Plug-In Electric Vehicle Charging Response Characterization for Grid Integration

Implications for Smart Charge Management

CHARGEX
consortium

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ANL-25/26

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All vehicles used for testing in this study were either vehicles from an existing research fleet or were kindly volunteered by employees at Argonne National Laboratory. All vehicles were tested as provided, without prior assessment of the health of the vehicle's mechanical, electrical, battery, or software systems. The goal of this examination was simply to assess how production vehicles would respond to the fundamental actions that an EVSE can use to control an AC-level charge session. If an aggregator or system operator were to utilize PEV charge sessions to provide grid services, they would do so on production vehicles, such as the ones evaluated in these tests. These results are not intended to criticize or commend any vehicle manufacturer for the performance of their electric vehicles, nor should they be considered indicative of the performance of an entire vehicle make. This study simply intends to build a foundation for future research into advanced EV charging applications, such as smart charge management and seamless grid integration.

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Executive Summary

The rapid expansion of plug-in electric vehicles (PEVs) has created a unique challenge for electrical grids due to their significant power demand. At the same time, PEVs also create a unique opportunity to ease their own burden on the power grid, as they create a growing fleet of distributed energy resources capable of providing grid services such as demand response, frequency regulation, and renewable balancing. For aggregators and grid operators to effectively integrate PEVs into grid management, it is essential to first understand and characterize how they would respond in such situations.

This study examines 25 models of PEVs across 25 makes, spanning model years from 2013 to 2025, to characterize their responses to the basic controls used in vehicle-grid integration (VGI): stopping, starting, and modulating the charge rate. Each vehicle was tested in a controlled laboratory setting to evaluate its performance in response to varying the maximum allowable current via the SAE J1772 control pilot signal, as well as its response to wake-up commands outlined in SAE J1772. Results show measurable differences across vehicle makes in the accuracy, latency, and precision with which PEVs respond to changes in ampacity, as well as varying sleep and wake-up behavior.

The test results show that all vehicles respond to changes in ampacity, though with varying accuracy, precision, latency, and resolution. Wake-up behavior also differs across makes and models. These findings indicate that effective grid integration strategies must account for these differences. The results provide a foundation for understanding current vehicle behavior and advancing smart-charging methods while also highlighting the need for further testing, broader standardization, and manufacturer collaboration to ensure the successful integration of PEVs into the electrical grid.

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List of Abbreviations

Abbreviation	Description
AC	Alternating Current
ANL	Argonne National Laboratory
DER	Distributed Energy Resource
EV	Electric Vehicle
EVSE	Electric Vehicle Supply Equipment
INL	Idaho National Laboratory
MAE	Mean Absolute Error
MAPE	Mean Absolute Percentage Error
NREL	National Renewable Energy Laboratory
PEV	Plug-in Electric Vehicle
PWM	Pulse-Width Modulation
RTO	Reginal Transmission Operator
SCM	Smart Charge Management
SOC	State of Charge (pertaining to a vehicle’s battery level)
VGI	Vehicle Grid Integration
VPP	Virtual Power Plant

1. Introduction

This report examines how plug-in electric vehicles (PEVs) respond to changes in the SAE J1772 control pilot signal during Level 2 alternating current (AC) charging. Electric Vehicle Supply Equipment (EVSE) are limited to four fundamental actions for controlling a charge session: they may start or stop a charge session, and they may increase or decrease the amount of current available to a vehicle. An EVSE may perform these four actions only by manipulating the control pilot signal, defined in the SAE J1772 standard as a ±12V pulse-width modulated (PWM) square wave across a dedicated pin on the charging coupler, with the duty cycle of this signal controlling the maximum allowable ampacity. The ampacity refers to the maximum current that can safely flow through the charging hardware and wiring to ensure safe charging. This should be viewed as a limit rather than a setpoint, as a PEV is not required to pull the maximum available amperage, but a vehicle may not attempt to pull additional current.

To characterize vehicle behavior, four tests were conducted to evaluate the performance of 25 different makes of PEVs in response to varying current limits across four key areas: accuracy, precision, resolution, and latency. SAE J1772 also specifies a method of waking an electric vehicle (EV) from a sleeping state during AC PWM charging by changing from Pilot State B1 to State B2, but it is unclear how consistently manufacturers have implemented this procedure. Accordingly, an additional set of tests assessed each vehicle’s wake-up response.

This report summarizes the results of testing 25 PEV makes, covering model years 2013 through 2025. A separate report was created for each vehicle tested, giving a full account of results and analysis. Taken together, these findings show how current vehicles respond to AC charging control and provide a foundation of knowledge needed to design reliable smart-charging methods that support effective grid integration.

2. Methodology

2.1 Test Environment

To minimize the influence of external factors on vehicle charging behavior, all testing was performed in a standardized laboratory environment. Each test was performed with an ambient temperature between 68°F and 77°F and a PEV battery temperature between 50°F and 86°F. Each PEV began the testing with an initial State of Charge (SOC) below 50%. Whenever possible, vehicles under test were kept below 80% battery for the full duration of testing. In all cases, the vehicle’s current draw was monitored during testing to ensure that it did not curtail its own charge rate due to the battery nearing the end of its charge.

Vehicles were sourced either from employee volunteers at Argonne National Laboratory (ANL) or from existing research fleet vehicles. No vehicle was modified for testing.

2.2 Test Equipment

A programmable Level 2 EVSE (designed and developed at ANL) which is capable of precisely varying PWM duty cycles was used to control EV charging and perform all tests. This EVSE was equipped with a high-accuracy, calibrated meter to measure the actual current drawn by the PEV. Custom Python scripts were developed for each test. These scripts automated each test and logged the required data.

2.3 Data Collection

Data for the PWM response assessment tests were sampled at a rate of 10 samples/sec or 10 Hz. Each sampling consisted of an epoch timestamp, the control pilot PWM limit as commanded by the EVSE, the measured duty cycle, measured current, measured voltage, the active power, reactive power, apparent power, power factor, AC supply frequency, and energy. This dataset enabled the calculation of accuracy, precision, latency, and resolution metrics.

Data for the pilot wake assessment tests consisted of the time required for the PEV to fall asleep, measured in seconds, and a binary success or failure based on whether the PEV awoke and began charging after a given transition. A PEV was considered asleep the moment that the voltage across the proximity pin fell to 0 V. A transition was considered successful if the vehicle reached control Pilot State C2 (charging) with no additional input beyond the Pilot State transition.

2.4 PWM Response Assessment Test Procedures

For each PWM response assessment test, the appropriate Python program was started on the programmable EVSE, and the EVSE's cable was plugged into the PEV's charging port. Upon the vehicle reaching control Pilot State C2, the EVSE set its duty cycle to 83.3% (50 A available current) for a period of two minutes and recorded the highest stable current that the vehicle drew. This maximum current draw was used to ensure that each experiment was tailored to evaluate the complete charging capabilities of each vehicle at the time of the test. After this two-minute period finished, the PWM duty cycle (current limit) was then set to the first limit of the experiment and the vehicle was allowed to stabilize at that limit before the test began. A formal test plan was drafted for these procedures; the key steps are summarized below. There were 4 PWM Response Assessment tests.

1. Accuracy and Precision Test – The EVSE varied the maximum allowable ampacity from 6 A to the given vehicle's maximum charge capability in 1 A increments, both ascending and descending, pausing for 5 seconds after each increment. This sequence was repeated three times. The measured current was then compared against the maximum allowable ampacity to calculate error, mean bias, and variability across repetitions.
2. Latency Test – The EVSE varied the maximum allowable ampacity from 6 A to the given vehicle's maximum charge capability in 7 evenly spaced steps before introducing varying size steps, including 6 A to and from the PEV's maximum current capability. Latency was determined as the difference between when a

PWM change was initiated by the EVSE and when the measured current drawn by the PEV stabilized to a value within the mean absolute percentage error, as calculated for each vehicle during the accuracy and precision test.

3. Resolution Test – The EVSE incrementally adjusted the maximum allowable ampacity from 6 A to the vehicle's maximum current capacity and back in steps of approximately 25 mA. The smallest duty cycle change that produced a measurable current response defined the PEV's resolution.
4. V1G Frequency Regulation – Each PEV was subjected to a 40-minute test to assess the ability of the PEV to follow the standardized PJM RegD frequency regulation signal. The normalized RegD test waveform was scaled to each vehicle's maximum charge current and inverted to account for demand-side operation. Performance scores were then calculated using the PJM evaluation template after normalizing and downsampling the PEV current response.

2.5 Pilot Wake Assessment Test Procedures

For each PWM response assessment test, the appropriate Python program was started on the programmable EVSE, and the EVSE's cable was plugged into the PEV's charging port. Upon the vehicle reaching control Pilot State C2, the EVSE began the automated testing procedure.

A PEV was deemed "asleep" once the voltage across the proximity pin fell to 0 V. A formal test plan was drafted for these procedures; the key steps are summarized below.

