Journal of Power Sources 282 (2015) 265–276

Contents lists available at ScienceDirect

Journal of Power Sources

journal homepage: www.elsevier.com/locate/jpowsour

Quantifying EV battery end-of-life through analysis of travel needs with vehicle powertrain models

Samveg Saxena [a, *], Caroline Le Floch [b], Jason MacDonald [a], Scott Moura [b]

[a] *Lawrence Berkeley National Laboratory, Berkeley, CA, United States*
[b] *University of California at Berkeley, United States*

HIGHLIGHTS

- EV batteries meet driver needs well beyond 70–80% remaining capacity EOL threshold.
- Even after substantial capacity fade EV batteries accommodate long unexpected trips.
- Energy capacity fade is a more limiting factor governing retirement than power fade.
- EV battery useful life is further extended by enabling charging in more locations.
- Battery retirement metric can be defined instead by when daily driver needs not met.

ARTICLE INFO

Article history:
Received 5 November 2014
Received in revised form
23 December 2014
Accepted 13 January 2015
Available online 14 January 2015

Keywords:
Electric vehicles
Battery degradation
Capacity fade
Power fade
Battery second life
Battery retirement

ABSTRACT

Electric vehicles enable clean and efficient transportation, however concerns about range anxiety and battery degradation hinder EV adoption. The common definition for battery end-of-life is when 70–80% of original energy capacity remains, however little analysis is available to support this retirement threshold. By applying detailed physics-based models of EVs with data on how drivers use their cars, we show that EV batteries continue to meet daily travel needs of drivers well beyond capacity fade of 80% remaining energy storage capacity. Further, we show that EV batteries with substantial energy capacity fade continue to provide sufficient buffer charge for unexpected trips with long distances. We show that enabling charging in more locations, even if only with 120 V wall outlets, prolongs useful life of EV batteries. Battery power fade is also examined and we show EVs meet performance requirements even down to 30% remaining power capacity. Our findings show that defining battery retirement at 70–80% remaining capacity is inaccurate. Battery retirement should instead be governed by when batteries no longer satisfy daily travel needs of a driver. Using this alternative retirement metric, we present results on the fraction of EV batteries that may be retired with different levels of energy capacity fade.

1. Introduction

Vehicle electrification is a key objective for policy makers, and major studies have shown that electrification of transportation is needed soon and at significant scale to meet climate goals agreed to by governments around the world [1]. Greater deployment of electric vehicles faces several challenges, including range anxiety, availability of charging infrastructure, the potential to adversely impact grid stability by overloading grid infrastructure, higher cost compared with conventional vehicles, and concerns about the useful lifetime of batteries due to degradation that occurs with cycling and calendar ageing.

On the range anxiety and charging infrastructure issues, recent studies [2] have shown that EVs can satisfy the daily travel needs of a vast majority of US drivers using standard 120 V electrical outlets that are widely available. Further addressing the charging infrastructure issue, several states and municipalities across the US and around the world are investing substantial resources to build publicly-available EV charging stations. On the issue of grid stability, several studies have demonstrated that EVs and PHEVs when properly coordinated can offer valuable grid services to improve grid stability and enable integration of intermittent renewable power generation [3–9]. A recent study [10] has also demonstrated that EVs are a highly flexible load, and during demand response

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* Corresponding author.
E-mail address: samveg@berkeley.edu (S. Saxena).

http://dx.doi.org/10.1016/j.jpowsour.2015.01.072

events 75–95% of EV charging loads can be removed without adversely affecting driver mobility needs. On the higher cost issue, several state-level and federal incentives exist to lower the capital cost of EVs and PHEVs for car buyers [11,12], and component-costs (e.g. batteries) continue to fall [13]. These incentives and component-level costs also influence the second life economics of vehicle batteries.

The issue of battery degradation amplifies both the range and cost challenges for EVs. Batteries experience capacity fade with time and with usage [14–16] causing EVs to lose driving range capability over their lifetime. If a vehicle battery pack degrades to sufficient levels it will need to be replaced, possibly resulting in substantial additional cost for the car owner to replace the battery pack. Prior research in battery degradation, economics of EVs, and second life applications of EV batteries have assumed that batteries must be retired from their vehicle application once they have 70–80% of their original energy storage capacity remaining [17–25]. In order to offset the high costs of batteries, many studies have explored the use of these degraded batteries in a second life where they are used as stationary batteries to offer grid services.

Although it is a persistent criterion in nearly all studies, the use of a 70–80% remaining capacity threshold has not been questioned. However, a recent study [2] showed that batteries with 80% remaining capacity continue to meet the needs of a vast majority of drivers. Quantitative analysis is needed to determine when drivers are likely to retire their vehicle batteries, based on when these batteries no longer meet the daily travel needs of the driver. The ability of EV batteries to meet driver daily travel needs is influenced both by energy storage capacity (which affects EV range), and by power capacity (which affects acceleration, gradeability and regenerative braking capabilities) – the present study examines both energy and power fade in terms of satisfying driver needs. Redefining the threshold in remaining energy and power capacity for battery retirement has the potential to redefine the economics of EVs as batteries may last longer in their first life (in vehicles), and therefore enter their second life with much lower levels of remaining energy and power capacity than has been assumed in prior analyses. This paper presents quantitative analysis to understand the levels of remaining battery energy and power capacity that meet the daily travel needs of drivers, thereby redefining what level of energy and power capacity batteries may have remaining when they are retired from their vehicle life.

2. Specific objectives

This study quantifies how EV battery energy capacity fade and power fade impact the ability of EVs to satisfy the daily travel needs of U.S. drivers. The vehicle-to-grid simulator (V2G-Sim) [2,10,26,27] is used to predict the battery SOC profile for vehicles driven according to trip itineraries specified by the National Household Travel Survey. To understand the impact of battery energy capacity fade, simulations are run in V2G-Sim with a parametric sweep of gradually lower levels of usable battery energy capacity levels. The fraction of drivers whose daily travel needs are satisfied under each level of usable battery energy capacity is quantified as the fraction of drivers that can complete their daily travel itinerary without running out of charge. Further, the impacts of power fade are quantified by running drive cycle, acceleration, and gradeability tests with increasing levels of battery power fade. Specifically, this study is conducted with the following objectives:

1. Quantify the impact of battery energy capacity fade upon the ability of EVs to meet the daily travel needs of U.S. drivers.
2. Quantify the impact of battery power fade upon the ability of EVs to meet common performance requirements, including acceleration and gradeability.
3. Demonstrate that vehicle batteries can have useful life within a vehicle beyond today's commonly used metric of retiring batteries once they have lost 20–30% of their rated energy capacity.
4. Quantify the levels of remaining capacity in EV batteries if they were retired based on when they no longer meet the daily travel needs of drivers.

3. Methodology and validation

3.1. Vehicle-to-grid simulator

A simulation tool called the vehicle-to-grid simulator (V2G-Sim) [2,10,26,27] is created, validated and applied in this study to provide quantitative metrics to accomplish the above objectives. For this study, V2G-Sim is provided input data from the National Household Travel Survey (NHTS) [28], which provides a survey of the 24-h vehicle usage profiles of a random sample of drivers across the United States, including trip start and end times, trip distances, and types of locations where vehicles are parked. Travel itineraries are provided from the NHTS, resulting in 159,844 representative samples of weekday and weekend vehicle usage for drivers across the United States. Table 1 provides an example of the travel itinerary information provided to V2G-Sim from the NHTS data source.

For each type of activity (e.g. driving, plugged-in, or parked) in the travel itineraries listed in Table 1, V2G-Sim calls an appropriate sub-model which tracks energy consumption in the vehicle powertrain, or power transfer between the electricity grid and the vehicle. In this manner, each vehicle's battery state-of-charge (SOC) is computed on a second-by-second basis.

Predicting the energy consumption and battery SOC of a vehicle while it is on a given trip requires a trip-specific drive cycle of the vehicle's second-by-second velocity profile and the terrain during the trip. For the results presented in this paper, the trip-specific drive cycles are generated from EPA standard drive cycles for city, highway, and high speed driving, however trip-specific drive cycle generation methods have been built into V2G-Sim [2,10,26,27] which enable drive cycles to be generated which consider traffic conditions, city vs. highway fractions within a single trip, etc.

