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Disclaimer

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List of Acronyms

A	Ampere
AC	Alternating Current
AIO	All-In-One
ATM	Automatic Teller Machine
BC	Battery Conditioning
BMS	Battery Management System
BPC	Battery Pre-Conditioning
CCS	Combined Charging System
CPO	Charge Point Operator
DOE	U.S. Department of Energy
DC	Direct Current
DCFC	Direct Current Fast Charger
EV	Electric Vehicle
EVSE	Electric Vehicle Supply Equipment
HVAC	Heating Ventilation and Air Conditioning
IEC	International Electrotechnical Commission
kW	Kilowatt
kWh	Kilowatt-Hour
L1/L2	Level 1/Level 2 Charging
Li-Ion	Lithium-Ion
MCS	Megawatt Charging Standard
MW	Megawatt
NACS	North American Charging Standard
NGP	NextGen Profiles
OEM	Original Equipment Manufacturer
PHEV	Plug-in Hybrid Electric Vehicle
PTC	Positive Temperature Coefficient Heater
SOC	State of Charge
SOH	State of Health
TMS	Thermal Management System
W	Watt or Watts

Executive Summary

As part of the U.S. DOE EVs@Scale consortium, the *NextGen Profiles (NGP)* project presents analysis and results from the study of High Power Charging Electric Vehicles and Battery Charging Infrastructure. High Power Charging equipment is capable of recharging electric vehicle traction batteries at power levels of 200KW and above. The intent of the project is to further understand the most recent technological capabilities of the electric mobility industry related to charging performance. The project aims to develop EV, EVSE, and fleet characterization testing practices and comprehensive analysis with inputs from key industry stakeholders.

The results published in this NextGen Profiles project discuss how EV specifications and initial charge conditions, State of Charge (SOC) bounding limits, temperature considerations and DCFC station topologies impact DCFC charging performance. Examination of the SOC bounding limit scenario finds that charging to 100% SOC can significantly increase the length of a charging session for only marginal range gains. Examination of temperature considerations finds that the impacts of extreme temperatures can be mitigated by maximizing the use of battery preconditioning functions of the vehicle and by taking weather forecasts into account during trip planning. Examination of DCFC station topologies finds that DCFC stations with power sharing topologies and high utilization rates can limit charging speeds but also enable more effective utilization of installed DC charging infrastructure. Additional high-power charging results are anticipated in future publications in support of the U.S. DOE EVs@Scale consortium NextGen Profiles project.

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1 Introduction

An increasing Electric Vehicle (EV) adoption rate in the US brings a growing need for a mature EV charging network. Most EV charging happens while vehicles are parked and the owners are away, such as overnight at home or at the workplace during office hours. These tend to be slower AC charges which can take many hours to fully charge an EV battery.

In contrast, EV drivers on the go require Direct Current Fast Charging (DCFCs) infrastructure to rival the refueling experience of liquid-fueled vehicles by charging their EV battery to 80% State of Charge (SOC) in less than 30 minutes. These chargers are typically used on long road trips where it is more important to quickly replenish the available driving range than fully charging a vehicle to 100% SOC. An extensive DCFC network comprised of a diverse range of charging system manufacturers, models and operators is growing and evolving in North America. Many installations have at least 4 to 6 charging points per site, but due to the remote and sparse nature of these installations, their space requirements, high cost, complexity associated with interconnection on the electric grid, and the scenarios in which EV drivers use these DCFCs, their utilization rate can have a significant impact on their financial viability, the user experience and impact on the electric grid. Interoperability issues and broken charging points also significantly impact profitable operation of DCFC charging stations.

An EV driver’s working knowledge of the operation and limitations of their EV and of the DCFCs that make up the North American EV charging network can significantly impact charge station operation and the experience of all EV drivers. By understanding factors such as optimal SOC levels, charge acceptance curves and how shared charge station usage impacts dwell times, drivers can make strategic decisions, such as concluding a charge session once sufficient range is available to reach the next destination, which frees up the charging station for other EV drivers. Familiarity with the differences between AC and DC charging, connector types and impacts of temperature, congestion and SOC bounding improves access for other EV drivers and can reduce charge station dwell time.

This report summarizes factors that impact DCFC charging station performance, user experience and operational efficiency. Where available, real-world operating data is used to assess charging time, user experience, EV battery performance and longevity. The most significant contributing factors are identified, reviewed and presented alongside strategies and recommendations to mitigate their effects that the EV driver can optimize and influence.

1.1 Motivation

This study is inspired by the large variance in DCFC charging experience across the United States. It is based on the testimonials of multiple researchers at NREL, both from personal experience and experience conducting real-world experiments as part of other research and is further corroborated by discussions with industry partners and consensus amongst stakeholders participating in the

North American EV charging landscape (CR Survey Research Department 2023) (Plug In America 2023). Improving charging consistency and user experience has the potential to lower costs, improve profitability and expand access to electrified forms of moving people and goods across America while ensuring global competitiveness across a critical US industry.

For electrified forms of transportation to be available to all users of the North American road and highway system, EVs and EV charging must be cost-competitive or cost-advantaged to traditional forms of liquid-fueled transportation. Therefore, it is imperative that all users utilize available DCFC infrastructure as effectively as possible while the North American public charging system is built out. This report does not consider Alternating Current (AC) charging using slower AC chargers in a residential, commercial, or workplace settings.

1.2 Focus Areas

The following factors or focus areas are identified as the most significant contributors:

1) EV Specifications and Initial Charge Conditions
2) SOC-Based DCFC Limits
3) Temperature-Based DCFC Limits
4) DCFC Station Power Sharing

Each of these focus areas are investigated in more detail in the following sections of this report.

2 EV Specifications and Charge Conditions

Several EV design specifications that dictate the theoretical ceiling of EV charging speeds must be defined:

1) Battery size: This refers to the amount of energy that the battery can store. With all other variables held constant, increasing the size of the battery will require more time to charge the EV. Section 2) SOC-Based DCFC Limits details how lowering the charging session SOC objective essentially reduces the effective size of the battery and consequently increases charging session performance with reduced dwell time.

2) Peak charging power: This refers to the maximum advertised charging power of the EV. In the current EV market, this typically ranges from 50 kW to 400 kW. With all other variables held constant, higher peak charging power generally translates to a higher average charging power which leads to shorter charging times. Sections 2) SOC-Based DCFC Limits, 3) DCFC Station Power SharingTemperature-Based DCFC Limits and 4) DCFC Station Power Sharing will examine how SOC bounding, temperature and DCFC power sharing impact peak charging power.

3) EV thermal management system: This refers to the EV's battery heating/cooling capabilities including design capacity, thermal efficiency, and software algorithm. The traction battery is the single most expensive component in an electric vehicle, so it is important to regulate battery temperature during DCFC to prevent premature battery aging and thermal runaway (Mihalascu 2023). Section 3) DCFC Station Power SharingTemperature-Based DCFC Limits discusses these considerations in detail.

Charging conditions are factors that specifically relate to the state of the EV and surrounding environment during a charge session. These factors may change from one charge session to another.

1) Battery SOC: SOC refers to the remaining energy capacity of a battery generally expressed as a percentage of its full capacity. A fully charged battery is considered to have 100% SOC while a completely depleted battery is considered to have 0% SOC.

2) Battery temperature: Lithium-Ion batteries can generally charge fastest when the battery temperature is between 15°C and 35°C (Pesaran, Santhanagopalan and Kim 2013). Original Equipment Manufacturers (OEMs) heavily curtail charging speeds as temperatures approach and fall below 0°C to protect the battery from damage that can occur while operating at extreme temperatures and preserve useful battery life. At higher battery temperatures, other factors like thermal management and preventing thermal runaway play a role in curtailing charging speeds.

3) Ambient temperature: Ambient temperature refers to the surrounding air temperature. At hot and cold extreme temperatures, it becomes more difficult to maintain the battery's temperature at an optimal range.

4) EV auxiliary loads: During a DCFC charge session, a small fraction of the energy provided by the charger goes to auxiliary loads like cabin Heating Ventilation and Air Conditioning (HVAC), power outlets, infotainment and battery thermal management instead of the traction battery. Additional research to quantify the effects of EV auxiliary loads on vehicle charging is required.

5) Communications standards: Communication standards refer to the digital communication protocol used by EV and DCFC Electric Vehicle Supply Equipment (EVSE) to exchange information related to the charge session. This communication takes place on the pilot wire connection established using the charging cable. Mismatch in protocol implementations between the EV and EVSE is the primary contributor to interoperability related issues which lead to revenue loss for the DCFC site and can negatively impact their reputation. Standards improvement is one area of interoperability where industry and research are investing intensely for improvement (Idaho National Laboratory 2025).

3 SOC-Based DCFC Limits

Modern commercial EV battery packs contain a Battery Management System (BMS) which monitors and ensures the battery is kept within safe operating conditions. The BMS is a dedicated module that supervises EV battery's integrity and safety by enforcing an OEM-specific battery management strategy that maintains useful battery life by preventing unintentional damage to the battery from over-heating, over-charging and over-discharging. The BMS is responsible for observing battery state, determining operating limits and sharing battery information with other vehicle systems.

Battery state can be very detailed and comprise of many parameters, including instantaneous readings of voltage, current, and power. Charging and discharging limits of voltage, current, and power can also be included. Readings of SOC and temperature can be included for the packs, modules, or down to the individual cells. Other possible parameters include thermal management system (TMS) status, electrical isolation, battery age, cycle life, and State of Health (SOH). The BMS controls the charge session and sends commands which are passed to the EVSE to increase or decrease the charging rate so the battery can be charged in the shortest amount of time possible while maintaining the battery state inside of its normal operating window.