1. Demand-Response Event – After charging in Pilot State C2 (50% duty cycle) for two minutes, the EVSE transitions to Pilot State C1 (100% duty cycle). In response, the PEV transitions to Pilot State B1. The EVSE waits for the vehicle to fall asleep before initiating a transition from State B1 → B2 to wake the vehicle and resume the charging session.

2. Power Outage Event – After charging in Pilot State C2 (50% duty cycle) for two minutes, the EVSE transitions to State E (0 V, 0% duty cycle). After the vehicle falls asleep, the EVSE transitions from State E → B2 to wake the vehicle and resume the charging session.

3. EVSE Failure Event – After charging in Pilot State C2 (50% duty cycle) for two minutes, the EVSE transitions to State F (-12 V, 100% duty cycle). After the vehicle falls asleep, a transition from Pilot State F → B2 is performed to wake the vehicle and resume the charging session.

4. Sleeping Vehicle Test – A vehicle that has fallen asleep is plugged into an operational EVSE to attempt charging without any external stimuli (i.e., opening a door, unlocking via key fob, etc.).

5. Delayed Charge Test – A vehicle is plugged into an EVSE and remains in State B1 until it has fallen asleep. After an additional 10 minutes, a pilot transition from State B1 → State B2 occurs to wake the vehicle and begin a charging session.

3. Results

3.1 PWM Response Assessment Results

3.1.1 Accuracy and Precision Test

The accuracy and precision test was designed to measure how accurately a PEV responds to 1 A steps in ampacity by changing the control pilot PWM duty cycle and assessing the consistency of the PEV's current response across multiple runs. The actual charge current at each step was compared to the maximum allowable ampacity based on the control pilot duty cycle. Accuracy was calculated as the Mean Absolute Error (MAE) and the Mean Absolute Percentage Error (MAPE) between the measured and limit values (Equation 1 and Equation 2). Precision is defined as the standard deviation of the errors (Equation 3). Mean Bias, calculated using Equation 4, measured the average deviation between the actual current draw and the current limit, accounting for the direction of the error, with sign preserved to indicate whether vehicles drew less or more current than the allowed limit.

$$Mean\ Absolute\ Error = \frac{1}{N}\sum_{i=1}^{N} |Measured_i - Limit_i|$$

Equation 1: Mean Absolute Error (MAE)

$$Mean\ Absolute\ Percentage\ Error = \frac{1}{N}\sum_{i=1}^{N} \left|\frac{(Measured_i - Limit_i)}{Limit_i}\right| * 100$$

Equation 2: Mean Absolute Percentage Error (MAPE)

$$Precision = \sqrt{\frac{1}{N}\sum_{i=1}^{N} (Measured_i - Limit_i - \overline{Accuracy})^2}$$

Equation 3: Precision

$$Mean\ Bias = \frac{1}{N}\sum_{i=1}^{N} (Measured_i - Setpoint_i)$$

Equation 4: Mean Bias

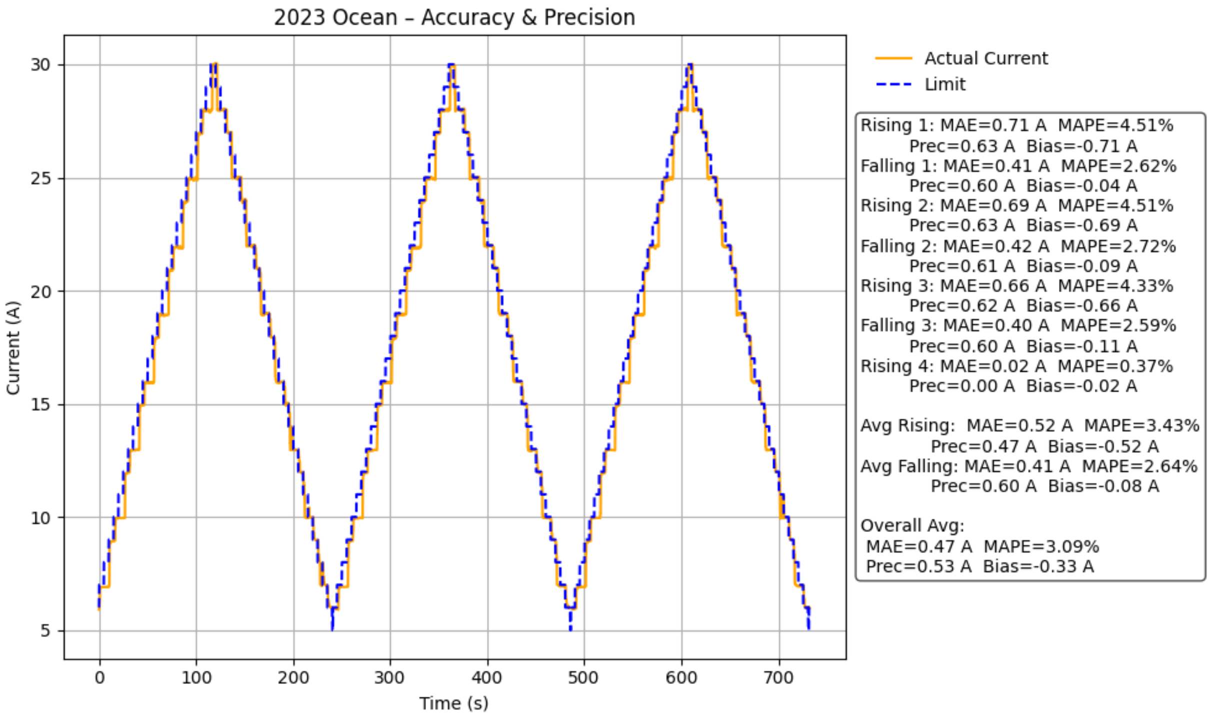


Figure 1: 2023 Fisker Ocean Accuracy and Precision Test Results

Figure 1 is an example results plot from the accuracy and precision test of a 2023 Fisker Ocean. The accuracy and precision results are reported separately for rising, falling, and overall conditions. The rising metrics refer to the MAE, MAPE, precision, and bias that was observed when the current limit was increasing; falling metrics represent decreasing current limits; and the overall metrics combine both.

In general, vehicles responded to falling current limits with greater accuracy and precision and less bias than they did to rising current limits. Only two of the vehicles tested during this study responded to an increase in the maximum ampacity with greater accuracy and precision than to a decrease in maximum ampacity. However, the difference in rising versus falling responses was often small. Of the 25 vehicles tested, 12 of them had an average rising MAPE within 1% of their falling MAPE, and only two vehicles had an MAPE that differed by more than 5%.

Most vehicles were found to have a negative bias, meaning they pull less current than the EVSE current limit. Only four vehicles displayed a positive bias (0.02 A, 0.04 A, 0.46 A, and 0.54 A), indicating that they drew more current than the EVSE's current limit. This could be due to errors in sampling the control pilot duty cycle by the PEV. This is significant because it could be deemed a safety issue.

Box-and-whisker plots visualizing the distribution of MAE, MAPE, precision, and bias across all vehicles are shown in Figure 2 through Figure 5. On average, the PEVs tested tracked the EVSE limit with a mean absolute error of 0.63A, corresponding to an average deviation of 3.99%. This means that, on average, the measured EV charge current is within 96.01% of the maximum ampacity of the EVSE. On average, the PEVs track the EVSE current limit with a precision of 0.53 A and exhibit an average overall bias of -0.44 A. Individual PEV results are presented in Appendix A.

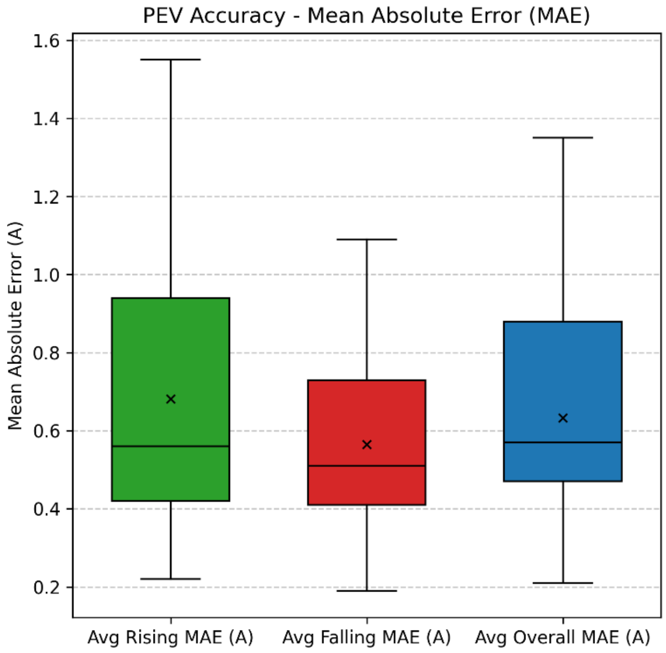


Figure 2: Distribution of Average Mean Absolute Errors (MAE)

