The Impact of High Ambient Temperatures on PEV Charging Efficiency

September 2017

The National Center for Sustainable Transportation Undergraduate Fellowship Report

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In association with the UC Davis Plug-in Hybrid & Electric Vehicle (PH&EV) Research Center

In collaboration with Nathaniel Kong and Jonathan Gordon
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Acknowledgments
This study was funded by a grant from the National Center for Sustainable Transportation (NCST), supported by USDOT through the University Transportation Centers program. The authors would like to thank the NCST and USDOT for their support of university-based research in transportation, and especially for the funding provided in support of this project. The author would also like to thank Gil Tal, Dahlia Garas, Katrina Sutton, and the rest of the Plug-in Hybrid & Electric Vehicle Research Center as well as the UC Davis Institute of Transportation Studies as a whole for their generous resources and mentorship.
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Introduction

It is largely known that plug-in electric vehicles (PEVs) are more efficient than internal combustion engine vehicle (ICEVs). Because of this, the operation of PEVs is both cheaper and less damaging to the environment than that of ICEVs. Despite this, PEVs still struggle to sell anywhere near as much as ICEVs. One primary reason for this is the difference in upfront cost. PEVs, as a relatively new technology, are generally more expensive than ICEVs, even with government incentives. This disparity will not be resolved until the price of vehicle batteries drops low enough so that PEV powertrains become financially competitive to those of ICEVs [1]. Until then, there are various strategies available that can allow potential PEV owners to shave off costs associated with PEV ownership, making their overall investment pay off faster. By further reducing costs in this way, the heftier upfront price tag can be easier to swallow for the average consumer.

One such strategy is to reduce costs associated with PEV charging. Many forms of charging, such as those done at home, involve payment per amount of energy used by the charger. Just how much needs to be output by the charger in order to fill the PEV battery is dependent on how efficient the charging session is. As such, optimizing the efficiency of PEV charging is key to minimizing the amount of energy that must be output, thus minimizing the amount of energy you must pay for. This presents one significant way to reduce operating costs. This pushes us to explore the variables that impact charging efficiency. Ambient temperature is one of these variables. This study will test the effect of ambient temperature, specifically within a high range, upon PEV charging efficiency.

Background & Previous Studies

Temperature is an important factor on the efficiency of battery operations. Batteries, by their very nature, function through chemical reactions. These chemical reactions are harnessed for their electron flow, producing useable power. Chemical reactions are impacted by temperature, thus battery usage and charging is in turn impacted by temperature. A number of past studies have looked into the effects of ambient temperature on vehicle charging efficiency, to different results. A 2013 study by the Vermont Energy Investment Corporation (VEIC) compared charge efficiencies for 17 same-model-year Chevrolet Volts between three different ambient temperature groups: less than 53°F, more than 70°F, and between 53°F and 70°F. They found that for both Level 1 charging (120 V) and Level charging (240 V), charge efficiency decreased both below 53° and above 70°F, by an average margin of just a couple percent [2].
This suggests optimal charging efficiency can be achieved somewhere around 60°F. This conclusion is corroborated by a 2016 study that found that both PEV charge and discharge efficiency is maximized around 68°F [3]. However, a different 2013 study, also conducted by VEIC, produced results that conflict with that of their first study. This second study involved a very similar setup, but with the three temperature groups defined by 50°F and 70°F, instead of 53° and 70°F. The second study also featured a greater number and variety of vehicles: 75 Chevrolet Volts and 39 Nissan Leafs. The results of this second study affirmed the trend seen in the first study, but only for Level 1 charging. For Level 2 charging, efficiencies actually increased outside the 50°F - 70°F range, opposite of what is seen in the first study [4].

<table>
<thead>
<tr>
<th>Charge event dataset</th>
<th>Average Level 2 Charge Efficiency</th>
<th>Average Level 1 Charge Efficiency</th>
<th>Efficiency gain of Level 2 charging</th>
</tr>
</thead>
<tbody>
<tr>
<td>High energy only (&gt;2kWh charge) between 53°F and 70°F</td>
<td>87.8%</td>
<td>85.8%</td>
<td>2.1%</td>
</tr>
<tr>
<td>High energy only (&gt;2kWh charge) and less than 53°F ambient temperature</td>
<td>87.3%</td>
<td>84.0%</td>
<td>~3.4%</td>
</tr>
<tr>
<td>High energy only (&gt;2kWh) and greater than 70°F ambient temperature</td>
<td>85.3%</td>
<td>82.2%</td>
<td>~3.2%</td>
</tr>
</tbody>
</table>

**Table 1. Summary of results of first VEIC study [2]**

However, it is important to note that for both of these studies, the change in efficiency is minimal. The average difference in efficiency between all temperature-based groups across both studies is only 1.7%. The second study also graphed their results, which can be seen below. Though no trendline is provided, it is visually clear that the trend appears flat.

