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Extended Range Electric Vehicle Driving and Charging Behavior Observed Early in the EV Project

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ABSTRACT

ECOtality North America, OnStar, and the Idaho National Laboratory have partnered to collect and analyze electronic data from Chevrolet Volts enrolled in The EV Project, which is a large-scale plug-in electric vehicle infrastructure demonstration being conducted in 21 metropolitan areas across the United States. This paper presents results of an early analysis of these data. The data set analyzed came from 923 privately owned vehicles, which logged over 4.7 million driving miles from October 2011 to October 2012. These data are used to identify the potential of electric vehicle (EV) mode driving, based on driver and charging behavior.

Driving and charging behavior is quantified with metrics such as daily vehicle miles traveled, number of charging events performed per day, and distance driven between consecutive charging events. Drivers averaged 40.7 miles per day, with a median of 31.6 miles per day. Vehicles were charged 1.46 times per vehicle day driven on average, with a median of 1 charging event per day driven. This results in an average of 27.9 miles between consecutive charging events and a median distance of 19.8 miles between charging events. Underlying distributions for these metrics also are examined to find a wide variation in driving and charging behavior across vehicles and vehicle days.

Overall, 81% of the vehicles averaged 40 miles or less between consecutive charging events. Assuming a fixed EV mode range of 35 miles, vehicles in this study had the potential to drive 73% of their miles in EV mode. These results show that Chevrolet Volt drivers participating in The EV Project found frequent opportunities to charge their vehicles, such that a high percentage of their driving was performed in EV mode. Also, drivers took advantage of their vehicle's extended range mode to meet their driving needs beyond the all-electric range of their vehicle.

INTRODUCTION

The EV Project is a large plug-in electric vehicle (PEV) infrastructure demonstration, which is partially funded by the U.S. Department of Energy's Vehicle Technologies Program and led by ECOtality North America. ECOtality is installing approximately 13,000 Blink brand AC Level 2 and 200 dual port DC fast-charging units in 21 metropolitan areas across the United States. ECOtality partnered with Nissan North America and General Motors to enroll up to 8,000 Nissan LEAF™ battery electric vehicles and Chevrolet Volt extended range electric vehicles sold in these areas in The EV Project.

ECOtality partnered with OnStar and the Idaho National Laboratory to collect and analyze electronic data from the Chevrolet Volt vehicles participating in the EV Project. This paper presents summary statistics of in-use vehicle data collected from these vehicles in the first year of Volt enrollment in The EV Project. These statistics characterize early driving and charging behavior of participating Chevrolet Volt drivers.

The Chevrolet Volt is an extended range electric vehicle with a 16-kWh battery pack. The vehicle is capable of electric-only propulsion while in charge-depleting mode, which is also referred to as electric vehicle (EV) mode. EV mode range, when starting with a fully charged battery pack, is estimated to be 35 miles for the MY2012 Volt [1]. This range varies with conditions. Once the battery is depleted, the vehicle operates in extended range (ER) mode. In this mode, the vehicle uses a gasoline-fueled auxiliary power unit to charge its battery for propulsion, using a charge-sustaining control strategy. To operate in EV mode, Volt drivers can charge their vehicles using any available AC Level 2 charging unit (including those not part of The EV Project) or by connecting the vehicle's AC Level 1 cordset to any standard 120-V outlet. Data were collected (with customer consent) from participating Chevrolet Volt vehicles by OnStar.

The purpose of this paper is to identify the potential of EV mode driving, based on driver behavior and the available charging infrastructure.

BACKGROUND

To accomplish its goals, The EV Project is installing a vast network of charging units, otherwise referred to as electric vehicle supply equipment (EVSE). This charging infrastructure is concentrated in 21 cities in nine U.S. states and the District of Columbia. Figure 1 identifies these cities.

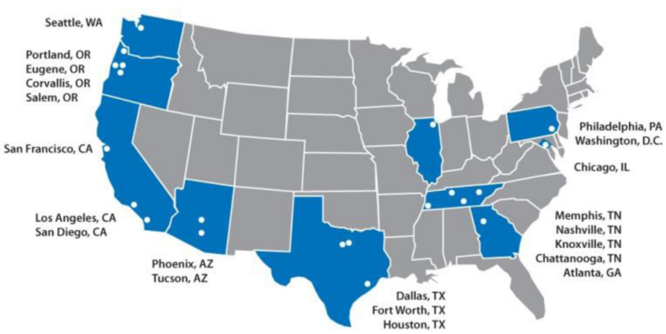

Figure 1. Cities participating in the EV Project.

ECOtality partnered with Nissan North America and General Motors to invite Nissan LEAF and Chevrolet Volt customers in these metropolitan areas to participate in The EV Project. Vehicle owners who qualify to participate in The EV Project received a Blink AC Level 2 (240-VAC) residential EVSE at no cost. In addition, installation incentives may have been available from The EV Project, depending on location. In return, project participants agreed to allow data collection from their vehicles and EVSE. Data collection from EV Project vehicles and charging units will continue through 2013.