Commercially available EVs, with specifications resembling a Nissan Leaf, are simulated in V2G-Sim to travel along the individual daily travel patterns specified by the NHTS data, using drive cycles for a specific trip. While driving, each vehicle's energy consumption and battery state-of-charge (SOC) is predicted using vehicle powertrain sub-models in V2G-Sim that are validated against measurement data [29], as shown in Fig. 1. These powertrain models determine the EV's energy consumption during a trip while

Table 1
Example of travel itinerary information for a randomly selected vehicle provided to V2G-Sim. A total of 159,844 travel itineraries are provided to V2G-Sim in this format using data from the National Household Travel Survey.

Start time	End time	Event type	Distance/charge type	Location type
12:00 am	7:50 am	Plugged in	L2	Home
7:50 am	8:50 am	Driving	43.5 mi	N/A
8:50 am	3:00 pm	Parked	N/A	Work
3:00 pm	3:10 pm	Driving	4.8 mi	N/A
3:10 pm	3:40 pm	Parked	N/A	Restaurant
3:40 pm	3:50 pm	Driving	4.8 mi	N/A
3:50 pm	7:00 pm	Parked	N/A	Work
7:00 pm	7:40 pm	Driving	43.5 mi	N/A
7:40 pm	12:00 am	Plugged in	L2	Home

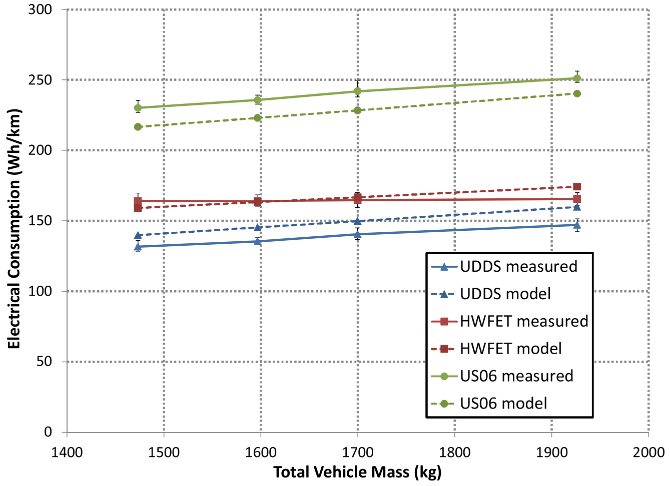

Fig. 1. Comparisons of powertrain model prediction against chassis dynamometer measurement data.

accounting for the high energy conversion efficiency of chemical to electrical energy in the battery, and electrical to kinetic energy in the motor.

Detailed powertrain models can be used to predict the energy consumption of any vehicle make/model on any trip-specific drive cycle (including terrain considerations), and with any level of ancillary power loading (e.g. from a vehicle's HVAC system). However for this study, only a single powertrain type (resembling a Nissan Leaf[1]) is simulated on 3 drive cycles that are modified to fit trip-specific distance/duration targets. Thus, to enable rapidly executing simulations the detailed powertrain model is used to calibrate a simpler model of energy consumption per unit distance travelled by each vehicle. Fig. 2 illustrates the component-level dynamics that are considered in a detailed powertrain model of an EV, and Table 2 presents the powertrain specifications and averaged energy consumption values on the given drive cycles.

When a vehicle parks at a location where it can plug into a certain type of charger (e.g. level 1 charger at 1.4 kW, level 2 charger at up to 7.2 kW, or fast charger), power transfer from the electricity grid to that vehicle is calculated using charging sub-models which are calibrated with measurement data, similar to the data illustrated in Fig. 3 [30].

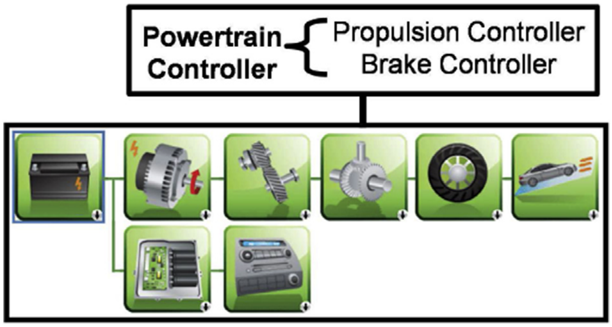

Fig. 2. EV powertrain model architecture and included component-level models.

Table 2
Specifications of simulated vehicles.

Vehicle & powertrain specifications	Vehicle mass (kg)	1550.0
	Traction motor	80 kW AC
	Total battery energy capacity (kWh)	23.83
	Usable SOC (%)	95–7.5%
	Useable battery capacity (kWh)	20.85
	Battery chemistry	Li-ion
	Final drive ratio	7.9377
	Tire size	205/ 55R16
	Drag coefficient	0.285
	Frontal area (m^2)	2.6
	Ancillary load (kW)	1.00
	Road Grade (%)	0%
Average electrical consumption while driving (Wh/km)	EPA City (UDDS)	143.25
	EPA Highway (HWFET)	161.75
	EPA High Speed (US06)	220.60

3.2. *Quantifying the impact of battery energy capacity fade*

Battery energy capacity affects the range that can be traversed by an EV, and as energy capacity fade occurs in an EV's battery pack the vehicle will be less likely to accommodate the daily travel needs of a driver. For the purposes of this paper, we define a battery as failing to meet a driver's needs if the battery would run out of charge before completing a driver's planned daily travel activity. In order to assess how energy capacity fade impacts drivers, we simulate each vehicle in the NHTS database at different levels of derated battery energy capacity and examine whether a vehicle will run out of charge during its travel day. Vehicles are simulated using NHTS travel itineraries assuming battery energy capacities from 100% (23.83 kWh) to 30% (7.149 kWh) in increments of 10%. Overall vehicle mass and all other parameters listed in Table 2 are held constant as the battery energy capacity is varied. For each vehicle at each level of battery energy capacity fade, vehicles are simulated in six different scenarios of charging, including Level 1 or Level 2 charging at home and work locations. Fig. 4 shows an example of the battery SOC profiles for two randomly chosen vehicles in several charging scenarios, for a case where no energy capacity fade has occurred (e.g. the batteries have 100% of their original rated energy storage capacity):

The SOC profiles in Fig. 4 illustrate how V2G-Sim simulations at each level of battery energy capacity fade are used to determine whether a vehicle still meets the daily travel needs of its driver. Battery SOC profiles are computed over the full planned travel itinerary, and a vehicle is assumed to meet the driver's daily travel needs if it does not run out of charge during the driver's planned travel. Similar SOC profiles are computed for each travel itinerary in the NHTS database at each level of energy capacity fade down to 30% remaining energy storage capacity.

In addition to quantifying how energy capacity fade impacts the ability of vehicles to satisfy the daily travel needs of drivers, we quantify how much reserve range drivers would have for unexpected travel. The worst case scenario in terms of accommodating an unexpected trip would be if the unexpected trip occurred at the time of day when the vehicle had its lowest SOC value. For instance, in Fig. 4 for vehicle number 98,170 the worst case scenario would be if the unexpected trip occurred at 12:50 pm (this is the time when the lowest SOC is encountered). For each charging scenario, this

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[1] Although the simulated vehicle in this study has specifications resembling a Nissan Leaf, the study's results are applicable to most EVs on the market, particularly because most other vehicles have similar or greater battery energy storage capacity to a Nissan Leaf. For instance, the Nissan Leaf, Ford Focus EV and Fiat 500e all have battery packs with rated energy storage capacity near 24 kWh.