<table>
<thead>
<tr>
<th></th>
<th>N</th>
<th>Mean Charge Efficiency (%) ± SD</th>
</tr>
</thead>
<tbody>
<tr>
<td>All charge events</td>
<td>114</td>
<td>85.7 ± 0.09</td>
</tr>
<tr>
<td>All Level 1 charge events</td>
<td>63</td>
<td>83.8 ± 0.08</td>
</tr>
<tr>
<td>All Level 2 charge events</td>
<td>51</td>
<td>89.4 ± 0.05</td>
</tr>
<tr>
<td>Level 1 charge events &lt; 4kWh</td>
<td>11</td>
<td>74.2 ± 0.12</td>
</tr>
<tr>
<td>Level 2 charge events &lt; 4kWh</td>
<td>13</td>
<td>87.2 ± 0.06</td>
</tr>
<tr>
<td>Level 1 charge events &lt; 50°F</td>
<td>32</td>
<td>83.0 ± 0.09</td>
</tr>
<tr>
<td>Level 2 charge events &lt; 50°F</td>
<td>9</td>
<td>90.6 ± 0.04</td>
</tr>
<tr>
<td>Level 1 charge events &gt;70°F</td>
<td>23</td>
<td>81.4 ± 0.09</td>
</tr>
<tr>
<td>Level 2 charge events &gt;70°F</td>
<td>10</td>
<td>89.9 ± 0.04</td>
</tr>
</tbody>
</table>

**Table 2. Summary of results of second VEIC study [4]**
Additionally, these two studies analyzed a rather “mild” temperature range, from the low 50s to 70°F. As the graph above illustrates, the second study did experience a wide range of temperatures (from below freezing to almost 90°F). However, the majority of points are clustered around the “mild” range. This inherently limits the practical application of this analysis to said mild temperature range. More studies are needed to explore the effects of ambient temperature in different climates.

More specifically, there is very little literature on the effects of high ambient temperatures on PEV charging. Given the climate of Vermont, the studies of the Vermont Energy Investment Corporation could hardly achieve measurements over 80°F. However, many regions in the United States contain climates with temperatures that regularly surpass 90°F during warmer seasons, and these tend to be the regions that are most quickly developing. California in particular is the most populous state in the nation and experiences hot summers almost everywhere within its borders. In Davis specifically, the average daily high temperature runs more than 90°F through both July and August, and averages in the upper 80s for June and September. In addition, California is known for being environmentally and technologically progressive, a niche PEVs fit into very well. As such, a study into PEV charging efficiency during a hot California summer is a relevant yet underexplored subject of research. That is the purpose of this study.

Methods

The core of this study centers around 3 measurements: ambient temperature, energy “output” by the charger, and energy “input” into the PEV battery. The charging efficiency is simply this
“input” divided by the “output”. To measure ambient temperature, we used an infrared (IR) thermometer. For the output we used an established HOBOlink system, and for the input we used FleetCarma. These will be elaborated upon below.

**Data Sources & Explanation**

In terms of vehicles, we acquired eight different PEVs, consisting of one of each: 2017 Chevrolet Bolt, 2011 Chevrolet Volt, 2018 Chrysler Pacifica Hybrid, 2018 Honda Clarity PHEV, 2011 Nissan Leaf, 2012 Nissan Leaf, 2013 Tesla Model S P85, 2017 Toyota Prius Prime. These vehicles are all owned by fellow coworkers at the UC Davis ITS. These vehicles all regularly charge during workdays in the parking lot behind the PH&EV Center. This was requested for the study, as all three chargers in our lot are hooked up to the building’s HOBOlink system. HOBOlink is a remote electrical monitoring system that can be used, among other things, to continually measure electrical circuits in real time. The PH&EV Center has such a system, with all circuits monitored, including those for the PEV chargers. This provided the metric for charger energy output.

**Figure 2. Office circuit breaker panel equipped with HOBOlink (hardware visible atop panel)**

Of the eight vehicles in the study, five were equipped with FleetCarma. FleetCarma is a fleet monitoring and management service that can track and report various operational metrics of a vehicle. Such metrics include real time location, speed, timestamps for trips, etc. This is possible through a small module “logger” that remains plugged into a vehicle’s OBD-II port, with an
additional GPS “puck” applied to the inside of the windshield to communicate this information via satellite. For PEVs, FleetCarma is also capable of measuring state of charge (SOC), charging session timestamps, and charging session input energy. This provided the metric for battery input energy. For the three remaining vehicles not equipped with FleetCarma, input energy was initially measured through an alternative system that involved rather crude estimates. These estimates were derived by simply taking the difference between the vehicle’s self-reported ending SOC and starting SOC for a charge session, and multiplying this difference by the vehicle’s overall battery energy capacity, as reported by the manufacturer. This process was later dropped due to its insufficient accuracy.

