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Consumer Behavioral Adaption in EV Fast Charging Through Pricing

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Title page

Consumer Behavioral Adaption in EV Fast Charging Through Pricing

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Abstract

Despite recent developments surrounding fast electric vehicle charging and an ever growing interest in research, little is known about how people actually use direct current fast chargers (DCFC) or how different pricing may affect their recharging behavior. Understanding consumer behavior in DCFC usage is critical to successful deployment of DCFC and economical pricing of the service usage. This paper analyzes real-world field data to examine DCFC usage in the United States. In particular, it examines changes in recharging behavior between periods when the charging service was free and when it was not. Results from this study show evidence that a flat-rate fee has a negative effect on the usage efficiency of DCFC stations.

Keywords:

electric vehicle

fast chargers

public charging infrastructure

1. Introduction

Electrification of motor vehicles is one of the most important tasks to be achieved for ensuring the energy security of the United States. With an ever longer driving range and lower cost, new models of electric vehicles (EV) continue to be introduced by car manufacturers around the world. In the United States, major automobile manufacturers (such as General Motors, Nissan, and Tesla) have started selling electric cars in the $30,000 range, with other manufacturers following that industry lead. Liu and Lin (2017) predicted that by 2050, 29% of vehicles sold in the United States will be electric. Commensurate with the increasing number of EVs on the road, there has been a drastic increase in charging infrastructure in the United States over the past few years. As of December 2016, ChargePoint America, one of the largest operators of EV charging stations, operated more than 31,000 connected charging spots (ChargePoint 2017a).

One undesirable characteristic of an EV is its slow refueling relative to gasoline refueling. For example, a 2012 Nissan Leaf equipped with a 24-kWh battery takes about 8 hours to achieve a full charge from empty with a 240-volt alternating current (AC) Level 2 charger (Nissan 2012). While AC Level 2 chargers may be suitable for overnight charging at home, a faster speed of charging is required to enable drivers to more easily adapt to EV refueling by making the recharging process more like traditional gasoline refueling. Direct current fast chargers (DCFC) are capable of charging at a much faster rate than AC Level 2 chargers, possibly making them a viable alternative to Level 2 chargers. Recently, there have been great advances in DCFC technology. Manufacturers of public EV fast charging stations are breaking ground on this technology by offering ultra-fast chargers that are capable of adding tens of miles of range in minutes (EVgo 2017, ChargePoint 2017b). With advanced DCFC technology and proliferation of EVs in the light-duty vehicle market, efficient allocation and operation of DCFC infrastructure and developing successful business models for DCFC deployment are amongst the topics of high interest for research in both academia and industry.

Despite recent developments surrounding fast EV charging and an ever-growing interest in research, little is known about how people actually use DCFC or how different pricing may affect their recharging behavior. In the past, many assumptions were made about user behavior when modeling charging demand. For example, it was often assumed the driver parked the vehicle at the recharge station for 30 minutes (or up to 80% full) and then the station was immediately available for the next recharge when the previous one finished (Zhang et al. 2015, Zenginis 2016). However, service utilization of charging stations by consumers and pricing of the service are much more complicated in reality because the EV DCFC technology works quite differently than traditional gasoline refueling. Therefore, understanding consumer behavior in DCFC usage is critical to successful deployment of DCFC and economical pricing of the service. This paper analyzes real-world field data to examine DCFC usage in the United States. In particular, it examines the effect of a flat-rate fee by analyzing changes in recharging behavior between two periods: (1) when the charging service was free and (2) when it was not. The authors hopes that the work presented here provides greater understanding of consumer decisions regarding EV fast charging and helps advance research on charging station infrastructure deployment and operation for both academic researchers and infrastructure planners.

2. Technology and Economics of Direct Current Fast Chargers

A faster charging speed can enable drivers to more easily adapt to the EV refueling experience by making the recharging process more similar to gasoline refueling. It also can greatly extend the distance over which an EV can travel in a day beyond a vehicle's full-charge range. Generally speaking, a DCFC is capable of charging at a rate several times faster than an AC Level 2 charger; however, the technology has limits. Firstly, a DCFC's maximum rate of charge can vary among different EV models and depends on the vehicle battery's charge acceptance rate, which is managed by the onboard battery management system. For example, regardless of a DCFC's power rating, the 2012 Nissan Leaf will limit the charging rate to up to 50 kW. At this rate, the DCFC is capable of recharging a Leaf battery from a 10% state of charge to an 80% state of charge in about 30 minutes (Nissan 2012). Secondly, unlike gasoline refueling, the rate of charge is not constant over time. Idaho National Laboratory has tested the rate of charge of various DCFC systems in the past (INL 2017). Figure 1 shows the state of charge (SOC) of a 2011 Nissan Leaf plugged into a Hasetech DCFC for recharging over time. As shown in the figure, the rate of charge diminishes over time. This is due to the fact that the charging rate becomes slower as SOC level increases; for example, when SOC is below 30% at the beginning of charge, the rate of charge is about 0.72 kWh per minute, whereas after the SOC level is at 80%, the rate drops to 0.16 kWh per minute, which is less than a quarter of the rate at the beginning of charge.

