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EV Fingerprinting

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Abstract

Electric vehicles (EVs) hold the potential to greatly shape the way the electric power grid functions. As a load, EVs can be managed to prevent overloads on the electric power system. EVs with bidirectional power flow (V2G) can provide a wide range of services, including load balancing, and can be used to increase integration of renewable resources into electric power markets. Realizing the potential of EVs requires more advanced communication than the technology that is in wide use. Common charging standards do not include a means for an EV to send key vehicle characteristics such as maximum charge rate or battery capacity to a charging station and thus to the grid. In response to the need for a means of obtaining vehicle parameters without advanced communication, this paper suggests a mechanism that would allow electric vehicle supply equipment (EVSE) to identify the type (manufacturer, model and year) of the vehicle plugged in, and so learn several of the needed parameters. The approach for identification is proposed based on our measurements of variations in a standard charging protocol implementation across different EV types. We suggest that these variations may uniquely identify, or constitute a "fingerprint" for EV types. This paper describes the tools and methods used to collect data to investigate this proposition. The results of our analysis suggest that the proposed mechanism works well for identifying EV types based only on information available through the interface defined by a common standard for conductive charging. Further work will expand upon these results to develop tools for EVSE to identify the types of EVs connected to charge.

Introduction

Objective

As the movement towards electrification of transportation systems gains impetus, road vehicles promise to become increasingly connected to the electric power grid. Electric vehicles (EVs) are expected to play a key role in diversifying energy resources, providing economic and environmental benefits [2]. Thus, despite challenges facing increased usage of EVs the movement towards large-scale acceptance of electric vehicles continues to gain ground in multiple regions of the world [3, 4, 5]. This growth raises the question of how to best manage the demands of vehicles connecting to the electric power grid to charge.

EVs with V2G capability can be a storage resource, or a flexible load that can provide benefits to the power grid. Parties attempting to manage EV charging to achieve these benefits would need access to information regarding the EVs connected to the EVSE in the system under management. This information includes battery capacity and the maximum power draw. Such information could serve not only to facilitate optimized charge strategies, but also provide insights into how various vehicles interact with different conditions in the grid or environment. Advanced communication systems are key to realizing the benefits of coordinated charging. Such systems have been demonstrated on a small scale by various research and development groups [6], but have not yet been standardized or widely implemented [7]. Without an established framework for advanced communication, EV and EVSE manufacturers will continue implementing existing charge protocols that support little to no explicit information exchange between the EV and EVSE.

The objective of the project described below is to develop a mechanism by which EVSE can obtain important parameters about an EV connected to charge without relying on any explicit self-identifying communication from the EV. The approach taken is based upon our testing and experience with EVs, showing that key information needed about an EV is determined by the EV's type (manufacturer, model and year). Also, different EV types exhibit detectable differences in their implementation of charging standards that could serve to identify or "fingerprint" that EV type.

Background and Motivation

Various studies have shown how, if left unmanaged, EV charging can stress electric power distribution systems and decrease the life of service equipment[8, 9]. Conversely, if EV charging is managed well, this stress can be minimized [9, 10] without upgrades to the distribution system. With the implementation of V2G systems, EVs may even become a resource to the power grid, offering valuable services such as frequency regulation [11, 12]. EVs can also enable increased incorporation of renewable energy sources, such as wind and solar, by supplying storage for these inherently intermittent providers [12]. In order to achieve coordinated charging and V2G services, a substantial body of research has grown up around EV charging to propose strategies, systems and standards for controlled charging and V2G services.

Most if not all systems proposed for managing EVs rely on information regarding the EVs plugged in. This information includes items such as minimum and maximum charging power, battery capacity, how much energy an EV needs and how long it will be plugged in [13, 14, 15, 16] This information is generally expected to come from the EV requesting charge, or from the party charging the EV. This approach poses a potential problem. As mentioned above, while standards defining information exchanges between an EV and EVSE have been developed, they are not widely implemented [7]. In the absence of a consensus in the industry on the protocols to be used for such information exchange, manufacturers will default to the existing charge protocols and the number of vehicles in operation that do not support advanced communications will continue to grow, limiting controllers' ability to manage EVs that plug in to charge.

