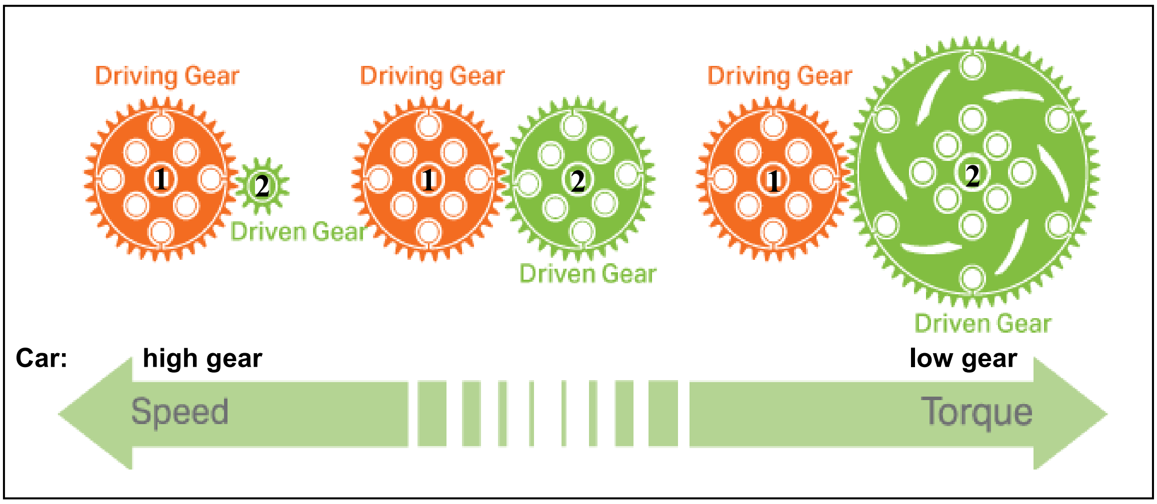
Hybrid Synergy Drive (HSD) and Hybrid System Indicator (HSI)

Summary

The gen5 Toyota rav4 hybrid AWD car (AXAH54) delivers force to the wheels from: an A25A-FXS (2.5 l, naturally aspirated, simulated Atkinson-cycle) internal combustion engine (ICE: 131kW, 221N·m), a front electric motor (MG2: 88kW, 202N·m) and a rear electric motor (MGR: 40kW, 120N·m). These motors can also contribute 'regenerative' charge to the traction battery (HB: 6.5Ah NiMH). Further electric power to charge HB comes from ICE via a generator (MG1: 31kW, 54N·m) which can also act as a motor to keep ICE rpm in an efficient range. The 245V DC from HB is converted into (≤650V) 3-phase AC for the motors, by voltage boosters and inverters. These control AC voltage, frequency and current; thus power, speed and torque of the wired-stator, permanent-magnet, synchronous motors. Current can flow between MG1 and MG2 via the inverters. All of this is managed by a computer control system, and at the front axle a planetary gear set that integrates forces to and from ICE, MG1 and MG2. This transmission system is referred to as the (gen 4) 'Hybrid Synergy Drive' (HSD). It is sometimes given the generic name 'Toyota Hybrid System' (THS-II, of which there are many sub-variants). The car has several options to display the direction of power flows between ICE, battery, motors and wheels (data sources behind such graphics are unspecified). In addition, the magnitude of power flows is presumably used in the Hybrid System Indicator (HSI) display. This article presents some real-world logs, and attempts to explain what can be discovered by owners about these systems.

