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Effects of Electric Vehicle Fast Charging on Battery Life and Vehicle Performance

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Abstract

As part of the U.S. Department of Energy's Advanced Vehicle Testing Activity, four new 2012 Nissan Leaf battery electric vehicles were instrumented with data loggers and operated over a fixed on-road test cycle. Each vehicle was operated over the test route, and charged twice daily. Two vehicles were charged exclusively by AC level two electric vehicle supply equipment, while two were exclusively DC fast charged with a 50 kilowatt fast charger. The vehicles were performance tested on a closed test track when new, and after accumulation of 50,000 miles. The traction battery packs were removed and laboratory tested when the vehicles were new, and at 10,000-mile intervals throughout on-road mile accumulation. Battery tests performed include constant-current discharge capacity, electric vehicle pulse power characterization test, and low peak power tests.

The data collected over 50,000 miles of driving, charging, and rest are analyzed, including the resulting thermal conditions and power and cycle demands placed upon the battery. Battery performance metrics including capacity, internal resistance, and power capability obtained from laboratory testing throughout the test program are analyzed. Results are compared within and between the two groups of vehicles over the test period. Specifically, the impacts on battery performance, as measured by laboratory and track testing, are explored as they relate to battery usage and variations in conditions encountered, with a primary focus on effects due to the differences between AC level two and DC fast charging. The contrast between battery performance degradation and the effect on vehicle performance is also explored.

Introduction

Battery-electric vehicles (BEV) have reemerged in the light-duty vehicle market in the past few years, having many of the features of conventional passenger vehicles, with the notable exceptions of driving range between refueling, and refueling time. Seven 2014 model-year BEVs under $40,000 MSRP achieved EPA full-charge ranges varying from 62 to 87 miles, with the group averaging 77 miles [1]. While many drivers' daily travel requirements may be met with the range of these moderately priced BEVs assuming overnight charging, others will require greater range on a frequent basis, while all BEV owners will likely need to travel beyond their vehicle's full charge range on occasion. Fast charging of the battery is one way of extending the trip distance capability of BEVs, by reducing the time to charge the battery through higher power charging. Vehicle batteries lose capacity gradually as they are cycled through driving and charging, though the rate is dependent on the chemistry, management of usage, and ambient conditions. One study explored the effects of fast charging of lithium titanate cells, finding minimal capacity fade throughout their experiment while charging at a 6C rate, which charges a battery at a peak current equal to six times the battery capacity per hour [2]. Both the capability to accept high charge currents and the resultant cycle life when subjected to fast charging is affected by the battery chemistry. The generally accepted theory has been that faster charging rates will increase the rate of degradation. This theory has implications on what types of charging BEV owners will leverage and what electric vehicle supply equipment (EVSE) manufacturers will bring to market. A study to increase understanding of the degradation effects of faster charging was initiated by the U.S. Department of Energy's Advanced Vehicle Testing Activity (AVTA). The AVTA program is managed by the Idaho National Laboratory, and Intertek Testing Services, North America managed all of the test vehicle operations, and performed the vehicle and battery testing.

This study quantifies the effects on the vehicle battery for a set of vehicles that are exclusively direct current fast charged (DCFC), and compares it to an identical set of vehicles that are exclusively charged using alternating current level two (AC L2) electric vehicle supply equipment. The vehicles used in this study are model year 2012 Nissan Leafs powered by lithium ion traction batteries, and equipped with the optional CHAdeMO DCFC port. The battery pack on this vehicle is rated at 24 kilowatt-hours and 66.2 Amp-hours, and is rated to provide 73 miles of driving range per EPA testing [1]. The pack is constructed from 192 prismatic cells, packaged in 48 modules each consisting of two sets of paralleled cells connected in series. The cell active materials consist of an LMO with LNO cathode and a graphite anode [3]. The pack is located under the vehicle floor, and is sealed. Heat is dissipated passively; there is no exchange of fluid through the pack.

This paper details the methodology used to obtain baseline metrics against which degradation is calculated, accumulate mileage among the test vehicles under a comparable set of conditions, take measurements of the battery health at uniform mileage intervals, and finally, obtain battery capacity metrics from on-road operation throughout the testing. The conditions the batteries were subjected to and the differences between test groups are explored including power profiles and thermal characteristics. The resultant capacity and power capability fade are presented, and compared to conditions to which the battery packs were subjected.

Testing Methodology

To study the effects of fast charging on battery life and vehicle performance under a set of real-world conditions, four 2012 Nissan Leaf BEVs were commissioned to accumulate mileage through on-road operation in Phoenix, Arizona. Initial performance was gauged by a series of tests, beginning with baseline testing when the vehicles were new, and at fixed intervals throughout the project. Two vehicles were used as the control group, and were restricted to only AC L2 charging. The other two vehicles were restricted to only DCFC. To isolate differences in battery conditions to charging effects, careful vehicle management during mileage accumulation phases was necessary.

Several methods were designed to measure changes in battery and vehicle performance as the vehicles accumulated miles. These include, in order of increasingly controlled conditions, evaluation of data collected during on-road operation, track testing, and lab testing of the batteries. Methods for on-road mileage accumulation, data collection, and analysis are detailed, along with the track and lab testing.

On-Road Mileage Accumulation

Driving

The vehicles were typically driven six days per week, with each vehicle driven on public roads in Phoenix, Arizona, over a prescribed route twice per day. Each day consisted of one drive in the morning and the other in the evening for each vehicle. To minimize variation in drive-cycle and environmental variables, vehicles were driven together as a pair, consisting of one DCFC group vehicle and one AC L2 charge group vehicle. Because pairs of test vehicles were driven serially, there were early- and late-morning drives, typically beginning around 5:30 and 7:30 AM respectively. The same scenario was applied to evening drives, typically beginning around 5:30 and 7:30 PM. Vehicle pairs alternated between early and late morning and evening groups daily, such that one pair of vehicles was not consistently driven during a cooler or hotter part of the day, or during rush-hour traffic. The professional drivers were also alternated between cars to minimize any bias due to particular driver-specific habits, though this was primarily controlled through driver training and written procedures for accessory usage.