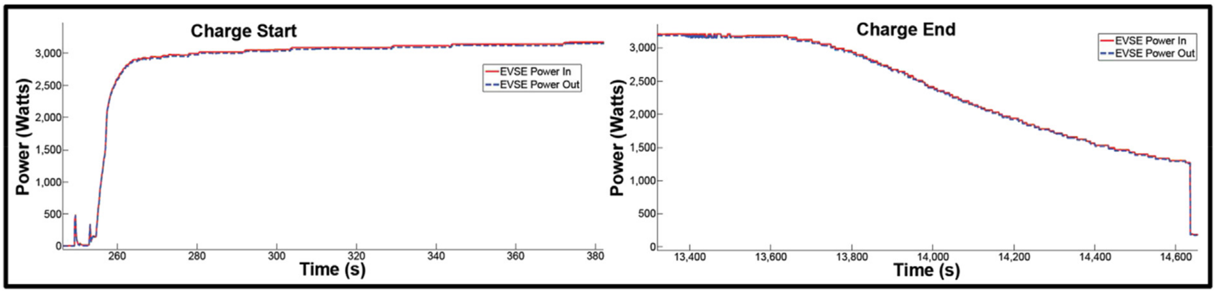

Fig. 3. Measurement data of power transfer vs. time profile for a ChargePoint CT503 Level 2 charger. This data is used in calibrating the charger sub-models built into V2G-Sim for these simulations [30].

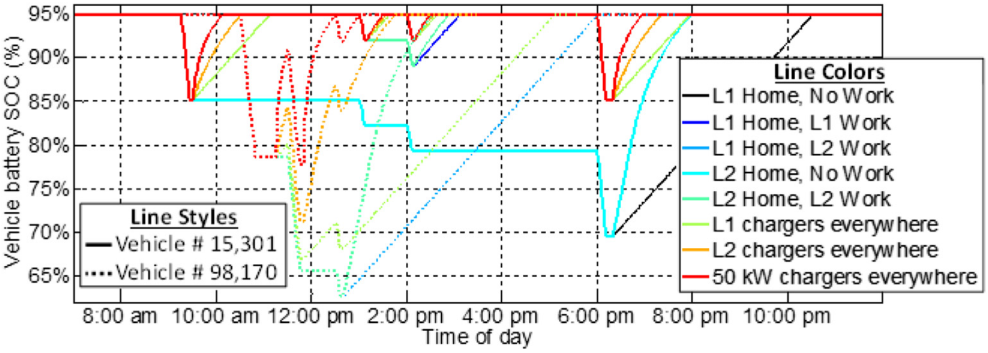

Fig. 4. Battery SOC profiles for two randomly chosen vehicles in the NHTS travel itinerary database in several scenarios for charger availability, for vehicles that have 100% of their original rated battery capacity (e.g. no capacity fade has occurred). In each charging scenario for the case with vehicles that have experienced no capacity fade, these vehicles are not at risk of running out of charge during their planned daily travel itinerary – thus, these vehicles meet the travel needs of their drivers. Similar simulations are run for each level of battery capacity fade to determine the level of battery capacity fade when the vehicle will no longer meet driver needs (e.g. it will run out of charge during its planned daily travel).

minimum SOC value is converted into an approximate EV travel range assuming 55% city driving and 45% highway driving (based on EPA guidelines for standard US driving [31]).

3.3. Quantifying the impact of battery power fade

The maximum discharge power output limit of an EV battery affects the vehicle's driveability in terms of acceleration and gradeability performance. The maximum charging power limit affects the maximum deceleration that can be accommodated by regenerative braking (e.g. before mechanical brakes must be used), and may also affect maximum power transfer rates on EV battery charging while plugged in. As batteries experience power fade their maximum charging and discharging power limits are lowered and Section 4.2 of this study examines the impact of battery power fade. For a fresh battery (which has not experienced any power fade), the discharging and charging power transfer limits are determined using cell-level measurement data (as explained in Section 4.2). The maximum charging and discharging power limits are gradually reduced from 100% to 30% in 10% increments, and acceleration, gradeability, and drive cycle tests are run for each case to determine how power fade impacts the driveability of EVs.

4. Results

4.1. Energy capacity fade

4.1.1. Base case results

4.1.1.1. Impact of battery capacity fade on the ability of EVs to satisfy U.S. drivers' daily travel needs. The National Household Travel Survey (NHTS) includes a large sample size of 24 h vehicle usage itineraries for drivers across the United States. These NHTS travel itineraries are simulated in V2G-Sim assuming that each vehicle has specifications resembling a commercially available EV, as listed in Table 2. The simulations include different scenarios for where vehicles are charged, and what type of charger vehicles plug into in different locations (e.g. L1 or L2 at home or work, etc.). The V2G-Sim simulations predict the vehicle battery SOC throughout a full travel day using the given travel itineraries, and these SOC results are used to identify how many vehicles are able to satisfy their travel itineraries (i.e. complete planned trips without running out of charge). Parametric sweeps are run in the V2G-Sim simulations to identify the fraction of drivers whose daily travel needs are satisfied as each vehicle loses more of its battery energy storage capacity.

Fig. 5 summarizes parametric simulations that quantify how battery energy capacity fade impacts the ability of EVs to satisfy the daily travel needs of U.S. drivers. As expected, the results show that as vehicle batteries lose more of their capacity they are able to satisfy the daily travel needs of fewer drivers. Two important results are apparent in Fig. 5 which have not been quantified in prior literature. First, a sizable fraction of U.S. drivers' daily travel needs continue to be satisfied by EVs even after they have experienced substantial levels of battery energy capacity fade. For instance, in the "L1 Home, no Work" charging scenario, over 85% of drivers' daily travel needs continue to be satisfied even after the battery has degraded to 80% of its remaining battery capacity (the commonly accepted threshold for retirement of EV batteries). Second, the useful life[2] of EV batteries can be extended by enabling charging in more locations. For instance, in the "L1 home no work" charging

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[2] In this context, useful life is defined as the timespan and level of battery capacity fade in which a battery continues to meet a driver's daily travel needs.

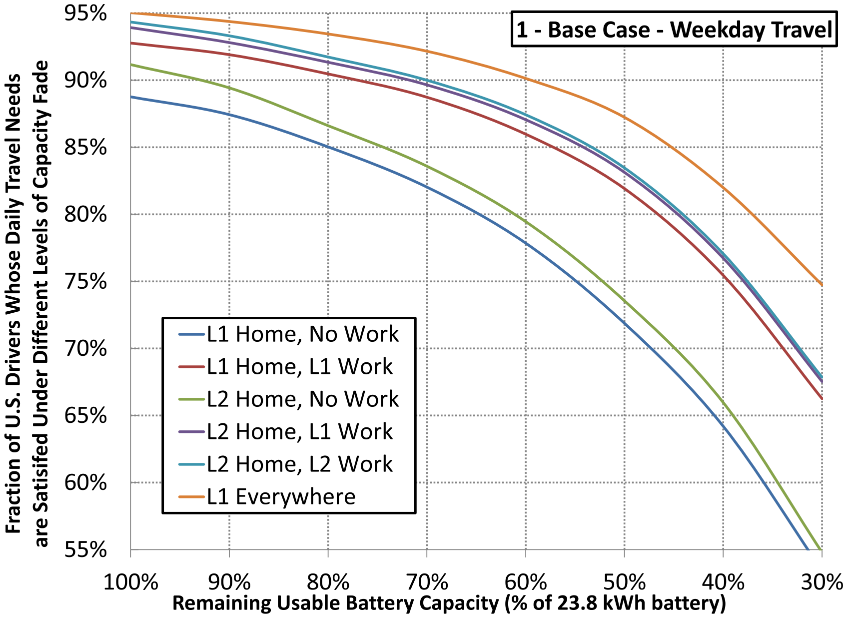

Fig. 5. Impact of battery capacity fade on the ability of EVs to satisfy the daily weekday mobility needs of U.S. drivers for several scenarios of charger availability. Results show that a high fraction of daily weekday travel needs continue to be satisfied beyond the commonly accepted battery retirement threshold of 80% remaining capacity, and making chargers available in more locations enables a substantial extension to the useful life of a vehicle battery.