How A Conventional Manual Gearbox Works

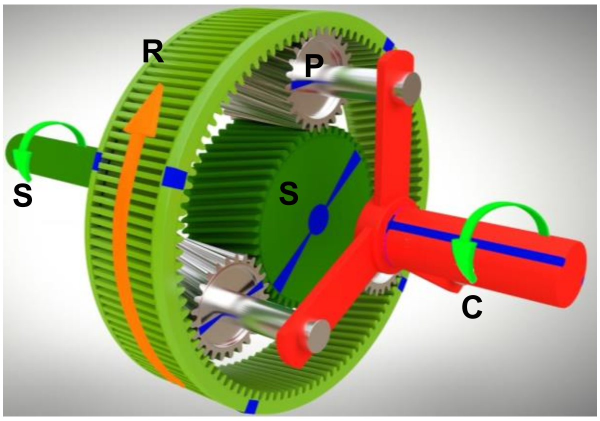
In a conventional gear train (with gears in series), torque is increased in direct proportion to the decrease in rpm, through the difference in gear diameters (or tooth numbers). In a car, such a gear train may be used with a series of alternative driven gears, to transmit ICE power while changing ICE rpm and torque in ratios useful at various car speeds. Maximum torque varies with ICE rpm; but at any given ICE torque, ***wheel torque is proportional to ICE : wheel rpm ratio***.



Gear Ratio = #Teeth2/#Teeth1 = Diameter2/Diameter1 = rpm1/rpm2 = Torque2/Torque1

How HSD works

The HSD is NOT a conventional gearbox. Instead it uses computer control of multiple inputs and outputs with a planetary gear set, aiming to keep engine rpm in an efficient range, keep the traction battery (also called high-voltage battery or hybrid battery - HB) at an appropriate state of charge (SOC), and provide additional wheel torque when needed from an electric motor. Indeed, in the HSD system, the same gear can sometimes drive and at other times be driven (in either direction), even if the car is moving forward. Liu (2008) provides a detailed description.



[Planetary](#) ([epicyclic](#)) gear sets include a central (sun, S) gear, planet or pinion (P) gears joined by a carrier (C), and an outer ring (R) gear. The three layers intermesh. S, C and R are concentric. When several are driven, the effects can be counter-intuitive. In HSD:

C connects via a damper to ICE. Unlike this figure, running ICE (thus C) does not rotate in both directions.

S is splined to MG1. S can rotate in both directions.

R connects via conventional gears to MG2, the front differential, and front wheels (all of which can reverse).

A computer controls MG speed, direction and torque. Controlling MG1 controls both rpm of ICE and electricity generation by MG1. (MG1 is also called 'speeder' or 'generator'; MG2 'torquer' or 'traction motor'). The computer integrates control of MG1, MG2, MGR, fuel and spark to ICE, in response to demand (through the accelerator pedal or cruise control). It aims to keep ICE in an efficient range (1300-2500 rpm?), operate the traction motors efficiently, and maintain HB SOC; if load and other factors such as temperature of ICE, motors and HB allow. The only sensible measure of 'gear ratio' in a HSD system is the ratio of ICE rpm to wheel rpm.

Attempts to define HSD 'gear ratio' in terms of planetary gear diameters (or tooth numbers) betray a failure to understand the principle behind HSD. The planetary gear set is sometimes called a power-split device, PSD (because power from ICE is split between MG1 and the wheels) or e-CVT (because it can vary ICE rpm continuously and independently of wheel rpm). ***MG2 also provides front wheel torque, which is not proportional to ICE : wheel rpm ratio.*** Combined output (~160kW, ~279 N·m) is less than the sum of the specified levels from ICE and MG2, though it is not clear where these are specified along the drive train. Shared current from HB and MG1 also limits combined MG2 and MGR output. Control algorithms are not disclosed.

A Bit More Planetary Gear Set Physics (skip this if you must)

As a result of mechanical connections through the gear teeth; in a steady state, the speed and torque relationships between the sun gear (S), the ring gear (R), and the carrier gear (C) are (Liao 2006; Miller 2006; Huang 2017):-

$Z_s*\omega_s+Z_r*\omega_r = (Z_s+Z_r)*\omega_c$ {C, R, MG2, Diff & Wheels rotate in the same direction; ω_s is computer-controlled}

As an aside, in a common single-stage planetary gear set (as in HSD) $Z_r = Z_s+2*Z_p$.

