Hybrid Battery Cooling

Summary

All hybrid vehicles need some form of cooling of the traction battery. In the case of cars with a NiMH battery pack under the rear seat, this is typically accomplished by control of a fan that blows air from the cabin over and through the battery pack. This involves some compromises between fan noise in the cabin and battery cooling. This article uses logs from sensors in a 2019 (gen5) Rav4 hybrid to show some features of the hybrid battery temperature control system.

Why is Cooling Needed?

Hybrid cars use an internal combustion engine (ICE) along with electric motors driven by a rechargeable battery (traction battery) of substantial capacity. The traction battery capacity and chemistry varies between car models, but NiMH and LFP batteries predominate in 2021. While the car is driven, these traction batteries undergo repeated cycles of partial discharge (to drive the electric motors, which contribute to driving the wheels) and recharge (from a generator driven by the ICE and often also by regenerative braking). These processes are not 100% efficient, so some energy is lost as heat in the traction battery, which therefore increases in temperature. LFP batteries are quite temperature-sensitive (most should not be run above 40ºC) and many cars with LFP traction batteries use a system with a radiator and circulating liquid to cool the battery. NiMH batteries can be designed to tolerate higher temperatures (*https://industrial.panasonic.com/cdbs/www-data/pdf/ACG4000/ACG4000COL12.pdf*), but battery life will still probably be shortened by use above 50ºC. Many cars with NiMH traction batteries use air from the cabin, driven over and between the battery modules to cool the battery, as in the gen5 Toyota Rav4 examined here.

Slight overheating of a traction battery will not cause immediate failure, but heat accelerates many chemical reactions, including adverse reactions in rechargeable batteries, so there is a likelihood of additive effects that eventually shorten battery life. It is difficult to be more precise about this in a concise analysis, because there are so many combinations of parameters, and not so many documented analyses. But traction batteries are expensive (both to the owner and the environment), so it is worthwhile to control their temperatures below levels that are likely to shorten operational life.

Control of Hybrid Battery Cooling

Because the traction battery is in a confined space (under the rear seat in many cases) air for cooling must be driven by a fan (also called a blower). This creates some conflicting demands:

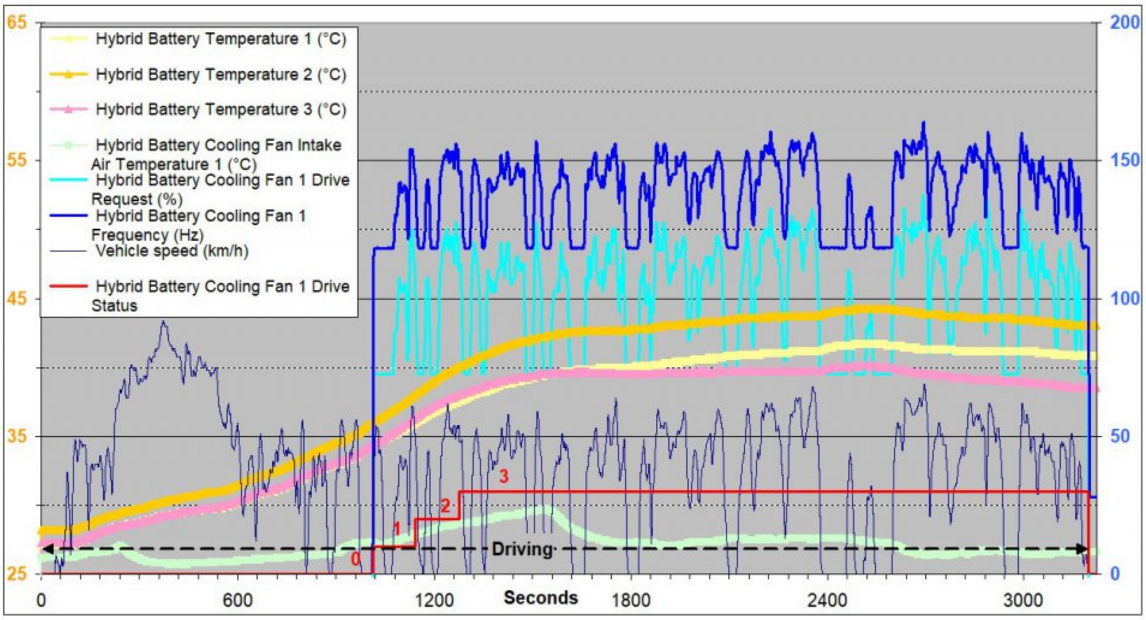
1. The fan will have a life, depending substantially on how fast and how long it is run.
2. The fan will use energy (from the ICE / generator / traction battery) and produce heat, depending substantially on how fast and how long it is run.
3. Cabin air may not be perfectly clean, resulting in blockage of the fan filter, blades or ducts over time, unless appropriate maintenance is applied.
4. While running, the fan may be audible in the cabin, depending on how fast it is run and the amount of ‘masking’ noise in the cabin while the fan runs.
5. Cooling of the hybrid battery will depend on cabin air temperature, any restrictions in the air path, and how fast and long the battery cooling fan is run.

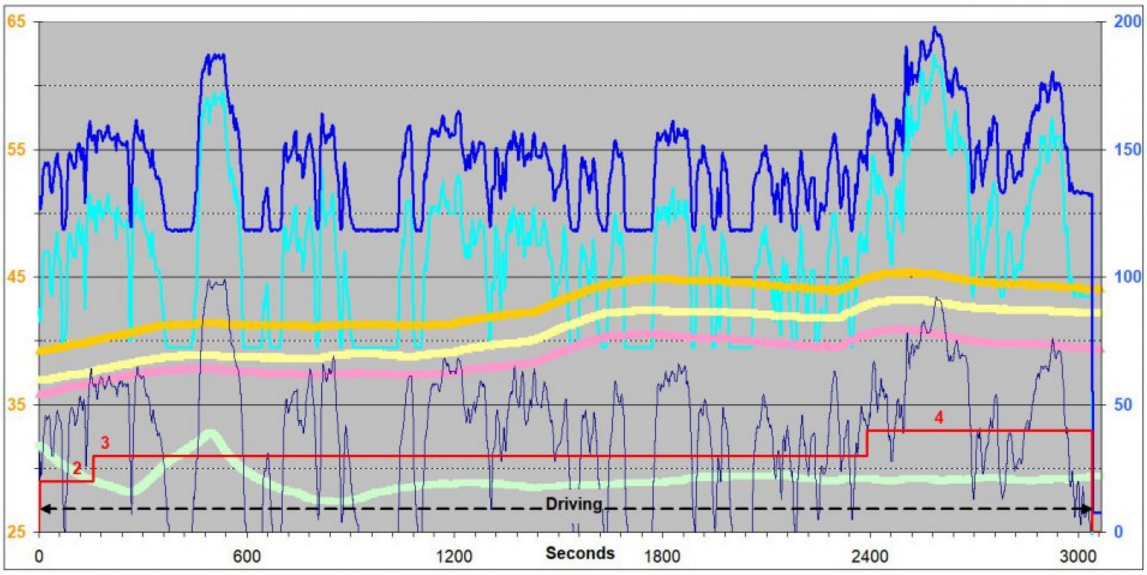
Car manufacturers design algorithms for cooling fan operation, based on input from multiple sensors, in an attempt to balance these conflicting demands. Typically there is only one algorithm per car model, and this algorithm is neither revealed to nor adjustable by car owners. Typically, if one or more of the sensors indicates a problem (something outside the design parameters set by the manufacturer), the driver is notified by a warning, usually a symbol on the dashboard display.

