), signifying that they were all charging at DC Fast locations. All LEAF fast charging occurred at public stations outside of SRP territory. It is not known what kind of charging network these LEAF vehicles belong to, whether they are incentivized to charge at these stations, or if the charging stations are simply the most conveniently located ones in terms of home and workplace.

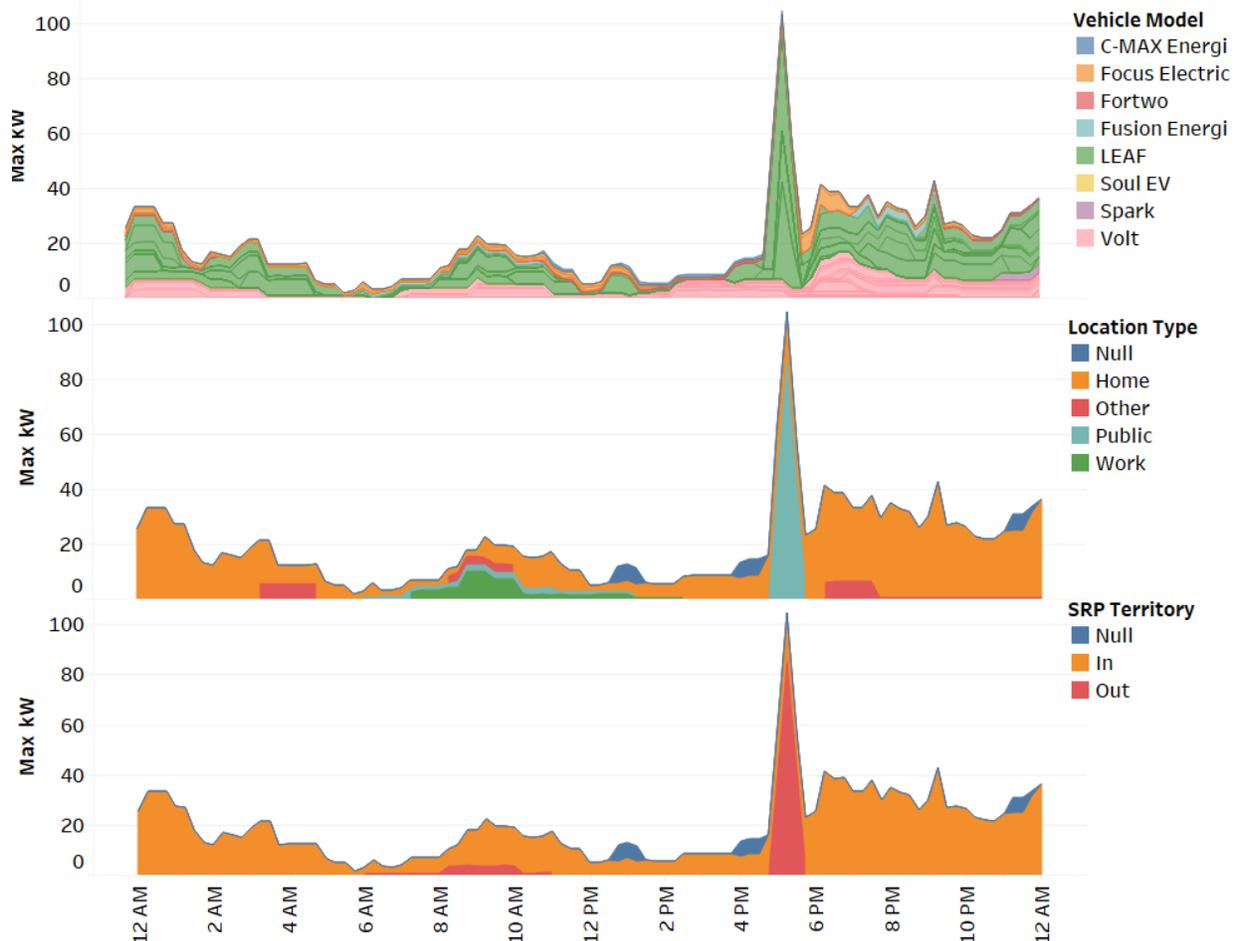


Figure 6-5
Example kilowatt load on January 24, 2017. Top panel: total load colored by vehicle model. Middle panel: total load colored by charging location type (H: Home, P: Public, and W: Work). Bottom panel: total load colored by whether or not charging takes place in SRP territory.

March 24, 2017

On March 24, 2017, the peak load was nearly 100 kW. In the case shown in Figure 6-6, while there are many vehicles charging, only one vehicle is DC Fast charging. The rest of the load is all due to Level 2 or Level 1 charging from nine LEAFs, seven Volts, and two other vehicles. Without the DC Fast charging event, the kilowatt total most likely would have been around 50 kW. Just over 50% of the load occurs at public charging; however, unlike the other two cases, almost all the charging is in SRP territory.

