Energy Research and Development Division

FINAL PROJECT REPORT

Next-Generation Grid Communications for Residential Plug-in Electric Vehicles

California Energy Commission

Gavin Newsom, Governor

January 2019 | CEC-500-2019-009

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ACKNOWLEDGEMENTS

ChargePoint thanks the Energy Commission and its staff for their support throughout the project. Additional thanks to project partners Lawrence Berkeley National Laboratory and Mercedes-Benz Research & Development North America.

PREFACE

The California Energy Commission's Energy Research and Development Division supports energy research and development programs to spur innovation in energy efficiency, renewable energy and advanced clean generation, energy-related environmental protection, energy transmission and distribution and transportation.

In 2012, the Electric Program Investment Charge (EPIC) was established by the California Public Utilities Commission to fund public investments in research to create and advance new energy solution, foster regional innovation and bring ideas from the lab to the marketplace. The California Energy Commission and the state's three largest investor-owned utilities – Pacific Gas and Electric Company, San Diego Gas & Electric Company and Southern California Edison Company – were selected to administer the EPIC funds and advance novel technologies, tools, and strategies that provide benefits to their electric ratepayers.

The Energy Commission is committed to ensuring public participation in its research and development programs that promote greater reliability, lower costs, and increase safety for the California electric ratepayer and include:

- Providing societal benefits.
- Reducing greenhouse gas emission in the electricity sector at the lowest possible cost.
- Supporting California's loading order to meet energy needs first with energy efficiency and demand response, next with renewable energy (distributed generation and utility scale), and finally with clean, conventional electricity supply.
- Supporting low-emission vehicles and transportation.
- Providing economic development.
- Using ratepayer funds efficiently.

Next-Generation Grid Communications for Residential Plug-in Electric Vehicles is the final report for the Next-Generation Grid Communications for Residential PEV project (Contract Number EPC-14-078 conducted by ChargePoint Inc. The information from this project contributes to Energy Research and Development Division's EPIC Program.

For more information about the Energy Research and Development Division, please visit the Energy Commission's website at www.energy.ca.gov/research/ or contact the Energy Commission at 916-327-1551.

ABSTRACT

As residential plug-in electric vehicle charging loads increase, they represent significant contributions to local distribution circuits, and if not managed, can have negative effects on local electricity grid stability. For residential plug-in electric vehicle participation to be effective for grid stabilization, it is key to have detailed data collection, coordination at charging stations owned by different parties, sensitivity to each driver's needs and preferences, and real-time understanding of each vehicle's state of charge or charge necessary before the vehicle leaves. There are no adequate interfaces used that help communicate between utilities, charging stations, and residential plug-in electric vehicle customers. This limits the capability for aggregated commercial charging applications to interface with the electric grid.

Using the International Organization for Standardization/International Electrotechnical Commission 15118 standard, this project developed cloud-to-cloud Open Automated Demand Response 2.0b communication so the consumer can receive daily rate schedules from the utility. The team successfully used and tested the 15118 standard with a Daimler Smart Electric Drive vehicle.

The project also explored using control methods that do not require vehicle charging information. A pilot project was conducted with 30 ChargePoint Level 2 residential charging stations. The project results showed that electric vehicle charging loads are flexible. However, with some knowledge of driver behavior and utility tariffs, significant potential exists to realize cost savings for residential drivers without having to change driver behavior, while being responsive to grid needs.

Keywords: Electric vehicle charging, 15118 standard, controlled charging, residential charging, OpenADR, charger communications, vehicle communications, charging station

Please use the following citation for this report:

Patadia, Shana.; Rodine, Craig (ChargePoint). 2019. *Next-Generation Grid Communications for Residential PEV*. California Energy Commission. Publication Number: CEC-500-2019-009.

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EXECUTIVE SUMMARY

Introduction

As the number of plug-in electric vehicles (PEV) continues to rise, the home energy demand load associated with PEV charging will also increase. This added load can put stress on local distribution circuits, and if not managed properly, can have negative impacts on local grid stability. Currently, no adequate interfaces exist that facilitate communication between utilities, PEV charging stations, and residential PEV customers. Even for aggregated commercial charging applications, only a limited capability exists to provide grid stability. Residential PEV participation in grid stabilization requires detailed data collection, charging coordination at PEV charging stations owned by different parties, sensitivity to each driver's needs and preferences, a real-time understanding of each vehicle's state of charge (amount of energy stored in the vehicles battery at any given time), and the charge required before the vehicle leaves the station.

Widespread adoption of connecting Level 2 (240 volt) home chargers is necessary and can help turn PEV load from a liability into an asset for the electric grid. Using Level 2 chargers is necessary because Level 1 chargers do not provide a fast enough charge to vehicles with medium to large batteries, like the Nissan Leaf or Chevrolet Bolt, resulting in no real opportunity for load shifting or responding to utility pricing or load control signals. Level 1 chargers operate with standard 120-volt household outlets while Level 2 chargers operate at 240 volts or 208 volts. Level 2 chargers have significantly more power capability than Level 1 chargers which allows for faster charging. As automakers continue to progress in extending the PEV driving range through efficiency improvements and larger batteries as well as lowering ownership cost, Level 1 chargers may become insufficient to adequately charge PEVs overnight. Networked, or "smart" chargers are also essential because they allow utilities or third parties to have increased visibility into PEV charging patterns and real-time data. Networked chargers also give utilities the ability to control the demand load from residential chargers on a preprogrammed or in real-time based on grid demand.

The advantage that PEV charging has compared to other controllable loads is there is a significant amount of flexibility in PEV charging needs. While other controllable loads on commercial and home power levels (heating, lighting, industrial loads, etc.) affect either individual comfort or operational processes for most households during the evenings and nights, PEV charging loads can be shifted with absolutely no inconvenience to the driver. For example, most drivers are agnostic as to whether their vehicle is charged from 11pm to 2am, or 1am to 4am.

Project Purpose

This pilot project tested the technology ecosystems required to handle adding significant PEV load to the grid. The processes will allow real-time signals to be sent by the utility and subsequently allow drivers to opt-in or -out of shifting their PEV load, responding to these signals. Processes developed show significant potential to save PEV drivers money, save the grid

from expensive transformer or distribution level upgrades, and improve the efficiency and carbon intensity of the electric grid.

Project Process

The first sub-project involved a home pilot program, which tested the communication process:

- ChargePoint's ability to receive pricing signals from San Diego Gas & Electric (SDG&E) through open automated demand response (OpenADR).
- ChargePoint's ability to send opt-in/opt-out notifications to drivers through ChargePoint's mobile app.
- ChargePoint's ability to receive and accordingly implement the driver's preference to opt-in or –out.
- ChargePoint's ability to generate and send a controlled charging schedule to the charging station.

The pilot program consisted of 1,005 charging events with 27 drivers in the San Diego Gas & Electric (SDG&E) service territory. To enable driver/customer participation in utility residential vehicle-grid integration, and allow Level 2 chargers to exchange smart charging data and control messages, ChargePoint integrated the International Organization for Standardization/International Electrotechnical Commission (ISO/IEC) 15118 Edition 1 standard protocol into a prototype CPH25 Home model charging station. In collaboration with project partner Mercedes Benz Research and Development North America the project validated the CPH25 prototype by successfully charging a production PEV (the Daimler/Mercedes Benz Smart Electric Drive) using the High Level Communication and smart charging features of 15118.

Lawrence Berkeley National Labs (LBNL) conducted a simulation of the electric grid using the vehicle-to-grid (V2G)-Sim software to assess the vehicle-grid integration effects on the wider electric grid and the benefits of load control for future scenarios of high electric vehicle adoption.

Project Results

During the project, ChargePoint collected valuable information and associated it with individual chargers and locations: time of charge, duration of charge, power level used, total energy used, and customers opt-in or opt-out decision. This information, coupled with the addresses and local distribution grid data, provides the utility significant insight into these potentially controllable PEV loads. ChargePoint used the "connections" feature to group these drivers within their control system, so that they could be easily managed as a group. These features could be valuable to a utility if they grouped all the chargers in continuous geographical areas that does not include significant transmission constraints (sub-load aggregation point into one connection and then, for example, controlled their charging load to maintain a power ceiling on that circuit). With ChargePoint networked home chargers, this information could be made available to the utility using energy management application programming interfaces or through OpenADR.

The grid analysis by LBNL, using their V2G-Sim tool, shows that with proper coordination of charging patterns, PEV charging loads on the grid can be almost entirely eliminated during peak demand periods without compromising the mobility needs of drivers. This suggests that given the appropriate technology – specifically networked Level 2 charging stations – PEVs can be highly flexible loads and conducive for participation in load control programs. This load flexibility can reduce the stress on the grid and be used to defer transformer or distribution level upgrades by managing the peak load in an area.

In collaboration with test system supplier Vector North America, Inc. and project partner MBRDNA, ChargePoint tested the 15118 protocol integrated into a Home AC charging station. ChargePoint achieved a high degree of conformance to the 15118 standard, specifically to a basic feature set that supports alternating current (AC) charging using High Level Communication for AC charging and an external identification means, such as radio frequency identification.

By testing the prototype Home station against multiple 15118 PEV controllers and test systems at a 15118 Test Symposium, ChargePoint became confident that the prototype was highly compliant to the standard as used by diverse parties in the PEV industry. ChargePoint was also able to observe that interpretations of the standard have converged, indicating the viability of 15118 as a standard for advanced charging features and functions.

During 15118 testing, ChargePoint used the "smart charging" feature of 15118, which has messages allowing the PEV to specify to the electric vehicle supply equipment or charging station, the amount of energy requested, and allowing the electric vehicle supply equipment to specify the power levels, and relative cost of energy for the charging session. ChargePoint demonstrated that the Daimler Smart ED vehicle would change its charging behavior (power draw) based on the varying levels of available power using the 15118 data element. This charging adjustment indicates that using the 15118 standard allows for a more sophisticated method of data exchange and communication between the grid, charger, and vehicle. The additional information obtained may allow for improved optimization.

