Is It Feasible to Use an LFP Auxiliary Battery in a Hybrid Car for Improved Deep-Cycle Performance?

Summary

The use of a $LiFePO_4$ (LFP) 12V battery is only worth considering by a few hybrid car owners: those who drive in mild climates, use power-consuming accessories such as dashcams while parked, and are willing to ensure that battery state of charge remains high enough for safe recharge currents. The capability might be improved by interposing an LFP-optimised charger and return power diode in the 12V circuit, but this would be expensive, and a job for a professional automotive electrician. For most current hybrid car owners, feasibility requires some help from the manufacturer, in the absence of which it is best to stay with the OEM (lead-acid) auxiliary battery. Those who drive at ambient temperatures beyond the 0-40ºC range, and/or do not want deep-cycle ability from a 12V battery, should certainly stay with lead acid.

Background

I have only experimented with a Toyota gen5 rav4 hybrid. The stock 12V battery in this car is a Yuasa 345LN1 or 355LN2. These are small (45-60Ah depending on model and vintage) flooded-cell, lead(/calcium)-acid, ‘cranking’ batteries. They are “maintenance free” (MF) but not sealed or AGM. They have electrolyte level lines and cell fill caps (under a clear plastic cover). They seem to have been chosen to meet EU regulations, rather than matched to hybrid vehicle use.

This hybrid-electric car does not use the 12V battery to crank the engine, just to activate the brake relay and boot the car electronics into ‘READY’ mode. Then the high-voltage NIMH battery can start the engine whenever required by the computer system. All the car electrics (except the air-con, traction motors and HV converter) run from the 12V system, and the 12V battery is charged when the vehicle is in ‘READY’ mode, by a step-down from the hybrid car’s high-voltage system. With ongoing slow drain into the car electronics (<0.12-1.2W, depending on ‘sleep’ state) and a dashcam (~2.9W) while parked, the deep-cycle characteristics of LFP may be more suitable as the primary 12V battery for this hybrid car. The potential can be seen in the performance chart:

A rough indicator of discharge (http://www.batteriesinaflash.com/guides, and manufacturers):

	Open circuit (resting) voltage*		0.125 / 0.5C, 25ºC	Colour Guide
State of Charge	**Flooded-cell cranking battery**	**AGM deep cycle battery**	**$LiFePO_4$ battery**	**Expected recharge cycles**
100%	12.7	12.8	13.6 / 13.4	Green: at least 1000
90%	12.5			(normal use)
80%	12.42		13.3 / 12.9	
75%		12.54		
70%	12.32			
60%	12.20		13.2 / 12.8	
50%	12.06	12.24		Yellow: at least 100
40%	11.9		13.1 / 12.75	(avoid this abuse)
30%	11.75			
25%		11.94		
20%	11.58		12.8 / 12.6	Red: probably fewer than 100
10%	11.31		12.5 / 12.0	
0	10.5	11.64	10.0 / 8.0	(never go here)

* Caution: varies with brand, battery age, temperature (and any recent load)

Renogy, Power-Sonic and others supply 50Ah 12V LFP batteries around 197L*166W*171H mm. These fit easily in the rav4 battery holder (LN2 = 242L*175W*190H mm). They weigh only 6.3-6.7kg and are rated at 2000 cycles with 80% discharge (at 25ºC and ≤0.5C discharge rate)! The attraction is obvious, but LFP needs a suitable charge profile for safety and performance.

Experiments

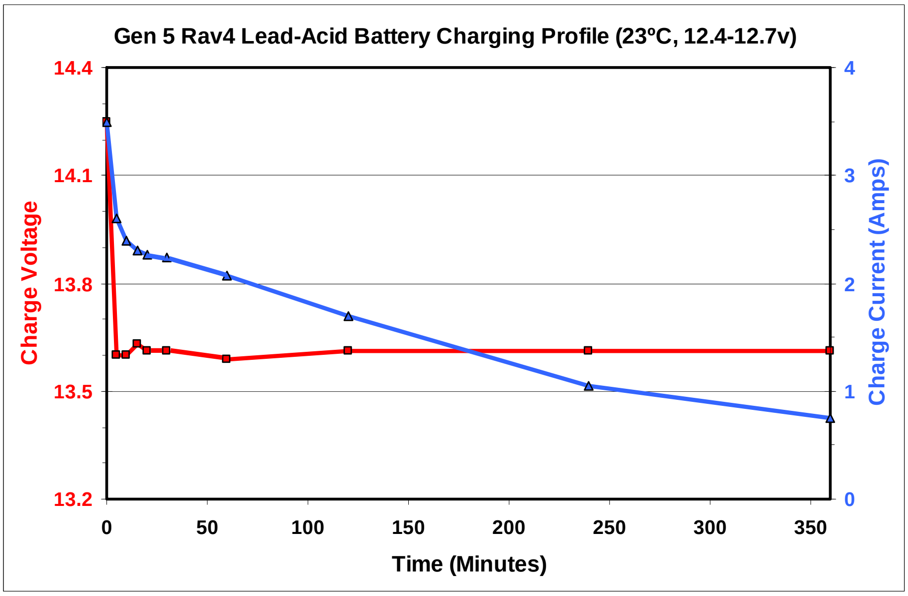
All my tests were made in Eco mode. Someone who claims to be "an EE with battery tech experience" reports less battery charging in Eco than in Normal mode in another Toyota (https://www.toyotanation.com/threads/what-is-your-start-battery-voltage-not-hybrid.1698197/post-14436106).

OEM Lead Acid Battery Charging

Using the method described in https://www.rav4world.com/posts/2846974/, I measured 12V battery charging voltage and current provided by the gen5 rav4 while it is in 'READY' mode, in 'Park'. My model has parking lights that stay on in this mode (in my garage), but I think this (along with the dash display and other electronic drain) should not affect the 12V battery charging, which is well below the system's rated current flow. No doubt it increases the frequency with which the ICE starts automatically to recharge the NiMh battery bank. In my case, this was for about 3min every 50min (during which 12V battery charging was unaffected).

When I started the test, the 345LN1 battery measured 12.4V with the usual <10mA 'deep sleep' drain. Some people call this 'dark current' or 'parasitic' drain. It goes on all day and is useful for the vehicle; so to a biologist it is better called 'commensal'; but I digress. The battery was below full capacity of 12.7V, so I expected it to activate recharging from the NIMH bank on 'READY'.

Here is the result: the initial charge at 14.25V and 3.5A (CC / bulk mode?) quickly dropped to 13.6V at 2.6A, then the current dropped to below 1A (CV / absorption or float mode?) over 6 hours (when I terminated the test, and the battery showed 12.7V). Bulk mode may be longer with lower initial state of charge.



The results comply partly with the Yuasa guidelines (in Japanese, for the 50Ah 355LN1: https://gyb.gs-yuasa.com/assets/data/manual_enj-3.pdf) of a normal charging current of 2.5A for 5-10 hrs, to terminate when gas is produced in any cell. No charging voltage is specified by Yuasa.

On these numbers, there seemed to be no danger of damage to an LFP battery through over-voltage charging from the vehicle, but it might not exploit either the fast-charging or the high-capacity of LFP chemistry. An external charger might be needed to bring the LFP battery to full capacity. The possibilities of vehicle error codes, failure to charge through excess sensed voltage, and/or altered charging into a lower-resistance LFP battery were still open questions.

LFP Battery Charging at High State of Charge

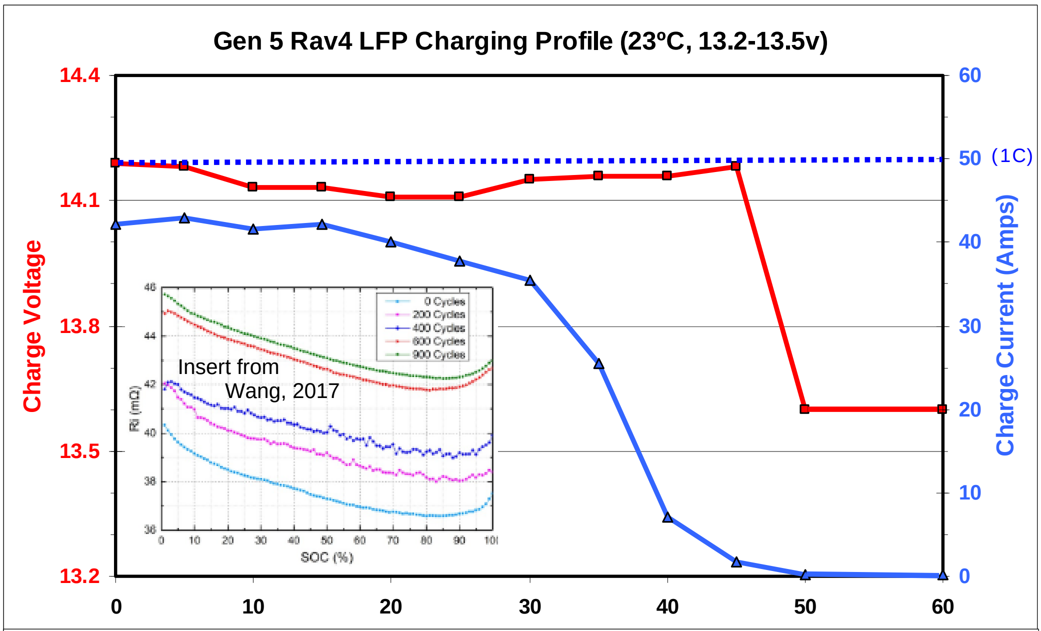
I experimented with a Renogy 12V 50Ah LFP battery (bought on sale for less than either a 45Ah 345LN1 lead-acid battery or a 6.4Ah Cellink Neo LFP dashcam battery). There may be room for dual batteries in a larger 'truck', but not in a rav4. Therefore I replaced the 345LN1. I ventilated the battery compartment first, and was careful to avoid sparks or short circuits during the whole process. All functions in my rav4 worked fine after a battery change without maintaining ECU power. The 50Ah LFP battery is a bit smaller than LN1, so I used timber packing under the top clamp for a snug fit (firmer than the polystyrene in the photo below). I used M8-SAE post adapters from Fullriver (which fit the Toyota battery post clamps and also provide M8 threads into the brass SAE posts). Sealed LFP batteries do not vent hydrogen or toxic fumes (https://gwl-power.tumblr.com/post/141674260966/), so they do not need the rav4 vent tube, which I secured aside using a cable tie. I live in a mild climate, so the LFP temperature constraints (0~45ºC for charge; -20~60ºC for discharge), and the usual temperature compensations in lead acid (LA)-optimised chargers (-16 to -32mV/ºC), are fine for me.