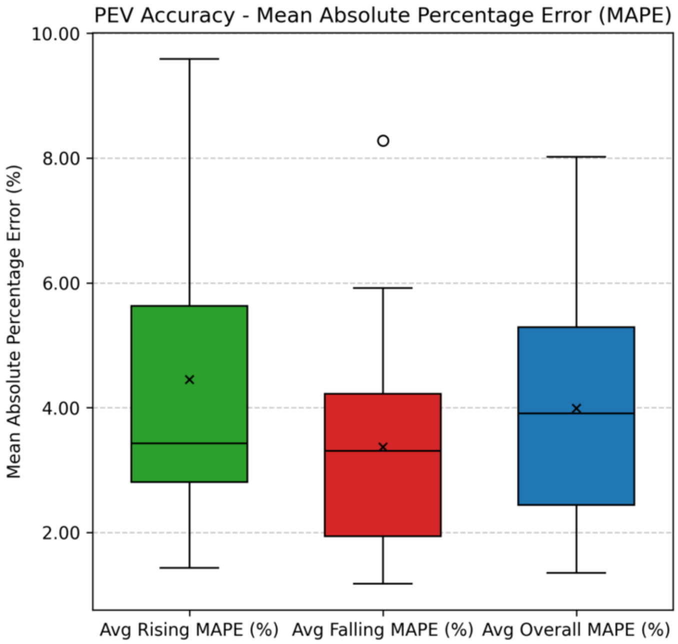


Figure 3: Distribution of Average Mean Absolute Percentage Errors (MAPE)

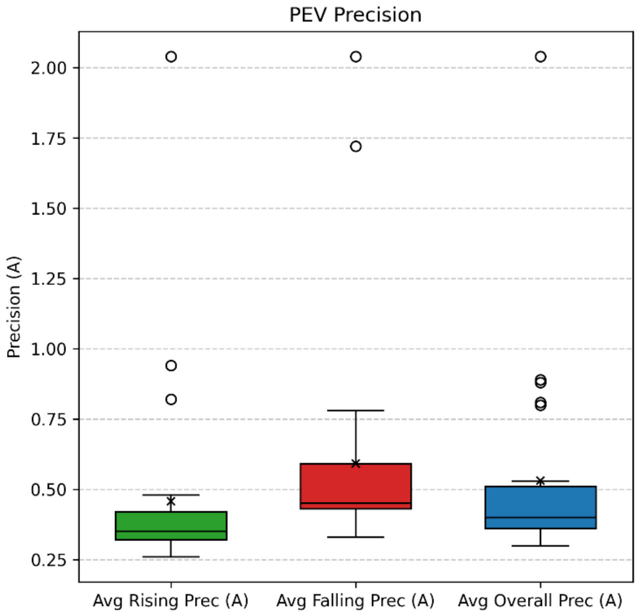


Figure 4: Distribution of Average Precisions

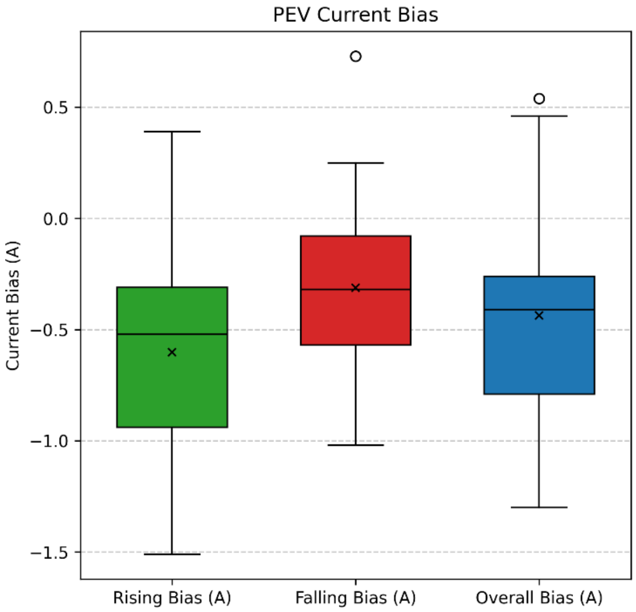
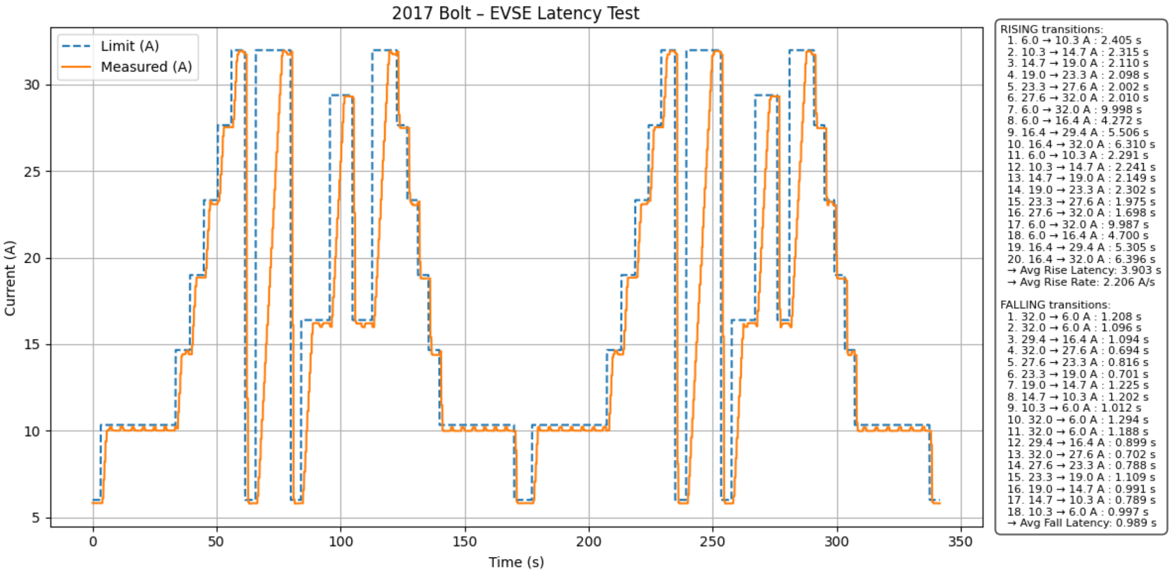


Figure 5: Distribution of Average Biases

3.1.2 Latency Test

The latency test is designed to quantify how quickly the PEV adjusts its charging current in response to sudden changes in current limit. The PEV's response time could dictate what SCM strategies it would be able to perform in the future. Figure 6 shows the plotted results of the latency assessment test run on a 2017 Chevrolet Bolt. The latency was determined by measuring the time difference between when the EVSE initiated a current limit change and when the measured current reached its new settling point, which was defined as ±5% of the maximum allowable ampacity.



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RISING transitions:
  1. 6.0 → 10.3 A : 2.405 s
  2. 10.3 → 14.7 A : 2.315 s
  3. 14.7 → 19.0 A : 2.110 s
  4. 19.0 → 23.3 A : 2.098 s
  5. 23.3 → 27.6 A : 2.002 s
  6. 27.6 → 32.0 A : 2.010 s
  7. 6.0 → 32.0 A : 9.998 s
  8. 6.0 → 16.4 A : 4.272 s
  9. 16.4 → 29.4 A : 5.506 s
  10. 16.4 → 32.0 A : 6.310 s
  11. 6.0 → 10.3 A : 2.291 s
  12. 10.3 → 14.7 A : 2.241 s
  13. 14.7 → 19.0 A : 2.149 s
  14. 19.0 → 23.3 A : 2.302 s
  15. 23.3 → 27.6 A : 1.975 s
  16. 27.6 → 32.0 A : 1.698 s
  17. 6.0 → 32.0 A : 9.987 s
  18. 6.0 → 16.4 A : 4.700 s
  19. 16.4 → 29.4 A : 5.305 s
  20. 16.4 → 32.0 A : 6.396 s
  → Avg Rise Latency: 3.903 s
  → Avg Rise Rate: 2.206 A/s