The program consisted of 1,005 charging events with 27 drivers in the SDG&E service territory who used the controlled charging schedule 58 percent of the time. Several participants indicated that they would have been interested in using the controlled schedule more if they were able to have more insight into the state of charge (equivalent of a fuel gauge for the PEV). Multiple drivers specifically noted that they wished to cap their state of charge at 80 percent to best take advantage of their vehicle's regenerative braking capabilities or to protect their battery health. Other drivers commented that they would like to see the amount of their batteries or information about how much battery charge they need the next day. The communications standards do not allow that level of information to be conveyed to the charger, but this feedback indicates that implementing the 15118 standard may increase the driver's willingness to participate in controlled charging programs.

Data for three participants was not used for this analysis because their participation in the controlled program was so minimal that there was insufficient data for analysis. This

information is also valuable as it indicates that there may be certain drivers/customers whose driving patterns or preferences are not aligned with such a controlled charging program and their load may not be shifted.

Technology/Knowledge Transfer/Market Adoption

ChargePoint participated in numerous events and workshops to disseminate information and learnings from this project. ChargePoint participated in and presented at the California Energy Commission's third and fourth annual vehicle grid integration workshops in 2016 and 2017, the Integrated Energy Policy Report workshop in June 2018, and the vehicle and charging technology showcase in October 2018. At these workshops and events ChargePoint provided updates on its progress with 15118 integration and the findings from the residential controlled charging program with 27 homes in SDG&E territory.

ChargePoint is also an active participant in 15118 test symposiums and 15118 standards groups where they shared information about this project and the findings. These test symposiums have hundreds of top electric vehicle engineers and programmers from around the world working on interoperability of charging solutions and conformity to the 15118 standard.

Completing this project accelerated the timeline in which ChargePoint investigated and integrated the 15118 standard. As a result, this project will accelerate ChargePoint's ability to offer a 15118 enabled-charger when vehicles implementing the standard become available on the market.

Benefits to California

This work clearly identified PEVs as a highly flexible load, which can be very conducive for participating in load control programs. An ideal approach would allow PEVs to participate in demand response programs without compromising the mobility needs of individual drivers. Drivers could potentially choose not to participate or could alternatively have an opt-out option for short periods when their behavior is more variable. Overall, using a controlled program to schedule the charging for PEV is beneficial for the driver and the electricity grid.

Fundamentally, this work supports greater electricity reliability and lower or deferred costs in upgrading local distribution infrastructure by providing a mechanism for demand management for local distribution networks. According to Fleetcarma "Studies suggest that higher penetration of PEVs can increase transformers' loss-of-life factor, by up to 10,000 times. As an example, the Sacramento Municipality Utility District has recognized that 17 percent of their transformers need replacing as a result of PEV-related overloads, at an average estimated cost of $7,400 per transformer". However, the work completed in this project demonstrates that home PEV load is quite controllable and utilities could shift and stagger the PEV load to help reduce these costly distribution upgrades. Demand visibility and management will level the power demand curve to lower electrical generation costs and reduce power fluctuations across distribution level electrical equipment, increasing distribution system reliability. Ratepayers will also benefit from improved air quality and reduced greenhouse gas emissions from the efficient management of electricity generating resources and from increased PEV utilization.

The controlled charging pilot created a beneficial cost reduction for the participants. For example, the data showed that with the utility price signal used, the charging cost when customers were not on a controlled charging schedules, was 28.62 cents/kilowatt hour (kWh); whereas, after participating in the controlled program, the average charging cost decreased significantly to 15.64 cents/kWh. The participants saw a 12.98 cents/kWh savings for their PEV charging needs. For homeowners who add 300 kWh of charge to their vehicle from their home charger each month, they could reduce their monthly electricity bill by $39 and their annual bill by $467.

CHAPTER 1
Vehicle-Charger Communications Testing

Emerging vehicle-to-charger communication standards can be a tool to manage plug-in electric vehicle (PEV) charging loads. The International Organization for Standardization/International Electrotechnical Commission's (ISO/IEC) 15118 standard is a communication protocol that can be used to vary and optimize the individual vehicle-charging rate to manage PEV charging loads. ChargePoint and project partner Mercedes Benz Research and Development North America tested the ISO/IEC 15118 protocol integrated into a Home AC charging station designed and manufactured by ChargePoint.

Vehicle Grid Communications

To allow Level 2 AC chargers to exchange smart charging data and control messages with plug-in electric vehicles (PEV), ChargePoint integrated the International Organization for Standardization/International Electrotechnical Commission (ISO/IEC) 15118 Edition 1 standard protocol (15118) into ChargePoint's prototype "Home" model charging station (CPH25). In collaboration with project partner Mercedes Benz Research and Development North America (MBRDNA), ChargePoint validated the prototype by successfully charging a production PEV (the Daimler/Mercedes Benz Smart ED) using the high-level communication – alternating current (HLC-AC) and smart charging features of 15118.

Before vehicle charging, ChargePoint tested the CPH25 Home prototype's conformance to the 15118 standard using a test system in a lab setting. After the prototype was successful with the production PEV, ChargePoint performed testing with four teams during an industry test symposium. Through interoperability testing, ChargePoint proved that our implementation of the 15118 standard worked successfully with only a few minor differences. A high degree of convergence was also confirmed with the ChargePoint HLC/AC 15118 implementation and auto OEM BMW and Verisco's 15118 test system.

EVSE-Test System Configuration and Preliminary Results

ChargePoint integrated and performed an in-house implementation of the ISO/IEC 15118 (Edition 1) protocol in a prototype version of a CPH25 "Home" alternating current (AC) charging station. The implementation of 15118 capabilities on this new hardware was done with the aid of a Vector CANoe test platform.

The configuration of the Vector test system was straightforward. When ChargePoint had questions on specific steps or details, Vector provided valuable support and customer service.

A length of PEV cable terminated in a Society of Automotive Engineers (SAE) J1772 inlet was used as a physical and electrical interface to the Vector test system, and the Home J1772 connector was inserted into the inlet. The 15118 enabled home charging station and Vector system are shown in Figure 1 and Figure 2. The pilot and ground conductors were connected to

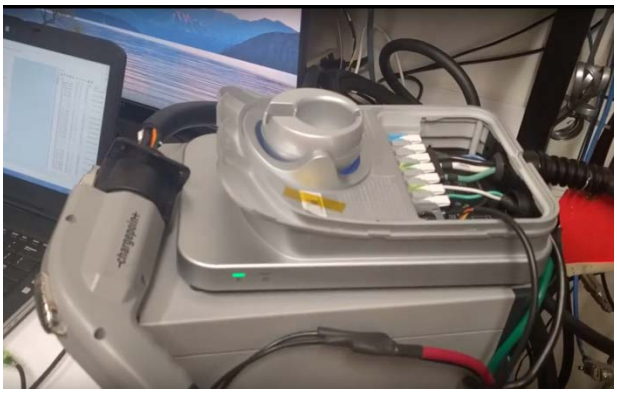
the VT7900/VT7870 input terminals. (Inductive coupling is no necessary; the Vector module accepted a direct electrical connection.) The two AC conductors were connected to a small desktop load (heating coils).

Figure 1: Vector Test System

6-slot chassis and VT7900/VT7870 module in use

Source: ChargePoint, Inc.

Figure 2: 15118-Enabled Home Station Atop the Vector Test System



SAE J1772 charging station connector coupled to an inlet, connected to the Vector test system

Source: ChargePoint, Inc.

The Vector CANoe software can be used as a PEV simulator to test a charging station, and can execute 15118 messages open-loop; by selecting sub-sets; or one by one. For example, one can start a test "charging session" from the beginning (idle state) and run until failure or completion. One could also choose to test only the messages used for energy target setting and charge schedule selection, if that were the section of the 15118 protocol of interest.

Proceeding through the charging session phases described in 15118-2/-3 (Communications Set-up; Identification, Authentication and Authorization; Target Setting and Charge Scheduling; and End of Charge processing), ChargePoint used the Vector test system to "bring up" all the features required for the project on the prototype Home AC charging station.

The first sequence involves switching from the pulse width modulation (PWM) signal used for "basic AC charging" (as defined in the SAE J1772 and IEC 61851-1 standards) to the HomePlug Green PHY broadband powerline carrier signal specified in 15118-3 for High-Level Communication (HLC). This switch is done by setting and maintaining the PWM duty cycle at a nominal 5 percent value, which signals to the PEV that it can begin HLC initialization. The PEV and EVSE proceed through PEV-EVSE matching and the creation of link-layer (layer 2) interfaces to the IP stack on each device.

The HLC establishment is a delicate process and represents a substantial portion of the testing effort. Fortunately, HLC is used for direct current (DC) charging using the DIN 70121:2014 standard as well as AC and DC charging using 15118, so the integration and testing effort required to support this part of the 15118 standard[1] can be leveraged for almost all charging stations.