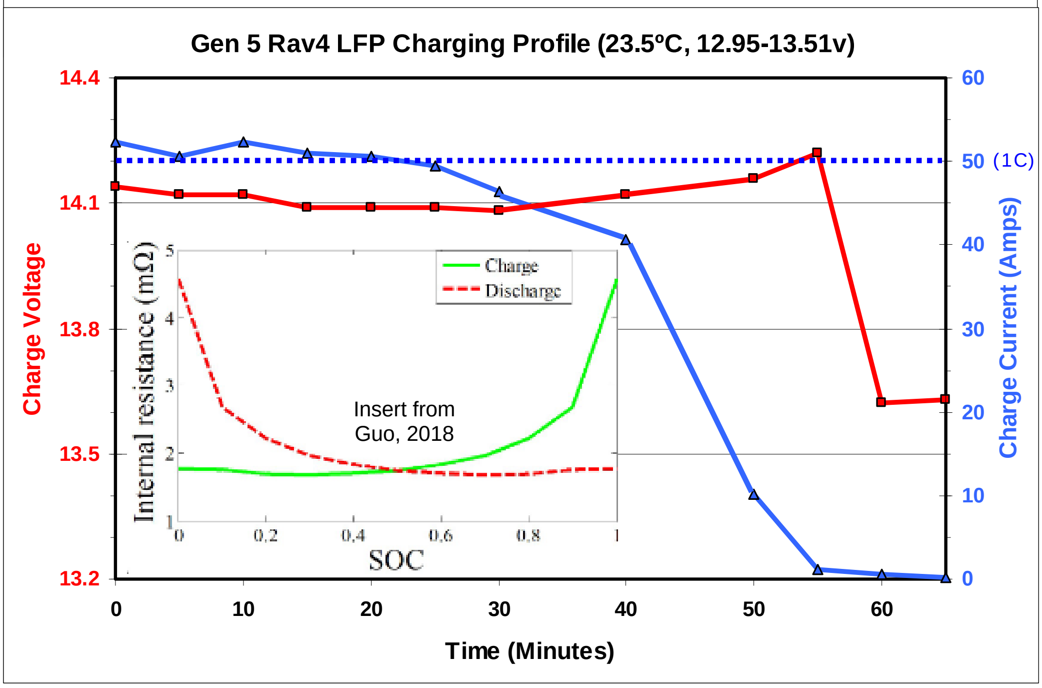
To 70% discharge (about 13V at 25ºC with the expected low current drain) this battery should power my Viofo A129 plus duo dashcam in 1fps time-lapse parking mode (2.9W) for more than 6d. My 256Gb SanDisk Max Endurance micro-SD card will hold about 18d of 1fps parking-mode recordings before overwriting. (Viofo claims that this unit does not overwrite any recording that includes an event that triggers its impact monitor, but that is not my experience in time-lapse parking mode). The "sweet spot" may be 2fps. The remaining 30% battery charge should hold the rav4 (at up to 120mW average commensal drain) for several months without jump starting. I have not tested these calculated times. They will vary with the efficiency of voltage converters, cut-offs etc. Cigarette lighter-usb converters that I tested varied from 1.7-24mA current draw (22-307mW) with no load, and 56-83% efficiency with loads around 100mA (at 12.8V). At high load, higher conversion efficiency may outweigh low standby drain of the converter. My one test with dashcam load gave LFP battery drop from 13.20V to 12.95V (~35% of battery charge at 23ºC) at 2fps parking mode (with lots of door opening = higher vehicle commensal drain) over 48hr.

I decided against the Viofo HK3 after reading https://dashcamtalk.com/forum/threads/hk3-hard-wire-kit-terrible-voltage-regulation.44244/. With no load, HK3 draws 86mW before and 35mW after cut-off. It does not have suitable voltage options for LFP, I prefer thicker wires, and I don't want to stand on my head to find the right fuse sockets then leave the fuse box cover off because of piggy-back fuse connectors. So I decided on a Victron Smart BatteryProtect, which has the advantage of more adjustable cut-off and restore voltages. It is wired after a 10A fuse near the battery, then double-insulated 1.5mm^2 (AWG16) wires run to a cigarette lighter-USB converter in the console box. My dascham will not draw more than 1A through this 7m circuit, so there should be no problem with voltage drop or heating of the cable. BatteryProtect power use is very low at1.2mA before and 0.7mA after cut-off (16⇒9mW). Adding 0.2mA (3mW) to enable Bluetooth provides an accurate 2-decimal voltmeter (to a phone with battery-save off). Cheaper units using continuous monitoring and a non-latching relay, instead of periodic sampling and a MOSFET, have much higher drain. However, MOSFETS can be stressed by voltage spikes from inductive loads, and if they fail silently they normally keep power to the controlled circuit.

Wires were fairly easily routed under the trim: forward from the auxiliary battery to the side of the NiMH traction battery, along the front base of the NiMH battery to the centre, under the carpet and felt beside the tunnel, and under the console trim to enter the console box with the dashcam cable. (Pop off the rear seat and a few trim panels, but there are no screws or bolts to undo. The tunnel was trickiest because of cross-braces, but no big deal. I used a packing strap from the Renogy battery to find the route. An electrician's plastic guide would also work, just twist and push gently to get past any obstructions). This allowed me to use a usb Y cable for automatic parking mode as described in a companion article.

After the battery change, I conducted tests like the one described above, at several starting voltages:





Starting at 12.95V battery voltage (estimated 25% SOC), it was a bit scary to watch 52.3A at 14.14V flow into the battery. While many LFP batteries (including the Renogy 50Ah) are specified for charging up to 1C (50A in this case), and the battery got barely warm to touch at the side after 30min, I would not like the charging current to go any higher. The fast charge (and high current) is a result of low resistance presented by the LFP battery. This varies with charge vs discharge, SOC, battery age and temperature (Mahmud 2017, Wang 2017, Guo, 2018).

Some car alternators might struggle with 50A continuously for 30min (https://www.victronenergy.com/blog/2019/10/07/careful-alternator-charging-lithium/), but the rav4 hybrid DC-DC converter seems fine with it. Toyota hybrid car DC-DC converters are typically ≥100A (https://priuschat.com/threads/please-explain-12v-system-to-me.183008/), and the rav4 12V circuit fusible link is 120-140A (https://www.rav4world.com/threads/pure-sinewave-inverter-for-ac-power.298553), so there should be enough headroom for all other current draws. The ICE ran more frequently while the current into the auxiliary battery was high (for about 3min every 15min while current was 40-50A).

The charge voltage dropped suddenly to 13.6V when the current was below 1A (at 50-60min in the charts above). I do not understand why the drop to 13.6V occurred at a charging current >2.6A with LA but ~1A with LFP. Could it be Coulomb counting with an algorithm tailored to the inefficient charging of LA? In any case, almost no charge is expected to flow into an LFP battery at 13.6V (and 1A is the recommended current for termination of charge to 50mAh LFP), so I turned off the vehicle at 60-65min, at which time the LFP battery voltage was 13.5V.

There was more variation when driving: when the battery was below full, system voltage stayed between 13.6v-14.2V; but when the battery was near-full system voltage dropped below 12.7V and remained below 13.5V for long periods. The voltages at any moment in the rav4 are unpredictable; but no combination of driving mode, A/C, headlight, fog lamp and defog switches prevented the drop below 13.0V. I assume this is intended to save fuel by reducing DC-DC converter output. But it is poor implementation by Toyota to let system voltage when driving fall below the open circuit voltage of the auxiliary battery. GM Spark EV got this right back in 2014!

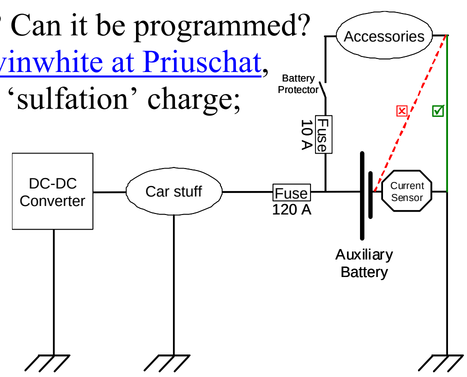
LFP Battery Discharging

Then I kept watching battery voltage and current flow. In the first experiment, the commensal current draw by the rav4 dropped to about 100mA within 10min, about 15mA within 20min, and below my clamp meter limit of 10mA within 3hr (when battery voltage was 13.34V). In the second experiment, the current draw was about 450mA after 10min, about 100mA after 20min, and <10mA within 30min (when battery voltage was 13.38V). The time to reduced drain varied somewhat between experiments, for reasons I do not understand. But the stepped levels of drain from the LFP battery were as for the OEM LA battery. Using an OBD device, after parking overnight (locked or not) the Aux. Bat. Dark Current PID usually reads 7mA, or 27mA with the Viofo A129 plus duo dashcam plugged in and turned off (yes, this unit adds about 256mW of stand-by drain). In any case, commensal drain takes the top off the fully-charged battery voltage when the car is stopped, then drops to a low level until a door is opened. After several hours drive with system voltage below 13.5V, the LFP battery voltage was 13.33V.