In general, the BMS allows a battery with low SOC to charge at high power, which tapers off as SOC approaches 80% and higher. This dependency between maximum charge power and SOC is known as a charge curve and differs between various EV OEMs. Other research has collected and presented vehicle charge acceptance curves for multiple EVs under various charging conditions (Thurston and Wells 2023). It is important to note that EV maximum charging power is only available under optimal battery conditions. As the battery temperature gets hotter, colder or SOC increases above an OEM-specific threshold, the charge power requested by the BMS will decrease. Concepts related to temperature dependency of a DCFC session are discussed in further detail in Section 4 of this report.

An example of these charge curves is shown in Figure 1 for several different EV manufacturers and models. This plot represents the maximum charging power each EV battery can accept as SOC increases over the charge session. This also shows how different OEMs can have distinct charge current profiles, how long peak charging current can be maintained, and how OEMs derate the charging current as SOC increases.

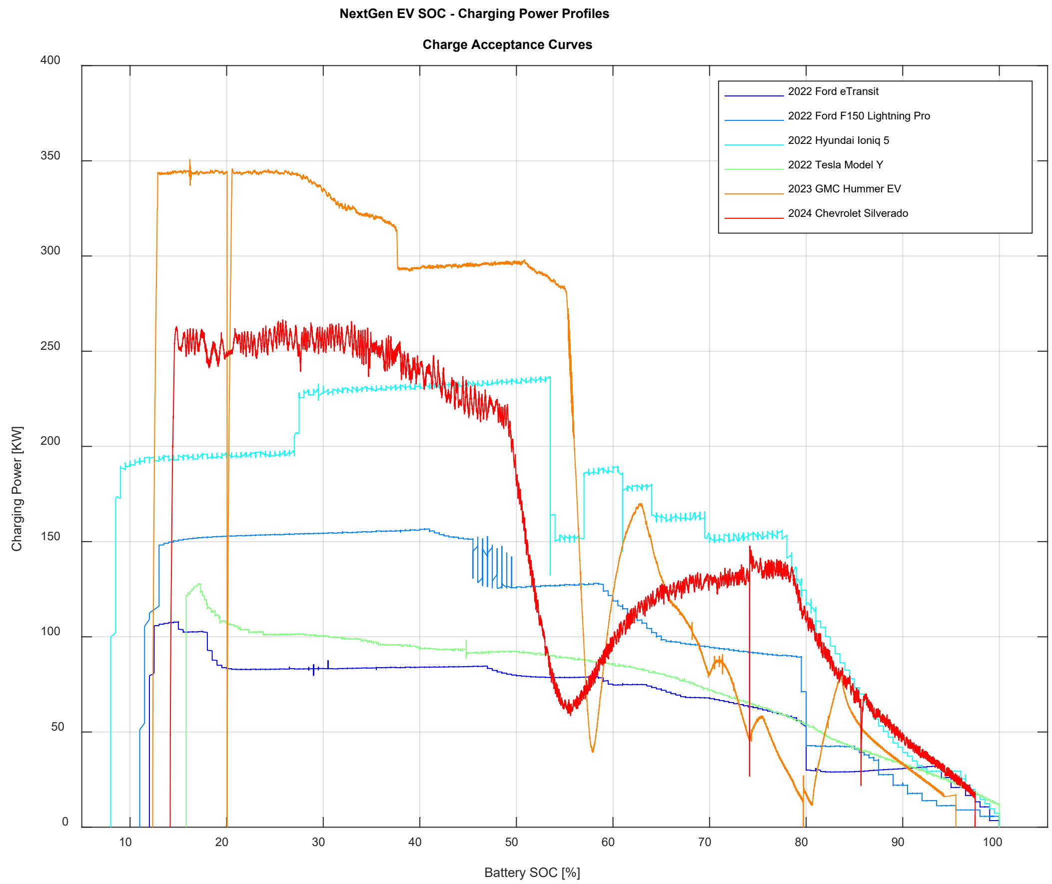

Figure 1. Example Charge Acceptance Curves

3.1 Effects of SOC based limits

Figure 1 shows how EVs replenish their SOC at a nonlinear rate. Table 1 tabulates and Figure 2 depicts how battery SOC increases in a 2022 Ford F150 Lightning Pro during a DCFC charge session. This exemplifies the diminishing rate of charge power, SOC and corresponding range increase as SOC approaches 100% full charge during a typical EV DCFC charge session.

Table 1 – 2022 Ford F150 Lightning Pro Unmanaged DCFC Charge Session Milestones

SOC [%]	Elapsed Charge Session Time [Hours:Minutes::Seconds]
10 (Initial)	0:00::00
50	0:15::09
80	0:32::48
100	2:07::09

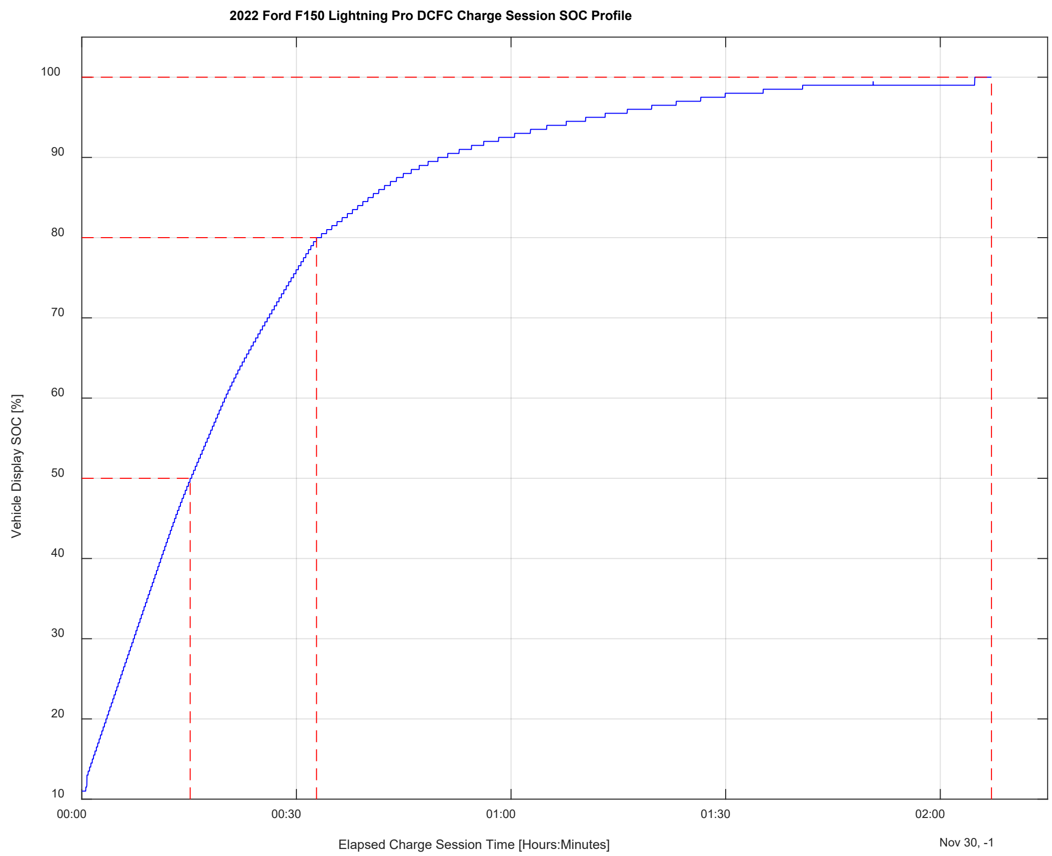

Figure 2. 2022 Ford F150 Lightning Pro Unmanaged DCFC Charge Session SOC Profile

The major takeaway from Table 1 and Figure 2 is the EV adds 70% SOC after approximately 33 minutes but to add the remaining 20% SOC it takes an extra 1.5 hours (95 minutes) to fully charge the battery.

Battery SOC is a measure of its remaining usable energy and is proportional to vehicle's available range. Range added during the charge session can be estimated by distributing the approximately 130 minute DCFC charge session into 26 consecutive 5-minute intervals and interpolating the differential SOC values with the OEM-stated maximum range of the Ford Lightning Pro. Figure 3 depicts the 5-minute binned range added value as well as cumulative range added over the elapsed charge session.