FALLING transitions:
  1. 32.0 → 6.0 A : 1.208 s
  2. 32.0 → 6.0 A : 1.096 s
  3. 29.4 → 16.4 A : 1.094 s
  4. 32.0 → 27.6 A : 0.694 s
  5. 27.6 → 23.3 A : 0.816 s
  6. 23.3 → 19.0 A : 0.701 s
  7. 19.0 → 14.7 A : 1.225 s
  8. 14.7 → 10.3 A : 1.202 s
  9. 10.3 → 6.0 A : 1.012 s
  10. 32.0 → 6.0 A : 1.294 s
  11. 32.0 → 6.0 A : 1.188 s
  12. 29.4 → 16.4 A : 0.899 s
  13. 32.0 → 27.6 A : 0.702 s
  14. 27.6 → 23.3 A : 0.788 s
  15. 23.3 → 19.0 A : 1.109 s
  16. 19.0 → 14.7 A : 0.991 s
  17. 14.7 → 10.3 A : 0.789 s
  18. 10.3 → 6.0 A : 0.997 s
  → Avg Fall Latency: 0.989 s
```

Figure 6: Latency Test Assessment Results of a 2017 Chevrolet Bolt

The latency of each PEV varied significantly across vehicles as shown in Figure 7 and Figure 8. Vehicles responded more quickly to increases in the current limit when operating at a higher amperage. For example, the 2017 Chevrolet Bolt responded to a rising step from 6 A to 10.3 A in 2.4 seconds, whereas it responded to a rising step from 27.6 A to 32 A in only 2.0 seconds. A similar pattern was repeated with every vehicle tested. Vehicles responded to increasing steps in an approximately linear fashion, after accounting for the differing response rate at different current levels and the initial time required for a vehicle to recognize and react to a change in limit. EVs responded to falling steps in the current limit in a similar timeframe regardless of the size of the step or the starting or ending amperage. Whereas the Chevrolet Bolt responded to a rising transition from 6 A to 32 A in 9.99 seconds over multiple attempts, the latency for a falling transition from 32 A to 6A varied from 1.09 to 1.29 seconds. Similarly, the EV's reaction for a small falling step took longer in some instances than for large jumps. These patterns were repeated across all tested vehicles.

SAE J1772 defines a PEV response time of 5 seconds in response to a change in the current limit. Overall, the average latency to a rising current limit was 4.09 seconds with an average rise rate of 5.07 A/s. The rising latency included several outliers, with some vehicles taking 10–14 seconds to respond. The average latency to a falling current was 1.54 seconds. Individual PEV results are presented in Appendix A.

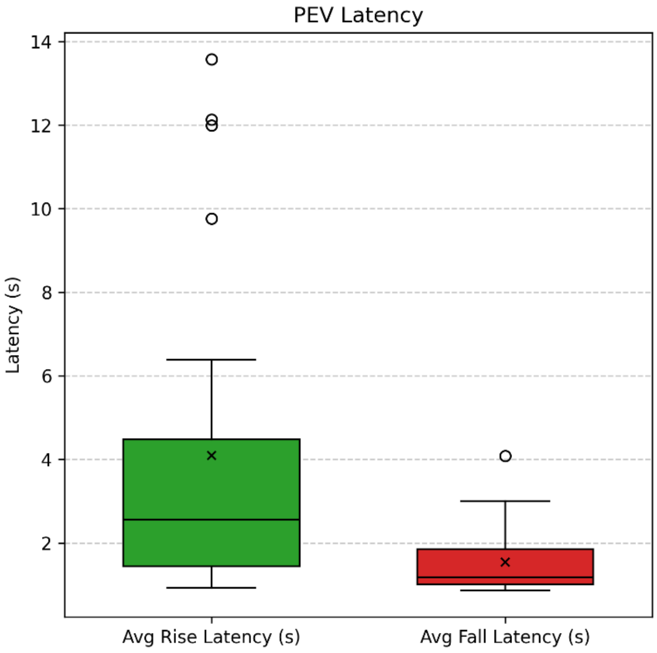

Figure 7: Distribution of Average Latency Times Across the Latency Response Assessment Test

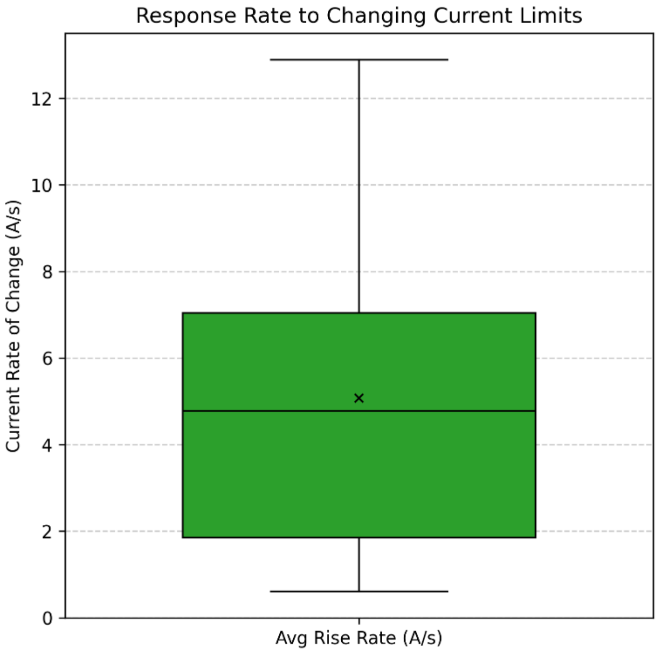

Figure 8: Distribution of the Average Rate of Response for Vehicles in Response to an Increasing PWM Duty Cycle

3.1.3 Resolution Test

The resolution test was designed to quantify the smallest change in the EVSE current limit to reliably produce a measurable response in the PEV's charging current. Figure 9 shows the plotted results of the resolution assessment test run on a 2024 Tesla Cybertruck. From the plot, you can see distinctive steps in the PEV's response; the magnitude of these steps is the PEV's resolution.

Vehicles displayed a wide range of resolutions, with some PEVs reacting to current limit changes as small as 0.13 A, while others did not respond until the current limit was altered by more than 1 A. It was noted that most PEVs had different resolutions based on whether the current limit was rising or falling. For most PEVs, the difference between the falling and rising resolutions was less than 100 mA, although for some, the difference was greater than 0.5 A. Even some PEVs had different resolutions depending on the current range.

Figure 10 illustrates the distribution of rising and falling resolutions, as well as the overall resolution. On average, the rising resolution of each PEV was 0.49 A and the falling resolution was 0.53 A, with an overall average resolution of 0.45 A. Individual

PEV results are presented in Appendix A.

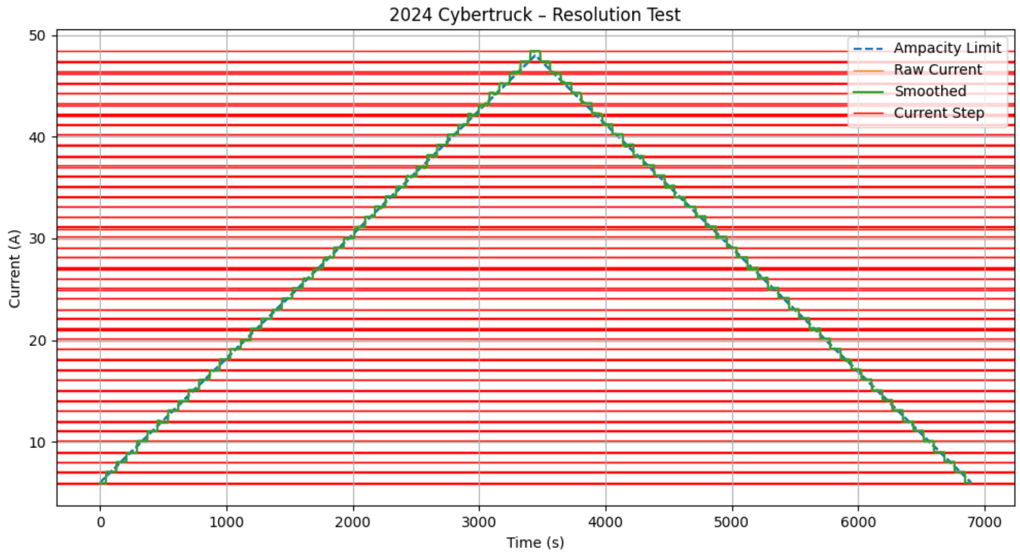

Figure 9: Resolution Test Results for a 2024 Tesla Cybertruck

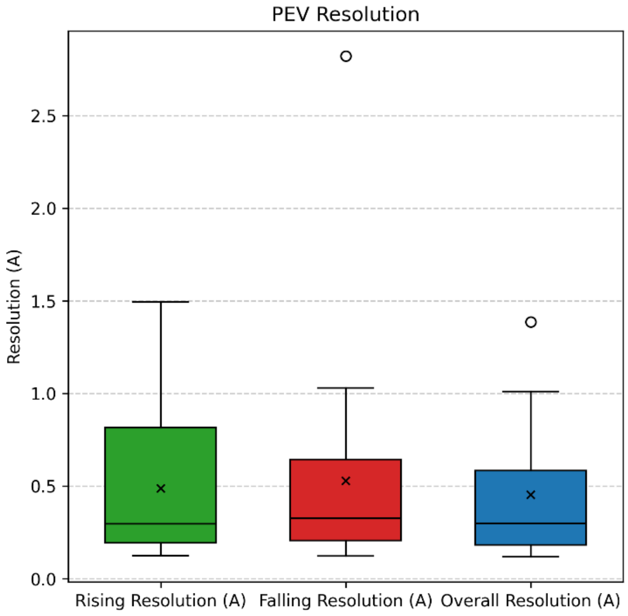

Figure 10: Distribution of PEV Resolutions

3.1.4 V1G Frequency Regulation Test

PJM, a Regional Transmission Operator (RTO), operates a wholesale electricity market for the US Eastern Interconnection grid. One of the ancillary service markets that PJM oversees is the frequency regulation market. The goal of this service is to maintain the grid frequency at the nominal 60 Hz by balancing supply and demand in real-time. PEVs can be aggregated into Virtual Power Plants (VPP) that act as a distributed energy resource (DER). When controlled intelligently, these aggregated PEVs can provide fast, accurate responses to PJM’s regulation signals, creating new value streams for both grid operators and EV owners. This section presents results from testing V1G-based frequency regulation, where unidirectional charging power was adjusted in response to PJM’s RegD signal.

A PJM frequency regulation resource is provided revenue based on the resource’s performance score. Before October 1, 2025, this performance score was equally weighted between accuracy (correlation), delay, and precision. Accuracy measures how well the resource’s power output matches the regulation signal, delay captures the response time to changes in the signal, and precision reflects the consistency of output without excess noise or oscillation. After October 1, 2025, PJM moved to a precision-only-based performance score.