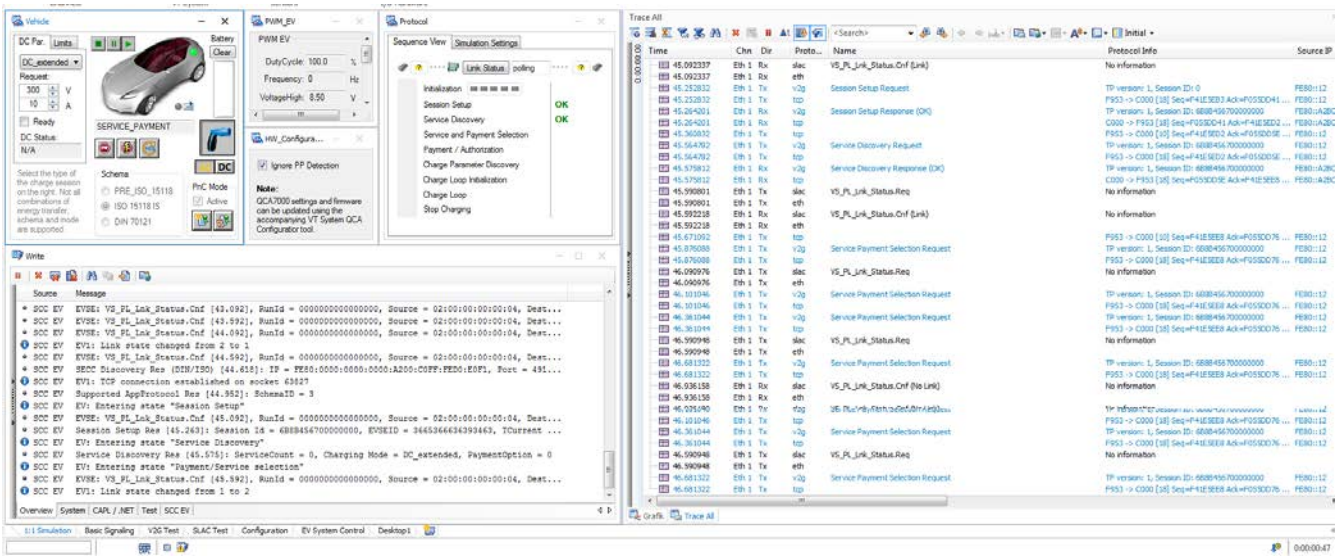
The challenges associated with HLC are related to the interaction of the two HomePlug Green PHY modem integrated circuits in the charging station and vehicle. A few parameters, such as signal amplitude levels and tone maps (notched channels), have to be set on each modem so the matching process results in solid communications at the physical and link (medium access control) layers. The matching process is described in IEC/ISO 15118-3; in practice, and specifically for this project, running identical firmware on both modems, which also used identical ICs, ensured that the 15118 station-vehicle matching was successful.

Another major effort was required to get Efficient Extensible Markup Language (XML) Interchange (EXI) message compression to work correctly. The Vector system served as a reference for ChargePoint to validate the behavior of the EXI encode-decode software for AC charging messages before moving on to test with a real PEV.

The choice of EXI as a critical component of 15118 messaging is unfortunate. EXI is not widely used and there are few code bases available for adoption in products. Given the data rates of HomePlug Green PHY and IEEE 802.11n – the two PHY/MAC options supported in 15118 Edition 2 – it is arguable whether compression of the XML messages should be required. As the standard evolves, timing requirements are becoming better understood. Especially for AC charging, the cost-benefit tradeoff of using EXI is very much in question; however, its removal or replacement seems unlikely in 15118 Edition 2, due to the timeline of publishing Edition 2 of the 15118 standard. Figure 3 shows a screenshot of the Vector test system interface during testing.

[1] IEC/ISO 15118-3:2015 (Edition 1).

Figure 3: Vector CANoe Test System Interface In Use



Note the settings: Schema = 'ISO 15118 IS'; PWM PEV DutyCycle, Frequency, and Voltage; etc.

Source: ChargePoint, Inc.

After successfully validating the 15118 capabilities of the prototype Home station using the Vector test system, ChargePoint was ready to try charging a real PEV with the HLC-AC features of the 15118 standard.

EVSE-PEV Testing and Preliminary Results

Project partner Mercedes-Benz Research and Development North America loaned ChargePoint a production Smart ED electric vehicle that supports 15118 protocol AC charging features. From July-November 2017, ChargePoint was able to test and validate all the features needed to support the end-to-end VGI goals of EPC-14-078.

After testing with the Vector system, charging the Smart ED with 15118 was straightforward. It took less than a day from receiving the PEV to successfully run a complete charging session. Only a few minor code tweaks and no electrical modifications were needed. Normal 15118-based AC charging (e.g. the EVSE delivered as much energy as available from the AC service, in this case 32 Amps, until the PEV indicated termination with a full charge) was consistently reliable over the entire four-month testing period.

The test configuration for PEV-EVSE testing was simple and straightforward.

- The 15118-enabled Home (7 kW AC) charging station was connected to a 240 VAC single-phase supply.
- The SAE J1772 connector was inserted into the Smart ED's SAE J1772-compliant charging inlet.
- A Linux laptop was connected to the USB (serial communications) port of the Home prototype station, enabling monitoring of 15118 exchanges from the station's vantage point, and control of the charging session.

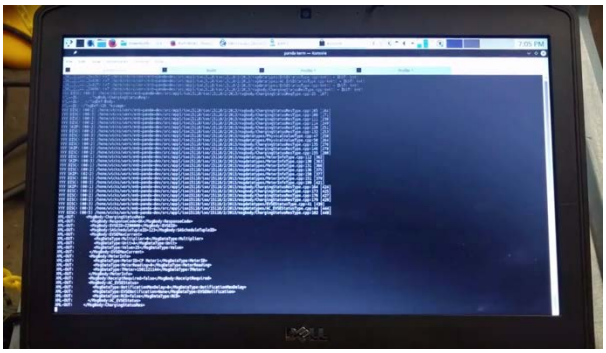
- The Smart ED's steering-column display was used to monitor PEV charging behavior. (There was no need for any modifications or under-the-hood connection, for example. connection to an internal CAN bus.)

The following figures show testing in progress: EVSE and PEV (Figure 4); 15118 message traces on the Linux laptop monitoring and controlling the Home station (Figures 5 and 6); and the Smart ED dash readouts during testing (Figures 7 and 8).

Figure 4: Close-Up of the Smart Ed Charging With 15118

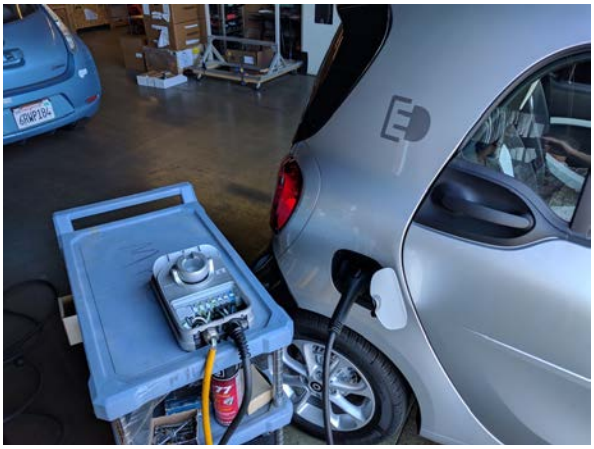
Source: ChargePoint,Inc.

Figure 5: Linux Laptop Console During 15118 AC Charging



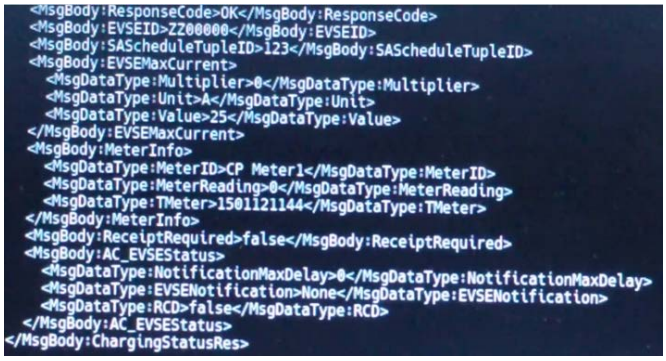
Source: ChargePoint,Inc.

Figure 6: Prototype Home Station and Smart ED Ready for Testing in ChargePoint's Lab



Source: ChargePoint,Inc.

Figure 7 Linux Console Close-Up During Charging Loop



```
<MsgBody:ResponseCode>OK</MsgBody:ResponseCode>
<MsgBody:EVSEID>ZZ00000</MsgBody:EVSEID>
<MsgBody:SAScheduleTupleID>123</MsgBody:SAScheduleTupleID>
<MsgBody:EVSEMaxCurrent>
  <MsgDataType:Multiplier>0</MsgDataType:Multiplier>
  <MsgDataType:Unit>A</MsgDataType:Unit>
  <MsgDataType:Value>25</MsgDataType:Value>
</MsgBody:EVSEMaxCurrent>
<MsgBody:MeterInfo>
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  <MsgDataType:TMeter>1501121144</MsgDataType:TMeter>
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  <MsgDataType:NotificationMaxDelay>0</MsgDataType:NotificationMaxDelay>
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</MsgBody:AC_EVSEStatus>
</MsgBody:ChargingStatusRes>
```

Source: ChargePoint,Inc.

Figure 8: Smart ED Steering Column Display

Source: ChargePoint,Inc.

Testing 15118 Smart Charging

ChargePoint next tested the “smart charging” feature of 15118, implemented with messages allowing the PEV to specify to the EVSE the amount of energy requested, and allowing the EVSE to specify the power levels and relative cost of energy for the duration of the charging session. These parameters are exchanged in the Target Setting and Charge Scheduling phase of 15118. The elements exchanged are EAmount, SASchedule, PMaxSchedule, SalesTariff, and optionally DepartureTime. Testing was focused on the explicit PMaxSchedule mechanism rather than SalesTariffs, whose indirect relative pricing, combined with unspecified service pricing choice algorithms on the PEV, can lead to indeterminate results. In addition, the 15118 standard provides no limits on renegotiation nor requirements ensuring convergence on energy pricing between PEV and EVSE. This can make it challenging to thoroughly test these provisions of the standard.

It was demonstrated that the Smart ED would change its charging behavior (power draw) based on the EVSE varying levels of available power using the 15118 PMaxSchedule data element. For example, in one test run the Home station changed its available power between 16 and 32 Amps (i.e. “half power” and “full power”) every three minutes. This power adjustment is shown in the Smart ED indicator in Figure 9 and Figure 10.

These changes to the operative PMaxSchedule were initiated by the Home charging station using the 15118 renegotiation mechanism.[2] The Smart ED responded within a few seconds, as expected and required by the 15118 protocol. The result was quick and seamless transitions between power levels.

[2] Renegotiation is described in Annex I of 15118-2.

Figure 9: 15118 AC Charging With Full Power (32 Amps)

Source: ChargePoint,Inc.

Figure 10: 15118 AC Charging With Half Power (16 Amps)

Source: ChargePoint,Inc.