The EV Project also is installing several thousand Blink commercial EVSE in and between the project cities. These charging units are networked, which allows data collection.

PROJECT STATUS

Enrollment of Chevrolet Volt owners in The EV Project began in late summer 2011, with 21 vehicles enrolled and transferring data by the end of September 2011. Enrollment rose steadily throughout the following year. By September 2012, 1,052 Chevrolet Volts had been enrolled in the project and transferred data. During this year, the number of publicly available Blink EVSE installed in EV Project regions increased at a similar rate. Table 1 presents the number of EV Project vehicles enrolled and Blink commercial EVSE deployed, by region, at the end of September 2012.

Table 1. EV Project Chevrolet Volt and commercial EVSE deployment in regions with Volts enrolled through September 2012.

EV Project Region	Number of Chevrolet Volts Enrolled	Number of Blink Commercial EVSE Installed
Phoenix, AZ	83	314
Tucson, AZ	7	92
Los Angeles, CA	146	216
San Diego, CA	153	282
Washington, D.C.	177	23
Oregon	87	350
Chattanooga, TN	11	54
Knoxville, TN	17	153
Memphis, TN	19	18
Nashville, TN	29	193
Dallas/ Ft. Worth, TX	133	157
Houston, TX	69	72
Washington State	88	238
Chicago, IL	19	5
Atlanta, GA	5	2
Philadelphia, PA	9	0
Total	1,052	2,169

Most of the commercial EVSE listed in Table 1 are available for public use. The number of vehicles shown in Table 1 represents vehicles that have been enrolled in the EV Project and from which data have been collected. This is a subset of the total sales of Chevrolet Volts in these regions.

RESULTS

Summary metrics and distributions were calculated to quantify driving and charging behavior of Chevrolet Volt owners. For this paper, results come from the analysis of in-use electronic data collected from 923 Chevrolet Volts enrolled in The EV Project from October 2011 through September 2012. These vehicles are privately owned and operated for personal use. They are located in each of the project regions shown in Table 1. By the end of the study period, these vehicles had logged 4,757,672 miles; 579,828 trips; and 170,311 charging events.

Influences on Behavior

Before presentation of results, it is necessary to identify conditions that may have influenced driving and charging behavior during the year of operation being studied in this paper.

Although the nearly 5 million miles in the data set are significant, the contribution of miles from most vehicles through September 2012 was relatively small. Figure 2 quantifies the contribution of each vehicle by showing the distribution of odometer readings, or miles-in-service, of these vehicles at the end of the study period. The left y-axis in Figure 2 applies to the histogram of vehicle miles-in-service (blue bars). The right y-axis applies to the cumulative distribution (red line).

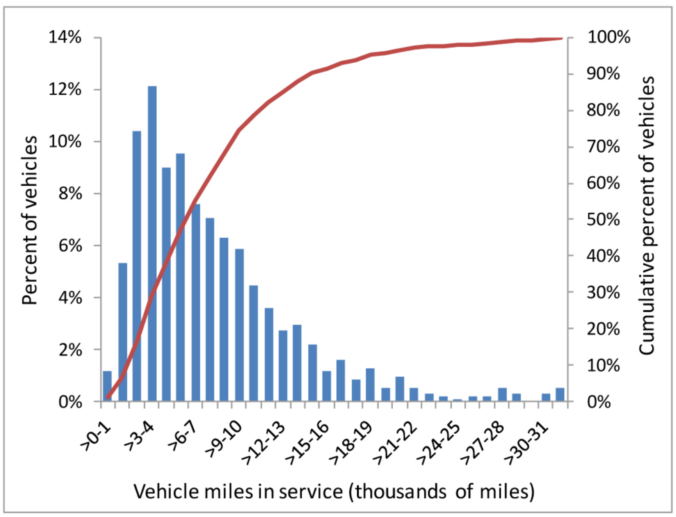

Figure 2. Distribution of vehicle miles-in-service.

The median miles-in-service was 6,248 miles. By the end of the study year, 74% of vehicles had driven 10,000 miles or less. This is because most of the vehicles represented in the data set joined the project after the start of the 1-year period, with the majority enrolled in the second half of the year. In fact, the Chicago, Atlanta, and Philadelphia project regions were added to the project in August 2012. Therefore, the statistics shown in this paper describe the behavior of vehicle owners who were mostly still new to their Chevrolet Volt ownership experience. This is an important distinction, because behavior may change over time as Volt owners become accustomed to their new vehicle and the nuances of its new technology, especially its dual-fuel nature.