With a single input:- $T_s : T_r : T_c = 1 : (Z_r/Z_s) : -(1+Z_r/Z_s)$

So with input only to C (from ICE):- $T_s = -T_c*Z_s/(Z_s+Z_r)$ $T_r = -T_c*Z_r/(Z_s+Z_r)$

where Z_s and Z_r are the number of teeth (or the diameters) of the sun gear and the ring gear, ω is gear angular velocity (eg rpm), T is gear torque, $_r$ denotes ring gear, $_s$ denotes sun gear, and $_c$ denotes carrier gear.

Also, $T_s + T_r + T_c = 0$ {assuming100% efficiency, no other outputs and no gearbox rotation}

And, $P_s + P_r + P_c = 0$ {conservation of energy; power in = power out, assuming 100% transmission efficiency}

Torque & velocity have the same sign for a motor {shaft is driven}; opposite signs for a generator {driven by shaft}.

So in HSD: **IF** (i) there was steady state, no acceleration; (ii) only ICE was providing drive; and (iii) there was no friction, and no slip in the damper or wheels:- $Ts : Tr : Tc = 1 : (78/30) : -(1+78/30) = 1 : 2.6 : -3.6$

In this state, ICE torque would be divided ~28% to S (generator) and ~72% to R (then to wheels).

Sign of torque can be confusing. Above it is specified out from the planetary gear set. Thinking in the opposite direction, when C receives + torque from ICE, S receives - torque from MG1 (resistance while generating) and R receives - torque from the wheels (resistance to acceleration). The torque from ICE acts on both MG1 and wheels to move them against resistance. Through the planetary gear set, power from ICE is split between MG1 (for electricity generation) and wheels (for forward motion).

Other reference frames (such as direction of shaft rotation or vehicle movement) can be applied, seemingly arbitrarily, complicating interpretation. A convention for sign of torque and rotation (used in Toyota PIDs, but not clear in TIS) is that clockwise is +. This depends on viewing position.

A steady-state situation with ICE driving the wheels and the generator may arise during highway cruising. But steady-state analysis is not adequate for a system undergoing acceleration (messy things like inertia, shaft rigidity and load-proportional losses all get in the way). The proportion of ICE torque to planetary R (and eventually to the wheels) or to planetary S (and thence to the rotor of MG1) will vary in the same car under different conditions. Even under 'steady state' conditions, the proportions probably vary with load. The equations are complex, and we do not know the values of all parameters, but the effect on the distribution or overall transmission of torque is probably only a few percent under most conditions. Multiple inputs in HSD have a greater effect on torque experienced by any component of the planetary gear set at any moment (see below).

In HSD, the damper further complicates transmission of torque from ICE when accelerating. In any case, wheel torque from ICE is inadequate for spirited acceleration. Toyota handles this by using multiple, computer-controlled, inputs to HSD (which is more than the planetary gear set). MG2 can contribute torque to the wheels when traction battery SOC is sufficient (at low speed most, and in reverse all, torque comes from MG2). ICE can power MG1 as a generator to supply electricity to MG2 (via the inverters to control the 3-phase AC frequency and current to MG2). Toyota and the Kelly video describe discrete ‘control modes’, but mechanical components can not instantly reach electronically requested endpoints, so many ‘transitions’ are continuous.

While driving, ICE does NOT run a constant rpm (though the computer does try to keep it in an efficient range if power demand and available supply allows that). The car does NOT run at a constant gear ratio (in the sense of ICE : wheel rpm). It is NOT ‘always in top gear’ in the sense of either car acceleration or ICE noise.