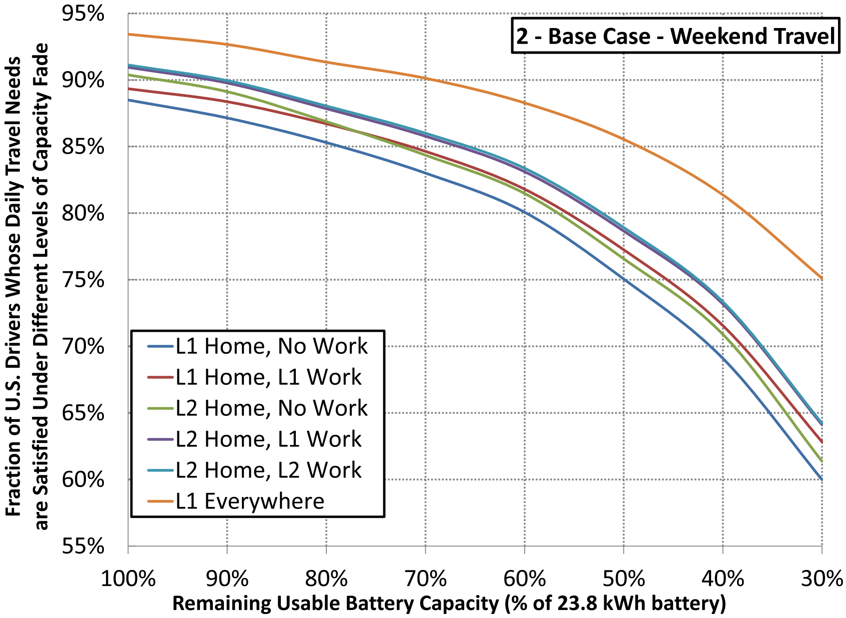

Fig. 6. Impact of battery capacity fade on the ability of EVs to satisfy the normal weekend travel needs of U.S. drivers for several scenarios of charger availability. Results show that a high fraction of normal weekend travel needs continue to be satisfied beyond the commonly accepted battery retirement threshold of 80% remaining capacity.

scenario 85% of drivers' daily travel needs are satisfied when a battery has degraded to 80% remaining capacity. This same level of satisfying 85% of travel needs is possible down to 57% of remaining capacity if L1 charging is added in work locations as well.

Fig. 6 presents similar results as Fig. 5, but for weekend travel. The overall trends of the weekend results are identical to the weekday results, however the fractions of drivers' daily travel needs satisfied under various levels of battery capacity fade are slightly higher suggesting that weekday travel is more likely to represent a limiting case. For weekend travel, it can also be seen that vehicle batteries continue to meet the daily travel needs for sizable fractions of U.S. drivers even beyond degradation to 80% of remaining energy capacity.

From Figs. 5 and 6 it is important to note that even when vehicle batteries degrade down to 30% of their original energy storage capacity, the daily travel needs of over 55% of U.S. drivers continue to be satisfied. A common concern by prospective EV buyers is that they will have to replace a battery pack well before the end of a vehicle's useful life. However, the results in Figs. 5 and 6 suggest that vehicle batteries can continue to satisfy daily driver needs even after experiencing substantial levels of energy capacity fade. With these results, it can logically be concluded that vehicle batteries can continue to provide the energy storage needs to satisfy driver daily mobility requirements for the full lifetime of an electric vehicle. Although some degradation will occur in these batteries, the results suggest that this degradation need not necessitate replacement of a vehicle battery.

In evaluating the implications of the results of Figs. 5 and 6, it is important to note that these results represent a base case which does not necessarily capture the full range of vehicle use by drivers. For instance, the results thus far have assumed that drivers use their cars only for planned travel. In reality, drivers often make unexpected trips above and beyond their normal daily travel. The results in Section 4.1.1.2 quantify the ability of EVs to accommodate unexpected travel as their batteries lose energy capacity. Further, the results thus far have simulated each EV having a moderate (1 kW) level of power consumption from ancillary components (e.g. cabin air conditioner, lighting, etc.), and driving only on flat terrain. Higher levels of ancillary power consumption and driving on uphill terrain will lead to lower levels of driver daily mobility needs being satisfied as batteries degrade, and these factors are explored in the sensitivity analyses presented in Section 4.1.2.

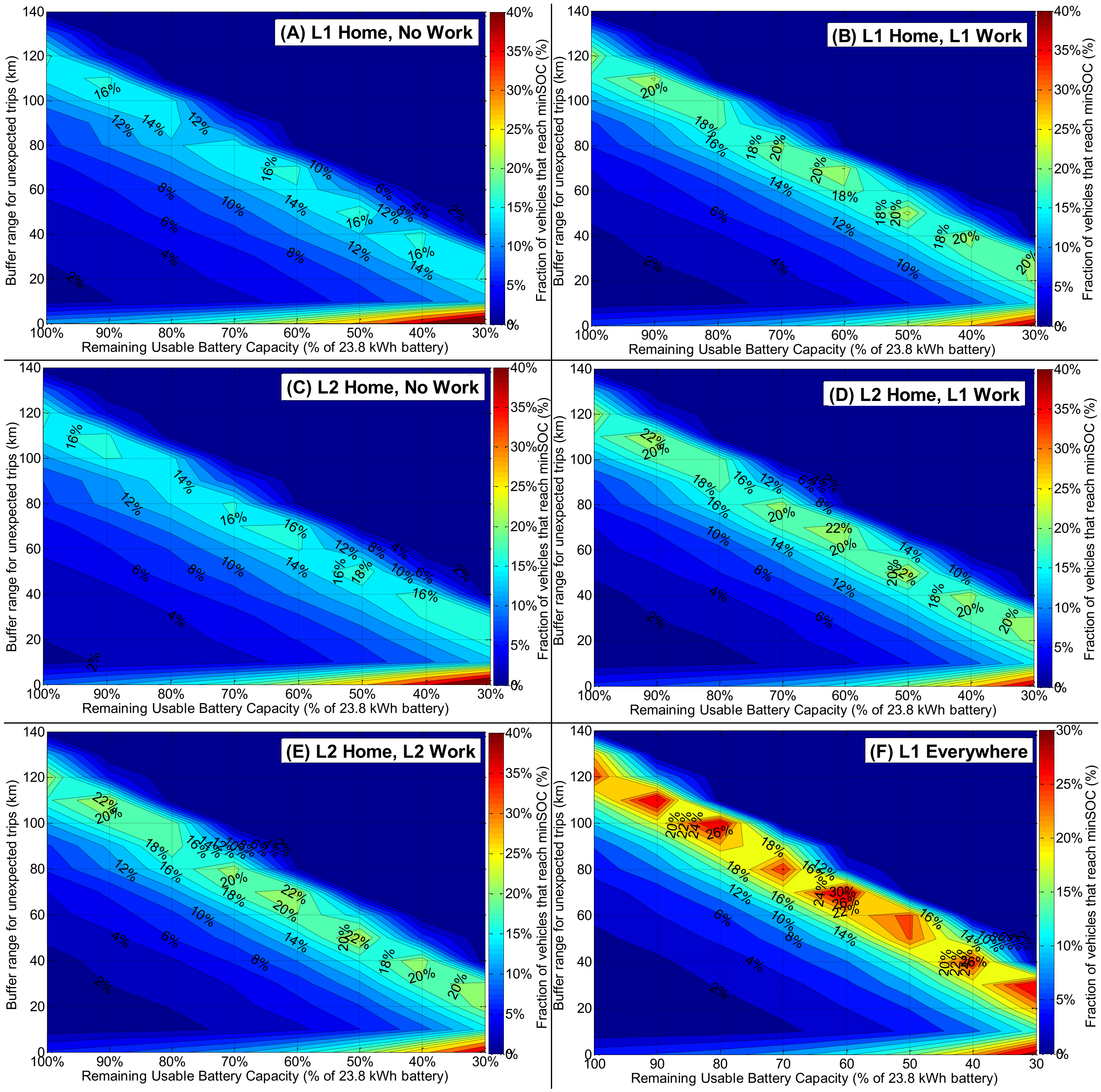

Fig. 7. Contour plots of the fraction of EVs that have different levels of reserve EV range if an unexpected trip occurs at the time when vehicles have their minimum SOC in a day. Each plot includes a parametric sweep (x-axis) for different cases of battery capacity fade, and each of the different plots shows a different case of where EVs are charged. Overall results show that as vehicle batteries lose greater capacity (moving rightwards on each plot), vehicles tend to have lower reserve range for unexpected trips and larger fractions of EVs have no buffer at all for unexpected trips.