Each vehicle was operated with the automatic climate control enabled and set at 72°F such that heat or air conditioning would automatically maintain a comfortable cabin environment, constantly between vehicles. Drivers were instructed to drive with the flow of traffic, and to follow a set route consisting of highway and city portions. The route returned the vehicles to an urban loop for the final part of the drive, keeping them close to the charging facility as the remaining range indicator approached zero. This loop was driven until the dashboard range indicator read 5 miles, upon which the vehicle would return to the nearby charging facility and immediately begin charging. Each vehicle would then commence on another drive cycle with a fully charged pack, approximately 10-14 hours after the previous cycle began. As the project progressed, differences in range among vehicle charge-type groups required up to a week of catch-up driving for the cars with less battery capacity remaining, once those with more capacity and range reached a 10,000 mile test interval.

Charging

Upon returning to base after a drive, each vehicle was plugged in, and charging was initiated. For the DCFC group vehicles, an off-board DC fast charger with a CHAdeMO connector and protocol was used. This charger was set up for a maximum output current of 120 Amps, and output voltage up to 500 Volts DC. The DCFC would terminate prior to the battery fully charging. This required a re-start for each DC fast charge to fully charge a vehicle. During this second phase, the charge would typically terminate once charging current tapered to about one amp during the constant voltage phase of the charge.

For the AC L2 charging group vehicles, the Leaf's 3.3kW on-board charger was supplied by an AC L2 charger wired to a 208V circuit through a 30A breaker. This allowed the onboard 3.3 kW charger to operate at its maximum current. Voltage and current supplied to the test vehicle batteries, when new, are shown for a DCFC charge and an AC L2 charge in figures 1 and 2, respectively.

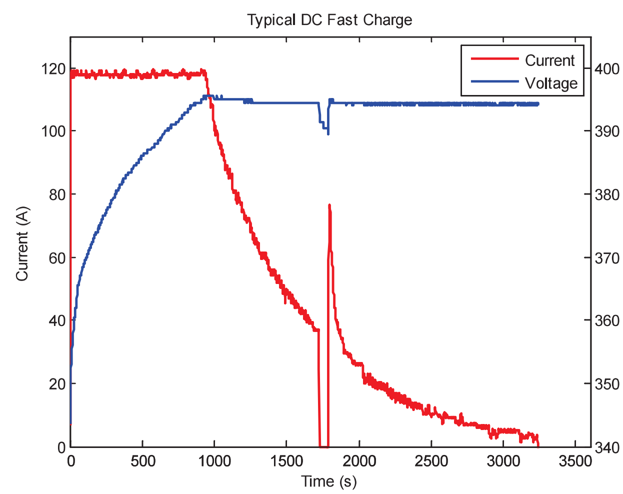

Figure 1. A DC fast charge is shown for a 2012 Nissan Leaf charged with a 50kW fast charger. The charge automatically ended after 1725 seconds, and another charge session was initiated shortly after the first one ended to fully charge the battery.

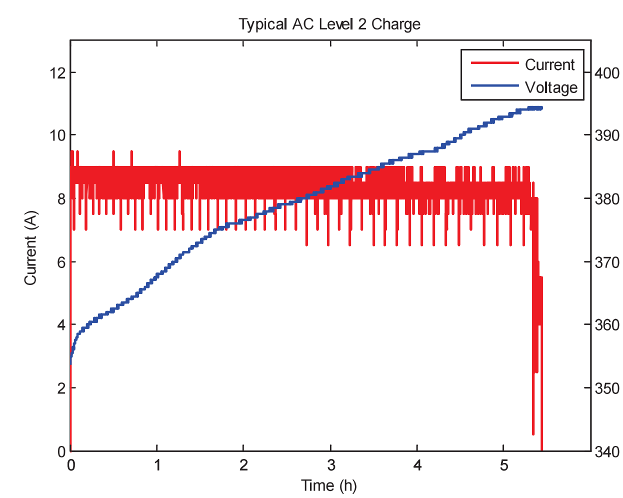

Figure 2. An AC level two charge is shown for a 2012 Nissan Leaf with a 3.3 kW onboard charger.

Data Collection

Vehicle data were acquired during all on-road operation and charging by a data logger recording signals at a frequency of 1 Hz. Controller area network (CAN) data were used, when available, and additional temperature data were gathered by thermocouples placed on the bottom of the pack, top of the pack, and near the front bumper for ambient air temperature. During periods when the vehicles were parked, CAN controllers would stop sending messages, and only the analog thermocouple data were gathered. Signals gathered from the CAN bus included vehicle speed, battery pack current, voltage, temperature, and state-of-charge. These data were wirelessly transmitted to servers every time a vehicle returned for charging. The data were then loaded into a database, and processed into event-level records, while maintaining the second-by-second raw data for each event. Because temperature inside the pack, averaged from four sensors distributed across the pack, was sourced from CAN messages that ceased during periods where the vehicle was parked and not charging, an estimated pack temperature between periods of CAN communication was created by linear interpolation.

On-Track Vehicle Performance Testing

Track testing was performed at Ford's Arizona Proving Ground to determine constant-speed range and maximum acceleration capabilities for each vehicle. These tests were performed when the vehicles were new to establish baseline performance, and after 50,000 miles of operation as described in the on-road mileage accumulation section. Vehicles were instrumented with calibrated equipment to measure ground speed, battery current, and battery voltage in addition to vehicle CAN data. This served a dual purpose, allowing verification of vehicle based CAN signals with respect to calibrated instrumentation, as well as collecting precise speed, distance and energy data. Each was ballasted to the delivered curb weight plus 332 ± 10 pounds, including the weight of both the driver and instrumentation. No vehicle accessories were used for any track testing, other than the headlights. The constant-speed range test for each of the four vehicles began with a full ACL2 charge. Each test vehicle was driven a fixed distance to the oval track, where it was driven at 45 MPH until it could no longer maintain within 2 MPH of the target speed. Acceleration tests were also begun with full ACL2 charges. Each vehicle was accelerated from a stop at wide-open throttle for one mile on a straight-away track. This was performed for up to 11 back-to-back runs with no intermediate charging, and no dashboard indication of reduced performance due to reaching low state-of-charge. From this data, IVM to 60MPH times were measured and averaged across the 11 runs, along with the maximum speed achieved and peak power drawn from the battery.

