CRC Report No. SM-E-18/E-142

V2X Requirements to Support the SAE J1634 Short Multi-Cycle Test and Setting Initial SOC for Plug-in Hybrid Electric Vehicles

Final Report

July 2024

COORDINATING RESEARCH COUNCIL, INC.
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V2X REQUIREMENTS TO SUPPORT THE SAE J1634 SHORT MULTI-CYCLE TEST AND SETTING INITIAL SOC FOR PLUG-IN HYBRID ELECTRIC VEHICLES

FINAL REPORT

CRC Project No. SM-E-18/E-142
SwRI® Project No. 03.28034

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LIST OF ACRONYMS AND ABBREVIATIONS

AC Alternating Current
BEV Battery Electric Vehicle
CARB California Air Resources Board
DC Direct Current
DIN Deutsches Institut für Normung
EPA Environmental Protection Agency
EV Electric Vehicle
FMEA Failure Mode effect and Analysis
HVAC Heating, Ventilation and Air Conditioning
IEC International Electrotechnical Commission
ISO International Organization for Standardization
MCT Multi-Cycle Test
NACS North American Charging Standard
OBD On-Board Diagnostics
OEM Original Equipment Manufacturer
PHEV Plug-in Hybrid Electric Vehicle
RPN Risk Priority Number
SCT Short Cycle Test
SMCT Short Multi-Cycle Test
SMCT+ Short Multi-Cycle Test+
SOC State of Charge
UBE Useable Battery Energy
US United States
V2G Vehicle-to-Grid
V2H Vehicle-to-Home
V2L Vehicle-to-Load
V2X Vehicle-to-everything

LIST OF FIGURES

EXECUTIVE SUMMARY

The United States (US) Environmental Protection Agency (EPA) and California Air Resources Board (CARB) require the use of SAE J1634 recommended practice to determine battery electric vehicle (BEV) range on a chassis dynamometer. The Short Multi-Cycle Test (SMCT), introduced in 2021, is one of the several methods described in the standard that can be used to estimate the range. Unlike other methods mentioned in the standard, the SMCT enables performing a significant portion of the test by discharging the battery using a cycler or a load, freeing up dynamometer time. While the SAE J1634 provides general requirements about the test conditions, it does not provide all the details necessary for execution. This work developed a method and recommended guidelines for performing energy discharge, utilizing an industry standard V2X (Vehicle to X, where X can be grid, vehicle, building, etc.) communication protocol together with a battery cycler. The recommendations cover software, communications, hardware, and safety requirements pertaining to the vehicle and the test cell.

In addition, methods to charge or discharge the battery pack of plug-in hybrid electric vehicles (PHEVs) to achieve a desired battery state of charge (SOC) for "SOC conditioning" were identified. Automation guidelines for each of the identified methods were provided and a comparison was made highlighting the pros and cons of the methods using a Pugh chart. The work also includes demonstrating a few SOC setting methods on a Prius Prime PHEV.

1.0 INTRODCUTION

1.1 SAE J1634 SMCT

The SAE J1634, Battery Electric Vehicle Energy Consumption and Range Test Procedure, is a standard document referred to by the industry and regulators to test the range of Battery Electric Vehicles (BEVs). The 2021 version of the document provides multiple methods to conduct this testing. These methods include Multi-Cycle Test (MCT), Single Cycle Test (SCT), Short Multi-Cycle Test (SMCT), and Short Multi-Cycle Test + (SMCT+). The SCT consists of repeating individual cycles (city and highway separately) to deplete the battery from "full" to "empty" to assess energy consumption and Usable Battery Energy (UBE). The MCT combines different drive cycles into one test, reducing the test duration. While the MCT takes less time compared to the traditional SCT, it still takes sic (6) to 12+ hours on the chassis dyno. In the 2021 revision, the Short Multi-Cycle Test (SMCT) was introduced, significantly reducing the dynamometer test burden to a 2.1-hour drive cycle followed by discharging the remaining battery energy into a battery cycler. The SMCT+ test is similar to SMCT, except that the charge depletion phase still occurs on the dynamometer. Figure 1 provides a comparison of MCT, SMCT+, and SMCT test procedures.

The objective of this work was to develop a standard method to perform the DC discharge portion of the SMCT.

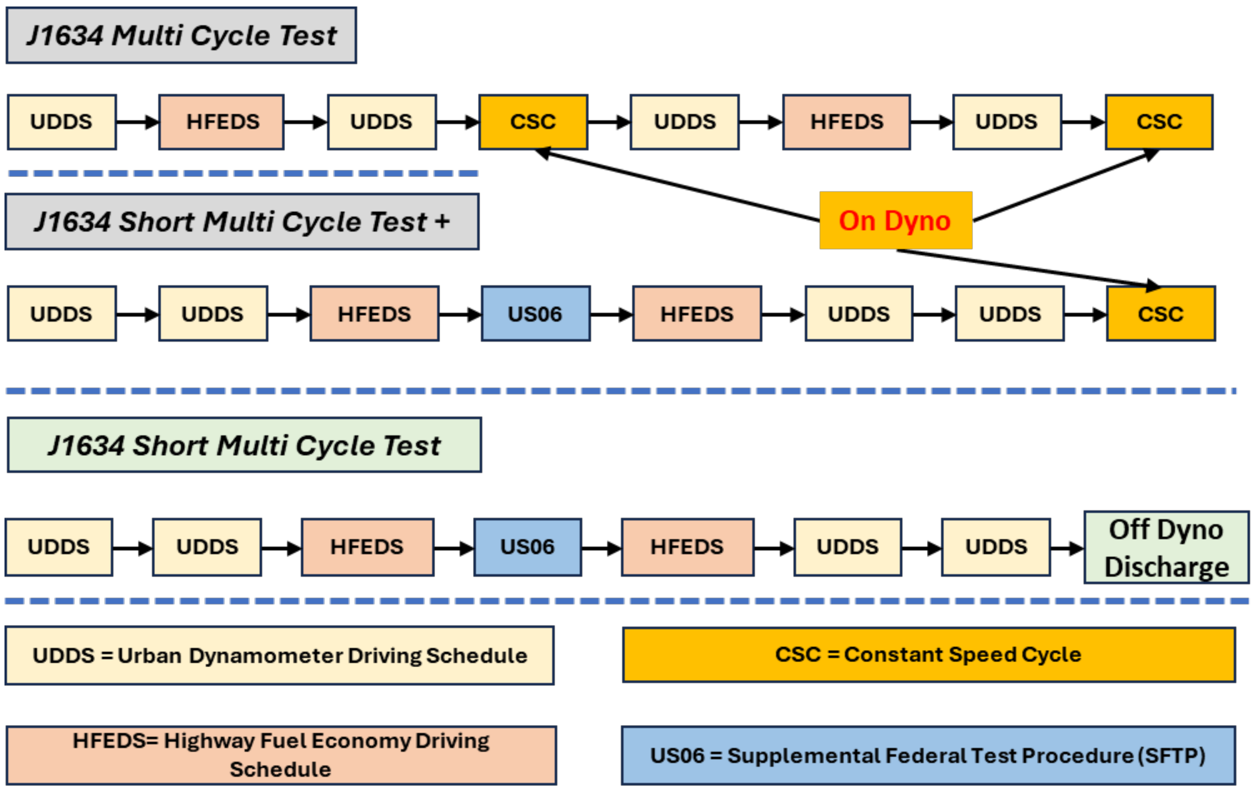

FIGURE 1: COMPARISON OF VARIOUS METHODS OUTLINED IN SAE J1634[1]

1.2 PHEV SOC Conditioning and Prius Prime Demonstration

The second goal of the project was to identify and document various methods to condition the SOC of a PHEV. This involved two specific tasks:

1. Identify, document, and demonstrate methods to discharge the Prius Prime PHEV to 50% SOC within 5 hours. This was to support an anticipated CRC Emission Committee project.
2. Identify and document methods to condition SOC of PHEVs, in general, and compare the methods based on their complexity in setup, execution, discharge rates, and potential to automate. In this context, the term conditioning means setting SOC to a pre-determined value.

[1] SAE International Surface Vehicle Recommended Practice, "Battery Electric Vehicle Energy Consumption and Range Test Procedure," SAE Standard J1634, Rev. April 2021

2.0 SAE J1634 SMCT DISCHARGE PROTOCOL DEVELOPMENT

The development of the SAE J1634 SMCT Discharge test protocol consisted of the following steps:

1. Reviewing existing standards, protocols, and implementations.
2. Performing an FMEA to derive requirements, process flow, and work instructions.
3. Compiling a document containing recommendations and the process.

2.1 Review of Communications Protocols and Test Requirements

The team performed a search on existing solutions for V2L, V2H, and V2G, collectively known as V2X, to determine if the current production hardware and software can support the required battery discharge power levels for the J1634 SMCT or if a new approach is necessary. It was identified that few vehicles in the market have V2X capability. Furthermore, the maximum discharge power rating among these vehicles is 9.6 kW, whereas the mean power requirement for BEVs sold in 2023 would have been around 17 kW. More details on this are in *Appendix A, Section 4.1*. It was determined that a new method is needed. The team conducted a comprehensive review of V2X protocols to derive the minimum set of requirements and recommended protocols for communications that could enable performing an SMCT in an automated manner. These are covered in detail in *Appendix A, Section 5*. The review covered the following standards:

- ISO 15118: Road vehicles -- Vehicle to grid communication interface
  - Part 1: General information and use-case definition
  - Part 2: Network and application protocol requirements
  - Part 3: Physical and data link layer requirements
  - Part 20: 2^{nd} generation network layer and application layer requirements
- IEC 53196-1: Plugs, socket-outlets, vehicle connectors and vehicle inlets - Conductive charging of electric vehicles
- IEC 61587-1: Mechanical structures for electrical and electronic equipment - Tests for IEC 60917 and IEC 60297 series - Part 1: Environmental requirements, test setups and safety aspects
- DIN 70121: Electromobility - Digital communication between a DC EV charging station and an electric vehicle for control of DC charging in the Combined Charging System
- IEEE 1547: Standard for Interconnection and Interoperability of Distributed Energy Resources with Associated Electric Power Systems Interfaces
- SAE J1772: SAE Electric Vehicle and Plug in Hybrid Electric Vehicle Conductive Charge Coupler
- SAE J2931/1: Digital Communications for Plug-in Electric Vehicles
- SAE J2931/4: Broadband PLC Communication for Plug-in Electric Vehicles
- SAE J2931/7: Security for Plug-in Electric Vehicle Communications
- SAE J2847/2: Communication Between Plug-In Vehicles and Off-Board DC Chargers
- SAE J2836: Instructions for Using Plug-In Electric Vehicle (PEV) Communications, Interoperability and Security Documents

- NACS: Tesla North American Charging Standard.
  SAE J3400, a technical information report released by SAE that includes NACS, was released while writing this report. *Appendix A-2* contains a review of SAE J3400 to perform SAE J1634 SMCT off dyno discharge.

Based on the SAE J1634 SMCT requirements and a review of communications protocols, a test setup, as shown in Figure 2, was proposed and the setup is explained in *Appendix A*, *Section 4*. The vehicle requirements were also derived based on the communications and test requirements and are summarized in *Appendix A, Section 6*.

2.2 Failure Mode Effect and Analysis

A failure mode and effects analysis (FMEA) was performed to identify and address any shortcomings in the proposed setup by analyzing the system one node and one interface at a time. The outcome from the FMEA helped identify software, hardware - functional, and safety requirements. Additionally, it guided in developing a process flow to derive the work instructions. These are covered in *Sections 7 and 8 of Appendix A*. *Appendix A-1* contains the process flow diagram. The FMEA approach consisted of three key steps:

1. System Diagram Development
2. Parameter Diagram and Functional Analysis
3. FMEA

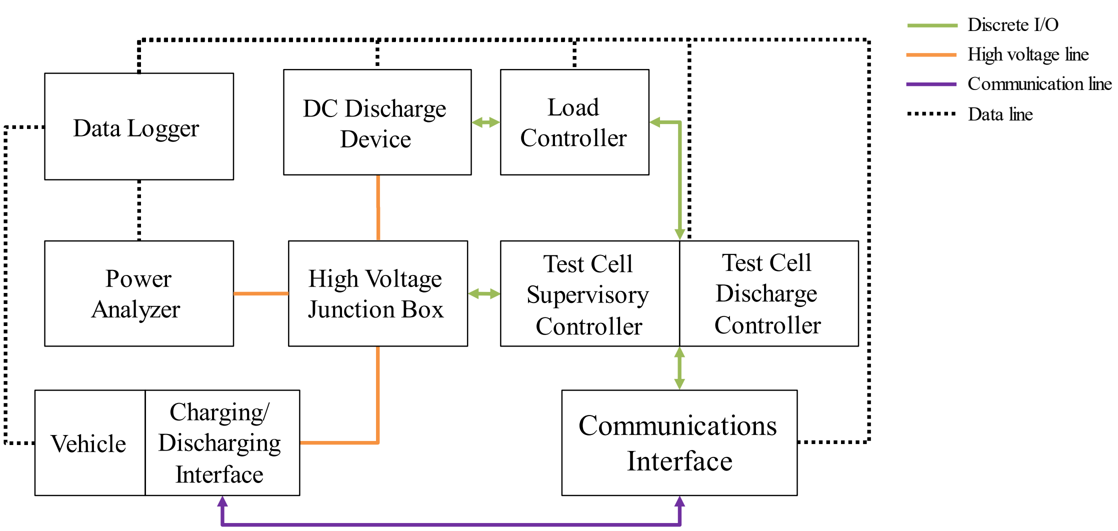

FIGURE 2: AN OVERVIEW OF TEST SETUP TO PERFORM SAE J1634 SMCT DC DISCHARGE

These are described in Figure 3. The first step in the process was understanding the system and every component within the scope for the FMEA based on current design. This was used as the basis for the second step, which was to construct parameter diagrams (P-diagram) for each functional component and interface within the system. The considerations made during this step covered the functional aspect of every component, interface, and explored potential ways in which the function(s) could fail. It also listed external factors that could influence the function(s). The third (and last) step in the process was to extract the information from the P-diagrams and populate the FMEA structure shown at the bottom of Figure 3.

There were three factors that are accounted for in this FMEA process: severity of the failure (S), probability of the failure to occur (O), and certainty with which the failure can be detected (D). There are guidelines on rating each of these factors. The product of all three factors is represented by the Risk Priority Number (RPN) which is a rough indication of the importance of a given failure mode – the higher the RPN, the more critical it is to devise countermeasures. A cross-functional team at SwRI, comprising members who specialize in electrified powertrain, vehicle testing, controls, and communications, reviewed the FMEA structure (step three). The outcome from the FMEA helped identify software, hardware - functional, and safety requirements.

Finally, a list of lab equipment that can be used to perform the SAE J1634 SMCT in an automated manner was compiled. This can be found in *Appendix A, Section 9*.

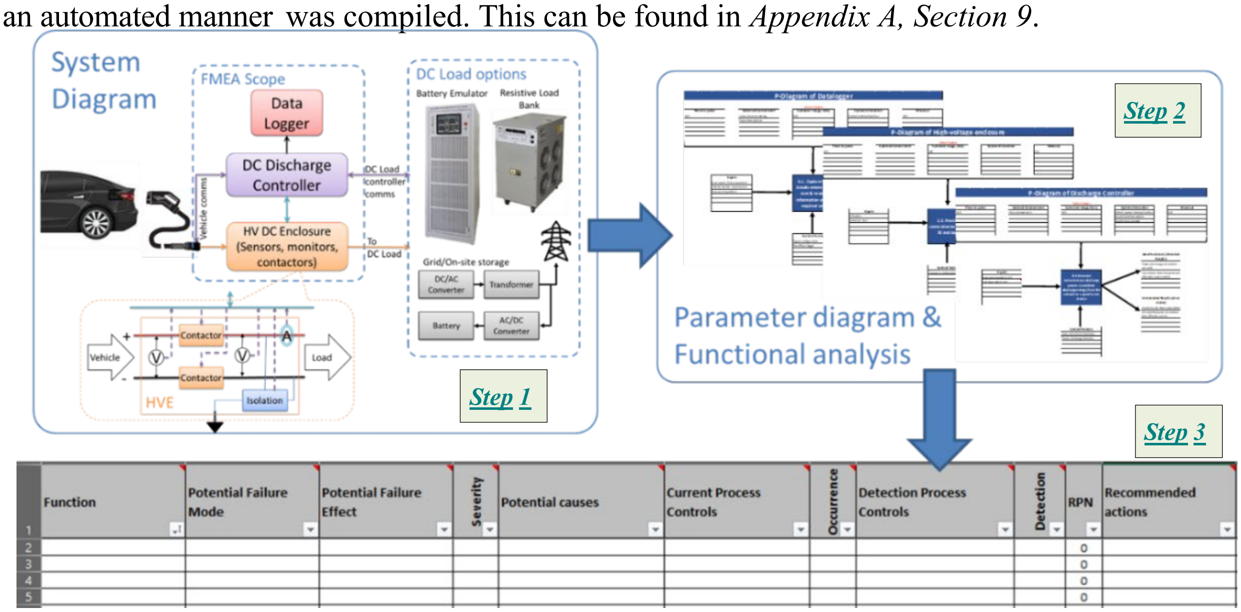

FIGURE 3: FMEA PROCESS FOR DC DISCHARGE

2.3 SAE J1634 SMCT DC Discharge Protocol Document

A document entitled "V2X Requirements and Recommended Practices to Support the SAE J1634 Short Multi-Cycle Test" was developed as a deliverable for the work. In addition to containing the communication requirements, it also describes a process flow along with recommended hardware and software requirements to conduct the J1634 SMCT in an automated manner. *Appendix A* of this report contains the document. Broadly, it is structured as follows:

- Introduction, scope of the document, and reference standards
    - *Sections 1-3*

- Requirements defined in SAE J1634 for SMCT
    - *Section 4*
- Review of industry standard V2X communication protocols and recommended protocols for conducting SAE J1634 SMCT
    - *Section 5*
- Vehicle hardware, and software requirements
    - *Section 6*
- Test procedure and process flow
    - *Section 7*
- Test cell hardware and software requirements for safety and functionality
    - *Section 8*
- Examples of required laboratory equipment
    - *Section 9*

3.0 PHEV SOC CONDITIONING AND PRIUS PRIME TESTING

3.1 Prius Prime Testing

Three methods were studied to discharge the 2017 Prius Prime PHEV (8.8 kWh battery pack capacity) from a full charge down to 50% SOC. The methods are as follows:

- Method 1: Setting the Heating, Ventilation, and Air Conditioning (HVAC or climate control system) to the lowest temperature setting while setting the seat warmers to the highest setting
- Method 2: Setting the HVAC to the highest temperature setting while setting the seat warmers to the highest setting
- Method 3: Adding a load to the auxiliary 12-volt battery

For all test cases, the vehicle lights and accessories were turned off. Additionally, all doors were closed, but the windows were open. Further, it is worth noting that the SOC displayed on the dashboard after an overnight charge was 100%, while the SOC reported by the On-Board Diagnostics (OBD) was around 83%. The test setup and detailed results are discussed in *Appendix B*.

Figure 4 summarizes the time required for each of the studied methods. All three methods achieved a discharge to 50% SOC well within the required time constraint of five (5) hours. The fastest method involved setting the HVAC to the highest temperature setting, which depleted the battery pack in approximately 1 hour and 15 minutes. None of the methods resulted in the engine turning on at any time during the discharge process, nor did the vehicle go into a sleep mode. For the auxiliary load test, an external inverter was directly connected to the 12 V auxiliary battery. The load consisted of two fixed-speed fans and two variable-speed fans for a load of approximately 740-780 Watts. The load was selected such that the power draw was less than the rated power of the DCDC converter. This ensured discharge of the high-volage battery and prevented depleting the auxiliary battery.

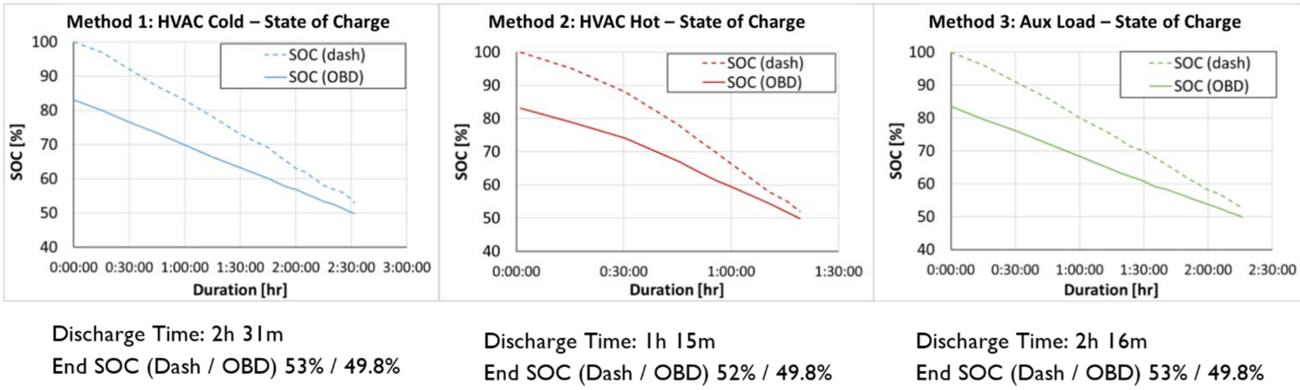

FIGURE 4: COMPARISION OF THE THREE METHODS TO DISCHARGE PRIUS PRIME BATTERY PACK

3.2 PHEV Battery SOC Conditioning

Methods to set the SOC of a Plug-in Hybrid Electric Vehicle (PHEV) to a predefined value were studied as part of this work. The methods described in Section 3.1 of this report were generalized, and additional methods were studied.

Specific use cases were considered to formulate appropriate constraints. One plan focused on emissions testing needs, as per CRC member feedback. This would form a condensed version of SAE J1711[2] charge-depleting and charge-sustaining mode testing, which mandates a full vehicle charge before testing. In cases where the primary objective is to measure PHEV emissions during charge-sustaining operation and capture the transition from charge-depleting to charge-sustaining, there is potential to start tests at a lower SOC. Achieving this involves either depleting the high-voltage battery during a soak or limiting the charging to a target SOC, effectively excluding engine-on events from the proposed conditioning methods.

Furthermore, CRC members recommended documenting any other methods that the team could propose. The Original Equipment Manufacturers (OEMs) or testing organizations could refer to this document, identify the methods that might be suitable for their application, and use it for testing.

For generalization of methods, it was critical to understand conditions that allow discharging the high voltage battery pack by closing the main contactors while adhering to constraints, such as the desired maximum SOC conditioning time or preventing the engine from starting during the process. The main contactors need to be closed to enable power draw from the high voltage system[3]. This enables charging the low-voltage systems via the high voltage battery through the DC-DC converter. Figure 5 shows a representative example of the contactor

[2] Light Duty Vehicle Performance and Economy Measure Committee. "Recommended Practice for Measuring the Exhaust Emissions and Fuel Economy of Hybrid-Electric Vehicles, Including Plug-in Hybrid Vehicles". SAE International, 2023. (SAE Standard J1711)

[3] Battery Safety Standards Committee. "Safety Standard for Electric and Hybrid Vehicle Propulsion Battery Systems Utilizing Lithium-Based Rechargeable Cells". SAE International, 2013. (SAE Standard J2929)

distribution network in hybrids, PHEVs, and BEVs[4]. Note that other variations of this setup may exist across different OEMs and that the DC Fast Charge may not be applicable to all PHEVs.