Figure 1. Line plots of changes in SOC, voltage, and current over charging time

The reason for this diminishing rate of charge is that lithium ion batteries are typically charged using a constant-current, constant-voltage charging algorithm. The battery may be charged at a constant current at or below its maximum-rated continuous charge current until its maximum charge voltage limit is reached. At this point, charging current is tapered to maintain the battery near this top-of-charge voltage. For a pack made of several cells, a battery management system monitors the voltage of each parallel cell connection to ensure no cells are overcharged. In a perfect battery pack, all cells function identically; however, variations in resistance and capacity due to manufacturing defects or aging can cause cell imbalance. In this case, the charging rate of the entire pack is limited by the cell that reaches the maximum charge voltage first. Because of this, the overall pack voltage where constant voltage charging begins may differ. The onboard battery management system controls the charge rate by calculating and continuously communicating the maximum charge current to the DCFC over the duration of the fast charge event.

Although the availability of DCFCs is limited relative to AC Level 2 chargers, some charging station operators in the United States operate DCFCs for public use. Because fast charging entails a somewhat complex trade-off between time and amount of charge, the economics of DCFC deployment is an intertwined problem with technological characteristics. In addition, because of high capital and installation costs, deployment of DCFC infrastructure requires both deliberate pricing and efficient allocation (i.e., DCFCs can promise fewer charging stations because of their fast charging capability, while their equipment and installation costs are much higher than slower chargers). In fact, unlike gasoline, which is typically priced for a constant amount per gallon, the price of DCFC usage can vary significantly from one service provider to another. For example, while EVgo offers DCFC charging plans that consist of a fixed fee (either monthly or per session) plus an additional fee per minute, ChargePoint charges a flat rate of $9.95 per use (EVgo 2017, ChargePoint 2017b). This variation in usage fees, combined with inherent variation in charge rate, results in a large variation in cost for the amount of energy delivered.

Many studies about simulation/optimization (He et al. 2013, Liu et al. 2013, Wu et al. 2015, Zhang et al. 2016, Lam et al. 2015, Bernardo et al. 2016) and business and economic analysis (Kley et al. 2011, Schroeder and Traber 2012, Madina et al. 2016) of EV charging infrastructure have been conducted. However, research on consumer behavior of EV charging usage can hardly be found in the peer-reviewed literature. The existing studies on EV charging demand are often based on stated preference data (Jabeen et al. 2013, Axsen and Kurani 2012). To the authors' knowledge, only four studies have been published in peer-reviewed journals that examine real-world field data to research consumer behavior of EV charging usage.

Sun et al. (2015) analyzed field data collected in Japan with a focus on the driver's choice of timing for EV recharging at home (including company premises). Their data contained records for time-of-day, location, vehicle state, odometer reading, air conditioner on/off state, and battery state of charge. The authors conducted a discrete choice analysis about the decision to charge after the last trip of the day by defining the choice set, which consisted of no charging and three discretized times of charging (i.e., immediately, night-time charging, and charging at other times). The authors concluded that SOC, number of days before the next travel day, and distance of the last trip are the main predictors for whether users charge their vehicles or not. Although the authors concluded that those identified variables are the main predictors, it is unclear if the identified variables were, in fact, "the main predictors" of the choice of charging timing because the authors' conclusions were solely based on the statistical significance of the variables despite the sample size being quite large.

Zoepf et al. (2013) conducted a somewhat similar study using data collected in the United States. Their data consisted of prototype 2010 Toyota Priuses equipped with data loggers (i.e., a plug-in hybrid with a range of 21 kilometer on battery). Zoepf et al. fitted a binary mixed logit model; the choice indicator was whether the vehicle was charged at the end of a trip or not. The specification of their model is similar to that of Sun et al. (2015); however, unlike Sun et al. (2015), the authors specified the model with timing of EV charging as explanatory variables rather than choice alternatives. Although their model seems to show a need for re-specification, the authors concluded that SOC, time until next trip, and distance traveled have effects on the choice of whether to charge at the end of a trip or not. Their model did not show strong evidence that trip end times, discretized into 4-hour periods, have a consistent effect as a model specification. Their results may not be applicable to charging behavior with full electric vehicles because the decision to recharge a plug-in hybrid is not as critical a decision as for full electric vehicles, which may result in different charging behavior.

Sun et al. (2016) analyzed the same data as in Sun et al. (2015), with a focus on public fast charging station choice. To the author's knowledge, this is the only paper that has analyzed real-world data collected from the vehicle side on DCFC station usage. The authors generated a choice set by defining accessible stations as stations that are located within a distance equivalent to the distance between the origin and destination plus 2.8 kilometers. The authors segmented the sample by vehicle type (i.e., private and commercial) and whether it was a working day or not; they estimated a separate discrete choice model for each subset of the data. They concluded that the effects of various factors on DCFC station choice vary depending on whether the vehicle is private or commercial and whether the day is a working day or non-working day.