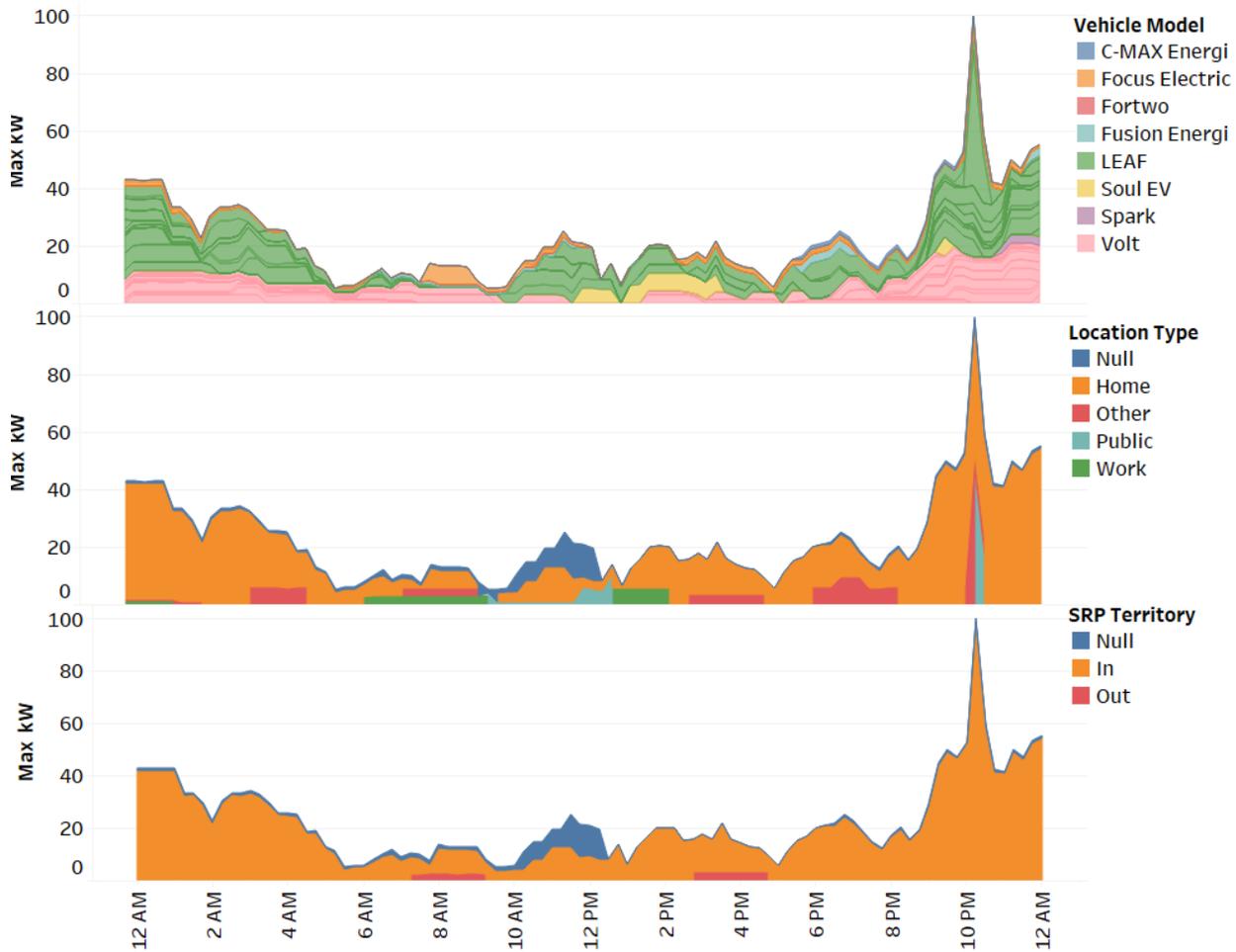


Figure 6-6
Example kilowatt load on March 24, 2017. Top panel: total load colored by vehicle model. Middle panel: total load colored by charging location type (H: Home, P: Public, and W: Work). Bottom panel: total load colored by whether or not charging takes place in SRP territory.

July 27, 2017

On July 27, 2017, there was a peak of nearly 140 kW at 8:30 p.m., as shown in Figure 6-7. Similar to the previous case, here the peak is due to one Tesla DC Fast charging; however, given the fact that Teslas are able to charge at a much faster rate than other BEVs, the spike here is more pronounced. The Tesla contributes 111 kW to the total load. Similar to the previous event, the peak is due to public charging (Tesla Supercharging network) and is located outside of SRP service territory.