4.1.1.2. Impact of battery capacity fade on ability of EVs to accommodate unexpected trips. The results presented in Section 4.1.1.1 showed that the daily travel needs of a sizable fractions of U.S. drivers can be satisfied by EVs even after the EV batteries experienced substantial levels of energy capacity fade. These results, however, did not consider whether vehicle batteries that have experienced energy capacity fade will still be able to accommodate unexpected trips by drivers. This section quantifies the ability of EVs to accommodate unexpected trips after the EV batteries have experienced varying degrees of energy capacity fade.

Fig. 7(A) through Fig. 7(F) present contour plots that quantify the fraction of EVs that will have different amounts of buffer range for unexpected trips. Each contour plot is created by using the battery SOC projections from V2G-Sim results to identify the minimum SOC value that each vehicle will encounter during its travel day. The minimum SOC value is converted into an estimated EV range (assuming 55% city driving and 45% highway driving) that would be available if a driver makes an unexpected trip at the time of day when the vehicle is at its minimum SOC. The contour plots in Fig. 7 summarize the results of this procedure by showing the fraction of EVs that will have different levels of buffer range for unexpected trips. For example, in the 90% remaining energy capacity case in Fig. 7(A), the results show that 16% of EVs will have between 100 and 110 km of buffer range if an unexpected trip occurred at the time that each vehicle had its minimum SOC.

Several important results can be seen from the contour plots of Fig. 7. First, for each charging case the contour plots show a bar of high concentration with a linearly decreasing slope as batteries experience more capacity loss. This trend in each plot indicates that as batteries experience more energy capacity fade the magnitude of buffer range for unexpected trips decreases. The y-axis magnitudes of these high concentration regions are important to note, as they show that even under extreme degradation cases, large fractions of EVs will be able to accommodate unexpected trips of substantial distance. For example, the results in each plot show that with only 60% remaining energy capacity, a substantial fractions of EVs will have over 50 km of buffer range for unexpected trips. Second, for each charging case the contour plots show a region of high concentration emerging near zero buffer range (bottom of y-axis) for the cases with the greatest levels of battery capacity fade (right side of x-axis). This trend indicates that the fraction of vehicles that are not able to accommodate any unexpected trips sharply increases as battery capacity fade approaches 30% of remaining energy capacity.

The contour plots in Fig. 7 showed that as EV batteries fade to the lowest capacity levels simulated (30% remaining energy capacity) there are many vehicles (up to 40%) that will not have any buffer to accommodate unexpected trips. However, the results also show that even with substantial levels of battery capacity fade (e.g. down to 60% of remaining capacity), the largest fractions of EVs can still provide substantial buffer range (e.g. above 50 km) for unexpected trips. These results show that EV batteries can indeed continue to meet the needs of EV drivers even beyond the commonly accepted battery retirement threshold of 80% remaining capacity.

4.1.2. Sensitivity to ancillary loading and uphill driving

The results in Section 4.1.1.1 quantified the ability of EVs to satisfy the daily travel needs for drivers with various levels of battery capacity fade for a base case, where vehicles have moderate levels of power consumption by ancillary components, and all trips are on flat terrain. This section quantifies the impact of the highest levels of ancillary power consumption (4.8 kW ancillary load) and uphill driving (3% continuous uphill grade on all trips).

Fig. 8 shows the results for sensitivity analysis simulations that quantify the impact of higher levels of ancillary power consumption and uphill driving upon the ability of EVs to meet the daily travel needs of drivers as their batteries lose capacity. Results are presented for four charging scenarios. Three important trends can be identified from Fig. 8. First, as expected, uphill driving and higher levels of ancillary power consumption lower the fraction of drivers whose daily travel needs are satisfied by EVs. This result applies to each charging scenario simulated. Second, there is a more pronounced negative impact from higher ancillary power consumption and uphill driving upon the ability of EVs to satisfy the daily travel needs of drivers as greater levels of battery capacity fade are encountered. Third, enabling charging in more locations (e.g. adding workplace charging) goes a long way towards offsetting the impacts of higher ancillary power consumption or uphill driving as vehicles lose more battery capacity. For instance, even under extreme degradation cases where vehicles have lost 50% of their energy storage capacity, when enabling workplace L1 charging over 50% of drivers' daily travel needs can be satisfied by EVs under worst-case scenarios with simultaneously high ancillary power consumption and driving on uphill terrain.

4.2. Power fade

Energy capacity fade, discussed in Section 4.1, impacts the range capabilities of EVs. Power fade, discussed in this section, impacts the driving performance of EVs in terms of acceleration, gradeability, and maximum charging during regenerative braking or charging events. Section 4.1 presented results quantifying the impact of battery energy capacity fade on the ability of EVs to meet the daily travel needs of drivers. Prior metrics defining the retirement criteria for EV batteries have focused only on energy capacity fade, for instance specifying retirement to occur once batteries reach 70–80% of their original rated energy storage capacity. Prior research [32], however, has shown that batteries also lose their ability to deliver or absorb high power levels over time and with cycling and therefore batteries may also be retired from vehicle usage due to power fade which causes an inability to meet charging or discharging power requirements. The subsequent sub-sections present results to quantify how power fade will impact an EV's ability to meet performance requirements, including drive cycle tests, acceleration tests, and gradeability tests.

The maximum charging and discharging power capabilities for a fresh Nissan Leaf battery pack are shown in Fig. 10. The pack-level maximum charging and discharging power limits are calculated as shown in Eqs. (1) and (2) from measurement data [33] for each cell in the battery pack, and scaled by the total number of cells in series and modules in parallel within the pack.

$$P_{pack\max,chg}(SOC) = \frac{V_{cell\max} - V_{\mathrm{cell\ OC}}(SOC)}{R_{\mathrm{cell\ int,chg}}(SOC)} \times V_{cell\max} \times N_{\mathrm{cell\ series}} \times N_{\mathrm{mod\ parallel}} \tag{1}$$

$$P_{pack\max,\mathrm{dis}}(SOC) = \frac{V_{\mathrm{cell\ OC}}(SOC) - V_{cell\min}}{R_{\mathrm{cell\ int,dis}}(SOC)} \times V_{cell\min} \times N_{\mathrm{cell\ series}} \times N_{\mathrm{mod\ parallel}} \tag{2}$$

$N_{\mathrm{cell\ series}}$ is the number of battery cells in series within the pack and is set to 96, and $N_{\mathrm{mod\ parallel}}$ is the number of modules in parallel in the pack and is set to 2. $V_{\mathrm{cell\ min}}$ and $V_{\mathrm{cell\ max}}$ are minimum and maximum allowable cell voltage levels, and are taken to be 3.1 V and 4.2 V respectively. $V_{\mathrm{cell\ OC}}(SOC)$, $R_{\mathrm{cell\ int,chg}}(SOC)$ and $R_{\mathrm{cell\ int,dis}}(SOC)$ are respectively the open-circuit voltage, the internal resistance on charging, and the internal resistance on discharging, all as a function

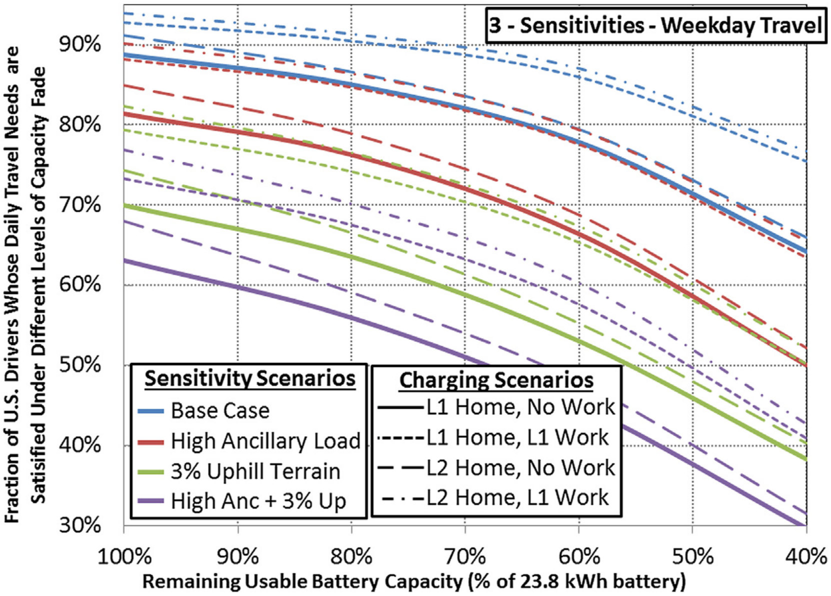

Fig. 8. Sensitivity to high power consumption by ancillary components (4.8 kW continuous load) and uphill driving (3% uphill grade for all trips) on the impact of battery capacity fade and the ability of EVs to satisfy drivers' daily mobility needs. Results are for weekday travel for four different scenarios of charger availability. As expected, the results show that higher ancillary power consumption and uphill driving lower the ability of EVs to satisfy drivers' daily mobility needs. More importantly, the results show that higher ancillary power consumption and uphill driving have a more pronounced effect on reducing the fraction of drivers' daily travel needs that are satisfied as greater levels of battery capacity fade are encountered.