Morrissey et al. (2016) collected charge event data in Ireland. Unlike the above-mentioned studies, data were collected via data loggers that were located in the charging stations rather than the vehicle when a charge event occurred. The authors conducted various analyses of variance on the differences between charge start/end timing, energy consumption, and charge frequency for different charging station types and use cases. Their data show that there is a high degree of heterogeneity over use cases and infrastructure types in terms of charge timing, energy consumption, and charge usage frequency. Based on the observed high frequency of usage, the authors suggest that DCFC stations are the most likely type of publically available charging infrastructure to become commercially viable in the short to medium-term and recommend development of a highly connected network of DCFCs.

To our knowledge, no study has examined the effects of a fee on consumer behavior in regard to public DCFC recharging using real-world field data.

3. Data

The data used in this study were collected as a part of the EV Project, which was a plug-in electric vehicle infrastructure demonstration project funded by the U.S. Department of Energy between 2011 and 2013. Over 6,000 private owners of Nissan Leafs across the United States participated in the project. Project participants gave written consent for project researchers to collect and analyze data from their vehicles. All households that participated in the project had AC Level 2 charging stations at their residences. Data analyzed herein consists of DCFC charge events recorded during 2013. All DCFC charging events in the data occurred at public stations located either at workplaces or publicly accessible locations. DCFC charging was free between January and June 2013, but a flat-rate fee of $5 was gradually introduced across all sites between July and August 2013. Table 1 shows the information collected for each participating Nissan Leaf owner. As shown in Table 1, each charge event was recorded in terms of time the vehicle was parked at a DCFC charge station (i.e., park duration was not necessarily all spent charging) and the SOC increase (i.e., the difference in SOC at key-off and after parking). SOC is the indicator of how much charge is left in the battery: 0 indicates empty and 100 indicates full.

Table 1. Variable description

4. Methodology

In order to examine the change in charging behavior, our focus was applied on the duration the vehicle was parked at the charging station and the SOC increase. The variable park duration was computed as the difference between park start time and park end time. Because the timing of the introduction of the fee varied across different regions between July and August and it was not recorded, we defined the period dating from April to June as the pre-fee period and September to December as the post-fee period. The pre-fee period contains data from 888 Nissan Leaf drivers who used DCFCs and a total of 4,910 fast charging events. The post-fee period contains 685 Nissan Leaf drivers using DCFCs (i.e., a 23% decrease from the pre-fee period) and a total of 2,805 fast charging events (i.e., a 43% decrease from the pre-fee period).

A descriptive analysis was conducted for park duration and SOC increase, respectively. Figure 2 shows the histograms of park durations at DCFC stations during the pre-fee period and post-fee period, respectively. The distribution is skewed to the right in both periods; however, the mode of distribution moved slightly to the right during the post-fee period. The mean and median of park duration are 24.19 and 26.28 percent during the pre-fee period and 26.75 and 28.81 percent during the post-fee period, respectively. Figure 3 shows the histograms of SOC increase during the pre-fee period and post-fee period. The amount of SOC increase follows an approximately normal distribution in both periods. The mean and median of SOC increase are both about 36% during the pre-fee period and 38% during the post-fee period. Therefore, the unweighted mean of the SOC increase per minute of park duration is 1.48% during the pre-fee period and 1.42% during the post-fee period, which shows a decrease in the average rate of charge for every minute of park duration. Among 31% of the charge events during the pre-fee period, the vehicles were parked for more than 30 minutes and the proportion increased to 40% during the post-fee period. Because recharging an EV from nearly empty with DCFC for much more than 30 minutes is an inefficient use of DCFC in terms of the rate of charge, these statistics show some evidence that consumers engaged in less efficient recharging behavior after the flat-rate fee was introduced.

Although single variate comparison of the mean indicates that the increase of SOC per park duration minute deteriorated from the pre-fee period to post-fee period, this difference is small (i.e., 0.06). More importantly, the difference in the mean of the SOC increase per minute between the two periods may be attributed to the difference in the variation of SOC at key-off between the two periods. For example, people might be incentivized to charge their vehicle for a longer time to get more charge due to the fee; however, that effect on SOC increase is different depending on SOC at key-off (i.e., if the charge was started at a lower SOC at key-off, the increase in park duration contributes more to SOC increase than if the charge was started at a higher SOC at key-off due to the diminishing rate of charge once current begins to taper during the constant voltage portion of the charge). Therefore, in order to account for the variation in SOC at key-off, we conducted a multi-variate analysis. More specifically, we ran a regression to examine the difference in the mean effect of parking duration on SOC increase, while accounting for variation in SOC at key-off. The regression model was specified as:

$$SOC\ Increase = \beta_0 + \beta_1 Charge\ Duration + \beta_2 Charge\ Duration^2 + \beta_3 Fee \times Charge\ Duration + \beta_4 Keyoff\ SOC \times Charge\ Duration + \varepsilon$$