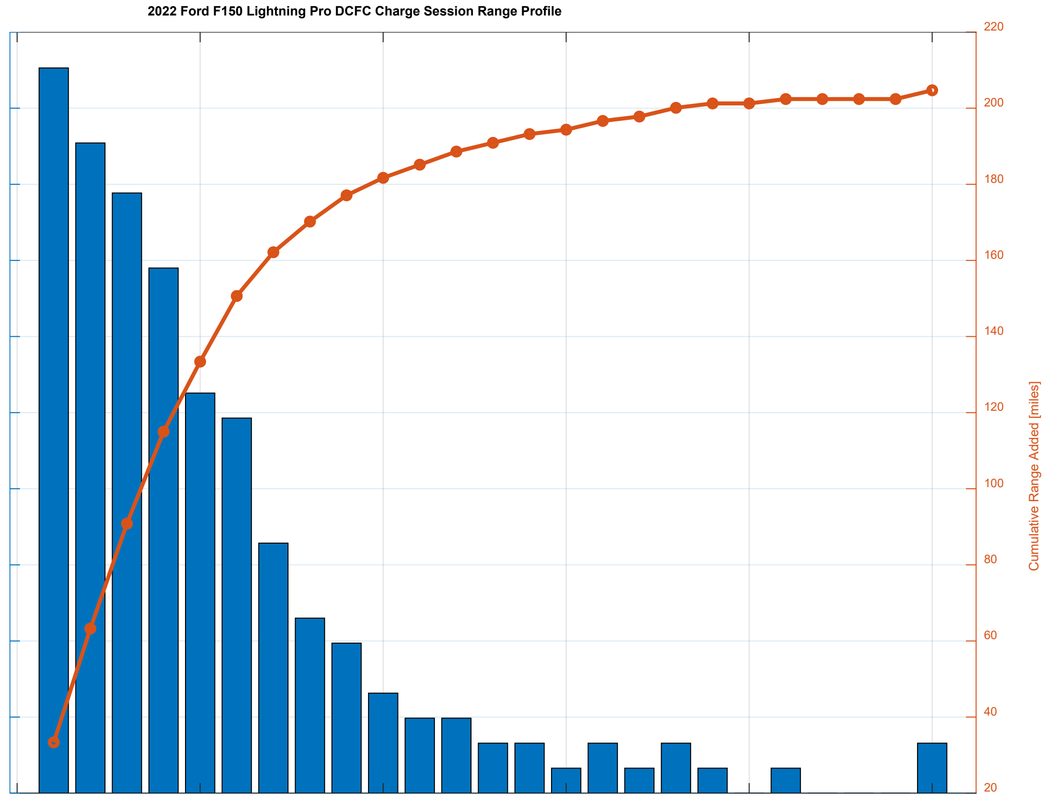

Figure 3. 2022 Ford F150 Lightning Pro Unmanaged DCFC Charge Session Binned Range Profile

Figure 3 shows that the DCFC session adds about 65 miles in the first 10 minutes and an additional 50 miles in the next 10 minutes. This results in approximately 115 miles of range added in the first 20 minutes of the charge session, which is higher than the recommended driving distance to cover between breaks on a road trip (Lawrence 2024) (Weekly Safety n.d.). After 30 minutes, the rate at which range is added significantly diminishes, taking about an additional hour and a half to replenish the remaining 54 miles of range to get the battery to full SOC (100%). This plot highlights the non-linear nature of battery replenishment and the diminishing returns of charging to higher SOCs.

Cost considerations must also balance charge session time considerations for situations where an EV must be charged to full (100%) SOC. Research has assessed that electricity dispensed from DCFC infrastructure is roughly three times as expensive as electricity dispensed from residential AC Level 2 (L2) EVSEs, although significant variations in cost exist across geography and time (Borlaug, et al. 2020). For this reason, significant cost per mile savings can be realized and limited DCFC charging ports can be freed up by fully charging EVs from 80% to 100% on AC L2 EVSEs.

Additionally, pushing an EV battery to its extremes by fully charging to 100% SOC every time and fully discharging to around 0% SOC every time reduces the health of the battery in the long term. (Menya, Camara and Dakyo 2025). Over time, the battery's capacity to store the same amount of energy at full charge deteriorates consequently reducing vehicle's maximum range. Thus, banding the vehicle SOC in the range of 20% to 80% during regular use is good for maintaining battery health for the lifetime of the vehicle.

Electricity supplied via DCFC EVSEs is more expensive than that of slower Direct Current (DC) and AC chargers due to the complexity and cost of capital infrastructure involved. High power DCFCs do not dispense electricity at low power levels very efficiently, all of which plays a role in reducing energy cost to the end EV driver.

Some EV Charge Point Operators (CPOs) have already begun implementing restrictions in their charge station networks that prevent EV drivers from charging their vehicles above 85% SOC to limit congestion at their charging sites (Electrify America 2025). This program will be crucial in reducing waiting times at high utilization and congested DCFC sites.

4 Temperature-based DCFC Limits on Battery EVs

Lithium-ion battery temperature impacts DCFC performance and charge time; operation at extreme temperatures can reduce battery health over time. Li-ion batteries generally perform best when battery temperatures are between 15 and 35°C (Pesaran, Santhanagopalan and Kim 2013). Vehicle charging performance is also indirectly affected by the ambient temperature, which can limit the performance of the vehicle's battery thermal management system. Factors that impact temperature-based constraints include:

1) Battery Conditioning (BC): This is the process where the vehicle's thermal management system works to maintain the traction battery's temperature during driving or charging. The ambient temperature plays a huge role in determining the efficacy and efficiency with which the vehicle maintains battery temperature.

2) Battery Pre-Conditioning (BPC): BPC is the process of heating or cooling the vehicle's battery before driving the EV or initiating a charge session to increase battery performance. Heating or cooling power can be provided from external energy sources or from the EV battery pack, which will reduce available range.

BC is dependent on EV OEM strategy and is not controlled by the EV driver. From a user experience and DCFC operating profitability perspective i.e., battery longevity, charge times and DCFC site dwell time, BPC can make a significant difference and is in control of the EV driver.

4.1 Battery Conditioning

BC can refer to either heating or cooling the battery pack depending on real-time battery conditions during driving or charging, external weather conditions, and the OEM thermal management approach. Thermal management system design encompasses performance requirements, component design, software strategy and cost. Because fast charging generates heat and elevates EV traction battery temperature, BC is crucial to maintain proper battery temperature during high power charging.

Figure 4 depicts a representative example of BC behavior during a DCFC charge session. The EV thermal management system works to maintain battery temperature in an optimal range for faster charging speeds to extend battery life and prevent thermal runaway from occuring. The thermal management system is supplemented by the BMS, which is aware of the battery's state (i.e., SOC, charging condition, temperature) and issues commands to regulate charging speed and reduce charging heat generated to maintain battery temperature at acceptable levels.

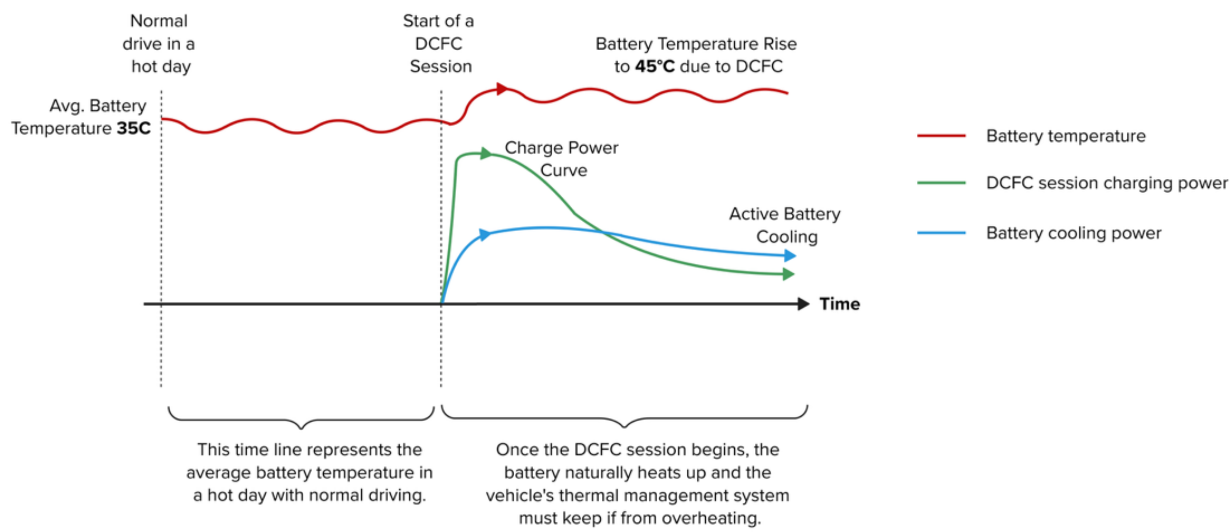

Figure 4. Representative DCFC Session Battery Temperature and Thermal Management Profile

Figure 5 depicts a representative case where BC is achieved via charge speed regulation from the BMS because the vehicle's thermal management system is unable to keep up with extreme environmental conditions. In this case, charging power is curtailed and the length of the charge session is extended to minimize elevated battery temperatures that would accelerate battery degradation and increase fire risk.

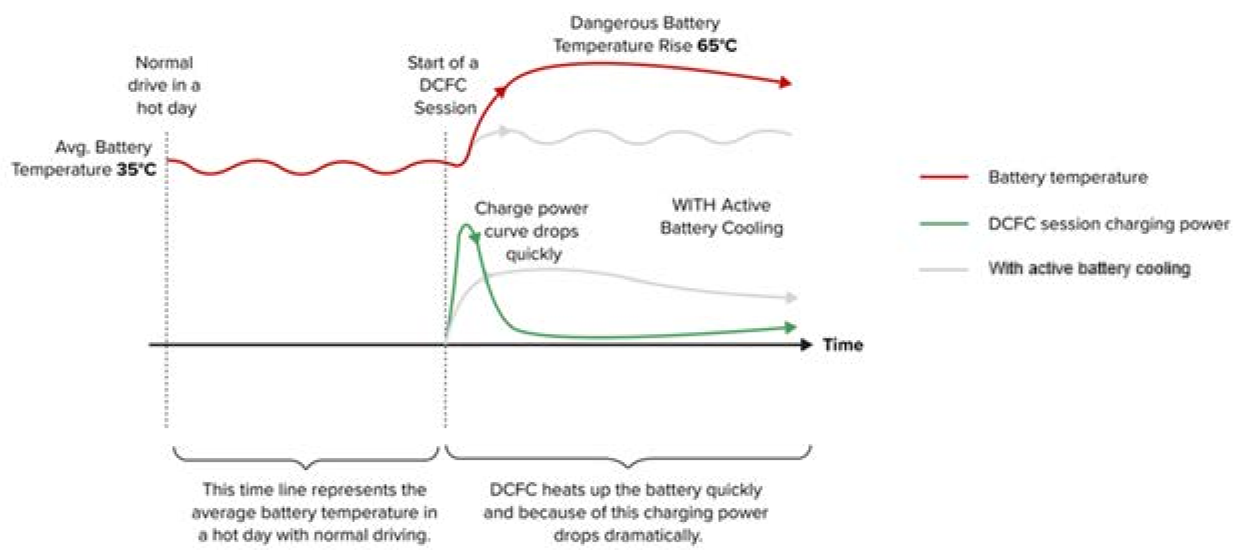

Figure 5. Representative Battery Temperature and Charging Profile with Insufficient Battery Thermal Management

4.2 Battery Pre-Conditioning

Many modern EV OEMs include a BPC feature in their vehicles to help maximize their vehicle's performance. BPC and charging behaviors are managed by the vehicle's internal BMS: BPC features can be triggered either automatically when selecting a DCFC site as a destination via the vehicle's navigation screen or manually from the vehicle's on-screen menu.