A method to identify an EV type from the EVSE has many possible uses. Insight into EV charging behavior is critical to continue developing both vehicles and charging infrastructure. Understanding the usage that existing charging stations are getting may be beneficial for business or government organizations developing plans for deploying more stations. The ability to identify EV types would allow manufacturers to discover bugs in, or incompatibilities between, service equipment and particular EV types, thus expediting the process of troubleshooting such issues. It might also allow the parties managing an EVSE greater ability to identify problems with an EV, as when a vehicle attempts to charge at a rate higher than that for which its type is rated.

Scope

This paper describes an initial mechanism to identify EV types without advanced communication, and demonstrates it in practice. This mechanism works within the J1772 standard with the idea that principles discovered in this research could be applied in a similar way to provide identification using other standards. This approach may serve as a method of obtaining vehicle parameters both where advanced communication and authentication are implemented, and in situations where these capabilities are not supported.   Section II describes methods, including the process for choosing what parameters to use in the identification scheme, and Section III describes the process of acquiring data. Section IV gives a brief analysis of the data, which are discussed in Section V. The final section draws conclusions and outlines proposed future work.

Parameter Selection

The experiments described used vehicles with the SAE J1772 standard for conductive charging. SAE J1772 was the earliest standard to be widely accepted in the electric automobile industry [17]. It has remained a common standard for Level 1 (100 - 120 VAC) and Level 2 (200 - 240 VAC) charging. J1772 defines the physical connections between the EVSE and the EV [1]. Figure 1 shows these connections and Table 1 explains them further.

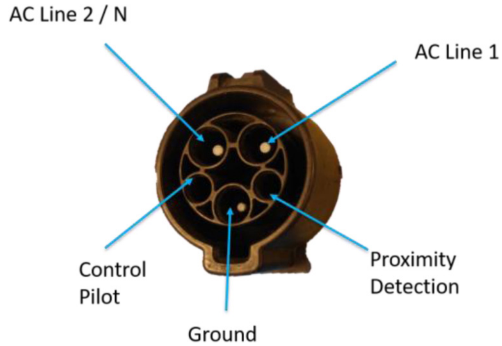

Figure 1. Physical connections for charge inlet (EV side) defined by J1772

Table 1.

Connection	Function
AC Line 1	Provides power for charging
AC Line 2 / N	Provides power for charging
Ground	Connects EV chassis ground to EVSE ground
Proximity Detection	Allows EV to detect that the charge connector has been connected
Control Pilot	Allows EVSE and EV to exchange information to control charging

J1772 defines a protocol for communication between the EV and EVSE, as illustrated in Figure 2. Signaling takes place over the control pilot line, hence "pilot" for shorthand. When no vehicle is plugged in, the EVSE is in state A, and the EVSE holds the pilot line at 12 V. When an EV is plugged in, the EV pulls the pilot line down to 9 V, and the EVSE moves into state B1, where the EVSE has recognized the presence of an EV, but not yet signaled the EV that the EVSE is willing to offer charge. If the EVSE is willing to charge the EV, it will generate a 1 kHz PWM on the pilot line, moving into state B2. The duty cycle of the PWM informs the EV of the maximum allowable charge rate. When the EV detects a 1 kHz PWM with a valid duty cycle, the EV closes a switch to pull the pilot down to 6 V, signaling to the EVSE that the EV wants to charge. The EVSE then closes the contacts to allow charge. At that point, the EVSE is in state C. Figure 3 illustrates the progression through states.