Another condition that may have affected behavior is the opportunity for vehicle charging away from home. Over the study period, the opportunities for vehicle charging at dedicated charging units in public varied geographically and with time. As seen in Table 1, the number of commercial EV Project charging units varied by region and was relatively low in some areas by the end of the study period. Furthermore, installation of these units occurred throughout the year being studied. The same can be assumed about installation of publicly available charging units by other manufacturers in the EV Project regions. The opportunity for connecting the vehicle to a standard 120-V outlet did not necessarily change with time. However, previous studies of conversion plug-in hybrid electric drivers found that many PEV drivers are uneasy about charging their vehicles by using outlets that do not belong to them [2]. Therefore, it is expected that the practiced etiquette for charging PEVs using public 120-V outlets varies by region and over time as social norms evolve. Finally, it is expected that the drivers' interest in charging their vehicles away from home varies widely, based on their motivation for EV mode versus ER mode driving, their travel patterns, and a host of other factors.

Perhaps the most important factor to recognize for contextualizing results is that the PEV market, as a whole, is immature. Therefore, any purchaser of a PEV to this point would be classified as an early adopter. These consumers often have different interests and behaviors than other consumers. It is generally accepted that their use of a product is not representative of the mass consumer market. This paper does not attempt to divide project participants into categories. Instead, it suffices to say that the results presented herein are representative of an early market.

Observed Driving and Charging Behavior

Table 2 presents summary metrics describing driving and charging of the 923 vehicles studied, including the relationship between driving and charging frequency.

Table 2. Driving and charging summary statistics.

Mean/median trip distance (miles)	8.2/4.3
Mean/median distance driven per vehicle day driven (miles)	40.7/31.6
Mean/median number of trips between charging events	3.4/3
Mean/median distance driven between charging events (miles)	27.9/19.8
Mean/median number of charging events per vehicle day driven	1.46/1

The mean and median values in Table 2 give an idea of the overall behavior of the Volt drivers in the study. For example, on average, Volts are driven 40.7 miles per day and charged 1.46 times per day, which results in 27.9 miles between consecutive charging events. Considering that the estimated

EV mode range on a fully charged battery is 35 miles, this suggests that *on average*, a high percentage of Volt driving is done in EV mode. Of course, individual drivers do not follow average behavior, but rather drive and charge according to their individual needs and routines. Therefore, this paper will present the underlying distributions of behavior corresponding to the metrics in Table 2.

Table 2 shows that at this point in the project, Volts were driven 8.2 miles per trip on average, with a median trip distance of 4.3 miles. This indicates that the underlying distribution is left-skewed, rather than normally distributed. Figure 3 visualizes this skew by showing the distribution of trip distance observed in the data set.

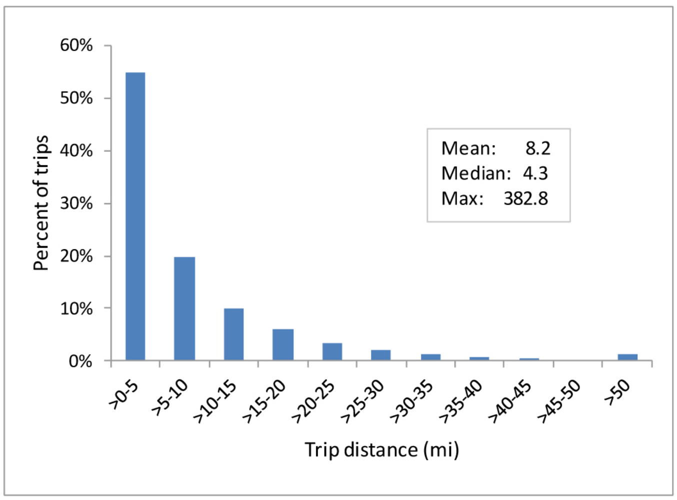

Figure 3. Distribution of trip distance.

Figure 3 shows that over half of all trips were less than 5 miles. This is reasonable, given that all vehicles enrolled in The EV Project are based in densely populated metropolitan areas. The maximum trip distance observed was 382.8 miles. This also is reasonable, given the U.S. Environmental Protection Agency's estimated range for the MY2012 Volt of 375 miles when starting with a fully charged battery and full gasoline tank [1]. (This also emphasizes the fact that actual vehicle range varies with driving conditions.)

Daily Vehicle Miles Traveled

Travel behavior studies have quantified daily driving by conventional light duty passenger vehicles in the United States and compared these statistics to expected PEV EV mode driving ranges [3, 4]. One metric frequently reported is daily vehicle miles traveled. This can be reported as a per-vehicle average distance driven per day. Figure 4 shows this metric for the 923 Volts in the data set. Only days when each vehicle was driven are counted in the averages.

The cumulative distribution (right y-axis) shows that 53% of the vehicles averaged 40 miles or less per day on days when the vehicle was driven. A small number of vehicles averaged over 100 miles per day, with one vehicle averaging as high as 136 miles per day driven. Figure 5 further breaks down daily driving by showing the distribution of miles driven per vehicle day. Rather that comparing each vehicle's average, this figure shows the distribution of daily miles driven on all 116,983 vehicle driving days in the data set, without respect to which vehicle performed the driving on each day.