One common BPC function is cooling the battery in extreme hot weather conditions before driving or charging to prevent the battery from reaching high temperatures that could accelerate degradation and increase the risk of thermal runaway associated with unmanaged temperature. This type of BPC typically starts automatically and is more evident in regions such as Arizona or Nevada during the summertime. This report's discussion of BPC does not include strategies related to battery cooling prior to commencing a DCFC session as pre-heating the EV battery in cold conditions prior to a DCFC session has the largest impact on charging session dwell time.

Under extreme cold conditions the internal battery chemistry slows down, which increases the difficulty of transferring charge and storing energy. Performing BPC in cold conditions, i.e., heating the EV battery prior to initiating a DCFC session, mitigates this effect so charging power can be increased. The primary benefits of BPC for fast charging are:

- Faster charging times: Conducting a DCFC session on a vehicle with a pre-conditioned battery can reduce the time spent at the charger by 50% to 70% (Thurston and Wells 2023).

- Charging performance consistency: BPC makes the fast-charging user experience more predictable, especially in extreme weather conditions by bringing the battery closer to its optimal temperature range before the charge session starts. Thus, BPC ensures a consistent fast charge experience despite external weather conditions.

- Extended battery lifespan: Charging a battery at extreme cold temperatures and high-speed stresses battery internals leading to accelerated degradation (Pesaran, Santhanagopalan and Kim 2013). Utilizing an EV's BPC feature prior to fast charging will maintain useful battery life.

Since BPC is most often used when the EV driver is heading towards a public DCFC, battery energy is typically used to pre-heat the battery. EV OEMs have different approaches to pre-heat the battery using the onboard energy, which is further explained in Section 4.4. Figure 6 depicts a representative BPC temperature profile.

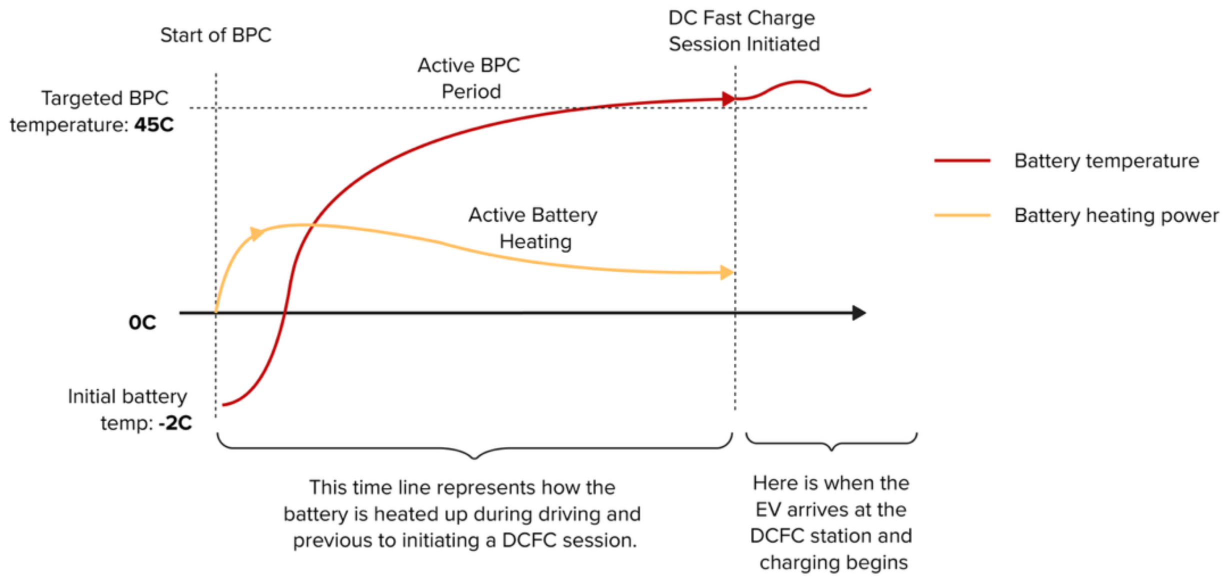

Figure 6. Representative Battery Pre-Conditioning Temperature Profile

To provide a complete picture of the differences between pre-conditioned and unconditioned batteries, Figure 7 and Figure 8 present representative depictions of how pre-conditioning affects charging performance. Figure 7 presents the ideal case where the EV arrives at a DCFC after completing BPC in cold weather conditions. Upon charge start, the battery is at an optimal temperature and thus, is not a limiting factor for charging. It is observed that the vehicle's BMS commands the maximum available charge power to achieve high SOCs in a short period of time while maintaining the battery temperature within normal operating limits.

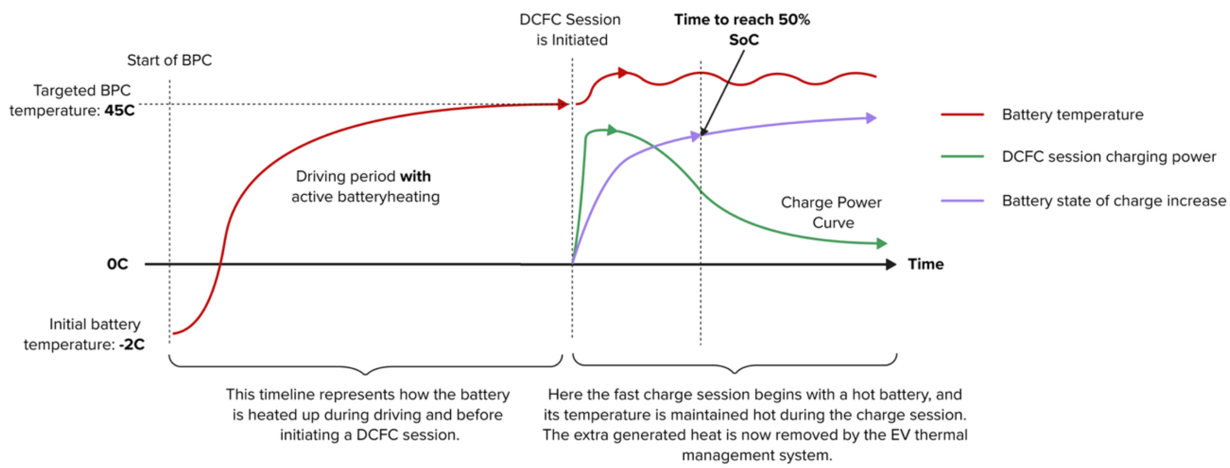

Figure 7. Ideal Representative EV Charging Profile with Battery Pre-Conditioning

Figure 8 depicts a scenario where there is no BPC before arriving at a DCFC site in cold weather. Consequently, the fast charge session begins with charging power curtailed because the vehicle's BMS must wait for the battery to warm up before incrementally commanding additional charging power until full charge power is reached. The amount of time required for the battery to reach optimal temperature will vary widely based on vehicle specifications and conditions of use. An added factor negatively affecting this scenario is that by the time the battery heats up to its optimal temperature due to charging, the charging speed may be limited by SOC, thereby further reducing overall charging speed and extending charging station dwell time.

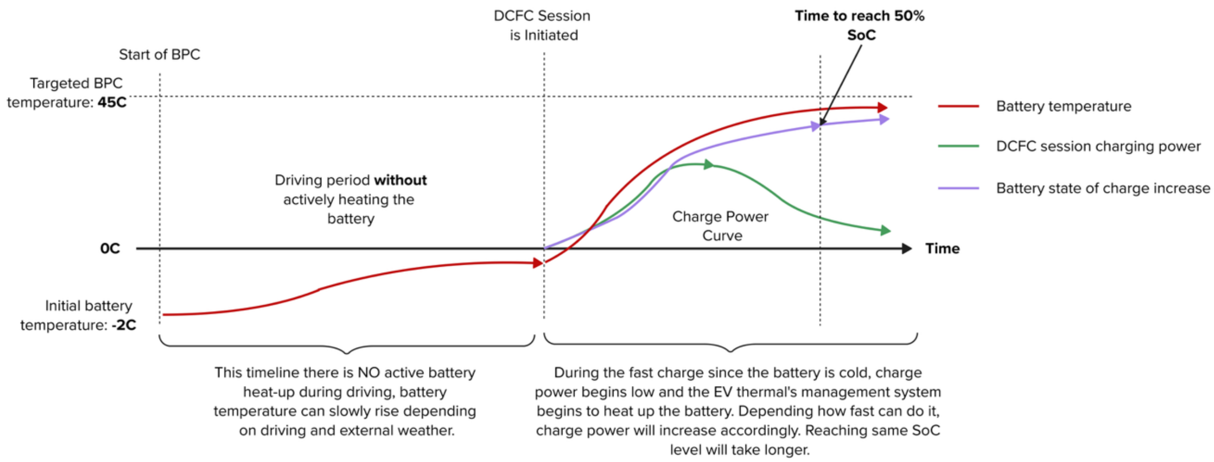

Figure 8. Representative EV Charging Profile without Battery Pre-Conditioning

Figure 9 and previous research highlight that it takes as much as three times as long to reach the same SOC level in cold conditions with an unconditioned EV battery as it would with an EV with a pre-conditioned battery (Thurston and Wells 2023).