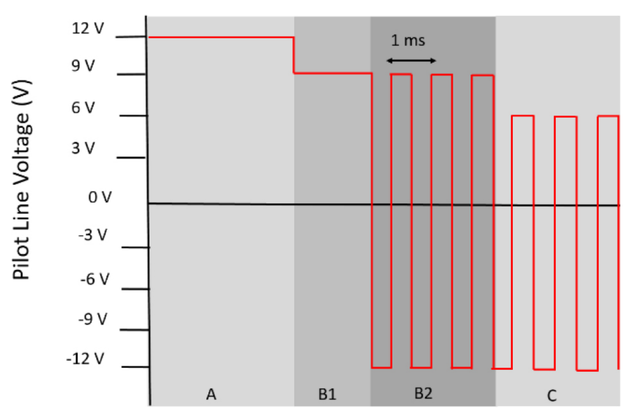

Figure 2. Pilot line characteristics by states as defined by the SAE J1772

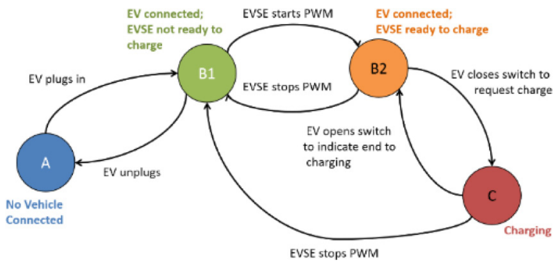

Figure 3. Progression between states when EV charges.

According to this protocol, aside from pulling the pilot line to different voltage levels, the EV does not actively communicate with the EVSE. The EVSE "tells" the EV if and at what rate the EVSE is willing to provide charge. The EV determines how much current it does draw - if the EV is standard - but that current should never be more than the maximum value communicated by the EVSE. Thus, timing and amount of current for charging can also be used to distinguish among EVs. The maximum current allowed for L2 charging by J1772 is 80 amps [1], however, most of EVs currently in use charge at a lower current. Even though several EVs are rated at the same nominal charge rates, the actual current drawn while charging (I_{final} in Figure 4) varies from one model to another. The time an EV takes to start drawing current once the EV enters state C (t_1 in Figure 4) and the time taken to reach the maximum charge current (t_2 in Figure 4) are also distinguishing features.

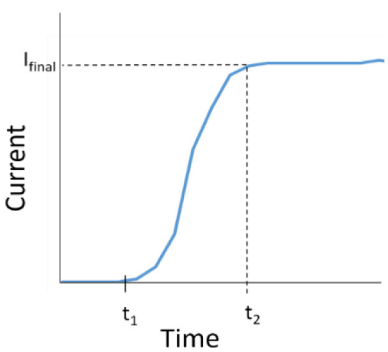

Figure 4. Plot of current drawn by EV at the start of a charging event

The features of the J1772 signaling protocol most relevant for fingerprinting are the pilot voltage levels in states B1, B2 and C, and the time spent in state B2. The voltages on the pilot line are formed by a source and a voltage divider with components on both the EVSE and the EV sides. The standard allows a 3% tolerance in the resistors used. Variations in the resistors in the EV may result in slight differences in the pilot line voltages, which could serve as an identification parameter. Also, the time spent in B2 is, at least theoretically, only dependent on the EV; it is the time taken for the EV to recognize the presence of a valid PWM, and close a switch to pull the pilot line down to 6 V.

Based on this interface and protocol, the following parameters were chosen as attributes for a classification algorithm.

- The pilot voltage in states B1 and B2, and in state C
- The time taken to transition from B1 to C
- Charge profile characteristics (delays and final current value).

These values were chosen with the expectation that none of these is singly able to identify a PEV type. The goal in evaluating these parameters is to determine which combinations were most likely to be useful for identification, and how to measure and report these.