In-Laboratory Battery Testing

The battery packs were removed from each vehicle and tested in the laboratory at 10,000 mile intervals. Each pack was tested for capacity using the Constant Current Discharge Test from the USABC Electric Vehicle Battery Test Procedures Manual, Revision 2 [4]. For this test, each pack was fully charged, allowed a one hour rest, then was discharged at a 3-hour rate of 22.07 Amps until the minimum cutoff voltage was reached. This test was repeated three times for each pack at every 10,000 mile interval, while energy discharged was measured. The voltage profile for successive 10,000 mile interval tests for one vehicle is shown in figure 3.

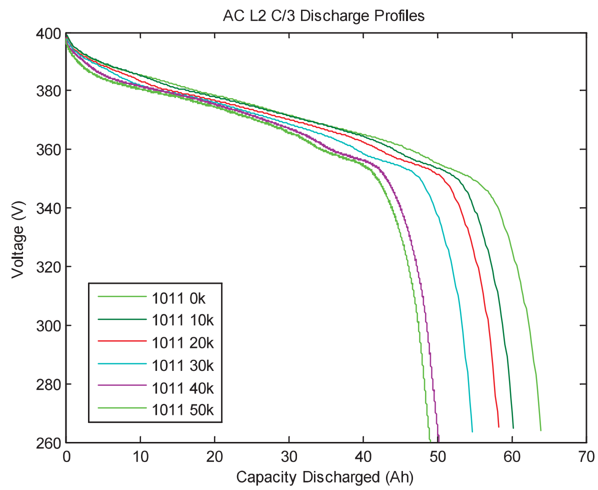

Figure 3. The voltage traces of several constant current discharge tests for one of the AC L2 control group vehicles (VIN ending in 1011) is shown. The area under each curve indicates the energy discharged during the test.

Another test performed is the Electric Vehicle Power Characterization (EVPC) test. This test is similar to the Hybrid Pulse Power Characterization test from the FreedomCAR Battery Test Manual for Power-Assist Hybrid Electric Vehicles [5] with a few distinct differences, including the charge and discharge current levels, and the number of pulses performed. The test begins with a single iteration of the Constant Current Discharge Test, referenced previously. Following the discharge, the pack is again fully charged, allowed to rest for one hour, then a series of 30 second discharge and 10 second charge pulses are applied from 100% SOC to 10% SOC, at 10% SOC intervals. From these pulses, charge and discharge resistance are calculated, along with charge and discharge power capability.

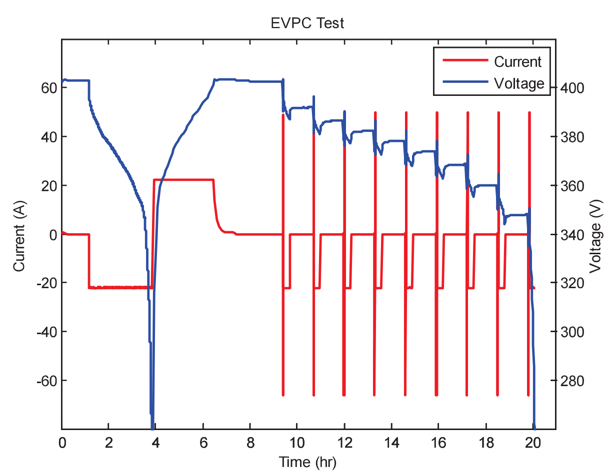

Figure 4. Current and voltage traces for an EVPC test conducted for one of the AC level two control group vehicles are shown

Finally, a modified Peak Power test was conducted. This test, another method of calculating discharge power capability, is procedure #3 in the USABC Electric Vehicle Battery Test Procedures Manual, Revision 2 [5], with the High Test Current substituted for a Low Test Current equal to the one-hour discharge rate, or 66.2 Amps and the Base Discharge Rate equal to the three-hour discharge rate, or 22.1 Amps. The results of the modified Peak Power tests are not discussed in this paper.

During these tests, the power processing machine was connected directly to the pack output, and the onboard battery management system was not powered.

Results

Following cycling of the batteries through on-road driving and charging, battery and vehicle testing, the collected data were analyzed to characterize the conditions to which the batteries were subjected during driving and charging, with a focus on differences between the charging type test groups. Next, battery capacity and power capability fade are analyzed. Finally, the impacts that this degradation had on range and acceleration are presented.

Battery Conditions

The battery data from driving and charging were analyzed to determine the conditions to which each pack was subjected. All of the vehicles were run together on the same calendar schedule throughout the project, with the minor exception of catch-up driving by the vehicles that lost capacity faster than others, logging less miles per day and needing a few more trips to get to the testing interval mileage. The battery discharge and regen current levels during driving are quantified, and compared among vehicle test groups. The battery temperature for each is also examined. Figures 5 and 6 show battery current and battery temperature for an ACL2 car and a DCFC car for the same 24 hour period representing a single test day.

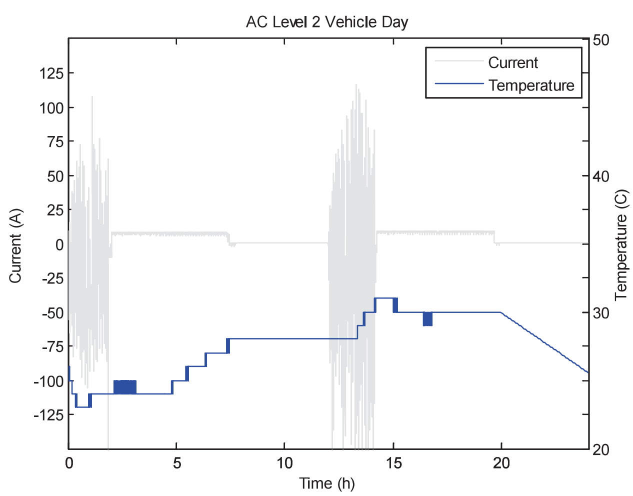

Figure 5. A 24 hour period is shown for an ACL2 vehicle (1011), with the time beginning at the start of the morning drive. Battery current and battery temperature are shown.