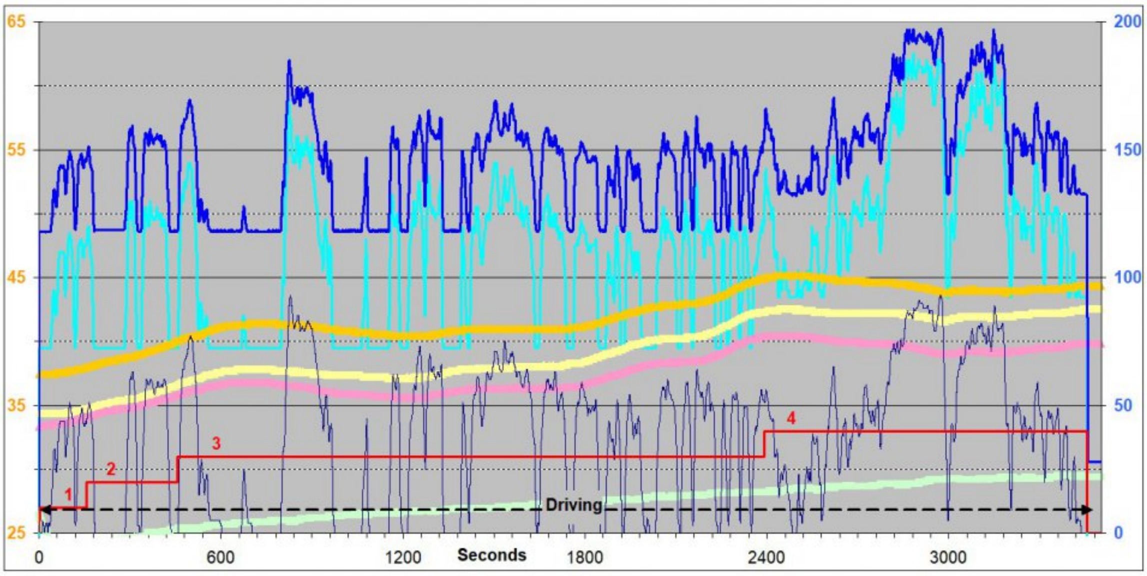
Some owners question whether the (unknown) compromise decided by the car manufacturer best suits their individual driving conditions, and some owners implement non-OEM methods of cooling fan control. For example, some owners use OBD software to drive the fan continuously at a moderate or high speed when the vehicle is on. Others swap to a higher-capacity fan which may use user-programmable control parameters. Sometimes these decisions are triggered by an adverse experience or by a perception that individual driving conditions (eg hot and mountainous terrain; picnic stops or parking in the sun) may be outside the range of the OEM design. But from what has been published, they are rarely preceded by analysis of what is happening with the OEM-designed system; though such analysis is cheap, simple and within the ability of most interested car owners as described below.

Logs and Interpretation from the 2019 Rav4

I have used OBDLink software with an MX+ OBD interface to log parameters relevant to hybrid battery cooling in a 2019 (gen5) Toyata Rav4 hybrid. As discussed elsewhere (*https://scithings.id.au/OBD_PID.pdf*) OBDLink is an inexpensive and convenient option for many car owners. Some typical logs are shown below. All temperatures (ºC) and ‘Hybrid Battery Cooling Fan 1 Drive Request (%)’ are plotted on the left Y axis. Vehicle speed (km/h) and ‘Hybrid Battery Cooling Fan 1 Frequency (Hz)’ are plotted on the right Y axis.







If I am interpreting the logs correctly, at cabin temperatures of 25-30ºC, the cooling fan is activated when 'Hybrid Battery Temperature' reaches ~35ºC. The fan ('Hybrid Battery Cooling Fan 1') runs between 120-200 Hz, maybe more if things get hotter. As detailed below, this is probably equal to 1800-3000 rpm.

Fan speed is controlled by 'Hybrid Battery Cooling Fan 1 Drive Request' (which seems to operate between 40-63%, maybe more if things get hotter), combined with 'Hybrid Battery Cooling Fan 1 Drive Status' (which can range from 0=off to at least 6).

As far as I can see, Hybrid Battery Cooling Fan 1 Drive Status responds in steps to Hybrid Battery Temperature. If the temperature is rising only slowly when status 1 first activates, the fan speed remains 'minimal'. Otherwise, I can not see any effect of fan drive status from 1-3 on the way fan speed is controlled by fan drive request. When the car is stopped (in READY), the fan drive request increases from 39.5% at fan drive status 3 to 43.5% at fan drive status 4.

The resemblance between the patterns of car speed and fan speed is striking. Fan drive request (and thus fan speed) drops to a low level when the car stops, then ramps up with car speed. This is the method used to keep cooling fan noise from becoming intrusive, as it is masked by other (engine and road) noise at higher car speeds (*https://www.jstor.org/stable/26562342*). The trade-off is that cooling is reduced in stop-start traffic, when it may be needed.

At all car speeds, the ratio of fan speed to fan drive request is higher at fan drive status 4 than at fan drive status 3. At any given fan drive status, fan speed increases in linear proportion to fan drive request. Both increase in approximate proportion to the logarithm of car speed above 20 km/h (I do not know the exact algorithm).

At a cabin temperature up to 30ºC, the cooling fan at the automatically selected fan drive status 4 kept the gen5 Rav4 hybrid battery temperature below 45ºC under these moderate (non-towing, non-mountainous) driving conditions. The system has some headroom (fan drive status 5-6) if needed.

From specs of replacement blowers, the reported value from the fan tachometer 'Fan Frequency' is most likely 4 times the speed of physical fan rotation. Thus cooling fan rpm = 'Fan Frequency (Hz)' * 60/4 or, put another way, cooling fan rpm = Hz * 15. At a reported 200 Hz, the cooling fan is probably working at a reasonable 3000 rpm. There are various ways to sense motor speed in Hz, using optical or Hall effect or back-EMF or magnetic sensors (*https://www.digikey.com/en/articles/how-to-power-and-control-brushless-dc-motors*).
Cooling (heat transfer coefficient) is unlikely to have a linear relationship to fan rpm (*www.offroadvw.net/tech/wes/fan.html*), but cooling will increase if fan speed increases. Reporting on fan rotation is an improvement on reporting fan voltage (as in some earlier models), as the input voltage did not tell us whether the fan was rotating in response.

DC fan speed control typically uses voltage for brush and commutator motors; and PWM for brushless motors. I assume that 'Hybrid Battery Cooling Fan 1 Drive Request' in the gen5 Rav4 uses PWM, but I don't know what Toyota or other HV manufacturers used in each model and year.