Data Collection

Data acquisition relied on the charging stations associated with the V2G project installed on the University of Delaware campus. These are UD-designed, 75-amp J1772 charging stations now distributed by Nuvve Corp in San Diego. In these charging stations, a Vehicle EVSE Link (VEL) board controls low-level, non-safety critical decisions for the EVSE. The heart of this board is a 16-bit microcontroller. The microcontroller's ADC, configured for 10-bit resolution, samples the pilot voltage using a voltage divider as shown in Figure 5. The resistors used in the divider have a tolerance of 1%. The system is set to trigger an interrupt on an edge of the pilot line, at which point the pilot line is sampled and the state is updated. In absence of edges on the pilot line, the EVSE samples the pilot voltage regularly (at intervals of less than 10 milliseconds). The VEL passes data including pilot voltages and state to a management program running on an off-the-shelf embedded board. In most of the charging stations, this board also receives power flow information from an EKM Omni V.4 pulse meter, which can report data up to 800 times per kilowatt hour. In the system used, current is sampled usually every two or three seconds, though intervals as long as seven seconds have been observed. From the embedded board, information is sent via a hardwired Ethernet connection to a server from which the data is acquired for analysis.

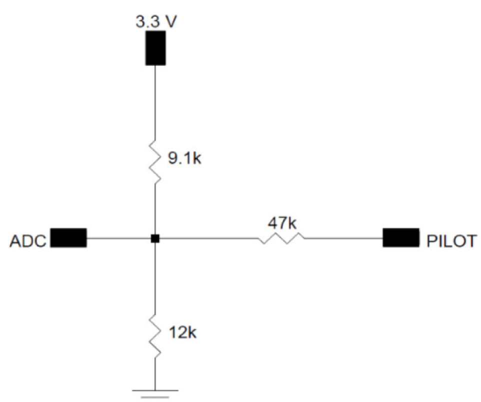

Figure 5. Circuit used to sample pilot line

Testing vehicles to obtain the required data occurred in multiple stages. In the first stage, data was collected whenever EVs plugged into the EVSE being monitored. This method of collecting information proved inefficient for various reasons, and also did not give access to information about the vehicle's starting state of charge. Thus, a standard operating procedure for testing was adopted to generate data by repeatedly plugging and unplugging a vehicle with two minutes plugged in, and two minutes unplugged. Two minutes was chosen as a sufficient time to allow the vehicle to reach its maximum charge rate, and for the system to reset after the EV is unplugged. This procedure was used in subsequent stages of testing.

In the second stage of testing, five charging stations were used to collect data from four vehicles: a 2013 BMW i3, an AC Propulsion eBox (a Toyota Scion up fitted as an electric vehicle capable of 80 Amp bidirectional charging), a 2013 Nissan Leaf, and a 2011 Chevrolet Volt. Each vehicle was tested on at least two charging stations, and each charging station was tested with at least two vehicles to reduce the chance that the differences detected between EVs would actually be due to differences in the supply equipment.

As a first step, much of the data was plotted for visual inspection, to determine if the parameters chosen were relevant, and if there were parameters that needed to be added. Figure 6 shows a plot of the pilot voltage by EV in each of the states. The state machine in the EVSEs contains non-standard states (B0, LT, LN, LR, NT, NN and NR) in order to support advanced communication to coordinate bidirectional power flow. The states are fully compatible with J1772. States B0 and NT, allow the EVSE to quickly test if the EV supports specialized communication for V2G. If the EV does not support this communication, the EVSE moves into state B1. A0 is equivalent to A, B1 and B2 are equivalent to their counterparts in J1772, and C2 equivalent to C. The eBox was the only vehicle tested that could enter the advanced communication states. The plot in Figure 6 was not particularly enlightening as to whether the pilot line voltage in states B1, B2 and C was a distinguishing parameter. However, it did show that taking a sample of the pilot line at the time of a state change, when the pilot line is changing voltage and possibly carrying a PWM, often resulted in measuring the voltage at an inopportune time. The resulting values often did not accurately represent the nominal value of the pilot line voltage for the state being entered. As a result, firmware on the EVSEs used was updated to record multiple samples of the pilot in the first few milliseconds after a state change.