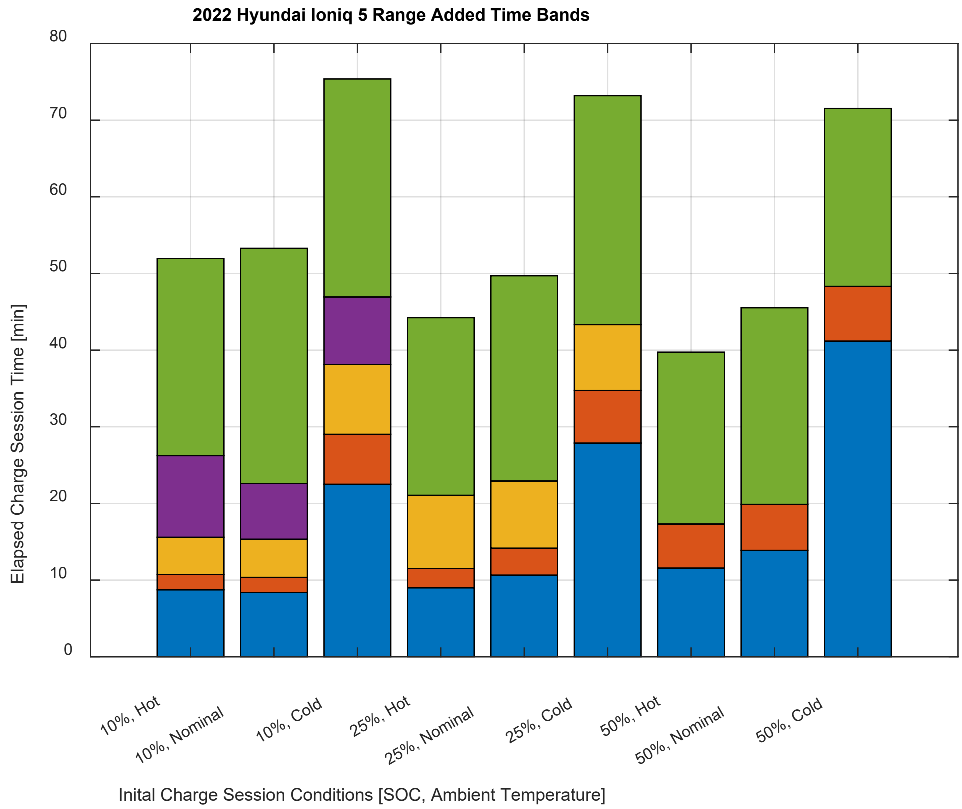

Figure 9. EV Charging Times Under Various Soak Temperatures and Starting SOC

4.3 Factors affecting BPC

EVs have controls and limitations placed on them with the objectives of:

- Protecting the battery from over-charging, over-discharging and over-temperature
- EV being used in conditions that result in battery degradation
- Preventing a battery thermal runaway

These controls and limitations can negatively impact the EV user experience since ensuring battery safety and longevity typically takes priority and is the primary reason EV customers experience reduced charging speeds at DCFC stations, especially when BPC is not performed prior to the charge session. BPC helps mitigate the tradeoffs between operational battery limitations and user experience.

The most important factors to understand and consider when performing BPC in cold weather prior to a DCFC session are:

- Ambient temperature and initial battery temperature
- EV battery size and thermal management capabilities

- Time allocated to conduct BPC prior to the DCFC session

4.3.1 Ambient Temperature and Initial Battery Temperature

Extended soaking in cold ambient conditions lowers the battery's temperature, resulting in increased time and energy consumption during the BPC heating routine to reach its target temperature. Additional effort must also be exerted by the thermal management system as ambient temperature decreases. Figure 10 depicts a graphical representation of this phenomenon.

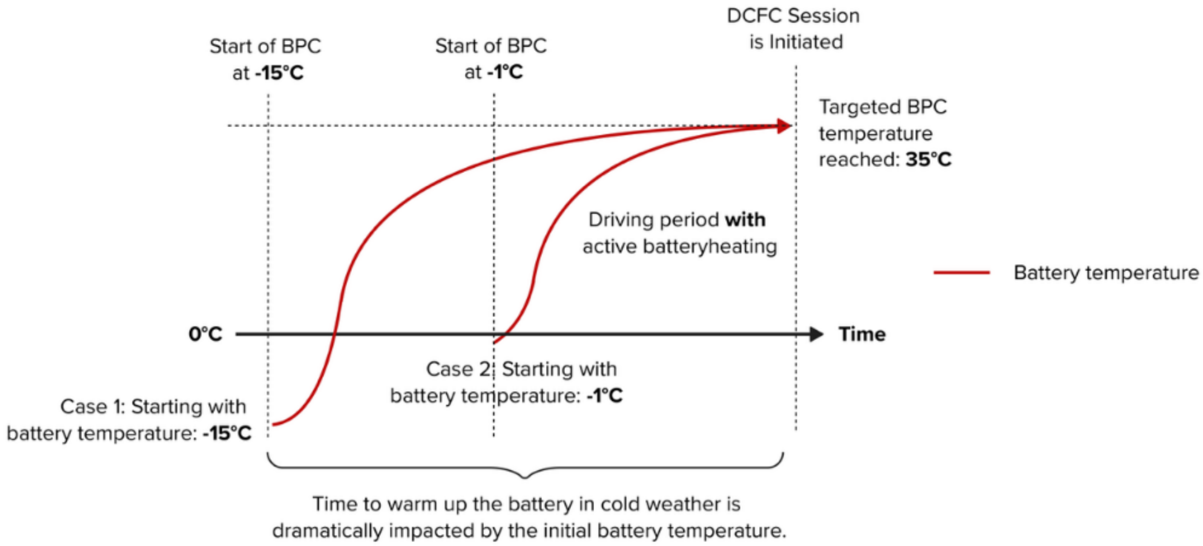

Figure 10. Representative BPC Time Comparison

4.3.2 EV Battery Size and Thermal Management Capabilities:

A second set of factors affecting BPC time is the EV battery's thermal mass and the ability of the vehicle's thermal management system to warm up the battery. As thermal mass increases, so does the BPC time and energy required to achieve the target temperature. Influences on thermal management system performance include:

- Vehicle thermal capacity: This refers to the capabilities of on-board thermal systems to produce or absorb heat to either increase or reduce the temperature of the target, such as cabin or battery pack.
- Heat capacity: This refers to how efficiently the heat can be transferred to or from the targeted device, i.e., how much energy is required to change pack temperature by one degree.
- Thermal insulation: The immunity of the battery pack to ambient conditions greatly impacts pack temperature.

Vehicle thermal management considerations are complex. Battery thermal management system design (Positive Temperature Coefficient [PTC] heater or heat pump), capacity, system cost, conditions of use, pack thermal insulation and heat transfer characteristics all affect how quickly the battery temperature can be preconditioned and how much energy is consumed in doing so. A combination of these factors and the cost involved for manufacturing these systems dictates the BPC performance of EVs including time taken and energy consumed for BPC.

4.3.3 Time allocated to Conduct BPC Prior to the DCFC Session

A third factor affecting pack temperature and charging performance is the time allocated to perform the BPC routine. Avoiding an early or a late start to BPC is key to balancing energy consumption with optimal battery pack temperature when the charge session commences. If BPC is not performed long enough or commences too early before the charge session, the effect of pre-conditioning will be suboptimal: a BPC session can be suboptimal in the sense that the battery temperature is not ideal for charging when the charge session starts, or suboptimal in the sense that more energy than necessary was required to maintain the battery at optimal temperature when the charge session starts.

One of two scenarios will result if the BPC routine is started too early. The first scenario considers EVs for which the BPC algorithm will not maintain the battery at BPC temperature once the battery pack reaches its targeted temperature. In this case, the battery thermal management system lets the battery cool down between the time the target temperature is achieved and the charge session starts, resulting in a non-temperature optimized battery pack and sub-optimal charge time. Figure 11 depicts this scenario.