As shown in Figure 1, the marginal increase in SOC has a diminishing relationship with SOC; thus, an interaction term between key-off SOC and park duration was included in the model. In order to examine the difference that the effect a 1-minute increase of park duration has on SOC increase between the two periods, an interaction term between park duration and a dummy variable for the post-fee period (i.e., Fee) was included. Because the effect of key-off SOC should be the same between the two periods, the interaction term between fee and key-off SOC was not included. The residuals versus the fitted plot indicated the presence of a quadratic relation even after the effect of key-off SOC on the slope of park duration was accounted for; therefore, a quadratic term of park duration was also included in the model.

Figure 2. Histograms of park duration

Figure 3. Histograms of SOC increase

5. Result

The interpretation of our regression model deserves careful attention. First, it is important to note the model describes the relationship between how much the vehicle was charged (i.e., SOC increase) and for how long the vehicle was "parked" at the charging station; charging made up an unknown portion of that parking event. Second, all variables have expected signs. A positive sign of park duration means there is a positive relationship between the amount of time the vehicle was parked at the DCFC station and the amount the vehicle was charged. The coefficient value of 2.27 means that when the charging was started at the initial SOC of zero percent in the pre-fee period, one minute of charge duration increases SOC by 2.27 percentage points on average. A negative sign on the quadratic term of park duration means that the magnitude of the positive relation between park duration and SOC increase decreases as park duration increases. A negative sign on the interaction term between park duration and key-off SOC means that the slope of park duration also depends on the SOC at which the charging was started (i.e., the higher SOC is at key-off, the slower the rate of charging). More specifically, when the charging was started at one unit higher in the key-off SOC, the amount of SOC increase per minute is decreased by 0.015 unit on average. All results are consistent with the nature of DCFC. Finally, the interaction term between park duration and fee shows the difference in the effect of charging duration between the pre-fee period and post-fee period. A negative sign for that interaction term means the rate of charge per minute of park duration is lower during the post-fee period and this diversion of the rate of charge between the two periods expands as park duration increases. This result reflects the facts that people plugged their vehicles for a longer time at a diminishing rate of charge after the fee was introduced and there were more extremely long charge events during the post-fee period than during the pre-fee period. For example, the model predicts that if the charging was started with the key-off SOC of 20 %, the average rate of charge of a 30-minute long charge in the pre-fee period is 1.383 SOC unit per minute and that in the post-fee period is 1.354 SOC unit per minute (about 2% decrease on average).

The model has a good fit to the data because both the R-squared and adjusted R-squared values are 80.6%. Post-estimation model diagnostics showed some signs of violation of the normality of residuals and heteroscedasticity. Neither logarithmic nor Box-Cox transformation of the variables alleviated those issues significantly; thus, original variables without transformations were used for the model.

Table 2. Table of coefficients

6. Conclusions

This paper presents the first study to examine the effect of a flat-rate fee on how consumers use public DCFC stations. A regression analysis was used to examine the effect of introducing a flat-rate fee on the average rate of charge while accounting for the diminishing rate of charge over SOC level. Results show strong evidence that the flat-rate fee had a negative effect on the efficiency of DCFC station usage, meaning the amount of charge per minute of park duration was lower during the post-fee period and it further decreased as the park duration increased. This means that during the post-fee period, drivers parked their vehicles at DCFC stations for a longer time than during the pre-fee period for the same amount of SOC increase, resulting in a lower average rate of charge. The increasing negative effect of the fee on the rate of charge over park duration during the post-fee period is a result of the increased proportion of the charge events where the vehicle was parked at the DCFC station even after the rate of charge significantly deteriorated, despite a slightly lower key-off SOC. This is an indication that drivers unnecessarily occupied the stations while other drivers potentially could have used them. In fact, for about 40% of the charge events during the post-fee period, the vehicle was parked for more than 30 minutes.

The flat rate fee also had an effect on recharge timing in terms of SOC. Figure 4 shows the histogram of SOC at key-off. Higher proportions of charge events took place at low SOC during the post-fee period compared to the pre-fee period. This means the fee made some people wait to recharge their cars until SOC became low relative to when charging was free. There are two conceivable reasons for this. First, people may have wanted to get the most out of a single DCFC charge session and the cost of charge was fixed per session; therefore, people may have been incentivized to recharge their vehicles when emptier so they could get more charge for the same price. Another reason is that because the number of charge events decreased once the fee was introduced, it is reasonable to think people wanted to avoid using DCFC because they had significantly less expensive home charging and they only used DCFC when needed to complete a trip or maintain a comfortable SOC.