Given a way to send a new PMaxSchedule from the Smart ED (for example, using a dash HMI or OEM smartphone app), PEV-initiated renegotiation could be tested. As no interface was available for managing data sent by the vehicle, the proper behavior of the Home EVSE in the case of PEV requests for change in energy schedule was verified using the Vector test system in PEV simulation mode.

Similarly, price-based energy management or optimization could not be tested because there was no way to set the Smart ED's parameters for DepartureTime or SalesTariff values. Further testing over the intended range of these parameters would be needed to understand the options available to charging service providers for implementing effective VGI programs using 15118.

Participation in a 15118 Test Symposium

In November 2017, ChargePoint participated in a two-day Test Symposium sponsored by ISO and other industry organizations, and hosted by the Canadian Standards Association in Mississauga, Ontario, Canada. Participation in this Test Symposium was not part of the EPIC contract, but the testing was relevant to the grant work. This Symposium was dedicated to testing EVSE and PEV communications controllers (in 15118 terms, Supply Equipment Communication Controller and Electric Vehicle Communication Controller, respectively) separately from the charging station and vehicles in which they normally operate. Testing the communication controllers separately greatly simplifies logistics and allows for meaningful testing, especially of emerging or advanced features that might not yet be implemented in commercially supported products. Other Test Symposium events involve full-system, end-to-end testing of production stations and vehicles.

ChargePoint's 15118-enabled Home station is highly integrated, and thus, isolating the 15118-communication controller in a fully functional charging station is challenging. Instead, ChargePoint tested by running the prototype residential station with a 'stub' program simulating functions associated with power transfer, and routing the signal that carries HLC (on

the J1772 the pilot wire) to a connector that plugged into the test partner's PEV communication controller or test system.

In Toronto, ChargePoint was able to test the prototype 15118-capable Home AC charging station against four other implementations:

- Vedecom –public-private research institute tested using their 15118 PEV controller that has been integrated into a Renault Zoé BEV. (Vedecom demonstrated this prototype PEV and an experimental 15118-capable EVSE at the previous ISO 15118 Test Symposium (#6), 22-23 June 2017, Versailles, France; and at the IEC TC69 – ISO TC22/SC31 JWG11 standards meeting held at the EDF Lab, Paris-Saclay, France in September, 2017.)[3]

- TU Dortmund / Verisco – a start-up commercializing advanced, standards-based automated technology developed at the Communications Networking Institute, Technische Universität, Dortmund. Verisco principles authored the protocol testing standards in the ISO/IEC 15118 series (15118-4 and 1518-5).[4]

- BMW / GIGATRONIK München GmbH – the major German PEV manufacturer tested using their prototype 15118 PEV controller for AC charging, developed with partner/supplier Gigatronik. BMW production vehicles do not yet utilize 15118 for AC charging.[5]

- CarMediaLab GmbH – an innovative small firm based in Bruchsal, Germany that has developed a technology platform using 15118 for Wireless Power Transfer, an advanced capability planned for the next version of 15118 (Edition 2). CarMediaLab's PEV controller could readily be used in a production PEV for 15118-based AC conductive charging.[6]

Each testing session was scheduled for two hours, which provided ample time for participants to test multiple virtual 'charging sessions', discuss and negotiate interpretations of standards requirements, and adjust and refine their implementations (such as modify and re-compile code).

Participation in the Test Symposium yielded several items learned:

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[3] http://www.vedecom.fr/veh-06/

[4] http://www.verisco.de/

[5] http://www.gigatronik.com/en/industries.html (see under 'Electromobility and smart grid')

[6] https://www.linkedin.com/company/carmedialab-gmbh/
https://www.youtube.com/watch?v=JbY5cPqIsuY

- **Broad Conformance to the IEC/ISO 15118 Standard**
  ChargePoint confirmed that the 15118-capable Home station prototype conformed to other implementations to a very high degree. This conformance result was not especially surprising, since all the partner implementations (PEV controllers or simulators) had previously been tested against reference implementations, test systems, and/or other 15118 charging stations. Nevertheless, it was important to verify that except for a few minor, non-critical discrepancies and one anomaly, the Home prototype executed the 15118 charging protocol flawlessly with all partner devices.

- **Identifying Anomalies**
  One anomaly was identified during testing: one PEV controller could not recognize and operate with the ChargePoint prototype's HP-GP signal (or vice versa, the problem presentation is intrinsically symmetrical). As noted, establishing HLC can be difficult, although no such problem arose with any other test partner. This partner also was able to establish HLC with all other EVSE/PEV and test system partners. See the next section, "Next Steps" for a brief analysis of this anomaly and steps ChargePoint can take to resolve this.

- **Highly Detailed Conformance Testing**
  When testing with a reference system not previously used in integration or testing, a few minor inconsistencies were uncovered – such as not sending a valid return code, or sending a different numerical type than expected. This system was developed specifically to verify that implementations on ChargePoint's charger and network conform fully to the 15118 standard requirements as published. It was valuable to be able to test with this partner, since it helped improve ChargePoint's embedded 15118 code and gave insight into how a reference would perform. Such a reference is critical to broad adoption of 15118, since pairwise interoperability testing can result in diverging interpretations and ultimately, incompatible behavior between implementations.

- **Increased Industry and Technology Exposure and Awareness**
  ChargePoint was able to get a glimpse, between sessions, of testing between other parties who had implemented some advanced features of 15118, specifically plug-and-charge and automatic (contract) payment, which use transport layer security (TLS) and public key infrastructure (PKI) – signed certificates and behind-the-EVSE infrastructure that is not well specified in the 15118 standard. There is reason to believe that these advanced features of 15118 have been tested only provisionally and not proven at scale; they will likely require significantly more testing before operational deployment.[7]

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[7] BMW, ChargePoint, Daimler, Vector, Verisco and many other firms that participate in the ISO Test Symposium events are active participants, via their engineers' membership in national committees, in the development of Edition 2 of 15118.

Next Steps and 15118 Roadmap

During the Test Symposium, the mismatch identified between the ChargePoint Home prototype and a PEV controller was challanging to diagnose because it occurred at the radio signal encoding (HomePlug Green PHY) level of the 15118 protocol and was below the threshold of available test equipment. The test partners agreed to follow up by comparing results of wire format traces and signal measurements done in their separate labs, to see if they can discover the root cause.

Along with additional testing of PEV smart charging behavior mentioned above, ChargePoint plans to test the Plug-and-Charge and Automatic Payment (Contracts) features of 15118 in the coming months. These require establishing a secure channel between EVSE and PEV, and that a system "beyond" the EVSE be operating in the charging system network and IT infrastructure. These 15118 options depend on installing a PKI scheme that has not been thoroughly tested, nor proven to be interoperable and workable at scale.

Nevertheless, some test vendors have introduced digital certificates, simple contracts, and other items needed to at least test the foundations of plug-and-charge and contracts in the context of ISO 15118 Test Symposium events. ChargePoint is aiming to work with these vendors in the future to test the prototype 15118-enabled Home charging station at future test symposium events.

The longer roadmap for 15118 is emerging in drafts of Edition 2, which include provisions for many new features. These include extended options for energy management; signaling to select and control bidirectional and wireless power transfer; support of multiple contracts for different energy services; absolute pricing; along with refinement of associated aspects and operations such as service discovery and negotiation, parameters exchanged during the charging loop, certificate management, etc. The importance and complexity of testing 15118 will only grow as more features are introduced into the standard and more PEV and EVSE products come to market.

Conclusion

In collaboration with test system supplier Vector North America and project partner Mercedes Benz Research and Development North America, ChargePoint tested the ISO/IEC 15118 protocol integrated into a Home AC charging station. ChargePoint verified a high degree of conformance to the 15118 standard, specifically to a basic feature set that supports AC charging using high level communication and an external identification means (EIM – RFID or similar).

By further testing the prototype Home station against multiple 15118 PEV controllers and test systems at an ISO 15118 Test Symposium, ChargePoint gained confidence that the prototype is highly compliant to the standard as implemented by multiple, diverse parties in the PEV industry. ChargePoint also gained confidence that interpretations of the standard have converged, indicating the viability of 15118 as a standard for advanced charging features and functions.

Several broad points can be concluded:

1. There is sufficient industry investment and momentum behind the ISO/IEC 15118 Edition 1.0 standard to enable vendors to test basic conformance of their AC charging stations and plug-in electric vehicle implementations. As interest and investment in 15118 grows, more detailed and in-depth conformance test capabilities should be forthcoming in the market. The regularly scheduled Test Symposium events were critical to 15118's progress and uptake to date.

2. There are aspects of the 15118 standard that no longer seem to be essential or practical and should be reconsidered in future editions of the standard. Specifically:

    a. HomePlug Green PHY seems an impractical choice for PHY/MAC technology on the point-to-point connection between charging station and vehicle. There is increasing interest in using IEEE 802.11n (the basis of Wi-Fi) instead; however, this will require further work on the requirements for station-vehicle association, cybersecurity, and related issues.

    b. The choice of XML for the definition of 15118 messages is helpful as it is a familiar and readable representation; however, the message encoding in the EXI format has severe disadvantages and is no longer practical or justified. There are much more widely adopted and technically suitable alternatives that could replace EXI to great advantage.

3. Conformance testing of 15118 will become significantly more complex as features of the standard beyond basic AC charging, which ChargePoint integrated and validated in this project, come into play. The current test infrastructure for Edition 1 features – including Smart Charging (such as. re-negotiation, measurement and validation of charging power schedules) and Plug-and-Charge (for example actual Internet-based PKI for certificate installation, contracts, metering and digitally signed receipts, etc.) – is immature and not well exercised. Sustained and increased investment in test systems and testing events will be required.

Finally, with the introduction of more advanced features in ISO/IEC 15118 Edition 2 – including messages for the control of wireless and bi-directional power transfer, dynamic power management, and more –the complexity and the criticality of conformance testing will only increase.