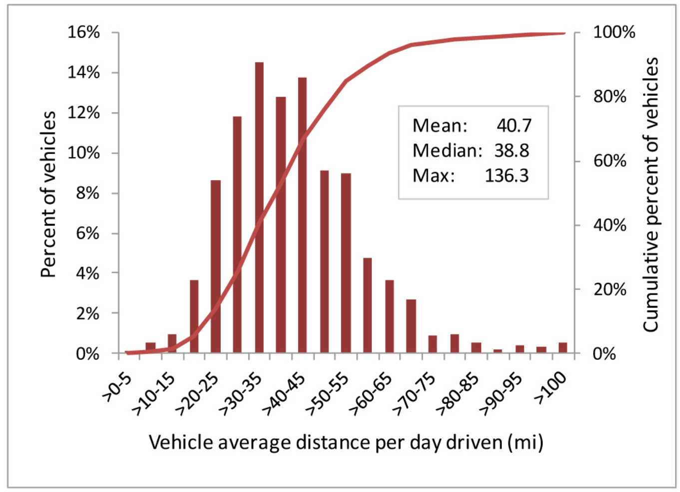

Figure 4. Distribution of vehicle average distance driven per day on days when the vehicle was driven.

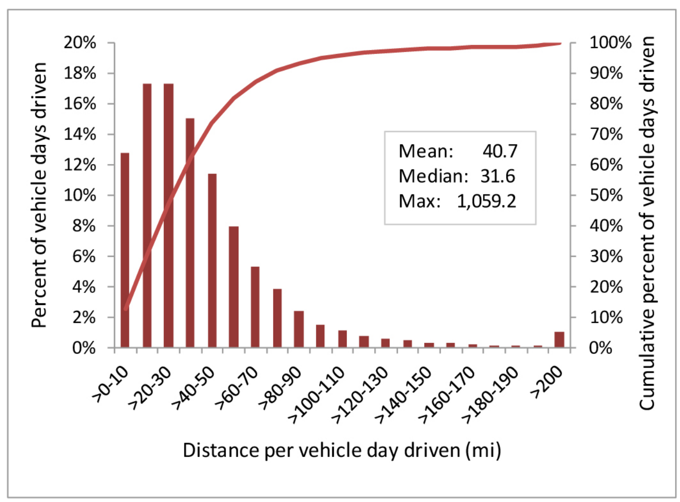

Figure 5. Distribution of distance driven per vehicle day on days when the vehicle was driven.

Figure 5 shows that Volts were driven 40 miles or less on 62% of vehicle driving days. Volts were driven over 100 miles on 5% of the days. One vehicle was driven over 1,000 miles in one 24-hour period. This indicates that Volt drivers could accomplish the majority of their daily driving if they were to fully charge their vehicle each night. It also means Volt drivers frequently took advantage of their vehicle's ER mode to meet their driving needs.

Investigation of the distribution of daily miles driven for individual vehicles found tremendous variation in driving distance from day to day for all vehicles, regardless of the vehicle's average daily driving distance. All vehicles had many days with less than 1 mile of driving. Many vehicles with a low average daily distance (for example, less than 25 miles) had individual days when they were driven well over 100 miles. To visualize the upper end of this variation, Figure 6 shows the distributions of the maximum, 95th percentile, and median daily driving distances for each vehicle.

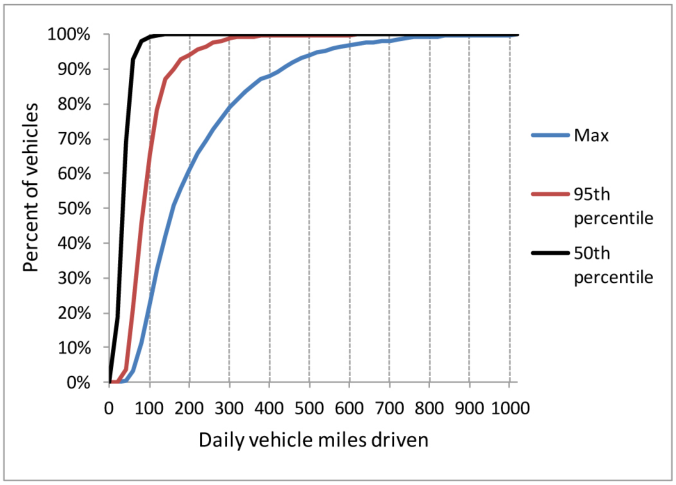

Figure 6. Distributions of maximum, 95th percentile, and median distance per day driven.

The blue line in Figure 6 represents the distribution of the maximum daily distance driven by each vehicle. This curve indicates that 23% of the vehicles never drove more than 100 miles in one 24-hour period. To ignore any extreme outliers (i.e., a single day when a vehicle drove an unusually long distance), the distribution of the 95th percentile distance for each vehicle also is shown (red line). This curve indicates that 65% of the vehicles drove less than 100 miles on 95% or more of their driving days. Conversely, 35% of the vehicles drove over 100 miles on 5% or more of their driving days. This is another indication that Volt drivers have taken advantage of the vehicle's range-extending option. Finally, the 50th percentile, or median distribution (black line), indicates that 99% of vehicles drove less than 100 miles on at least half of their driving days.