So Far, So Good (with Some Niggling Doubts)

On these results, the rav4 is fine with a 50Ah LFP battery that is kept above 25% SOC. At 14.2V and ≤1C during the bulk/CC phase, there is no danger of damage to a properly top-balanced battery through overcharging, and the vehicle exploits fast-charging capability of LFP chemistry. I might be happier at 0.2C for longest cycle life (by reducing the possibility of irreversible plating of lithium metal onto the anode), but dascham users who need to recharge the battery during short drives will appreciate the faster charge near 1C (if allowed by the battery manufacturer).

The 'automatic' drop in charging voltage at 50-60min (and 0.02C) in both experiments with LFP was reassuring. It behaved the same way a month later (14.2V @ 47.5A dropping to 13.6V @ 0.5A at 50 min, from an initial 13.1V battery), and I confirmed that with a fully-charged battery it dropped from 14.3V @ 0.7A to 13.6V @ 0.3A within 3min after starting. But to understand if it might vary in a way harmful to an LFP battery, we need to know how the drop is triggered: Charging current? Coulomb counting? Does it count when the car is off? Does it correct for charging efficiency, temperature or battery age? Is it adaptive? Can it be programmed? If so, which parameters are programmable? As advised by kevinwhite at Priuschat, the Chevy Spark EV may without notice apply a high-voltage 'sulfation' charge; which would be very bad for an LFP battery. Sadly, Toyota reveals less than GM to interested owners.



Any accessories that drain current while the vehicle is running should have their return/ground connection wired downstream of the current sensor, if the system is to regulate based on charging (not total) current.

Trickle charging of LFP batteries should be avoided, but the rav4 float/trickle at ≤13.6V does not raise concerns for durations of a few hours. For long drives, a lower float voltage (ideally 13.3V) would be better for LFP life, and can be achieved in a correctly-programmed 'fuel-saving' mode.

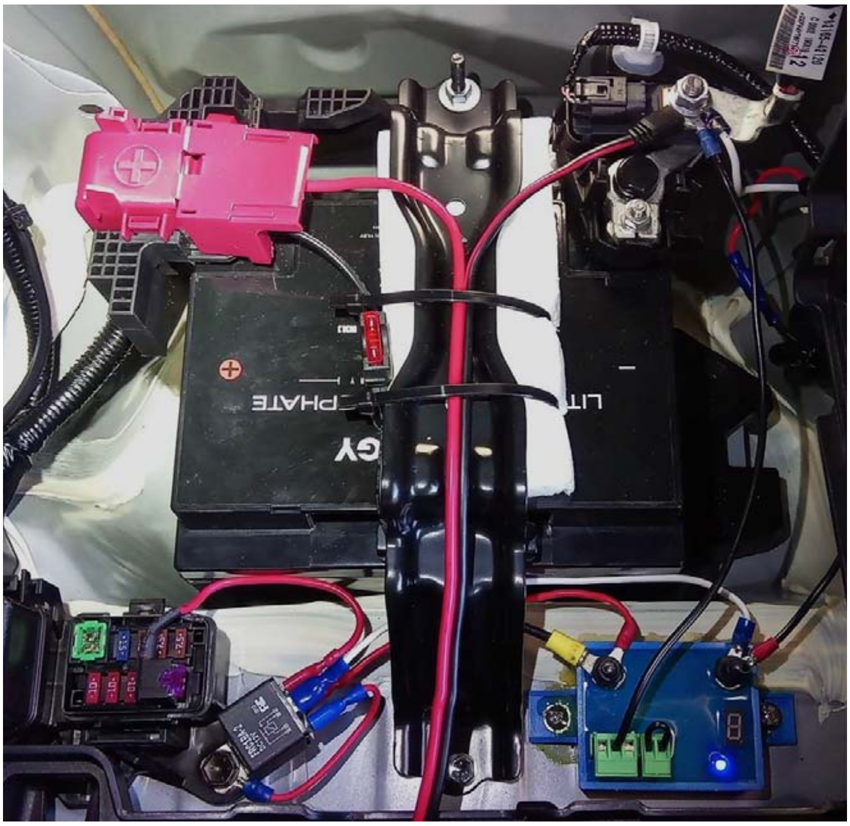
There were no problems with fusible links, sensors, relays or fuses. No errors have been displayed. The vehicle entered 'READY' mode as usual from the LFP battery at 25-95% SOC. If anything, fuel economy should improve due to the light weight and efficient charging of LFP, but this may be hard to see among other driving variations. The rav4 at 14.2V charged LFP to an estimated 90-95% SOC at 23ºC, which is fine for most purposes and good for battery life. Those who want 100% SOC (or more 'absorption/CV' time at >14V for cell balancing or erasing any memory effects) will have to use something supplementary, like a good LFP wall charger.

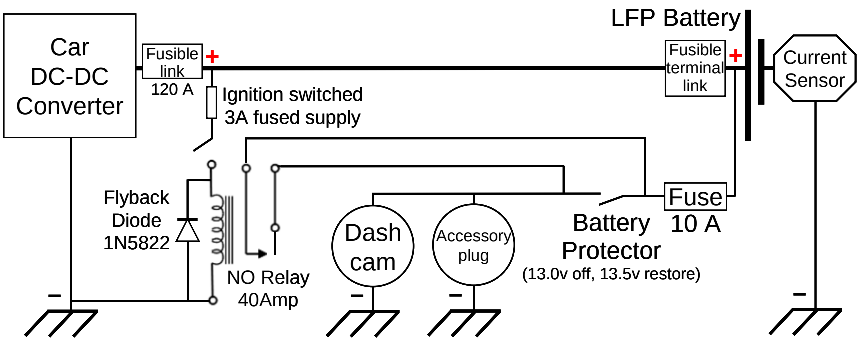
I have a Victron Blue-Smart IP65 12v/10A wall charger that can be programmed for the optimal charging specs from Renogy, except that it lacks the ability to set absorption charge termination based on charge current (try Enerdrive chargers for this feature). For charge termination based on current, a Victron user would need to watch charge current by Bluetooth (reported to 0.1A), and turn off the charger at the wall when it reached the desired level (1A = 0.02C for 50Ah). Charge termination based on cell current additionally requires a BMS with this output (which is not in the Renogy 50Ah) and an interface to the charger, which is lacking in everything I own. The Victron charger has split leads that can permanently attach to the LFP battery (as in the photo). It includes the ability to report charging status and history via bluetooth.

In default Lithium mode (14.2V charge, 2h absorption) the Blue-Smart added only 0.2+0.4 = 0.6Ah to the charge from the rav4. At 14.6V (with 1 hr absorption for full charging and cell balancing) it added 10.3+0.2 = 10.5Ah (much more than I expected).

The Victron Blue-Smart can also maintain an LA battery (now my spare 345LN1). At 14.4V charge it reported the 345LN1 as 3.7+11.1 = 14.8Ah ie 33% undercharged by the rav4, perhaps a reflection of the low charging efficiency of LA chemistry). At 14.7V charge as recommended for lead-calcium batteries, it added another 0.0+0.2 = 0.2Ah.

The photo and circuit diagram show the installation, with an added relay discussed below.





***A Very Important Caution*: Excessive Charging Current at Lower State of Charge**

BUT, the initial charging current rose to over 73A when the 50Ah LFP battery was discharged further, to around 12.7V (~20% SOC at 23ºC). Simplistically, charge current increased in proportion to the difference between system voltage and battery voltage. The unmodified rav4 is not suited for this task, as the applied current at >1C is above the level that will damage the battery. This high current might also damage the rav4 DC-DC converter and/or 12V circuit.

Toyota implies that using other power-consuming parts of the vehicle (headlights, blower, rear window defogger, radio) can reduce charging current to the battery. But in my experience the maximum effect is a few Amps, not enough to avoid LFP battery damage in this situation. LA batteries present much higher resistance to the charger and thus receive much lower current.

Amazingly, many writers about LFP batteries for cars do not even mention this issue. Some recommend batteries that are too small for substantial parked current drain (like a dashcam), and evidently do not think about recharge current at low SOC. Some people believe that the LFP battery Protection Control Module (PCM or BMS) regulates all essential charge features. But many PCMs do not monitor charging current. A typical PCM acts only as a safety cut-out. It should prevent failures that could injure vehicle occupants, but it may not prevent all conditions that can damage the battery. It acts like a circuit breaker and is absolutely NOT a charging current regulator. This capability must be designed into the charger (DC converter circuit in hybrid cars).

Could the Manufacturer Help?