Figure 4. Histograms of key-off SOC

This study also revealed several important insights into consumer behavior about DCFC usage. In spite of the assumption often made during research, the empirical evidence in this study shows that vehicles were often parked at DCFC stations for more than 30 minutes. In fact, even during the pre-fee period, more than 30% of the charge events took more than 30 minutes. Although we cannot know the real reason for this, several different explanations can be considered. For example, it may be that consumers used the DCFC stations as parking spots. Some of the DCFC stations are located in business properties and people may have left the DCFC sites for dining or shopping while their vehicles might have been charged more than 80% full or even well after completion of the charge. However, this behavior should have been the same even after the fee was introduced; therefore, it does not explain why the SOC increase per minute of park duration decreased after the fee was introduced. On the other hand, our regression analysis shows evidence that there is a discrepancy between consumers' understanding of electric refueling and how DCFC technology works. It is likely that the reason for the decrease in SOC increase per minute of park duration is that the flat-rate fee incentivizes consumers to plug their vehicles at the stations for a longer time to get more charge. However, as discussed earlier, recharging using DCFC, whose refueling rate diminishes with time after a point (i.e., the CC-CV transition), is quite different from gasoline refueling, whose refueling rate is constant. Because people are accustomed to the experiences of gasoline refueling, they may not have realized the diminishing return to the time spent in DC recharging. In other words, people might have tried to get more bang for the buck by keeping their vehicles plugged in for a longer time without knowing that they are not necessarily getting much additional charge out of it.

With a flat-rate fee, users are not incentivized to move their vehicles after the rate of charge significantly deteriorates. The benefit of DCFC is its fast rate of charge. Occupying the station after the rate of charge diminishes considerably may defeat the purpose of DCFC charging and is time costly to other users who may need to recharge their vehicles. This also possibly makes DCFC less profitable for station operators. The pricing scheme should be set to incentivize the user to vacate the station for the next use quickly after recharge. With proper incentives (e.g., effective pricing and consumer education on DCFC technology), consumers may adapt to more efficient charging behavior. A user interface at the station could indicate the cost of time and money for how much is left to be gained. The charge rate will only continue to go down with time; therefore, information like this could be communicated to the user. Further research is needed to examine the pros and cons of other pricing schemes to optimally determine the successful pricing scheme for DCFC services.

As DCFC technology continues to evolve and its usage grows, the widespread adoption of electric vehicle may result in an exponential rise in electricity use. Because impacts of charging demand may significantly impact local electricity distribution, the stakes of building a network of fast charging stations involve not only a charging station operator but also utility companies and planning agencies. To maintain sustainable energy supply, policy makers will need to carefully plan for DCFC deployment taking into account the influence of EV load on power system stability. Current typical operation of DCFC potentially allow an inefficient use that may falsely call for additional installments of DCFC, which can lead to more burden on power system. To promote efficient uses of DCFC, policy makers will need to partner with public and private stakeholders and engage the public through education on how to use EV fast charging efficiently.

Finally, this study has some limits. Each observation was treated as an independent charging event. However, external factors such as characteristics of the charge station's surrounding environment may have contributed to variation in park duration. For example, stations located in the parking lot of a shopping mall are likely to be used more frequently than stations in a remote place. In addition, those stations with nearby amenities may have longer park durations because drivers could leave their cars at the stations for shopping or dining. However, because the locational characteristics of the charging stations are difficult to quantify and the classification can be subjective, their effects were left out of the scope of this study. It is also important to note that all the charging stations were located in the states with moderate winter climate (Washington, Arizona, California, Oregon, and Tennessee); thus we did not account for effects of severe cold weather to EV charging rate.

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Table1

Variable	Description
	Sample size: 7715
Key Val	Unique ID for each record
Vehicle Number	Unique ID for each vehicle
Date	Date of the trip start time for each record Date is adjusted so a day starts at 4 a.m. and end ends at 4 a.m. the next day
Trip Start Time	Time when trip started
Park Start Time	Time when vehicle was parked
Park End Time	Time when vehicle started next trip
Key On SOC	SOC at start of trip
Key Off SOC	SOC at the end of trip before a fast charging event
SOC Increase	Increase in SOC after parking
Trip Distance	Trip distance in miles
Distance Home	Distance in miles the vehicle is parked from its home
Location Type	Location of vehicle: home, work, or some other place