For temperature, we developed a system of regular ambient temperature measurements near the batteries. For the vehicles in the study, we determined the location of their battery packs along their undersides (given the great mass of batteries, most PEVs house them at the base of the body, usually in the center). We marked four specific points on the underside of each vehicle that mapped out the location and shape of the vehicle’s battery pack. Then, for every hour of every day that these vehicles were charging, we measured the temperatures of these points using an IR thermometer laser. The four temperatures for each point were then averaged to determine an effective ambient temperature around the battery pack at that time.
It is important to note that this ambient temperature measurement is not the actual battery temperature. That would require an internal measurement reported by the onboard vehicle computer. We did not have access to these readings, so we instead proceeded with the system described above. In addition, the actual battery temperature was not technically the focus of our study. While the internal temperature is definitely the actual metric that physically impacts charging, ambient temperature is a significant influence upon it. We assumed a strong enough correlation was present between nearby ambient temperature and battery temperature, despite the other factors that influence battery temperature (heat gain from operation, primarily). Our study also aimed to use a temperature metric that is relevant and accessible to the average consumer, whom we are hoping to inform. The internal battery temperature is too technical of a metric for the average consumer, and is a metric they likely would have no way of measuring anyway, thus the ambient temperature proved more suitable.

**Execution & Issues**

With this combination of IR temperature readings, HOBOlink, and FleetCarma, the study was conducted from July 16th to September 5th 2018. For data compiling and analysis, all charging sessions were divided into 1-hour increments, using temperatures measured at the start of each hour. As hoped, temperature readings very frequently surpassed 90°F, and often 100°F. Unfortunately, a variety of issues greatly reduced the data we could later analyze. A summary of them is listed below.

- Despite the nearly 2-month span of the study, the presence of these PEVs at the office was inconsistent. The owners were often away from due to other obligations, or chose to ride bikes to the office instead.
- The three vehicles not equipped with FleetCarma were effectively removed from the study, as there was no way to accurately report input energy. There was also no way to
install FleetCarma for them, because the FleetCarma logger firmware was incompatible for these vehicles.

- For the five vehicles that did have FleetCarma, two were later removed from the study due to technical issues involving AC-DC conversion obscurity.
- Of the three remaining vehicles, two were later removed due to issues with FleetCarma’s recording of the data for those specific vehicle models.

This resulted in the 2017 Prius Prime being the only vehicle with valid data. It alone is what constitutes the results below.

Results & Discussion

Figure 5. Study results, using 2017 Toyota Prius Prime

As expected, the majority of data points fall within a high temperature range, especially between 90°F and 100°F. Though in terms of efficiency, there is no significant trend with respect to ambient temperature in this range. The slope is slightly positive; however, this bears almost no significance given the noise of the data. More noteworthy is the breadth of different efficiencies, ranging from 0.88 to 0.95. This suggests the presence of the other variables that affect charging efficiency, and questions how much they are responsible for this variety of results. Of course, a large degree of variety is due to simple statistical randomness. Had everything worked correctly with study, we would have had much more sample points to draw from. This likely would have presented a more meaningful trend that would have been more safe to draw conclusions from.
However, it is important to note that the aforementioned studies in Vermont found a similarly flat, insignificant trend despite having a much more robust sample size. While this certainly does not forgive the noise above, it does propose the hypothesis that maybe the variation of efficiency within temperatures of non-extreme climates (within the entire range of temperatures we’ve seen so far) is marginal at best.

**Potential for Future Study**

Quite simply, this study would be best repeated with more PEVs and systems that function as intended, and over a longer course of time (perhaps late May through late September). This would provide much more sample points, thus allowing for more meaningful analysis. In addition, a more robust study could provide a variety of other variables to analyze. We could compare the trends of efficiency-by-temperature variation between different charge levels, vehicle models, vehicle ages, etc. Another interesting proposition would be to run simultaneous studies using both ambient temperature measurements (similar to our process) and internal battery temperature measurements. If a strong correlation could be drawn between the two, that would truly validate the usage of ambient temperature measurements.

**Conclusion**

Studies have found variation in PEV charging efficiency due to ambient temperature. The variations found so far have been small and generally inconsistent. Larger studies with greater sample sizes and reliable processes are needed to provide significance to these variations, and thus show real trends. Strategies can then be developed to maximize charging efficiency given this new knowledge of temperature’s impact. For example, PEV owners could choose to charge at different times of day, or in more/less exposed charging spots, to utilize different available ambient temperatures. With strategies like this, PEV owners and prospective PEV owners will have another way to reduce costs associated with PEV ownership. This reduction is critical to facilitating the PEV revolution in the automotive industry.
References