As the rav4 has a current sensor on the auxiliary battery, it would be ideal if Toyota could program the vehicle for a maximum auxiliary battery charging current (10-50A for 0.2-1C charging of a 50Ah LFP battery), and 'float' (triggered at 1A charging current) at ≤13.3V (which will stop any current flow into the LFP battery). 'Fuel-saving' mode should require >85% SOC with low auxiliary battery current, and DC converter output should equal the open circuit voltage of the auxiliary battery. Voltages can be suitable for both LA and LFP batteries. The programming of the DC converter 12V module has not been revealed by Toyota, but evidently it includes capability to control voltage and current outputs. Maintaining supply to the vehicle 12V system; while accurately sensing, controlling and terminating 12V battery charge current; may require separation of charging and load circuits. This may already be implemented, but available circuit diagrams are somewhat ambiguous. It would not be trivial to implement after manufacture.

The rav4 current sensor includes a thermistor that informs PIDs including "Smoothed Value of Auxiliary Battery Temperature". Although this sensor is probably influenced more by surrounding air temperature than battery cell temperature, it would be great if it reduced battery charging current at elevated battery temperatures, as in some earlier models (*www.trav4.net/battery_temperature_sensor_circuit-438.html*). Voltage to an LFP battery should not change with temperature, but at the usual compensation of ~-27mV/ºC for a 12V battery it is not a big deal at normal cabin temperatures. I have no idea what the "Auxiliary Battery Integrated Thermal Load" PID does.

Some modern vehicles seem too smart (or dumb) when their mechanisms are kept secret. An owner can set all the relevant parameters in a quality 'smart' battery charger costing $150. Yet the same owner is not permitted to know (let alone adjust) the same parameters in a rav4 hybrid costing $40,000. Amazingly, a Toyota car owner is required to pay a fee to view *Car Features,* even though it lacks technical detail (https://techinfo.snapon.com/TIS/Register.aspx). Surely an owner is entitled to know the technical features of a purchased car. Toyota, it is time to lift your game!

Toyota (USA) responded: "Toyota does not recommend or assist with modifying our vehicles from the original factory specifications." Fair enough, though I asked about my rav4 not theirs; and such advice ignores the millions of Toyotas out there with non-OEM modifications such as dual-battery systems, or even dual dashcams or battery chargers. Perhaps compatibility with LFP auxiliary batteries will feature in original factory specifications of Toyota hybrids in the future.

Is it Feasible to DIY?

Any technically-adept owner thinking about DIY installation of an LFP battery (at their own risk) should read https://marinehowto.com/lifepo4-batteries-on-boats/. If the BMS cuts off during charging, it may cause a voltage spike through the circuit, risking damage to other components. The same applies to cut-off through an isolation switch, circuit breaker or fusible link while charging. Such spikes arise from high current through any inductive load (any coil, such as a motor or solenoid).

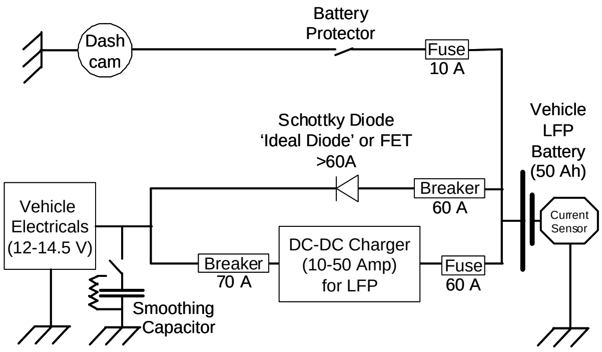
The rav4 hybrid does not have an alternator, and the 12V DC circuit is effectively isolated through the DC-DC converter from major inductive sources like the high-voltage generators. If the BMS cuts off the battery during charging, any inductive loads should continue to receive power from the DC-DC converter. But a connected car battery acts as a buffer (capacitive load) for the vehicle electrical system. The interactions between control circuits for the 12V and high-voltage systems are unknown (to me). It is preferable not to run any vehicle without a connected battery. With these things in mind, we wish to ensure that the LFP is never charged above 1C, but we do not want to disconnect an LFP battery at low SOC after the vehicle (thus the charger) is on.

An OBDLink device with Toyota PIDs can display auxiliary battery voltage, current and smoothed temperature. Remove the OBD device when parked to save 2mA (if sleep works) - 40mA (idle). The car draws 3-7mA in 'deep sleep'. My Viofo dashcam draws 220mA for 1fps time-lapse, or 20mA in standby (switched off at the dashcam). My 12V-5V converter draws 5mA, but it is ~80% efficient at voltage conversion. The best compromise is to use a high-efficiency voltage converter when the dashcam is used, and pull the converter from the socket when the dashcam is not wanted. Use a quality battery protector in the dashcam circuit, ensuring that subsequent LFP charging current is not >50A / 1C. I use 13.0V cut-off, but this may vary with factors including temperature and battery age. Variations in system voltage while driving then trigger cut-off. A work-around is to add a relay to power the dashcam when ignition is on (with the protector working when ignition is off). Protector and relay should be rated for capacitive and inductive load effects in the dashcam. Data logging in OBDLink shows wide cycles of LFP charge and discharge as system voltage oscillates while driving (see the logged examples below). This is probably undesirable. Parking mode can not operate unless power to the dashcam continues. Thirty sec in Park before switching the car off will ensure battery protector restore, if set at 13.5V. All this is too complex for many owners. *Programming car DC-DC converter output voltages would solve all this. Limiting charge current would allow dash-cam cut-off at 12.7V while parked. Car owners cannot make these adjustments without help from the manufacturer. Currently this is withheld by Toyota.*

Check battery voltage any time substantial discharge is suspected. If the LFP battery is ever below 12.95V at 25°C, it must be disconnected to avoid excessive charging current. That leaves problems of how to start and run the car. To ensure that this can never arise, it is necessary to seek professional advice. Remember that because the methods of charging control in the rav4 are unknown to owners, the car could overcharge and damage an LFP battery at some time, even if it seems OK initially. In the absence of help from Toyota, identification of any other risks needs analysis of the entire car electrical system by an electrical engineer familiar with LFP batteries.

An interposed DC-DC charger can limit charge current, but there are complications. A smoothing capacitor may restore buffering in the 12V circuit, but how the car would react to altered signals from the current sensor is untested. Most DC-DC chargers are unidirectional and can not provide power from the battery through the charging cable to the car electrical system. A bidirectional device, or at least an added power diode or master and slave DC converters would be needed.

Some converters can not tolerate connection of input and output. You will need advice from an automotive electrician. On preliminary advice, it may be feasible but expensive. There is limited space near the rav4 auxiliary battery for added components. If this approach is feasible, a device could be chosen with the desired charger current, charge termination method, and recharge voltage threshold for LFP. Also check standby current use. It seems far simpler for Toyota to offer a modified charging profile (see below).



Without these features in the charging system, life of an LFP battery kept above 25% SOC in a rav4 hybrid will be less than 2000 cycles (specified under ideal conditions at 0.2C charge and no float). But if there is substantial cycling, LFP life should be far greater than any LA battery of similar capacity, if a well-installed and high-quality LFP battery is used at moderate temperatures.

LFP Considerations

An informative site about LFP battery technology is http://nordkyndesign.com/category/marine-engineering/electrical/lithium-battery-systems/. A good academic review is http://hdl.handle.net/10125/101139. Reported calendar life for well-managed LFP batteries is >10y. I have been convinced about the benefits of LFP auxiliary batteries for hybrid cars, but anyone considering a change should note:

- LA is a more robust technology; because it is more temperature-tolerant, and because lead is more stable than lithium. But the strong acid electrolyte and hydrogen gas production from LA batteries are dangerous. Experts disagree on which battery technology is safer overall (both require care for safety).
- LFP is more stable than Lithium-Cobalt (used in most Li-ion and Li-Po powerbanks), but it still needs at least a dedicated battery controller (called a PCM or BMS) for safety. This may be built into the battery or wired in. It must connect to each cell within the bank that forms the battery. It is essential as the 'protection of last resort' to avoid over-charging and over-heating (which can be dangerous as well as damaging to the battery) and over-discharge (which can quickly destroy the battery).
- For safety, no lithium battery chemistry other than LFP should currently be considered for in-vehicle use. LTO is a possibility for the future. Although unlikely with properly installed LFP batteries, thermal runaway followed by a lithium fire is such a dangerous scenario that redundant protections should be used against it. Protections should be redundant in the battery and charger, in case either fails in a way that keeps the circuit active.
- Most external battery (charging) management systems use some form of battery voltage sensing. LFP batteries present higher charged voltage (~13.5V) so they have used at least 50% of capacity (>80% at low discharge rates) by the time they drop to the LA maximum around 12.7V. At 0.1-0.3C current and 20-30ºC, voltage drops steadily to 12.5V at 80-90% discharge, then rapidly to 100% discharge (typically defined by the internal BMS as 10V). See the charts below. True 'resting voltages' (with no commensal drain) would be a little higher. The slope is small from 5% to 80% discharge, and the relationship depends on both temperature and discharge rate. So a small error in specified or measured voltage, or estimation at an incorrect temperature or discharge rate, can give a large error in estimated battery state of charge (SOC). Some experts recommend Amp-hour or Coulomb counting or more complicated algorithms to estimate SOC; others find them unreliable.
- A dumb bulk charger for LA (or even a Li-Po charger) may push out more than 14.6V and dangerously overcharge LFP. A smart (multi-stage) charger for LA may not provide any current at LFP battery voltage. Or it may work just fine if it uses suitable voltage and current cut-offs. As a conservative charger setting for LFP, a regulated 13.8-14.4V at 0.2- 0.5C should be fine for the bulk/CC stage (but check your battery specifications). As battery resistance rises with SOC, current at this regulated charging voltage will drop (absorption/CV stage). Even 'ripple' above the regulated voltage can be damaging if it goes over the safe voltage limit for LFP charging. Below 13.4V there will be no charging (or very slow charging and greater risk of memory effects from partial charging).