Charging Frequency

The EV Project provides one of the first opportunities to examine a large data set to observe actual charging behavior in addition to driving behavior. A simple way to characterize charging behavior is to count the charging frequency with respect to time. Figure 7 provides the distribution of vehicle average number of charging events per day driven. For the purposes of this paper, a charging event is defined as any instance when the vehicle was connected to an off-board electrical power source and some charging energy was consumed by the vehicle. The amount of energy stored by the battery varies by charging event.

Figure 7 shows that over 80% of the vehicles were charged more than once per day, on average. It also is apparent that considerable variation existed in charging frequency from vehicle to vehicle. One vehicle averaged as high as 3.2 charging events per day, when the vehicle was driven. Some vehicle owners did not seem as compelled to charge their vehicles; the minimum vehicle average charging frequency was 0.14 times per day driven or once per week.

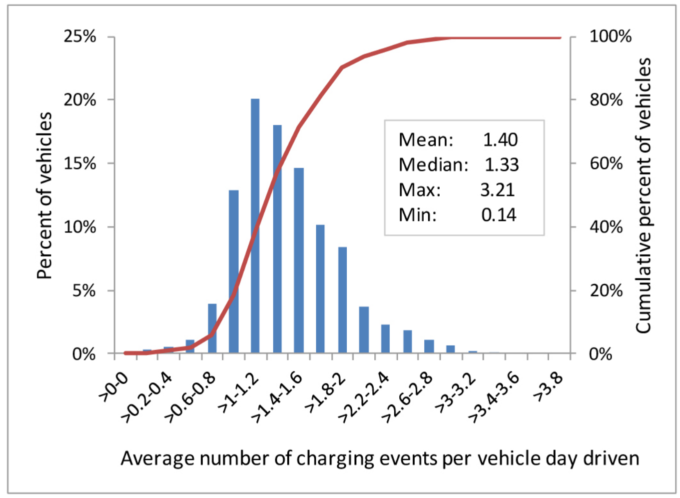

Figure 7. Distribution of average charging events per vehicle day driven.

There are many conceivable reasons why charging frequency varies from vehicle to vehicle. Previous studies of conversion plug-in hybrid electric vehicle drivers found that driver motivation to plug in his/her vehicle varied dramatically from driver to driver. Some took it as a challenge to maximize their driving in charge-depleting mode (or fuel economy if that was their metric of interest). These drivers expressed interest in actively seeking opportunities to plug in their vehicles and adopt more efficient driving habits. Others simply saw their car as a means of transportation and did not notice their vehicle's mode of operation or place a priority on charging their vehicle. Finally, drivers with the most sophisticated understanding of their vehicles and their daily driving habits typically charged their vehicles *less* frequently than others. These drivers understood how much they needed to charge their vehicles to achieve their desired amount of EV mode driving and they chose not to charge more often than was necessary [2, 5]. It appears that the sample of Chevrolet Volt drivers in this study have similarly diverse interests and levels of understanding.

Given that EV Project participants are early adopters of electric vehicle technology, one may assume that the majority of the Volt owners in this study are motivated to understand their vehicle's operation and to experience EV mode operation. However, it is conceivable that some individuals may be satisfied with the image their vehicle portrays or some other emotional aspect of the vehicle, regardless of its mode of operation.

The variation in charging frequency is further observed by plotting the charging frequency distribution with respect to individual vehicle days, rather than per-vehicle averages. Figure 8 shows the distribution of charging events per day driven, across all vehicle driving days.

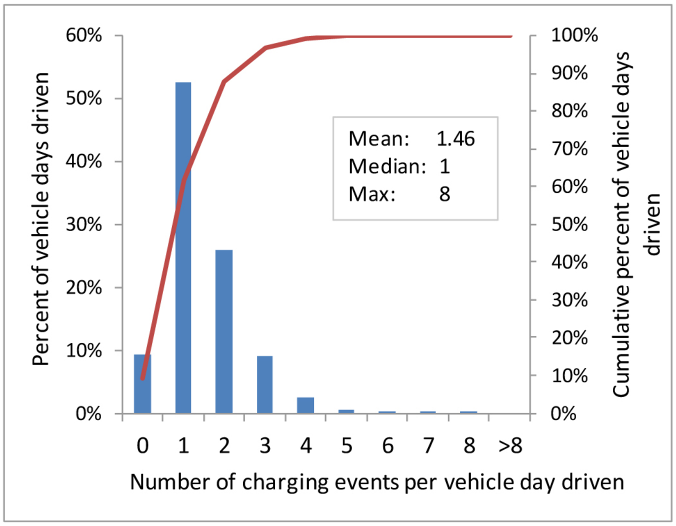

Figure 8. Distribution of number of charging events per vehicle day driven.