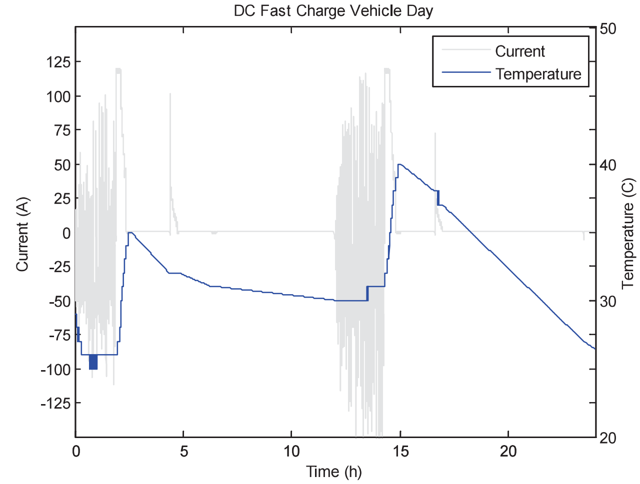

Figure 6. A 24 hour period is shown for a DCFC vehicle (2078), with the time beginning at the start of the morning drive. Battery current and battery temperature are shown.

Battery Current and Energy

Driving

The efforts described earlier to manage vehicle operation during driving successfully minimized differences in energy consumption during driving among the test vehicles. The largest difference between any two vehicles was less than 3 percent. The individual vehicle energy consumption, averaged through the duration of the project from driving events, is shown in table 1.

Table 1. Average driving energy consumption over the duration of the project is presented for each vehicle.

Group	ACL2	ACL2	DCFC	DCFC
Vehicle Number	1011	4582	2078	2183
Energy Consumption (DC Wh/mi)	225	229	231	229

While the average energy consumption was consistent, the distribution of current magnitude during discharge and regen need also be comparable among cars. It was confirmed that minimal differences existed between vehicle test groups, as is illustrated in figure 7.

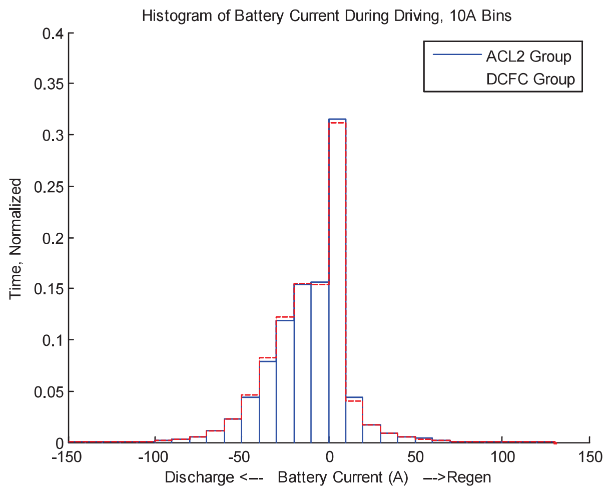

Figure 7. The frequency of driving battery current, separated into 10 Amp bins, is shown. Positive battery current represents current flowing into the battery during regen, while negative current represents discharge of the battery.

Charging

A similar analysis was performed for the charging data, though differences between test groups were part of the experiment. For the AC L2 group, nearly all of the time during charging events occurred at less than 10 Amps as expected. The DCFC group charging profile was mainly distributed between 0 and 120 Amps, as shown in figure 8. Most fast charges began with a constant current portion around 120 Amps for several minutes, which accounts for the relatively large percent of time in the 110-120 Amp range.

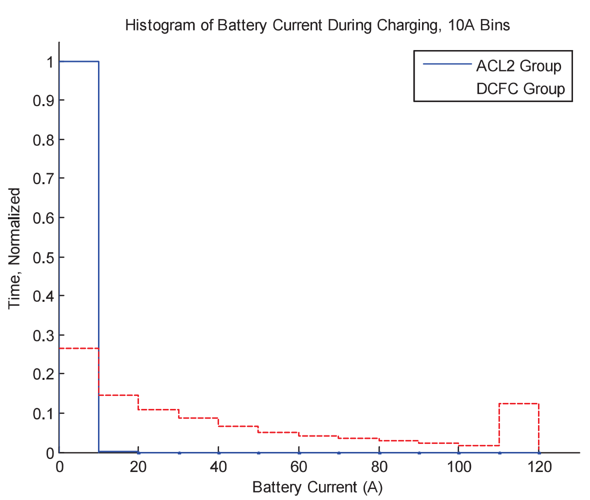

Figure 8. The frequency of battery current during charging, separated into 10 Amp bins, is shown.

To put this in perspective to the pack capacity, the peak charge current approaches, but does not exceed a 2C rate. During charging events heat generation, due to internal resistive losses within the battery, is proportional to the square of the charge current. Given the order of magnitude increase in charge current for a significant portion of charging, differences in thermal response of the batteries in each test group is explored.

Thermal Response

Variables affecting the thermal state of the battery include heat production within the pack, physical properties of the pack, and ambient conditions, each varying with time. Since the vehicles are all identical, were driven in the same routine, and were operated in the same ambient conditions as described earlier, differences in temperature between test groups are expected to have begun during charging events, due to the differences in charging rate characterized above. After the completion of charging, with little to no current flowing, and lacking an internal heat source, the packs begin to approach equilibrium with the ambient conditions, which are common among the group of vehicles. The test vehicles were equipped with an optional battery heater, activated automatically during periods of cold weather. These were determined to not have been activated at any time during the testing due to the lack of cold temperatures. Data were analyzed to characterize the pack temperature at the beginning of charging, temperature rise through charging, and then finally pack temperature at the beginning of a driving event. The project was conducted year-round in Phoenix Arizona, and there was significant seasonal variation in ambient temperature.

The longest zero current soak occurs between the end of a charge, and the beginning of the next drive, which can be seen in figures 5 and 6. For a period of 250 consecutive test days, the pack temperatures of the DCFC and ACL2 vehicles in the early morning driving pair are shown, along with the difference between the two for every day in figure 9. The DCFC vehicle pack was, on average 2.1°C hotter than the ACL2 pack for each morning drive, where this difference was normally distributed about a median temperature difference of 2°C. It appears from this data that residual heat from the fast charging does elevate the pack temperature slightly for the next drive, however the change is minor compared to the seasonal variation in temperature.