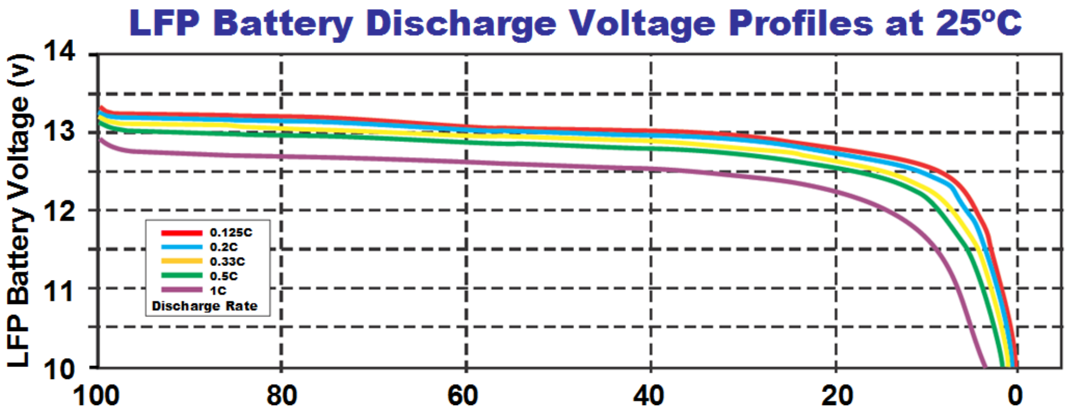
- Some experts recommend charging well-matched cells to only 13.8V to avoid challenges of balancing at higher voltages. Others use at least 14V and absorption to 0.05C to avoid memory effects. Some BMS units only commence cell balancing above 14V. In any case, a prolonged absorption phase (> 4 hr) should be avoided.
- Absorption/CV charging should stop before charging current drops to 0.02C (1A for a 50Ah battery); but not all chargers (even those with 'lithium' profiles) have this feature, and it is complicated by any substantial 'parasitic load'. Some chargers use a higher cut-off current, some use timed cut-off of the absorption phase, and others go on until stopped manually. If you are happy with 90% SOC (and longer cycle life) you do not need any absorption/CV charging; just a bulk/CC stage to 14.0-14.4V. To get 100% capacity (and possibly for cell balancing and avoidance of memory effects), you will have to check specifications and measure your particular systems (vehicle and external chargers and battery). Most likely, battery specifications will call for absorption charging to terminate at some fraction of C, in the absence of any 'parasitic load'. The fraction may vary with charge voltage: some would say 0.03C (1.6A for a 50Ah battery) when charged to 14.2V. It is sometimes recommended to terminate charging based on BMS readings from individual cells, which are unavailable in many LFP batteries.
- Memory effects occur in LFP after partial charge combined with partial discharge, and become more difficult to erase after multiple partial charge cycles to the same level. To clear memory effects it is usually only necessary to charge fully (terminating by absorption current) a few times a year.
- LFP batteries are safest, and show highest capacity and cycle life, at moderate temperatures (around 23ºC). They must never be charged at freezing temperatures, or discharged at elevated (engine bay) temperatures. Vehicle cabin temperatures are generally OK (humans function best in the same range), but can reach unacceptable levels if parked outdoors in hot or freezing conditions. Temperatures over 40ºC can greatly shorten the life of LFP batteries.
- LFP batteries are generally not designed to be cranking batteries. If you want to be able to jumpstart another (non-hybrid) vehicle, you should use a battery designed for cranking.
- High-quality LFP batteries can be recharged quickly (0.2-1C at a charge voltage up to 14.6V, depending on the brand and model). There are compromises between highest charge rate and capacity vs highest cycle life. For safety they should never receive a higher-voltage 'desulfation' or 'equalisation' charge, and for long life they should not be trickle/float charged for a long period. Short-term float at 13.8V or below should not be damaging. Unlike LA, their stored life is longest with a partial charge, ~50% SOC (and at < 25ºC). When fully discharged, they should be recharged (at least partially) as soon as possible. Algorithms for LFP batteries in active use typically trigger 'recharge' at a battery voltage of 13.1-13.2V (aimed to keep >50% SOC).
- The vehicle charging system must be checked for safety with LFP. It may be necessary to modify the vehicle system for safety, and/or use a smart wall charger and/or manual intervention for high capacity and cycle life. Unregulated auxiliary battery charge current and poor implementation by the manufacturer of 'fuel saving mode' are difficult for an owner to work around.
- Also consider whether your typical and extended drive durations would replace used battery capacity. LFP can typically charge much faster than lead acid (if the vehicle provides sufficient current, at charging voltages of 14.0-14.6V). But cycle life will be greater with 0.2C than with 1C charging; and with current-based charge termination.
- Ideally, the charging system should ensure that the LFP battery has discharged substantially before initiating a current-limited and current-terminated recharge. Vehicle 12V battery charging systems are not yet designed this way.
- LFP batteries vary in quality. There are important differences in BMS features (sensing of temperature and charge current, cell balancing, communication), wire size, vibration resistance, electrolyte composition, cell type, cell matching, true capacity, life-span, warranty and recommended charge or discharge profiles. The buyer is rarely able to check these features, so it is safest to use a reputable brand. Fortunately, prices are dropping.
- Vehicle warranty may be affected if a case can be made that use of a non-OEM LFP battery was relevant to damage to the vehicle. Insurance is a potential minefield.

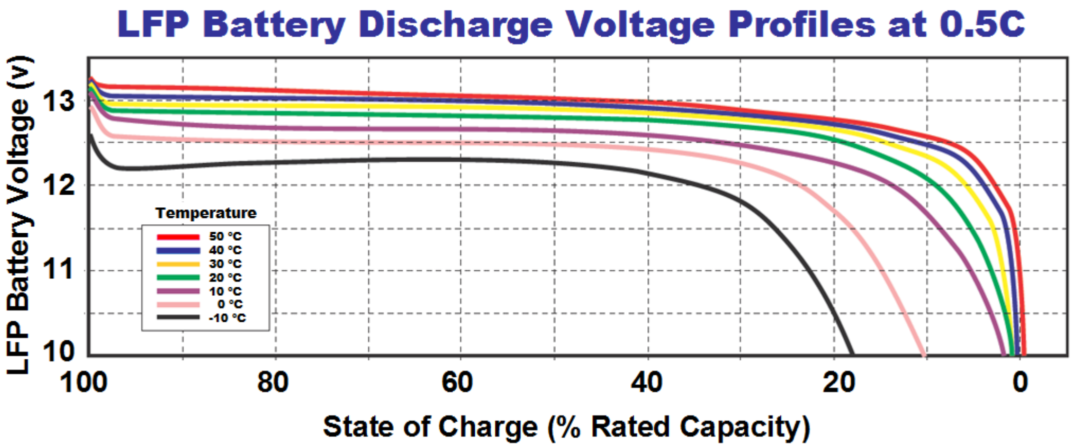
Although widely used as light, fast-charging, deep-cycle batteries in hybrid vehicle traction systems and recreational vehicles (where they may have separate cooling and charge/discharge management systems), they are not necessarily the best choice for all hybrid vehicle owners as replacements for the vehicle 12V auxiliary battery. LFP batteries work best for regular cycling. LA batteries are better for prolonged standby at full capacity. Most current mobile systems with LFP use it in parallel with at least one LA battery. There is no such thing as a simple LFP 'drop-in' replacement for an LA vehicle battery. It is at least essential to consider the extremes of cabin temperature in your location, and to check the suitability of the vehicle battery charging system, especially looking for excessive charging current at low battery SOC. If in doubt, stay with the OEM-supplied battery. Before even thinking about DIY installation, read https://marinehowto.com/lifepo4-batteries-on-boats/ and look at http://nordkyndesign.com/category/marine-engineering/electrical/lithium-battery-systems/. Marine and land-vehicle uses share many potential pitfalls.

Ideal Settings for an LFP Auxiliary Battery (kept in a cabin around 25ºC)

Stage	**Voltage**	**Current into battery**
Charge (Bulk)	14.0V - 14.2V charge	≤0.2C (needs to be limited)
Charge Termination	--na--	0.02C (>90% SOC)
Float	13.0V - 13.3V charge	0 (none will flow at this voltage)
Recharge threshold	13.1V battery (~50% SOC)	--na--
BatteryProtect (non-essential circuits)	12.7V battery (>10% SOC) IF charge current is limited	--na--
'Fuel-saving' DC-DC output (>85% SOC with low battery current)	auxiliary battery voltage or 13.3v	--na--

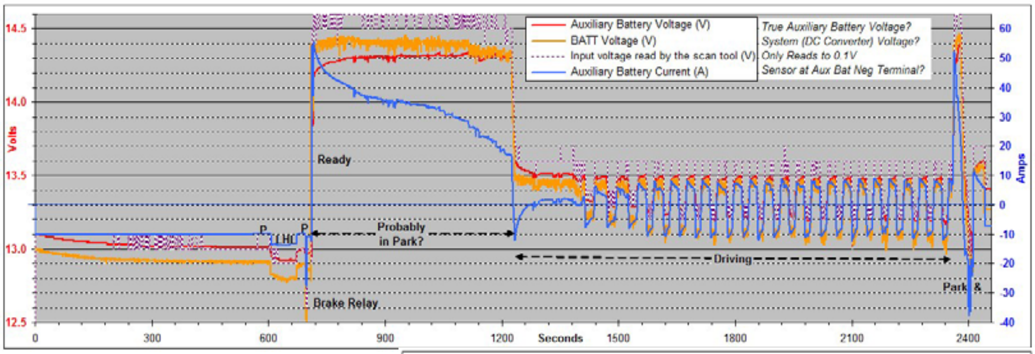
Charts clarified from Power-Sonic
https://www.power-sonic.com/wp-content/uploads/2020/07/PSL-12500-Technical-Document.pdf:



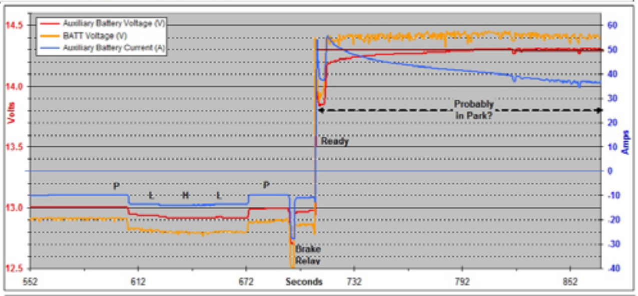


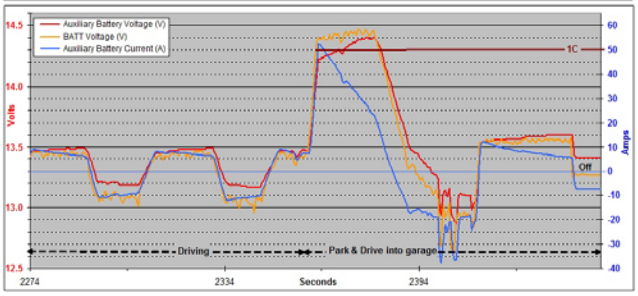
A useful (commercial) site about batteries in general is: https://www.mpoweruk.com/sitemap.htm

Hybrid 12V battery charge control



Timing and depth of 'fuel save' voltages vary daily. Temperature may be relevant. A mild example is shown (from OBDLink logs using Toyota-licensed PIDs).

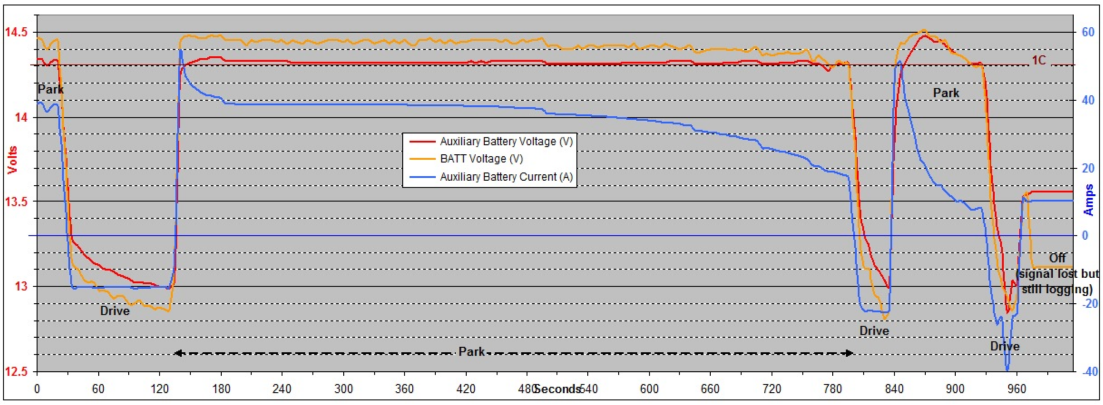




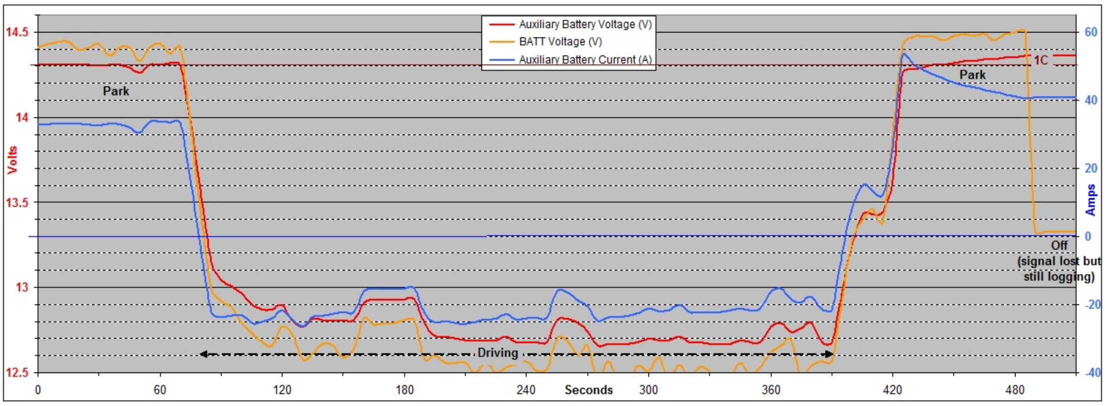
'BATT Voltage' and 'Auxiliary Battery Voltage' evidently come from separate sensors. 'BATT Voltage' may be 'System Voltage' (from the DC-DC converter) with some low-side limit from aux battery input to the circuit. The LFP aux battery appears to discharge when system voltage drops below 13.3V; and be charged by system voltages above 13.3V. System voltage is set to drop below LFP voltage initially, and in 'fuel saves' (which occur in about 1/2 minute cycles). Sometimes it drops immediately, even with an LFP at a low SOC, resulting in further discharge of the battery while driving! It is poor implementation to let system voltage when driving fall below the open circuit voltage of the aux battery. A second poor implementation in the Toyota aux battery charging algorithm causes 'wild swings' in current to and from the LFP at the end and/or start of a drive, even at high battery SOC. The car seems to be programmed to 'top up the aux battery' when speed drops to 10km/h (maybe with a sharp turn, not usually in traffic), and when 'READY / Park' is engaged, without initial regard to SOC. System voltage at these times varies from 14.5V to 12.5V. Such swings are probably not great for LFP battery life, but thankfully they usually are brief. Sometimes the system voltage goes high and stays there for a long period, with a fully charged LFP at freeway speeds. Could this be some kind of 'desulfation mode'? Thankfully it remains within a safe range for LFP, and resistance limits charge current, but it is not ideal.

Programming 'fuel save' voltage to match auxiliary battery voltage (or stay above 13.3V) should reduce the first problem. *A car owner can not make this adjustment without help from Toyota.*

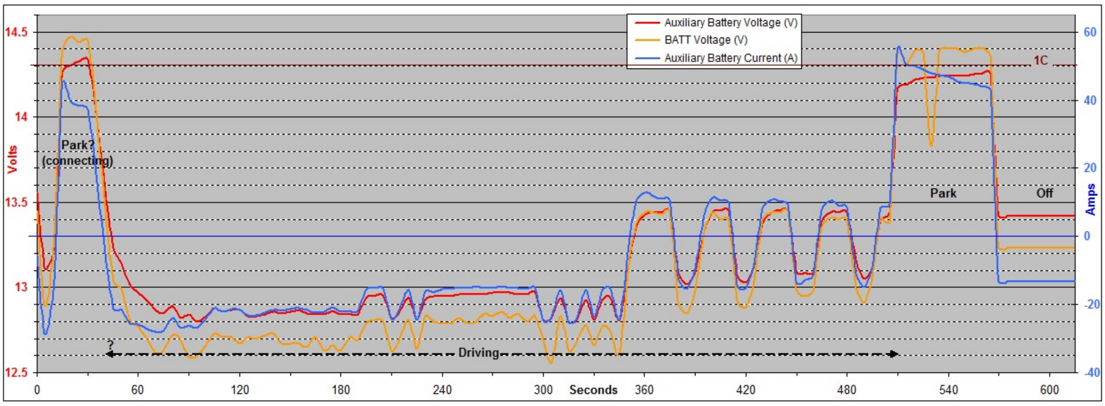
Toyota permits rav4 owners to select a preferred distance to the vehicle ahead at 110 km/h, but not a preferred auxiliary battery chemistry? Give me a break. We are not seeking to tinker with safety systems like braking, or with emission systems like catalytic converters. But 12V battery chemistry and charging profiles are properly owner prerogatives, like car colour, seat covers, winter tyres, dashcam, or OBD reader. All we ask is for Toyota to enable service departments to install (for an appropriate fee) a charging profile that matches the car owner's chosen auxiliary battery chemistry. From the evidence above, one important parameter is V_{min} in 'fuel saving' mode. If maximum charge current could be set to remain below 1C, an LFP battery user could set dashcam cut-off lower (~12.7V rather than 13V); to get the most out of LFP deep-cycle ability while parked, without risking excessive (>1C) charging current. Is this too much to ask? No doubt technically-oriented car owners would test it for free. A company with a mandate for profit from sales must give some heed to customers. Speak up (potential) customers. *Come on Toyota.*



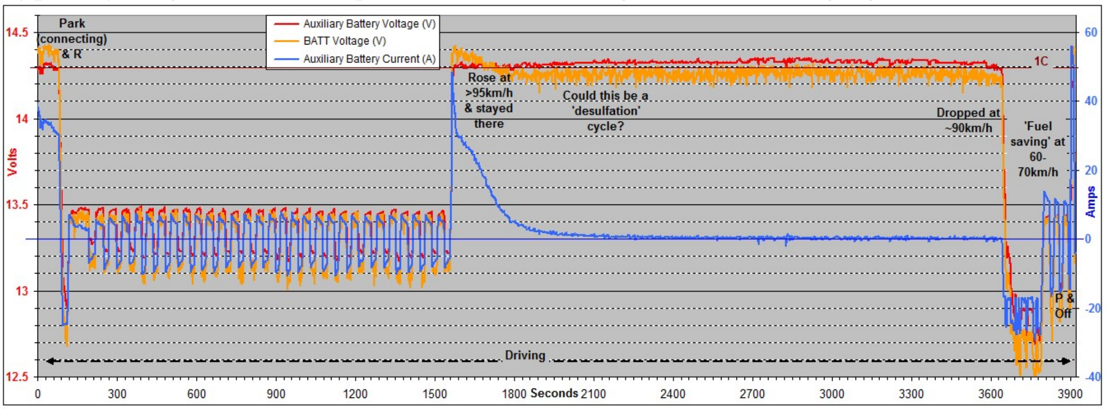
There is a big difference between auxiliary battery charging behaviour in ‘Park’ vs ‘Drive’.