CHAPTER 2: Residential Controlled Charging Pilot

Residential PEV Charging

At the household level, plug-in electric vehicles are a substantial load. As PEV adoption tends to occur in concentrated geographic areas, electric utility-scale demand response (DR) programs can help ensure the stability of distribution systems and can allow for deferral of infrastructure upgrades. Participating PEVs in DR programs can be challenging since without adequate charge a PEV can leave a driver stranded during a trip. PEV drivers should carefully consider how participating in DR programs will affect their mobility.

To better understand the willingness of residential customers to control PEV load and test this out on real residential customers, ChargePoint ran a residential charging pilot in San Diego Gas and Electric (SDG&E) territory.

Pilot Project Structure

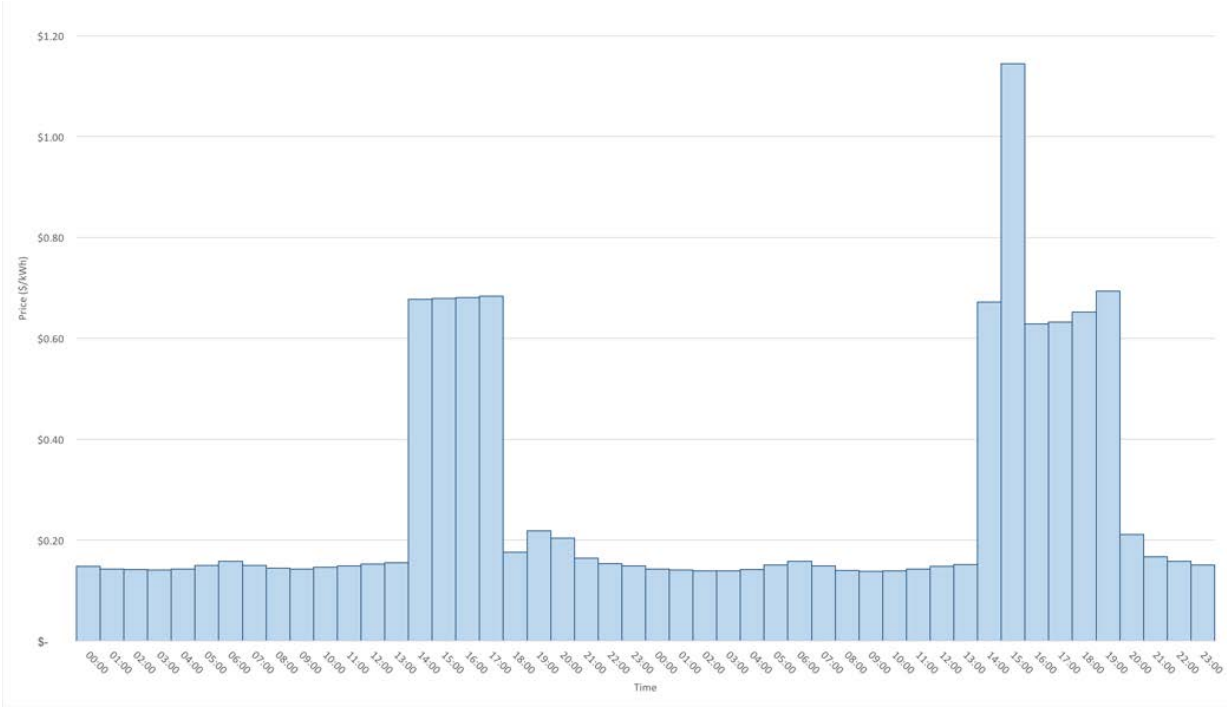
ChargePoint's pilot project sought out 30 PEV drivers who lived in SDG&E territory. ChargePoint had several key criteria for selection: single family homes; daily commuters; drivers who did not already own a home charging station; use of an Android or iOS smartphone to download and use the ChargePoint app; and no concurrent enrollment in any other demand response program.

These drivers agreed to join a three-month pilot program. As an incentive for participation, they received a free commercially available ChargePoint home station and some portion of their installation expenses were covered by the program. No driver was asked to change the utility rate that they were currently on; therefore, some drivers were on time-of-use (TOU) rates and some were on flat rates. All drivers were informed during a project kick-off webinar and in follow up emails/documents that they must turn off any in-vehicle charging schedules, so that ChargePoint had full control of their charging schedule.

The pilot was run in two phases. Phase 1 of the pilot was one month where ChargePoint primarily collected data about the drivers' charging behavior. Phase 2 of the pilot was two months and during this time ChargePoint used the information previously learned about the drivers from Phase 1 and an algorithm to send controlled charging schedules to the vehicles. Each driver also received a mobile notification with an opt-out option when they plugged in their vehicle each day; selecting to opt-out would mean their vehicle would bypass the controlled charging and instead begin charging immediately. The algorithm for the controlled charging schedule utilized driver data and hourly energy price information received day-ahead through OpenADR 2.0b. The price schedule obtained from SDG&E included a VGI Base Rate as well as an hourly CAISO adder. This rate showed significant variability, going from $0.15 cents to $1.15 in a day (Figure 11).

As mentioned, drivers were not asked to change their utility rate, so their electricity bill did not reflect an experimental rate. Drivers were informed ahead of time that the program may increase their energy bill slightly if they were on a TOU, because the experimental rate may not coincide perfectly with the TOU rate. Drivers did not consider this an impediment to participation however and they were informed that the bill impact would be slight, relative to the value of the free charger and installation costs that were covered by this pilot.

Figure 1: The SDG&E Price Signal Used in the Pilot



The bars represent $/kWh for a sample day.

Source: ChargePoint, Inc.

Pilot Data Analysis

Thirty residential customers participated in the pilot project, but of those only 27 used the charger with sufficient frequency for analysis. In the analysis, 27 chargers are represented. Program data was collected from July 10, 2017 to October 10, 2017.

From each charging session, the data collected contained the average charging power, peak charging power, cumulative energy consumed, hourly charging price and time. The time interval used for data collection was 15 minutes.

In total, 1,005 charging sessions were collected and can be divided into two scenarios: uncontrolled charging scenario and controlled charging scenario. In the uncontrolled charging scenario, the charging operation starts at the time a PEV connects to a charging station. In the

controlled charging scenario, the charging operation starts at the time when the aggregator schedules the station to charge. Charging data, such as the time of the charging session and the charging power, is recorded and can be sent to an aggregator or electric utility.

For each session, charging energy, cost, and average price were calculated using these equations:

$$\text{Energy}_{charged} = \text{Power}_{average} \cdot \text{Duration} \quad (1)$$

$$\text{Cost} = \text{Price}_{hourly} \cdot \text{Duration} \quad (2)$$

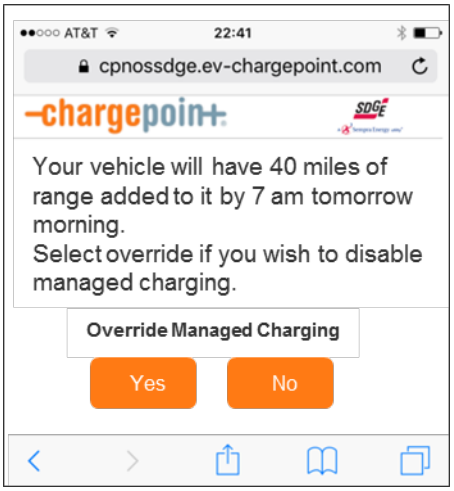
$$\text{Average price} = \frac{Cost}{\text{Energy}_{charged}} \quad (3)$$

In the collected charging sessions, 421 charging sessions belong to the uncontrolled charging scenario. The average price for these uncontrolled charging session is 28.62 cents/kWh. This value can be used to compare with the average charging price in controlled charging scenario.

Develop the Controlled Program

The control algorithm ChargePoint developed was trained on one month's worth of each driver's car charging data to create an individual model of their charging habits and needs. This data was coupled with a day ahead, hourly pricing signal from the utility, to create a tentative schedule for each driver. Schedules were designed to meet the charging needs predicted by the model and minimize the electricity costs based on the utility pricing signal. Drivers were notified of how many miles would be added when they plugged in and could override the schedule if additional charging was necessary; an example notification can be seen in Figure 12. The charging needs supplied by the model were rounded up to the next hour to provide a buffer as a safeguard against undercharging and to simplify the code, the charging needs supplied by the model were rounded up to the next hour to provide a buffer.

Figure 2: Example of Driver Notification



Source: ChargePoint, Inc.

The Effect of the Controlled Program

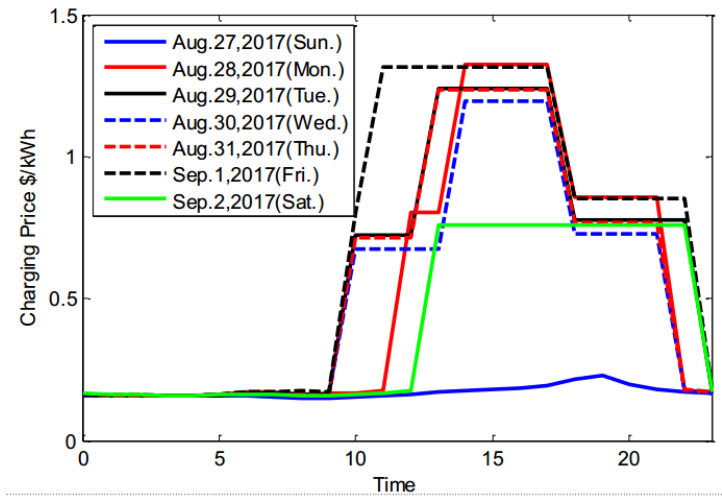
Data Collected During Scheduled Charging Control Program Implementation

For each home charging session, program participants were able to opt-in or opt-out of having their charging session scheduled. To quantify their tracking stations, 27 PEV program participants were tracked and include:

1. Time
2. User number
3. Charging duration
4. Charging power
5. Accumulative charged energy
6. Electricity price
7. Participating in or not

The program test was conducted from August 15 to October 10, 2017. The ChargePoint residential charging stations recorded the actions of the users including their opt in/out choice, cost, accumulated charged energy, charging power, and charging duration. Figure 13 shows the wide range of charging prices. During hours 0-5, specifically midnight to 5 AM, the charging price is usually as low as 15 ¢/kWh (Figure 14); however, from the SDG&E price signal, the maximum observed charging price is significantly higher at $1.32/kWh. The charge scheduling method attempts to avoid charging during the high charging price period. The controlled charging schedule method must meet the users' energy requirements to be beneficial to the users. Under the precondition of meeting the users' energy requirement, the driver benefits most if the vehicle is charged when the electricity price is low. In the next section, the result of participating in the controlled schedule charging is discussed to judge whether the controlled program realized the previous target of reducing the charging cost and avoiding the expensive charging period.