Some drivers found the opportunity to plug in their vehicle as much as 8 times in one 24-hour period; however, the majority of days (62%) had 1 or 0 charging events. This prompts investigation of how charging frequency varies by vehicle. Did the vehicle or vehicles that charged 8 times per day always charge numerous times per day? Did vehicles that rarely charged ever have a day when they charged multiple times? To answer these questions, vehicles were grouped by their average charging frequency. Figure 9 shows the distribution of the number of charging events per day across all vehicle driving days for each group.

Figure 9 shows that as vehicle average charging frequency increases (i.e., the mean of the curve shifts to the right), so does the variation in charging frequency (i.e., the spread of the curve widens). This also is evident in Table 3, which provides the standard deviation for each of the four vehicle groups. This increasing spread, with increasing average charging frequency, indicates that drivers do not sustain high charging frequency from day to day. This may be because it is difficult or because it is perceived as undesirable or unnecessary. Figure 7 and Table 3 also show vehicles that typically rarely charge occasionally find the opportunity to charge as many as 4 times on some days.

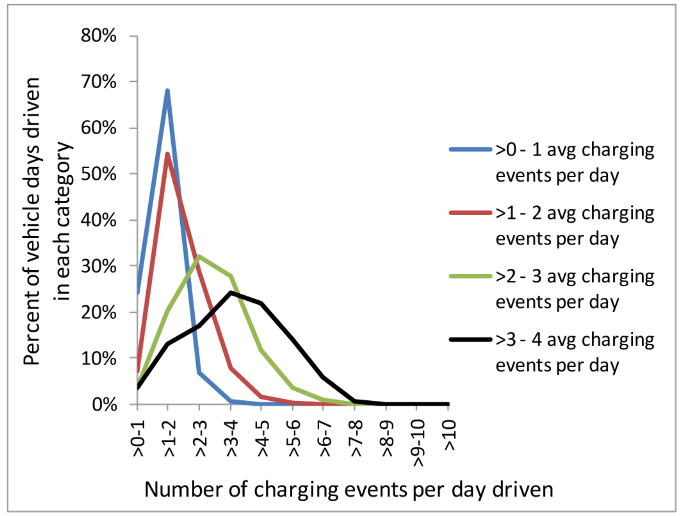

Figure 9. Distribution of average charging events per vehicle day driven.

Table 3. Statistics for vehicle average charging frequency groupings.

Range of average charging frequency (events per day driven)	>0 – 1	>1 – 2	>2 – 3	>3 – 4
Number of vehicles	173	659	88	3
Number of vehicle driving days	17,332	86,573	12,468	610
Maximum number of charging events per day	4	8	8	7
Median number of charging events per day	1	1	2	3
Standard deviation	0.6	0.8	1.2	1.5

It seems reasonable that most vehicles charged between once and twice per day. Still, some drivers apparently were highly motivated to plug in their vehicles on many days. Data from a small sample of frequently charged vehicles were investigated. Most of these vehicles left from and returned to home numerous times during the day, and they were plugged in every time the vehicle was parked at home. The drivers of these vehicles may have been motivated to maximize EV driving or they may have simply formed the habit of plugging in their vehicle every time it is parked at home. Other vehicles found opportunities to charge in public, including at business and industrial parks (presumably places of work), as well as schools, retail outlets, and places of recreation. Future studies will track charging frequency trends with respect to location.

Driving with Respect to Charging

Studying daily driving and charging patterns is intuitive when considering human behavior. However, it is the relative amount of driving and charging that impacts the vehicle's ability to drive in EV mode versus ER mode. Therefore, driving distance, with respect to charging, was examined. Figure 10 gives the distribution of vehicle average distance driven between consecutive charging events.

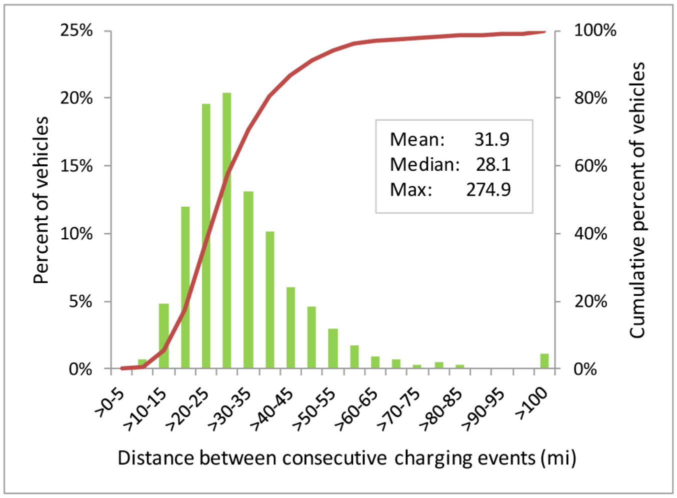

Figure 10. Distribution of vehicle average distance driven between charging events.