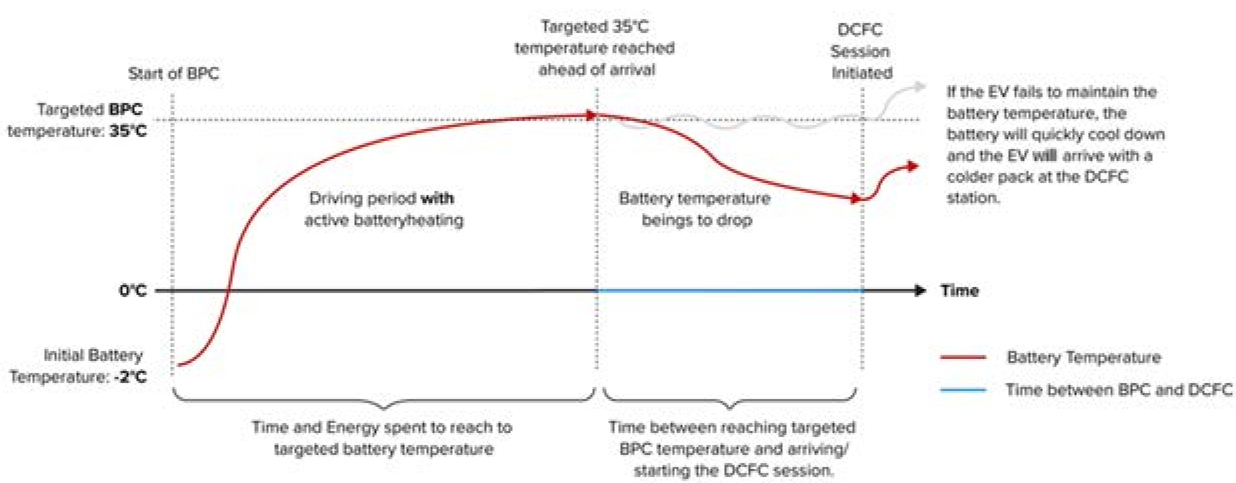

Figure 11. Representative Early Pre-Conditioning Battery Temperature Profile without Maintaining Optimal Battery Temperature

The second scenario of a BPC routine started too early considers EVs for which the BPC algorithm maintains the battery at the targeted BPC temperature until the charge session starts. In this case, the thermal management system consumes additional energy to maintain the battery temperature, resulting in increased battery depletion and charge session cost, though the pack is temperature-optimized and dwell time is minimized. Figure 12 depicts this scenario.

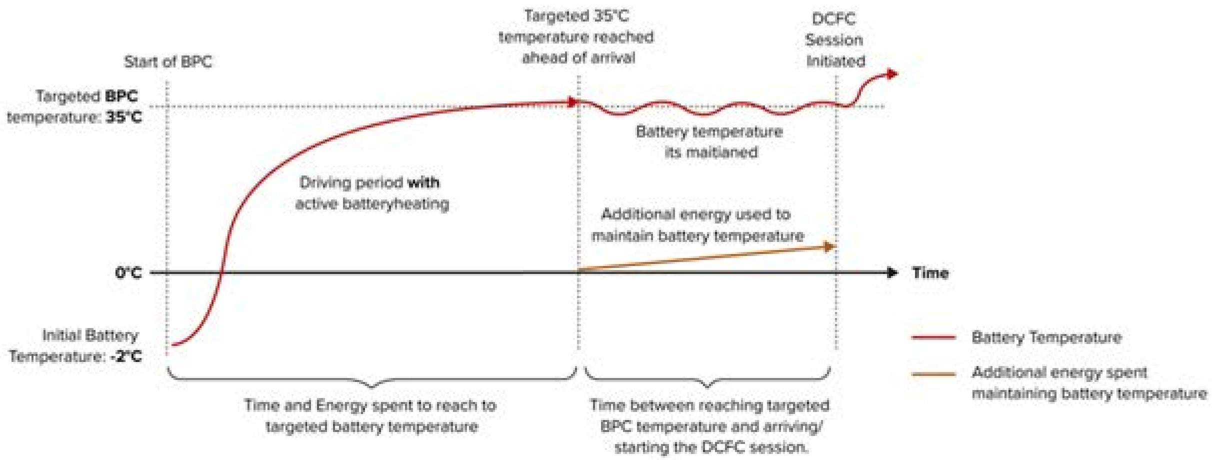

Figure 12. Representative Early Pre-Conditioning Battery Temperature Profile with Maintaining Optimal Battery Temperature

If the BPC routine is started too late, the EV battery will not be able to reach the target temperature for optimized DCFC, which will increase station dwell time. Figure 13 depicts this scenario. The additional time required to complete the charge session will depend on the battery and ambient temperature, the amount of time the BPC routine was performed, battery size, vehicle TMS capabilities and BMS charging limits.

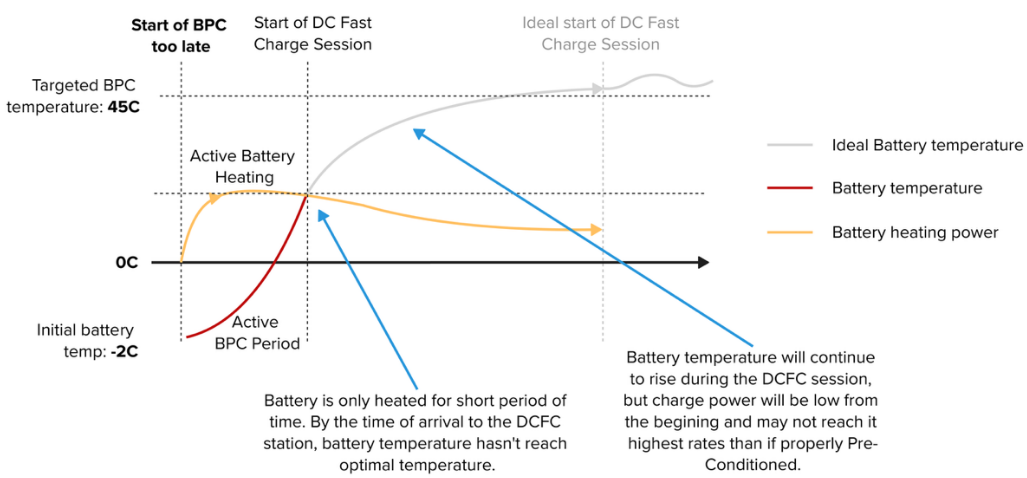

Figure 13. Representative Late Pre-Conditioning Battery Temperature Profile

Issues associated with limited public charging infrastructure and extreme cold weather can cascade when BPC is performed too late or not at all and in extreme cold weather conditions. For example, a Chicago snowstorm in January 2024 stranded many EV owners because long wait times, frozen charging cables and cold batteries significantly extended charge sessions (Schmall and Gross 2024). The situation sparked broader conversations about the need for improved cold-weather charging solutions.

4.4 EV OEM Thermal Management Approaches

Multiple approaches have been taken by EV OEMs to manage EV traction battery temperature:

- HVAC compressors and refrigerant systems: These are dedicated systems to removing heat from the cabin compartments in most types of liquid-fueled and electric vehicles. EVs also utilize HVAC compressors to remove heat from the main battery pack when cooling is required. These systems are outside the scope of this report.
- Resistive heating elements: Positive Temperature Coefficient (PTC) heaters, also known as resistive heating elements, convert electrical power into heat with no moving parts. These heaters are "self-regulating" in nature since their electrical resistance increases with rise in temperature and convert 100% of electrical power into heat. PTC heaters are most effective in extreme cold weather conditions, such as -40°C or below.
- Heat pumps: Heat pumps are energy-efficient devices that move heat between areas or systems rather than generating new heat from other energy sources. Heat pump-equipped EVs transfer heat between ambient air, the cabin and the EV battery.
- Waste heat recovery: To improve vehicle thermal system performance and efficiency, EV heat pumps can be configured to remove wasted heat from traction inverters, electric motors, HVAC compressors, and other heat generating components in the vehicle to the battery pack.

4.4.1 PTC Heaters

PTC heaters are typically mounted inside a liquid heat exchanger where the liquid absorbs the heat produced by the PTC, is pumped through piping inside the battery pack and transfers the heat to the pack cells and modules. The colder liquid coming out of the battery pack returns to the PTC heater and the cycle continues during the BPC routine. Automotive grade PTC heaters come in many different package designs.

The biggest disadvantage of PTC heaters is that the energy used to pre-heat the battery pack has to be sourced from the battery itself: every kWh of energy applied to the battery in the form of heat requires discharge of one kWh of electrical energy, plus natural losses, from the battery pack, which will noticeably reduce the available driving range and increase charging session cost.

4.4.2 Heat Pumps

Rather than directly converting electrical energy to thermal energy like PTCs, heat pumps move existing heat to/from the surrounding environment from/to the battery or passenger cabin. Heat pumps have been shown to efficiently remove heat from sub-zero ambient temperatures and the energy consumed from the battery in this process is typically 60% to 70% less than that of a traditional PTC heater (Wilson, et al. 2024). In contrast to a traditional PTC heater, the energy consumed by heat pumps is only for moving the refrigerant around the heating/cooling circuit, which contributes to the added energy efficiency of heat pumps although their performance degrades rapidly around 0°C (Zhang, Li and Hrnjak 2024). Due to the relatively recent nature of their widespread adoption, the technology involved in heat pumps is continuously improving. The main disadvantage of heat pumps is that they can only go down to certain cold temperatures before being unable to perform efficiently.

4.4.3 Waste Heat Recovery

Some OEMs utilize heat pumps to move waste heat from drivetrain components such as inverters, electric motors and HVAC compressors to the battery pack. Since these components organically produce heat when the EV is being driven which would otherwise be dumped into the surrounding environment, using waste heat energy to pre-heat the battery is more efficient by approximately 2% than the other methods described above (Dagar, et al. 2023). Some EV OEMs use special motor-inverter techniques to operate the motor-inverters more inefficiently, which produces extra heat to boost the pre-heating process. Advantages of this approach are improved heat pump performance in extremely low temperature environments and boosted overall closed system efficiency.

4.5 Observations from real-world BPC performance

EV OEMs employ a variety of BPC strategies depending on their set of performance requirements, design constraints, software strategy, cost and factors mentioned in Section 4.3. Table 2 shows a summary of the real-world BPC performance of some EVs.