Figure 3: Energy Price Range For a Week



Source: ChargePoint, Inc.

Scheduled Charging Program

Table 1 presents summary statistics for the period before the program test period when charge scheduling was uncontrolled, during the program test period with controlled charge scheduling, and for both periods combined. Table 1 shows:

- Under the uncontrolled case, the average per kWh price of electricity for charging is 28.6¢/kWh.
- After participating in ChargePoint's controlled charging, the average per kWh price of electricity for charging decreases to 15.6¢/kWh.
- Compared with the uncontrolled case, the average unit price of the controlled program decreases 45.4 percent.

The hourly electricity price data was supplied by ChargePoint / SDG&E (August 15, 2017 to October 10, 2017). The charged energy is calculated using the formula (1), using charging session data with a time resolution of 15 minutes.

Table 1: Influence of the Controlled Program on Users

	Without Charge Scheduling	With Charge Scheduling	All Charge Sessions
Number of sessions	421	584	1005
Energy (kWh)	3423	4672	8095
Cost ($)	980	731	1171
Unit Price (¢/kWh)	28.62	15.64	21.14

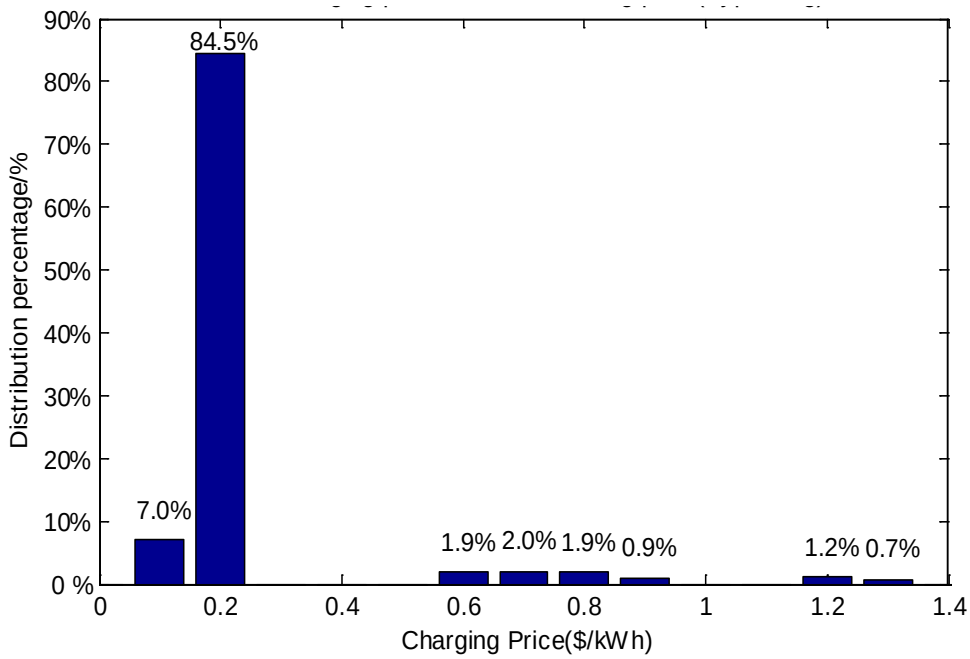
Source:

Evaluating the Controlled Charge Scheduling Program

Controlled Charging Session Results

In this section, the overall charging features are analyzed to study the impact of using the controlled program versus uncontrolled charging. The price range (0,1.4] is divided into 15 bins: (0,0.05], (0.05,0.15],(0.15,0.25]…. (1.25,1.35], (1.35,1.4]. The distribution of the charging duration in bypassing the charging schedule program is shown in Figure 14.

Figure 14: Distribution of Charging Events Against the Energy Price at the Time of Charging



Source: ChargePoint, Inc.

The figure shows that before participating in the controlled charging schedule project, charging occurred during the full range of prices, even if the charging price was very high. For example, around 2 percent of charging happened even when the charging price was higher than 1.2 $/kWh. By adopting the controlled charging schedule, the controller can shift charging so it is all completed when the price ranges from 15¢/kWh to 20 ¢/kWh. Controlled charging enables all charging to happen in the low end of the price range.

Individual Charging Station Features

In the previous section, the data demonstrated that controlled charging creates significant room for charging session cost reduction. Charging sessions can easily be shifted from the highest cost hours to the inexpensive periods; however, it is important to consider whether the controlled program can be effective to reduce the average charging price for any individual user. What percentage of the users can lower their total charging cost after participating in the controlled charging program? This section addresses these questions.

Table 2 shows the individual charging prices in the participating and bypassing cases for the 27 charging stations. The discrepancies in the cost differences from driver to driver are explained by the number of times each individual driver opted out. Those drivers who opted out of the

controlled charging schedule the fewest times saw the most significant cost reductions. The conclusions that are reached are:

- For the stations numbered 1 to 25, the average price in the participating case is lower than that of the bypassing case.
- For the stations numbered 26 and 27, all charging sessions happened in the scenario of controlled charging schedule.
- In total, based on all the charging station data, the average price for participating in controlled charging is lower – in some cases, significantly so, than the average price for bypassing the controlled charging schedule.

All users can save money after participating in the scheduled charging program.

Table 2: Average Charging Price for Participating and Bypassing Controlled Charging

Station No.	Average Price with participation in controlled charging ($/kWh)	Average Price while bypassing controlled charging ($/kWh)	Difference (Cost when Bypassing - Cost when Participating)
1	$ 0.155	$ 0.165	$ 0.009
2	$ 0.156	$ 0.174	$ 0.017
3	$ 0.156	$ 0.165	$ 0.008
4	$ 0.157	$ 0.384	$ 0.227
5	$ 0.155	$ 0.162	$ 0.007
6	$ 0.156	$ 0.350	$ 0.194
7	$ 0.156	$ 0.390	$ 0.234
8	$ 0.166	$ 0.317	$ 0.152
9	$ 0.157	$ 0.158	$ 0.001
10	$ 0.155	$ 0.292	$ 0.137
11	$ 0.159	$ 0.165	$ 0.006
12	$ 0.160	$ 0.195	$ 0.035
13	$ 0.157	$ 0.371	$ 0.214
14	$ 0.156	$ 0.158	$ 0.001
15	$ 0.159	$ 0.204	$ 0.045
16	$ 0.155	$ 0.157	$ 0.002
17	$ 0.156	$ 0.215	$ 0.059
18	$ 0.157	$ 0.259	$ 0.102
19	$ 0.159	$ 0.199	$ 0.040
20	$ 0.155	$ 0.221	$ 0.066
21	$ 0.157	$ 0.171	$ 0.013
22	$ 0.156	$ 0.305	$ 0.149
23	$ 0.155	$ 0.399	$ 0.244
24	$ 0.156	$ 0.420	$ 0.264
25	$ 0.156	$ 0.167	$ 0.012
26	$ 0.157	NaN*	
27	$ 0.156	NaN*	

* These participants never opted out of the controlled schedule. Therefore, there is no estimate for an average price while bypassing.

Pilot Results

Participating in the controlled charging program created a beneficial cost reduction for participants. Based on the measured data, the original charging cost is 28.62¢/kWh; after participating in the controlled program, the average charging cost decreases significantly to 15.64¢/kWh. For a homeowner who adds 300 kWh of charge to their vehicle from their home charger each month, they could reduce their monthly electricity bill by $39 and their annual bill by $467.

Conclusions

ChargePoint's 30 residential driver pilot successfully demonstrated the ability of the Home system to effectively control residential load while meeting driver's needs. Three of the 30 participants opted out the majority of the time. These three participants are an indicator that this sort of controlled charging program will not work for all drivers, and therefore there must always be an option for drivers with atypical driving patterns or a low tolerance for having their charging times offset.

The majority of the participants (27 drivers) demonstrated an appetite and interest to engage in a controlled charging program. These drivers were willing to offer their load to be shifted per the utility price signals in about 58 percent of the charging sessions. During participation hours, the average cost of charging decreased by 12.98¢/kWh. Ultimately, this controlled charging strategy is a win-win situation as the drivers are able to complete all their charging needs with minimal behavior change and at a lower cost, while the utility is able to achieve load shifting that better supports grid operations.

CHAPTER 3:
Grid Simulation of Controlled Charging

Vehicle Grid Communications

Data collected from the pilot demonstrated that there is a significant cost saving that the driver can benefit from by using a controlled charging program. Ultimately, the price signals that are sent to influence the charging behavior are created by the utility to create grid benefits. Thus, there are some additional questions to answer to consider the wider impact of controlled charging:

- Is the controlled program helpful for grid stability?
- What percentage of PEVs can adapt their charging patterns to participate in the controlled program without adversely impacting the driver's mobility needs?
- How will the charging level influence the charging system?
- How can the energy requirement for an individual car be resolved?
- Using a controlled program, how much can the peak demand be reduced by instead gradually charging?

Calculating Vehicle Energy Consumption

Simulating Driving Routes

A simulation tool called the vehicle-to-grid simulator (V2G-Sim) was used in this study to provide quantitative metrics to accomplish the project objectives. For this study, V2G-Sim takes input data from the National Household Travel Survey (NHTS), which provides a survey of the 24-hour vehicle use profiles of a random sample of drivers across the United States, including trip start and end times, trip distances, and types of locations where vehicles are parked.