Compared to vehicle average daily distance driven, this distribution is shifted to the left, because vehicles with more daily driving tended to be charged more than once per day. This resulted in 81% of vehicles averaging 40 miles or less between charging events, whereas 53% of vehicles averaged 40 miles or less per day. The distribution of distance driven between consecutive charging events also can be shown with respect to individual "driving segments" between charging events. A driving segment is defined as the sum distance driven in all trips between consecutive charging events. Figure 11 shows this distribution.

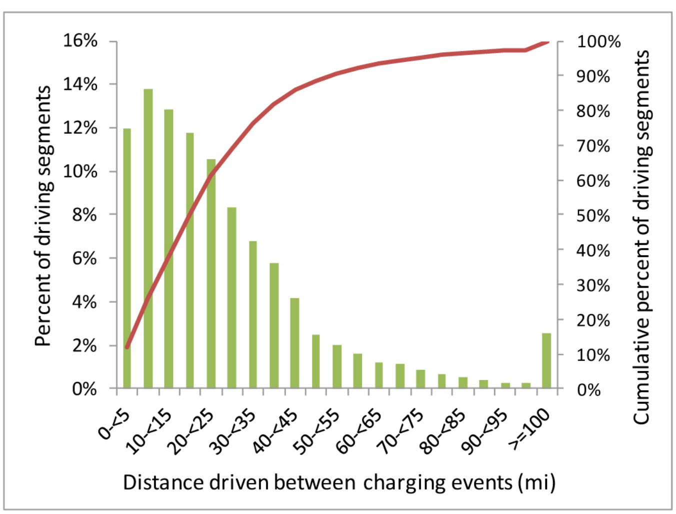

Figure 11. Distribution of driving segment distance between charging events.

Continuing with the 40-mile benchmark, Figure 11 shows that 86% of driving segments were 40 miles or less. If all charging events ended with a completely charged battery, nearly all the miles in these segments would have been driven in EV mode.

In order to visualize the total amount of driving that could be accomplished in EV mode, a miles-weighted distribution of distance driven between charging events is shown in Figure 12. Each bar in the histogram represents the sum of all distances driven in driving segments of a certain distance. For example, if a vehicle was to drive 10 miles between charging, then 12 miles, then 14 miles, the total miles driven in driving segments between 10 and 15 miles would be 36 miles.

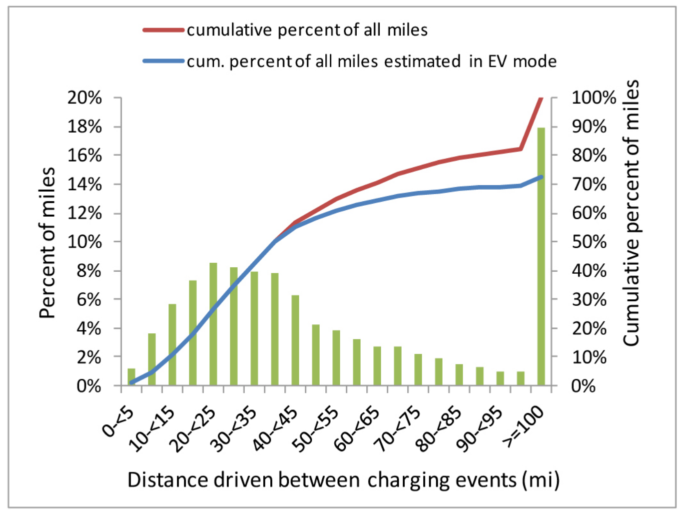

Figure 12. Miles-weighted distribution of driving segment distance between charging events.

Ultimately, it is the total distance driven in each segment beyond the vehicle's all-electric range that determines the percentage of EV mode driving. If all charging events were to have ended with a full battery and if the vehicle's EV mode range was always exactly 35 miles, then the first 35 miles of each segment would be driven in EV mode. This would result in EV mode operation for 73% of all miles driven in the data set, as shown by the cumulative distribution (red line) in Figure 12. Keep in mind that the actual amount of EV mode operation varies from this idealized estimate, based on charging duration, power level, battery state of charge (SOC) at the beginning of charging, driving style, and driving conditions.

Charging Completeness

In the previous section, the distance driven between charging events was examined and compared to the expected range of the vehicle. Another way to analyze driving and charging tendencies with respect to EV mode range is to look at the vehicle battery pack's SOC at the start and end of charging events. Battery SOC at the start of charging is an indicator of how much of the battery pack's capacity had been depleted prior to charging. Figure 13 shows the distribution of battery SOC at the start of charging for all charging events in the data set. This distribution is given separately for home and away-from-home charging events for comparison. As stated earlier, all EV Project participants have a Level 2 charging unit installed at their residence. Therefore, it is assumed that all charging at home is performed at the Level 2 charging rate. Away-from-home charging can be conducted using a dedicated, publicly available, AC Level 1 (120-VAC) or Level 2 EVSE unit or any standard 120-volt outlet.