In cold climates, the hybrid fan control system may perform another function: circulating heated cabin air over the cold battery to bring it up to preferred operating temperature. I do not have any experience with this.

It is reasonable to wonder where the air blown over the traction battery goes next. For cooling efficiency and occupant comfort, it makes sense to have this (heated) air leave the vehicle, at least when conditions are warm. I have not pulled the Rav4 hybrid apart to understand the hybrid battery cooling air flow, but from what I can see it does not have an exhaust duct to the auxiliary battery area (as in some Prius models). I assume that the blown air mostly stays in the volume under the rear seat and behind the luggage compartment trim, and exits the vehicle via the vent with rubber flap into the exterior behind the rear left quarter panel. This vent is visible from the luggage compartment if the inspection port at rear left is popped. The same vent is variously said to cater for egress of air blown into the vehicle (to keep the occupants awake) and when the hatch or doors are closed. If the same vent serves all of these functions, there must be substantial leakage between the main cabin and the volume under the luggage compartment trim. Another consequence might be that hybrid battery cooling worked more efficiently with the fresh air vent open, to provide some positive pressure and replenish air leaving the vehicle via the hybrid battery cooling stream.

I took the gen5 rav4 hybrid for a drive (in Eco mode) to Lowood (flat) over Mt Glorious (Up, elevation ~600 m) and back to Brisbane (Down), while logging.

Some PIDs were not what I guessed from their names, so I did not plot them. In case anyone is interested the parameters on the left Y axes are Auxiliary Battery Voltage, (System?) BATT

Voltage, all Temperatures (ºC), Hybrid Battery Cooling Fan 1 Drive Request, Engine RPM and HV System Indicator (which is named as a %, but clearly is not: it ranges to >1000 but the unknown units do not really matter). All the others are on the right Y axes of course, except Hybrid Battery Cooling Fan 1 Drive Status which gets its own labels. Note that some parameters are scaled as specified, to be revealing in the plots.

The hybrid battery is ‘shut down’ at times (hybrid battery current near 0 and HV system indicator below 100 in the ‘lower’ graphs) but this does not depend on Hybrid Battery Temperature alone. It happened at times on the flat (when the battery was still cool) as well as up- and down-hill. Around town, the same condition is often obvious in the graphs when the car is stopped.

As can be seen ‘between’ the graphs, and depending on previous driving conditions, hybrid battery temperature may increase by a few degrees after the car is parked (which turns the cooling fan off), then gradually drop to cabin temperature. When parked in the sun, cabin air temperature will rise faster, but given enough time the hybrid battery temperature will equilibrate with it.

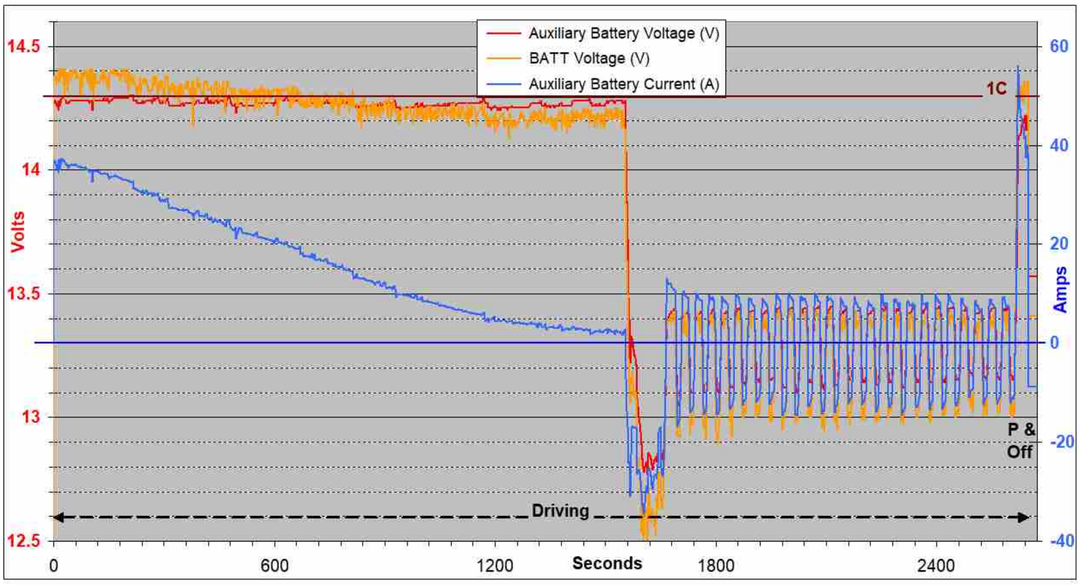
4WD was used often and seamlessly in ascent (on a good bitumen road suitable for 2WD). Rear wheel drive in the rav4 HV is entirely electric. As can be seen in the graphs, hybrid battery SOC was reduced at times, but the car evidently took opportunities to recharge as they arose. The control algorithms probably vary for different models and surely for different battery chemistries. For a (NiMH) gen5 rav4 HV, HB2 at 46ºC is not a problem, provided a blocked filter or other fault does not interfere with cooling as intended while driving. HBCF Drive Status seems to be programmed with the aim of keeping HB2 temperature between 40ºC and 46ºC, though even 46.5ºC did not trigger Drive Status 5. Some say this requires >50ºC, which would be a bit hot for my liking. Others say that EV mode stops at ~42ºC and HB charging stops above ~46ºC (depending on SOC; if charging stops, motor drive will soon stop).

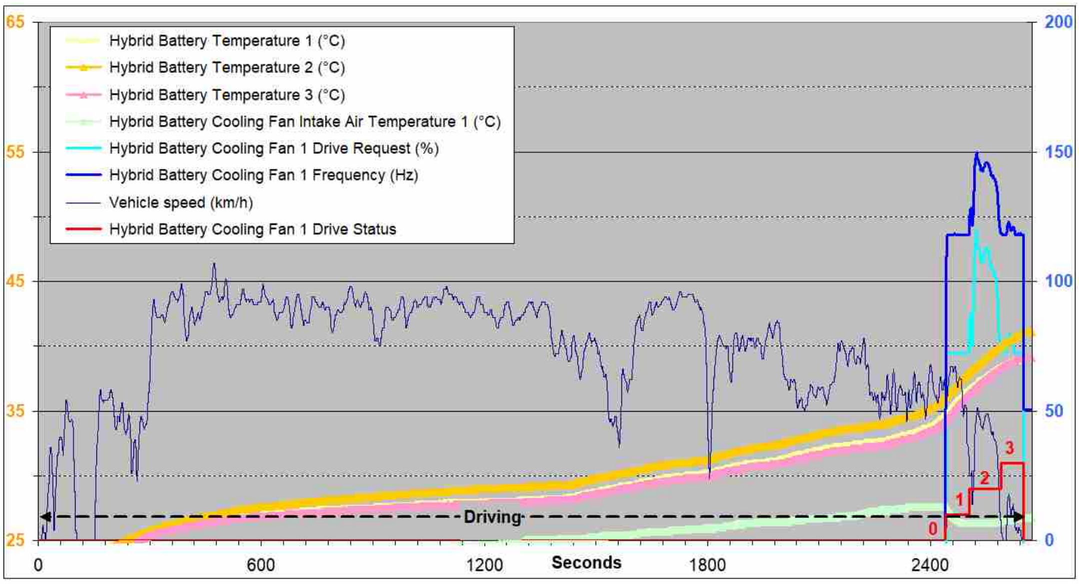
The rav4 HV is probably not a vehicle for prolonged, low speed, uphill, off-road driving. I have previously tested it in ‘Trail Mode’ (without OBD logging) on a very steep, rough gravel, 4WD-only track and it performed admirably (considering the stock tyres, limited clearance and limited wheel articulation). But it may overheat something if this is kept up for too long (which should trigger a warning on the dash). I vividly recall that coming back down was more hair-raising. The car has no descent control function and no substantial (off-road type) engine braking, even when low gear is selected; so brake early and continuously to descend very slowly and securely. Of course the rav4 is not designed to be a serious ‘off-roader’; it is a ‘soft-roader’ (even if it is marketed as an ‘adventure vehicle’).