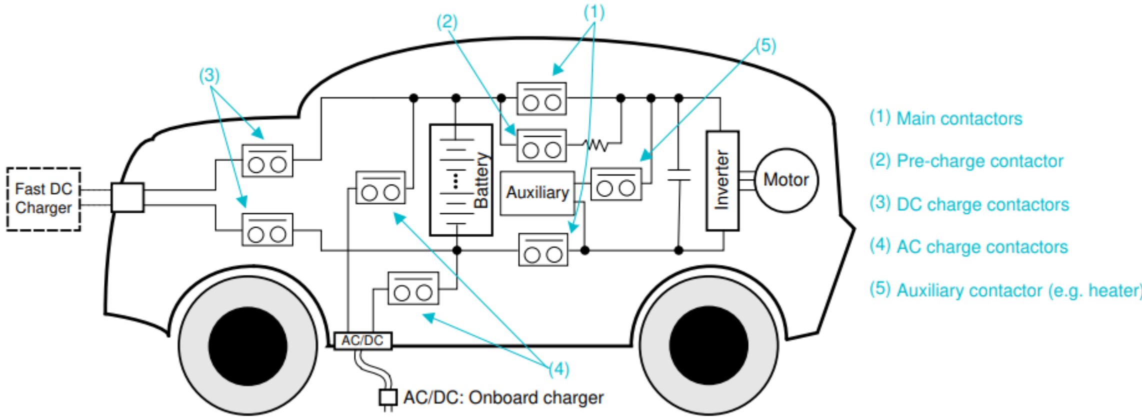

FIGURE 5: REPRESENTATIVE CONTACTOR DISTRIBUTION NETWORK IN HYBRIDS, PHEVS, AND EVS7

It is evident from this diagram that the main contactors (and possibly the auxiliary contactor) need to be closed for high voltage battery discharge. The contactor closing logic is often OEM proprietary[5]. It can be assumed that the main contactors close in the "run" or "ready-to-drive" mode (not the accessory mode[6]). Further, in most cars, the engine turns on after a certain duration in this mode[7], which is again very OEM specific.

With these considerations, the team reviewed service and repair information for three PHEVs: Toyota RAV4 Prime, Jeep Wrangler 4xe, and Mitsubishi Outlander, to gain a better understanding of the variations that exist among OEMs for the considerations listed above. The team identified five methods that could achieve the objectives of this task. These were:

1. HVAC and accessory loads
2. External loads on low voltage bus
3. External loads on high voltage bus
4. Discharge via DC charge/discharge port
5. Partial charging

Tasks were then classified and compared based on complexity in set up, execution, and ability to automate. Further, hardware, software, instrumentation, and setup requirements for each of the methods were identified for various levels of automation. These details are documented in *Appendix C*.

[4] Dong, Shuangbin. "Driving High-Voltage Contactors in EV and HEVs". Technical White Paper (Texas Instruments). 2021

[5] Jing, Junchao, Yiqiang Liu, Jie Wu, Weishan Huang, and Botao Zuo. "Research on power management and allowed propulsion control in pure electric vehicle." Energy Reports 8 (2022): 178-187

[6] ACDelco Training. "Hybrid & Electric Vehicle Operation, Diagnosis, and Repair

[7] https://www.insideevsforum.com/community/index.php?threads/clarity-as-a-back-up-power-source-dc-dc-converter-size-idle-behavior.1027/

Below is a summary of key findings:

- It was identified that methods 1, 2, and 5 are more readily applicable to current production vehicles. The Partial Charging method (method 5), although determined to be the best conditioning method, has a specific limitation — it is only applicable for increasing the SOC. This means its utility is confined to scenarios where the battery needs to be charged, and it isn't suitable for discharging or depleting the battery's SOC.
- On the other hand, External Loads on Low Voltage Bus (method 2), scored well in terms of required OEM involvement and generalizability, suggesting it's a versatile method that can be easily adopted across various vehicle models. This method could be preferred in situations where there's a need for a broadly applicable approach without extensive customization for different PHEV systems.
- HVAC and accessory loads (method 1) appeared to be less favorable in terms of automation potential and test speed, which might make it less desirable for high-throughput or labor-sensitive environments. However, it could still be the method of choice in scenarios where manual control is necessary or preferred, such as in detailed research settings where each aspect of the SOC conditioning needs to be closely observed and manipulated by a technician.
- Methods 3 and 4 were determined to be unproven in nature. Significant effort would be needed to develop those systems to perform the conditioning work.

The suitability of each method can be influenced by factors such as available resources, desired test speed, the need for automation, and the specific PHEV models being tested. The decision on which method to develop further should consider these operational contexts and the overall goals of the SOC conditioning process.

4.0 PROPOSED NEXT STEPS

4.1 SAE J1634 SMCT

Appendix A, the primary deliverable for test protocol development for SAE J1634 DC discharge using industry standard V2X protocols, was developed by focusing on achieving specificity in various aspects of the process while also considering potential variations in test setup and procedures across diverse implementations of hardware and software components. The process was defined based on functions rather than equipment, considering that a single piece of equipment can handle multiple functions. The next steps in this regard would include testing the process with known equipment and modifying it as needed. Aspects of the process that need to be determined during execution include:

- Determine the appropriate ISO 15118 use cases to trigger the discharge process:
  - Use case E7 standalone mode: More suited for standalone or non-grid applications.
  - Use case E8: Allows for dynamically setting charge and discharge limits.
- Process flow:
  - Measurement tolerance to trigger sanity check fail and abort test: Expect some discrepancy in measurement between power analyzer and DC discharge device, dependent on measurement location and test cell setup.

  - Communication timeout tolerance to discard a test and potential recourse.
- Usability of certain communications gateway or devices:
  - A few options for communications gateways are mentioned in *Appendix A*. These include production intent application and prototype controller test devices.
  - While the production grade ISO15118 charge-discharge controller seem like a robust and logical option, there are aspects of this test that still need to be resolved and thus a prototype controller test device might be useful for initial trials.
- Usability of different discharge devices and battery cyclers.

In addition to identifying these aspects for updating the process flow, testing will need to be conducted to determine whether the UBE estimates align with the existing dyno-only procedures of SMCT+ or MCT.

4.2 PHEV SOC Conditioning

The team identified unproven methods that require further exploration and development. These include the use of the DC charge port to discharge the high-voltage battery or loads on the high-voltage bus. With the increasing size of PHEV batteries, the DC charging option may become a common feature in future vehicles and could serve as a potential pathway for SOC conditioning. These methods have the potential for further development through testing on vehicles and could potentially be standardized with OEM support.

5.0 CONCLUSION

The team successfully completed the two objectives of the program. Communication protocols that can enable conducting SAE J1634 SMCT in an automated manner were identified. A standard method and recommended guidelines were developed for performing energy discharge utilizing an identified protocol together with a battery cycler. The recommendations covered software, communications, hardware, and safety requirements pertaining to the vehicle and the test cell and included a process flow for automated testing.

Furthermore, methods that adhere to the requirements of the anticipated CRC Emissions Committee work were identified and tested for discharging the Prius Prime PHEV. Additional methods were identified and subsequently generalized to be applicable to PHEVs in the market. Comprehensive guidelines were developed to facilitate the use of these methods, covering hardware, software, and instrumentation requirements for varying levels of automation. Lastly, a comparison was conducted among these methods, considering factors such as setup complexity, execution, performance, and automation.

6.0 CLOSURE

SwRI would like to thank CRC and its members for this opportunity to develop new test procedures that propel the industry forward. If you have any questions or comments regarding this final report, please feel free to contact Mr. Piyush Bhagdikar via e-mail at piyush.bhagdikar@swri.org, or telephone at (210) 522-3330.

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APPENDIX A
V2X REQUIREMENTS AND RECOMMENDED PRACTICES TO SUPPORT THE SAE J1634 SHORT MULTI-CYCLE TEST

V2X REQUIREMENTS AND RECOMMENDED PRACTICES TO SUPPORT THE SAE J1634 SHORT MULTI-CYCLE TEST

Southwest Research Institute and University of Michigan
Version 1.1
July 2024

Benefiting government, industry and the public through innovative science and technology

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LIST OF ACRONYMS AND ABBREVIATIONS

AC Alternating Current
BEV Battery Electric Vehicle
BMS Battery Management System
BPT Bidirectional Power Transfer
CARB California Air Resources Board
CDDC discharge ampere-hours
CDM Controlled Discharge Mode
CPM4PE Certificate Provisioning Mode for Private Environment
DAQ Data Acquisition
DC Direct Current
DCFC DC Fast Charge
DIN Deutsches Institut für Normung
ECU Electronic Control Unit
Edcdischarge DC discharge energy
EIM External Identification Means
EPA Environmental Protection Agency
EV Electric Vehicle
EVSE Electric Vehicle Supply Equipment
FMEA Failure Mode effect and Analysis
HFEDS Highway Fuel Economy Driving Cycle
HLC High-Level Communication
HPGP HomePlug Green PHY
HV High Voltage
IEC International Electrotechnical Commission
IP Internet Protocol
ISO International Organization for Standardization
IVI Interchangeable Virtual Instruments
LIN Local Interconnect Network
MCT Multi-Cycle Test
NACS North American Charging Standard
OBD On-Board Diagnostics
OEM Original Equipment Manufacturer
OSI Open Systems Interconnection
PE Private Environment
PEV Plug-in Electric Vehicle
PLC PowerLine Carrier
PnC Plug and Charge
PWM Pulse-Width Modulated
RBP Remote Binary Protocol
SAP Service Access Point
SCPI Standard Commands for Programmable Instruments
SCT Short Cycle Test
SDP SECC discovery protocol
SECC Supply Equipment Communication Controller

SLAC Signal Level Attenuation Characterization
SMCT Short Multi-Cycle Test
SOC State of Charge
Std Standard
TLS Transport Security Layer
UBE Useable Battery Energy
UBEestimated Estimated Usable Battery Energy
UDDS Urban Dynamometer Driving Schedule
V2G Vehicle-to-Grid
V2H Vehicle-to-Home
V2L Vehicle-to-Load
V2X Vehicle-to-everything
VAS Value Added Services
VCU Vehicle Control Unit
XML Extensible Markup Language
y_estimated Estimated DC Discharge Time

1.0 INTRODUCTION

The US Environmental Protection Agency (EPA) and the California Air Resources Board (CARB) require electric vehicle range to be determined according to the SAE surface vehicle recommended practice J1634 - Battery Electric Vehicle (BEV/EV) Energy Consumption and Range Test Procedure. In the 2021 revision of the SAE J1634 [1], the Short Multi-Cycle Test (SMCT) was introduced. The proposed testing protocol eases the chassis dynamometer test burden by performing a 2.1-hour drive cycle on the dynamometer, followed by discharging the remaining battery energy into a battery cycler to determine the Useable Battery Energy (UBE). Opting for a cycler-based discharge is advantageous due to the extended operating time required to fully deplete a 70-100 kWh battery commonly found in BEVs.

2.0 SCOPE

The SAE J1634 provides guidelines for testing BEVs using standardized procedures using the SMCT method. However, certain gaps exist in the document, particularly regarding discharge methods and protocols. This document aims to address these gaps by proposing necessary requirements, procedures, and recommended practices to ensure the comprehensive testing of BEVs. The document also summarizes the Vehicle-to-everything (V2X) communication requirements to enable performing SAE J1634 SMCT in an automated manner. In this context, V2X mainly covers vehicle-to-load (V2L), vehicle-to-home (V2H), or vehicle-to-grid (V2G) communications.

While addressing the gaps related to discharge methods, it is crucial to ensure compatibility and integration with the existing J1634 framework. The proposed enhancements should seamlessly complement the current practice, allowing for the comprehensive testing of BEVs while maintaining consistency and comparability across different testing facilities and research organizations. The standardized procedures will enable consistent testing practices, reliable data comparisons, and accelerate industry advancements.

3.0 REFERENCE STANDARDS

The primary document which describes the communications required to implement bidirectional power flow is the ISO 15118-20 [2] and ISO 15118-2 [3]. The ISO 15118 describes direct communication between the EV and electric vehicle supply equipment (EVSE). The EVSE uses a protocol such as SEP2, OpenADR, or OCPP, to communicate with the electric utility, or other entity for scheduling and pricing information. SAE J1772 [4] engagement logic is used for Direct Current (DC) charging and discharging. A PowerLine Carrier (PLC) communication on the control pilot is recommended to be used for digital communication. Requirements for this communication are defined in SAE J2931/1 [5] and SAE J2931/4 [6]. The communication messages for controlling reverse power flow are defined by J2847/2 [7]. The J2847/2 also indicates a schema for bidirectional power flow based on the older ISO-15118-2 [3] specification with the addition of a service, and negative values for current and power. If the vehicle’s Battery Management System and software implementation of the PLC communication are unable to support reverse power flow, reverse flow will not be possible even though the external electronics are capable of generating Alternating Current (AC) power and pushing it onto the grid/ sink. Primarily, the standards that contain the hardware requirements and communication protocols required to perform the SAE J1634 SMCT test are SAE J1772 [4], North American Charging Standard (NACS) [8], SAE J2847/2 [7], ISO 15118-3 [9] and ISO 15118-2 [3] or -20 [2].

Other standards referenced in this document are: IEC 53196-1 [10], DIN SPEC 70121 [11], SAE J2836 [12], J2931/7 [13], IEEE 1547:2018 [14], ISO 15118-1 [15], and IEC 61581-1 [16]. These are discussed further in Section 5.0.

It should be noted that in this document, "V2G" is used as an overarching term for protocols and communications associated with the discharge of the EV battery pack. This is based on the language and notation used in ISO 15118. Typically, Original Equipment Manufacturers (OEMs) limit state of charge (SOC) and power to protect the battery for V2G applications; however, such limitations are not imposed by ISO 15118.

4.0 SAE J1634 TEST STANDARD

This section contains a summary of information from SAE J1634 [1], relevant for performing SMCT. Traditionally, the determination of range and energy consumption for battery electric vehicles has been done using the Short Cycle Test (SCT). As per SCT the vehicle has to be driven repeatedly over the same drive cycle until its battery is fully depleted. However, its long and indeterminate nature makes it cumbersome to perform. To address these challenges, the multi-cycle test (MCT) procedure has been developed. MCT is a full depletion test consisting of multiple phases of one or more drive cycles and it enables the determination of range and energy consumption for each of those cycles. As battery technology continues to advance rapidly leading to higher UBE and range, a shorter test method such as the SMCT was required to determine range and energy consumption. While the data elements being recorded and test setup remain similar, dynamometer usage is reduced by approximately 50% since the longer duration tests (such as UBE) can be performed in a soak room by discharging the energy onto a load device. The test procedure helps determine both the city and highway range and energy consumption values using the partial depletion dynamometer test along with the DC energy discharge procedure. A comparison of the MCT, SMCT and SMCT+ is in Figure 1.

The UDDS and HFEDS cycles provide cycle-specific DC energy consumption values needed in order to calculate city and highway range and AC energy consumption. Within an hour of completing the dynamometer test the vehicle must be discharged, with DC discharge energy ($Edc_{discharge}$) and DC discharge ampere-hours (C_D) being measured continuously in a soak room environment. The constant discharge rate is determined based on the estimated usable battery energy ($UBE_{estimated}$) obtained from discharge and the total time taken to run the traditional MCT or SMCT+ test (including soak times during testing). The time taken to complete the test can either be provided by the manufacturer or estimated using good engineering judgment. Depending on whether the power accepting device can be programmed using constant power or constant current load, the following equations [1] can be used to compute load (constant discharge rate, CDR):

$$Estimated\ CDR\ (Watts)@20°C = \frac{UBE_{estimated}}{y_{estimaed}} \quad (1)$$

$$Estimated\ CDR\ (Amps)@20°C = \frac{Estimated\ CDR\ (Watts)}{HV\ Battery\ Nominal\ Voltage} \quad (2)$$

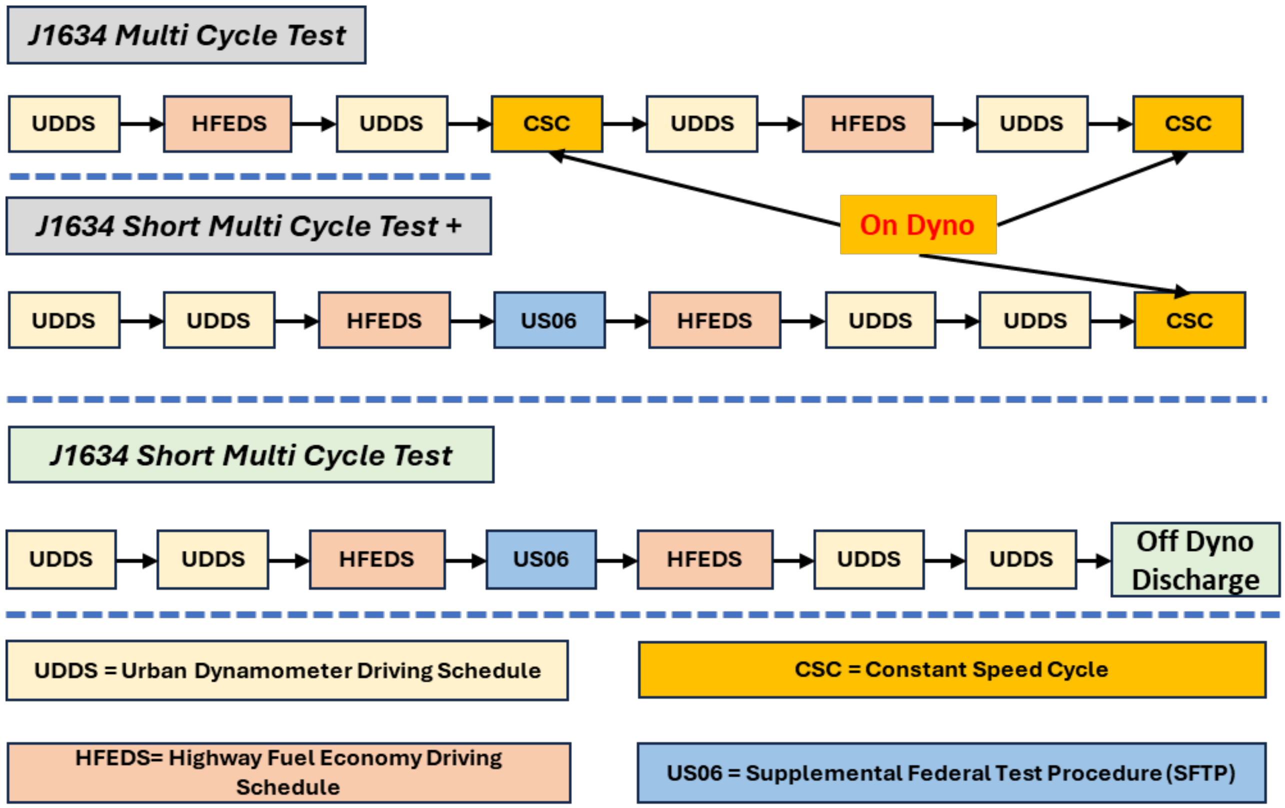

FIGURE 1: COMPARISON OF VARIOUS METHODS OUTLINED IN SAE J1634 [1]

4.1 Power Requirements

SMCT and SMCT+ share the same initial standard drive cycle portion. Figure 2 demonstrates a calculation that shows how the discharge phase for SMCT (DC Discharge) is less severe than that of SMCT+ (65 mph dyno constant speed discharge). In this context, Tx represents the time taken for a given test phase such as standard (std) cycles, 65 mph depletion (65), or DC Discharge (DC), Px represents the average power during phase "x", and Ex represents the total energy consumption during a particular phase "x". Furthermore, the procedure allows for the use of any other value for y estimated, provided it is determined through good engineering judgment and gains agreement with the appropriate administrator. This means that the 65-mph discharge rate can be used if there is an agreement regarding its usage between the manufacturer and the administrator.

The key takeaway here is that the power draw values are similar in magnitude and thus this analysis provides a roadmap towards sizing components for the test setup, and if the current V2L, V2H, and V2G options available in the market are suitable for the application.

SMCT+

Std Cycles	65 mph
$E_{std} = P_{std} * T_{std}$	$E_{65} = P_{65} * T_{65}$

SMCT

Std Cycles	DC Discharge
$E_{std} = P_{std} * T_{std}$	$E_{DC} = P_{DC} * T_{DC}$

$$E_{std} + E_{65} = E_{std} + E_{DC} \quad \text{... (SAE J1634)}$$
$$T_{DC} = T_{65} + T_{std} \quad \text{... (SAE J1634)}$$

$$\rightarrow P_{std} * T_{std} + P_{65} * T_{65} = P_{std} * T_{std} + P_{DC} * T_{DC}$$
$$\rightarrow P_{DC} = P_{65} * T_{65} / T_{DC}$$
$$\rightarrow P_{DC} = P_{65} * T_{65} / (T_{65} + T_{std})$$
$$\rightarrow P_{DC} < P_{65} \text{ for all non 0 } T_{std}$$

FIGURE 2: COMPARISON OF DISCHARGE POWER DURING SMCT AND SMCT+

Figure 3 depicts the distribution of road-load power required by the electrified vehicles from the 2023 EPA test car list [17]. The data contains 156 carlines with unique road-load coefficients, using electricity as “fuel.” The power requirement ranged from 12 kW to 30 kW, with the mean being around 18 kW. Table 1 provides results of a search on V2L, V2H, or V2G implementation in production. Based on the power requirements described above, it is seen that none of the vehicles currently in production are capable of supplying the necessary power through current V2X methods. It remains unclear whether these limitations stem from software-related issues, which might be mitigated through a "dyno mode or controlled discharge mode" override, or if they are primarily attributed to hardware constraints such as wire gauges, battery charging limitations, and component current. In the latter case, an innovative discharge method would be required to overcome these limitations. The following sources cited are of a general nature and should be noted for potential inclusion of marketing or promotional content, along with any accompanying disclaimers. Vehicle testing would be needed to confirm specified values.