Because MG1 can drive (control rpm of) S, it can control rpm of C (thus ICE) at any rpm of R (∝ wheel speed). The transmission is an e-CVT because MG1 changes the ratio of ICE rpm : wheel rpm. In this sense it changes the ICE : wheel gear ratio, although planetary gear tooth numbers Z_c, Z_s and Z_r (thus the ‘steady-state’ torque split) are fixed.

Because MG1 can provide torque to S, it can change torque to R. This is exploited for dual front-electric motor drive in EV mode in ‘prime’ PHEV models, with a 1-way clutch between ICE and C. MG2 (using electrical power from MG1 in generator mode and/or from the traction battery) can apply torque to R: +ve torque during car acceleration and -ve torque depending on HB SOC, brake position and computer algorithms during car deceleration. To imagine torque only from ICE ignores the rationale behind HSD.

Assuming that at some moment when torque is needed, the torque from <221 N·m ICE is reduced by 28% (<62 N·m), MG2 can provide 202 N·m using electrical power that has been derived from ICE mechanical power by MG1 (in generator mode). Plus 120 N·m from MGR in an AWD! The actual numbers depend where various torques are specified along the drive train, and on available current, but in reality the wheel torque delivered from equivalent ICE capacity is much increased in HSD cars.

Because the ratio of rpm in S and R varies widely under control of MG1 (ultimately the car computers), the split of mechanical power (∝ Torque * rpm) transmitted from ICE to generator vs wheels also varies widely.

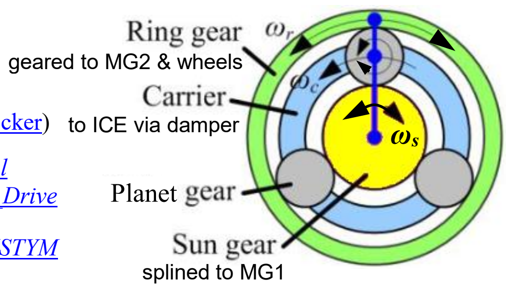
Torque is (angular) force (relative to a central axis). Depending on opposing forces such as friction it may not cause movement. Think of a tight wheel nut. In a planetary or differential gear set with paths of different resistance, torque may only cause movement (thus power) along the path of low resistance. A spinning wheel on an ‘open’ differential removes all engine power from a wheel with traction. Unless ICE is locked, power from MG1 flows to ICE, not to the wheels. MG1 must resist (apply torque to S) for ICE to power the wheels (via R). In contrast, ‘conventional’ gears on one shaft distribute torque in proportion to load. Thus little torque is wasted to spin MG1 freely when the wheels are powered by MG2 in EV mode.

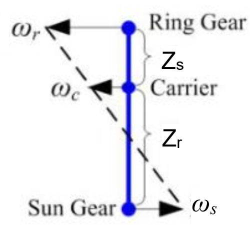
Power-split planetary gearboxes where S, C and R all move; and where inputs are provided to several gears cannot be understood as if they were planetary gearboxes with one component fixed, or with one input. In HSD: (1) S can receive torque from at least ICE {via damper} and MG1; R can receive torque from at least ICE, MG2 and the wheels; C from ICE, MG1, MG2 and the wheels. **Although the part of torque that comes from ICE is split near a ‘steady state’ ratio, total torque to any component varies widely, and often has no simple relationship to torque from ICE.** (2) In Park R is locked. Then all power from ICE flows to MG1 for HB regeneration, until HB SOC is high, when the car computers stop ICE. (3) When MG1 holds at 0 rpm {which happens often}, all power from ICE flows to the wheels. **There is no fixed split of power from ICE by the ‘power-split’ gearbox in HSD.**

The rpm relationships are simpler. AXAH54 uses transaxles P710 (front) and Q610 (rear). A GX has 225/65 R17 tyres, which require 440 revolutions / km (~ a few % more with typical load or inflation). At 100 kph the tyres rotate at 440*100/60 = 733 rpm. Let’s say 750 rpm. MG2 (3NM) rotates at 11.944*750 = 8,958 rpm. MGR (4NM) rotates at 10.781*750 = 8,086 rpm (OK for motors rated to 17,000 rpm). At 100 kph, I have seen the ICE from 0 to >5,000 rpm (often ~1,500 rpm). The computer can turn off ICE, and switch off current to/from the motors, but MG2 and MGR rotors will continue to spin because they are coupled by conventional gears to the wheels.