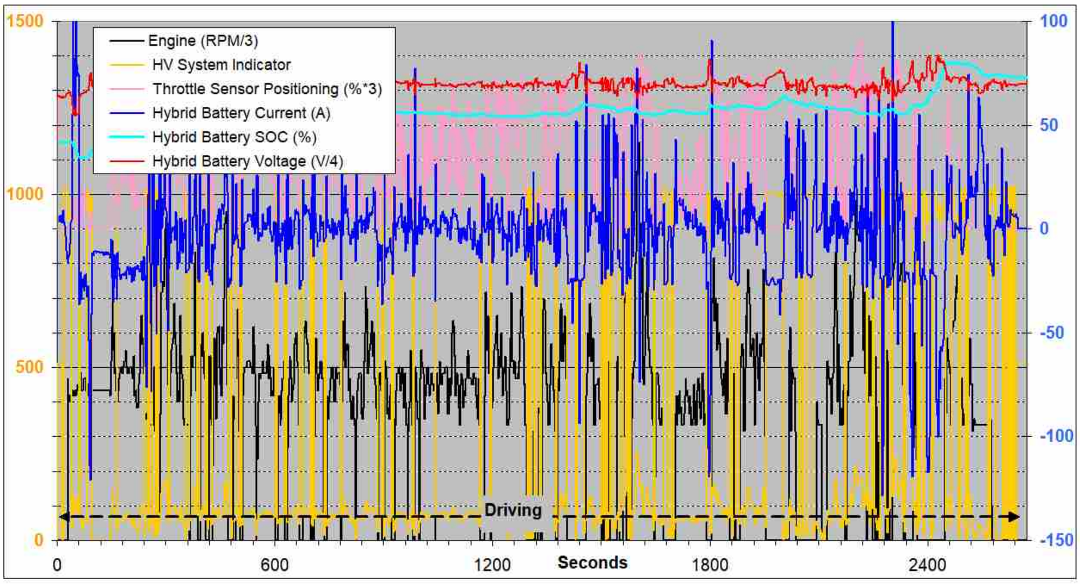
I am not a great fan of the Dr Prius app, but version 5.29 reads everything it offers (including HB current) correctly from the 2019 rav4 HV. For those who are sure that Toyota’s design does not suit them, the app has a function to override default fan thresholds. It is not necessary to go bonkers, a slight change in activation temperature is possible. But if Dr Prius behaves like Hybrid Assistant, it will jump to HBCF drive status 6 as soon as the set temperature is reached. Also, it is probably necessary to keep the app connected for a permanent effect. The capability was originally intended to help with traction battery warming in very cold climates, but it has been ‘adopted’ for other purposes. Some owners have hot-wired such an override, but I don’t recommend it.

Personally I am happy to leave the complex algorithm behind the HV battery to the engineers who designed it, but the graphs may help as a reference set for others. Here they are:

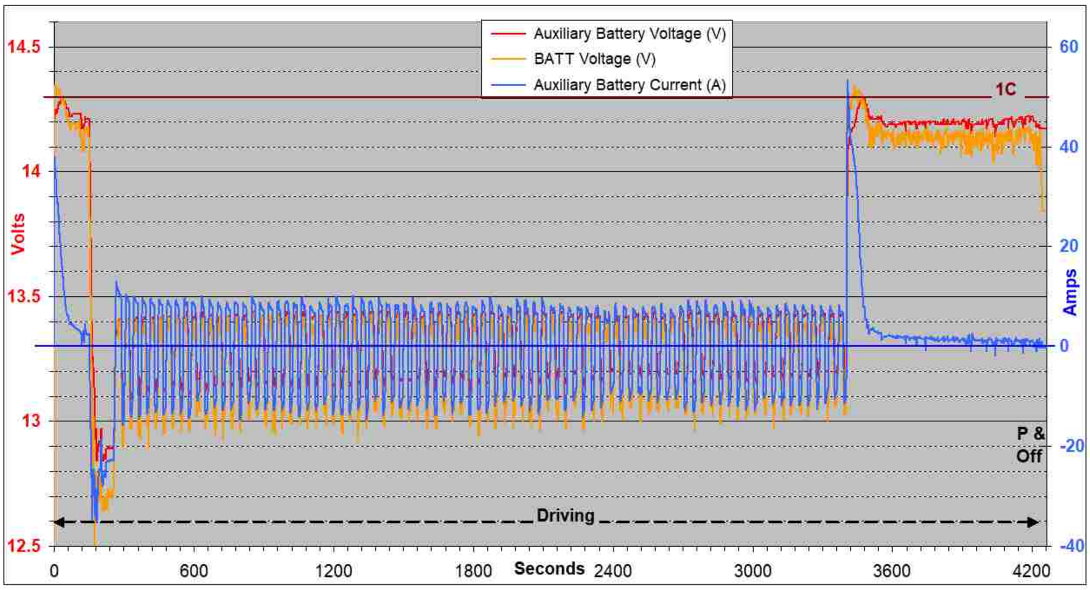
Flat

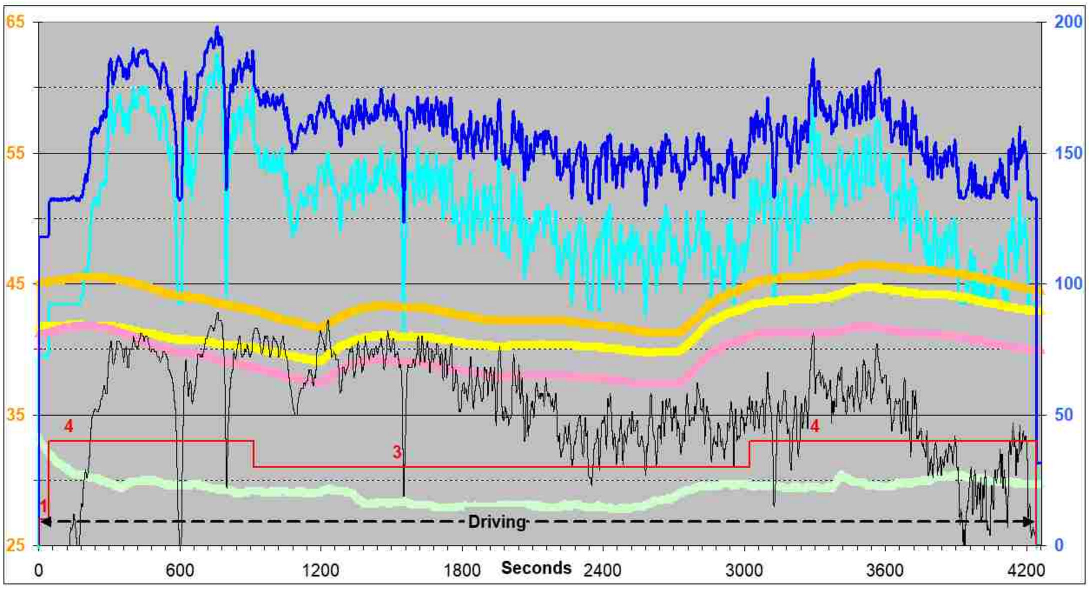

Auxiliary Battery Voltage (V)
BATT Voltage (V)
Auxiliary Battery Current (A)
14.5
14
13.5
13
12.5
Volts
60
40
20
0
-20
-40
Amps
1C
P &
Off
Driving
0
600
1200
Seconds
1800
2400

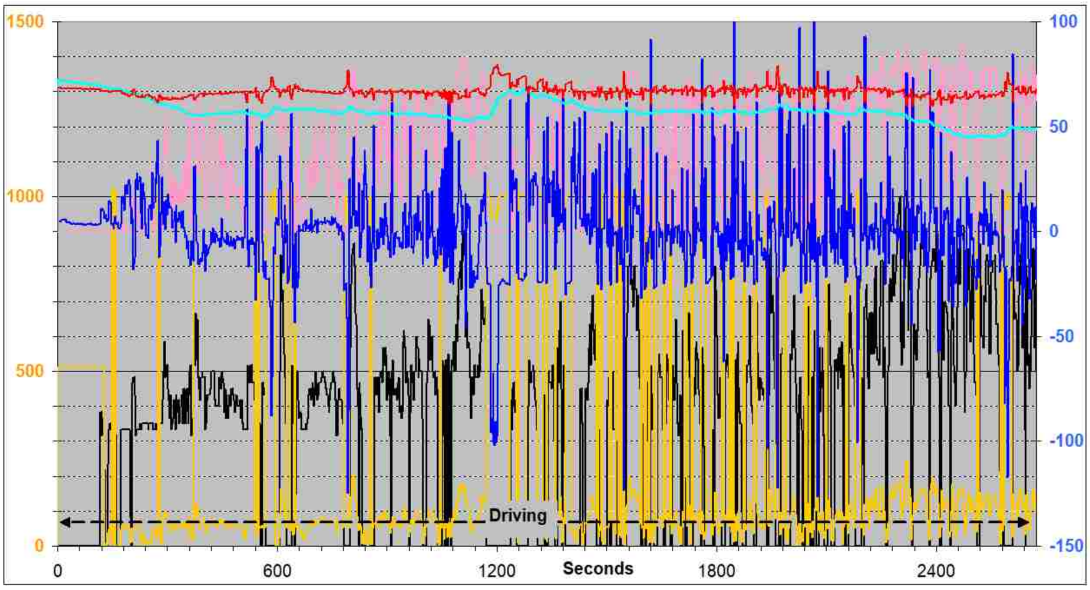

Hybrid Battery Temperature 1 (°C)
Hybrid Battery Temperature 2 (°C)
Hybrid Battery Temperature 3 (°C)
Hybrid Battery Cooling Fan Intake Air Temperature 1 (°C)
Hybrid Battery Cooling Fan 1 Drive Request (%)
Hybrid Battery Cooling Fan 1 Frequency (Hz)
Vehicle speed (km/h)
Hybrid Battery Cooling Fan 1 Drive Status
65
55
45
35
25
200
150
100
50
0
0
1
2
3
Driving
0
600
1200
Seconds
1800
2400


Engine (RPM/3)
HV System Indicator
Throttle Sensor Positioning (%*3)
Hybrid Battery Current (A)
Hybrid Battery SOC (%)
Hybrid Battery Voltage (V/4)
1500
1000
500
0
100
50
0
-50
-100
-150
Driving
0
600
1200
Seconds
1800
2400

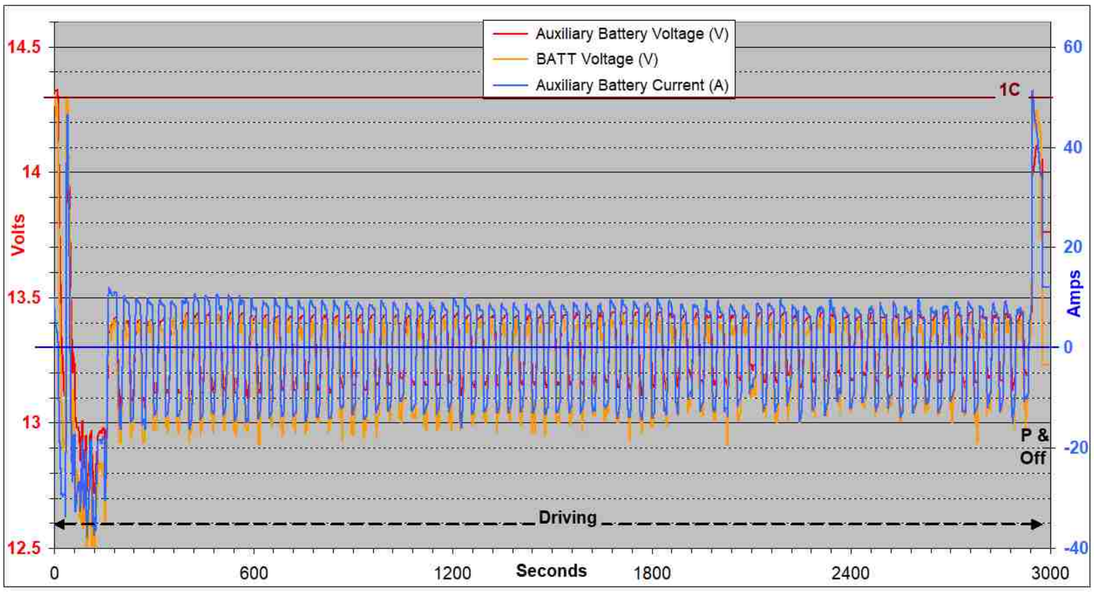
Up (after 50 min parked in the sun)