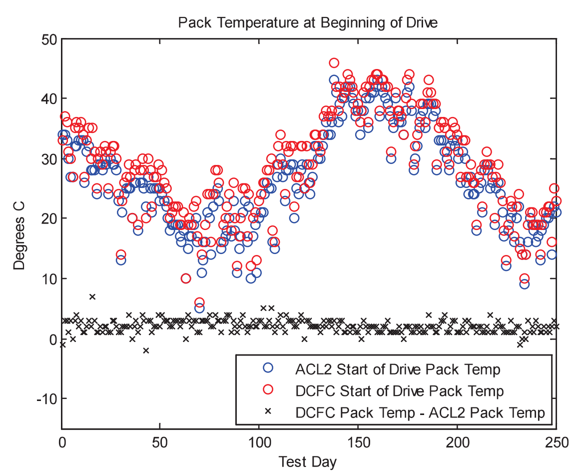

Figure 9. Battery pack temperature at beginning-of-driving is shown for an alternating test pair of one ACL2 vehicle and one DCFC vehicle over 250 consecutive test days.

Over these drive cycles, the DCFC vehicles packs cooled, on average, 1.1°C, and the ACL2 packs averaged a drop of 0.4°C. This behavior typically closed the minor gap in temperature that existed at the start of driving. Pack temperature at the end of each drive, which coincided with the beginning of charging is presented for both vehicles in the test pair in figure 10, representing the same days as shown in figure 9. The DCFC vehicle's pack was, on average, 1.4°C warmer than the ACL2 pack following the trip. Each charge was begun immediately upon completion of the preceding drive, so the end-of-drive temperature is synonymous with the beginning of charge temperature.

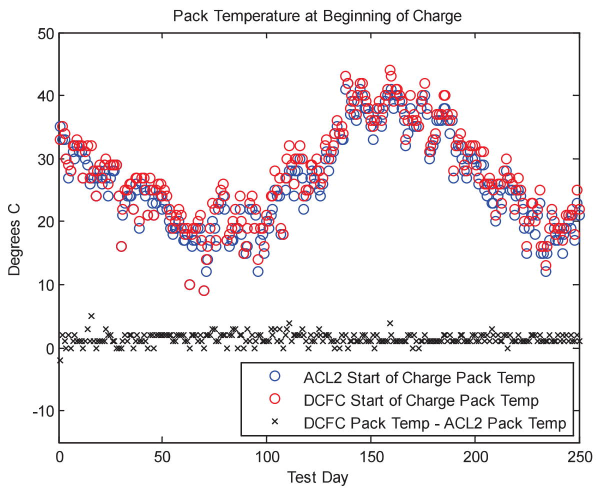

Figure 10. Battery pack temperatures at beginning-of-charge is shown for an alternating test pair of one ACL2 vehicle and one DCFC vehicle over 250 consecutive test days.

Given the driving route protocol and nearly identical battery duty cycle, it can be expected that only minor differences in battery temperature were found over driving events. The differences in charge rate among the groups, and the lack of active cooling account for greater temperature increase for the DCFC pack, as shown in figure 11. The average DCFC pack temperature rise during charging was 6.5°C, while the ACL2 pack average was 2.9°C,and the mean of difference between the two packs' temperatures at end-of-charge was 4.9°C.

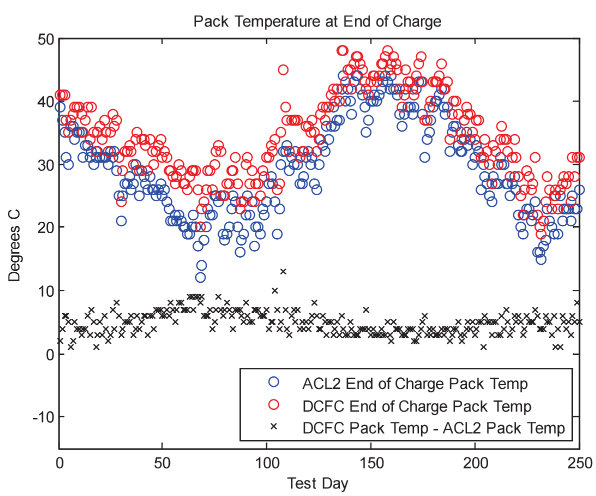

Figure 11. Battery pack temperatures at end-of-charge is shown for an alternating test pair of one ACL2 vehicle and one DCFC vehicle over 250 consecutive test days.

Average end-of-charge pack temperatures alone are not particularly meaningful, given the range of results due to the variation in ambient conditions native to year-round on-road testing. Instead, a distribution of pack temperature over the life of the project is presented for each test group in figure 12. Increased temperature over the control group is not in itself expected to be an issue affecting aging. Rather, time and cycling at temperatures above an ideal limit, dependent on cell chemistry, would be expected to be particularly detrimental to aging. A cumulative distribution is shown to indicate how much time was spent above any given temperature. Nissan service literature for the Leaf indicates that battery pack temperatures above 55°C will illuminate the dashboard high battery temperature warning lamp during driving, and battery temperatures above 55°C will cause a charge event to pause until temperature falls [6].

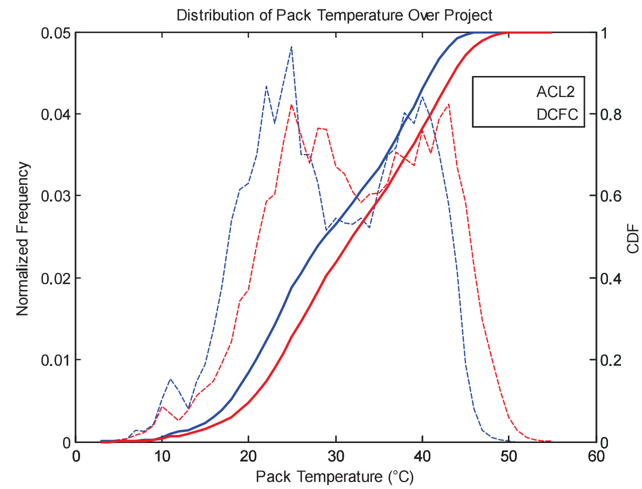

Figure 12. Battery pack temperature distribution for ACL2 and DCFC vehicles. The data represents 50,000 miles of driving, charging, and parking over more than 500 days. For the DC fast charged packs, 95% of time was spent under 46°C in one of the hottest regions in the continental US.

Lab Testing Results

Capacity

The constant current discharge tests indicated small differences among the packs when new. The energy capacities indicated are the average of the three tests conducted at each interval. These tests were each required to fall within 2% of each other to be considered stable and representative. The results of each test are shown in figure 13.