The V1G Frequency Regulation test utilized the PJM RegD test signal, which was inverted for demand-side regulation (loads) and scaled to each individual PEV. An example results plot is shown in Figure 11 of a 2023 Genesis GV60. The test runs for 40 minutes in which a new limit is set every 2 seconds. The RegD precision and composite scores were determined using the PJM 40-minute performance score template Excel workbook (PJM Interconnection)[3].

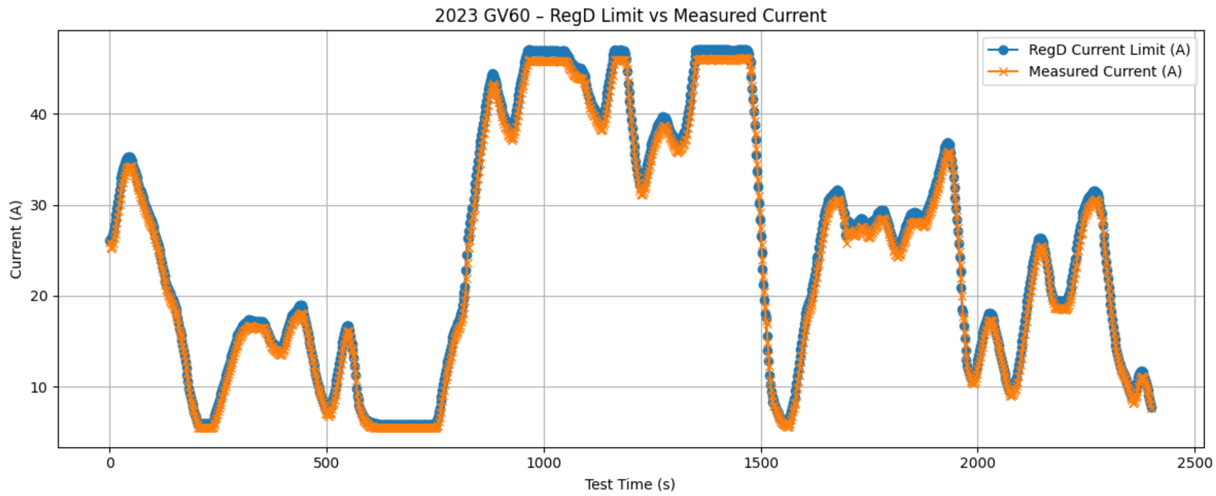

Figure 11: RegD Test Results for a 2023 Genesis GV60

The *precision score only* metric reflects the ability of the PEV to closely follow the RegD signal on a second-to-second basis, while the *composite score* incorporates precision,

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[3] https://www.pjm.com/-/media/DotCom/markets-ops/ancillary/40-minute-performance-score-template-reg-redesign.xlsm

accuracy, and delay but will not be used in the PJM regulation market moving forward. Across the vehicles tested, the individual PEV RegD precision only scores ranged from 0.7835 to 0.9192, with a median score of 0.8993. Figure 12 shows the distribution of these scores. Individual PEV results are presented in Appendix A.

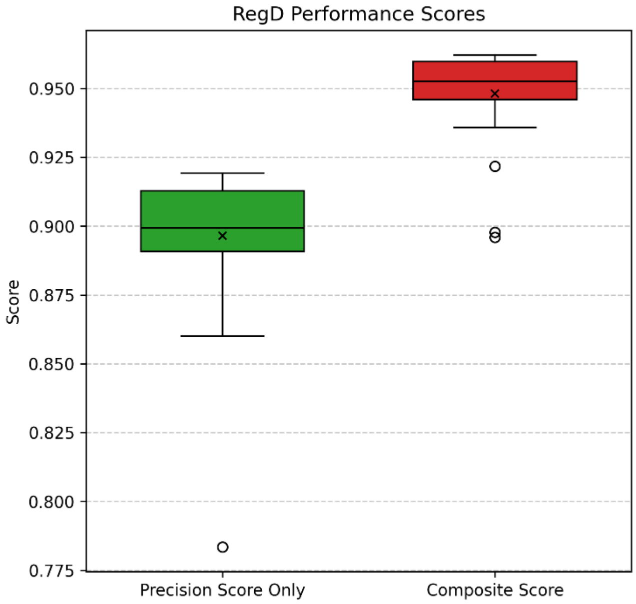

Figure 12: Distribution of the RegD Composite Score and the Precision Score Only

The precision score was the largest predictor of the composite score, as accuracy and delay scores were nearly perfect for every vehicle tested. The Accuracy and Precision test provided useful insights into step-response tracking but did not directly predict PJM RegD performance, since PJM's precision and composite scores reflect continuous signal following. Vehicles with coarse resolution or systematic bias could appear accurate in controlled tests yet perform poorly under RegD. Because accuracy and delay were nearly perfect for most vehicles, precision driven by resolution and bias was the dominant factor influencing composite scores. The data suggests the lowest performers suffered from coarse resolution, long latency, or high error/bias, while the best performers combined low error (<2% MAPE), fast latency (<2s), and fine resolution (<0.2A). Importantly, while not all PEVs would be equally effective as RegD participants, all vehicles tested exceeded PJM's minimum requirement of a 75% composite score.

3.2 Pilot Wake Response Results

3.2.1 Control Pilot Transition Test Results

SAE J1772 describes a method for waking a sleeping vehicle via the EVSE by simply transitioning from Pilot State B1 to State B2. The pilot wake tests were conducted to evaluate whether PEV manufacturers have implemented this wake procedure and to determine if EVs could be awoken with similar transitions. Five different conditions were tested; three tests evaluated whether a charging session can be resumed after a prolonged interruption causes the PEV to fall asleep, and two others tested whether a vehicle could begin a charge session without any external stimuli besides the Pilot State change. A vehicle was defined as being asleep, or in a sleeping state, when the voltage across the SAE J1772 proximity pin read 0V. After a vehicle fell asleep, a 15-second delay was observed before the EVSE initiated a Pilot State transition to wake the vehicle and resume charging; except for the delayed charge test, which observed a 10-minute delay before attempting to charge the vehicle. It was not tested whether a longer delay would impact a vehicle's wake behavior. A successful outcome is defined as a vehicle beginning or resuming a charge session (indicated by Pilot State C2 and the successful flow of measurable current) in response to the tested Pilot State transition, without any additional inputs or stimuli. These tests were performed on 24 of the 25 vehicles included in this study, as one vehicle never reached a sleeping state during the time that the vehicle was in possession of the researchers.

The vast majority of EV manufacturers appear to have implemented the wakeup procedure as noted in the SAE J1772 standard; only two vehicles tested did not resume a charge session on the standard B1 to B2 Pilot State transition. Of these two vehicles, only one also failed to begin a delayed charge session on the B1 to B2 transition. Whether other vehicles from these manufacturers would awaken on this transition is currently unknown.

Only one vehicle failed to resume a charging session that was interrupted by a simulated EVSE fault (Pilot State F). After failing to wake on a simple F to B2 transition, other similar transitions were attempted, and it was discovered that the vehicle would resume a charge session upon a series of Pilot State transitions from F to B1 to E to B2. Because every vehicle tested awoke and resumed charging on a Pilot State transition of E to B2, this indicates a possible workaround for EVSE operators to resume a charge session on a vehicle that would otherwise not resume charging from Pilot State B1 or Pilot State F. Further research is needed to assess the reliability of this method and to determine if similar workarounds exist.