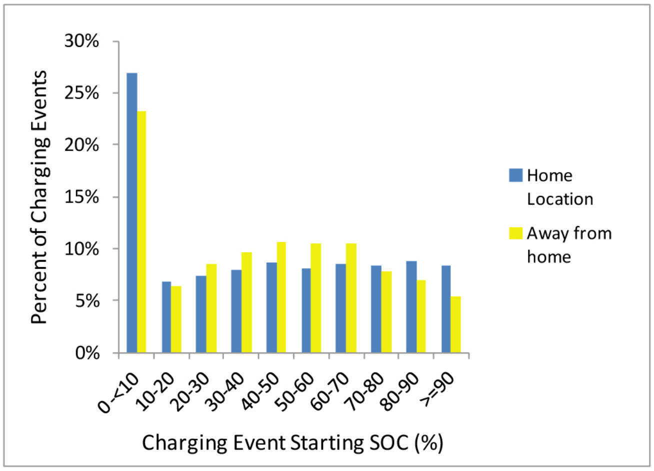

Figure 13. Distribution of battery pack state of charge at the start of charging by charging location.

Both distributions are fairly wide, with a sharp spike in the lowest SOC bin. Figure 13 indicates that for one quarter of the charging events, the battery had been fully or nearly fully depleted by the time the drivers plugged in their vehicles. The starting SOC distribution when charging away from home is slightly higher than the home distribution when SOC is mid range, suggesting that drivers were more likely to take away-from-home charging opportunities prior to fully depleting their pack.

The distribution of battery SOC at the end of charging represents how "full" the pack was when the driver began the first trip after charging. Figure 14 gives this distribution, breaking out home and away-from-home charging events.

The vast majority of home charging events resulted in a full or nearly full pack. In general, away-from-home charging ended with slightly lower SOC, but over 60% of away-from-home charging events were completed with greater than 90% SOC.

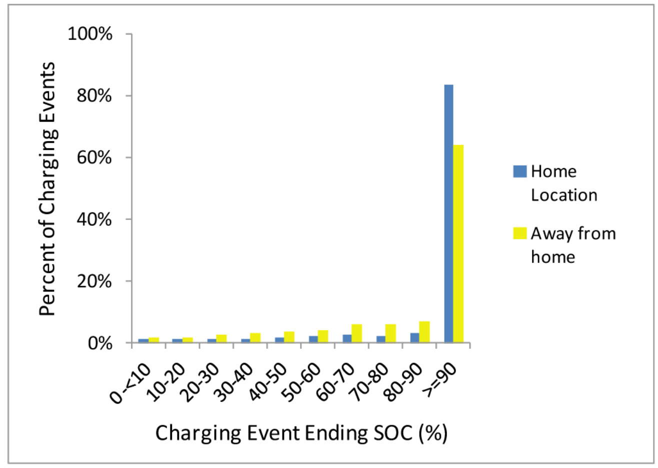

Figure 14. Distribution of battery pack state of charge at the end of charging by charging location.

SUMMARY/CONCLUSIONS

An early analysis of the data from Chevrolet Volts enrolled in The EV Project was performed. The data set analyzed came from 923 privately owned vehicles, which logged over 4.7 million driving miles in 2011. On average, Chevrolet Volt drivers drove 8.2 miles per trip and 40.7 miles per day. Median values were 4.3 and 31.6 miles, respectively. Drivers averaged 27.9 miles between consecutive charging events, with a median of 19.8 miles. The average and median number of times vehicles were charged per day driven were 1.46 and 1.0 charging events per day, respectively.

Distributions of trip distance, distance driven between charging events, distance driven per day, charging event frequency per day driven, and battery SOC at the start and end of charging were examined to find a wide variation in driving and charging behavior. Vehicles were driven from 0.1 to over 1,000 miles in a single day, with 40 miles or less being driven on 62% of the driving days. Vehicles were charged 0 or 1 times on 62% of the driving days. Vehicles with an average charging frequency above two charging events per day driven were found to have more variation in their charging frequency from day to day. These vehicles performed from 0 to 8 charging events in a 24-hour period.

In addition to charging frequency, charging completeness was quantified. Vehicles were found to have fully depleted battery packs prior to charging for about 25% of the charging events. Charging resulted in an SOC of 90% or greater for over 80% of the charging events at home and 60% of the charging events performed away from home.

Driving distance relative to charging frequency was investigated. Eighty-one percent of the vehicles averaged 40 miles or less between consecutive charging events. As a result, vehicles in this study had the potential to drive 73% of their miles in EV mode, assuming a fixed EV mode range of 35 miles.

These results indicate that Chevrolet Volt drivers participating in The EV Project thus far have found frequent opportunities to charge their vehicles, such that a high percentage of their driving has been performed in EV mode. Also, drivers have taken advantage of their vehicle's extended range mode to meet their driving needs beyond the all-electric range of their vehicle.

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DEFINITIONS/ABBREVIATIONS

EV - electric vehicle

ER - extended range

EVSE - electric vehicle supply equipment

PEV - plug-in electric vehicle

SOC - state of charge

DISCLAIMERS

Chevrolet Volt owners participating in The EV Project have given explicit written consent to allow data to be collected from their vehicles.

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