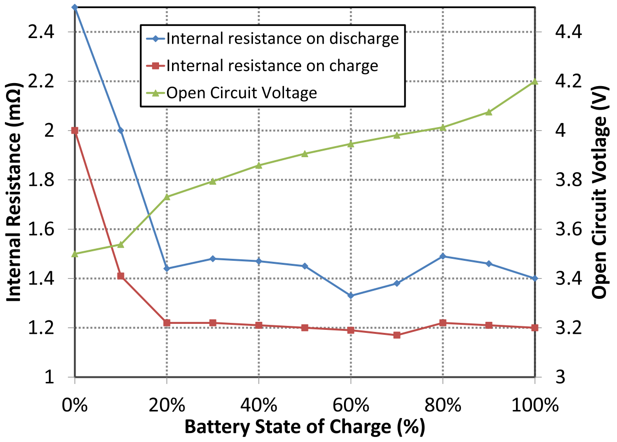

Fig. 9. Measurement data of open circuit voltage, and internal resistances on charging and discharging for a Nissan Leaf battery cell.

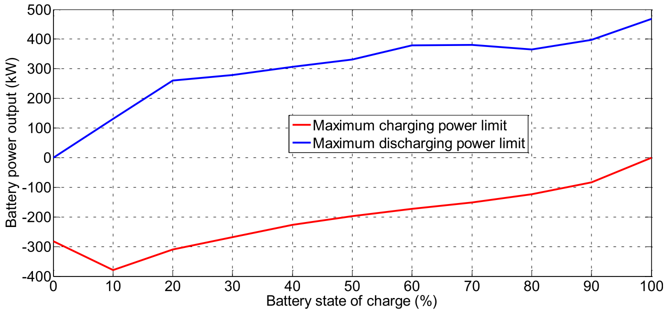

Fig. 10. Maximum charging and discharging power limits for Nissan Leaf battery pack with no power fade.

of battery state-of-charge. The measurement data for each of these three values for Nissan Leaf battery cells is plotted in Fig. 9.

4.2.1. *Impact of power fade on drive cycle performance*

Fig. 11 summarizes the results of the impact of power fade on the ability to meet the speed-time profiles specified in the EPA UDDS, HWFET and US06 drive cycles. The data points show the SOC vs. battery charging and discharging power on the three drive cycles.[3] These data points show that the highest charging and discharging power levels are encountered on the US06 drive cycle, which also has the largest acceleration and deceleration levels. The maximum charging and discharging power limits for each SOC value at each level of power fade from 100% to 30% remaining power capacity are overlaid on the plot. The results in Fig. 11 show that the maximum charging and discharging power levels of the UDDS and HWFET drive cycles can be accommodated without difficulty even down to power fade levels of 30% remaining power capacity. The US06 drive cycle, which has the highest charging and discharging power levels can also be accommodated across large portions of the SOC range down to 30% remaining power capacity. At the extreme SOC limits, however, batteries naturally have lower charging and discharging power limits. The results show that under conditions where a vehicle battery has experienced substantial power fade (e.g. below 50% remaining power capacity) and at the lowest SOC levels, the vehicle will have trouble accommodating the maximum discharging power levels in the US06 drive cycle. Under these extreme conditions, the acceleration capabilities of the vehicle will be diminished to levels that cannot accommodate the sharpest accelerations in the US06 drive cycle.

The results in Fig. 11 suggest that power fade even down to extreme levels where only 30% power capacity remains does not

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[3] Given that battery charge/discharge power profiles are plotted for all 3 drive cycles on a single plot, the simulations for each drive cycle were initialized with a different starting SOC value. This allows the three drive cycle battery power profiles to be easily distinguished from one another.

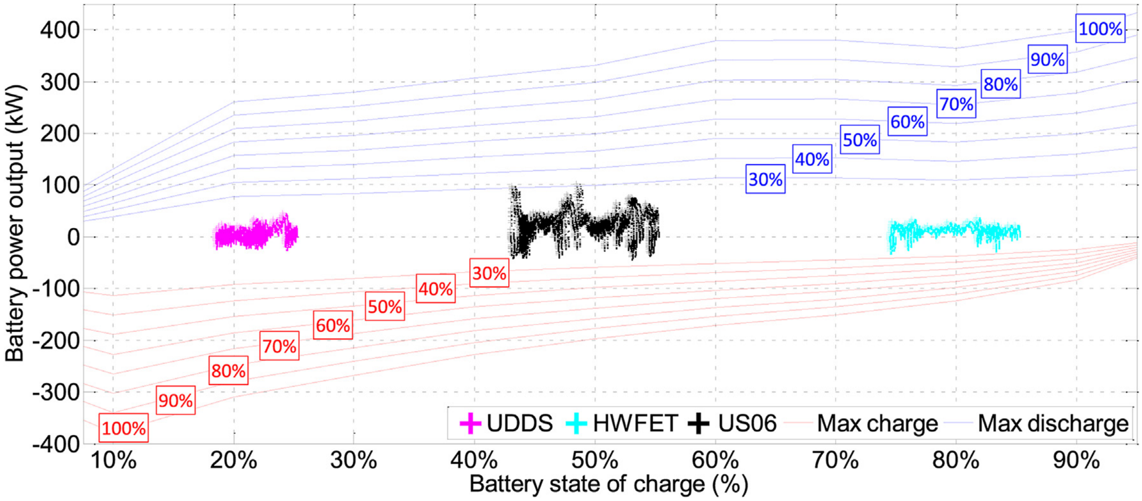

Fig. 11. Impact of power fade on drive cycle performance for EPA UDDS, HWFET and US06 drive cycles. Battery charging and discharging power levels are shown for each of the three drive cycles, overlaid with contours of the maximum charging and discharging power levels versus battery SOC for each level of power fade from 100 to 30% power capacity. Results show that power fade down to 30% remaining power capacity does not impact the ability to meet the UDDS and HWFET drive cycles. The maximum discharging power levels in the US06 drive cycle can generally be accommodated during the majority of the battery SOC range. However at SOC levels below 20% where maximum discharge power limits are lower, vehicles with high levels of power fade will have difficulty accommodating the sharp acceleration portions of the US06 drive cycle.

induce any significant restrictions on an EV's ability to perform on the EPA drive cycles. The results showed that peak acceleration values in the US06 drive cycle cannot be accommodated under the most extreme power fade levels at the lowest SOC levels, however this extreme condition is unlikely to define the need to retire an EV battery. Drivers are unlikely to demand substantial levels of acceleration and are likely to be comfortable with a loss in peak acceleration capabilities when their battery is at its lowest SOC levels.

4.2.2. *Impact of power fade on acceleration performance*

Fig. 12 quantifies the impact of power fade on acceleration performance in 0–60 mph (0–96.56 km/h) simulations. The acceleration simulations are run under different cases where the vehicle's SOC level at the end of the 0–60 mph test is progressively lowered (e.g. the test is started with progressively lower SOC values), as it was shown in Fig. 11 that discharge power capabilities are reduced at the lowest SOC levels. The results show that power fade down to 40% remaining power capacity has no impact on the 0–60 mph acceleration time. At 30% remaining power capacity, the 0–60 mph acceleration time increases from 8.2 s up to 10 s under the worst case where the battery SOC reaches 10% at the end of the acceleration test.