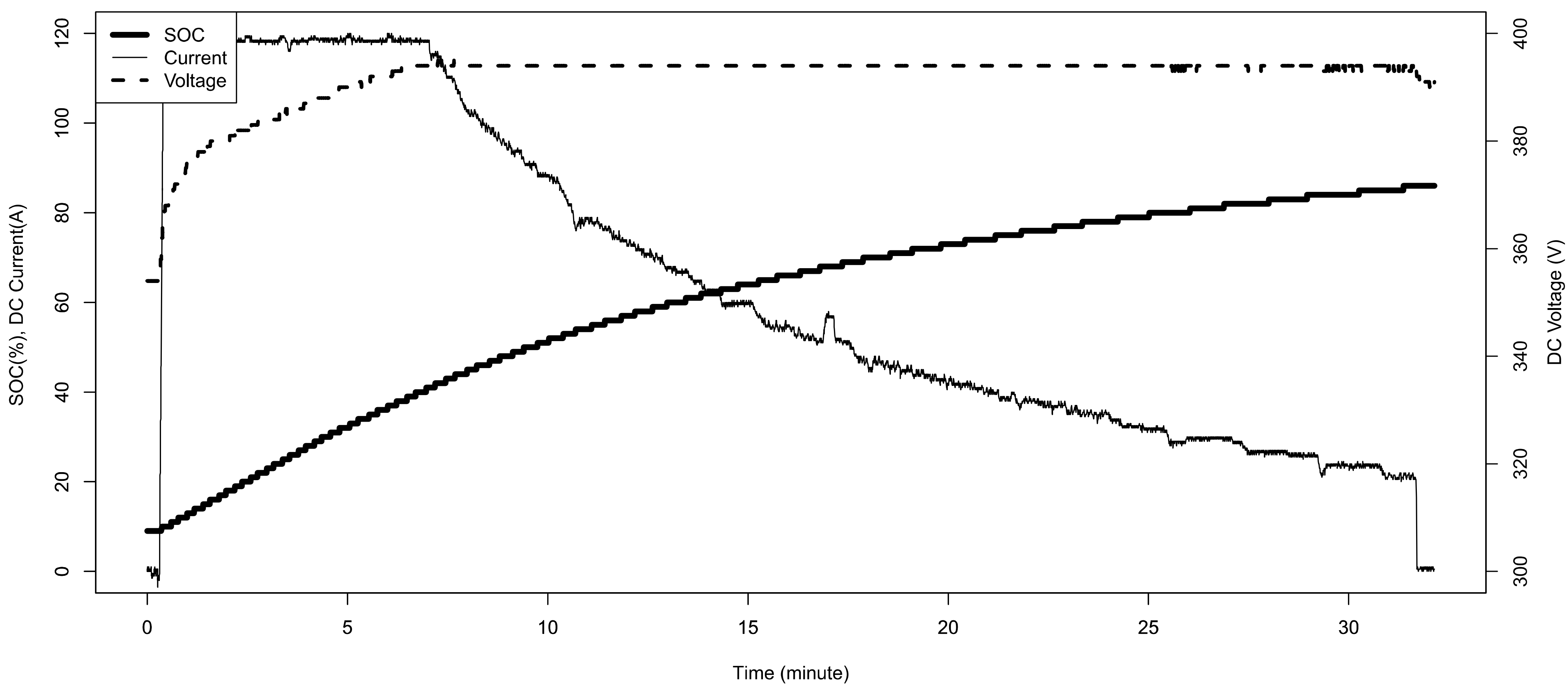
Table2

Variable	Estimate	SE	t stat	p value	CI 2.5%	CI 97.5%
Intercept	8.678	0.278	31.188	<0.01	8.133	9.223
Park Duration	2.266	0.019	121.967	<0.01	2.230	2.302
Park Duration Squared	-0.015	<0.001	-65.395	<0.01	-0.016	-0.015
Park Duration × Key-off SOC	-0.021	<0.001	117.361	<0.01	-0.021	-0.021
Park Duration × Fee	-0.028	0.005	-6.053	<0.01	-0.038	-0.019