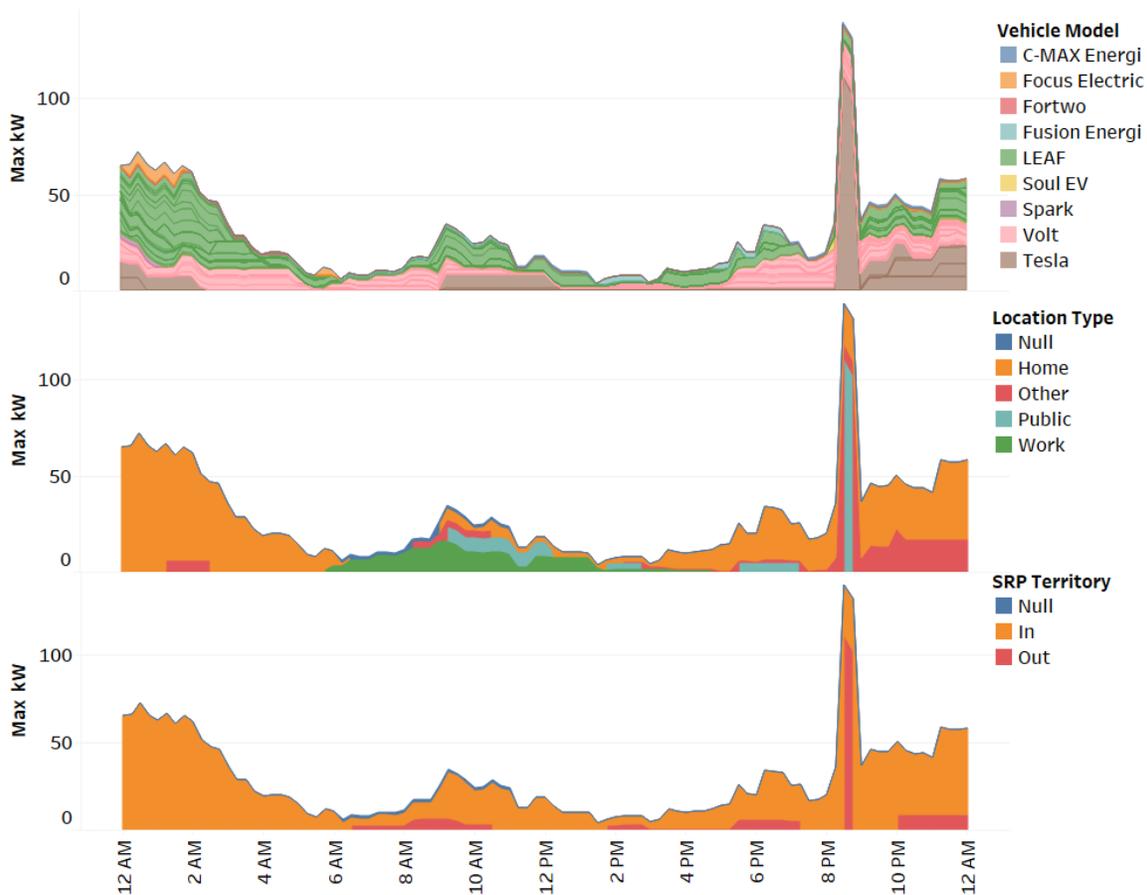


Figure 6-7
Example kilowatt load on July 27, 2017. Top panel: total load colored by vehicle model. Middle panel: total load colored by charging location type (H: Home, P: Public, and W: Work). Bottom panel: total load colored by whether or not charging takes place in SRP territory.

Additional analysis could be performed examining the likelihood of peaks given the various vehicle types and number of vehicles present, which may be helpful in determining how probable it is that peaks will occur. Such analysis—beyond the scope of this report—could also include more precise regional analysis to help understand which areas may experience more peaks.

One objective of this study was to be able to generate an average load shape for an EV and be able to project it forward as EV adoption increases. The next several figures show the average load shape over the study, load shape divided by vehicle type, and customer billing rate. Other figures will also examine the variability introduced by seasonal variations as well as weekday and weekend influences.

Figure 6-8 shows the average load shape over all vehicles, all rate plans, and all days of the week. The orange shading is one standard deviation above and below the average. The lowest point in the curve is at 6 a.m., when most nighttime charging has been completed and no one has yet arrived at work or plugged in when they wake up. The peak is at midnight (± 2 kW). As will be seen in later analysis, many of the study participants were enrolled in some type of rate plan that incentivized charging during nighttime hours.

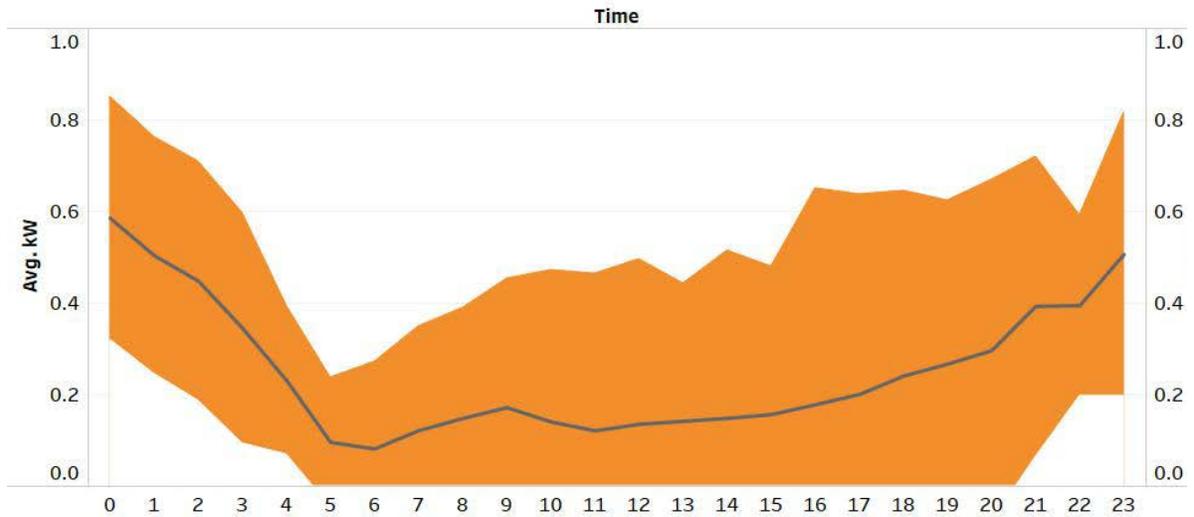


Figure 6-8
Average load shape over the entire study for weekend and weekdays as well as all vehicles

As shown in Figure 6-8, when people are more likely to be engaged in similar activities—such as at 5 a.m. when most people are asleep—the standard deviation (orange shading) is smaller as there is less variability in the data. However, when there is more variability in habits, then the standard deviation is greater.

As might be expected, EV driver behaviors vary greatly between weekdays and weekends. Figure 6-9 shows the percentage of kilowatt-hours charged on the weekend vs. during a weekday. Only 23% of the charging occurs on the weekend even though the weekend represents 29% percent of the week by time.

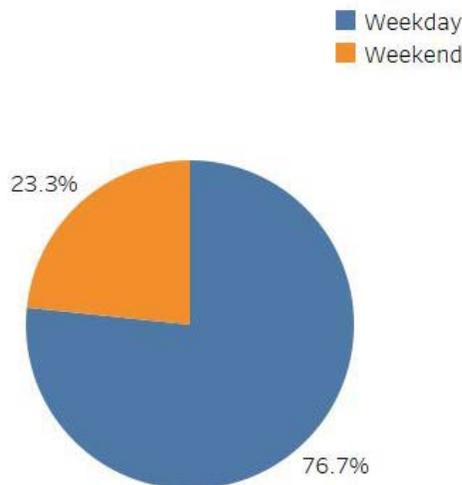


Figure 6-9
Percentage of charging by kilowatt-hours that occurs on the weekend vs. the weekday

To understand how the maximum kilowatt peaks change on the weekend vs. weekday, a histogram can be used. Figure 6-10 shows that during the weekends there are more times when either no one is charging or the load total load over all of the vehicles is very low. Weekdays have more times when there is a higher load between 30–80 kW. In the higher kilowatt ranges (80–140 kW), the distribution is more similar between weekdays and weekends.