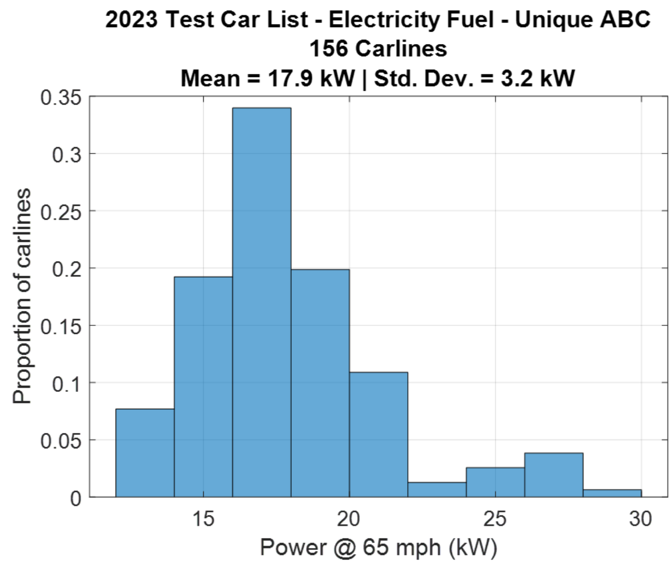

FIGURE 3: POWER DEMAND OF VARIOUS BEVS CORRESPONDING TO 65 MPH

TABLE 1: EXAMPLE V2X POWER LEVELS FOR SELECT VEHICLES

Vehicle	V2L (kW)	V2H (kW)
F-150 Lightning [1]	2.4 9.6 (Optional)	9.6 (With Ford bi-directional charger). Confirmed with Sunrun support via phone.
Hyundai G80 [2]	1.9 (accessory required)	Not available
Hyundai GV60	1.9 (accessory required)	Not available
Hyundai Ioniq [3]	3.6 (adaptor plugged into the charging socket)	Not available
KIA EV6 [4]	3.6 (adaptor plugged into the charging socket)	Not available
Nissan Leaf [5]	7.4 (requires a system only sold in Japan)	Not available

[1] https://www.motortrend.com/news/2022-ford-f-150-lightning-electric-truck-charging-generator-power/
[2] https://www.genesis.com/us/en/2023/genesis-electrifiedg80/performance.html
[3] https://thedriven.io/2021/11/04/vehicle-to-load-the-electric-cars-that-will-become-a-mobile-power-source/
[4] https://www.cnet.com/roadshow/news/hands-on-hyundai-kia-v2l/
[5] https://www.greencarreports.com/news/1127590_nissan-leaf-as-home-energy-device-wallbox-will-soon-enable-it-in-the-u-s

4.2 UBE Determination

Based on SAE J1634 [1], the DC discharge test procedure is performed after the SMCT standard drive cycle phase. The DC discharge phase ends when the battery discharge power required to maintain 61 mph at the vehicle roadload is not available anymore. End of test criteria in the latest published revision should be referenced in the event the SAE standard J1634 [1] is revised.

Usable energy in the SMCT cycle is the sum of DC energy consumed during the partial depletion phase, DC discharge energy, and any parasitic energy measured during the DC discharge procedure. $Edc_{parasitic}$ is the DC energy measured during the DC discharge test procedure that was consumed on-board the vehicle and not measured through the charging port. In some cases, this value may be 0, or may be already accounted for in the $Edc_{discharge}$ measurement.

$$UBE = Edc_{Total|PDT} + Edc_{discharge} + Edc_{parasitic} \quad (3)$$

The range for a given drive cycle is calculated using the UBE and the total cycle DC discharge energy consumption:

$$Range = \frac{UBE}{\sum K_i ECdc_{[phase]_i}} \quad (4)$$

$$Range_{city} = \frac{UBE}{ECdc_{city}} \quad (5)$$

$$Range_{highway} = \frac{UBE}{ECdc_{highway}} \quad (6)$$

4.3 Measurement and Equipment Requirements

The measurement requirements described below are from [1]. Voltage and current of the pack are measured directly using DC wideband voltage, ampere-hour, or watt-hour meter(s). Total accuracy of current and voltage measurements shall be 1% of the reading or 0.3% of full scale, whichever is large. Further, a device that can communicate with the vehicle's DC fast charge (DCFC) contactors to allow power flow from the vehicle to the DC cycler by closing this set of contactors in addition to the battery main contactors, is needed. The DCFC contactor should ideally be located between the HV battery and the vehicle's DC fast charge port, with no additional power flow between these locations. These contactors may be located internal to the HV battery pack as described in SAE J1772. A list of measurement requirements is available in SAE J1634.

4.4 Proposed Test Setup

Figure 4 contains a schematic of a proposed setup that would enable conducting the SAE J1634 procedure. Key functional components in the setup are described below.

1. *Vehicle*
    - This is the article under test.
2. *Test Cell Discharge Controller*
    - Accept user specific test parameters.
    - Start/Terminate discharge session.
    - Estimate instantaneous discharge power, cumulative discharge energy from the vehicle for a specific test session.

- Supervise the discharge process for safety and functional aspects.

3. *Load Controller*
    - Establish connection between *Test Cell Discharge Controller* and *Discharge Device* and exchange information.
    - Control load based on set points from *Test Cell Discharge Controller*.
4. *Vehicle Charging Interface*
    - Interface to connect vehicle and discharge device via appropriate intermediate devices as necessary.
    - Interface to connect vehicle and test cell discharge controller via appropriate intermediate devices as necessary.
    - The specifics are described in section 5.1.
5. *Communications Interface*
    - Establish connection, exchange information, enable/terminate process.
6. *Test Cell Controller*
    - Interface between *Test Cell Discharge Controller* and other test cell specific safety critical operations.
7. *Discharge Device*
    - Device that acts as a sink for discharged power.
8. *High Voltage (HV) Junction Box*
    - Provide connection between vehicle and load.
    - Provide taps for voltage and current measurement.
    - Contains contactors to isolate vehicle and load.
9. *Power Analyzer*
    - Perform power and energy calculations per J1634 requirements.
10. *Data Logger*
    - Device to log functional and safety critical data.

Components such as the communications interface, test cell supervisory controller, test cell discharge controller, discharge device, data logger, and power analyzer are listed separately in the above list. However, some of these can be combined into a single physical device depending on the implementation. The datalogger interface to vehicle could include recording on-board diagnostics (OBD) signals in addition to standard ISO 15118 signals.

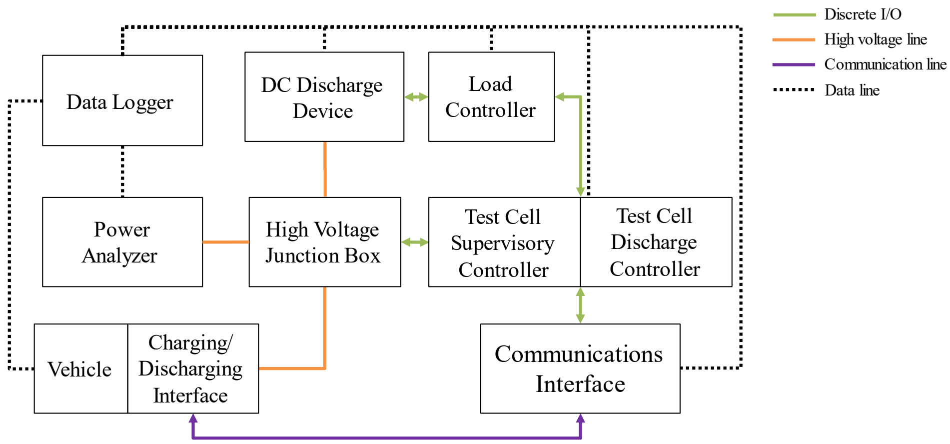

FIGURE 4: AN OVERVIEW OF TEST SETUP TO PERFORM SAE J1634 SMCT DC DISCHARGE

5.0 COMMUNICATIONS STANDARD TO SUPPORT SAE J1634 SMCT TESTING

5.1 Physical Interface

5.1.1 SAE J1772 & ISO 15118-3

SAE J1772 [4] is the surface vehicle standard for conductive charge couplers used for battery and plug-in hybrid electric vehicles. The EV battery is a DC device whose operating voltage depends on the nominal battery voltage, state of charge, and charging/discharging rate. The conductive charger mechanically couples the EV to the EVSE, converts AC current from the supply network to DC, and regulates the supply voltage to a level that permits a charge rate acceptable to the battery based on its voltage limits, current limits, and capacity as determined by the battery management system (BMS). The coupler functions with pins as depicted in Figure 11 of SAE J1772 [4]. Sample DC level 1 and level 2 coupler layouts are depicted in sheet C-4 of SAE J1772 [4]. The function of each pin and electrical ratings is summarized in Table 11 and Table 12 of SAE J1772 [4]. It should be noted that the electrical ratings of AC (level 1, 2 and 3) are distinguished based on voltage, which is different from the DC ratings summarized in Table 12 of SAE J1772 [4]. Further, the standard also addresses AC charging and power transfer, but these aspects are beyond the scope of this work and are not described. The control pilot circuit is the primary control means to ensure proper operation when connecting an EV to the EVSE. Control pilot state designations corresponding to the EV state are specified in Table 1 of SAE J1772 [4]. The proximity detection pin provides a means to detect the presence of the charging connector in the vehicle inlet when the two are connected.

5.1.2 HomePlug Green PHY (HPGP) on the Control Pilot Line

Powerline (carrier) communications are described in ISO 15118-3 [9] and SAE J2931/4 [6]. HomePlug Green PHY v1.1 ("HomePlug GP1.1") protocol (also known as HPGP) are used for the plug-in electric vehicle (PEV) - EVSE charging communications over the control pilot wires. HPGP contains specific features designed for application to EVs, such as Signal Level Attenuation Characterization (SLAC), tone mask negotiation between the PEV and the EVSE, and advanced power management. In this context, pins 4 and 5 for coupler in Figure 11 of SAE J1772[4] are the control pilot wires. These can be used to control the charging/discharging process. It consists of a data service access point (SAP) which is the interface between the Green PHY technology and the network layer. The PHY layer is what connects to the control pilot wire. The SAP supports applications using Ethernet II-class packets.

5.1.3 North American Charging Standard (NACS)

The North American Charging Standard (also known as the Tesla Charging Standard) [8] connector is shown in Figure 5. The NACS exists in both a 500V rated configuration and a 1,000 V rated configuration. The 1,000 V version is mechanically interchangeable (i.e. 500V inlets can mate with 1,000 V connectors and 500 V connectors can mate with 1,000 V inlets). The NACS specifies no maximum current rating. The maximum current rating of the inlet or connector shall be determined by the manufacturer, provided that the temperature limits are maintained. Tesla has successfully operated the North American Charging Standard above 900 A continuously with a non-liquid cooled vehicle inlet [8]. When subject to the temperature rise test of IEC 62196-1 section 24, the maximum interface contact temperature shall be 105 ºC.

For DC charging, communication between the EV and EVSE shall be powerline communication over the control pilot line as per DIN 70121 [11]. The NACS is compatible with ISO-15118 and supports V2X power transfer. Future versions of this technical specification will specify the functional requirements and specifications required to achieve V2X power transfer. The control pilot and proximity pilot function in the same manner as that of the SAE J1772 coupler [4].

It should be noted that SAE J3400, a technical information report released by SAE that includes NACS, was released while writing this report. Appendix A-2 contains a review of SAE J3400 to perform SAE J1634 SMCT off dyno discharge.

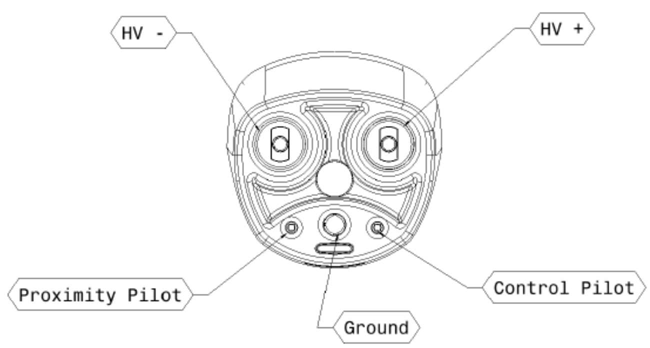

FIGURE 5: NACS CONNECTOR [8]

5.2 SAE J2847/2

SAE J2847/2 [7] is a surface vehicle standard that defines messages for energy transfer between plug-in vehicles and off-board DC chargers. The most recent version of this standard published in 2023 includes a schema that establishes DC bidirectional power transfer (BPT) using ISO 15118-2 [3], stating that implementing V2H and V2G only changes the vehicle application layer software, implying that OEMs can update their current designs to provide them with this capability. Since it only corresponds to ISO 15118-2 [3], it recommends providing negative values for current and power in case of BPT. ISO 15118-20 [2] on the other hand has a variation to the schema that already includes BPT. Security for high-level communication between the PEV and EVSE shall be as per SAE J2931/7 [13].

When starting the V2G process, the EVSE will offer the V2G service to the EV, and the EV will select this service to confirm that it fulfills this specification and is aware of the deviations from ISO 15118-2 [3]. V2G can be initiated either from the EVSE or through the EV. Negative signals for V2G start in the energy transfer stage, when the vehicle sends the initial *CurrentDemandReq* with positive values and the EVSE responds with negative values. The EVSE triggers V2G operation and subsequently the EV acknowledges the negative signals to complete the handshake. Alternatively, the vehicle can also initiate V2G by sending a negative current signal in its initial *CurrentDemandReq* message. Switching from negative to positive current or vice versa includes DC 0kW steps or pause, depending on the value of *EVSEMinimumCurrentLimit* (if it is not set to 0, the EVSE converter will not be able to switch from negative to positive current without a step of 0kW and a pause).

The 2023 version of this standard contains the complete DC V2G requirements to meet the specifications of IEEE 1547:2018 [14] and support home microgrid communication and controls. SAE J2847/2 [7] captures how the reference standards and documents refer to each other.

5.2.1 Authentication & Authorization in a Private Environment

In contrast to public infrastructure where authentication occurs using certificates without user intervention, we recommend that the off-dyno DC discharge process utilize a private environment (PE), if possible, in which case the EVSE's owner will have to grant the test EV the right to discharge at the EVSE. While ISO 15118-20 [2] mandates strong transport layer security in such private environments, ISO 15118-2 [3] allows a lower security level. As per SAE J2847/2 [7], reverse power transfer can be done using application layer messages from ISO 15118-20 [2] while implementing security protocol as per ISO 15118-2 [3]. ISO 15118-20 [2] provides Certificate Provisioning Mode for Private Environment (CPM4PE) to exchange trust and secure the communication channel between the EV and PE EVSE. CPM4PE requires user interaction on both the EVSE and the EV to initiate a pairing process. During the pairing process the supply equipment communication controller (SECC) transmits its root certificate as part of the TLS handshake's Certificate message and the EVCC learns it as a trust anchor for private environments. Subsequently, the EVCC will be able to properly authenticate the SECC during a future TLS handshake.

5.3 ISO 15118-1, 15118-2/ 15118-20, and IEC 61851-1

The communications between the vehicle and supply equipment can be classified into two categories: "basic signaling" and high-level communication (HLC). ISO 15118-1 [15] and 15118-2 /15118-20 [2, 3] specify the HLC whereas IEC 61851-1 [10] specify the "Basic Signaling."

The "Basic Signaling" comprises of vehicle states and control pilot handling for safety and initialization of the energy transfer process. It provides minimum basic control with state agreement between the EV and EVSE through a pulse-width modulated (PWM) voltage signal. The PWM duty cycle ranges from 5% to 96%; with 5% being the threshold for digital communication over the control pilot line.

HLC is used to enable functionalities such as identification, payment, load leveling, energy transfer control, and value-added services. It exchanges XML-based messages with TCP/IP protocol. In the case of DC energy transfer, the charger located in the EVSE shall perform the energy transfer control.

Primary actors are directly involved in the energy transfer process while the secondary actors supply information to the SECC, depending on the use case element. The secondary actor is not required to perform J1634 discharge testing. However, the power level for discharge could be controlled using these communication protocols with off the shelf DCFC equipment. Actor roles are captured in Figure 6 for reference.

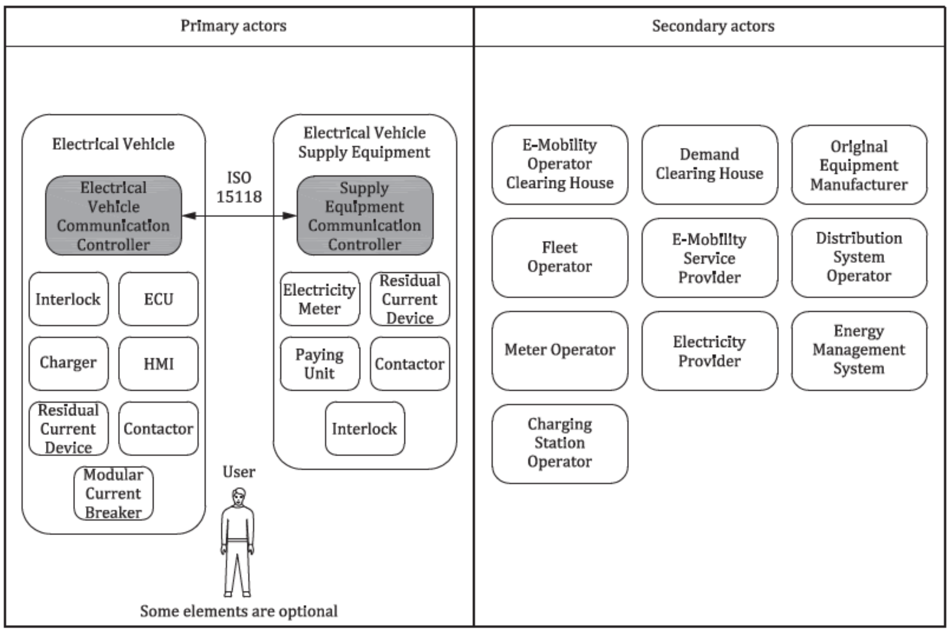

FIGURE 6: PARTICIPATING ACTORS IN THE CHARGE TRANSFER PROCESS [15]

5.3.1 Use Cases to Trigger the Discharge Process

The charge transfer process starts with use case A1, where the user plugs-in the EV at the EVSE and high-level communication is established at the data-link layer. The EVSE indicates a 5% PWM cycle, leading to a connection between the physical and data link layers. Pilot function and basic signaling shall be as per IEC 61581-1 [16] and the timing for process initialization shall be as per ISO 15118-3 [9].

After step A1 is completed successfully (shown in the flow chart of Figure 7), conductive communication is established between the EVCC and SECC in use step B1 where they are associated one-to-one via the handshake protocol defined in ISO 15118-20 [2] or 15118-2 [3]. At the end of step B1 the EVCC is capable of sending the first request message on the application layer to the SECC as per ISO 15118-20 [2].

Step B1 is followed by the certificate handling process to authenticate the devices where either an invalid or expired certificate in the EV is replaced with a new one by a secondary actor like an e-mobility service provider (step C1) or a new certificate is installed in the EV (step C2). In the Step D, there are two major groups of authorization: plug and charge (PnC) where contract certificates are used, and external identification means (EIM), where authentication/authorization is performed without using contract certificates.

Step E7 supports AC and DC reverse power transfer on standalone operation, which can be used to perform the off-dyno DC discharge portion of the SMCT test procedure. The SECC and EVCC exchange information about the AC/DC current and voltage limits using high-level communication and the EV discharges current accordingly. In case there is a change in the power transfer, the energy transfer processes can be controlled either by the SECC (Step F2) or the EVCC/user (Step F3). Alternatively, use case E8 can be leveraged, enabling dynamic control mode and power limit settings from the SECC.

The energy transfer loop is ended via Step H1, where the EVCC requests the SECC to end the process, and the EVSE opens its main switches. These steps are summarized in Table 2. ISO 15118-2 provides a mapping of the use case elements from ISO 15118-1 [15], to the corresponding application layer messages. However, it does not include the elements E7 and E8.

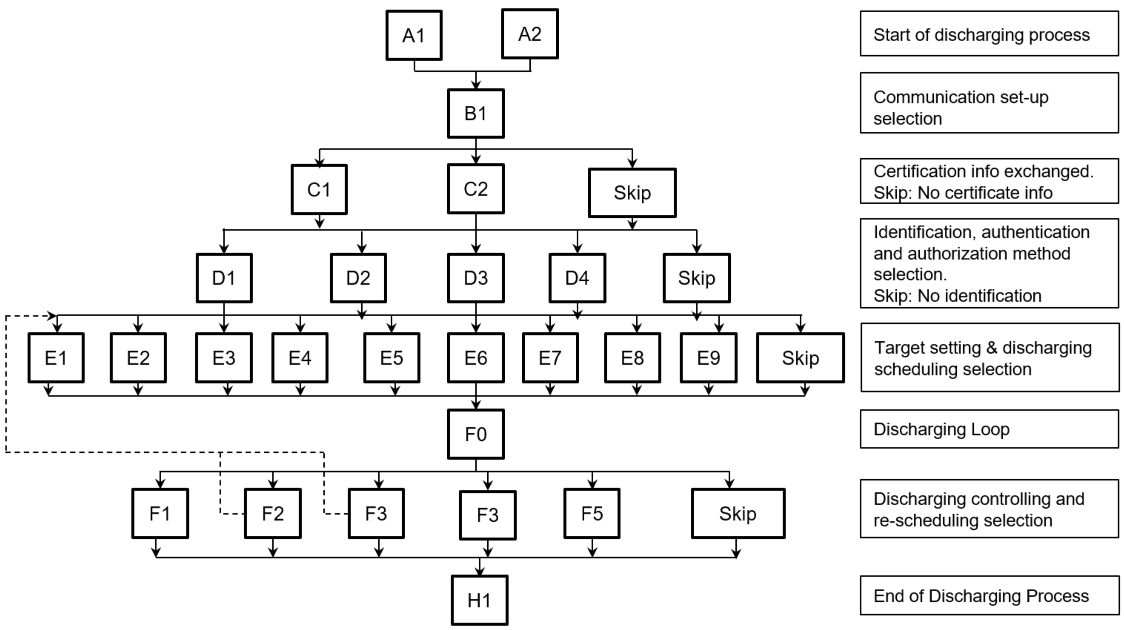

FIGURE 7: GRAPHICAL OVERVIEW OF THE DISCHARGING PROCESS [15]

TABLE 2: OVERVIEW OF ELEMENTS OF USE CASES (PERTAINING TO THE DISCHARGE PROCESS) [15]

Conductive Task Group	Use Case No.	Use Case Element Name
A	A1	Plug-in and forced high-level communication
	A2	Plug-in with concurrent IEC 61581-1 and high-level communication
B	B1	EVCC/SECC conductive communication setup
C	C1	Certificate update
	C2	Certificate installation
D	-	Authorization
E	E7	Reverse power transfer on stand-alone operation
	E8	Fast responding energy transfer services based on dynamic control mode
F	F2	Energy transfer loop with interrupt from the SECC

TABLE 2: OVERVIEW OF ELEMENTS OF USE CASES (PERTAINING TO THE DISCHARGE PROCESS) [15]

Conductive Task Group	Use Case No.	Use Case Element Name
	F3	Energy transfer loop with interrupt from the EVCC or user
	F4	Energy transfer control based on dynamic control mode
H	H1	End of energy transfer period

5.4 ISO 15118-2 / 15118-20 Messages

5.4.1 V2G OSI Architecture, Security Concept

The Open Systems Interconnection (OSI) layered architecture explains the interfaces between the individual communication protocol layers between the EVCC and SECC, specify communication timing requirements, and consequently realize the use cases described in ISO 15118-1 [15]. Vehicle to grid communication protocols and standards corresponding to each OSI layer are shown Figure 8. ISO 15118-2 [3] defines requirements applicable to layers 3-7, whereas layer 1 and 2 requirements are specified in ISO 15118-3 3 [9] and ISO 15118-8 respectively.

After connecting to charging/discharging equipment, the EV needs to uniquely identify the EVSE, and the identification mode consists of a group of messages covering a set of similar charging scenarios for a specific identification means. Depending on the use case and charging scenario, authentication modes PnC and EIM can be used. PnC is an authorization mechanism wherein the user simply plugs in their vehicle into the EVSE and all aspects of the charging process are taken care of using certificates stored in the EV without any user intervention. EIM consists of external authorization means for the user to identify their vehicle, which are outside the scope of ISO 15118-2 [3].