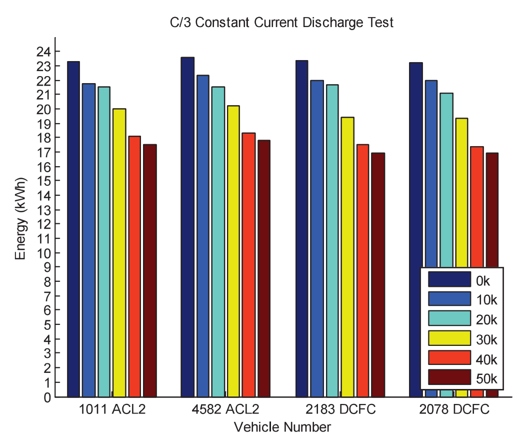

Figure 13. Battery capacity discharged for each pack at 10,000 mile intervals. Each

result is the average of three 3-hour constant current discharge tests, falling within 2% of each other.

There were small differences in the baseline energy capacity measured among the four vehicles. The DCFC group shows distinct differences in capacity loss compared to the ACL2 group, noticeable beginning with the 30,000 mile test results. The capacity change varies by interval. Figure 14 shows the average capacity remaining, as a percent of baseline, for each test group, and the slope of the line indicates how quickly capacity loss occurred during the interval. There are notable differences in this slope depending on the interval, though for any given interval, the difference between AC L2 and DCFC groups are less notable, and the capacity remaining for each group diverges gradually compared to the overall capacity loss. This indicates that while the DC fast charged vehicles did lose more capacity than the control vehicles, that difference is small relative to the total capacity loss.

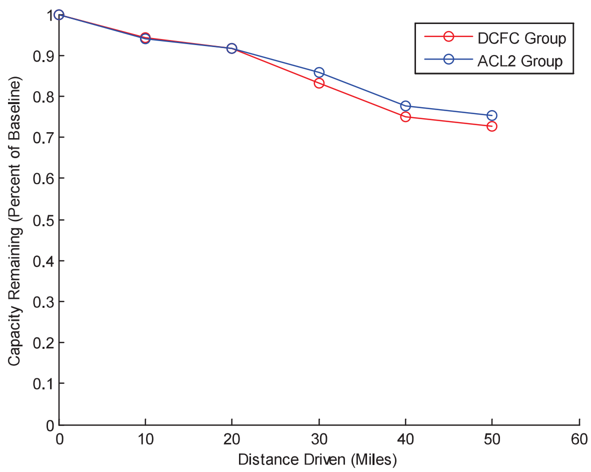

Figure 14. Battery capacity remaining, as a percent of baseline averaged for vehicles in each test group.

Resistance and Power Capability

Internal resistance of the pack was calculated by measuring the change in voltage during a discharge current pulse at each ten percent depth of discharge increment from fully charged. The EVPC test discharge pulse was performed at a 1C rate of 66.2A for 30 seconds, following a one hour rest. The low peak power test was conducted in the same manner, however no open-circuit rest was allowed between C/3 base current discharges at 22.1A and C1 pulses at 66.2A. The average increase in internal resistance, calculated as the average of the 30, 40, and 50% depth-of-discharge resistances, between baseline and 50,000 miles is shown in figure 15. If any difference in resistance growth occurred between the AC L2 group and DCFC group batteries, it is not shown in the data produced by the low peak power or EVPC tests performed. The two tests show small variations in the rate of resistance growth, though they disagree in which test group had the larger increase. The EVPC tests indicated 5 milliohms higher resistance in the DCFC group, while the LPP tests indicated 3 milliohms higher resistance in the ACL2 group. The difference was small, and indiscernible given the resolution of the testing hardware.

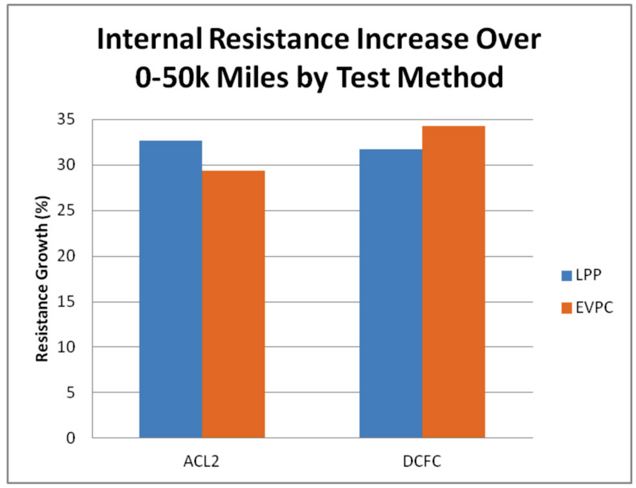

Figure 15. Battery internal resistance increase is shown between baseline and after 50,000 miles, as calculated using results from the low peak power and electric vehicle power characterization tests.

Discharge power capability, shown in figure 16, is calculated from the C/3 discharge voltage, and EVPC based calculated internal resistance at each 10-percent depth-of-discharge point, and minimum allowable pack voltage, for which 240 volts was used to obtain the following results. The actual minimum allowable voltage observed in vehicle operation was higher. As previously discussed, there was minimal difference in internal resistance between the test groups, though the voltage for the DCFC packs was lower than the AC L2 packs at each measurement point, resulting in a slightly lower power capability at 50,000 miles down to 50 percent depth-of-discharge. Depth-of-discharge is calculated by capacity discharged, in Amp-hours, divided by the rated capacity. Thus, as a pack loses capacity, a given DOD point will occur at an increasingly lower voltage. This effect is most notable in the 50,000 mile results beyond 50 percent DOD, beyond which pack voltage steeply decreases with further discharge, as shown previously in figure 3.