The results in Fig. 12 further support the conclusion that power fade will not induce the need for retirement of EV batteries, even under extreme cases where batteries have lost 60–70% of their power capabilities, leaving 30–40% remaining power capacity.

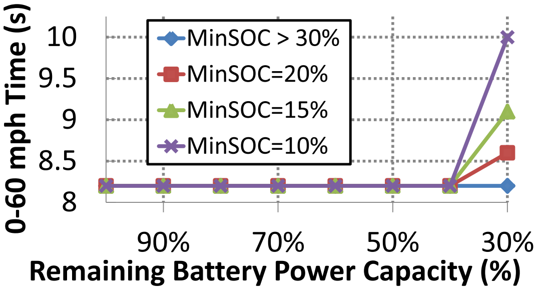

Fig. 12. Impact of EV battery power fade on 0–60 mph (0–96.56 km/h) acceleration time. The results show that power fade does not impact acceleration until the lowest power fade levels of 30% remaining power capacity. Under worst case conditions of the acceleration test occurring at the bottom of the vehicle's SOC range, 0–60 mph time increases from 8.2 s to 10 s.

4.2.3. *Impact of power fade on high speed gradeability performance*

The ability to maintain vehicle speed during hill climbs is another metric that is governed by the power capabilities of a vehicle. Fig. 13 quantifies the impact of battery power fade on the maximum grade that can be ascended at vehicle speeds of 70 km/h and 100 km/h. The results show that down to 60% remaining battery power capabilities there is no significant impact on the maximum grade that can be ascended while maintaining the desired speed. At further levels of power fade, the high speed gradeability performance decreases, with the onset of this decrease occurring earlier if the vehicle ends its high speed gradeability test at a lower SOC level. As shown in Fig. 11, the peak power output capabilities are lower when the SOC value is lower resulting in the reduced high speed gradeability results.

It is shown in Fig. 13 that battery power fade reduces the high speed gradeability capabilities of an EV, especially when the tests occur at low SOC levels. It should be noted, however, that the high speed gradeability specification for EVs requires the ability to maintain only 20 mph (32 km/h) on a 6% grade [34]. The results in Fig. 13 suggest that even with power fade down to 30% remaining power capacity, this specification will be easily met. As a result, it can be concluded that power fade will not induce the need for EV battery retirement based on high speed gradeability performance.

5. Discussions

5.1. *Redefining battery lifetime and remaining capacity at retirement*

The results in Section 4 show that retirement of EV batteries from their vehicle lifetime will be governed by energy capacity fade rather than power fade. Prior studies have almost uniformly assumed that batteries will be retired from vehicle use once the batteries have 70–80% remaining capacity, however the results presented in this paper have shown that batteries continue to meet driver needs well below this level of remaining energy capacity.

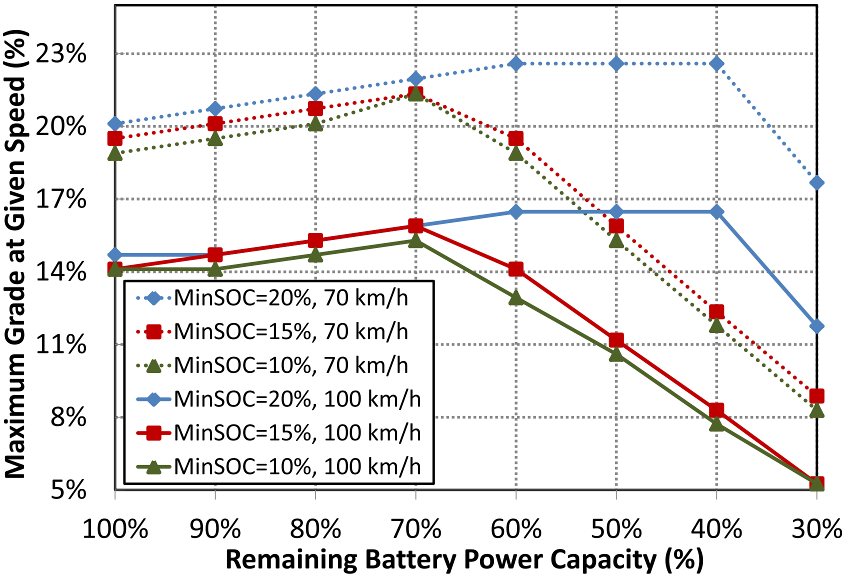

Fig. 13. Impact of EV battery power fade on gradeability, the grade of uphill slope beyond which a chosen vehicle speed can no longer be maintained. Results are shown for vehicle speeds of 70 km/h and 100 km/h. The results show that for each chosen vehicle speed, grade capabilities are not substantially reduced even up to 60% remaining power capacity. Beyond this level of battery power fade, the maximum grade that can be sustained at each vehicle speed begins to decrease.

Rather than assuming battery retirement at a fixed level of remaining energy capacity, as has been assumed in prior studies, we propose that retirement thresholds should be governed instead by when a vehicle's battery no longer meets the daily travel needs of a driver. Fig. 14 re-plots results from Figs. 5 and 6, with the earlier results normalized by the fraction of driving needs that are met at 100% remaining capacity.[4] If battery retirement is indeed governed by when a battery no longer meets driver's daily needs, Fig. 14 may be interpreted as presenting results for the fraction of EV batteries that will be retired from their vehicle life with different levels of remaining energy storage capacity.

5.2. Factors impacting the adequacy of substantially degraded batteries

The results summarized in Section 5.1 and earlier sections suggest that EV batteries will continue to meet the daily travel needs of drivers significantly longer than has been assumed in prior literature. For instance at 80% remaining energy storage capacity the results in Fig. 14 suggest that less than 5% of drivers' daily needs will no longer be met, thereby suggesting that less than 5% of batteries may actually need to be retired at this level of capacity fade.[5] Given the stark difference between these findings and prior assumptions, this section explains *why* EV batteries continue to meet the daily travel needs of drivers even with substantial levels of energy capacity fade.

Two underlying facts when considered together drive this study's findings:

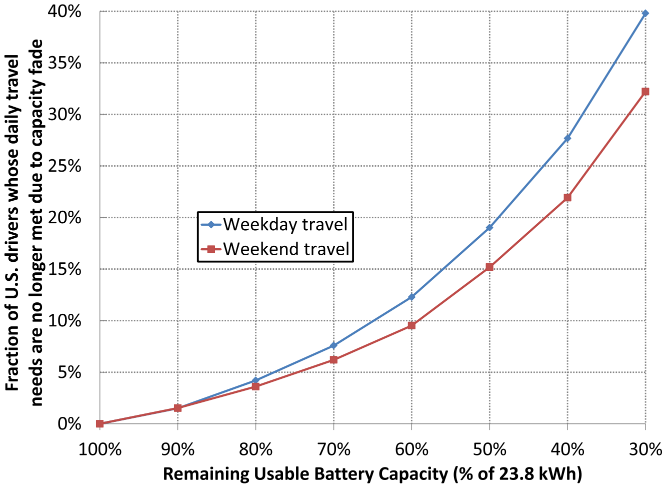

Fig. 14. Fraction of U.S. drivers whose daily travel needs are no longer met as a result of energy capacity fade for each level of capacity fade down to 30% remaining capacity. These results may provide an indicator of the fraction of EV batteries retired from vehicles that will have different levels of remaining energy storage capacity, assuming that no critical failure has occurred forcing battery retirement before reaching each level of capacity fade. It should be noted that vehicles may also enter the used car market once the first driver's daily travel needs are no longer met, thus batteries may not even begin to enter their second life until substantial capacity fade has occurred.

1. Electric cars are more energy efficient than their conventional internal combustion (IC) engine counterparts. The energy conversion efficiency of batteries and motors taken together is significantly higher than that of IC engines. Thus EVs need far less energy storage capacity than conventional vehicles in order to meet drivers' daily travel needs.
2. The way that people use their cars on a daily basis seldom requires driving range in excess of what an EV provides (even if its battery has experienced substantial levels of energy capacity fade), and given that vehicles spend a majority of their time being parked there is ample time for EVs to be charged.