Once the authorization step has been completed, a secure communication channel has to be set up between the EVCC and SECC. This is where the security concept comes into play, which provides a transport-based protection mechanism to authenticate communication channels and transfer data securely between the various actors in the charge transfer process. As per ISO 15118-2 [3], transport layer security for communication between the EVCC and SECC was mandated only for PnC and value added services (VAS). However, ISO 15118-20's security architecture requires TLS 1.3, strong cryptographic algorithms and tailored certificate profiles for all use cases and identification modes. Besides the security concept, the application layer messages are the same for ISO 15118-2 [3] and ISO 15118-20 [2]. In addition to the security concept, the key difference between ISO 15118-2 [3] and ISO 15118-20 [2] is that ISO 15118-20 introduces specific messages (such as DC_BidirectionalControlReq/Res) that directly support bidirectional energy flow and dynamic control.

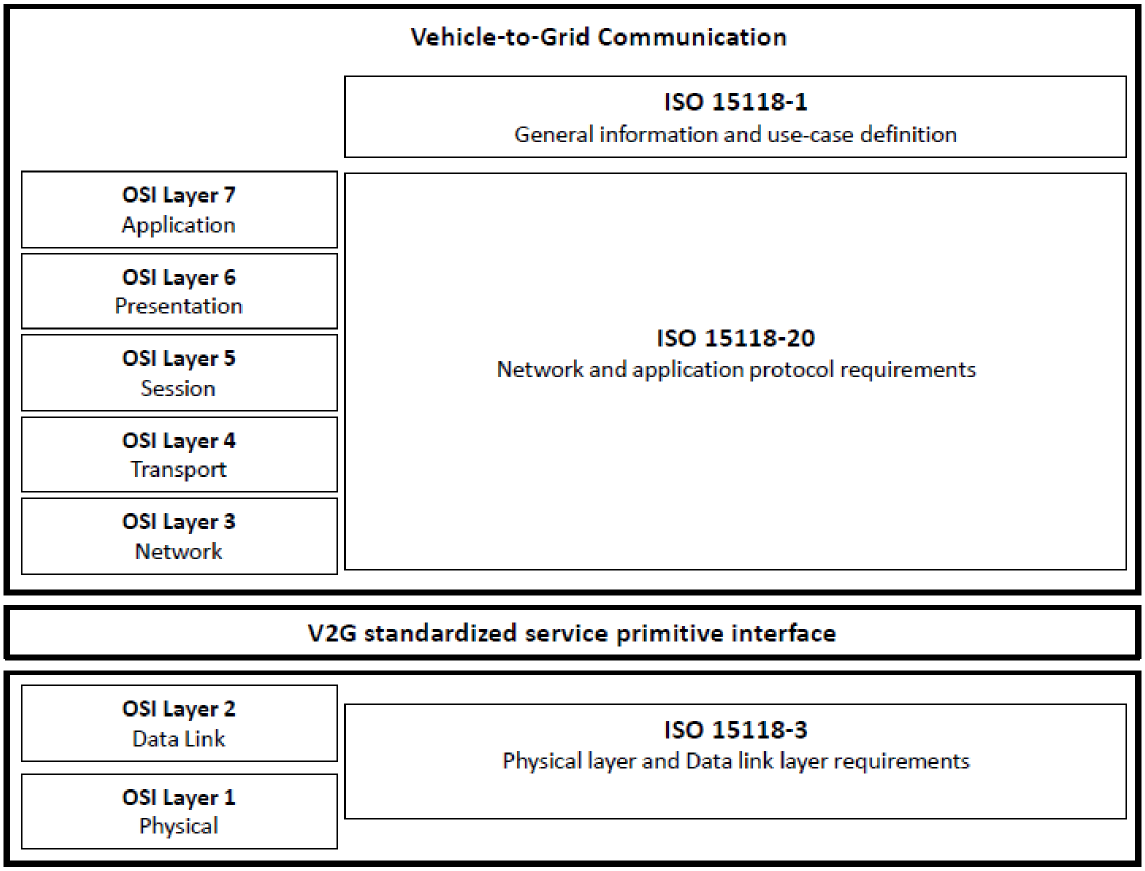

FIGURE 8: OVERVIEW OF THE ISO STANDARDS IN THE OSI REFERENCE MODEL [2]

5.4.2 Establishing Application Layer Communication

An EVCC uses the SECC discovery protocol (SDP) to get the IP address and port number of the SECC. The SDP client sends out SECC discovery request messages to the local link (multicast) expecting any SDP server to answer its request with an SECC discovery response message containing this information. After the EVCC receives the IP address and the port number of the SECC, it can establish a transport layer connection to the SECC. Depending on the physical communication layer different messages are used for the SECC discovery.

5.4.3 Application Layer Protocol Handshake

Before starting the application layer message exchange, an appropriate application layer protocol including its version shall be negotiated between the EVCC and the SECC. In order to negotiate the protocol between the EVCC and the SECC, the following application layer protocol handshake is performed:

- The EVCC shall initiate the handshake by sending a *supportedAppProtocolReq* message to the SECC containing a list of charging protocols that it supports.

- The SECC shall respond with the supportedAppProtocolRes message including ResponseCode and the SchemaID of the protocol/schema which is agreed as application protocol for the following communication session (for example, 15118:2:2013 with version 2.0). Thereby, the SECC shall select from its own list of supported protocols the protocol with highest priority indicated by the EVCC.

5.4.4 Application Layer Messages

The application layer messages are composed of client-server based messages exchanged between the EVCC and SECC to initialize and configure the energy transfer process to or from an EV. The messages defined in ISO 15118-20 [3] correspond to the use cases defined in ISO 15118-1 [15]. Messages use the EXI-based Presentation Layer. In the context of the OSI layered architecture model (Figure 8), the messages and flow represent the application layer. The EVCC always acts as a client (service requester) during the entire charging process, whereas the SECC always acts as a server (service responder). The EVCC always initiates communication by sending a request message to the SECC, then the SECC returns the corresponding response message.

Upon insertion of the connector into the vehicle inlet, the proximity detection circuit shall detect its presence. The PEV shall provide charge status information visible to the operator. The control pilot circuit verifies the vehicle connection, verifies equipment grounding continuity, confirms that the EV and EVSE are ready to exchange energy, and determines the need for indoor ventilation by sensing voltage. This is followed by the establishment of an authenticated and encrypted channel between the EVCC and SECC via the Transport Security Layer (TLS) by means of the EVCC verifying the SECC certificate. The SECC provides information about the available authorization modes and the EV selects one of them. After being authorized for charging at the EVSE (SECC) the EVCC and the SECC negotiate the energy transfer parameters. When using the dynamic control mode, the energy transfer parameters can be changed dynamically while in the charging loop. If the EVCC sends the message SessionStopReq with parameter ChargingSession equal to "Terminate", it shall terminate the process after receiving the message SessionStopRes.

Figure 9 provides a high-level overview of all steps and messages. The messages are described in the subsequent text and Figure 10 to Figure 13 show the relevant message structures.

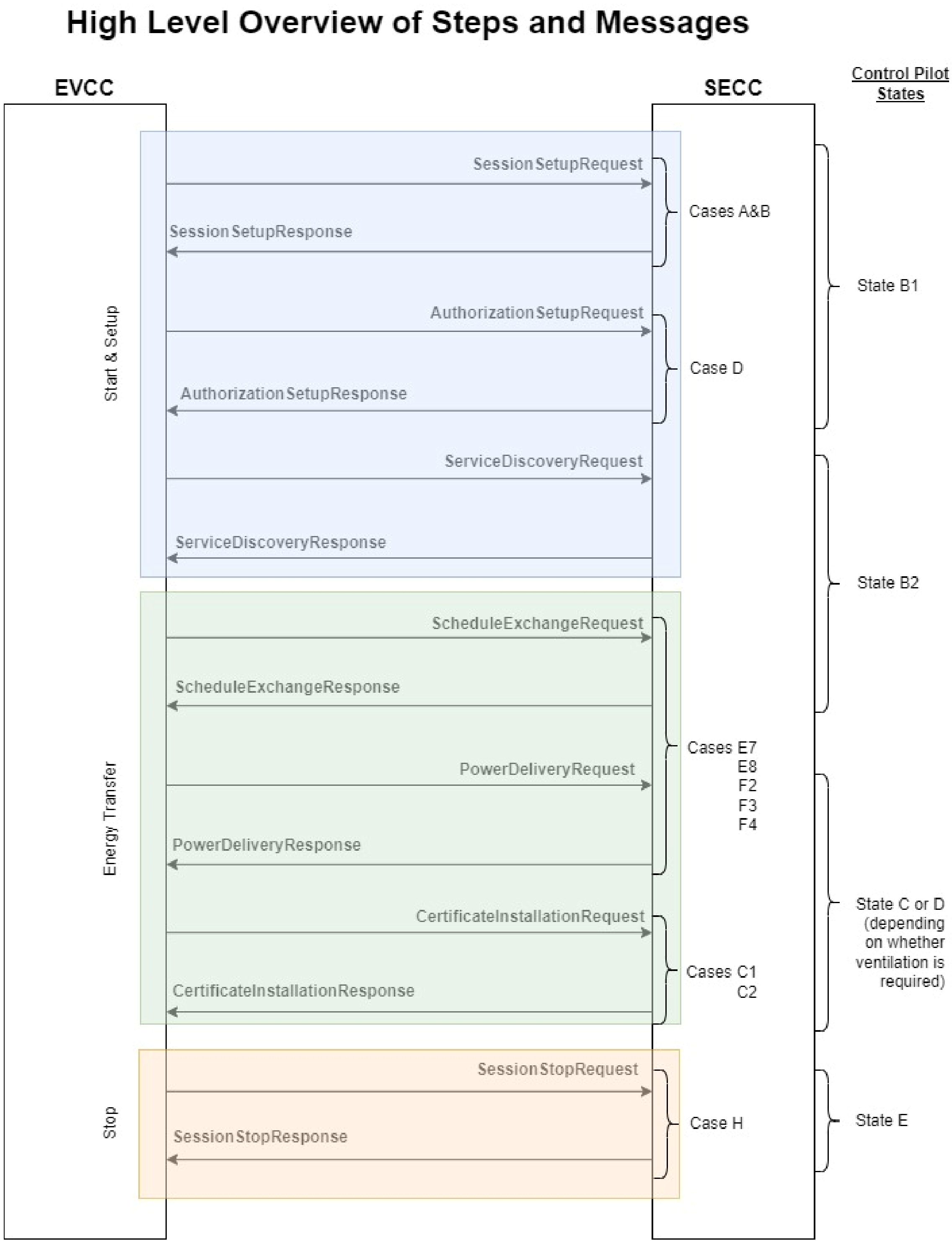

FIGURE 9: AN OVERVIEW OF THE MESSAGE EXCHANGE SEQUENCE FOR POWER TRANSFER & CORRESPONDING CONTROL PILOT STATES

5.4.5 Message Descriptions

SessionSetupRequest – The EVCC establishes a communication session.
SessionSetupResponse – The SECC notifies the EVCC whether establishing a new session was successful or not.
AuthorizationSetupRequest – Required to start the process of choosing the authorization method.
AuthorizationSetupResponse – The SECC provides information about the available authorization modes and whether the certificate installation service is available.
ServiceDiscoveryRequest – The EVCC finds out about all services provided by the SECC about charging and discharging. Each service (AC/DC/BPT) comes with a ServiceID.
ServiceDiscoveryResponse – The SECC provides a list of services from which the EVCC chooses one. The SECC informs the EVCC whether the selected services were accepted.
ScheduleExchangeRequest – The EVCC provides its energy transfer parameters like estimated energy amount for recharging & time when the user intends to leave the EVSE. EVCC can request for the energy transfer mode to be DC - dynamic or scheduled.
ScheduleExchangeResponse – The SECC responds with energy transfer mode set to DC.
PowerDeliveryRequest – The EVCC requests the SECC to provide power and transmits the "EVPowerProfile" it will follow during the energy transfer process. It can enable "BPT_ChannelSelection" to allow for reverse power flow/discharging. By sending "DC_ChargeLoopReq", the EV can display parameters like present voltage, current, SOC, and via the BPT messages specify limits for SOC, voltage, current, and power.
PowerDeliveryResponse – The SECC shall always accept the "EVPowerProfile" of the EVCC if it does not exceed the hard limits as defined by the boundaries of selected "ChargingSchedule", and in BPT use cases the "DischargingSchedule". If the limits are exceeded, the SECC may respond with the response code "WARNING_EVPowerProfileViolation" and trigger a schedule renegotiation.
CertificateInstallationRequest – The EVCC requests the SECC to deliver the certificates that belong to the currently valid contracts of the EV user.
CertificateInstallationResponse – The SECC sends the requested certificates which the EVCC installs as a contract certificate.
SessionStopRequest – The EVCC requests termination of the energy transfer process and can indicate the reason for doing so.
SessionStopResponse - SECC sends "SessionStopRes" informing the EVCC if terminating the energy transfer process was successful.

5.4.6 Messages to Initiate Discharge

The power delivery message exchange marks the point in time when the EVSE provides voltage to its output power outlet and the EV can start the power transfer. By sending the *PowerDeliveryReq,* the EVCC requests the SECC to provide power. The EVCC also transmits the *EVPowerProfile* it will follow during the energy transfer process. After receiving the *PowerDeliveryReq* message of the EVCC, the SECC sends the *PowerDeliveryRes* message including information if power will be available.

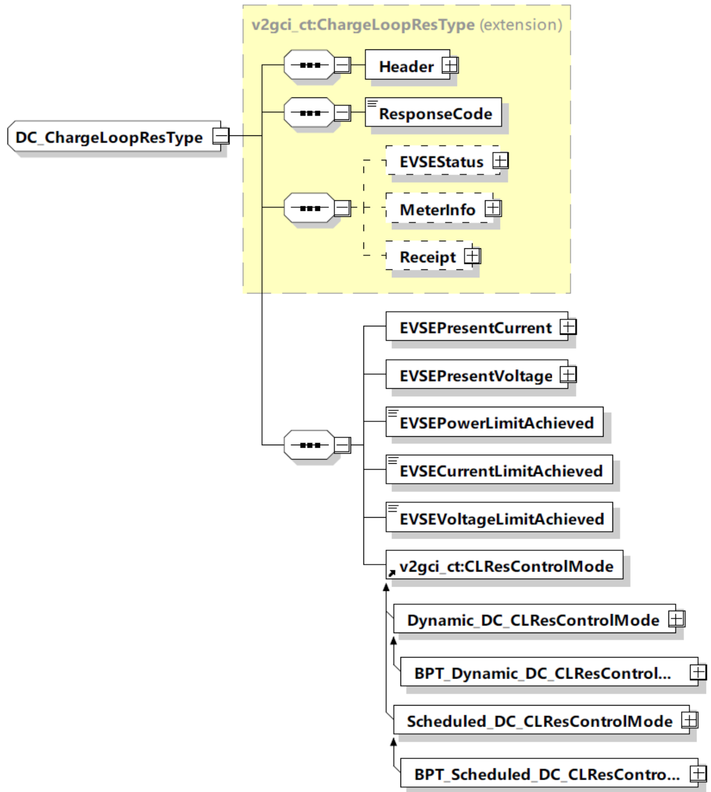

FIGURE 10: EVSE PRESENT CURRENT AND VOLTAGE BEING OBTAINED USING ISO 15118-20 [2]

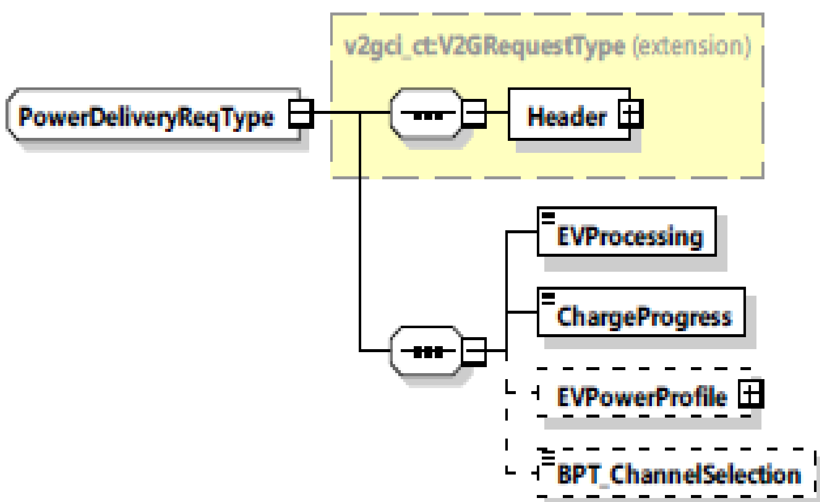

FIGURE 11: EVCC REQUESTING THE SECC FOR BIDIRECTIONAL POWER TRANSFER USING ISO 15118-20 [2]

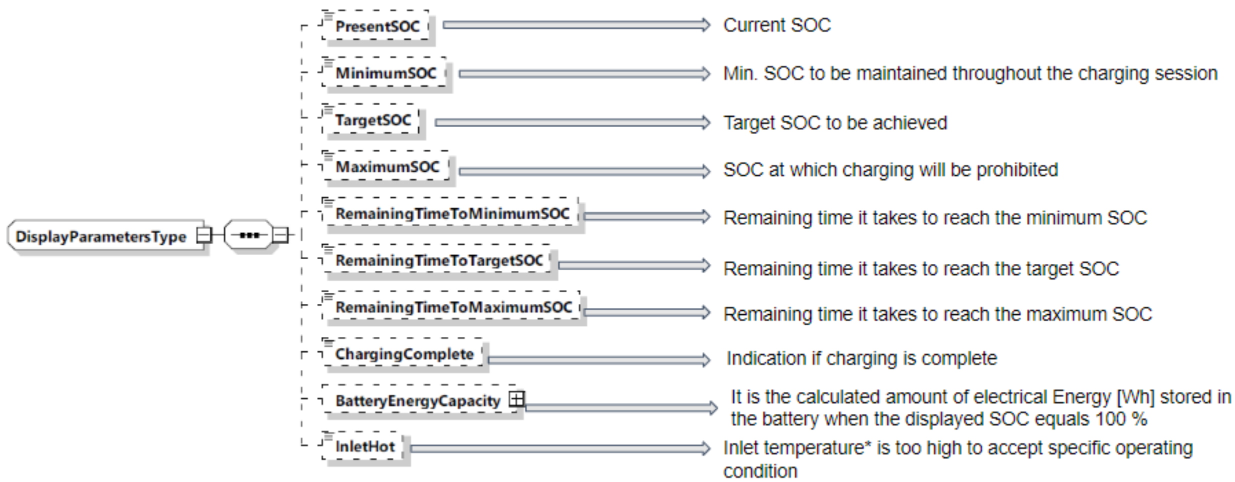

FIGURE 12: DISPLAYING SOC LIMITS, CHARGING STATUS AND BATTERY CAPACITY USING ISO 15118-20 [2]

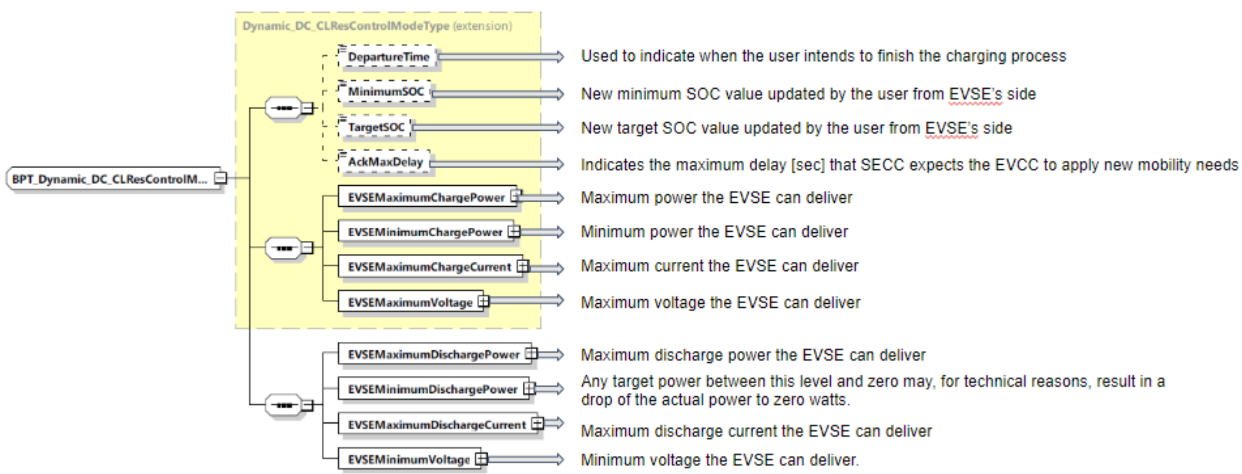

FIGURE 13: POWER TRANSFER LIMITS TRANSMITTED BY THE EVSE DURING DYNAMICALLY CONTROLLED BIDIRECTIONAL POWER TRANSFER USING ISO 15118-20 [2]

6.0 VEHICLE REQUIREMENTS TO ENABLE SAE J1634 SMCT

This section outlines the minimum requirements on the vehicles side that an OEM would need to implement or adhere to, to enable the SAE J1634 SMCT testing using ISO 15118 framework.

6.1 Hardware Requirements

6.1.1 Power electronics should be adequately sized to enable a DC discharge with power close to that of the 65-mph requirement through the charge/discharge port.

6.1.2 It should be ensured that there is no hardware with directional limitations, such as diodes or latches that only operate in one direction, thus preventing DC discharge.

6.2 Software and Controlled Discharge Mode (CDM):

The OEM must implement a method to put the vehicle in the SMCT Controlled Discharge Mode (CDM), like the dyno mode, using a scan tool or other triggers. This should:

6.2.1 Enable DC discharge when the vehicle is in park mode and override any power-down time-outs.

6.2.2 Allow DC discharge power levels that are comparable to the power limits enforced by the Battery Management System or Control Unit (BMS or ECU) during the discharge through the traction motor during normal driving, for the duration of the test. This includes any power limit enforced by the BMS (as it would during normal vehicular propulsion) that results vehicle speed limit threshold violation (<61 mph) thus signifying end of test. End of test criteria in the latest published revision should be referenced in the event the SAE standard J1634 [1] is revised.

- Most of the V2G and V2L power limits currently in production do not have the power rating required to conduct the J1634 SMCT.

6.2.3 Discharge must continue until the battery discharge power required to maintain 61 mph at the vehicle's stated road load is no longer available.

- 6.2.1, 6.2.2, and 6.2.3 collectively imply that the vehicle allows discharging AND at the desired rate AND allows a lower SOC.

6.2.4 Comply with ISO 15118.

- A communication stack based on ISO 15118 must be implemented in the Vehicle Control Unit (VCU).
- The communication stack should allow for the bi-directional power transfer with appropriate sign convention.
- This implementation should allow the vehicle to initiate a DC Discharge session based on communication with the discharge equipment.
- Based on the ISO standard:
    - The vehicle must be able to initiate a discharge session.
    - The vehicle must support the dynamic control mode, which enables the setting of discharge power limits from the discharge equipment side dynamically. Use case E8 supports this feature; use cases E6 or E7 can potentially be used with some modifications. This will depend on the implementation and could be studied during the implementation phase.
- The battery thermal management strategy should be active and maintained and all other safety systems should be active.
- Apply a battery thermal management strategy similar to traction operation, including active heating and cooling and temperature limits.