Although one vehicle failed to initiate a charging session from a sleeping A1 Pilot State, it is worth noting that the particular vehicle in question has a quirk where any door on the vehicle must be opened shortly before plugging in the J1772 connector to begin charging, regardless of the context. The same vehicle failed to begin charging during the Delayed Charging Test, likely for the same reason. Ergo, this outcome may be the result of a particularly stubborn vehicle rather than a representative of the entire line of EVs from this manufacturer. Researchers were unable to acquire a second vehicle of this make to confirm this behavior.

Every vehicle tested awoke and resumed charging on a Pilot State transition from E to B2. Therefore, State E may be useful in EV charge management for vehicles that will not resume charging from Pilot State B1. It may also be useful for resuming a charge session after an EVSE fault, as a vehicle that would normally not resume charging from Pilot State F may resume charging if it first transitions to State E.

Researchers observed that some PEVs required the charging cord to be unplugged and re-plugged between each pilot wake test for the vehicle to successfully resume charging, whereas others could repeatedly cycle between asleep and charging without incident. Therefore, the documented successes guarantee that a vehicle can be woken from a sleeping state at least once, but it was not tested how many times a vehicle could resume charging from a sleeping state without needing to be unplugged, if ever. Further studies should examine the reliability of PEV wake behavior in settings where a vehicle may need to cycle between sleeping and charging multiple times without being unplugged.

Some vehicles had electronic systems that would automatically attempt to close the charging port upon falling asleep. While this did not cause any apparent damage to the vehicle or charging cord during these tests, repeated exposure may cause undue wear on both the PEV's automated charging port closing system and the EVSE cable.

Figure 13 through Figure 17 summarize the results of the pilot wake testing. The complete pilot wake testing results can be found in Appendix B.

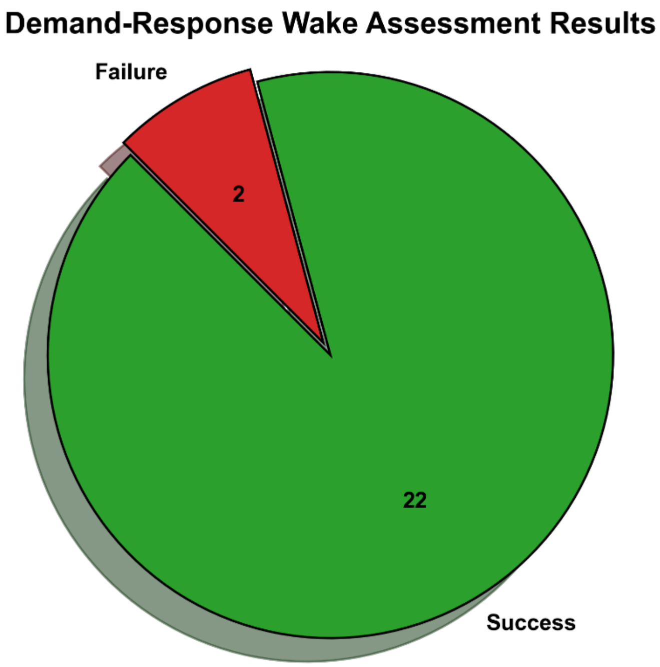

Figure 13: Demand-Response Wake Test Results

Which examined whether a PEV would resume an interrupted charge session on a Pilot State B1 to B2 transition.

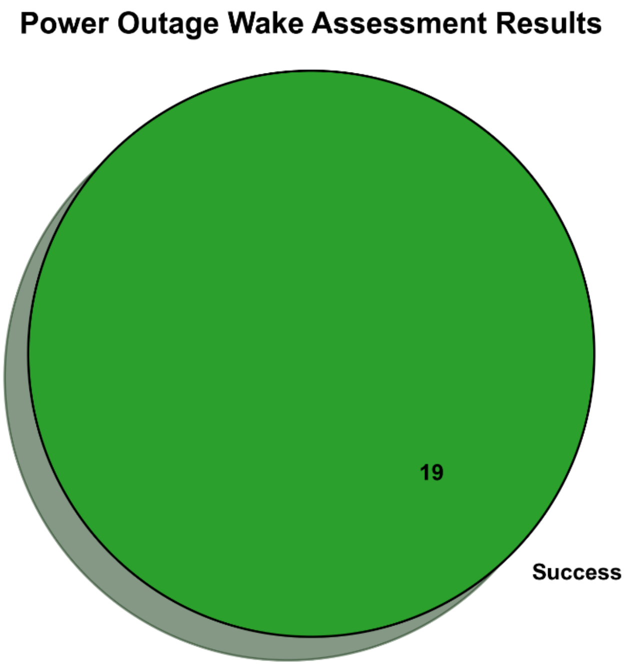

Figure 14: Power Outage Wake Test Results

Which evaluated whether a PEV would resume an interrupted charge session on a Pilot State transition from E to B2.

Figure 15: EVSE Failure Wake Test Results

Which examined whether a PEV would resume an interrupted charge session on a Pilot State transition from State F to B2.

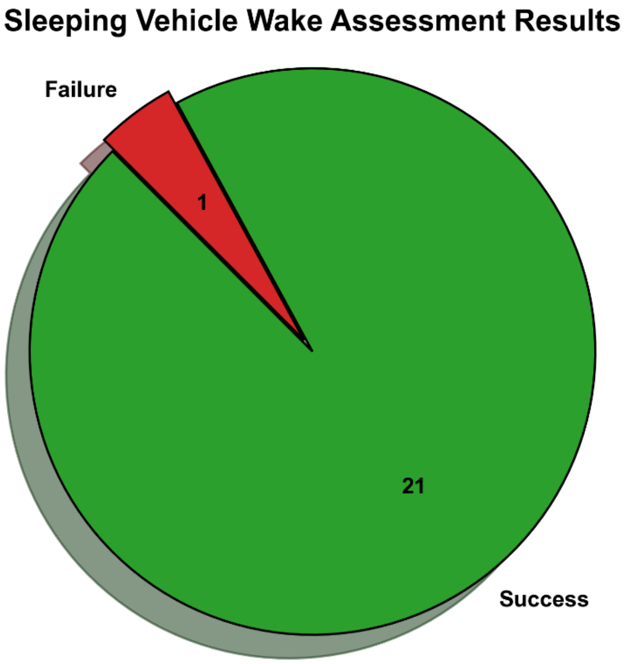

Figure 16: Sleeping Vehicle Wake Test Results

Which determined whether a sleeping PEV would begin an AC charge session upon plugin (Pilot State A to B2).

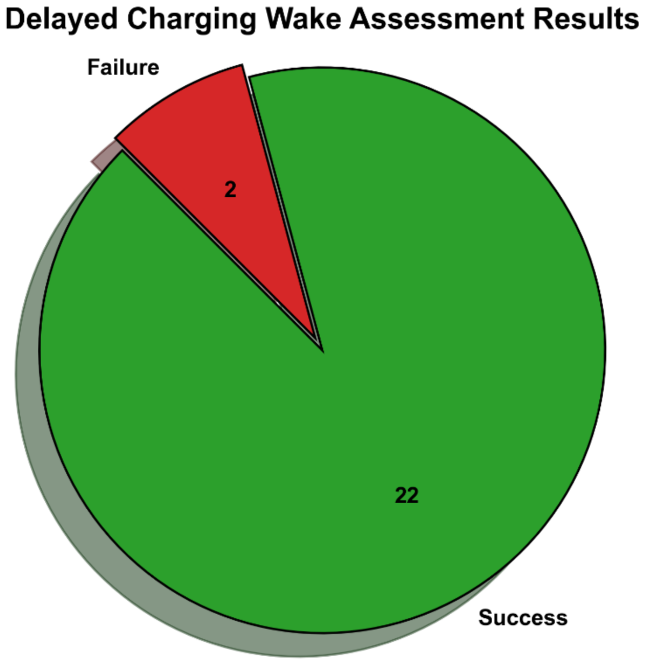

Figure 17: Delayed Charging Test Results

Which assessed whether a vehicle would wake and begin a charge session on a Pilot State transition from B1 to B2.

3.2.2 PEV Sleep Test Results

The amount of time required for a PEV to fall asleep varies substantially across vehicles and across contexts, as illustrated in Figure 18. The time required for a given vehicle to fall asleep often varies depending on the Pilot State. In one extreme example, a vehicle fell asleep in 91 seconds when left waiting in State B1 but remained awake for over 4 hours when left waiting in State E. Almost every vehicle tested took longer to fall asleep in State B1 when left waiting for an initial charge than when left waiting in State B1 after interrupting a charge. Individual PEV results are presented in Appendix B.

The recorded times for a vehicle to fall asleep during these tests may not be reliably repeatable. In one instance, a vehicle was put through the same pilot wake test in multiple successive attempts, resulting in various times to sleep, ranging from 90 seconds to 15 minutes. The time required for a vehicle to fall asleep may be insignificant in most applications, provided the vehicle can reliably resume charging from either a sleeping or non-sleeping state.

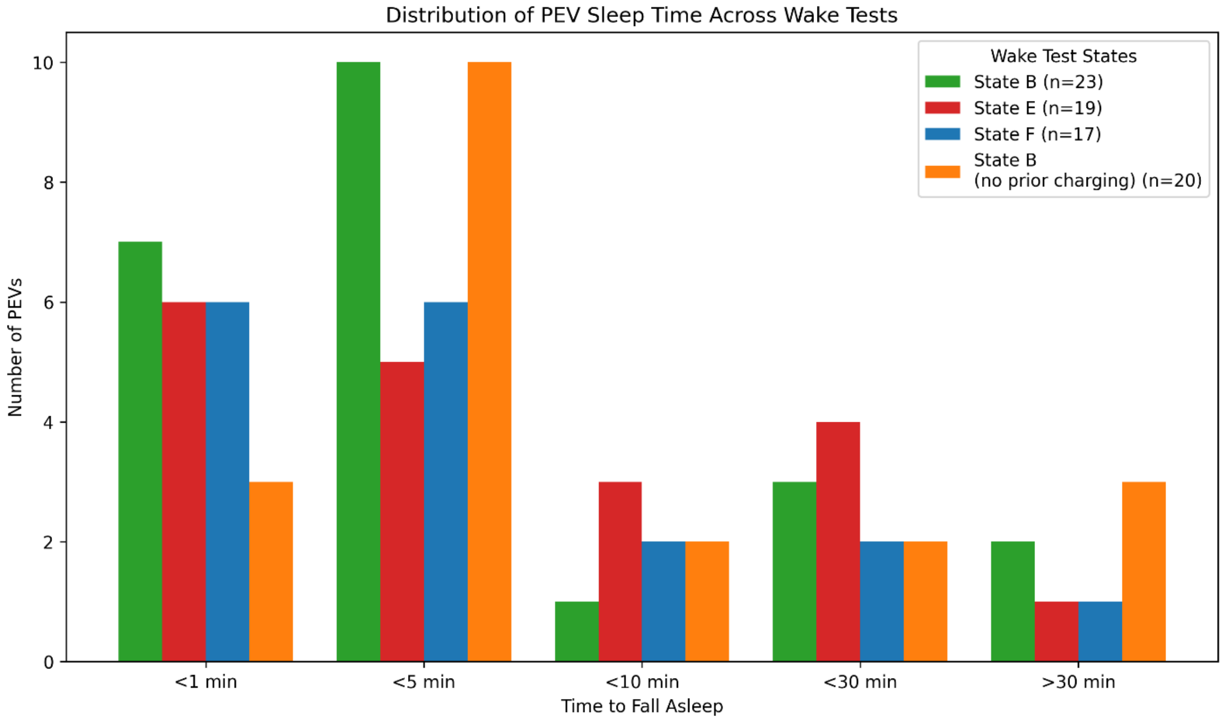

Figure 18: Distribution of PEV Sleep Times Across Wake Tests

4. Conclusion

This study evaluated the performance of PEVs from 25 different vehicle manufacturers in response to various EVSE-driven pilot signal tests, with emphasis on accuracy, precision, latency, resolution, and wake behavior relevant to grid integration.

The accuracy and precision tests revealed that vehicles generally responded with higher accuracy and precision to falling current limits than to rising ones, though the differences were often modest. Fleet-average overall MAPE was ~4%, with most vehicles undershooting by about −0.44 A on average. Latency tests indicated a similar trend, with vehicles responding more quickly to falling current limits than rising ones. Rising latency ranged from 0.93 s to 13.6 s (median ~2.6 s), while falling latency ranged from 0.87 s to 4.1 s (median ~1.2 s). The latency test also showed that vehicles respond to rising current limits more quickly when starting at a higher amperage, although the starting and ending amperage levels have seemingly no impact on a PEV's response to falling current limits. Bias values indicated that most vehicles draw less current than offered by an EVSE, suggesting a conservative charging system design approach from EV manufacturers.