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[4] Normalizing the results from Figs. 5 and 6 by the fraction of driver's needs met at 100% remaining capacity is analogous to converting the results to be in terms of fractions of likely EV drivers whose daily travel needs are met by a vehicle with a given level of remaining energy capacity. After all, if a new EV (with 100% remaining energy storage capacity) does not meet a driver's daily travel needs, that driver is unlikely to choose to buy an EV.

[5] Alternatively, EV owners whose travel needs are no longer met may simply sell their vehicle to other drivers for whom the vehicle will meet daily driving needs. As a result, the degraded battery may continue to have useful life in a vehicle.

The models applied in this study take into account the powertrain component-level details that lead to the higher efficiency, and the way that people use their cars. These factors are explained in greater detail in a prior study by the authors [2].

This study also showed that batteries which have experienced substantial levels of power fade will continue to meet driveability requirements. The underlying reason behind this finding is that acceleration and regenerative braking power limits in EVs are dictated by the traction motor rather than by the battery. EV batteries which are designed for high energy storage capabilities provide maximum charging and discharging power limits that are much higher than the power limits of a traction motor. For instance, in a Nissan Leaf the traction motor is limited to 80 kW while a new battery pack can accommodate substantially higher power levels. As a result, even substantial levels of battery power fade will have little to no effect on vehicle performance.

5.3. Implications of the results

The results presented in Section 4 have several important implications on the economics and perceived utility of EV batteries during their first life in vehicles and in their second life for stationary storage. Most importantly, the results in this paper show that EV batteries will continue to meet driver needs much longer than current literature suggests. A standard metric to define the retirement time of EV batteries is when the battery degrades to have 80% of its original rated capacity. This paper conclusively shows that EV batteries continue to meet the daily travel needs of a majority of drivers well beyond 80% remaining capacity. As a result, researchers, analysts, automakers and battery manufacturers should consider new criteria to define the time when EV batteries are retired. One proposed criteria is to define retirement of a battery once the daily travel needs of an individual driver are no longer met. The results of Figs. 5 and 6 quantify the fraction of drivers whose daily travel needs will no longer be met at various levels of battery degradation, and this can be taken as an indicator of how many batteries may be retired at different levels of remaining usable capacity (as in Fig. 14).

A second important implication from this study's results is that the useful life of EV batteries can be extended by enabling EV charging in more locations where vehicles are parked. For instance, Figs. 5 and 6 show that EVs that are charged at home and work locations continue to meet driver needs to much greater levels of battery capacity loss than vehicles that are charged at home only. Charging in secondary locations need not require build out of expensive charging infrastructure, simply adding a standard 120 V outlet in secondary locations has a dramatic impact on extending the useful life of an EV battery. In fact, only limited benefits are observed from deploying L2 chargers in work places over and above the benefits from adding 120 V outlets for charging.

A third implication from this study is that the second life and EV economic analysis literature needs to be re-examined using an end-of-life metric that considers retirement of EV batteries to occur when the batteries no longer meet the daily travel needs of individual drivers. A majority of prior literature [19–25] on second life potential and value for EV batteries assumes that EV batteries are retired from their vehicle life when 70–80% of the original rated capacity remains. This paper showed that EV batteries continue to satisfy the daily travel needs of a majority of drivers well beyond 70–80% remaining capacity and as a result, the vehicle life of batteries is likely longer than is used in prior analysis while the second life will be shorter. To help researchers who examine second life battery economics, Fig. 14 presented quantitative results of the fraction of batteries that may be retired with different levels of remaining energy storage capacity based on the fraction of drivers whose daily travel needs were no longer being met.

A final implication arising from this study's results are that degraded vehicle batteries may have a secondary use in vehicles that are rated for shorter range trips (e.g. intra-city travel). For example, if an EV battery is retired from its first life when it has 60% of its original capacity remaining, that battery can continue to meet the daily travel needs of over 75% of drivers. As a result, these used EV batteries may be utilized in an entirely new market of shorter range vehicles potentially enabling the deployment of short range EVs at substantially reduced cost. Alternatively, the degraded battery may remain in its original vehicle, but that EV may be sold in the used car market to drivers who only require a vehicle for local travel or commuting.

5.4. Degradation mechanisms that are not considered in this study

The cause of energy and power fade is attributed to a number of battery degradation mechanisms. These mechanisms include dendrite formation, electrode chemical and/or structural distortion, electrolyte decomposition, and solid electrolyte interphase (SEI) layer growth. Excellent reviews of these damage mechanisms and more are reported in Refs. [14,35]. In this paper, we do not consider how battery degradation evolves, or assess the rate of degradation as a result of continued EV use after 70–80% capacity fade. We assess the capability to complete daily itineraries for a given level of degradation. Critical failures, such as short-circuiting or thermal runaway events, will also force battery retirement however they are not considered in this paper.

6. Conclusions

This paper explored the impacts of battery capacity fade and power fade on the ability of EVs to satisfy the daily travel needs of U.S. drivers. Interpretation of the results leads to the following broadly applicable findings:

1. EVs meet the daily travel needs of over 85% of U.S. drivers even after losing 20% of their originally rated battery capacity. This result suggests that range anxiety may be an over-stated concern.
2. The commonly used retirement threshold (in a majority of prior literature) with EV batteries being retired from vehicle usage once they reach 70–80% of their rated capacity is overly conservative. This paper conclusively shows that EV batteries will continue to meet the daily travel needs of substantial fractions of U.S. drivers even after they have experienced substantial levels of battery capacity fade beyond 70–80% of remaining capacity.
3. Power fade does not have a significant impact on an EV's driveability performance, even with substantial levels of fade down to 30% remaining power capacity. As a result, EV battery retirement will be driven by energy capacity fade rather than by power fade.
4. The useful life of EV batteries can be extended by enabling charging in more locations, even if this charging is from 120 V wall outlets only.
5. Even after experiencing substantial levels of battery energy capacity fade, EV batteries provide the energy storage to enable substantial fractions of drivers to accommodate long unexpected trips exceeding 50 km.
6. Higher levels of ancillary power consumption, and driving on uphill terrain will cause a lower fraction of drivers' daily travel needs to be satisfied. This effect is more pronounced as greater levels of battery energy capacity fade are encountered, however

these effects can be partially mitigated by enabling charging in more locations where vehicles are parked.

7. Based on the results of this paper that show that 80% of remaining capacity is an overly conservative retirement criteria, new criteria is needed to define the time when EV batteries are retired and the capacity that will remain in these retired batteries. It is proposed that battery retirement should be defined to occur when a battery can no longer meet the daily travel needs of a driver. This paper quantifies the fraction of drivers whose daily travel needs are no longer met at various levels of battery capacity fade and this may be taken as an indicator of the levels of remaining energy storage capacity in batteries that are retired from their vehicle life.
8. The results of this study suggest that economic analysis into the utility of EV batteries during their first and second life needs to be reexamined. A great deal of prior analysis has assumed that EV batteries are retired at 70–80% of remaining capacity and this paper conclusively shows that this is an incorrect retirement threshold.
9. The results show that degraded batteries may continue to meet the daily travel needs of drivers who have shorter range trips. The secondary use of these degraded vehicle batteries in used cars or in EVs rated for shorter range (e.g. intra-city travel) can enable the deployment of inexpensive EVs that meet the daily travel needs for substantial fractions of drivers.

Acknowledgements

This work was supported with funding through the Laboratory Directed Research & Development program at Lawrence Berkeley National Laboratory, by the Director, Office of Science, of the U.S. Department of Energy under Contract No. DE-AC02-05CH11231.

The vehicle-to-grid simulator (V2G-Sim), which was developed and applied in this study, is available for use by all stakeholders. V2G-Sim provides a valuable research, development, and deployment platform for users to understand how different vehicles will perform for different drivers, and how different vehicles will interact with the electricity grid. Stakeholders benefiting from V2G-Sim include engineers, scientists, researchers, policy makers, analysts, and investors across the automotive industry, electricity grid industry, policy and regulatory sectors, and end users. More information is available at http://v2gsim.lbl.gov.

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