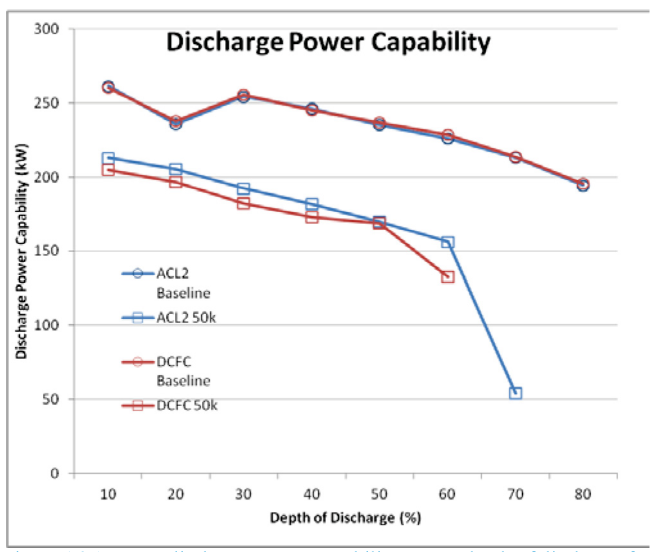

Figure 16.Average discharge power capability versus depth of discharge for ACL2 and DCFC groups at baseline and after 50,000 miles.

The lab power and capacity tests, while useful for comparing between intervals, do not necessarily equal the change usable energy available for driving, since this is restricted by the vehicle controller.

The vehicle must maintain significant discharge power capability throughout the allowable state-of-charge. Limitations on allowable DOD may also be used to increase battery life. On-road and track testing data were collected and analyzed to determine the usable energy at several test intervals.

Range and Acceleration Testing Results

The 45 MPH constant speed testing at baseline showed differences in both range achieved and energy discharged among the vehicles. The differences in baseline energy discharged during the track tests are more significant those seen in laboratory testing. Some variation may be inherent to battery capacity, though most likely some of this variation is due to vehicle controls; both the control of charge completion, or how full the battery is allowed to be charged, and discharge cutoff vary slightly through time, likely due to variation of conditions among cells in the pack, and the nature of state-of-charge measurement. The results of the constant-speed range testing for each vehicle is shown in table 2. The group-average range results at 45 MPH are shown in figure 17.

Table 2. Constant speed rack testing results at baseline and after 50,000 miles.

Group	ACL2	ACL2	DCFC	DCFC
Vehicle number	1011	4582	2078	2183
Baseline 45 MPH range (mi)	105.9	102.6	104.3	100.0
Baseline 45 MPH energy (kwh)	21.3	20.8	21.4	20.8
50k mile 45 MPH Range (mi)	80.9	82.4	68.9	71.4
50k mile 45 MPH energy (kwh)	15.4	15.4	14.2	14

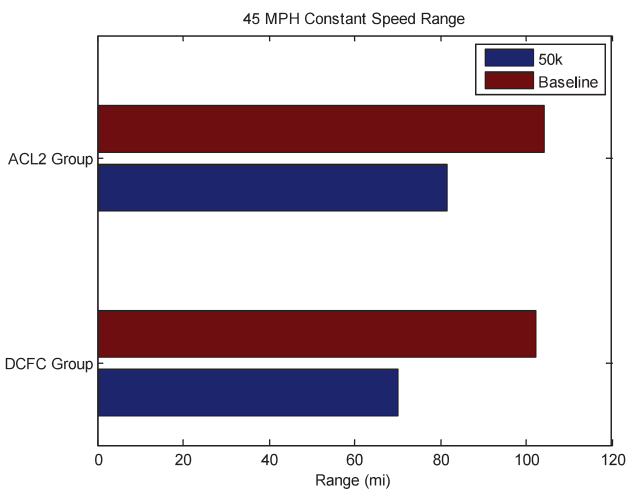

Figure 17. Constant-speed average range achieved for each test group at baseline and after 50,000 miles.

At 50k, additional range tests were conducted at 60 and 70 MPH. The higher speeds drew a higher average power, though the energy discharged remained comparable among speeds. The range and difference in range between test groups both decrease as speed increases though, due to the higher discharge power needed to maintain the set speed.

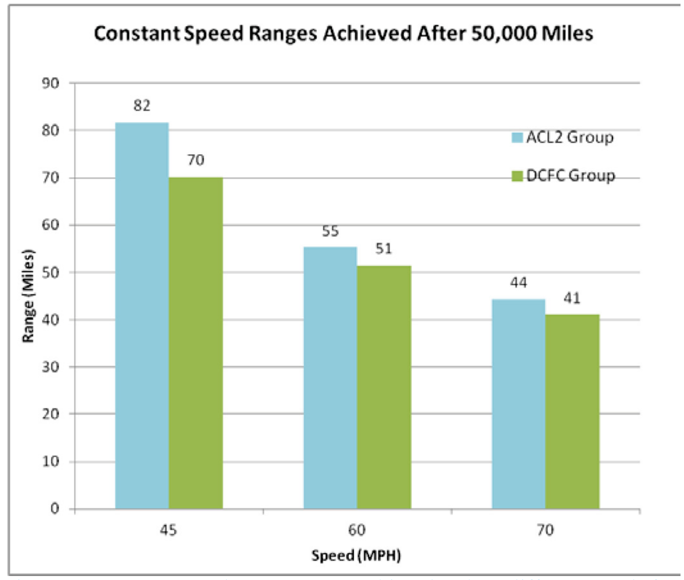

Figure 18. Constant-speed average range achieved at three different speeds for each test group after 50,000 miles.

Maximum speed and discharge power were taken from the highest observed during any one-mile acceleration run. Each vehicle reached maximum speed before the one mile mark for each run. The data from the acceleration testing is shown in table 3.

Table 3. One-mile acceleration track testing results at baseline and after 50,000 miles.

Group	ACL2	ACL2	DCFC	DCFC
Vehicle number	1011	4582	2078	2183
Baseline IVM-60 MPH time (s)	10.8	10.9	10.8	10.8
Baseline peak discharge power (kW)	89.7	87.7	88.7	89.2
Baseline max 1-mile speed (MPH)	92.4	92.7	92.7	92.6
50k IVM-60 MPH time (s)	10.9	10.6	11.0	10.8
50k peak discharge power (kW)	91.0	88.9	89.1	91.8
50k max 1-mile speed (MPH)	91.4	92.4	91.1	92.2

Maximum speed is assumed to be governed by the electric motor speed, so the minor differences in maximum speed achieved by each vehicle, about one MPH, and measured independently from the vehicle speedometer, is likely due to differences in tire wear related to when the tires were replaced rather than any changes in vehicle performance capability over the course of the study.