Table 3: Travel Itinerary Information for a Randomly Selected Vehicle from NHTS Data Provided to V2G-SIM

Start time	End time	Event type	Distance/Charge type (Charger types are defined by assumptions)	Location type
12:00 am	7:50 am	Plugged in	Level 2	Home
7:50 am	8:50 am	Driving	27 mi	N/A
8:50 am	3:00 pm	Parked	N/A	Work
3:00 pm	3:10 pm	Driving	3 mi	N/A
3:10 pm	3:40 pm	Parked	N/A	Restaurant
3:40 pm	3:50 pm	Driving	3 mi	N/A

3:50 pm	7:00 pm	Parked	N/A	Work
7:00 pm	7:40 pm	Driving	27 mi	N/A
7:40 pm	12:00 am	Plugged in	Level 2	Home

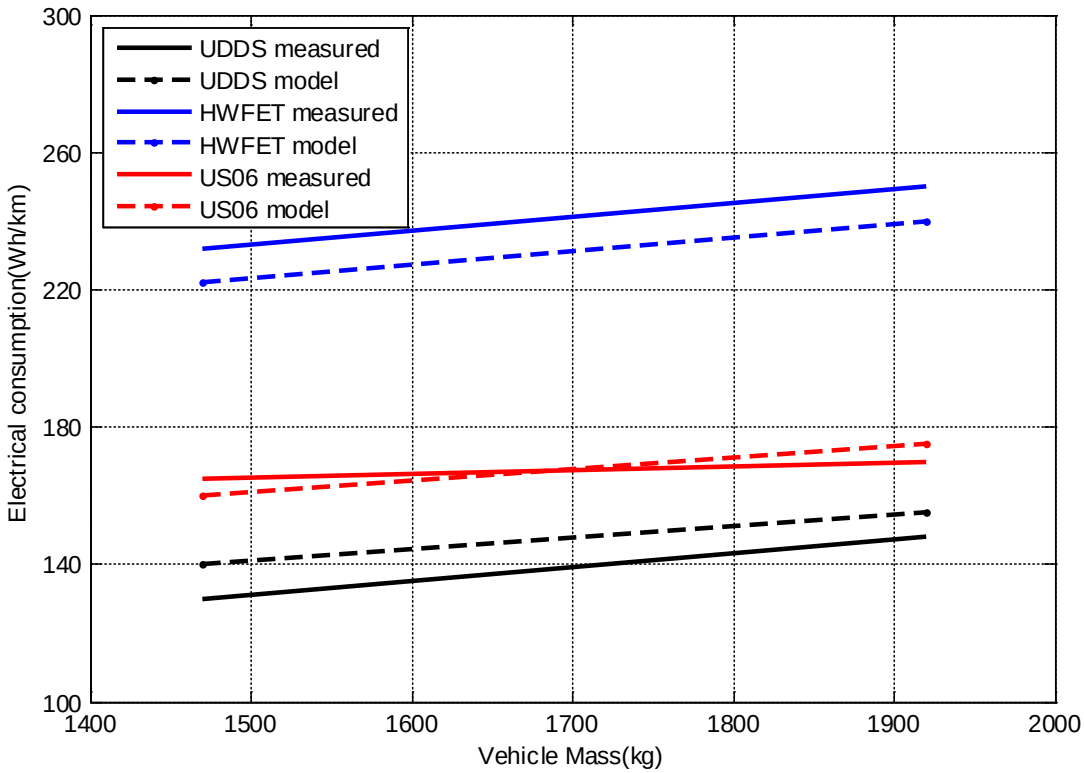
For each type of activity (such as driving, plugged-in, or parked) in the travel itineraries listed in Table 3, V2G-Sim calls an appropriate sub-model which tracks energy consumption in the vehicle powertrain, or power transfer between the electricity grid and the vehicle. In this manner, each individual vehicle's battery SOC is computed on a second-by-second basis for a chosen time interval (for example 24 hours).

Simulate the Vehicle Powertrain

Predicting the energy consumption and battery SOC of a vehicle while it is on a given trip, requires a trip-specific drive cycle of the vehicle's second-by-second velocity profile, and the terrain during the trip. For the results presented in this paper, the trip-specific drive cycles are generated from EPA standard drive cycles for city, highway, and high speed driving. However, trip-specific drive cycle generation methods have been built into V2G-Sim, which enable drive cycles to be generated that consider traffic conditions, city or highway fractions within a single trip.

The research team simulated commercially available PEVs, with specifications resembling a Nissan Leaf in V2G-Sim to travel along the individual daily travel patterns specified by the NHTS data, using drive cycles for a specific trip. While driving, each vehicle's energy consumption and battery SOC is predicted using vehicle powertrain sub-models in V2G-Sim that are validated against measurement data. These powertrain models determine the PEV's energy consumption during a trip while accounting for the high energy conversion efficiency of chemical to electrical energy in the battery, and electrical to kinetic energy in the motor. In this figure, there are three driving cycles: urban driving at low speed, highway driving with high speed cycle and aggressive driving cycle (US06). The US06 is the cycle in which the vehicle usually consumes more energy than the above two driving cycles. With the mass increasing, Figure 15 illustrates the electrical consumption at these three driving cycles, with the model and the measured data presented. This graph shows that the electrical consumption model can simulate the energy consumption at a high accuracy.

Figure 4: Comparison of Powertrain Model Predictions Against Chassis Dynamometer Measurement Data



Source: ChargePoint, Inc.

Detailed powertrain models within V2G-Sim can be used to predict the energy consumption of any vehicle make/model on any trip-specific drive cycle (including terrain considerations), and with any level of ancillary power loading (for example. from a vehicle's HVAC system). For this study, a single powertrain type (resembling a Nissan Leaf) is simulated on three drive cycles that are modified to fit trip-specific distance/duration targets specified by the NHTS input data. Thus, to enable rapidly executing simulations, the detailed powertrain model is used to initialize a simpler model of energy consumption per unit distance travelled by each vehicle. Combining the NHTS statistics data and the powertrain model, the energy consumption of the electric vehicle can be calculated.

Load Reduction Under Different Parameters

PEV Charging Load Reduction During Time

After getting individual vehicle energy consumption, the aggregated PEVs can be regarded as a flexible energy storage resource which interacts with the electricity grid. The flexible energy storage was used to adjust the grid load curve.

The core of the controlled program is to schedule the charging time for PEVs. Previously, once the outlet was connected, the charging action would start. However, when the charging price is

high or the PEV energy requirement is not large, it is the controlled program's primary task to delay the charging action until the charging price decreases to a low level. For the grid, the scheduled charging action can help to narrow the load range, which is helpful to keep the grid system stable and decrease the average electricity generation cost.

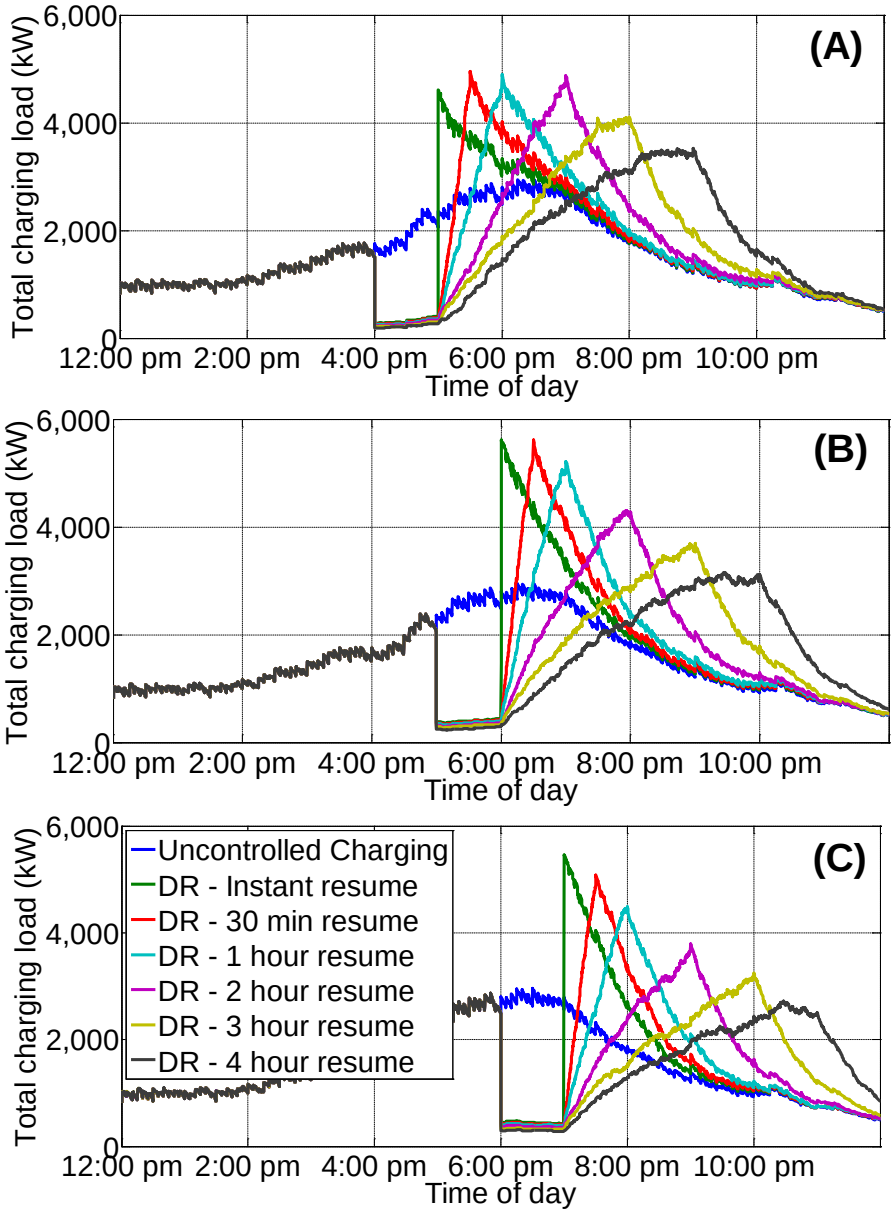
The uncontrolled charging case offers a baseline comparison of the load profile before implementing demand response control of PEV charging. Then, the percentage reduction is calculated for each time step and the maximum, average, and minimum load reduction is determined during the demand response (DR) period. V2G-Sim then quantifies the magnitude of the post-DR load peak if all vehicles resume charging simultaneously.