Table 2 – BPC Performance Summary

Anonymized EV name	Ambient Temperature [°C]	Initial Battery Temperature [°C]	Initial BMS Charge Current Limit [A]	Final Battery Temperature [°C]	Final BMS Charge Current Limit [A]	SOC Consumed [%]	Time Taken [min]
2022 Hyundai Ioniq 5	6	9	Not Available	23	Not Available	3	25
2022 Tesla Model Y	4	10	105	41	338	5	35
2023 GMC Hummer EV	5	16	Not Available	20	Not Available	1	20

It is observed in Table 2 that when the EV commences BPC, between 1% to 5% of battery SOC is consumed over 20 to 35 minutes to heat up the vehicle battery to the target temperature. Data from the 2022 Tesla Model Y shows that BPC increases battery temperature from 10°C to 41°C leading to the BMS increasing its maximum charge-current limit from 105A to 338A which is more than a three-fold increase in charging speed. This emphasizes how BPC improves charging speeds and consequently reduces charge times.

5 DCFC Station Power Sharing

EVs are not always the limiting factor determining charging speeds at DCFC sites. The EVSE, grid charging infrastructure, and the utility provider also play crucial roles in determining charging speeds. Performing BPC mitigates the potential restriction associated with EV battery temperature, but limiting factors related to other parts of the larger EV charging system may limit potential performance improvements associated with BPC. The most common EVSE charging constraints include:

- DCFC Station Topology
- DCFC Station Power Sharing.
- Environmental Factors
- Grid Conditions

5.1 DCFC Station Topologies

Residential chargers, typically known as Level 1 (L1) or Level 2 (L2) chargers facilitate AC power transfer from the grid to the EV. During an L1/L2 charge session, the EV utilizes an on-board converter to convert AC power into DC power to charge the traction battery. For contrast, DCFC AC-DC conversion occurs offboard the vehicle in an electrical enclosure that comprises the DCFC infrastructure. A DCFC EVSE transfers DC power directly into the EV traction battery, bypassing the on-board AC-DC converter. DCFC power conversion and charging are not subject to the same limitations that onboard power electronics are, so they can deliver more power and can also be larger and heavier, but also tend to have higher costs for delivered energy (Davidson, et al. 2024).

DCFC topologies exhibit a lot of diversity between manufacturers and models: power conversion electronics can be installed in enclosures that are separate from power dispensers or kiosks that house user interface screens and charging connectors. This design of EVSEs has evolved into more efficient and cost-effective multi-dispenser/multi-port topologies which are being widely adopted as DCFC charging sites grow in number of dispensers per site and increase available charging power. This topology enables the power conversion equipment to be installed away from vehicle parking spaces which improves flexibility for space, noise, and heat considerations and potentially improves system efficiency if power cabinets are located close to utility transformers.

A multi-port DCFC topology can deliver higher levels of charging power more efficiently and at lower cost than comparative “All-In-One" (AIO) EVSEs primarily due to economies of scale and reduced parts and labor requirements (Oreizi 2024). Figure 14 depicts an example of this topology, which can have a variable number of kiosks and EV connectors, depending on the technology used.

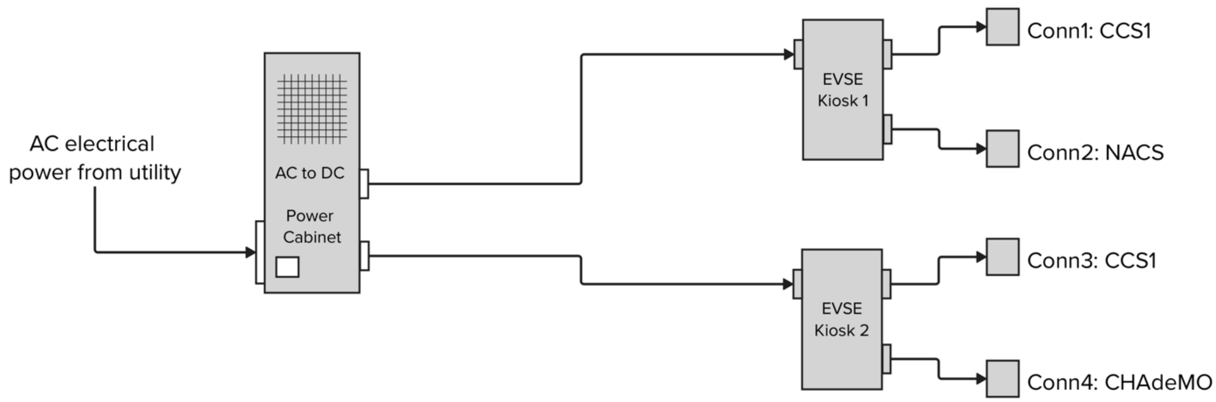

Figure 14. Modern Multi-Port Ultra-Fast Charge Station Topology

Alternatively, all components can be combined in a single AIO weatherproof enclosure that contains AC to DC power conversion equipment and one or two charging connectors as depicted in Figure 15. An AIO unit must be installed next to the parking space for EVs to charge.

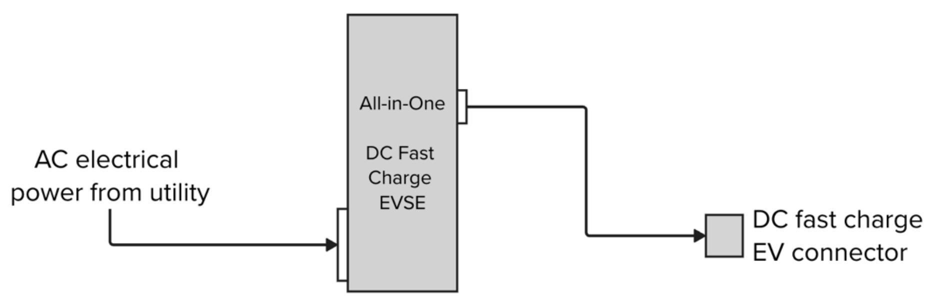

Figure 15. Representation of an All-In-One DCFC Topology

5.2 DCFC Station Power Sharing

DCFC EVSE power sharing topologies exist to reduce costs of installed infrastructure and maximize charging speed at low utilization rates. Infrastructure capital expense can be smartly reduced with DCFC power sharing topologies because EV drivers typically arrive at DCFC sites in a staggered manner and the time an EV demands peak power makes up a small percentage of the total charge session. Figure 16 depicts the 2022 Ford F150 Lightning Pro's power-banded charging performance across a 10% to 100% SOC charge session. It is observed that this vehicle charges at least 90% of OEM-rated peak charging power for approximately 10% of the total charge session length, no matter whether the vehicle is charging under cold, nominal or hot ambient conditions. These metrics can be improved: Figure 17 depicts the same vehicle's power-banded charging performance when the charge session is limited to 80% SOC. It is observed that in this scenario, charging power that meets or exceeds 90% of OEM-rated peak charging power comprises between 25% and 40% of the total charge session length depending on conditions of use. It is also noted that, regardless of the charge session SOC objective, EV charge acceptance curves request only request maximum charging power for a short period of time. This makes the DCFC station power sharing topology more economical as the DCFC charging capacity utilization factor is increased when shared amongst multiple vehicles whose uncoordinated charging schedules make it likely that they are not requesting maximum charging power.

Combining the results observed in Figure 16, Figure 17 and Table 3, we observe that the charging station that is used to only charge vehicles to 80% SOC will lower charging session cost for EV drivers and decrease congestion because most charging time is spent in the most optimal portion of the EV charge acceptance curve. Consequently, it also presents the opportunity for increased levels of utilization and profitability, with the tradeoff that at some specified utilization rate, unconstrained EV charging will no longer be possible due to DCFC power sharing or grid interconnection limits.

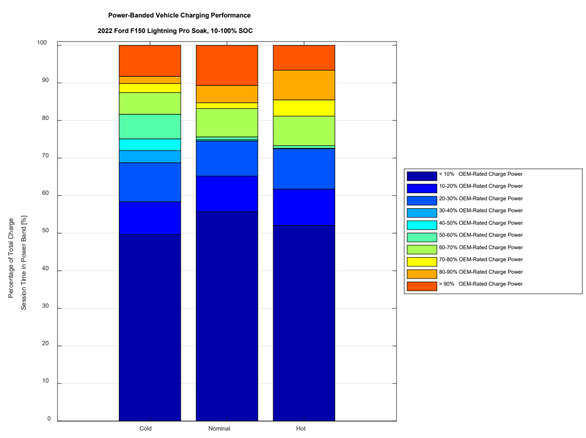

Figure 16. 2022 Ford F150 Lightning Pro 10-100% Charge Session Power Bands

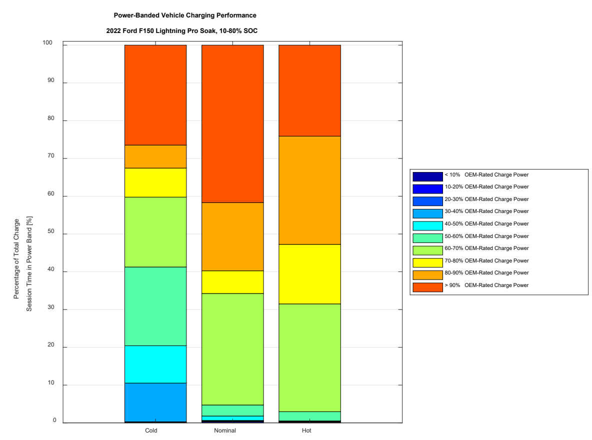

Figure 17. 2022 Ford F150 Lightning Pro 10-80% Charge Session Power Bands

Table 3 – 2022 Ford F150 Lightning Pro Charge Session Metrics

Charge Session	10-100% Charge Session Length [HH:MM:SS]	10-80% Charge Session Length [HH:MM:SS]	10-100% Charge Session Energy Charged [KWH]	10-80% Charge Session Energy Charged [KWH]
Cold Temperature Charge Session	02:10:24	00:40:46	92.97	71.37
Nominal Temperature Charge Session	02:06:47	00:32:26	89.25	67.45
Hot Temperature Charge Session	02:07:12	00:35:00	90.16	69.1

Figure 18 depicts a representative example of high vehicle utilization at a DCFC station. The AC-DC power converter inside the power cabinet can supply a maximum of 500 kW of charge power. Four kiosks are connected to the power cabinet, each capable of transferring 350 kW of power. Since all the kiosks are occupied with four EVs being simultaneously charged in this example, the DCFC station will attempt to split the power amongst the four EVs. Even though all EVs arrive with pre-conditioned batteries and low SOC, all four EVs will charge at a power level constrained by the total power capacity of the EVSE. Additional research is required to characterize and quantify DCFC power sharing behavior for market-available EVSEs that feature power sharing topologies.