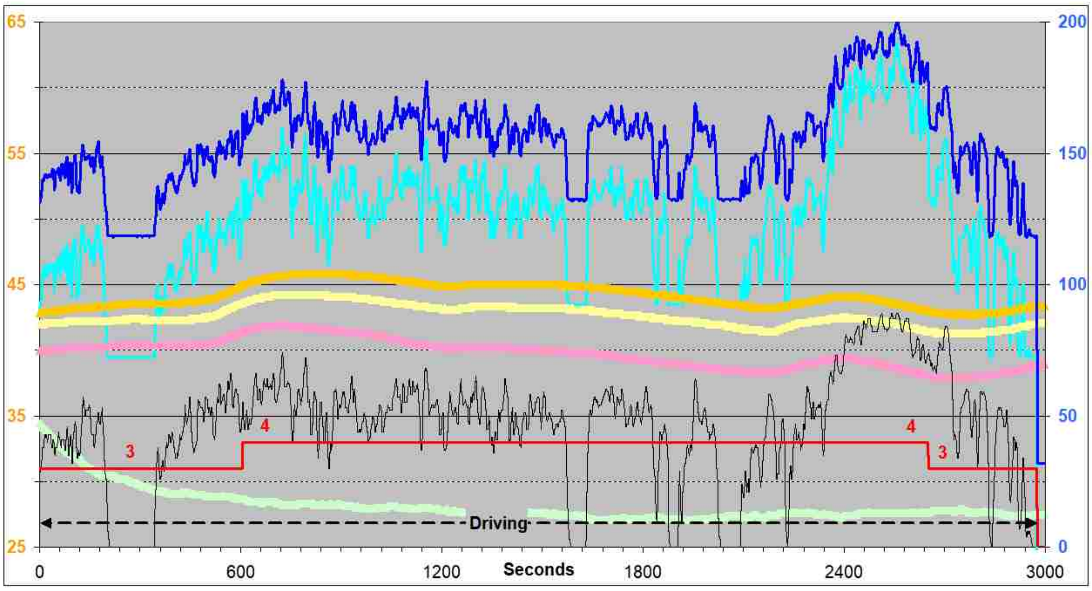


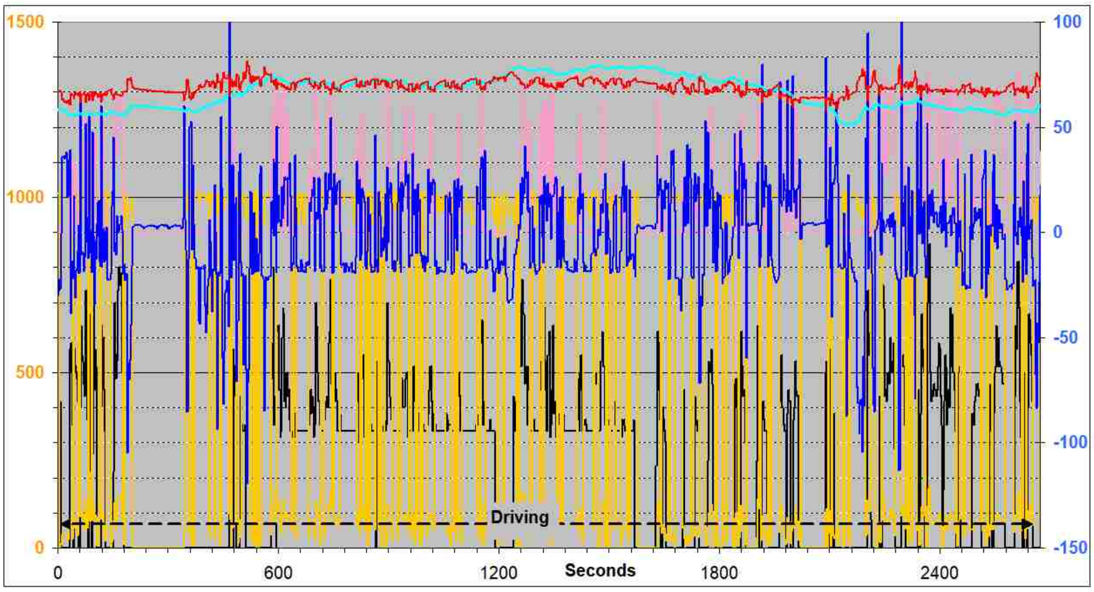




Down (after 60 min parked in the sun)

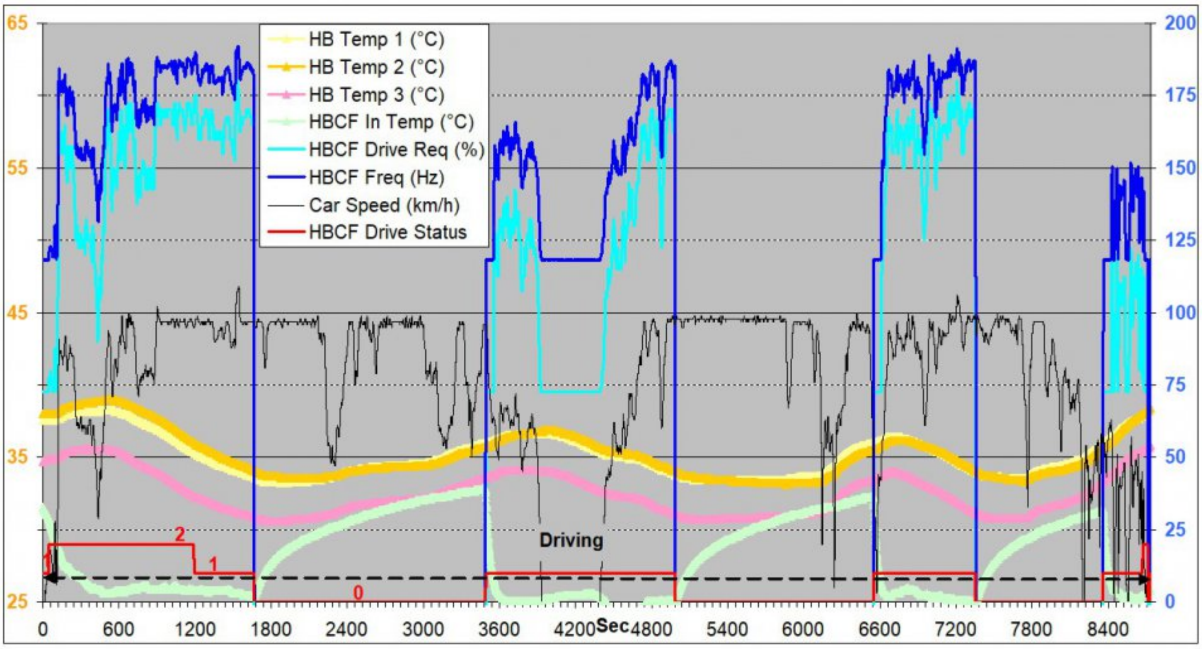






The patterns will be different for those who drive at different ambient or cabin temperatures, and for those who run a high fan speed continuously. When this is justified by the observation that fans are cheaper than batteries, I wonder "What will they do when the fan fails prematurely (as it surely will when used far outside of its design parameters) and they are days from home and hundreds of kilometres away from any chance of mechanical service?"