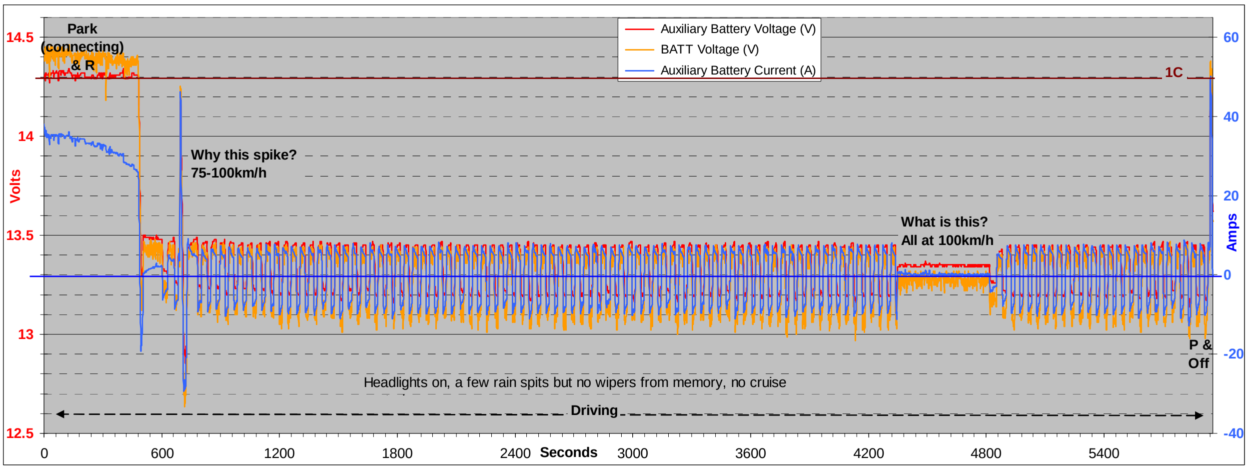
While driving, the rav4 aux. charging algorithm can further discharge an LFP battery at low SOC.

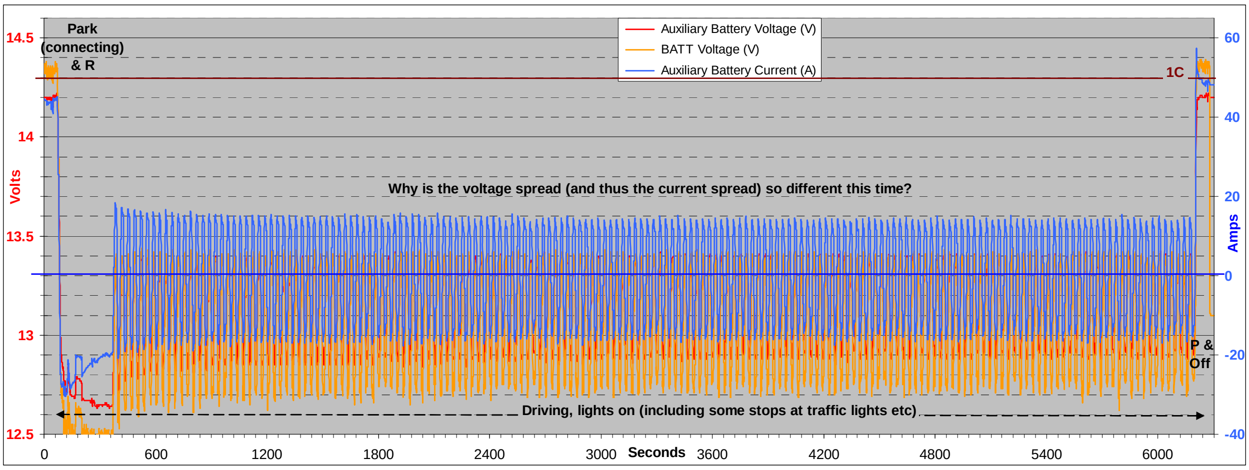


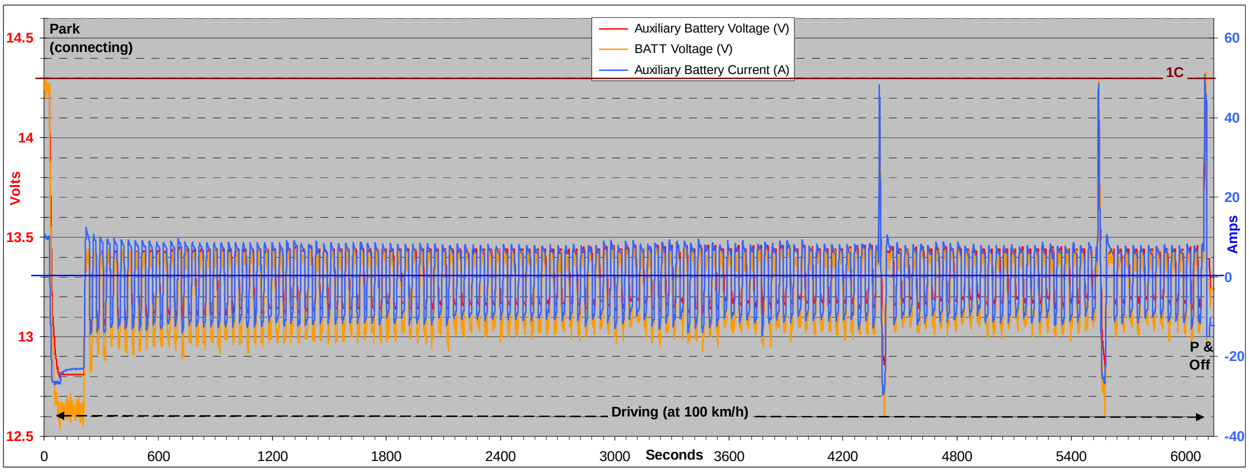
Typically it ‘gets over’ this problem behaviour (gives some charging) within ~5 min of driving.

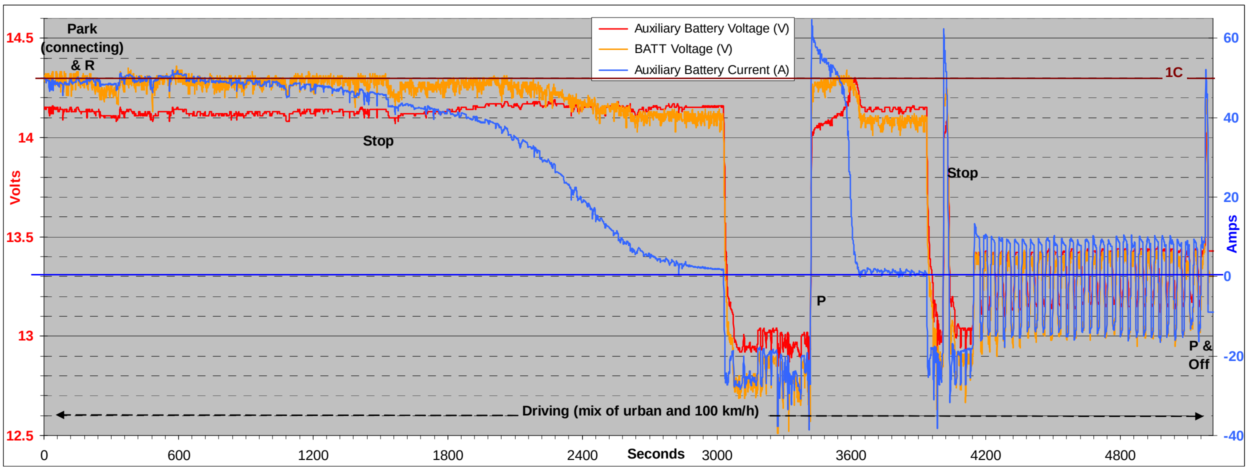


After looking at many logs, I am still unable to fully understand or predict rav4 hybrid auxiliary battery charging. Behaviour at the start of a drive is highly variable, but it often includes a period of serious battery discharge. Strange things can happen mid-drive. Under my conditions (with many long drives), the LFP auxiliary battery stays charged and does not increase in temperature while charging (from an SOC that keeps current <1C). It is too early to know about battery life.