There are substantial load peaks that result if vehicles simultaneously resume charging at the end of DR events. Gradually resuming the charging of vehicles over some duration after the end of the DR event helps to mitigate that post-reduction peak. In any controlled charging type scenario, ultimately this would mean that vehicle charging should be staggered relative to the TOU or price signal, rather than all being placed on the same schedule.

The size and duration of the vehicle battery are important in mitigating the load curve. Therefore, if vehicles with larger capacity batteries were deployed, those vehicles would have a greater ability to help optimize the load curve.

In this analysis, vehicles were set up to resume charging at a randomly chosen time during a specified post-DR resume charging period. For instance, in a simulation where the DR event ends at 5 pm and where the post-DR resume charging period is set as one hour, each of the 3,166 simulated vehicles will resume charging at a randomly chosen time between 5-6 pm. Parametric simulation results are presented in this section to quantify the magnitude of peak reduction from different post-DR resume charging settings, from 30 minutes to four hours. Results quantifying the peak reduction potential are presented in Figure 16 for cases with a one hour DR event, 20 percent reserve SOC setting, and for a scenario with 40 percent workplace charging using Level 2 chargers. 16 (A) shows simulation results for DR occurring from 4-5 pm, Figure 16 (B) shows DR from 5-6 pm, and Figure 16 (C) for DR from 6-7 pm. Different load profiles quantify the ability to reduce post-DR demand peaks by gradually resuming charging of PEVs either instantly after the DR end time, more than 30 minutes, 1-,2-,3- or 4 hours.

Figure 5: PEV Charging Profiles at Different DR Times



Source: ChargePoint, Inc.

The results in this figure show that offsetting the time for PEVs to resume charging over some duration has mixed effects on post-DR peak reduction. Figure 17 (A) shows that the post-DR peak actually increases as the resume charging duration increases up to two hours, but the decreases for a three hour or four hour resume charging window. Figure 17 (B) and Figure 17 (C), however, show that there is always a decrease in the post-DR peak as the resume charging duration increases – this is the trend that is expected. Figure 17 (A) does not show the expected trend because too many cars arrive at home and begin charging between 5-7 pm, and thus the added load from charging the additional vehicles outweighs the reduced charging from distributing the resume charging time over longer durations. All three cases in this figure show that the peak demand is moved to later hours with longer resume charging durations, and with

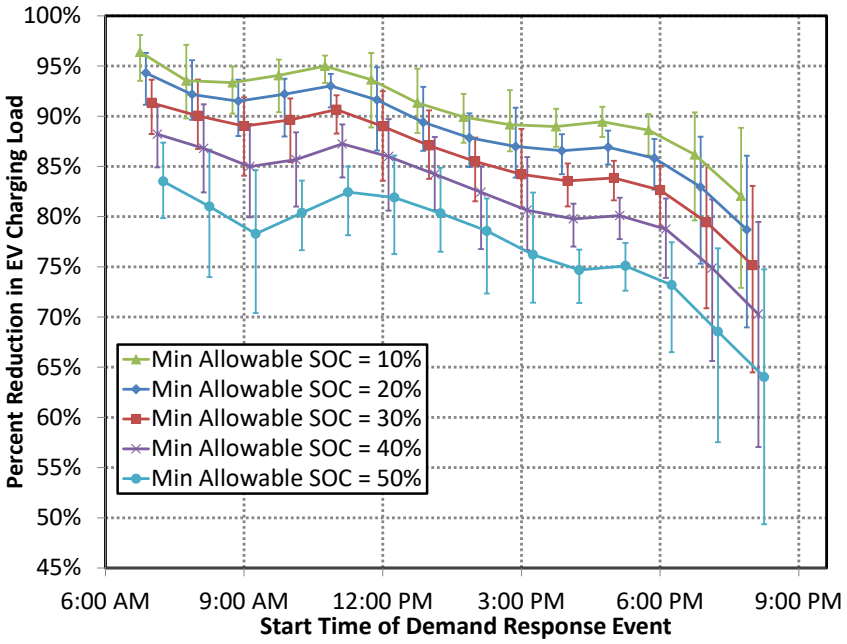
a resume charging duration of four hours, the magnitude of the post-DR peak is similar to the charging demand peak that occurs in the uncontrolled charging case.

PEV Charging Load Reduction During Uncertainties in Travel Itinerary

For this simulated analysis, the results and corresponding discussions were based on the availability of nearly perfect knowledge of each vehicle's travel itinerary over the upcoming 24 hours. However, in the real world people will make unexpected trips leading to uncertainty in the travel itinerary. The impact of this uncertainty in travel itineraries can be quantified by setting the managed charging controller to charge vehicles during DR events so that higher reserve SOC is available for unexpected trips, corresponding with higher specified values for the controller's SOCmin allowable parameter. With these higher reserve SOC settings, vehicles will have greater reserve range available to accommodate unexpected trips.

Figure 17 presents the results of parametric simulations to quantify how accommodating greater uncertainties in travel itinerary will impact percentage load reduction capabilities during DR events. Each simulation is for a case where vehicles resume charging right at the end of the DR period, and 40 percent of vehicles are charged at workplace locations using Level 2 chargers at home and at work, using 2 hour DR event durations.

Figure 6: Maximum Percent Reduction in PEV Charging Loads During DR Events



Reduction during DR events without adversely impacting driver mobility needs, for different reserve SOC values and for DR events occurring during different times of day.

Source: ChargePoint, Inc.

The results in this figure show that the DR percentage load reduction potential decreases as greater levels of uncertainty in vehicle travel itinerary must be accommodated. Though the DR reduction potential decreases, it is important to note that the magnitude of DR load reduction

is still substantially high (>65 percent) even when the DR controller aims to preserve 50 percent reserve SOC for unexpected trips. With 50 percent reserve SOC, vehicles will still be able to accommodate unexpected travel of substantial trip distances. From these results, it can be concluded that more than 65 percent of PEV charging load can be removed during DR events even if there is substantial uncertainty in trip itineraries.

Simulation Results

This study quantifies the magnitude of PEV charging that can be removed during demand response events, without compromising driver mobility needs. A simulation platform, called the vehicle-to-grid simulator (V2G-Sim), was developed and applied to predict the battery state-of-charge profile for N number of vehicles following different itineraries of when they drive, park, and charge. Vehicle usage itinerary data from the San Francisco Bay Area region of the National Household Travel Survey was used within V2G-Sim with the assumption that each vehicle had specifications similar to a Nissan Leaf. A managed charging controller was developed which, if a vehicle is plugged in during the demand response period, charges vehicles only if it is required to satisfy individual driver travel needs over the next 24 hours.

Simulations were run to quantify the percentage load reduction in PEV charging that can be obtained without adversely impacting driver mobility needs, and parametric simulations were used to quantify how the load reduction potential changes with different factors. The parametric simulations included sweeps of the timing and duration of DR events, different workplace charging scenarios, and accommodating different levels of uncertainty in travel itineraries. Additionally, the peak demand that occurs if vehicles simultaneously resume charging at the end of a DR event is quantified, and the effectiveness of a strategy to reduce this peak by distributing the resume charging time over a specified duration is quantified. The simulation results lead to the following broadly applicable findings:

1. PEV charging loads are extremely flexible. For demand response events occurring at any time of day, with DR event durations as long as four hours, more than 75 percent of charging loads can be removed without adversely affecting individual driver mobility needs, with the potential load reduction being as high as 95 percent in some cases. It is not possible to generally identify the most optimal time for load curtailment as it is dependent on the specific load profile of a given day; however, on average 5-6 pm was identified as a good time to begin the weekday charging schedule.
2. The percentage load reduction decreases as DR events are called later in the day, however, this is not a linear function.
3. The fraction of vehicles that charge at work locations and the type of charger (such as Level 1 or Level 2) used at work places does not substantially affect the percentage load reduction potential of PEV charging during DR events.
4. The percentage load reduction potential is greatest if there is good knowledge of the future travel itinerary for individual vehicles. The load reduction potential decreases as greater uncertainty in travel itineraries must be accommodated. However, even in cases with substantial uncertainty in travel itineraries, more than 65 percent of PEV charging load can be shed during DR events without adversely impacting driver mobility needs.

5. Substantial demand peaks are created if PEVs simultaneously resume charging at the end of a DR event. This post-DR demand peak can be addressed by gradually resuming PEV charging over some duration after the DR event. As this resume charging period is increased, the post-DR peak becomes smaller in magnitude and is shifted later. With a 4-hour resume charging window duration, the post-DR peak has a similar magnitude as the peak demand in an uncontrolled charging case.

Conclusions

The findings of this study show that with proper coordination in their charging, PEV charging loads on the grid can be almost entirely eliminated during peak demand periods without compromising the mobility demands of drivers. These findings suggest that PEVs are highly flexible loads and are very conducive for participation in demand response programs.

By creating an implementation approach that considers the mobility needs of the individual drivers, a demand response program can reduce or eliminate PEV charging that is coincidental with peak load. Overall, using the controlled program to schedule the charging for PEV is benefit for the individual driver and the electricity grid.

ACROYNMS AND ABBREVIATIONS

Term	Definition
AC	Alternating current
California ISO	California Independent Service Operator
CPH	ChargePoint Home Station
DC	Direct current
EIM	External identification means
PEV	Electric vehicle
EVSE	Electric vehicle supply equipment
HLC	High level communication
IEC	International Electrotechnical Commission
ISO	International Organization for Standardization
LBNL	Lawrence Berkeley National Labs
MBRDNA	Mercedes Benz Research and Development North America
OpenADR	Open automated demand response
PEV	Plug-in vehicle
PKI	Public key infrastructure
Smart ED	Smart electric drive vehicle
SOC	State of charge
SubLAP	Sub-load aggregation point
TLS	Transport layer security

REFERENCES

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