R-squared: 0.806

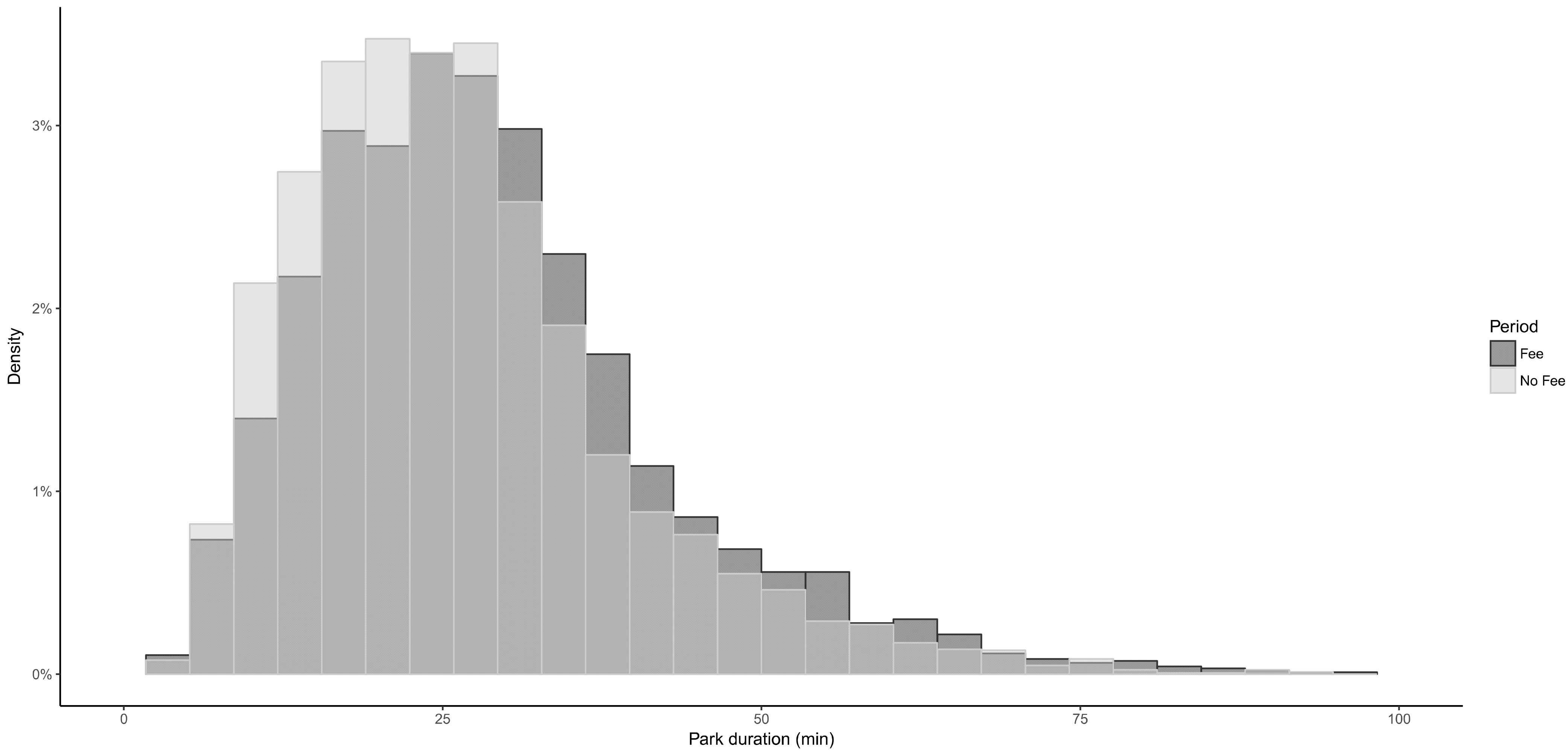
Adjusted R-squared: 0.806

Figure1



SOC
Current
Voltage
SOC(%), DC Current(A)
DC Voltage (V)
Time (minute)
0
20
40
60
80
100
120
300
320
340
360
380
400
0
5
10
15
20
25
30