Park
(connecting)
& R
Auxiliary Battery Voltage (V)
BATT Voltage (V)
Auxiliary Battery Current (A)
1C
Why this spike?
75-100km/h
What is this?
All at 100km/h
P &
Off
Headlights on, a few rain spits but no wipers from memory, no cruise
Driving
Volts
Amps
Seconds
14.5
14
13.5
13
12.5
60
40
20
0
-20
-40
0
600
1200
1800
2400
3000
3600
4200
4800
5400


Park
(connecting)
& R
Auxiliary Battery Voltage (V)
BATT Voltage (V)
Auxiliary Battery Current (A)
1C
Why is the voltage spread (and thus the current spread) so different this time?
P &
Off
Driving, lights on (including some stops at traffic lights etc)
Volts
Amps
Seconds
14.5
14
13.5
13
12.5
60
40
20
0
-20
-40
0
600
1200
1800
2400
3000
3600
4200
4800
5400
6000


Park
(connecting)
Auxiliary Battery Voltage (V)
BATT Voltage (V)
Auxiliary Battery Current (A)
1C
P &
Off
Driving (at 100 km/h)
Volts
Amps
Seconds
14.5
14
13.5
13
12.5
60
40
20
0
-20
-40
0
600
1200
1800
2400
3000
3600
4200
4800
5400
6000


Park
(connecting)
& R
Auxiliary Battery Voltage (V)
BATT Voltage (V)
Auxiliary Battery Current (A)
1C
Stop
Stop
P
P &
Off
Driving (mix of urban and 100 km/h)
Volts
Amps
Seconds
14.5
14
13.5
13
12.5
60
40
20
0
-20
-40
0
600
1200
1800
2400
3000
3600
4200
4800

In some cases (Avalon) Toyota uses BATT for a terminal (G47-3) of the hybrid vehicle control ECU (to which Auxiliary battery power is supplied), also called System Voltage.
http://www.tavalon.net/2536/system_voltage_batt_circuit_short_to_ground_or_open_p056014_.html

In ICE vehicles (Tacoma) Toyota distinguishes Battery Voltage, BATT Voltage and Alternator Voltage, with specified range for BATT Voltage = Alternator Voltage >> Battery Voltage.
http://www.ttguide.net/data_list_active_test-697.html

Other Toyota (CH-R) documents distinguish BAT from BATT, but not in terms of sensors or sources; and elsewhere gives +B Voltage as Battery voltage (BATT terminal)! Meaning seems to vary.
https://www.tochr.net/904/how_to_proceed_with_troubleshooting.html
https://www.tochr.net/912/data_list_active_test.html

What About Traction Batteries?

Toyota has mostly used NiMH traction batteries in hybrid vehicles, but a few Prius models used 'Li-ion' traction batteries and more models changed to Li-ion from 2021. Toyota is coy about which Lithium chemistry is used (LCO LMN, LFP, LTI; flammable liquid, non-flammable liquid, or gel electrolyte?). By contrast, the same company is happy to issue press releases about its research investment in a future solid-electrolyte Lithium battery technology.

Several operators offer LFP replacements for Toyota NiMH traction battery packs. As far as I can see, they provide no information relevant to expected life of their products when installed as recommended. From what I see, the testing has been relevant to safety (under conditions specified by CE, IEC, UN38.3), which tells us almost nothing about longevity (cycle or calendar life) when installed in a hybrid vehicle. For example, the charge test seems to use a controlled current (5A) and fixed voltage power pack. To my knowledge, that is not the way a Toyota hybrid car works. The car will supply current according to the resistance of the battery pack, up to whatever limits are inherent in the generator, HV converter and charge control circuits. At low SOC, this will be a lot more than 5A. I have seen more than 130A in routine charging of NiMH. LFP charging is very efficient, but not 100% efficient, and the inefficiency results in heating. What temperature might be reached inside the LFP cell within a car traction battery under the repeated charge and discharge cycles of prolonged urban driving? Will an air-cooling system programmed for more heat-tolerant NiMH prevent temperatures that reduce life of LFP?

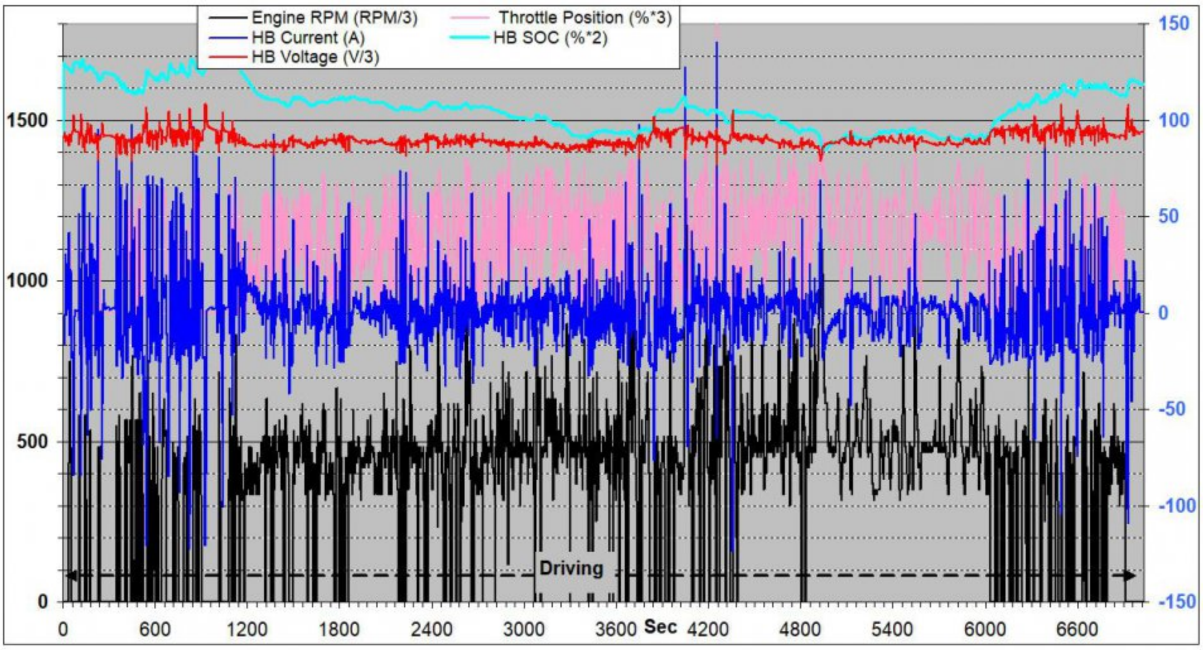
Given that the capacity is 6.5Ah, why does the advertising say '(Our) lithium battery delivers 260Amp peak power'. Is the battery rated for 40C during discharge? If not, this high rate would be bad for LFP battery life. Is the car NiMH high voltage system rated for the peak discharge and charge currents expected from a LFP traction battery? If not, it is probably bad for life of the car high voltage system. Of course Amps measure current, not power; so maybe the advertiser has a voltage other than the battery voltage in mind. This would need to be specified for the '260Amp peak power' claim to be meaningful.

Does the suggested installation use all of the car high voltage battery temperature sensors? Does the NiMH charge control algorithm use this temperature information in a way optimal for LFP? Does the NiMH charge profile suit LFP? How is charge termination accomplished? Could it keep charging beyond 0.02C? Could charge current ever exceed 1C? Could battery temperature ever exceed 40ºC? Could charging ever occur below 0ºC? Any of these would be bad for LFP battery life.

A good LFP battery BMS (=PCM) can be designed to shut down charge or discharge under unsafe conditions, but (a) these conditions should be specified to potential users; and (b) this shut-down is a good last line of defence, it still needs to be combined with a charging system that is designed for charging profiles that suit LFP (which are different from those designed for NiMH). It would also be good to specify whether the BMS manages cell balancing; and if so how.

Some batteries designed for special purposes (like RC aircraft) can have very high C ratings. "Often there are two C-Ratings printed on one battery – e.g. 45 / 80 C. The first specification (45 C) describes the so-called continuous current, which the battery can deliver permanently without being damaged. The second value (80 C) describes the maximum peak current that should be drawn from the battery." (*https://www.drone-zone.de/battery-guide-what-does-the-c-rating-of-lipo-batteries-stand-for/*). There must be a trade-off in things like price and longevity, but no doubt the specialist users understand those factors.

Here is a (1 second interval) log from my rav4 hybrid. Everything except engine rpm is on the right Y axis. Hybrid battery current (dark blue) does move around quickly, and it varies between approx +/- 130 Amps (with HB SOC from 42-70%). Cooling is shown elsewhere. I guess Toyota spent some serious research effort coming up with battery control and cooling algorithms that allowed their 10 year warranty on NiMH and Lithium traction batteries; but we are not told those algorithms. I think they almost certainly must differ for NiMH and Lithium; in general a change from Lead Acid to NiMH or NiMH to Lithium is not a 'drop in replacement'.



Traction battery life is a valid concern of hybrid car owners given the $ and environmental cost of traction batteries. It makes business sense for an intended long-term seller to give relevant specs to potential buyers. For 12V LFP batteries, examples of what I consider minimal and comprehensive specs from reputable companies are at:
https://www.renogy.com/content/RNG-BATT-LFP-12-170/LFP50100170-Manual.pdf and
https://www.power-sonic.com/wp-content/uploads/2020/07/PSL-12500-technical-specifications.pdf

The relevant details would be slightly different for a traction battery, but there is a lot of overlap. If a seller chooses not to provide specs relevant to longevity as well as safety in the recommended use, let the buyer beware. Provision of convincing specs may require some performance of tests in a car, but much can be deduced from published scientific testing of LFP. Ten years is a long time to wait for experience about longevity from enthusiastic early adopters.