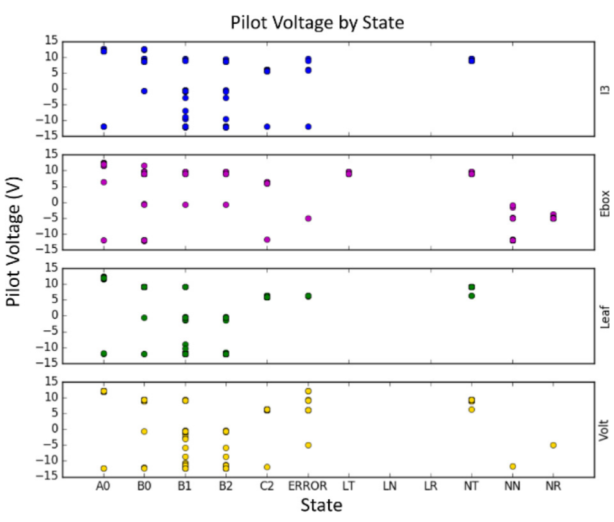

Figure 6. Pilot line voltage by state for the first EVs tested

Another item plotted was the current profiles of the vehicles tested. Figure 7 shows the plot for the Leaf, and Volt. In this figure, current is negative if it is flowing to the vehicle. The only vehicle tested that provided positive current was the eBox. This feature obscured the information needed, so this EV was not included in Figure 7, and was not used for subsequent testing. Data for the current profile of the i3 was not accessible due to equipment issues with the charging stations on which it was tested, leading to the i3 information eventually being removed from the dataset. From the remaining data, it was determined that current profiles were markedly different, not only in the maximum current drawn, but in the time needed to reach this current. The delay between entering C2 and the start of current flow could not be obtained due to synchronization problems between different log sets.

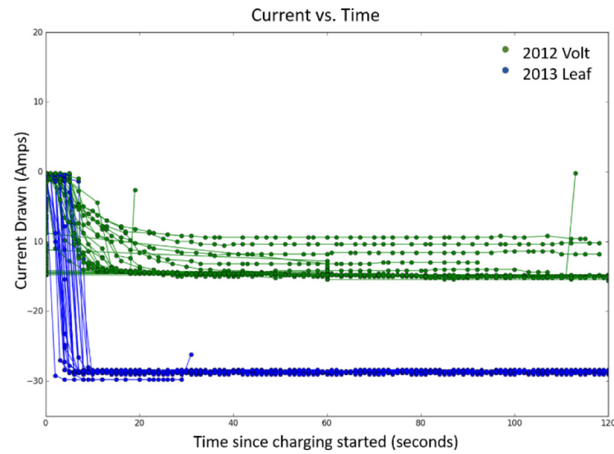

Figure 7. Current profile of Volt and Leaf

Based on the results from the second stage of testing, the parameters for the third stage of testing were set, and the firmware updates required to obtain these parameters were finalized.

In the third stage of data collection, two charging stations were used to gather information from four EVs: a 2011 Chevrolet Volt, a 2013 Nissan Leaf, a 2012 Mitsubishi i-Miev, and a 2015 Ford C-Max. As in stage two of testing, the vehicles were repeatedly plugged and unplugged at two minute intervals to generate data. The tests yielded data from 85 charging events (any time the EV being observed transitioned from not drawing current to drawing any nonzero current). The EVs and EVSEs tested are summarized in Figure 8.