The resolution tests revealed significant variability among vehicles, with some detecting current-limit changes of less than 0.13 A, while others required a change of greater than 1 A before reacting. Notably, vehicles like the VW ID.4 and Audi E-Tron registered changes of less than 0.2 A, while models such as the Subaru Solterra and Volvo XC60 required greater than 1 A steps before responding. An interesting observation was that many PEVs responded differently when tracking rising versus falling current limits.

The V1G Frequency Regulation Tests confirmed that all vehicles were capable of following PJM’s fast regulation signal. Composite performance scores ranged from 0.90 (Volvo XC60 Recharge) to 0.96 (General Motors Zevo 600), all of which surpassed PJM’s requirement of 0.75, demonstrating the feasibility of PEVs as resources in frequency regulation markets. Precision-only scores spanned from 0.78 (Volvo XC60 Recharge) to 0.92 (multiple), highlighting resolution as the dominant differentiator.

The Pilot Wake Tests demonstrated that most vehicles reliably transition from sleeping to an actively charging state. However, the time required for a vehicle to fall asleep varied significantly, with some vehicles entering a sleeping state in under a minute while others took over an hour.

Taken together, these findings show that while production PEVs display a broad range of behaviors, their overall performance is sufficient to support a spectrum of grid services, from bulk demand response to fast frequency regulation. However, the variability in wake behavior, resolution, accuracy, latency, and precision could hinder large-scale deployment unless control strategies and standards account for these differences.

Appendix A. PEV PWM Assessment Testing Results

Vehicle Make	Model Name	Model Year	Avg Rising MAE (A)	Avg Rising MAPE (%)	Avg Rising Prec. (A)	Rising Bias (A)	Avg Falling MAE (A)	Avg Falling MAPE (%)	Avg Falling Prec. (A)	Falling Bias (A)
Audi	E-Tron	2019	0.69	3.12%	0.42	-0.69	0.61	2.60%	0.45	-0.52
BMW	i4 M50	2024	1.55	6.76%	0.82	-1.51	1.09	3.99%	0.78	-1.02
Chevrolet	Bolt	2017	0.24	2.05%	0.28	-0.24	0.23	1.61%	0.36	0.05
Chrysler	Pacifica	2022	0.56	4.34%	0.31	-0.56	0.45	3.33%	0.41	-0.26
Fiat	500e	2018	1.22	9.11%	0.37	-1.22	0.59	3.83%	0.49	-0.48
Fisker	Ocean	2023	0.52	3.43%	0.47	-0.52	0.41	2.64%	0.6	-0.08
Ford	F-150 Lightning	2022	0.37	3.05%	0.36	-0.17	0.73	4.56%	0.63	-0.57
General Motors	Zevo 600	2023	0.55	4.33%	0.35	0.39	0.73	4.22%	0.43	0.73
Genesis	GV60	2023	0.94	5.63%	0.32	-0.94	0.79	3.58%	0.41	-0.76
Honda	Prologue	2024	0.49	2.81%	0.33	-0.49	0.4	1.94%	0.45	-0.05
Hyundai	Kona	2021	1.16	9.59%	0.28	-1.16	0.91	5.92%	0.36	-0.91
Jeep	Wrangler 4xe	2023	0.57	3.14%	0.35	-0.57	0.5	2.79%	0.46	-0.32
Kia	EV9	2024	0.49	2.10%	0.34	-0.49	0.46	1.88%	0.43	-0.31
Mazda	CX-90 PHEV	2023	0.23	2.44%	0.26	-0.04	0.19	1.40%	0.35	0.16
Mercedes-Benz	EQB 300	2024	0.22	1.43%	0.29	-0.2	0.31	1.79%	0.44	-0.05
Nissan	Leaf	2013	0.64	5.33%	0.36	-0.36	0.49	3.31%	0.46	-0.28
Polestar	Polestar3	2025	1.18	5.46%	0.48	-1.18	0.65	2.97%	0.47	-0.57
Porsche	Taycan 4 Cross Turismo	2022	0.42	2.17%	0.35	-0.36	0.39	1.94%	0.46	-0.13
Rivian	R1T	2022	1.14	7.42%	0.45	-1.14	0.76	3.85%	0.59	-0.67
Smart	ED	2018	1.21	7.49%	2.04	-1.14	0.64	4.60%	2.04	-0.32
Subaru	Solterra	2023	0.76	5.01%	0.94	-0.71	0.59	4.23%	0.78	-0.45
Tesla	Cybertruck	2024	0.24	1.48%	0.32	-0.15	0.26	1.18%	0.33	0.25
Toyota	Prius Prime	2024	0.31	3.05%	0.26	-0.31	1.01	8.28%	1.72	-0.73
Volkswagen	ID4	2023	0.56	2.85%	0.36	-0.52	0.42	2.01%	0.45	-0.09
Volvo	XC60 Recharge	2023	0.76	7.63%	0.34	-0.76	0.51	5.71%	0.43	-0.41

Vehicle Make	Model Name	Model Year	Avg Overall MAE (A)	Avg Overall MAPE (%)	Avg Overall Prec. (A)	Avg Overall Bias (A)	Avg Rise Latency (s)	Avg Rise Rate (A/s)	Avg Fall Latency (s)
Audi	E-Tron	2019	0.66	2.90%	0.43	-0.62	1.103	12.89	1.325
BMW	i4 M50	2024	1.35	5.57%	0.8	-1.3	9.759	2.105	1.019
Chevrolet	Bolt	2017	0.24	1.86%	0.31	-0.11	3.903	2.206	0.989

Chrysler	Pacifica	2022	0.52	3.91%	0.35	-0.43	4.166	1.491	4.085
Fiat	500e	2018	0.95	6.85%	0.42	-0.9	13.576	1.172	3.001
Fisker	Ocean	2023	0.47	3.09%	0.53	-0.33	1.705	5.154	1.093
Ford	F-150 Lightning	2022	0.52	3.70%	0.47	-0.34	6.385	1.373	0.888
General Motors	Zevo 600	2023	0.63	4.28%	0.38	0.54	2.487	5.346	1.992
Genesis	GV60	2023	0.88	4.75%	0.36	-0.86	1.526	8.974	1.009
Honda	Prologue	2024	0.45	2.44%	0.38	-0.3	2.716	4.786	2.796
Hyundai	Kona	2021	1.06	8.02%	0.31	-1.06	3.953	3.083	0.867
Jeep	Wrangler 4xe	2023	0.54	2.99%	0.4	0.46	4.481	1.85	1.317
Kia	EV9	2024	0.48	2.01%	0.38	-0.41	1.146	11.55	1.073
Mazda	CX-90 PHEV	2023	0.21	2.00%	0.3	0.04	0.925	9.299	0.954
Mercedes-Benz	EQB 300	2024	0.26	1.58%	0.35	-0.14	2.17	6.068	0.889
Nissan	Leaf	2013	0.57	4.47%	0.4	-0.33	1.235	5.887	1.124
Polestar	Polestar3	2025	0.92	4.21%	0.48	-0.88	2.561	7.044	2.927
Porsche	Taycan 4 Cross Turismo	2022	0.41	2.07%	0.4	-0.26	1.13	9.806	1.017
Rivian	R1T	2022	0.98	5.89%	0.51	-0.94	12.131	1.459	1.178
Smart	ED	2018	0.97	6.25%	2.04	-0.79	6.009	1.696	1.188
Subaru	Solterra	2023	0.69	4.67%	0.88	-0.6	2.584	3.354	1.955
Tesla	Cybertruck	2024	0.25	1.35%	0.32	0.02	1.438	10.155	0.92
Toyota	Prius Prime	2024	0.61	5.29%	0.89	-0.49	1.264	2.434	1.853