Figure2



Density
3%
2%
1%
0%
0
25
50
75
100
Park duration (min)
Period
Fee
No Fee

Figure 3

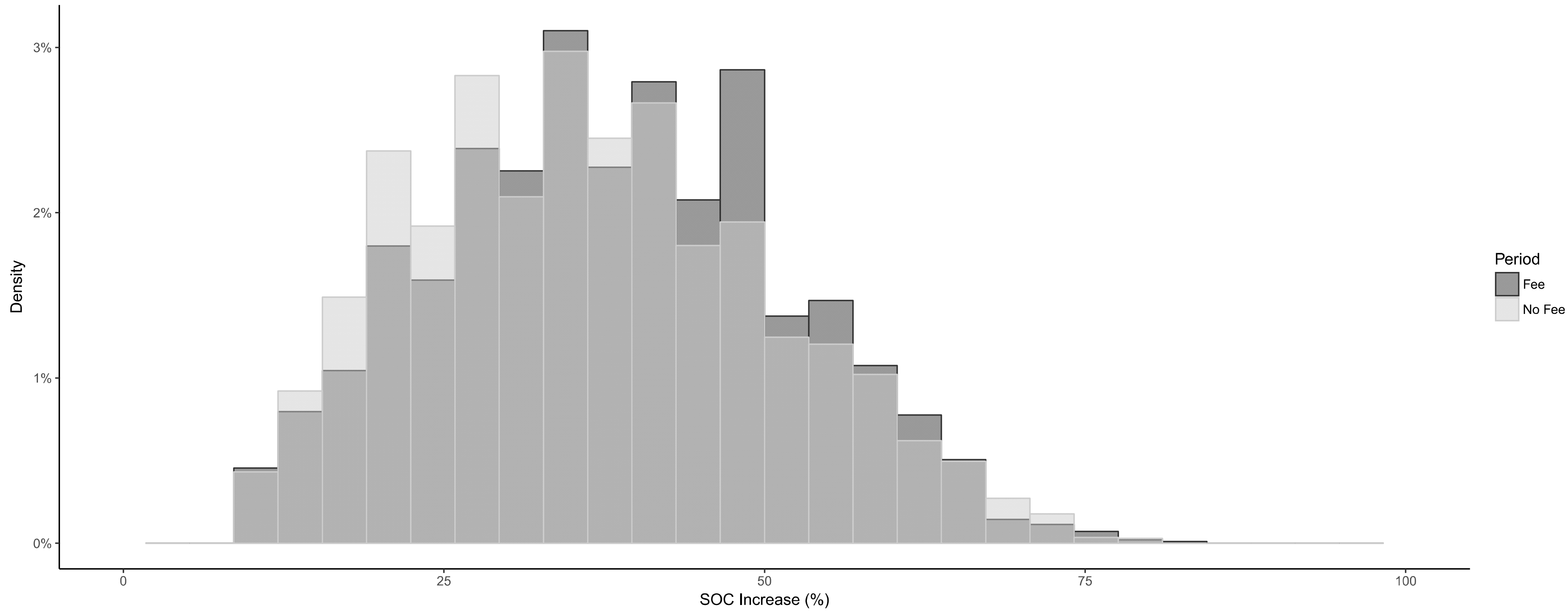
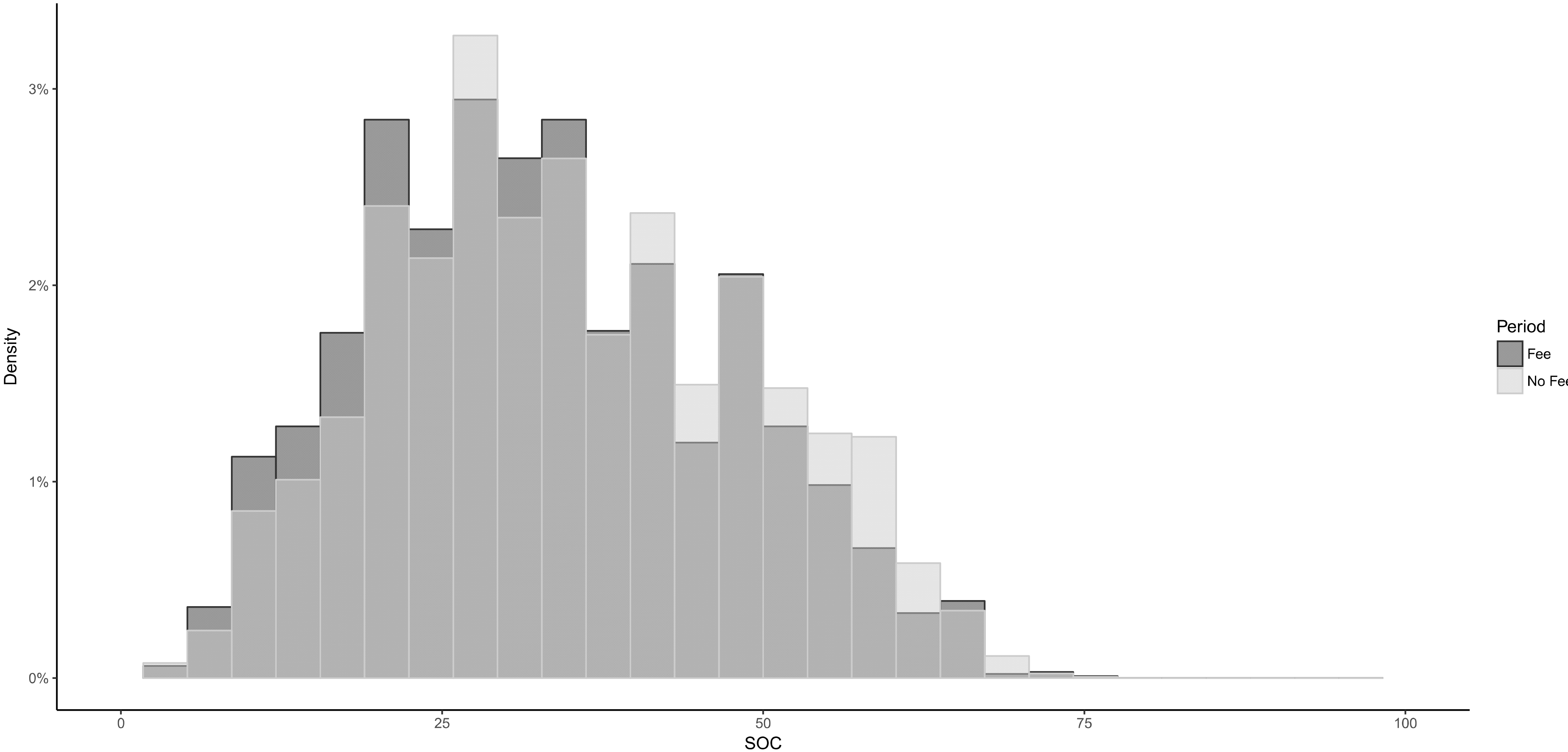


Figure4



***Highlights**

- Fast charging stations are often occupied for more than 30 minutes.
- The rate of charge of direct current fast chargers diminishes over time.
- A flat-rate fee incentivizes the user to spend a longer time at the charge station.
- With proper incentives, consumers may adapt to more efficient charging behavior.