7.0 SAE J1634 SMCT DC DISCHARGE TESTING PROCEDURE AND WORK INSTRUCTIONS

This section covers a provisional, generic DC discharge process including the work instructions for performing SAE J1634 SMCT in an automated manner. It is assumed that all controlled discharge will be performed under J1634 ambient conditions requirements.

7.1 Pre-checks:

1. Ensure HV cables are isolated from the common ground in the circuit (Isolation check).
2. Ensure connection integrity between the test cell discharge controller and the load controller.
    - Ensure the load controller and load have no active faults present.
3. Ensure HV cables and connections are intact and in good condition.
4. Ensure connection integrity between the test cell discharge controller and the data acquisition (DAQ) system.
    - Verify signal configuration, acquisition rates, signal resolution/noise, etc.
    - Verify all signals of interest are in the recording configuration.
5. Verify the calibration of all devices are current.
    - This includes voltage monitors, current monitors, isolation monitors, contactors, etc.

7.2 Dyno Testing Process and Test Pre-conditioning:

Process recommended in the SAE J1634 SMCT needs to be followed for on dyno part of testing. The devices and equipment for DC discharge shall be placed in a temperature-controlled environment, and the vehicle shall be pre-conditioned in accordance with SAE J1634 [1].

7.3 Vehicle Transfer Off Dyno:

The vehicle needs to be moved to a soak area, without operating, for the DC discharge process within 1 hour of completion of the dyno test process per SAE J1634 [1]. The vehicle should be checked for faults and error codes before commencement of the test. Other parameters such as SOC and battery temperature should be checked to be at reasonable values on the DAQ before starting the test.

7.4 Discharge Process:

The following section outlines the procedure for performing the SAE J1634 SMCT [1]. Steps 1-5 pertain to the test setup and must be carried out by an operator, whereas steps 6-10 can be automated, constituting the majority of the test duration.

1. User provides dynamometer coefficients for the vehicle (A, B, C), estimated useable energy (UBE), and estimated DC discharge time (y_estimated).
2. Test cell discharge controller calculates the required power for the test and criteria for end of test (as defined in SAE J1634).
    a. Results of the calculation are displayed on the user interface for the user to review, which include power levels and estimated time with test tolerances per SAE J1634.

3. User verifies that the information provided by the test cell discharge controller matches testing parameters.
    a. User either accepts (go to 3b) or declines (go to 1) the calculations. DAQ starts recording.
    b. Test cell discharge controller closes the HV junction box contactors and confirms status through the remainder of the process. If the contactor state doesn't align with the measurements (pre, post), the test cell discharge controller will terminate the test.
    c. Test cell discharge controller waits for the user to plug in the cable.
4. User enables "controlled discharge mode (CDM)" in the vehicle. The mode shall be enabled through a proprietary tool or a special sequence of commands.
    a. Vehicle either confirms (go to 4b) or denies (go to 4) CDM.
    b. Vehicle notifies the user that the mode has been activated successfully.
    c. Step #5 may need to be completed before Step #4 depending on the vehicle software state machine.
5. User plugs in the cable to the charge/discharge port accessible on the exterior of the vehicle.
6. The vehicle controller and the test cell discharge controller exchange information as dictated by the framework in ISO 15118-20/2 [2, 3]. The recommended sequence is:
    a. Plug and force HLC [A1].
    b. Conductive communication setup [B].
    c. No authorization [Skip D].
7. If the information exchange is unsuccessful, the session will be terminated by the vehicle controller i.e., end of energy transfer period [H]. The plug will need to be unplugged and plugged back in (go to step 4 or 5). Alternatively, the test cell discharge controller will set the CP to state E or F and switch back to state B.
    a. The test cell discharge controller will provide the reason for session termination or provide a transaction log of the communication exchange with the vehicle controller.
8. On successful completion of information exchange, the energy transfer process can begin.
    a. The test cell discharge controller will send a notification to the DAQ system to start the recording process.
    b. The DAQ system will provide confirmation to the test cell discharge controller that the energy transfer process has begun.
9. The fast-responding energy transfer services based on dynamic mode [E8] use case from the ISO 15118-20/2 [2, 3] standard can be leveraged. Alternatively, the reverse power transfer on stand-alone operation [E7] use case can be utilized from the same standard. Preference for one use case over the other will depend on experimental evaluation of an actual discharge process. This facilitates the study of the relative benefits and drawbacks, which may not be apparent in the standard.
    a. The test cell discharge controller will exchange parameters relevant to the test such as power limits, voltage, and current measurements, voltage, and current limits, etc.

The vehicle in CDM must be capable of accepting/acknowledging the test parameters specified by the test cell discharge controller.

b. The vehicle controller will close its internal contactors, providing access to the HV system.
c. The test cell discharge controller will check the isolation status and verify contactor status through voltage measurements. If any of these checks fail, the test will be terminated (go to 10).
d. The test cell discharge controller will begin the actual discharge by sending the power request to the load controller. The power request can be a ramp transition provided it doesn't exceed a rate of 100kW/s which is representative of moderate acceleration in a light duty vehicle.
    i. If the load controller starts the discharge process but is unable to meet the power requirements, the test shall be deemed invalid and terminated (go to 10).
    ii. The test cell discharge controller will monitor and compare the discharge power calculated using the measurement between the vehicle and the load, the power reported by the load controller, as well as any other independent measurements in the vehicle (conducted as part of the SAE J1634 dyno test). It is recommended that if a discrepancy of more than 2% is observed between the two measurements or calculations at any point during the discharge process, the test shall be deemed invalid and terminated (go to 10). The magnitude of discrepancy (2%) is derived from J1634 requirements, which mandate measurements within 1% of reading or 0.3% of full scale (whichever is higher). The initial assumption is that if two independent measurements are off by 1% in opposite directions, it would still be considered valid. Alternatively, a value other than 2%, determined based on measurement locations and good engineering judgment, could be used to account for variations in measurement setup and methods.
    iii. If communication between any nodes (test cell discharge controller, vehicle controller, load controller, DAQ, isolation monitor, etc.) is lost and not recovered within a suitable timeout period during the process, the test shall be terminated, and results deemed invalid.
e. The discharge process will continue until the end-of-test criteria is met. Alternately, the vehicle can terminate the process before the end-of-test criteria is met, which will result in an invalid test.
    i. The actual discharge power and vehicle's maximum discharge power as estimated by the BMS or ECU and available on CAN or OBD, should be monitored and compared. The off-board charger/ test cell discharge controller should terminate discharge process if the actual discharge power exceeds the maximum discharge power limit.

10. Once the end of test criteria is met, or if test is aborted due to faults, the test cell discharge controller will stop the discharge by sending the appropriate command to the load controller.
    a. If the load controller doesn't reduce the discharge power as requested by the test cell discharge controller, the test cell discharge controller will forcibly stop the process by opening the contactors (go to 12). The test will still be deemed valid, and the test cell discharge controller should alert the user.
11. If the preference is to use [E7] in step 9, then the energy transfer loop with interrupt from SECC (use case [F2]) can be leveraged to end the discharge session.
    a. Alternately, if use case [E8] is used in step 9, energy transfer control based on dynamic control mode [F4] has to be used by the test cell discharge controller to interrupt the process.
12. Once the end of discharge has been confirmed through independent measurement of current, the test cell discharge controller will open the contactors.
    a. Test cell discharge controller will send an indication to the DAQ system to stop the recording process.
13. In the last steps for terminating a session, the following framework is recommended:
    a. No certificate installation/update [Skip C].
    b. End of energy transfer period [H].
14. Upon completion of the session, the test cell discharge controller will notify the user to unplug the cable from the vehicle and will provide a pass/fail indication for the test. The pass-fail indication will also be based on Section 9.3.8 from SAE J1634, which requires the DC discharge time to be within 5% of the initially estimated time. This will be calculated by the supervisory controller. Other results, such as the battery energy used, equivalent distance covered, initial and final SOC, and discharge power may be displayed as well.

    The discharge process is depicted in the Process Diagram in Appendix A-1.

8.0 MINIMUM HARDWARE AND SOFTWARE REQUIREMENTS FOR SAFETY AND FUNCTIONALITY

The minimum hardware and software requirements for functionality and safety have been derived by going through a Failure Mode Effect and Analysis (FMEA) process. The following assumptions have been made in the FMEA:

1. The EV has an exterior charging connector compliant with SAE J1772 [4] or IEC 62196 [10] or NACS that supports ISO 15118 [8].
2. The EV charge/discharge controller and test cell discharge controller can support ISO 15118-20 (bi-directional energy transfer) and can exchange information as defined in the standard.
3. Since all communication requests (for charge and discharge) in ISO 15118 need to originate from the EV controller, the vehicle has to be able to enter a "controlled discharge

mode" (CDM), through user intervention, that provides unthrottled (within safety limits) access to the high-voltage (HV) system.

4. HV cables used are sized for maximum current expected during discharge.
5. The test cell discharge controller has access to the following components on the HV connection between the EV and the load:
    a. Independent contactor on both the positive and negative HV cables rated for 1,000 V and 100 A that can be directly controlled. It should also provide feedback of its current state (closed/open) through a secondary means (limit switch). Further, it would be beneficial to have it configured as an active low limit switch so that any loss in connection can be recognized before the test.
    b. Independent devices/transducers to measure voltage between the positive and negative HV cables before the contactor (towards the vehicle side) and after the contactor (towards the discharge side). The measurement accuracy of these devices/transducers should comply with SAE J1634.
    c. Independent device/transducer to measure current on the positive cable after the contactor (towards the discharge side). The measurement accuracy of this device/transducer should comply with SAE J1634.
    d. Independent device to measure the isolation between the HV cable and the common ground in the network.
6. The data acquisition system (DAQ) and its recorded signals and information meet the requirements for recording test data as specified in SAE J1634. These include engineering resolution, acquisition frequency, filtering, calculation, etc. If the acquisition, filtering, and calculations are done on a separate device (such as the test cell discharge controller), it needs to meet the SAE J1634 [1] requirements as well.
7. There should be a load controller that can ensure HV integrity throughout the circuit before initiating the discharge process. This can include passive circuits within the load itself that minimizes HV potential difference between the load and the vehicle before the actual power transfer.
8. The load controller can regulate load to accommodate fine adjustments in discharge power. It can also measure voltage, current, and calculate power and energy independently. It can report these measurements and calculations to the test cell discharge controller.

    Notes:

    The discharge process, hardware architecture, software architecture, and data exchange can be simplified by combining the test cell discharge controller, supervisory controller, load controller, and the DAQ into one hardware or software system. However, in this document, they will be referenced individually to differentiate their functional roles.

8.1.1 Hardware:

1. Isolation checks between the high voltage cable and common ground in the network must be performed before and during the discharge process to ensure safe discharge operation. [Safety]

    a. Configuration of the isolation monitor must be verified before the initiation of the test. This includes engineering limits and connection points used to assess isolation breakdown.
    b. The checks should be automated by the test cell discharge controller, especially for the ones done during the discharge process. To facilitate this, the isolation monitor should have a means to communicate the current isolation state to the test cell discharge controller.
2. Connection integrity between various devices (test cell discharge controller, DAQ, load controller, voltage monitors, current monitor, isolation monitor) must be verified before initiating the discharge process. [Safety]
    a. Cables (including HV) must be inspected for loose connections, wear, and improper orientation (bends, kinks, etc.) before initiating the discharge process.
    b. Once discharge is initiated, a robust connection state between various smart devices must be established through continuous checks (either via a watchdog or other mechanism). The devices include, at a minimum, the test cell discharge controller, the load controller, the vehicle controller, and DAQ.
    c. In the absence of this check, the discharge process should be terminated to ensure safety of personnel and equipment. The termination process should be automated to minimize the need for user intervention. The termination process could follow a shutdown routine as described in the process document.
3. In-vehicle measurement and instrumentation can be leveraged during the discharge test. Ideally, these measurements should be similar to the independent ones made by the load controller and test cell discharge controller, but some deviation can be expected. Only one of these measurement sources should be used for the actual calculations done to determine the end of test criteria and recording data. The others can be used for real-time verification and ensuring the validity of the test. [Functional]
4. In case of termination of the discharge process due to functional device malfunction (contactors, load, etc.), proper care must be taken to ensure the system is completely powered down and free of HV energy before inspection or troubleshooting. [Safety]
5. Battery backup power must be installed on all critical systems (test cell discharge controller, load controller, DAQ). [Functional and Safety]
    a. A hardware interlock must be present between these systems to recognize a power interruption and to facilitate a safe shutdown. This will not be required if these systems are combined into one function hardware, software unit.
6. Measurement devices should be routinely inspected for calibration status. Periodic maintenance should be performed on active devices (transducers, limit switches, etc.). [Functional and Safety]
    a. Device configuration (transducer switches, knobs, etc.) must be verified before initiating a test.
7. A physical emergency stop (e-stop) button must be present that can disable the HV circuit. The button should be easily accessible to the operator. [Safety]

    a. The e-stop can be tied to the independent contractors or the interlock circuit (if present and compatible) to remove HV from the circuit.

8.1.2 Software:

1. Signal configuration, resolution, noise, etc., should be confirmed to be within acceptable limits before initiating the discharge process. This includes signals on devices that dictate the sequence of the discharge process and may not be used for recording purposes. [Functional]
    a. Measurement signals should have valid calibrations to ensure data integrity.
2. The operator should have the ability to review and confirm discharge parameters, end of test criteria, and other test details before initiation of the test. This could include a procedural step in the process that prevents the start of the test before the operator accepts the test parameters. [Function and Safety]
3. State of the independent contractors should be confirmed throughout the discharge process. In case of discrepancy, the discharge process should be terminated. [Safety]
4. Faults or errors reported by the load controller, vehicle controller, or DAQ should result in termination of the discharge process. [Safety]
    a. ISO 15118 has a framework to report vehicle errors but may not provide details of the error itself.
    b. The load controller should be able to enter a safe state (which would include removal of any load from the HV circuit) upon encountering an error/fault. In case if it is unable to report this, the test cell discharge controller should recognize the abrupt removal of load through the independent measurement and initiate a termination of the discharge process.
    c. If the DAQ is unable to report error/faults, at a minimum it should stop the watchdog counter or any other mechanism used to establish communication integrity. The test cell discharge controller could then terminate the process based on 2b.
5. Throughout the discharge process, the operator/user interface must display the current state/step in the process. This could be a progress bar or state and remaining time display. [Functional and Safety]
    a. If the discharge process is terminated, the interface should display the reason for termination. It could be a normal termination (triggered by end of test criteria) or the result of self-reported fault(s) from one of the smart devices or forceful termination from the vehicle controller.
    b. Additional information such as plug state (connected/disconnected), voltage, current, SOC, power can also be included in this interface.
6. The test cell discharge controller acts as the central device throughout the process. It determines the beginning and the end of the process and therefore must coordinate with the DAQ to ensure all essential signals are recorded throughout the process. [Functional and Safety]

7. Isolation breakdown reported by the monitor should result in termination of the test. [Safety]
    a. If this is reported through digital communication, an integrity check (query/last response time) must be performed throughout the test to ensure the validity of the data received. If the communication integrity check fails (stale data), the test cell discharge controller should terminate the discharge process.
8. Independent measurements (voltage, current) and calculations (power, energy) done by the test cell discharge controller and load controller must be within set percentage of one another. The value needs to be determined based on measurement locations and good engineering judgment. In case of discrepancy between the two, the test cell discharge controller should terminate the process. [Functional and Safety]
    a. Furthermore, the two voltage monitors should be within 1% of each other when the contactors are closed and HV present.

9.0 KNOWN LAB EQUIPMENT

For the ISO 15118 communications interface, some off-the-shelf solutions are listed below:

- Vector VT7970 [18]
- dSPACE 5366 [19]
- Keysight SL1040A Charge Discovery Systems and SL1093A Charging Discover

Additionally, the communications stack can be implemented using open-source libraries hosted on GitHub [20]. Once the procedure has been shaken down and tested, suitability of off-the-helf and production-ready charge/discharge communications interfaces could be studied.

Devices listed in Table 3 can be used for DC discharge. It should be noted that this not an exhaustive list of all devices available in the market and that the product offerings, specifications and features could vary from the list.

TABLE 3: LIST OF KNOWN DC DISCHARGE DEVICES

Manufacturer	Model	Max Voltage	Max Current (A +-)	Max Power Draw (kW)	Method of Controlling Equipment Externally
NH Research [21]	9300 Series	600-1200	333-167	100	Interchangeable Virtual Instruments (IVI) Standard Commands for Programmable Instruments (SCPI) LabVIEW or Veristand

TABLE 3: LIST OF KNOWN DC DISCHARGE DEVICES

Manufacturer	Model	Max Voltage	Max Current (A +-)	Max Power Draw (kW)	Method of Controlling Equipment Externally
Bitrode Corporation [22]	FTF	750	1200	300	CAN Ethernet with VisuaLCN Lab Client software 3rd party software control through Remote Binary Protocol (RBP) via Ethernet connection.
Webasto [23]	ABC-150	420	265	125	CAN Remote Operation System DCOM Driver for LabVIEW C++ and Visual Basic

Additionally, devices listed in Table 4 offer the required specifications and features. These have been included based on the features mentioned on public-facing websites and specification sheets. In addition, DC load banks could be used if the controller can be setup appropriately as per the requirements and/or paired with a pre-charge circuit.

TABLE 4: ADDITIONAL LIST OF DC DISCHARGE DEVICES

Manufacturer	Model	Max Voltage	Max Current (A +-)	Max Power Draw (kW)	Method of Controlling Equipment Externally
Chroma Systems Solutions [24]	17040	1000	1500	600	SCPI CAN CAN FD Local Interconnect Network (LIN) LabVIEW, C/C++, Python, .NET
Maccor, Inc [25]	8500	1500	2000		CAN I2C SMBus

TABLE 4: ADDITIONAL LIST OF DC DISCHARGE DEVICES

Manufacturer	Model	Max Voltage	Max Current (A +-)	Max Power Draw (kW)	Method of Controlling Equipment Externally
Keysight [26]	SL1710A	1000	300	90	Can work with SL1040A and SL1093A for a complete package for J1634 testing [27]
Arbin Instruments [28]	RBT Series	1500	1000	1000	CAN

10.0 REFERENCES

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14. IEEE Standards Association, "IEEE Standard for Interconnection and Interoperability of Distributed Energy Resources with Associated Electric Power Systems Interfaces," IEEE Standard 1547™-2018, Rev. Feb. 2018.
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17. https://www.epa.gov/system/files/documents/2023-10/23-testcar-2023-10-25.xlsx
18. https://www.vector.com/us/en/products/products-a-z/hardware/vt-system/vt7970/
19. https://www.dspace.com/en/inc/home/products/special_solutions/smart-charging-solution.cfm
20. https://github.com/SwitchEV/iso15118

21. https://nhresearch.com/power-electronics-test-systems-and-instruments/battery-emulation/high-voltage-battery-emulator-9300-series/
22. https://www.bitrode.com/model-ftf/
23. https://www.evtestsystems.com/abc-150
24. https://www.chromausa.com/product/regenerative-battery-pack-test-17040/
25. http://www.maccor.com/Products/HevPhevEvTester.aspx
26. https://www.keysight.com/us/en/products/hev-ev-grid-emulators-and-test-systems/scienlab-battery-test-systems/sl1700a-series-scienlab-battery-test-system-pack-level.html
27. https://www.keysight.com/zz/en/product/SL1040A/sl1040a-series-scienlab-charging-discovery-system.html
28. https://arbin.com/battery-test-equipment/battery-test-product-series/rbt-series/