Here is another interesting (and unexpected to me) effect. When highway cruising, the car easily keeps the hybrid battery cool, but the interesting thing is that with the aircon set to Auto (in Eco mode) it automatically reduces the cabin temperature while it is cooling the hybrid battery. Maybe you thought 'climate control aircon' meant that it controlled constant temperature for passenger comfort; but it is regulating cabin temperature according to feedback from the HB temperature sensor. Nobody touched the aircon controls. The stop in the middle was at roadworks. Now you know why you sometimes feel cooler than at other times. Once you know what to look for, the effect is apparent even in urban driving.



Here are the HB2 temperatures at which changes to fan drive status occurred:

Hybrid Battery Cooling Fan 1 Drive Status	On (°C) Rising Temp	Off (°C) Falling Temp
0 (off)	--	--
1*	36	34
2*	38	36
3*	40	38
4	45	43
5	≥47	
6		

* No change observed in fan speed from status 1-3 (increased at status 4).

NiMH vs LFP Traction Batteries

I assume that Toyota uses a different cooling (and charging) algorithm in cars with 'Li-Ion' traction batteries, though nobody has contributed logs to confirm this. Toyota does not reveal what Li chemistry is used, though the dismantling guides for emergency workers indicate use a liquid organic electrolyte (so it is probably an older chemistry than LFP).

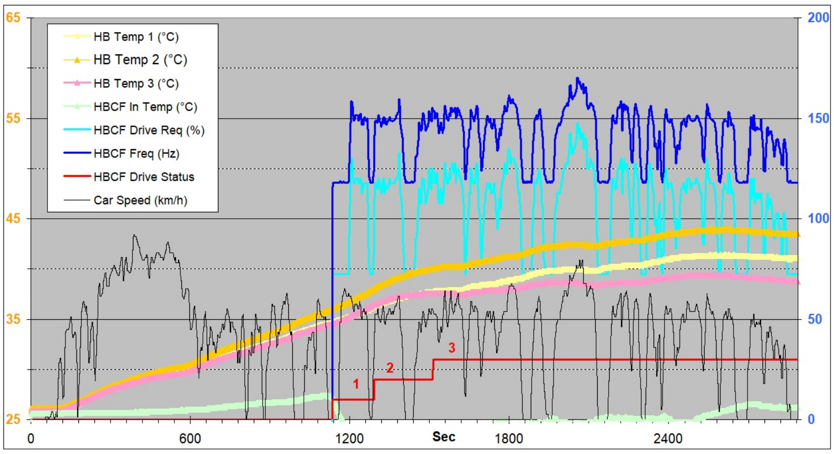
NiMH batteries show reduced cycle life at elevated temperatures (*https://en.globtek.com/nimh-battery-safety-notes*). NIMH variants with improved performance at elevated temperatures have been developed (eg *https://industrial.panasonic.com/cdbs/www-data/pdf/ACG4000/ACG4000COL12.pdf*), but it is not stated whether this includes cycle life. Most reputable manufacturers (eg *https://www.power-sonic.com/wp-content/uploads/2020/07/PSL-12500-technical-specifications.pdf*) and experienced users (eg *http://nordkyndesign.com/category/marine-engineering/electrical/lithium-battery-systems/*) consider that LFP suffers more than NiMH or LA from reduced cycle life at elevated temperature. However, LFP is very efficient, so it may heat less during cycling than NiMH. I have yet to see any evidence of an LFP variant with improved performance at elevated temperatures. Therefore, I treat claims of LFP packs suitable as 'drop in replacements' for NiMH traction battery packs with caution. Unless the charging and cooling algorithms are altered to suit LFP, it is hard to believe that these will provide a life span matching the 10 years expected of OEM NiMH traction batteries.

Temperature and ICE vs Battery

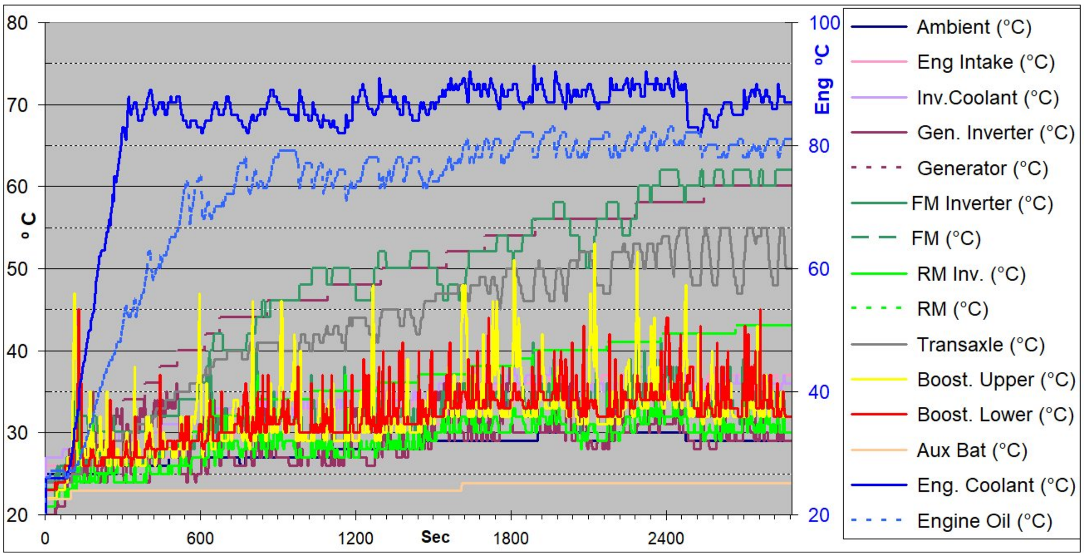
In PriusChat threads, SmellyTofu and alanclarkeau mentioned that temperature can have a big effect on the use of ICE vs traction battery (motor) to drive the wheels. In other words, hybrid torque strategy (eg Miller 2006, Liu 2008, Najem 2021) changes with temperature. This is reasonable; because ICE, traction battery, inverters and EMs all need temperature management. Thermal management involves control of power drawn from the device; and/or removal of heat, which consumes energy. An effect on torque strategy may be either direct (a temperature parameter in the hybrid system control algorithm) or indirect (eg increased temperature reduces traction battery charging more than discharging, so SOC decreases, causing an increase in the ratio of ICE:EM drive torque). It may also be predictive (eg Yang 2021).