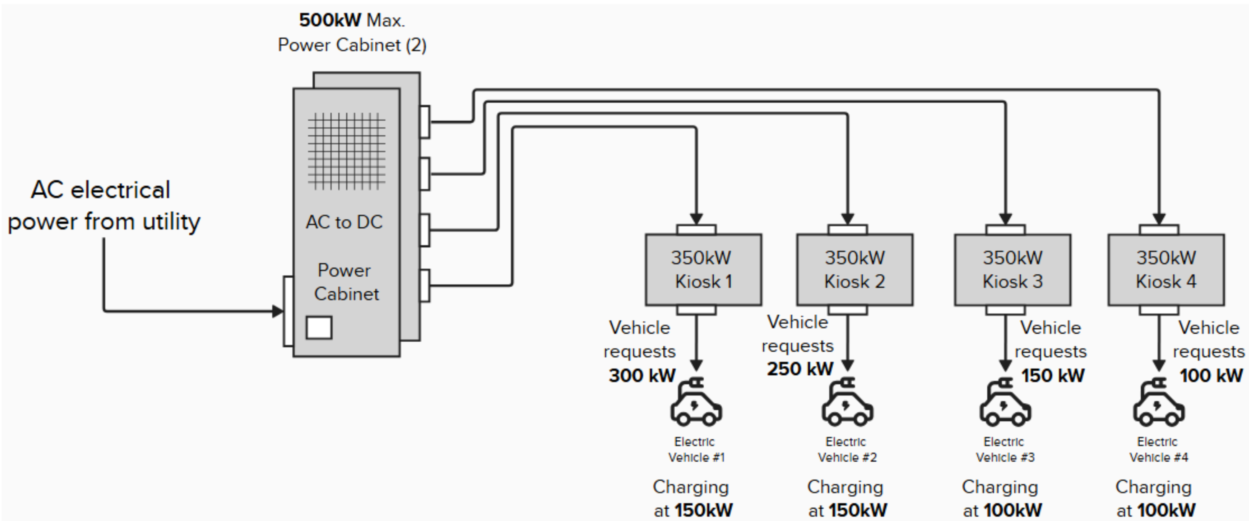

Figure 18. Representative Example of DCFC EVSE Power Sharing Across Multiple Simultaneous Charging Sessions

High DCFC site utilization can reduce available charging power, increase costs and extend the length of charging sessions. Charge power curtailment and/or elevated electricity rates could result from vehicle charging power demand exceeding the EVSE nameplate power rating or charging site interconnection power because most site charging plugs are in use. An EV driver can avoid these curtailments by selecting a port whose shared kiosks are not in use by other vehicles or by charging at times when station utilization is lower on average, and therefore less likely to incur power sharing penalties.

5.3 Environmental Factors

Maximum DCFC power is affected by excessive heat and high ambient temperatures. Many North American commercial DCFC stations typically utilize liquid-cooled high power charging connectors which remove generated heat from the charging cable and power electronics to an air-cooled heat exchanger. High ambient temperatures limit the amount of heat the charging system can transfer to the surrounding environment and may result in the EVSE reducing its power limits to reduce heat generation. There is not much an EV driver can do to prevent EVSE charging power curtailment: planning ahead to charge at times when ambient temperatures are lower (mornings, evenings, or at night) is the only available course of action. Research has shown that high EVSE temperatures resulting from high utilization of some EVSEs can result in enforcement of significant EVSEs charging power curtailment limits; this effect will be exacerbated by high ambient temperatures and has the potential to significantly extend charge session dwell time and degrade user experience (Carlson and Onar 2023).

5.4 Grid Conditions

Available DCFC power is affected at times of peak electricity consumption and energy demand. Electricity congestion and grid stress can cause charge station operators to curtail available charging speeds or charge surge pricing: electricity costs can be used as a proxy to infer electricity demand. As with high ambient temperature conditions, not many options are available to an EV driver to avoid charging during grid congestion other than charge at lower speeds or higher prices or wait until the electricity demand is lower.

6 Best Practices and Recommendations

EV drivers that adopt the best practices and recommendations discussed in this report and summarized in this section will maximize drivable EV range while minimizing charge station dwell time and charge session cost of publicly available DCFC charging infrastructure. Doing so will improve charge station financial and utilization metrics for CPOs, maximize the user experience for all EV drivers and reduce overall impacts associated with EV charging station operation. Over time, availability and performance of publicly available DCFC charging infrastructure has and will continue to increase, which will support continued adoption of electrified forms of transportation (Brown, et al. 2024) (Wood, et al. 2023).

Recommended practices for EV drivers include:

- Arrive at the DCFC site with the lowest possible SOC that the EV driver is comfortable with
- Bound EV SOC target to the minimum energy necessary to reach the next DCFC charger on the planned route or at the destination
- Where available and time permits, utilize L1 and L2 charging preferentially over DCFC
- Utilize EV battery pre-conditioning routines to the maximum extent practicable before charging, especially in environments with extreme ambient temperatures
- Activate BPC routines approximately 30 minutes before commencing high power DC charging
- Expect the BPC routine to consume $\leq$ 5% of available vehicle SOC
- Plan travel routes in advance while taking DCFC EVSE availability, weather, expected station congestion and grid congestion into consideration
- Prioritize utilizing DCFC charging ports that are not currently providing power to other vehicles in order to minimize power sharing amongst multi-port EVSEs

7 Conclusion

The consistent and efficient performance of North American public EV DCFCS is crucial for effectively supporting EV travel and positive user experience. Key factors that significantly impact DCFC charging times, user experience and cost effectiveness have been identified and analyzed. EV specifications and charging conditions that dictate real-world performance have been assessed, including battery size, OEM-imposed limitations, SOC and battery and ambient temperature. All these factors balance available charging power, charge session cost and charging station dwell time/queueing and wait time with preventing battery damage, premature aging and preserving battery longevity.

EV charging factors, such as SOC-based limits, taper charge speeds as SOC increases: using a DCFC to charge beyond 80% SOC can consume a disproportionate amount of time for a small gain in range. Temperature-based limits, especially in cold weather, can cause significant delays in charging time to preserve battery longevity; BPC and BC can have a profound impact on EV DCFC performance.

EVSE charging factors including power-sharing topologies, environmental conditions and grid conditions have the potential to limit EV charging speeds and should be considered in charging plans. EV drivers can significantly optimize their DCFC experience by adopting recommended best practices including SOC bounding, maximizing use of EV BPC and strategic route planning. By understanding and mitigating DCFC influencing factors, stakeholders can contribute to a more efficient, reliable, cost-effective and user-friendly North American EV charging ecosystem.

It is recommended that future research activities enhance the findings in this report by collecting data to not only characterize how charge acceptance curves change with the use of battery preconditioning but also quantify the energy consumption of battery preconditioning routines from multiple vehicle OEMs, assess the effectiveness of battery preconditioning routines under the suboptimal conditions evaluated in this report and publishing results in a future NextGen Profiles EV Profile Capture report. It is additionally recommended that future research focus on characterizing, quantifying and reporting on EVSE power sharing behavior.

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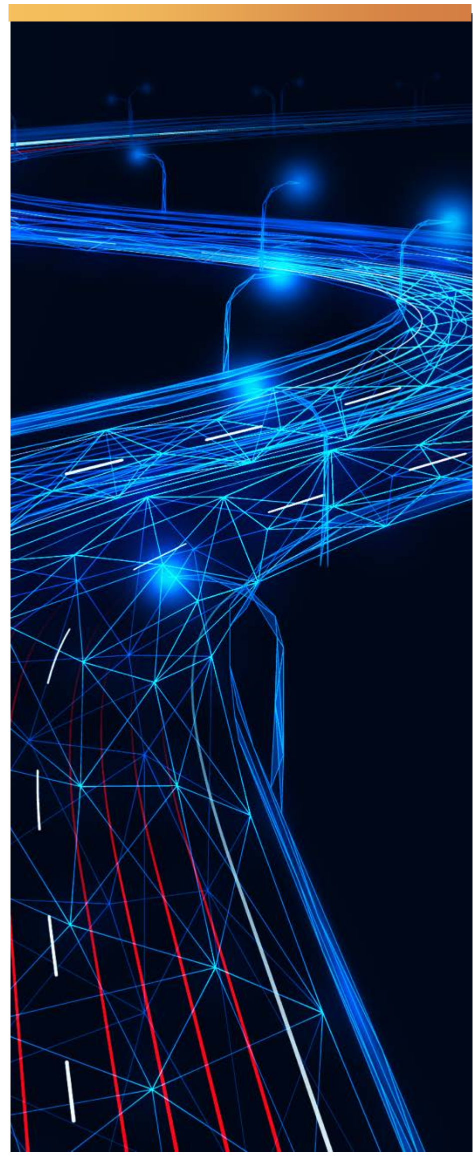

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