Additional References

(see also hyperlinks above)



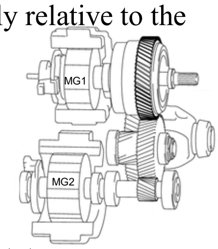


Warning: some links may have ads (I use a blocker)

http://www.benchtophybrid.com/PG_Intro.html
https://en.wikipedia.org/wiki/Hybrid_Synergy_Drive (outdated in places)
https://www.youtube.com/watch?v=dLNDGUISTYM (interesting comparison of earlier versions)
http://prius.ecrostech.com/original/Understanding/PowerSplitDevice.htm (with sub-pages, influential but wrong about actual torques)
http://eahart.com/prius/psd/ (animations changed from flash to javascript, but still blocked for security reasons by many browsers)
https://www.youtube.com/watch?v=O61WihMRdjM (excellent if slow, Kelly/Weber description of gen5 rav4 HV)

Rotation Directions ***(skip this is you don't care)***

Directions of rotation are wrong or unclear in some otherwise useful sources. In the car, MG2 sits higher than the differential. In the Kelly video, the transmission needs to flip up (with the part towards you in the video becoming the base) to match the orientation in the car: {a} forward is to viewer left (the MG1 end of the transmission); {b} the viewer is shown the stator assembly upside down, from the side where the rotors sit with shafts projecting into the transmission chamber that houses the planetary gear set, counter drive and differential. To complicate matters, the Prof sometimes fiddles the gears in the wrong direction. In TIS / NCF from Toyota, the P710 gear unit diagrams are flipped horizontally relative to the car (so all rotations appear reversed). Another site has excellent animations.



We know that in a planetary gear set: $Z_s*\omega_s+Z_r*\omega_r = (Z_s+Z_r)*\omega_c$
Inserting the teeth numbers for HSD: $30*\omega_s+78*\omega_r = (30+78)*\omega_c$

When the car is viewed from the right, and moving forward:

- The **wheels** and the **differential** driving the front **axle** are rotating clockwise (+).
- The differential is connected by external gears to the **counter-driven** shaft, which rotates −.
- The counter-driven shaft is connected by external gears to both planetary **R** and **MG2** (splined onto the motor reduction gear). Therefore both R and MG2 rotate clockwise (+).
- Planetary R is connected by an internal gear (the only one in the system) to the planet gears **P** which therefore rotate (and/or or turn with C) clockwise (+). We assume for now that **S** is stationary.
- The planet gears have their axes mounted in a carrier (**C**) that is splined via a torque damper to **ICE**, which runs only clockwise (+). Remember, we view from the right.
- The sun gear (**S**, splined to **MG1**) rotates in a direction that depends on other components:
  - In **EV** Drive (with enough SOC), or whenever ICE is off, C stops and S rotates opposite to R (−)
    - at -2.6*R speed = -9.4*wheel speed = -0.8*MG2 speed (no electricity is generated as MG1 is open circuit).
    - Some MG2 power is wasted to spin R & MG1. Most torque goes to the wheels, turned at ~0.08*MG2 speed.
    - In 'prime' models, MG1 can be powered in EV mode (with C locked), to deliver extra power via R to wheels.
  - In **Drive**, MG1 is computer-controlled and S can rotate (0) or (+) / (−) at variable speed
    - thus the computer can control ICE speed independently of wheel speed;
    - and ICE can both drive R / wheels and generate electricity via MG1;
    - power flows from MG2 mainly to the wheels; from MG1 to (rotating) C, arguably not (via R) to the wheels.
  - When **Regenerative Braking**, ICE is off and MG2 generates electricity by applying torque opposite to the direction of MG2 shaft rotation
    - up to MG2 torque and HB SOC limits.
  - In **Engine Brake** mode (rav4 'S'$_{\text{hift}}$ or prius 'B'$_{\text{rake}}$), MG1 controls ICE rpm, but combustion is off
    - so ICE rotates with R, providing braking through engine vacuum, compression (etc), at a level controlled by the speed of S (rav4 allows several levels from driver input);
    - and MG1 uses electricity from HB (and/or MG2 if it is generating) to control the speed of S.
- If S, C and R all rotate together with the same speed (X) and direction, 30X + 78X = (30+78)X
  - the rpm ratio between ICE and R is 1:1 (X:X), ie **direct drive**.
- At this same wheel (and therefore R) speed that gave direct drive:
  - If S increases (in the same + direction) C increases, so the car is in **underdrive** (ICE rpm more than R);
  - If S decreases (or reverses direction) C decreases, so the car is in **overdrive** (ICE rpm less than R).
- In **Park** (when SOC drops enough to run ICE), R is locked and S rotates in the same direction as C (+)
  - at 108/30 = 3.6*C speed. To charge HB, ICE runs ~1300 rpm, so MG1 runs ~4700 rpm.
- In **Reverse**, the direction of rotation of MG2 (and MGR if needed) is reversed to back the car.
  - There is no gearing to provide reverse drive from ICE.
  - While the car is moving in reverse, unless ICE activates due to low SOC, MG1 spins + freely.
  - If ICE does activate while the car is in reverse, MG1 can generate electricity.
  - At low speed, torque from ICE will be low compared with that from MG2,
    - an effect magnified by the gear ratios discussed below. The car continues in reverse.

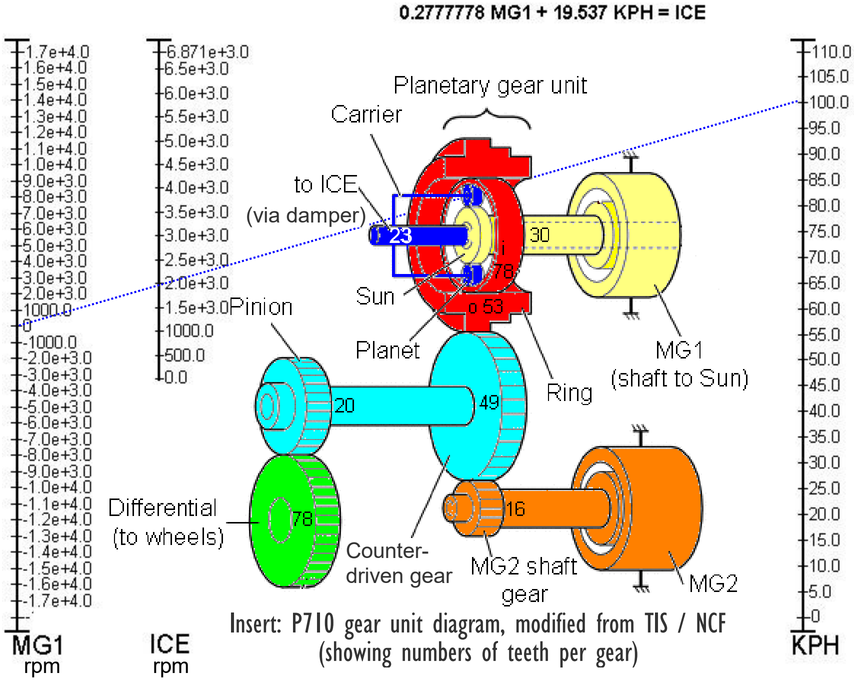
Remember that the direction of rotation and the **direction of torque** on a gear or shaft are not necessarily the same. {If a torque is applied opposite to the direction of rotation, the gear or shaft is decelerated, unless another force is applied to maintain speed. A generator applies torque opposite to rotation to generate electricity. An engine or motor applies torque with rotation to accelerate, or to maintain speed against the opposing force of friction.} Several devices (eg ICE and MG2) can provide additive torque to the same gear. Unless torque applied to a wheel can be absorbed by the contact between the ground and tyre, the wheel will spin.