Volkswagen	ID4	2023	0.54	3.05%	0.81	-0.29	1.934	7.038	1.515
Volvo	XC60 Recharge	2023	0.66	6.57%	0.38	-0.61	11.986	0.613	1.581

Vehicle Make	Model Name	Model Year	RegD Precision Score Only	RegD Composite Score	Rising Resolution (A)	Falling Resolution (A)	Overall Resolution (A)
Audi	E-Tron	2019	0.8929	0.9695	0.18647	0.18499	0.17672
BMW	i4 M50	2024	0.8902	0.94606	0.12975	0.20921	0.13203
Chevrolet	Bolt	2017	0.9114	0.95938	0.19392	0.41546	0.39923
Chrysler	Pacifica	2022	0.8993	0.95222	0.95006	0.95023	0.95118
Fiat	500e	2018	0.8841	0.94389	0.81524	0.8422	0.887
Fisker	Ocean	2023	0.8989	0.95258	0.99987	1.00874	1.00019
Ford	F-150 Lightning	2022	0.8796	0.94215	0.15918	0.16764	0.16603
General Motors	Zevo 600	2023	0.9192	0.96221	0.19478	0.20571	0.20415
Genesis	GV60	2023	0.8948	0.9513	0.16654	0.12379	0.11921
Honda	Prologue	2024	0.9127	0.95972	0.19846	0.19786	0.19864
Hyundai	Kona	2021	0.86	0.93583	0.46249	0.32647	0.38566
Jeep	Wrangler 4xe	2023	0.9106	0.95809	0.99449	1.02992	1.01061
Kia	EV9	2024	0.9128	0.9598	0.26799	0.30329	0.299
Mazda	CX-90 PHEV	2023	0.9131	0.95992	0.31824	0.35471	0.33821

Mercedes-Benz	EQB 300	2024	0.9133	0.96044	0.21023	0.19866	0.18347
Nissan	Leaf	2013	0.8982	0.95249	0.44068	0.45405	0.44745
Polestar	Polestar3	2025	0.9096	0.95777	0.31284	0.35471	0.29366
Porsche	Taycan 4 Cross Turismo	2022	0.9117	0.95915	0.29629	0.29893	0.13826
Rivian	R1T	2022	0.8966	0.95184	0.23443	0.22976	0.21498
Smart	ED	2018	0.9144	0.94898	1.17755	0.64422	0.58487
Subaru	Solterra	2023	0.8908	0.9217	1.49347	2.82101	1.38512
Tesla	Cybertruck	2024	0.9162	0.96118	1.01087	1.00952	0.98302
Toyota	Prius Prime	2024	0.8829	0.89783	0.21291	0.22674	0.18973
Volkswagen	ID4	2023	0.9172	0.96202	0.12444	0.12437	0.12212
Volvo	XC60 Recharge	2023	0.7835	0.89599	0.63994	0.54133	0.52545

Appendix B. Pilot Wake Response Results

Vehicle Make	Model Name	Model Year	State B1 → B2	State E → B2	State F → B2	State A1 (Asleep) → B2	State B1 →B2 (Delayed)
Audi	E-Tron	2019	Success	Success	Success	Success	Success
BMW	i4 M50	2024	Failure	Success	Success		Failure
Chevrolet	Bolt	2017	Success	Success	Success	Success	Success
Chrysler	Pacifica	2022	Success	Success	Success	Success	Success
Fiat	500e	2018	Success			Success	Success
Fisker	Ocean	2023	Failure	Success	Success	Success	Success
Ford	F-150 Lightning	2022	Success	Success	Success	Success	Success
General Motors	Zevo 600	2023	Success			Success	Success
Genesis	GV60	2023	Success	Success	Success	Success	Success
Honda	Prologue	2024	Success			Success	Success
Hyundai	Kona	2021	Success			Success	Success
Jeep	Wrangler 4xe	2023	Success	Success	Success	Success	Success
Kia	EV9	2024	Success	Success	Success	Success	Success
Mazda	CX-90 PHEV	2023	Success	Success	Success	Success	Success
Mercedes-Benz	EQB 300	2024	Success	Success	Failure	Success	Success
Nissan	Leaf	2013					
Polestar	Polestar3	2025	Success	Success		Success	Success
Porsche	Taycan 4 Cross Turismo	2022	Success	Success	Success	Success	Success
Rivian	R1T	2022	Success	Success	Success	Success	Success
Smart	ED	2018	Success	Success	Success	Failure	Success
Subaru	Solterra	2023	Success	Success	Success	Success	Success
Tesla	Cybertruck	2024	Success	Success	Success	Success	Success
Toyota	Prius Prime	2024	Success	Success	Success	Success	Success
Volkswagen	ID4	2023	Success	Success	Success	Success	Success
Volvo	XC60 Recharge	2023	Success				Failure

Where a success is defined as the PEV starting to resume a charge session from a sleeping state without any additional input or stimulus beyond the EVSE Pilot State change. A sleeping state is defined as any state where proximity pin on the PEV's J1772 SAE connector reads 0V.

Vehicle Make	Model Name	Model Year	Time to Sleep (State B)	Time to Sleep (State E)	Time to Sleep (State F)	Time to Sleep (State B - no prior charging)
Audi	E-Tron	2019	67	20	20	86
BMW	i4 M50	2024	125	496	160	127
Chevrolet	Bolt	2017	91	14491	682	104
Chrysler	Pacifica	2022	33	33	33	51

Fiat	500e	2018	51	51	50	65
Fisker	Ocean	2023	657	657	658	365
Ford	F-150 Lightning	2022	16	16	16	34
General Motors	Zevo 600	2023				
Genesis	GV60	2023	50	50	50	187
Honda	Prologue	2024	4538			4258
Hyundai	Kona	2021	46			
Jeep	Wrangler 4xe	2023	29	29	29	47
Kia	EV9	2024	56	56	56	189.74
Mazda	CX-90 PHEV	2023	360	360	360	267
Mercedes-Benz	EQB 300	2024	107	102	100	140
Nissan	Leaf	2013				
Polestar	Polestar3	2025	1013	1012		744
Porsche	Taycan 4 Cross Turismo	2022	167	167	167	212
Rivian	R1T	2022	261	896	3263	4003
Smart	ED	2018	68	68	68	151
Subaru	Solterra	2023	138	146	136	146
Tesla	Cybertruck	2024	626	627	626	733
Toyota	Prius Prime	2024	88	88	88	81
Volkswagen	ID4	2023	169	390	388	461
Volvo	XC60 Recharge	2023	3605			3605

The time required for a vehicle to fall asleep in a state was calculated from the moment that the EVSE set that state until the moment that the EVSE read 0V across the proximity pin.

About the ChargeX Consortium

The National Charging Experience Consortium (ChargeX Consortium) is a collaborative effort between Argonne National Laboratory, Idaho National Laboratory, National Renewable Energy Laboratory, electric vehicle charging industry experts, consumer advocates, and other stakeholders. The ChargeX Consortium's mission is to work together to measure and significantly improve public charging reliability and usability by June 2025. For more information, visit chargex.inl.gov.

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