APPENDIX A-1
PROPOSED DISCHARGE PROCESS

Acronyms

TCDC - Test Cell Discharge Controller

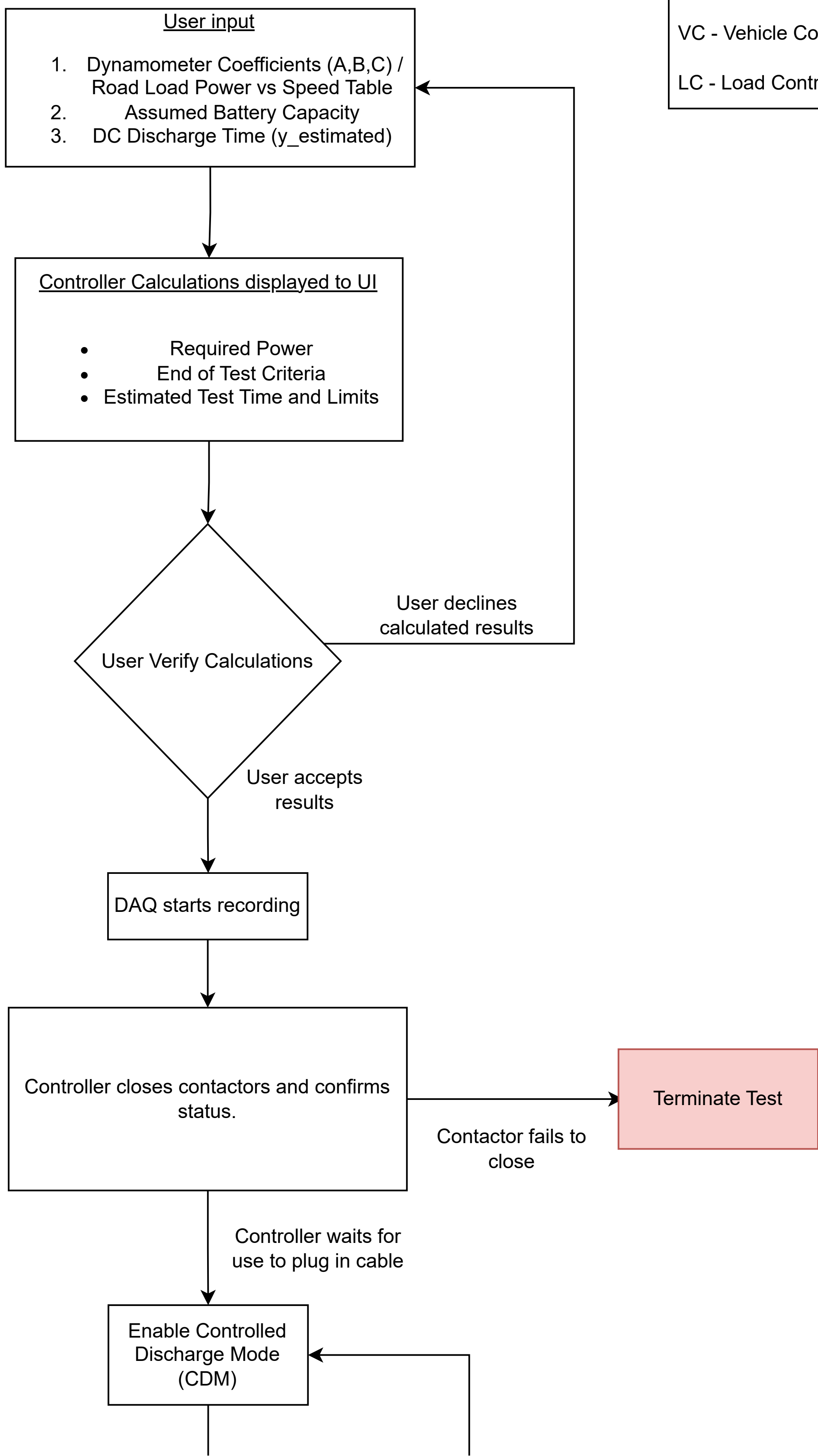
UI - User Interface

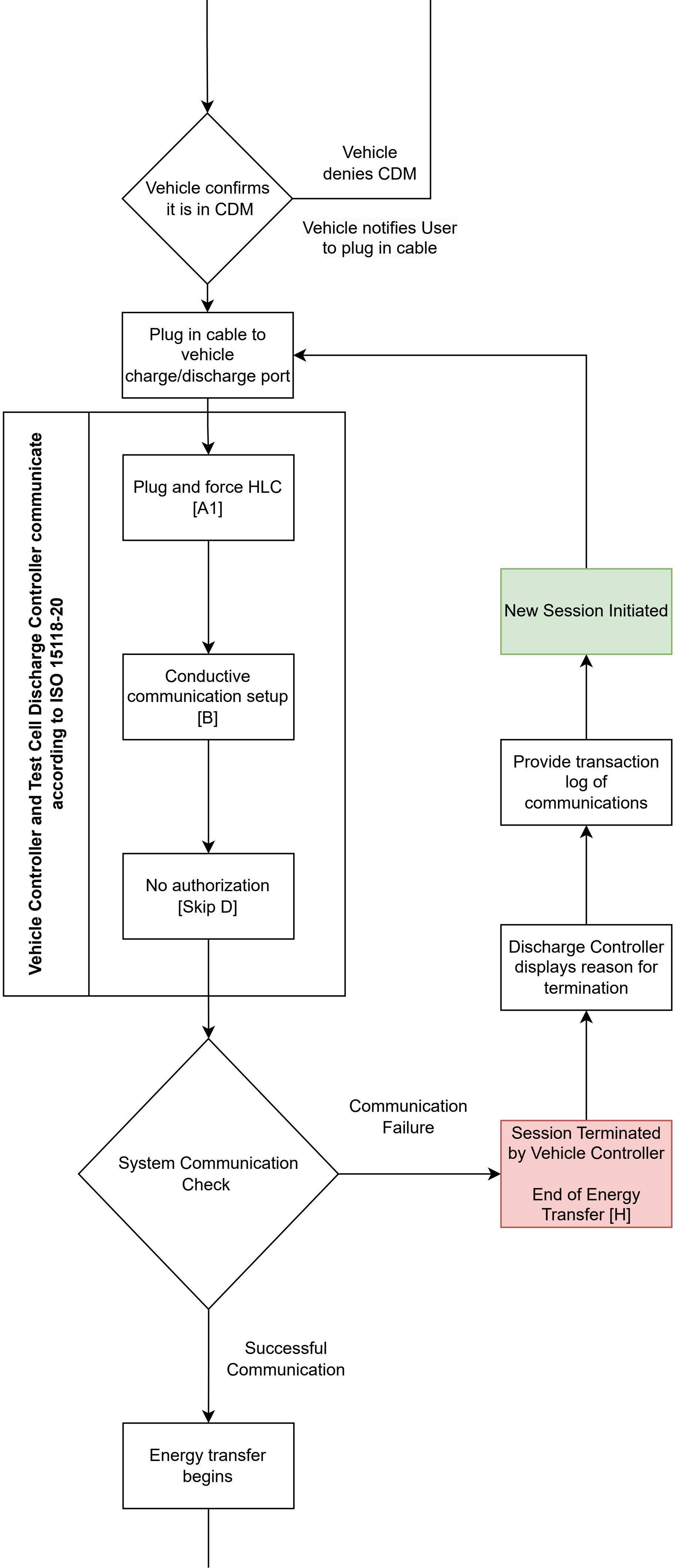
CDM - Controlled Discharge Mode

DAQ - Data Acquisition

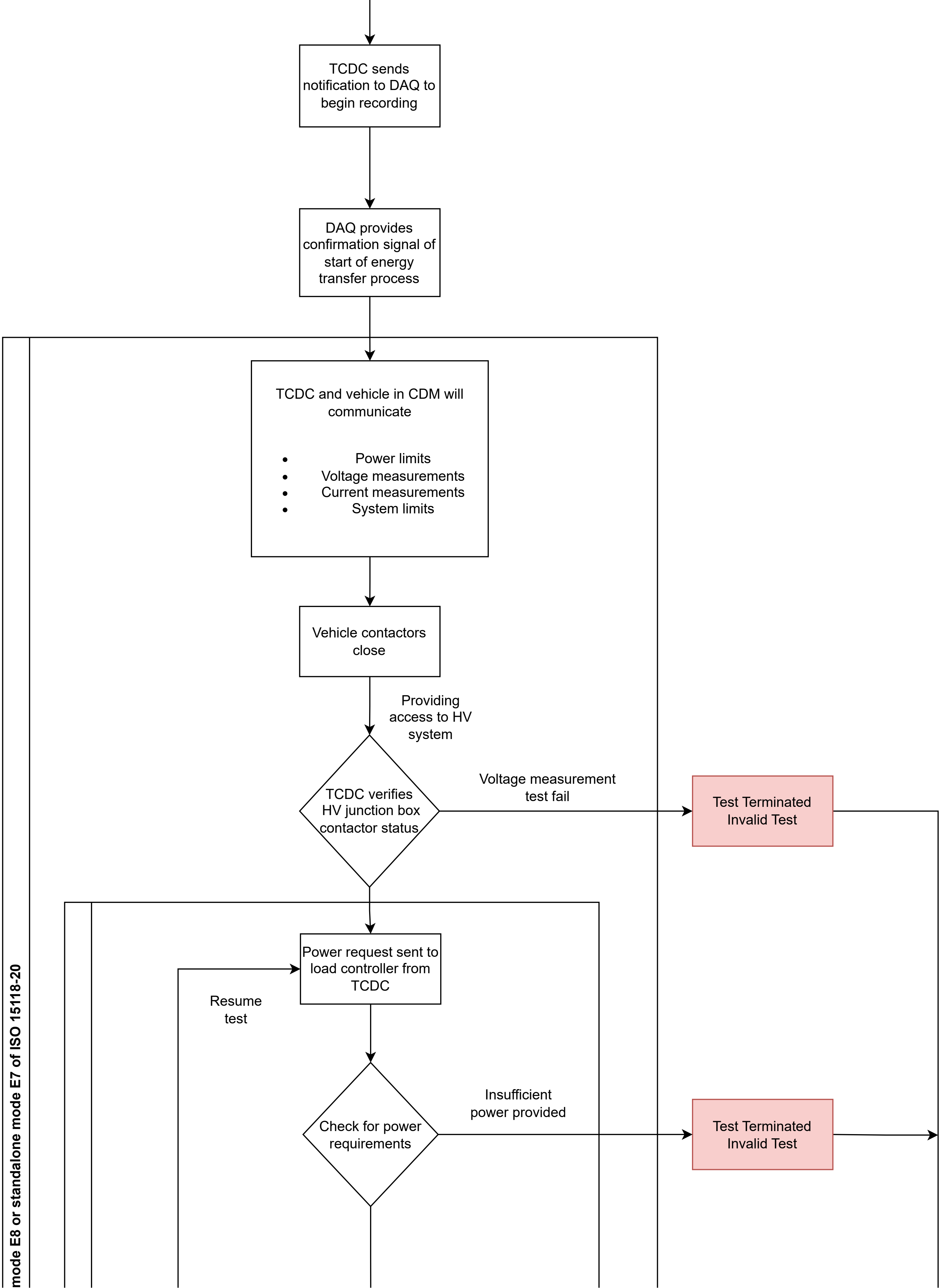
VC - Vehicle Controller

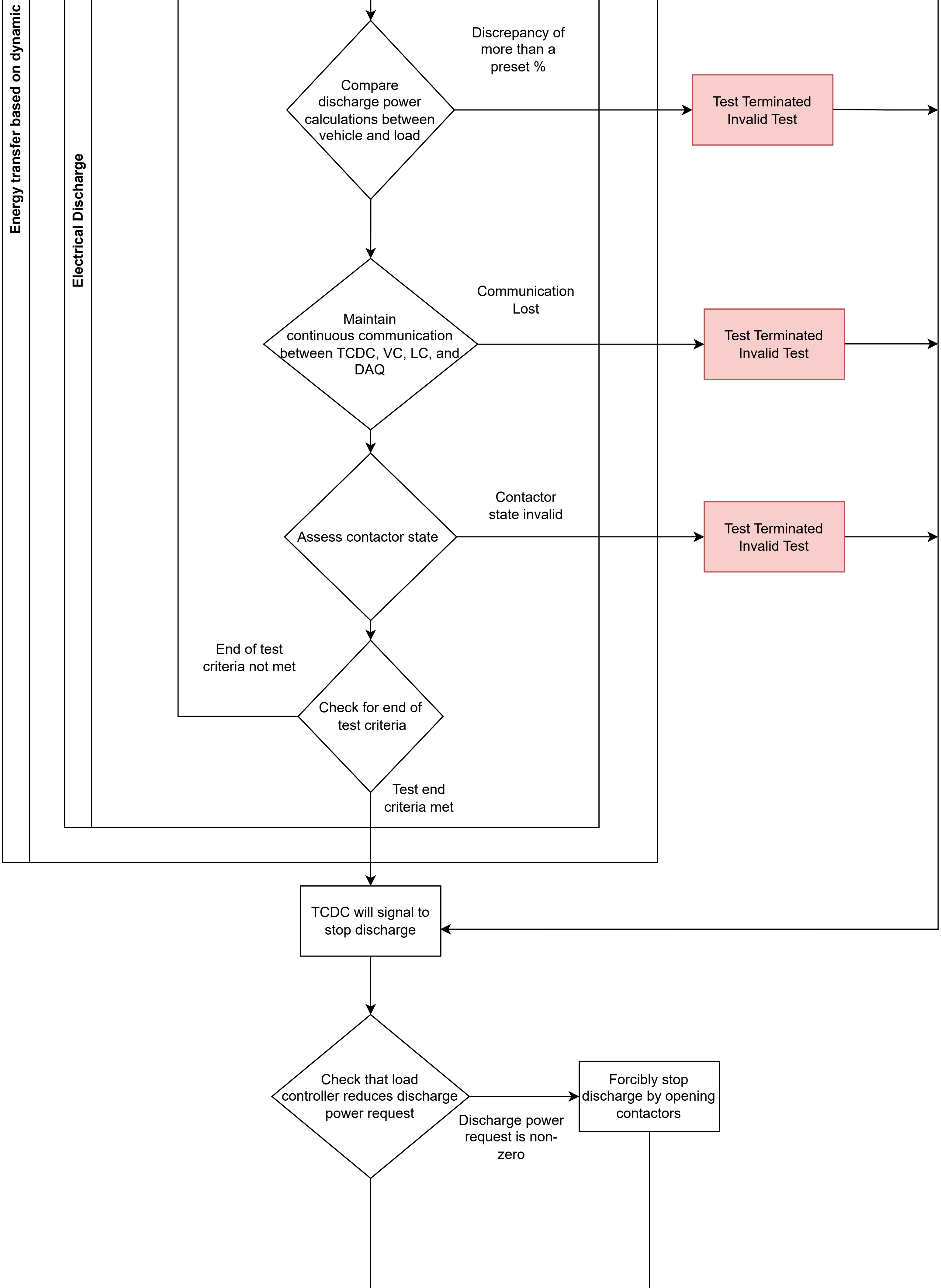
LC - Load Controller

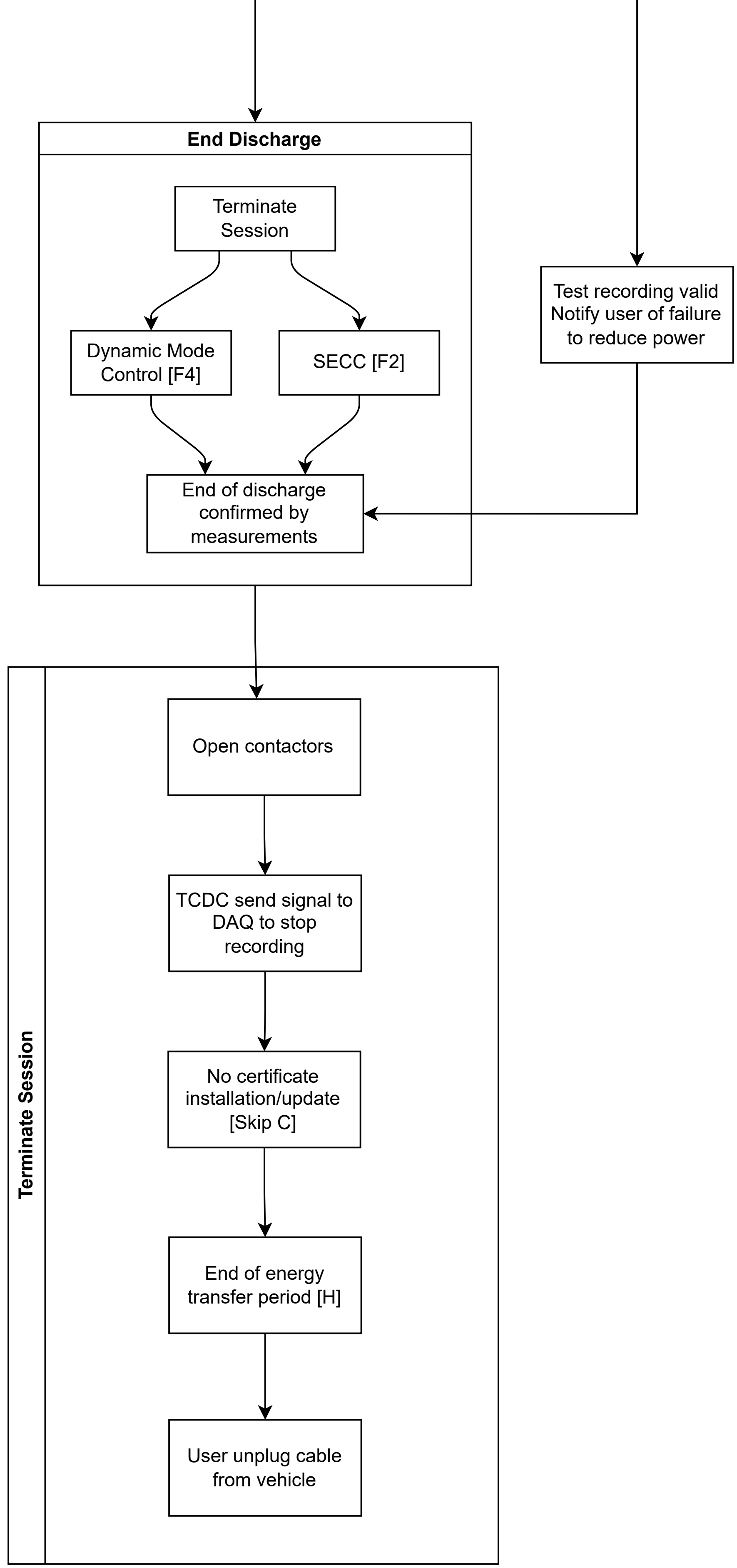




Vehicle confirms it is in CDM
Vehicle denies CDM
Vehicle notifies User to plug in cable
Plug in cable to vehicle charge/discharge port
Vehicle Controller and Test Cell Discharge Controller communicate according to ISO 15118-20
Plug and force HLC [A1]
Conductive communication setup [B]
No authorization [Skip D]
New Session Initiated
Provide transaction log of communications
Discharge Controller displays reason for termination
Communication Failure
Session Terminated by Vehicle Controller
End of Energy Transfer [H]
System Communication Check
Successful Communication
Energy transfer begins


TCDC sends notification to DAQ to begin recording
DAQ provides confirmation signal of start of energy transfer process
TCDC and vehicle in CDM will communicate
Power limits
Voltage measurements
Current measurements
System limits
Vehicle contactors close
Providing access to HV system
TCDC verifies HV junction box contactor status
Voltage measurement test fail
Test Terminated Invalid Test
Power request sent to load controller from TCDC
Resume test
Check for power requirements
Insufficient power provided
Test Terminated Invalid Test
mode E8 or standalone mode E7 of ISO 15118-20


Energy transfer based on dynamic
Electrical Discharge
Compare discharge power calculations between vehicle and load
Discrepancy of more than a preset %
Test Terminated Invalid Test
Maintain continuous communication between TCDC, VC, LC, and DAQ
Communication Lost
Test Terminated Invalid Test
Assess contactor state
Contactor state invalid
Test Terminated Invalid Test
Check for end of test criteria
End of test criteria not met
Test end criteria met
TCDC will signal to stop discharge
Check that load controller reduces discharge power request
Discharge power request is non-zero
Forcibly stop discharge by opening contactors



End Discharge
Terminate Session
Dynamic Mode Control [F4]
SECC [F2]
End of discharge confirmed by measurements
Test recording valid Notify user of failure to reduce power
Terminate Session
Open contactors
TCDC send signal to DAQ to stop recording
No certificate installation/update [Skip C]
End of energy transfer period [H]
User unplug cable from vehicle

APPENDIX A-2
REVIEW OF SAE J3400 FOR SAE J1634 SMCT

REVIEW OF SAE J3400 FOR SAE J1634 SMCT

SAE J3400, a technical information report covering safety and functional requirements for NACS connectors for DC or single-phase AC power transfer, was released in December 2023. The following standards are referred to for any V2X communication as part of AC and DC power transfer requirements:

- Subsection 7 of J3400 refers to SAE J2847/3 using IEEE 2030.5 for V2X communication for AC transfer.
- Subsection 8 of J3400 refers to SAE J2847/2 using ISO 15118-2 for V2G/V2H communication for DC transfer.

These standards have been reviewed in Appendix A, and no exceptions to the already recommended protocols for performing SAE J1634 SMCT testing are found in J3400.

Section 9 of SAE J3400 contains information on bidirectional power transfer, which is an optional requirement. If reverse power transfer is implemented, requirements in this section must be met. Subsection 9.4 of SAE J3400 covers general requirements for reverse power flow. It refers to:

- The ISO 5474 series, which has functional and safety requirements for reverse power flow, is currently under development and has not been published yet.
- It mentions that if ISO 5474 is not published, ISO 17409 can serve as a substitute, covering only safety requirements.

Additional requirements are under consideration for future revisions. Reverse power flow is not discussed in other sections of the report. Once the ISO 5474 series or future revisions of SAE J3400 are released, there will be more clarity on guidelines for reverse power flow.

APPENDIX B
PRIUS PRIME TESTING

TABLE OF CONTENTS

LIST OF ACRONYMS AND ABBREVIATIONS

CAN Controller Area Network
DAQ Data Acquisition
DTC Diagnostic Trouble Code
ECU/M Engine Control Module
EV Electric Vehicle
HCM Hybrid Control Module
HV Hybrid Vehicle
HVAC Heating, Ventilation, and Air Conditioning
HVBM High Voltage Battery Module
LV Low Voltage
OBD On Board Diagnostics
PCM Powertrain Control Module
SOC State of Charge

LIST OF FIGURES

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1.0 INTRODUCTION

The purpose of this testing was to explore off-dyno methods for discharging a high voltage battery pack from a high SOC to a specified target SOC. Several potential methods were identified for trial in this test plan. The desired outcome was to identify a method, or methods, that would discharge the HV battery from "full" to an SOC of 50% (+/-1%) within five (5) hours. Testing was conducted on a CRC-owned Prius Prime PHEV (PRI877).

2.0 METHODOLOGY

Each discharge method was initiated from a common starting condition. Before each discharge test, the vehicle was left to charge in a climate-controlled soak area for at least 16 hours. Prior to initiating a test, the vehicle's charge state was confirmed through both High Voltage Battery Module (HVBM), the control module on the vehicle that transmits the message on CAN/OBD and dashboard display values.

Three discharge methods were tested: two utilizing on-board climate control systems to provide the electrical load, and one with an externally applied electrical load. The state of charge was monitored at regular time intervals throughout the discharge tests until the HVBM reported an SOC of less than 50%. Throughout testing, the vehicle was monitored to ensure it did not automatically turn off (time out) or switch to engine/ICE mode.

Discharge rates and total discharge times were compared across the three methods to determine the most effective off-dyno discharge method.

3.0 TESTING

One test was conducted per day, with an overnight charge/soak period of at least 16 hours. Data was collected with a test stand DAQ system. Additionally, dashboard-displayed SOC and time was manually recorded on a test log.

3.1 Instrumentation and Measurements

External instruments used for testing are listed in Table 1. No additional aftermarket instrumentation/modification was required for the vehicle itself. Recorded test data and DAQ signals are listed in Table 2.

TABLE 1: REQUIRED INSTRUMENTATION

Instrument	Application	Rate/Accuracy
CAN/OBD Logger	Various OBD channels	~10 Hz
Digital Multimeter	Aux battery monitoring	+/- 0.05 V
Timer	Test monitoring	+/- 1 sec
1200 W Power Inverter	Power external load	N/A
External Load	750-1000 W power draw	Varies
Power Usage Monitor	Measure external loading	+/- 1 W

TABLE 2: DAQ SIGNAL LIST

Signal Description	Source	DAQ Rate	Unit	Accuracy
Test time	Test log	Varies	h:m:s	+/- 10 sec
Time of day	Test log	Varies	h:m	+/- 1 min
Dashboard SOC	Test log	Varies	%	+/- 1%
Ambient temperature	Dyno DAQ	10 Hz	deg F	+/- 0.1 deg
Engine RPM	OBD-ECU	~10 Hz	RPM	+/- 1 RPM
Battery voltage	OBD-PCM	~10 Hz	V	+/- 0.01 V
Ambient temperature	OBD-PCM	~10 Hz	deg C	+/- 0.01 deg
Engine run time	OBD-PCM	~10 Hz	sec	+/- 0.01 sec
Aux battery voltage	OBD-HCM	~10 Hz	V	+/- 0.01 V
Aux battery current	OBD-HCM	~10 Hz	A	+/- 0.01 A
Charger input power	OBD-HCM	~10 Hz	W	+/- 0.01 W
HVAC input current	OBD-HCM	~10 Hz	A	+/- 0.01 A
Aux battery temp (smoothed)	OBD-HCM	~10 Hz	deg C	+/- 0.01 deg
Target DC/DC converter V	OBD-HCM	~10 Hz	V	+/- 0.01 V
Engine Mode	OBD-HCM	~10 Hz	T/F	N/A
HVB AC consumption power	OBD-HBVM	~10 Hz	kW	+/- 0.01 kW
HVB current	OBD-HBVM	~10 Hz	A	+/- 0.01 A
HVB voltage	OBD-HBVM	~10 Hz	V	+/- 0.01 V
HVB SOC	OBD-HBVM	~10 Hz	%	+/- 0.01 %

3.2 Test Setup

As per standard safety and laboratory control procedures, testing was conducted with the vehicle installed on one of the available chassis dyno test stands (SwRI Building 87, Dyno 7). The vehicle was secured using front straps and rear wheel chocks, and the out-of-roof exhaust tunnel was attached to the tailpipe to capture exhaust gases in the event that the engine turned on at any point during testing. Any additional instrumentation was installed at this point (re: Test Procedure, Discharge Method 3 below).

A standard OBD scan tool was used to check the vehicle for any DTCs before each test, prior to connecting the vehicle to the test stand CAN Logger via the OBD port.

The vehicle was manually set to EV Mode. All windows were rolled down. Both the dashboard displayed, and OBD-reported SOC values were confirmed to report a fully charged state, 100% and ~83%, respectively, before initiating the test.