Some Interesting RPM Effects

Here is an idealized rav4 nomogram (ignoring slip by the damper and wheels):

Place the edge of a ruler over numbers of interest in any two columns, and read the effect in the third column. (Example shown: Speed 100 kph, ICE 2000 rpm → MG1 0 rpm).

For those not familiar with 'scientific notation'
e+3.0 = x 1000
e+4.0 = x 10000



Insert: P710 gear unit diagram, modified from TIS / NCF (showing numbers of teeth per gear)

From the nomogram:

- When the car is stopped (0 kph) and ICE is off (0 rpm), MG1 is at 0 rpm (as are the traction motors).
- When the car is at 50 kph and ICE is idling at 1000 rpm, MG1 is at 0 rpm.
- When the car is at 100kph and ICE is running at 2000 rpm, MG1 is at 0 rpm.
- The ±17000 rpm capability of MG1 allows ICE to be controlled over a wide engine rpm range, at any reasonable car speed:
  - to provide ICE power to the wheels when ICE is run with combustion of fuel; or
  - to provide engine braking when fuel and spark are denied to ICE (by the car computers).
- MG1 can serve as a generator of electricity at any reasonable car speed, by using power from ICE within a safe rpm range for ICE. Higher MG1 rpm generates more electricity.

PIDs and Wheel Torques

It is challenging to use torque PID values, because: (a) it is difficult to measure torques directly in a moving vehicle, so values are probably calculated {from electrical characteristics in the case of motors?}; (b) Toyota does not say where along the drive train each value is specified; (c) *sign* of torque PIDs seems to be at ICE and motor shafts, not following the convention ($T_s+T_r+T_c = 0$) used in the analysis of planetary gear set physics; (d) torque can be applied in all directions along a branched gear train with multiple inputs; and (e) inputs are computer-controlled.

Let us assume that most torque PID *signs and values* are specified at the device output (shaft of engine or motor), and ignore all losses through friction and transmission through gears. If we make the further assumption that all torque specified for MG2 and MGR flows to the wheels, the calculation of wheel torque is simply based on ratios of teeth in conventional gears:
MG2 wheel torque = MG2 torque * 49/16 * 78/20 = MG2 torque * 11.9438
MGR wheel torque = MGR torque * 41/15 * 71/18 = MGR torque * 10.7815

MG2 regenerative torque (PID value ≈ 3 * motor torque) may be specified at the counter-driven gear. If so,
MG2 regen wheel torque = MG2 regen torque * 78/20 = MG2 regen torque * 3.9
MGR regen torque is always 0 in the rav4 hybrid (no rear brake regen, just coasting regen).

If we assume 'steady state' (although this does not apply at most times), 72% of ICE torque goes to R
ICE wheel torque = ICE torque * 0.72 * 49/53 * 78/20 = ICE torque * 2.596