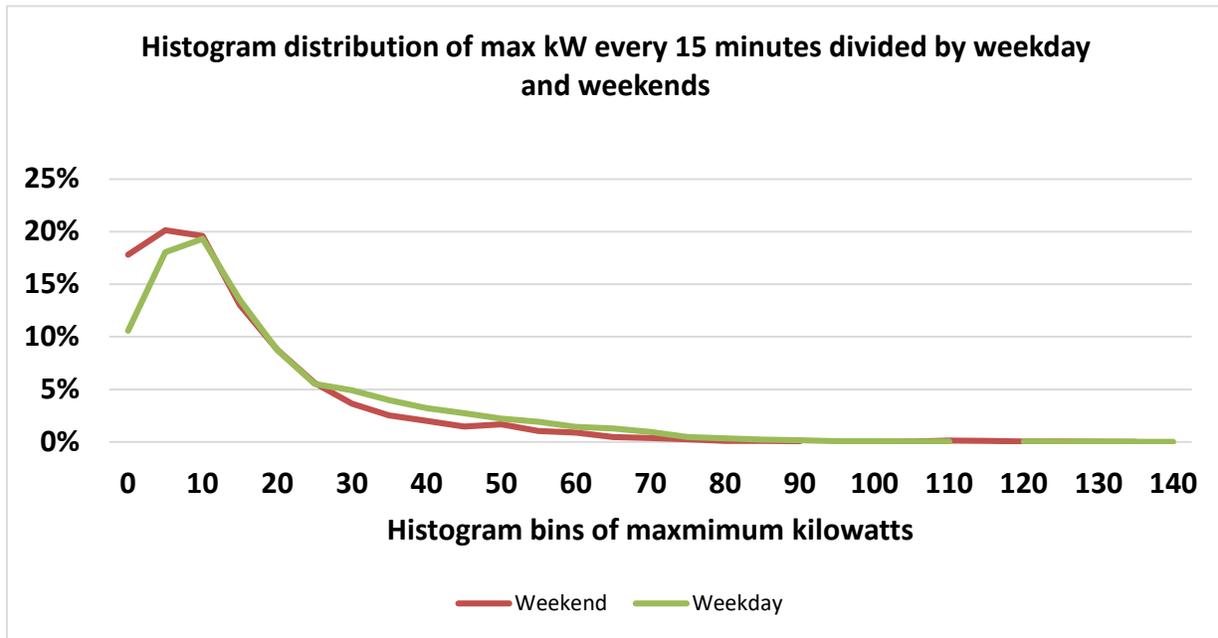


Figure 6-10
Histogram distribution of maximum kilowatt data divided by weekdays and weekends

Figure 6-11 shows the average load shape divided into weekend and weekday curves. The weekday curve is generally higher overall hours of the day except for 11 a.m. to 4 p.m.; however, given the standard deviation shown in Figure 6-12, the differences between those hours are not significant.

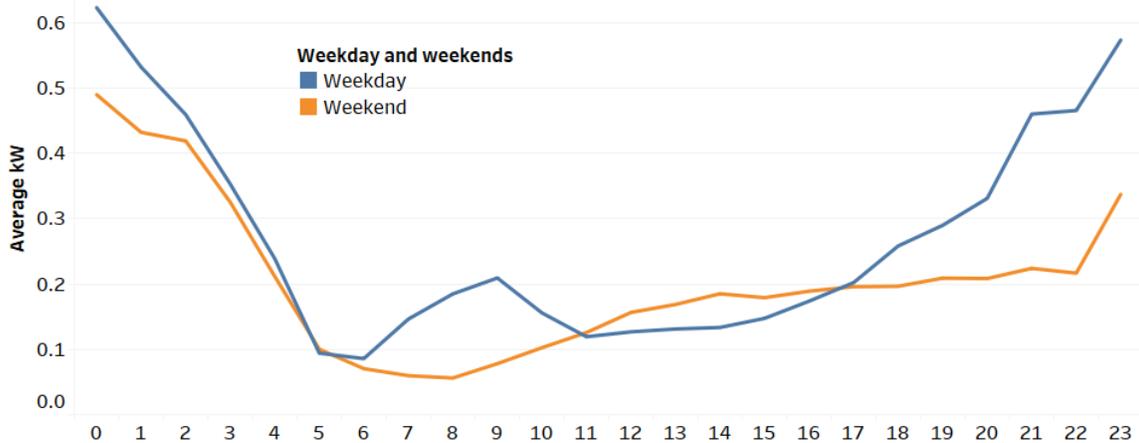


Figure 6-11
Average load shape over all vehicles colored by weekdays and weekends

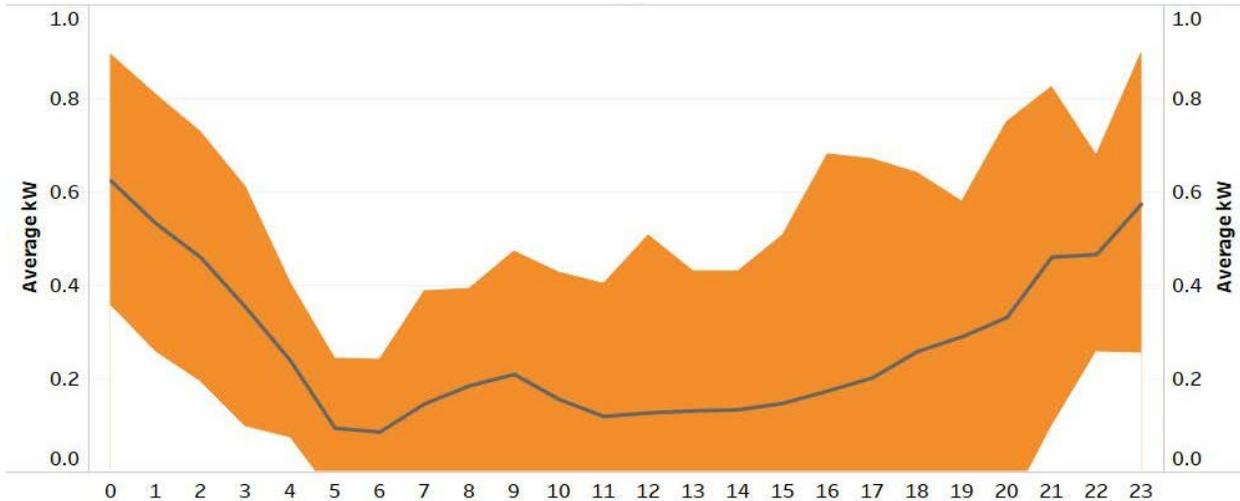


Figure 6-12
Average load curve with one standard deviation shading above and below the curve for weekdays

Due to battery sizes and, in the case of the Volt, the addition of a gasoline-powered engine, the different vehicles in this study have different load shapes. Figure 6-13 shows the average load shape associated with LEAFs, Volts, and Teslas. As mentioned earlier, there has not been a year's worth of Tesla data acquired in the study to date so this analysis is incomplete. The existing Tesla data are included here as they reveal a very different shape compared to both the Volt and LEAF data.