3.3 Test Procedure

Each test was initiated, with the DAQ system recording, by applying one of the electrical loading strategies described in section 3.4. The vehicle status and SOC were monitored throughout the test and recorded in the test log, according to OBD-reported SOC, by the following schedule:

- SOC > 65% - every 15 minutes
- SOC < 65% - every 5 minutes

Testing ended when the OBD-reported SOC dropped below 50%.

3.4 Discharge Methods

The following describe the three power-draw methods used to discharge the HV battery. These methods include use of vehicle accessories, external load, and Heating, Ventilation, and Air Conditioning (HVAC) system. Except those detailed by individual method below, all vehicle accessories (headlights, radio, etc.) were OFF throughout each test.

3.4.1 Method 1: HVAC Cold with Seat Heaters

- Climate control/HVAC
  - HVAC ON
  - HVAC fans set to maximum speed
  - HVAC set to lowest temperature
- Seat heaters on maximum setting

3.4.2 Method 2: HVAC Hot with Seat Heaters

- Climate control/HVAC
  - HVAC ON
  - HVAC fans set to maximum speed
  - HVAC set to highest temperature
- Seat heaters on maximum setting

3.4.3 Method 3: External Load

- Climate control OFF
- Seat heaters OFF
- External load applied via power inverter connected to the vehicle's auxiliary battery.

The external load was provided by a rack of cooling fans powered by the 12 V vehicle's auxiliary (low voltage) battery via a 1200 W inverter, shown below in Figure 1. The rack consisted of two fixed-speed fans (orange) and two variable-speed fans (yellow). The power draw was monitored using a residential-grade power monitor (Figure 2). The variable-speed fans were set such that the total power draw of the rack was between 750 W and 800 W.

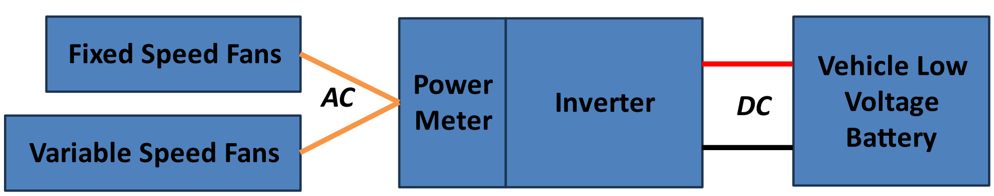

FIGURE 1: EXTERNALLY APPLIED LOAD SETUP

FIGURE 2: EXTERNAL LOAD POWER MONITOR

4.0 RESULTS

Tests for all three discharge methods were able to successfully complete without the vehicle shutting off or switching to HV mode (engine on). All three discharge methods were successful in discharging the HV to < 50% within the proposed 5-hour time limit, with the longest duration being method 1 (HVAC Cold) at 2.5 hrs. Method 2 (HVAC Hot) resulted in the fastest discharge time at 1.25 hrs. Method 3 (Aux Load) discharged the HV battery at a slightly faster rate than method 1. Total discharge times and ending SOC for each method are shown in Table 3.

TABLE 3: FINAL SOC AND TEST DURATION PER DISCHARGE METHOD

Method	**Dashboard SOC (final)**	**OBD SOC (final)**	**Total Duration**
1: HVAC Cold	53%	49.8%	2h 31m
2: HVAC Hot	52%	49.8%	1h 15m
3: Aux Load	53%	49.8%	2h 16m

It should be noted that the dashboard and OBD SOC read different values. However, the trends for the two sets of data, from different sources, followed a similar trend throughout the discharge process as shown in Figure 3. This was confirmed to be a linear relationship as shown in Figure 4. The HVAC power consumption rates for each test as shown in Figure 6, where Method 2 (HVAC Hot) shows 2 to 4 times the power consumption of Method 1 (HVAC Cold), and the HV battery terminal voltage (Figure 7).

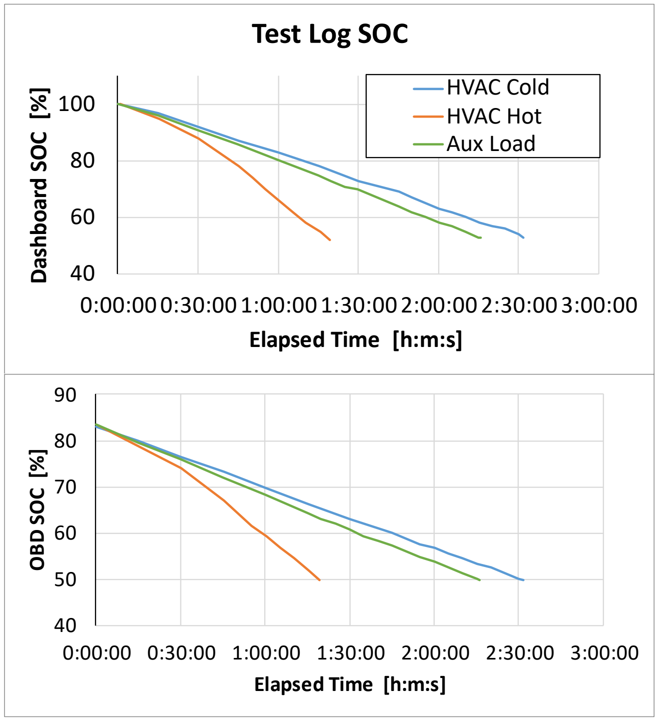

FIGURE 3: DASHBOARD DISPLAY AND OBD SOC RESULTS (TEST LOG)

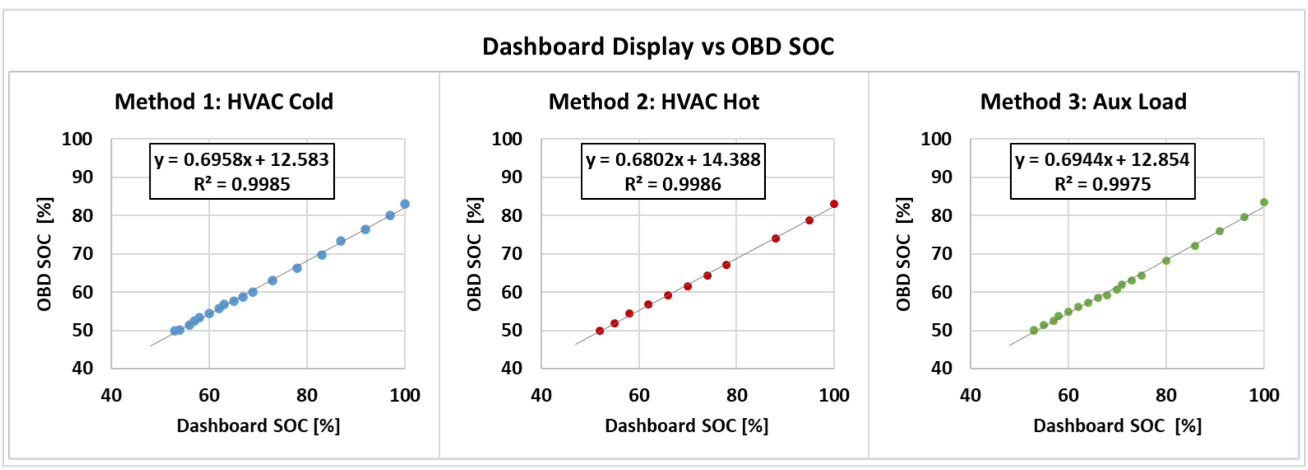

FIGURE 4: LINEAR FIT OF DASHBOARD VS OBS SOC

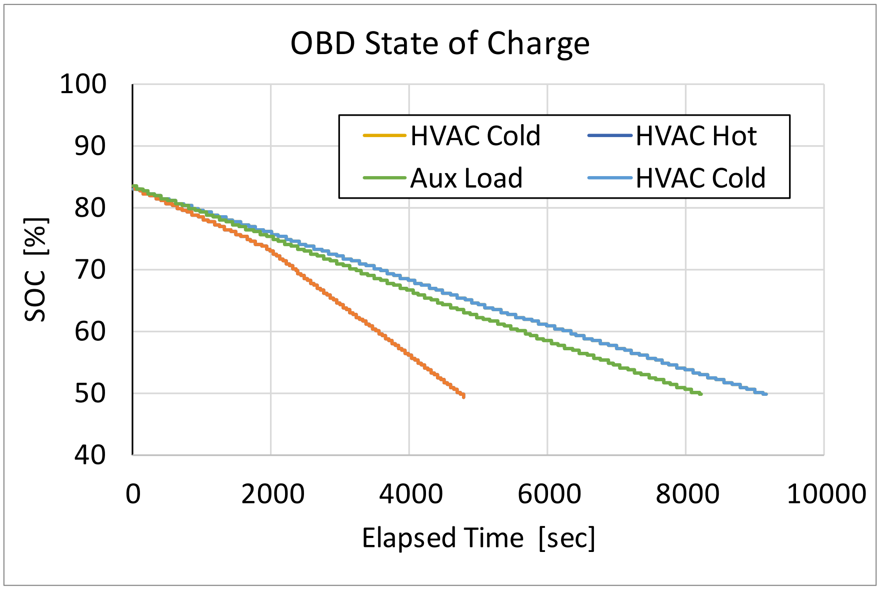

FIGURE 5: OBD RECORDED STATE OF CHARGE PER DISCHARGE METHOD

Data from test method 3 (Aux Load) showed that the externally applied load was sufficiently low as to not draw down the auxiliary battery voltage at a rate any higher than the other two test methods as shown in Figure 8. This indicates that the power to the external load was, in fact, supplied by the HV battery.

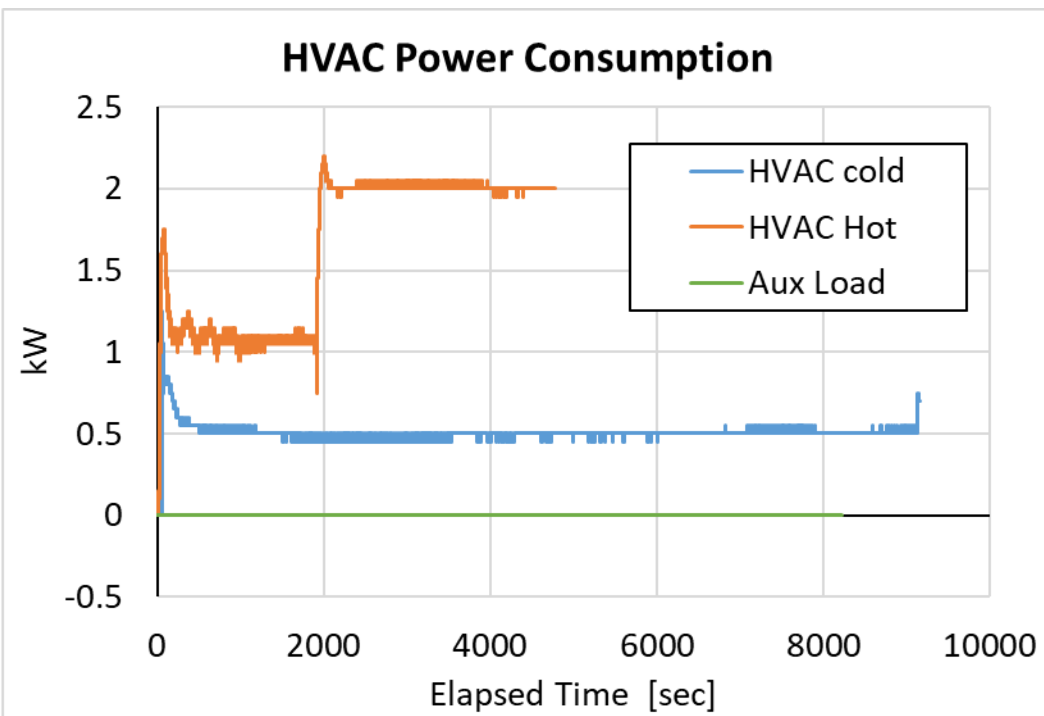

FIGURE 6: HVAC POWER CONSUMPTION PER TEST METHOD

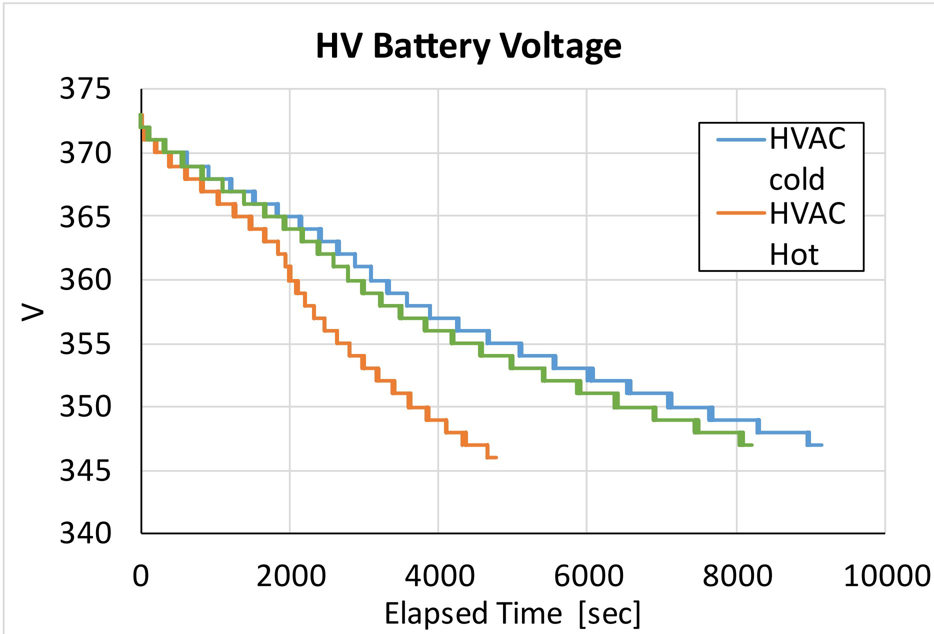

FIGURE 7: HV BATTERY VOLTAGE PER TEST METHOD

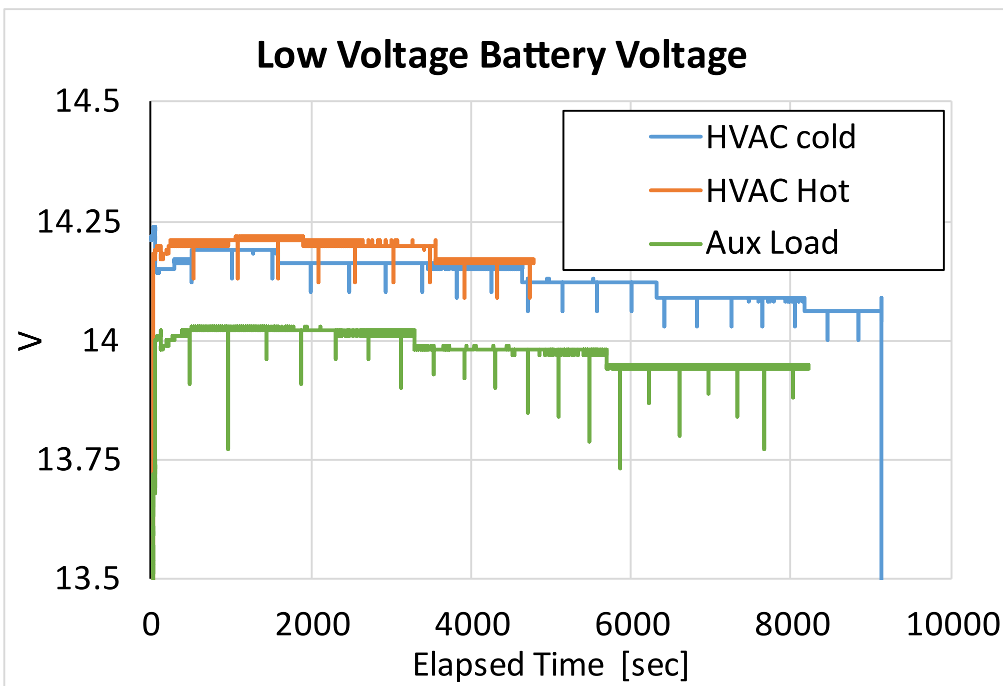

FIGURE 8: AUXILIARY (LOW VOLTAGE) BATTERY VOLTAGE PER TEST METHOD

5.0 CONCLUSION AND DISCUSSION

It was noticed that there was an increase in HVAC power consumption during the Method 2 (HVAC Hot) test roughly 35 minutes into the test. While the cause of this shift is not readily apparent, the initial power consumption of the vehicle's heater, when extrapolated, was still sufficient to discharge the HV battery at the fastest rate among the three methods tested as shown in Figure 9.

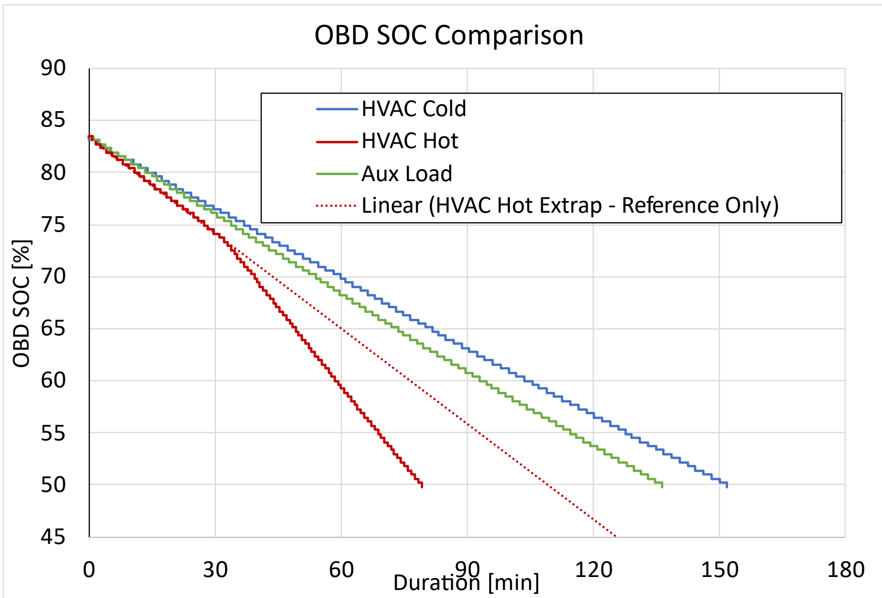

FIGURE 9: METHOD 2 (HVAC HOT) INITIAL DISCHARGE RATE EXTRAPOLATED

APPENDIX C
PHEV BATTERY SOC CONDITIONING PROCESS DOCUMENT

PHEV BATTERY SOC CONDITIONING PROCESS DOCUMENT

Southwest Research Institute
Version 1.0
July 2024

TABLE OF CONTENTS

LIST OF ACRONYMS AND ABBREVIATIONS

AC Alternating Current
BMS Battery Management System
CAN Controlled Area Network
DC Direct Current
DOE Department of Energy
HV High Voltage
HVAC Heating Ventilation and Air Conditioning
HVB High Voltage Bus
ICE Internal Combustion Engine
LV Low Voltage
LVB Low Voltage Bus
OBD On-board Diagnostics
OEM Original Equipment Manufacturer
PHEV Plug-in Hybrid Electric Vehicle
PPE Personal Protective Equipment
SOC State of Charge

1.0 OBJECTIVE AND SCOPE

The purpose of this document is to describe and document State of Charge (SOC) conditioning methods that are generally applicable to the current Plug-in Hybrid Electric Vehicle (PHEV). Methods and procedures are documented to set the (target) SOC of the PHEV within +/- 1%, while it remains stationary. Automation, instrumentation, as well as method comparisons are discussed in this document. As dictated by the scope of the project, the ICE shall not turn on during these tests. Additionally, this document includes minimum hardware and software requirements to set the SOC.

1.1 Assumptions

- Energy associated with SOC change will not be directly measured.
- Vehicle SOC readings will be trusted without verification.
- Model-specific concessions are to be expected.

2.0 VEHICLE SELECTION AND PREPARATION

This document's SOC Conditioning procedures focus on a specific subset of PHEVs available on the market. It's crucial to include various battery sizes to represent a diverse range of PHEVs. Based on this criterion, along with the availability of reliable information for each platform, the platforms listed in Table 1 were chosen as the basis for background research.

TABLE 1: RESEARCH VEHICLE SELECTION

Vehicle	High Voltage Battery Size (kWh)
Toyota RAV4 Prime	18.1
Jeep Wrangler 4xe	17.3
Mitsubishi Outlander	13.8

From these vehicles, an understanding of common characteristics of a typical PHEV are documented in a generalized sense for the current market in PHEV Characteristics. It is important to note that the availability of this data without direct OEM guidance is sparse and incomplete. This process will benefit from consistent updating of data as information is published and the state of the market evolves over time. These characteristics are important for a variety of reasons. Many PHEVs have control conditions where the Internal Combustion Engine (ICE) will turn on to reduce the drain on the HV battery. For this reason, undesirable ICE interference should be minimized. Additionally, it is important to know what on-board loads are available to the LVB and the HVB respectively. The HVB is often protected with contactors such that the bus can be connected and disconnected automatically for safety purposes. For this reason, it is important to understand the contactor architecture and control logic to maintain consistent access to the HVB.

It may be relevant to consider a vehicle time-out condition as well. For some vehicles, it may contain logic where a vehicle will turn itself off if it isn't driven within a certain timeframe. For the purpose of this document, this condition is not considered to be relevant; a key should be present in the vehicle and the ignition switched on.

2.1 PHEV Characteristics

1. Conditions that could trigger ICE interference with SOC conditioning process. [1, 19, 23]
   - Low SOC (~16-18%) (Generally Observed)
   - Hybrid system temperature too hot or cold (Observed in RAV4 Prime)
   - Cabin heater or defogger is turned on. (Generally Observed)
   - Cabin HVAC on high [20]
   - Engine hasn't run/cycled for extended period. (Observed in Outlander PHEV)
2. High-Voltage (HV) bus
   - Electric Machines
   - HVAC
   - DC charging/discharging
3. Low voltage bus load (commonly documented for all 3 subject vehicles) [21]
   - In-car entertainment system
   - Lighting
   - Seat heating
   - 12V outlets
   - Some HVAC capabilities
4. HV contactor architecture and contactor closing conditions are specific to each model. It is important to understand the scenarios in which the main contactors are open or closed. For instance, in cases where a load is applied across the low-voltage system, the main contactors need to be closed for power draw from the HV system [2,3,4]. This enables charging of the low-voltage systems via the HV battery through a DC/DC converter [5]. Figure 1 shows a representative example of the contactor distribution network in Hybrids, Plug-in Hybrid Vehicles (PHEVs) and Electric Vehicles (EVs) [6]. Note that other variations of this setup may exist across different OEMs, and that the DC Fast Charge may not be applicable to most PHEVs.