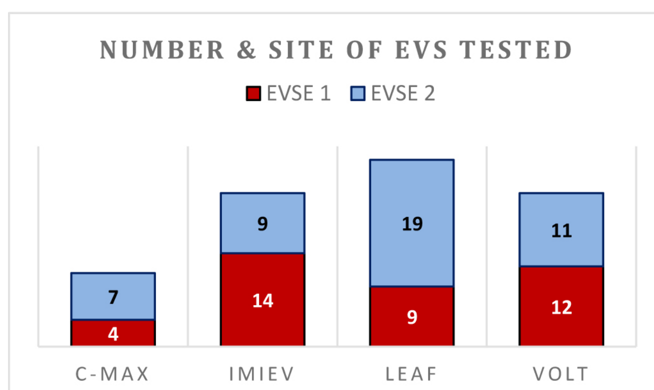

Figure 8. Summary of the EVSEs and EVs providing data

Analysis

For each day of data collection, the EVSE report dozens of logs, in different formats. These logs were downloaded, and those of the same format were combined. Logs of different types had to be synced manually, so that the pilot voltage and state change timing information from a charging event could be associated with the parameters describing the current profile for each test. These files were processed to extract the fingerprinting parameters. Pilot line voltages were obtained using the algorithm illustrated in Figure 9 for states B1 and B2. The same process was used for the pilot in state C.

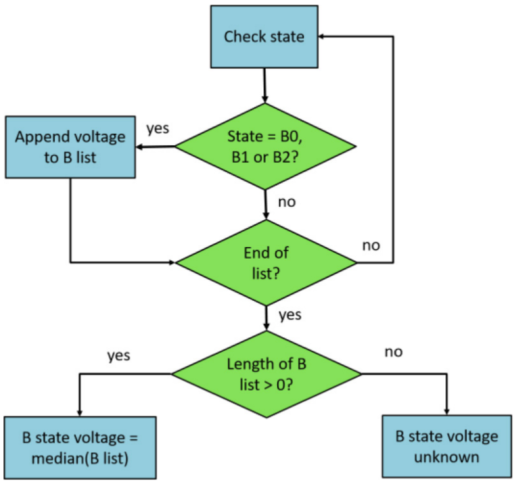

Figure 9. Algorithm for finding pilot line voltage in state B.

The final current was found by locating all points where the current was steady (deviated by less than 2 amps for at least three consecutive samples), recording the current value at those points, then taking the median of the recorded values. The rise time is the time between the first sample in a charge event when the current was nonzero, and the first sample to reach 90% of the final current. Figure 10 illustrates how this method worked. In the figure, the rise time and final current found are plotted on top of the current profile of one of the vehicles tested for one charge event.

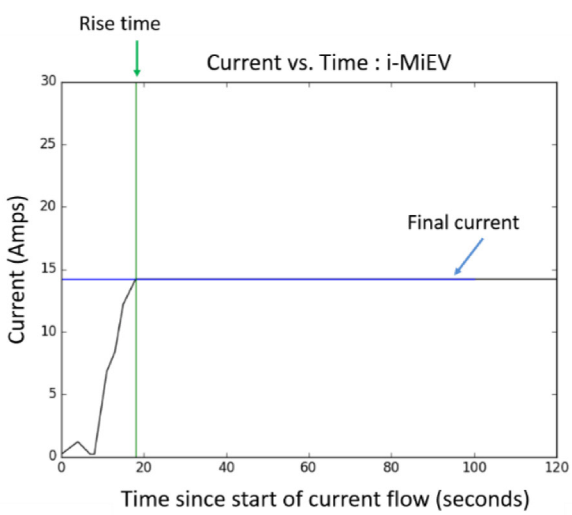

Figure 10. Extracting characteristics of current profile for an EV

The parameters needed were extracted and stored in a single csv file, which was imported to Weka data mining software for classification. The classifiers used performed well, correctly classifying 98 - 100% of the samples depending on the classifier used. Naïve Bayes performed the best, correctly classifying 100% of the instances. A J48 decision tree correctly classified 98.8% of the instances. A diagram of the tree built by the J48 classifier is illustrated in Figure 11 and the confusion matrix is shown in Figure 12.