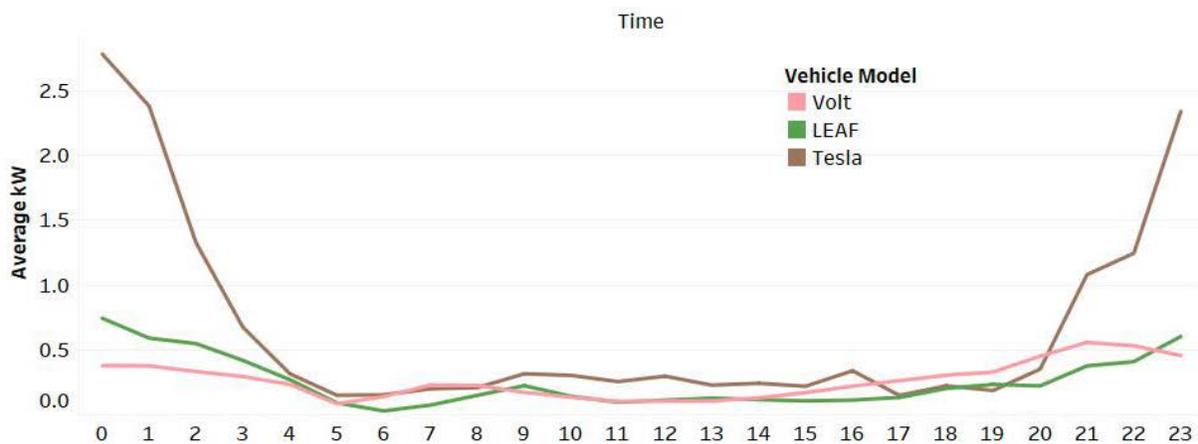


Figure 6-13
Average load shape (weekdays and weekends) for Volts, LEAFs and Teslas

While the vehicles show similar average tendencies in the middle of the day, the Tesla drivers in this study prioritized charging at night and at higher rates. They also drove more miles so the average load shape curve should be higher than those of the LEAF or the Volt.

Figure 6-14, Figure 6-15, and Figure 6-16, respectively, examine the individual load shapes of the LEAFs, Volts, and Teslas for weekdays only. Figure 6-17 examines the load shape for all vehicles excluding LEAFs, Volts, and Teslas for weekdays only. Weekdays were chosen as they show a higher load than the weekends.

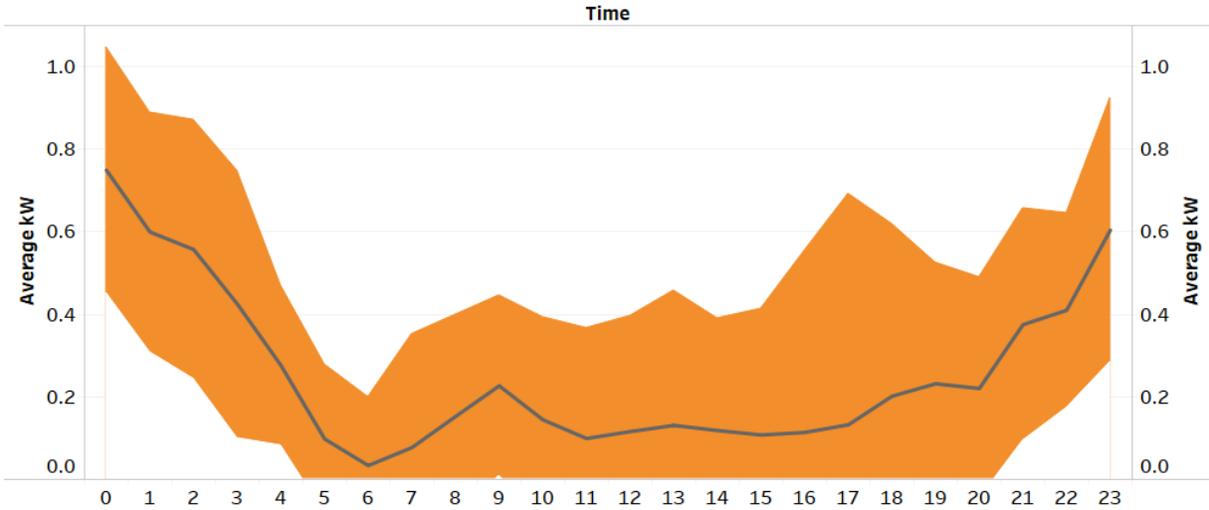


Figure 6-14
Weekday LEAF average load shape with one standard deviation shaded above and below the average line