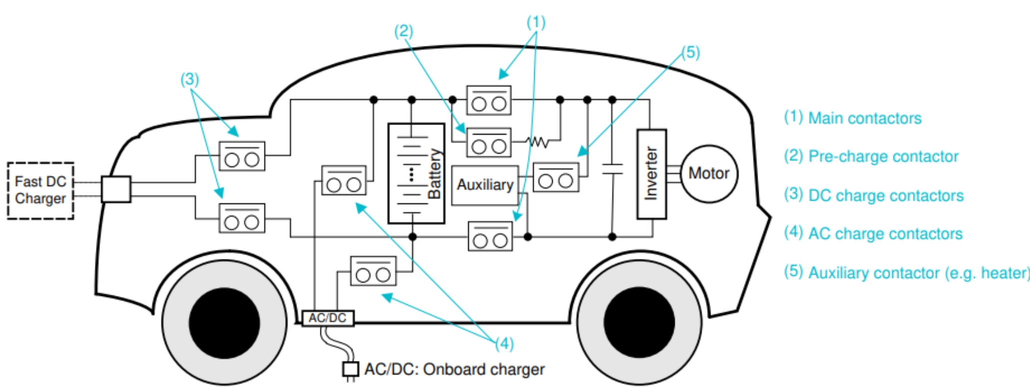

FIGURE 1: PHEV HV ARCHITECTURE

It is evident from Figure 1 that the main contactors (and possibly the auxiliary contactor) need to be closed for HVB discharge. The contactor closing logic is often OEM proprietary [7]. It can be assumed that the main contactors close in the "run" or "ready-to-drive" mode (not the accessory mode [5]).

3.0 INSTRUMENTATION AND DATA ACQUISITION

The instrumentation required to perform these tests include (at minimum) a CAN/OBD logger and a multimeter. An alternative to the CAN/OBD logger would be to use a camera with character recognition software to read signals such as battery SOC from the vehicles user interface. This method of SOC feedback would require development but may be desirable as a platform that is rapidly generalizable across platforms. This approach contains the caveat that the SOC read from CAN and the user interface may not be equal. Using feedback from the dashboard is only acceptable if the intended purpose is to set a desired dashboard SOC. The following signals need to be recorded, either via CAN (if available) or discrete instrumentation:

- HV battery SOC [%]
- LV battery voltage [V]
- Time [s]
- Ambient temperature [°C].

Based on the proposed objectives and scope of this work, the HV battery SOC must be measured with 1% accuracy. The desired accuracy of the other signals can be defined based on the available data storage capacity, dynamics of the recorded signal, and estimated test duration, among other considerations.

In this context, the expected test time can be used to define the sampling time and is dependent on the capacity of the HV battery, the load drawn from it, and the desired SOC at the end of the test. Consider a Toyota Prius Prime with an 8.8 kWh battery pack. If a 1.5 kW load is applied (typical HVAC consumption), it would take ~2.5 hours to discharge the pack to ~50% SOC. This can be used to derive the desired time signal accuracy.

4.0 SOC CONDITIONING METHODS

The testing described in this test plan falls into three (3) classes. This classification is done to generally describe the degree of complexity and intrusion to the vehicle. These classes are defined in Table 2.

TABLE 2: METHOD COMPLEXITY LEVELS

Class 1	In-situ. Relatively simple to implement and execute.
Class 2	Ex-situ. Modifications need to be made to the vehicle. Requires advanced test set-up and intimate knowledge of vehicle.
Class 3	Ex-situ. Requires advanced test set-up and intimate knowledge of vehicle. These methods may only be available on few models.

4.1 General SOC Conditioning Setup

Before beginning any of the SOC Conditioning methods provided, perform the necessary setup steps:

1. Establish a controlled environment with static ambient temperature based on test objectives. If using an emissions testing soak room: 68 – 86 °F.
2. Connect general instrumentation included in Section Instrumentation and Data Acquisition.
3. Set up the load monitoring system and data logging equipment as described in Section 3 and any additional equipment specified by the method specific test procedures in Section SOC Conditioning Methods.
4. Perform a comprehensive safety check.

Following the successful SOC Conditioning process, a generalized testing procedure is as follows:

1. Data Recording
    a. Record the operating time, power consumption, accessories used, and SOC changes.
    b. Monitor the overall system to ensure that the ICE does not turn on inadvertently.
2. In the event the ICE activates
    a. Immediately cease all accessory operations.
    b. Document the conditions leading to ICE activation for analysis and future test refinement.
    c. Safely decrease the loads and perform necessary steps to turn the ICE off.

Note: ICE could be triggered in scenarios where the vehicle's ECU determines that engine power is needed to limit draw from the battery due to a load beyond a certain threshold. Additionally, for some Hyundai/Kia [8] vehicles, the engine turns on when cabin heating is needed, with the heat rejected from the engine being used for cabin heating. The triggers for engine activation vary by OEMs; however, factors to consider include ambient conditions, required power draw for accessories, thermal considerations, and in some cases, timer-based triggers for engine or after-treatment protection.

3. Concluded Tests
    a. Once the desired reduction in SOC is achieved, deactivate all accessories in a safe order.
    b. Conduct a final safety inspection and power down all monitoring and recording equipment.
4. Post-Test Analysis
    a. Analyze the collected data to understand the efficiency and effectiveness of each load in conditioning SOC.
    b. Identify any challenges encountered, especially those leading to ICE activation, and modify the testing approach accordingly for future tests.

The data collection tables can be generalized using Table 3. It is recommended that the test time, duration, and HV battery SOC are recorded across all the proposed conditioning approaches.

In addition, test-specific channels (such as the 12 V battery voltage in [V], power draw applied in [W]) should be recorded for analysis.

TABLE 3: GENERALIZED DATA COLLECTION TABLE

Test Time	Test Duration	OBD/CAN-based HV Battery SOC [%]	Test-Specific Signals

4.2 Heating, Ventilation, and Air Conditioning (HVAC) and Other Accessory Loads

4.2.1 Description

Considering that all PHEVs offer electric-only operation for a certain range, it can be assumed that the A/C system (cooling) is run on the HV system [8,9,10,11,12]. Such vehicles can be operated in a stationary "run" mode with the AC and other electrical components like the audio system, lights, and heater activated to increase the load on the battery, thereby reducing its SOC. Due to the vastly different onboard electrical load configurations across models, this method would be difficult to fully automate. However, since these methods don't require any additional work, they are labeled as Class 1.

4.2.2 Testing Hardware / Software

To effectively carry out this testing method, the following hardware and software are required in addition to the general equipment outlined in Section Instrumentation and Data Acquisition:

- Accessory Load Monitoring System: To track the power usage of the HVAC system, audio system, lights, heater, and other electrical components. [28]
- Vehicle-Specific Electrical Load Information: Detailed information about the onboard electrical load configurations for the specific vehicle model.
- Safety and Diagnostic Tools: To ensure safe operation and to diagnose any issues during the test.
- Control Software: For managing and monitoring the operation of accessory loads and recording data.

4.2.3 Test Procedure

1. Experimental Load Determination
    a. Experimentally determine which accessory loads (HVAC, audio system, lights, heater, etc.) can be operational without triggering the ICE.
    b. Document the operational parameters and thresholds for each accessory to prevent inadvertent ICE activation.
2. Active Testing Phase
    a. Activate the selected accessories, such as HVAC, lights, and audio system, ensuring they remain within the established operational parameters.

b. Continuously monitor the power consumption and battery SOC levels to assess the impact on the battery.
c. Decrease load once within selectable threshold of desired SOC for slower discharge.
    i. Disable accessories based on load size as appropriate.
d. Disconnect load and stop test once desired SOC is reached.

3. Automation Guidelines
    a. Manual procedure: Switch off HVAC system and accessory loads when the desired SOC is reached.
    b. Semi-automated procedure: An audio and/or visual-based alert can be issued in an automated manner using battery SOC feedback. An alert would be provided on reaching the selectable threshold, requiring load changes, and another to stop the test. The operator would be required to make changes to the test/load conditions based on the alerts provided.
    c. Automated procedure: It is possible to outfit the vehicle with an interface such that the SOC conditioning procedure can be done in a fully automated manner where the onboard loads are manipulated by this vehicle interface to adjust the load as appropriate. This would require development of said interface where auxiliary control signals are reverse engineered and controlled directly. It is important to note that the automated procedure will still require an operator to power down the vehicle.

4.3 External Loads on Low Voltage Bus

4.3.1 Description

This method involves connecting devices that draw power from the 120 V AC outlets and onboard inverter. Devices such as portable coolers, lighting systems, or electronic devices can be used to discharge the battery to a desired SOC (similar to [13]). It is also possible to directly attach DC loads across the terminals of the 12 V battery. These loads are applied while the vehicle is in its "run" mode (with the main contactors closed). In this scenario, applying a load on the 12 V battery results in depletion of the HV battery SOC via the DC/DC converter.

This method would require a variable load with controller to maximize load on the LV system. This LV load will be restricted by the size of the DC/DC converter as well as current/fuse rating of the 12 V outlets. This method is labeled as Class 1 due to its universal application and non-invasive execution.

4.3.2 Testing Hardware / Software

To execute this method effectively, the following specific hardware and software are essential:

- Variable Load Module with Controller: To efficiently maximize the load on the Low Voltage (LV) system.
- Portable Power-Consuming Devices:

    - For drawing power from the 12 V outlets: portable AC, fans, lighting systems, and electronic devices.
    - For direct 12 V battery attachment: inverter, or DC consuming devices are mandatory.
- DC/DC Converter Size Information: Specific to each vehicle, to determine the load capacity. [14]
    - Ex: 2.5 kW on Jeep 4xe.
- Electrical Monitoring Tools: For measuring voltage, current, and load on the battery.
- Data Logging System: To record changes in SOC and other relevant electrical parameters.
- Safety Equipment: Including insulated tools and protective gear for electrical safety.
- Control Software: For managing the variable load module and coordinating the test process.

4.3.3 Test Procedure

1. Connection of Load Devices
    a. Connect the chosen power-consuming devices to the 12 V bus.
    b. Ensure that the total load does not exceed the capacity of the vehicle's DC/DC converter.
    c. Ensure that power draw from 12 V outlets does not exceed respective fuse ratings.
2. Load Adjustment and Monitoring
    a. Adjust the variable load module to maximize the load on the LV system without overloading it or triggering ICE to turn on.
    b. Continuously monitor the load, voltage, and current to ensure safe and efficient operation.
3. Active Testing Phase
    a. Operate the connected devices, monitoring the decrease in SOC as the battery discharges.
    b. Adjust the load as necessary to achieve the desired rate of SOC change.
    c. Decrease load once within selectable threshold of desired SOC for slower discharge.
    d. Disconnect load and stop test once desired SOC is reached.
4. Automation Guidelines
    a. Manual procedure: Switch off or disconnect applied loads once desired SOC is reached.
    b. Semi-automated procedure: An audio and/or visual alert can be issued in an automated manner using battery SOC feedback. An alert would be provided when the selectable threshold is reached, requiring load changes. Another alert is issued to stop the test. The operator would be required to make changes to the test/load conditions based on the alerts provided.
    c. Automated procedure: A controller can be designed to start and shut-off the electronically applied load based on battery SOC feedback. It is important to note that the automated procedure will still require the operator to power down the vehicle.

4.4 External Loads on High Voltage Bus

4.4.1 Description

This method is more complex than the aforementioned approaches and involves directly tapping into the high-voltage system of the vehicle. To do this, certain high-voltage contactors within the vehicle need to be closed to enable access to the HVB. Once access is established, external high-voltage loads can be connected to discharge or charge the battery. The connected HV load, such as specialized resistive elements or other high-power devices, draws power from the battery, reducing its SOC. This approach requires a thorough understanding of the vehicle's electrical system and strict adherence to safety protocols, as working with HV systems poses significant risks. It allows for more rapid and significant SOC adjustments compared to using onboard AC or 12 V outlets, but it must be undertaken with caution and expertise due to the higher risks and complexities involved.

It is notable that some OEMs have established procedures for discharging high-voltage batteries in PHEVs as a component of their servicing routines and diagnostic processes. Utilizing this method involves adhering strictly to the OEM's detailed discharge protocols, which are typically provided to authorized service technicians. Additionally, this process requires the use of specialized discharge tools designed specifically for the OEM's vehicles. [27] Given the specialized and proprietary nature of the tools and information, this method is categorized as Class 3, indicating a higher complexity and restriction in usage to those with specific OEM training and access.

At least one company has successfully connected to the HV battery of a variety of PHEVs to use the vehicle as a generator. [29] These products require a very intrusive installation in order to access the battery terminals but are capable of 3-5 kW of power output using an inverter and voltage transformer. [30, 31] This is evidence that this approach is feasible for many PHEV models.

4.4.2 Testing Hardware / Software

For this testing method, the following specific hardware and software are required:

- Understanding of High-Voltage Contactor Logic: To enable access to the vehicle's HV bus.
    a. Determined experimentally for a given model vehicle.
    b. Software provided by OEM to sustain contactor connections throughout conditioning.
- One of:
    a. External High-Voltage Load Modules: Specialized resistive elements or high-power devices for discharging or charging the battery.
    b. OEM specific HV discharge tool
        i. Protocol documentation: Detailed guidelines and procedures provided by the OEM for the safe and effective discharge of the battery.
        ii. Diagnostic software: Software that interfaces with the vehicle's systems to monitor the discharge process and ensure it is proceeding according to the specific protocol. [15]

- Electrical Safety Equipment: Including insulated gloves, safety goggles, and other personal protective gear.
- Voltage and Current Monitoring Tools: To track and control the flow of electricity during the test.
- Control Software: For managing the operation of contactors and monitoring the connected loads.
- Data Logging System: To record electrical parameters and SOC changes throughout the test.
- Emergency Shutdown System: To immediately cease operations in case of a hazard.

4.4.3 Test Procedure

1. System Connection:
    a. Close the high-voltage contactors to establish secure access with the HVB. [17, 18]
    b. Connect the external high voltage load/OEM tool to the HVB, ensuring a stable and secure connection.
2. Active Testing Phase:
    a. Begin the discharging or charging process using the external high-voltage loads.
    b. Continuously monitor voltage, current, and SOC levels using the monitoring tools and control software.
    c. Log all relevant data, including SOC changes, electrical readings, and time stamps, to assess the efficiency and safety of the process.
    d. Regularly check for any irregularities or safety issues during the operation.
    e. Make necessary adjustments to the load or contactor settings as required to maintain optimal testing conditions.
3. Automation Guidelines
    a. Manual procedure: Switch off/disconnect applied load once the desired SOC is reached.
    b. Semi-automated procedure: An audio and/or visual-based alert can be issued in an automated manner using battery SOC feedback. An alert would be provided once a set threshold close to the target is reached, requiring load changes. Another alert is issued to stop the test. The operator would be required to make changes to the test/load conditions based on the alerts provided.
    c. Automated procedure: A controller can be designed to start and shut-off the electronically applied load based on battery SOC feedback. It is important to note that the automated procedure will still require the operator to power down the vehicle.

4.5 Discharge via DC Charge/Discharge Port

4.5.1 Description

This testing involves accessing the HV battery via vehicle DC charging infrastructure. This will require an advanced charging/discharging controller as well as many OEM specific safety features as the DC charging infrastructure is usually not designed for bidirectional power transfer.

OEM involvement is recommended and likely required for safe and repeatable conditioning. Due to the scarcity of compatible PHEVs and complex interface required, this method is being considered Class 3. [23] However, ongoing relevant work suggests this may become a more feasible process in the future. [16].

It is possible that future PHEV development makes bidirectional infrastructure available. In this circumstance, a document outlining the test setup, communications requirements, hardware, and software requirements along with a test procedure and work instructions considering safety and functionality, has been developed as part of the same project SME-18/E-142.

4.5.2 Testing Hardware / Software

The testing necessitates interfacing with the HV battery through the vehicle's DC charging system. Key equipment includes an advanced charging/discharging controller capable of managing the demands of this procedure. Additionally, due to the nature of the DC charging infrastructure, which typically isn't designed for bidirectional charging, the implementation of numerous OEM-specific safety protocols is crucial. Collaborating with the OEM is essential to ensure safe and consistent conditioning of the battery system.

4.5.3 Test Procedure

1. Establish a connection between the controller and the vehicle’s DC charge/discharge port.
2. Active Testing Phase
    a. Begin the discharge process by instructing the controller to start drawing power from the HV battery.
    b. Monitor the discharge closely, using the diagnostic tools to track SOC, voltage, and current in real time.
    c. Continuously log all relevant data throughout the discharge process.

4.6 Partial Charging

4.6.1 Description

To condition the SOC when the target surpasses the current level, the vehicle's built-in charging system can be employed to elevate the SOC to the preferred threshold. This process necessitates only a basic charger and a straightforward control mechanism for automation. This simple method is labeled as Class 1.

4.6.2 Testing Hardware / Software

The core requirement for this test is the battery's charging process. Utilization of the vehicle's standard charging port along with a conventional charger is sufficient. This procedure will be affected by the charging standard that a given vehicle conforms to. The Outlander PHEV is one example of a PHEV outfitted with fast charging capabilities. [23]

For an automated procedure, the test requires a “smart switch” that utilizes SOC feedback. This switch should be compatible with the OEM-supplied charger, enabling automated control of the charging process based on SOC readings. The current PHEV market does not offer a programmable charge limit as the charging procedure is handled by the onboard Battery Management System (BMS) [24, 25, 26].

4.6.3 Test Procedure

1. Securely Connect Charger.
2. Active Testing Phase
    a. Continuously monitor CAN/OBD readings until the desired SOC percentage is reached.
    b. Disconnect load and stop test once desired SOC is reached.
3. Automation Guidelines
    a. Manual procedure: Switch off/disconnect the charger on reaching the desired SOC.
    b. Semi-automated procedure: An audio and/or visual-based alert can be issued in an automated manner to stop the test by using battery SOC feedback. The operator would be required to switch off/disconnect the charger based on the alerts provided.
    c. Automated procedure: A "smart switch" can be designed to stop the charging based on battery SOC feedback. This must be compatible with the OEM-supplied charger. It is important to note that the automated procedure will still require operator to power down the vehicle.

5.0 METHOD COMPARISON

To appropriately compare the methods that have been presented in this document, a Pugh chart is made from the following criteria: In-situ process, test setup complexity, test execution complexity, OEM involvement, and potential for automation. These evaluation criteria allow a conclusion to be drawn for the best test method to develop for the current PHEV market conditions.

1. <u>In-Situ</u>: This criterion assesses the capability of performing the SOC conditioning method using the vehicle's existing features, without the need for removing or externally manipulating the battery or other components.
2. <u>Test Setup Complexity</u>: This involves evaluating the level of difficulty in arranging and preparing the necessary equipment, software, and environment for conducting the test. A method with high setup complexity may require specialized equipment, intricate configurations, or extensive preparations, which can impact the feasibility and resource allocation for the test.
3. <u>Test Execution Complexity</u>: This criterion measures the intricacy involved in conducting the test. It includes considerations like the level of expertise required, the precision of operations, the monitoring and adjustment during the test, and the handling of unexpected issues. High execution complexity can affect the reliability and consistency of the test results.
4. <u>Technology Readiness Level (TRL)</u>: This criterion evaluates the maturity of a technology, specifically its development and readiness for practical application. In the context of SOC conditioning methods, a higher TRL indicates that the technology has undergone extensive testing, validation, and refinement, or is in production, making it more reliable and ready for integration into existing systems. These methods would be classified at TRLs 6 or higher, based on the Department of Energy (DOE) guide [32]. Conversely, a lower TRL suggests that the technology is still in the experimental or developmental phase, requiring further research and testing before it can be considered operationally viable. These would

typically be at TRLs 5 or lower and have been excluded from the comparison due to their unproven nature and limited immediate applicability. It should also be noted that the technology readiness values in the comparison are relative to one another and should not be confused with the discrete TRLs as defined by the DOE.

5. Generalizability: This assesses how broadly applicable a SOC conditioning method is across different vehicle models and types. A highly generalizable method can be applied with minimal adaptation to a wide range of vehicles, making it more versatile and cost-effective for diverse applications.
6. Potential for Automation: This criterion evaluates the extent to which the SOC conditioning process can be automated. A high potential for automation indicates that the method can be executed with minimal human intervention, possibly leading to increased efficiency, consistency, and safety, and reduced labor costs.
7. Speed of Test: This involves considering the duration required to complete the SOC conditioning process from start to finish. Faster methods are generally more desirable as they increase throughput and efficiency, especially in high-volume testing scenarios.

The above criteria was established in a manner relative to the other methods on a scale from -2 to 2 inclusive of 0 where the greater numbers are more advantageous for a given criteria.

TABLE 4: METHOD COMPARISON PUGH CHART

Criteria	HVAC and accessory loads	External Loads on Low Voltage Bus	Partial Charging
In-situ	2	1	2
Test setup complexity	1	0	2
Test execution complexity	1	1	2
Technology Readiness	2	2	2
Generalizability	0	1	2
Potential for Automation	-1	1	0
Speed of Test	-2	-1	-2
Results	3	5	8

The Partial Charging method, although scoring the highest overall, has a specific limitation: it is only applicable for increasing the SOC. This means its utility is confined to scenarios where the battery needs to be charged up, and it isn't suitable for discharging or depleting the battery's SOC.

On the other hand, External Loads on Low Voltage Bus scores highly in terms of OEM involvement and generalizability, suggesting it's a versatile method that can be easily adopted across various vehicle models. This method could be preferred in situations where there's a need for a broadly applicable approach without extensive customization for different PHEV systems.

HVAC and accessory loads appear to be less favorable in terms of automation potential and test speed, which might make it less desirable for high-throughput or labor-sensitive environments. However, it could still be the method of choice in scenarios where manual control is necessary or preferred, such as in detailed research settings where each aspect of the SOC conditioning needs to be closely observed and manipulated by a technician.

The suitability of each method can be influenced by factors like available resources, desired test speed, need for automation, and the specific PHEV models being tested. The decision on which method to develop further should consider these operational contexts and the overall goals of the SOC conditioning process.

5.1 Low TRL Method Consideration

Processes such as DC charge/discharge and directly loading the HVB should be considered carefully as they will require more intense development. Additionally, they likely require more invasive measures that would significantly alter the vehicle from its factory condition. However, OEM development into these methods could be particularly valuable as it could lead to more time, energy, and effort efficient automated SOC conditioning processes.

6.0 RISK ASSESSMENT, MITIGATION STRATEGIES AND SAFETY PROTOCOLS

6.1 Safety Protocol

- Prioritize safety throughout the test, ensuring that all protocols and guidelines are followed.
- Have trained personnel supervise the test to handle any potential issues.
- Ensure safety equipment (like fire extinguishers) and properly trained individuals are nearby.

6.2 Technical and Schedule Risks

- Inaccurate SOC measurement
  - Mitigation: Calibrate and validate SOC measurement equipment before the test.
- Data Integrity, Loss, or Corruption
  - Mitigation: Regularly back up data (such as, by taking photos of written documents) during the test to prevent any loss or corruption.

6.3 Financial Risks

- Equipment Damage or Failure
  - Mitigation: Have a contingency budget for repairs or replacements if necessary.
- Cost Overruns
  - Mitigation: Carefully plan and estimate all expenses before the test. Monitor expenditures throughout the process to stay within the budget.

6.4 Safety Risks

- High Voltage Battery Hazards
  - Mitigation: Review HV battery safety protocols. Use appropriate personal protective equipment (PPE).
- Heat-related Issues in Soak Room
  - Mitigation: Ensure proper ventilation and cooling in the soak room. Monitor ambient temperature and humidity during the test to prevent overheating risks.

6.5 Environmental Risks

- Contaminated Soak Room Environment
  - Mitigation: Keep the soak room clean and free from any contaminants that could impact the test results.
- Environmental Impact of Test
  - Mitigation: Comply with all environmental regulations and dispose of any waste generated during the test responsibly.

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