Discussion

Each method used to determine capacity fade showed some level of increased degradation in the DCFC vehicles, compared to the AC L2 vehicles after 50,000 miles. The difference in capacity loss is significantly smaller than the overall loss of capacity, as illustrated in figure 19. Again, the DCFC vehicles were charged twice daily at a high rate, twice as often as recommended by the manufacturer. Also, the vehicles were driven and charged year-round in a city with a very hot climate. Given this scenario, it is likely that the capacity loss observed in this study represents an upper bound for expected capacity loss for BEVs with similar battery properties.

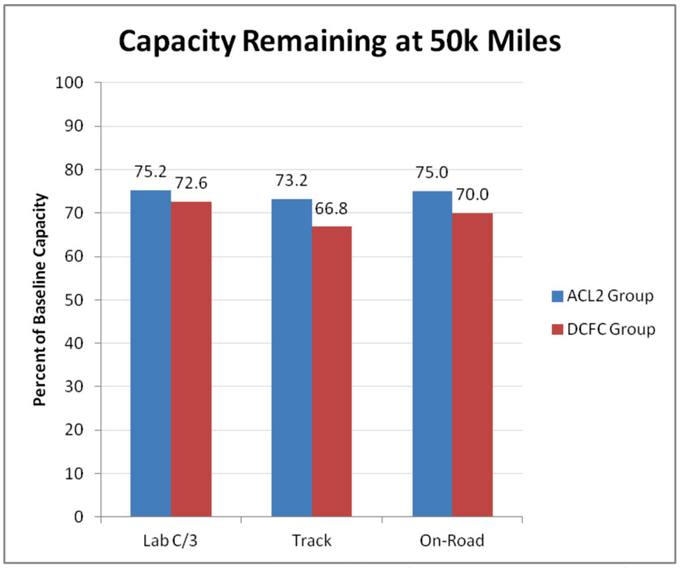

Figure 19. Battery energy capacity remaining after 50,000 as a percent of baseline capacity, measured or inferred by three methods; lab capacity testing, track constant speed range testing, and on-road data energy usage.

Path Dependence

The rate of capacity loss is depicted by the slope of the line in figure 20. The ambient temperature during the test period was highest for the intervals with the steepest slopes, including 20-30, and 30-40 thousand miles, and milder for the others. Table 4 shows the average temperature of the pack during all charges, by interval.

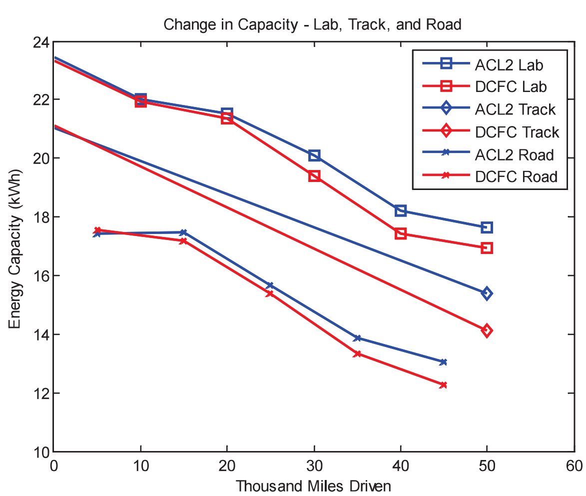

Figure 20. Battery capacity measured or inferred by three methods: lab capacity testing, track constant speed range testing, and on-road data energy usage.

As discussed earlier, the main difference in battery temperature between test groups was during charging. This is evident in table 4. The exception to the rate of capacity loss is the first interval, from 0-10 thousand miles, which was a relatively temperate interval. Testing and cycling of identical packs in a fixed temperature chamber, in-progress at the writing of this paper, show an initial rate of capacity loss that begins steeply, but slows for each successive test interval approaching a constant rate of capacity loss. The full results of that testing will be presented in a future publication and will serve to answer some questions posed by this testing and analysis.

Table 4. Average battery temperature during all charging events for each vehicle, by mileage interval.

Group	ACL2	ACL2	DCFC	DCFC
Vehicle number	**1011**	**4582**	**2078**	**2183**
0-10k Miles (Oct-Jan)	28.6	28.6	32.5	32.7
10-20k Miles (Jan-Mar)	22.7	22.5	27.6	27.6
20-30k Miles (Apr-Jul)	35.7	36.0	39.8	39.8
30-40k Miles (Jul-Oct)	38.2	38.4	40.8	40.8
40-50k Miles (Oct-Mar)	23.2	23.6	27.3	27.3

Figure 20 shows the on-road capacity, which is an average of the battery energy used, starting with a full charge, and running to a target of five miles indicated range remaining. The value, plotted at mid interval, indicates the average energy discharged per trip over the 10 thousand mile interval. The track based constant speed range testing shows a higher energy, however that testing was performed with no margin and vehicles were driven beyond minimal range warnings, until they could no longer maintain speed. The acceleration performance shows more variation between vehicles than at baseline, though these small differences in zero to sixty MPH acceleration times do not indicate notably decreased performance for either group after 50,000 miles. Each type of testing tells the same story for battery capacity and range, with the fast charge group losing capacity faster than the AC L2 group, but not largely different when compared to overall capacity loss.

Summary

The four BEVs driven in Phoenix, Arizona were faced with a hot climate, and two were fast charged twice as often as recommended by their manufacturer. Despite these conditions, the vehicles were operated without failure for 50 thousand miles. A greater loss in battery capacity was observed for the fast charged vehicles, though the difference compared to the level two charged vehicles was small in comparison to the overall capacity loss. The vehicle operation was, as intended, verified to be very similar between test groups, and the largest difference in conditions noted was battery temperature during charging. Hotter ambient temperatures appear to have accelerated capacity loss for all of the vehicles in the study, though the exact relationship remains to be seen. Testing is currently underway for two packs, identical to those tested in this study, under constant temperature conditions and identical cycling in the laboratory. The results of that testing combined with the data presented in this paper will serve to further answer the questions related to the rate of capacity, both in relation to time and temperature and will remove even small variations in conditions between the packs.

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Definitions/Abbreviations

A	Amp
AC	alternating current
C	Celsius
DC	direct current
DCFC	direct current fast charge
IVM	initial vehicle movement
L2	level-two
MPH	miles per hour
SOC	state of charge
V	Volt