Discussion

The results of the tests suggest that identifying the type of EV connected to an EVSE using only variation in standard voltage levels, and parameters regarding the current drawn may be possible. For the four vehicles tested, this was a fairly reliable set of measurements. Future research will test multiple instances of each type, to confirm that the variations seen are unique to EV types, and not to the specific EVs tested. The results of the tests suggest that additional parameters may be of interest. One of the vehicles from which data was collected exhibited a sharp, short-lived drop in the current drawn after the EV had been charging for some time. Since the data collection focused on the first two minutes of charging, this behavior was observed only a few times, but it merits further investigation.

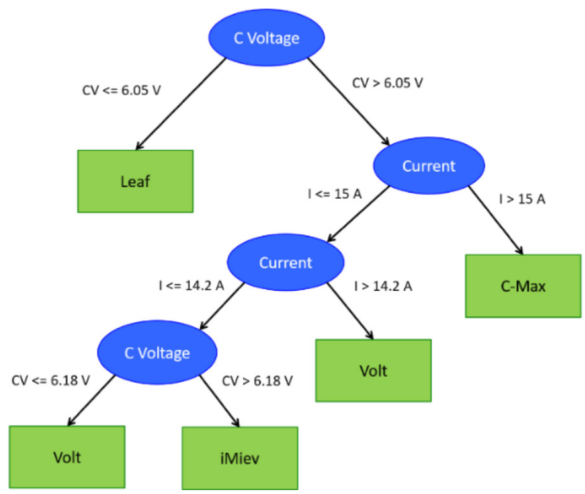

Figure 11. Decision tree built by J48 classifier based on fingerprinting data

Confusion Matrix

Leaf	Volt	i-MiEV	C-Max	← Classified as
28	0	0	0	**Leaf**
0	22	0	1	**Volt**
0	0	23	0	**i-MiEV**
0	0	0	11	**C-Max**

Figure 12. Confusion matrix associated with results from J48 classifier

Another important element to note is that to this point, the data collection and analysis has not focused on determining if and how much state of charge of the EV or the ambient temperature effect the parameters of interest. The EV and battery age and usage are also factors that may impact the fingerprinting parameters, and must be considered. Further testing of the same vehicles under different conditions, and of other vehicles of the same type, as well as of yet untested types are all areas of future work.

Conclusion

Parties managing EV charging would find it valuable to have information regarding the EVs requesting charge, for all the reasons noted in the introduction. Much of this information would become apparent if an EVSE could identify the type of EV plugged in. The authors of this paper suggest that the EVSE can identify, or fingerprint, an EV, using only the parameters measurable on the EVSE and available as variants in implementation of a commonly used charging standard.

To test this hypothesis, various EVs implementing the J1772 protocol were used to collect data regarding charging characteristics of different EV types. Analysis of those data identified parameters that effectively can identify the EV type. The resulting data was used as input to classifier models. The results were promising, as the classifiers correctly identified the vehicle for 98-100% of the 85 charging event instances used.

Further testing is needed to determine if the results seen can be generalized to a larger number of types of EVs, and to other EVs of the same type. Additionally, more information is needed on how additional factors such as ambient temperature, EV state of charge, and age of the vehicle or battery, affect the parameters used to fingerprint the EVs. These are areas to be explored with further research.

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Definitions

EV - Electric vehicle. As per the definition in [1] an electric vehicle is an automobile that relies on an electric motor and is designed to be used on a highway. In this paper, the term EV is used to denote both fully electric vehicles and plug-in hybrids.

EVSE - Electric vehicle supply equipment. This term includes all connectors, conductors and other hardware whose intended use is providing energy to an electric vehicle [1].

V2G - Vehicle to grid (V2G) refers specifically to technology and services involving bidirectional power flow. V2G makes potential services to the grid more valuable.

The Engineering Meetings Board has approved this paper for publication. It has successfully completed SAE's peer review process under the supervision of the session organizer. The process requires a minimum of three (3) reviews by industry experts.

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