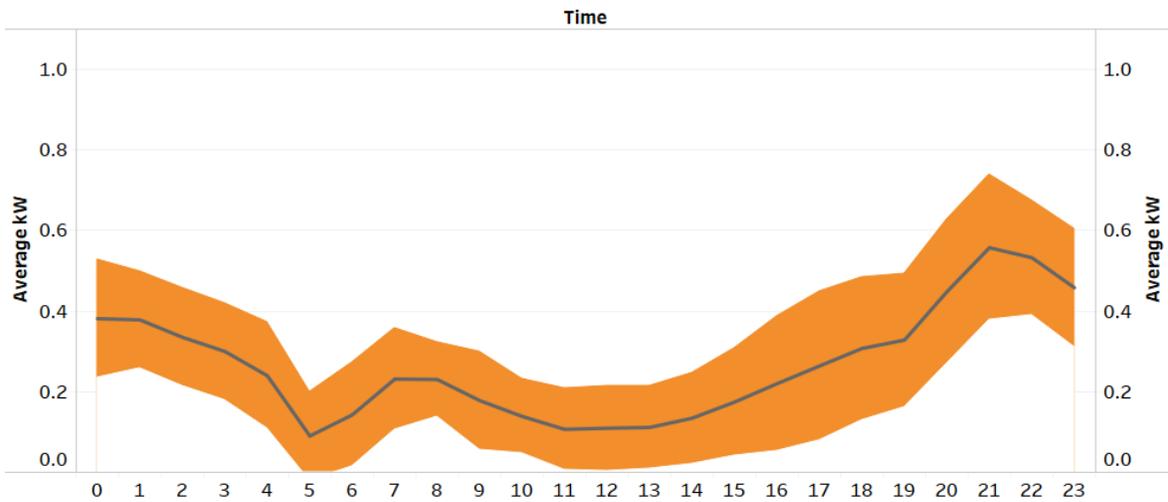


Figure 6-15
Weekday Volt average load shape with shading one standard deviation above and below the average line

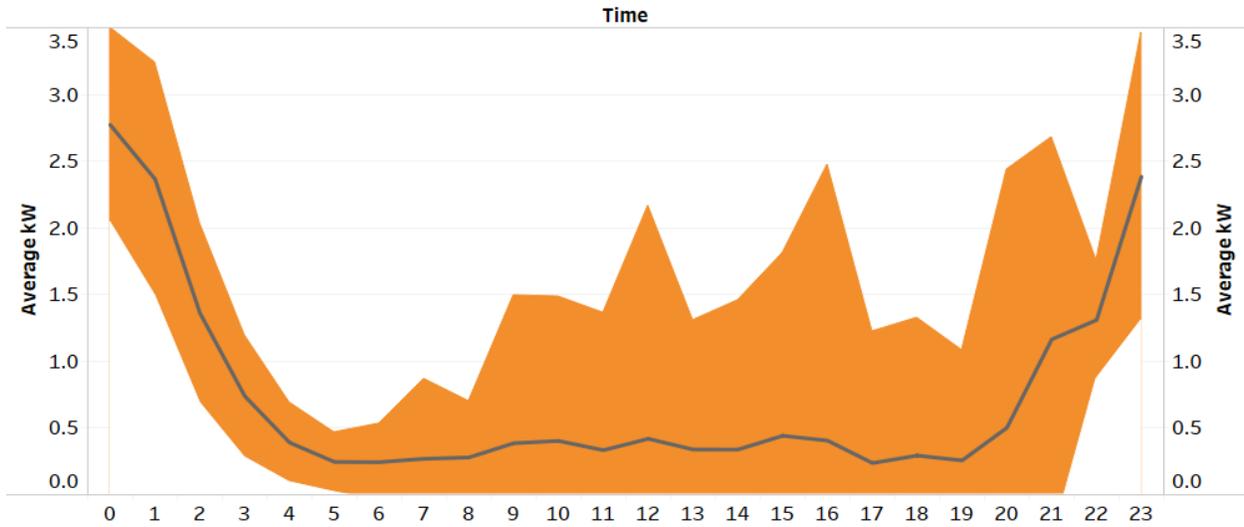


Figure 6-16
Weekday Tesla average load shape with one standard deviation shaded above and below the average line. Note that the y-axis scale is different from that of the LEAF and Volt weekday load shapes.

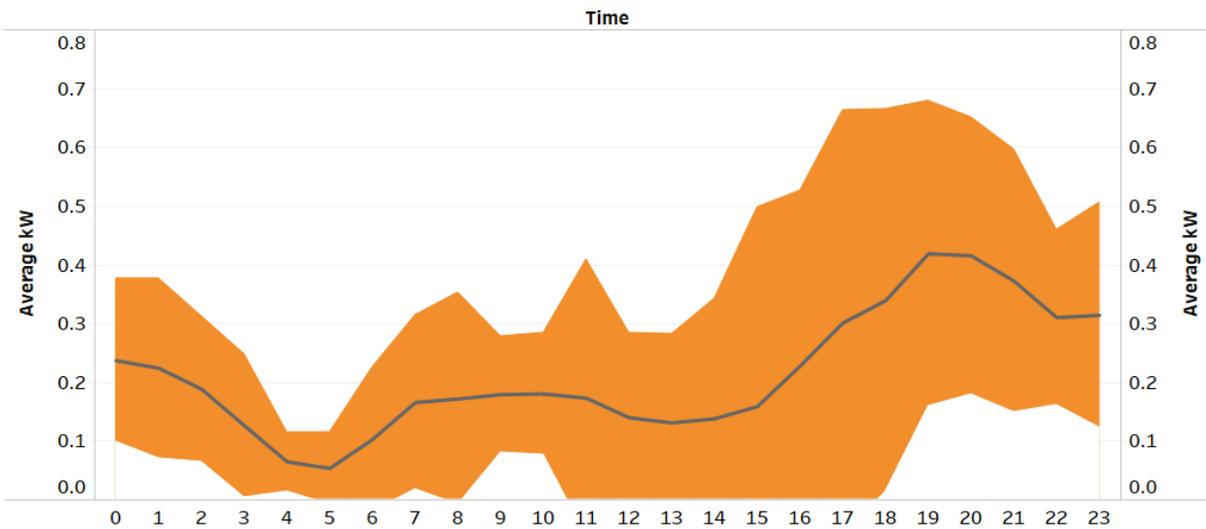


Figure 6-17
Weekday average load shape for all vehicles excluding LEAFs, Volts, and Teslas. Shading indicates one standard deviation above and below the average line.

Understanding how consumers behave with regard to their load plans is important. The following section divides the data into load shapes according to EV charging rate plans, as shown in Figure 6-18.