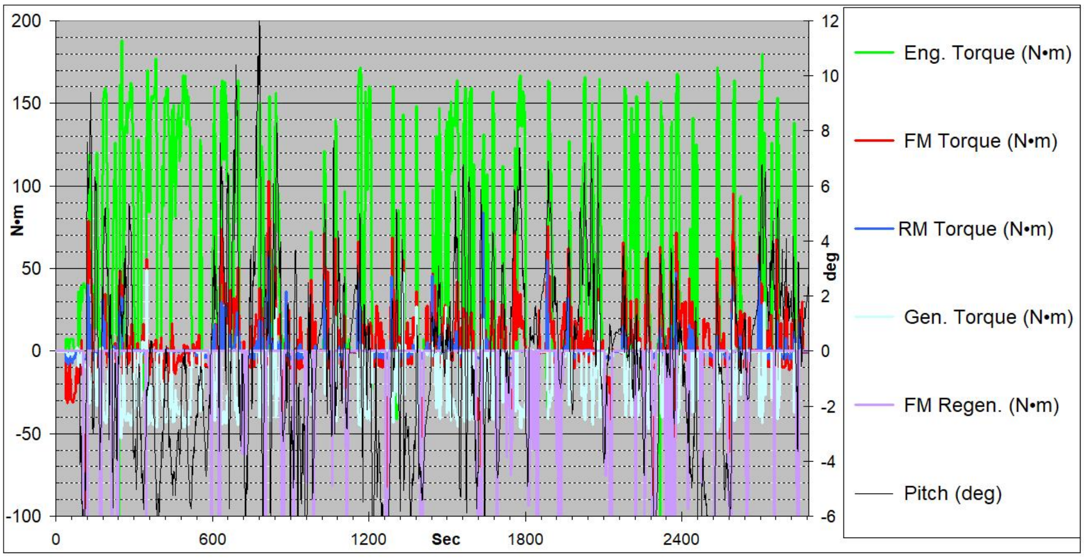
To assist in this analysis, I logged various temperature and torque PIDs in a rav4 hybrid AWD, using OBDLink. I could not find enough power PIDs to make that comparison (and too many assumptions were required to calculate power from torque * rpm). There are lots of other temperature PIDs, some of which are initial or maximum temperatures at specified locations.

I am uncertain whether torque is measured or estimated (mapped), and whether it is specified at the same place for the ICE and motors. If torque is specified at the output of each device, effects at the wheel are not easily comparable. Each device torque would then need a correction for gear ratio for equivalence to an axle torque. EM : axle gear ratios are fixed, but the three motor-generators are not always powered. Similarly, the ICE can be turned off. It can be confusing that the torque split between generator and axle from the ICE considered alone is fixed, but the ratio of ICE rpm to wheel rpm can be varied (by control of MG1), so the effective gear ratio of axle drive from the ICE is varied.

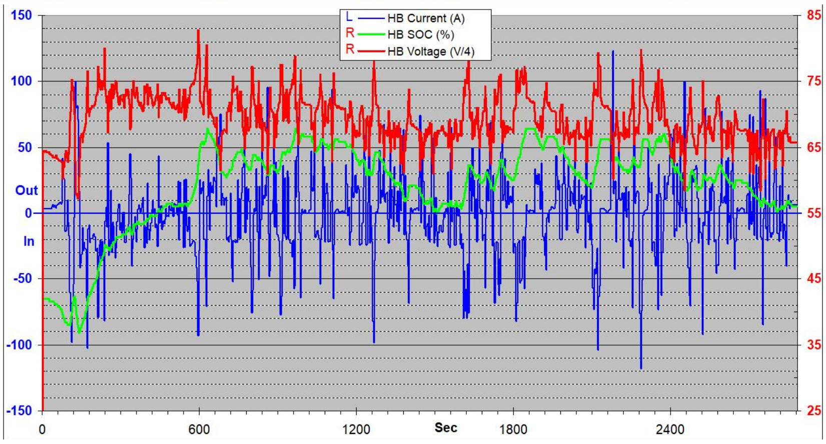


The car drive computer and planetary gearbox together vary the delivery of (front wheel) power and torque from ICE and MG2. It is designed to run ICE at efficient rpm (if possible given acceleration demand). The computer also calls on MGR for more power and torque (4wd) as required.

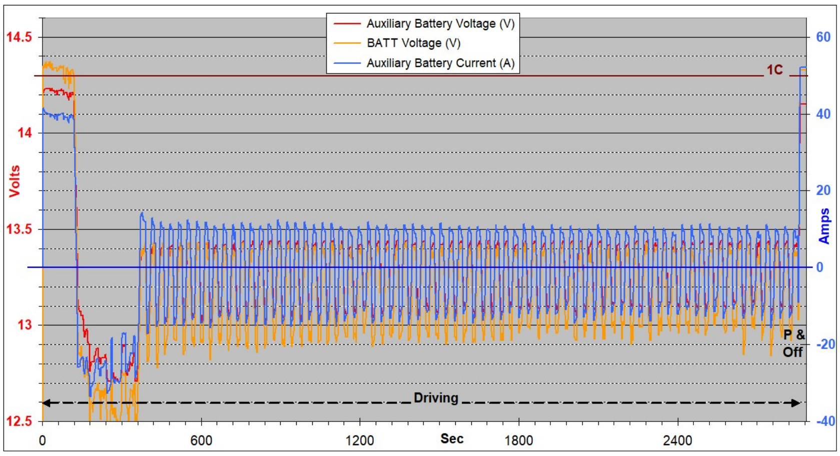




Some PID outputs were not what I expected (RM torque ratio), and some were null (RM brake regen.). Torque from the ICE and drive motors was usually positive, torque from MG1 and brake regen. was usually negative, but there were exceptions. I do not fully understand the difference between FM regen. and FM -ve torques.



It is interesting that this 6.5Ah NiMH traction battery frequently (but briefly) runs at >10C (but <20C) in both charge and discharge. It operates commonly at 1-5C.



In contrast, it is generally considered unwise to operate an LFP auxiliary battery beyond 1C, and 0.2C is preferred.

In the 2019 rav4 HV, the ICE (engine) and the inverters are liquid cooled (on separate coolant circuits). The stators of MG1 (generator) and MG2 (front electric drive motor) within the front transaxle case are sprayed with transmission fluid. Nevertheless, I have seen MG2 above 70 ºC during sedate (but hilly) urban driving. I doubt that the front transmission itself is liquid-cooled in the rav4 HV. (I have seen it above 55 ºC while the inverter coolant remained below 40 ºC) . MGR (rear electric drive motor) is apparently air-cooled, relying on heat-sink fins on the rear transmission case. The NiMH traction battery is cooled by fan-forced cabin air as described above. The auxiliary battery is not actively cooled.

The most obvious (and understandable) effect in the temperature vs torque logs was that uphill grades (+ve pitch) generally called for ICE and motor torque, whereas downhill grades (-ve pitch) were often associated with regenerative and generator torque. I can not discern a broad effect of temperature on hybrid torque strategy under these conditions. Many of the readings are very spiky, and the uncertainties mentioned above may interfere with interpretation. Various ratios that I examined did not help. It is possible to imagine various effects of various temperatures over short time periods, but these do not hold up over the journey. An effect might be clearer under controlled conditions with only one factor varied, but this would miss all the important interactions while driving. An effect might be revealed by more sophisticated mathematical (component) analysis, but this is beyond my ability.

That is not to say that SmellyTofu and alanclarkeau are mistaken. Maybe they were referring to higher temperatures. Or there may be too many other parameters in the HS control algorithm for me to discern the temperature effect from logged PIDs under these (relaxed urban) driving conditions. With the exception of some fairly direct effects on cooling fan operation, I am not sure that anyone has been able to reveal whether and how temperature PIDs are used in control. Unfortunately, Toyota does not reveal to car owners the parameters, let alone the algorithms, used to control operation of the cars that we own. Sigh.

Acknowledgement

Thanks to participants including burrito and ChapmanF at PriusChat (*https://priuschat.com/threads/hybrid-battery-temperature-control.228265/*) for help with this analysis.