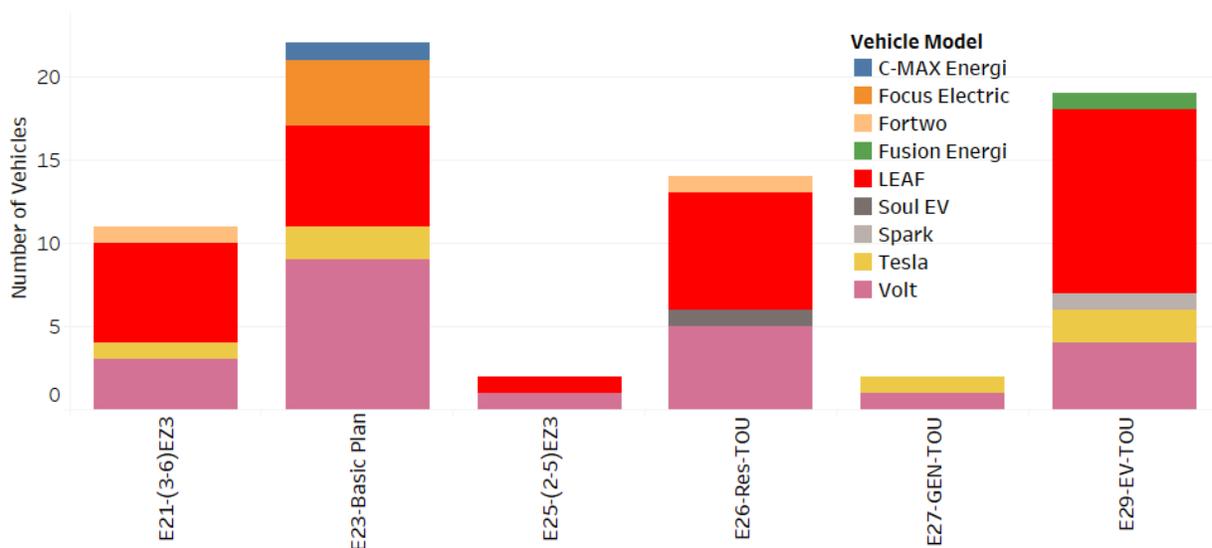


Figure 6-18
Number of vehicles enrolled in each rate plan colored by vehicle model

The basic load plan, E23, does not have any hourly restrictions; however, the rest of the plans incentivize EV drivers to avoid charging at certain times of the day, as shown in Table 6-1.

Table 6-1
Description of all of the EV charging rate plans. Only rate plans with at least 10 vehicles participating were included in the average load shape analysis.

Rate Plan Name	Description
E21-(3-6)EZ3	Avoid 3–6 p.m.
E23-Basic Plan	All charging times are the same
E25-(2-5)EZ3	Avoid 2–5 p.m.
E26-Res-TOU	Avoid 1–8 p.m.
E27-GEN-TOU	Solar Generation – Net metering
E29-EV-TOU	Avoid 1–8 p.m., Target 11 p.m. – 5 a.m.

Figure 6-19 shows the total amount of kilowatt-hours accumulated by each rate plan. The percentages shown by kilowatt-hour are very similar to the enrollment percentages shown in Figure 6-18.

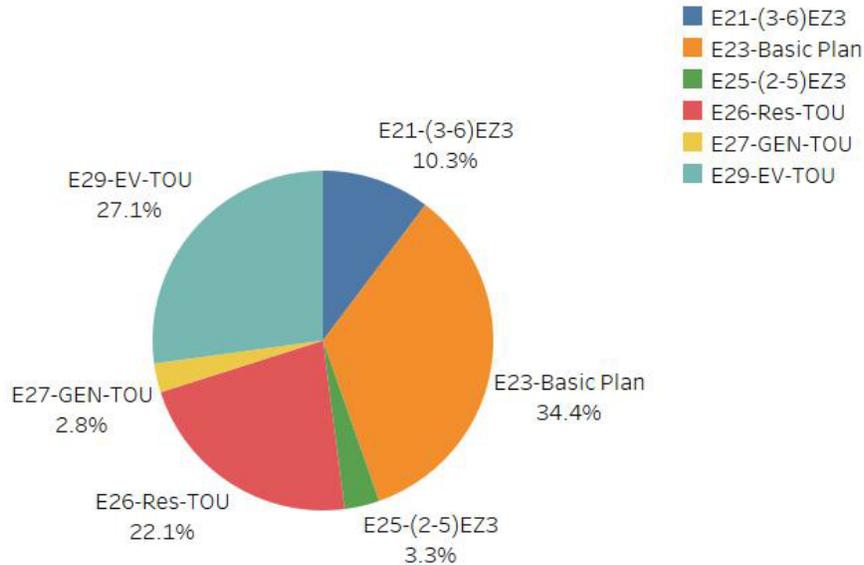


Figure 6-19
Percent of total kilowatt-hours used by each rate plan

While six rate plans were used in the study, only four load shapes are shown in Figure 6-20 since less data were associated with two of the plans. The basic plan, E23, shows an increase in charging from 3–10 p.m., most likely caused by the natural variability of people arriving home from work and plugging in their cars. It is interesting that there is a peak from 1–6 a.m. for the E23 (basic plan), likely due to the fact that a few vehicle owners programmed their cars to be ready to drive at 6 a.m., and thus they only charge for a few hours in the morning.

The E21 plan reflects avoided charging from 3–6 p.m., and the E26 plan shows a low average throughout the workday with a peak beginning at 8 p.m. The most dramatic curves are reflected in the E29 TOU rate, where the average curve goes from approximately 0.2 kW at 10 p.m. to 1.2 kW at 12 a.m. This again reflects the price incentive to charge between 11 p.m. and 5 a.m.

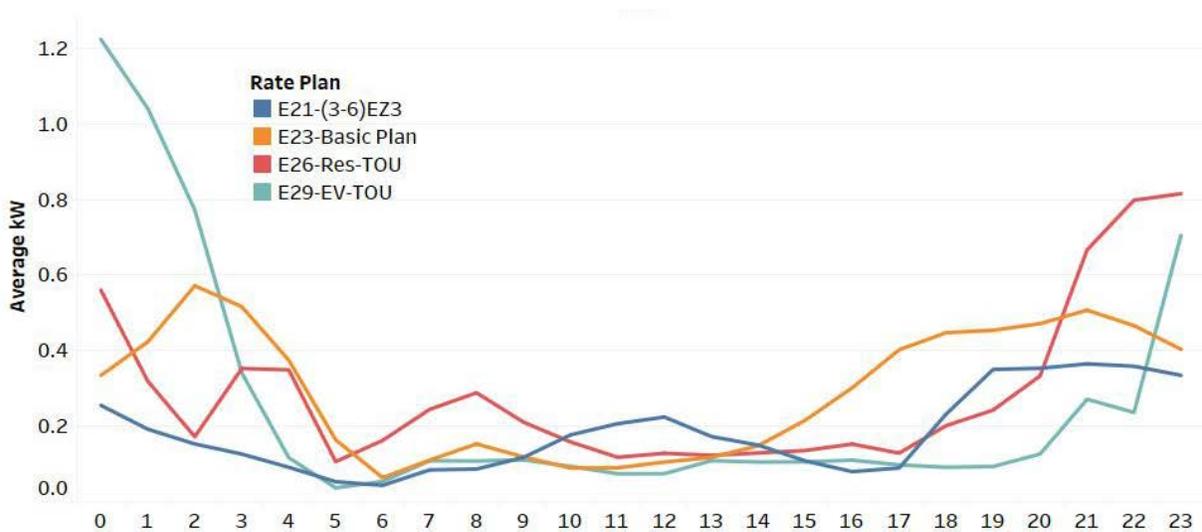


Figure 6-20
Weekday average load shape colored by four rate plans

As seen in the Driving Statistics section of the report, ambient temperature can play a significant role in individual vehicle efficiency. Figure 6-21 shows the weekday average load shape for winter months and summer months. The months were chosen to capture the coldest and warmest months of the year. Though individual drives show more of a temperature dependence on efficiency, when the statistics are averaged over all vehicles in the study, the difference in load shapes between hotter and colder months does not fall outside of one standard deviation. While there are temperature effects on the efficiency of the car, these effects are small compared to driver behaviors such as their frequency to fast charge or the aggressiveness of their driving. What was not tested in this study was the effect of very cold temperatures on the battery as those temperatures are not reached in Arizona.

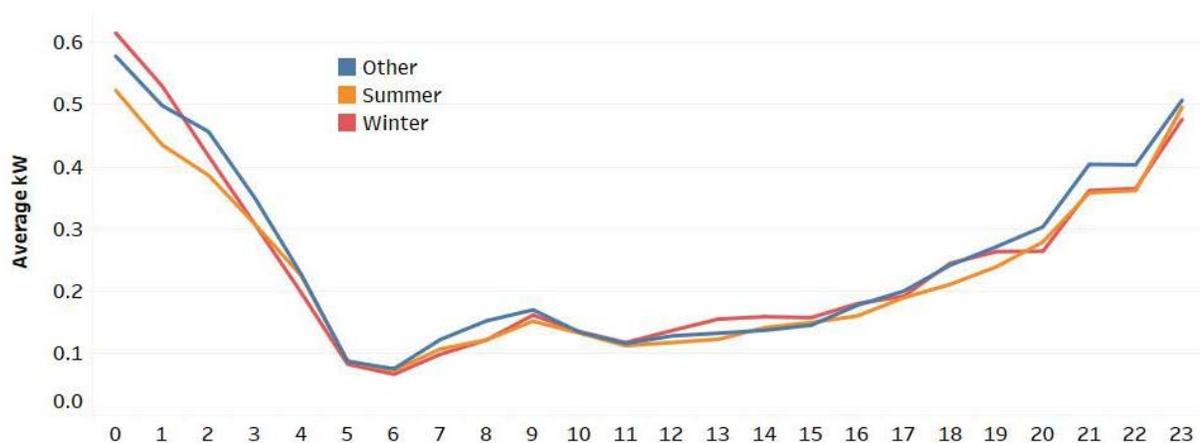


Figure 6-21
Weekday average load shape for summer months (June and July) and winter months (including the two coldest months of the year, namely, January and December)

7

CONCLUSIONS

While there have been attempts to understand and document EV driver behavior, many efforts fall short. Tracking studies that document utility advanced metering infrastructure (AMI) meter data miss the charging that occurs away from the base meter. Studies that use survey methods to log EV driver behavior often miss the mark because people generally cannot answer questions accurately on how much they drive (and charge). Finally, many studies track conventional vehicles and are then modified to adapt to an EV perspective, which requires far too many assumptions.

The deep dive presented in this report addresses issues regarding high-resolution minute-level data and tracking of vehicle movement from home to work as well as on road trips. The quality and resolution of the data obtained allow not only for summary-level statistics for drives and charges but also for time-series analysis of load data, which is usually only possible using meter data.

The data show that depending on the vehicle model, EVs use 2,700–3,300 kWh per year. Average load shape analysis indicates that EV drivers are sensitive to TOU rates, thus offering utilities a tool to help shape grid load when needed. The data also indicate that while temperature does impact EV efficiency, charging behavior outweighs those impacts.

While this groundbreaking study provides an excellent starting point for understanding EV driver behavior, EVs are a moving target. As mentioned in the introduction, the EV landscape is changing rapidly, with vehicles becoming larger, longer range, and less expensive over time. Additional charging infrastructure is being deployed and charging speed is improving. In the future, it will be important to understand the effect such changes will have on the average new vehicle buyer. It will also be important to consider whether a better and more familiar charging infrastructure will help EV drivers feel more confident in taking road trips (and therefore logging more miles). Another important consideration will be whether the presence of fast charging in under 10 minutes changes driving habits. The answers to such questions will be important in determining EV market share and accompanying load shapes.

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