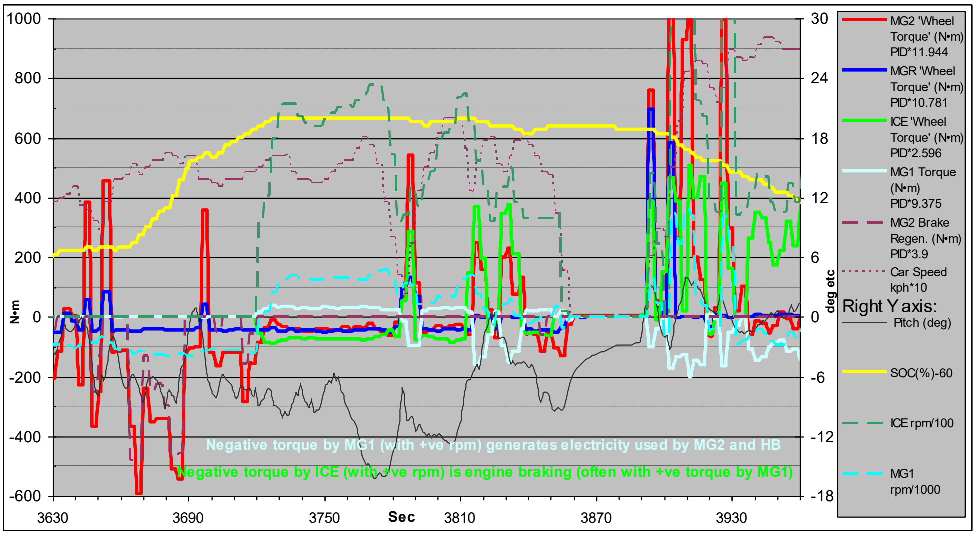
It appears that: (1) MG1 gives + torque only to start ICE and to increase ICE rpm for engine braking. (2) In drive, all - torque from MG1 is balanced by the 28% of ICE torque sent to S.
Thus estimated effect at the wheels should not consider torque from MG1.

Engine and Regenerative Braking

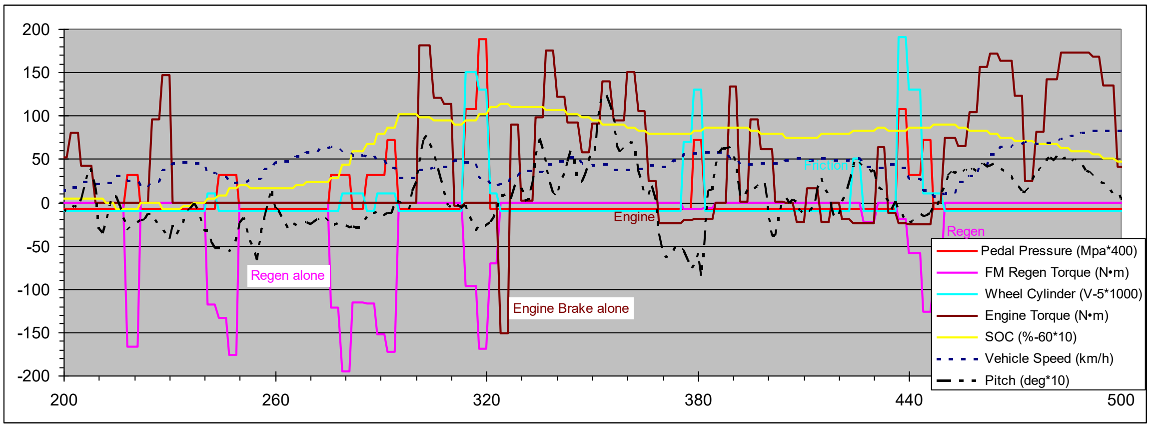
As shown below, the car automatically provides some engine braking (-ve wheel torque from ICE at 1000 rpm to 2500 rpm) when the traction battery approaches 80% SOC. At the same time, regenerative braking is sometimes disabled and MG1 consumes power from HB to regulate ICE. This effect differs from the brief spikes of -ve ICE torque PID that sometimes occur as ICE is started. At other times, generation by MG2 is enabled, and the electricity is used by MG1 to increase ICE rpm (and thus engine braking). ICE rpm may also be increased if 'S mode' / low gear is engaged manually, but the resulting engine braking is not enough for steep off-road use.

Many components contribute to overall engine braking. There are many opinions but scant data about relative contributions, which vary depending on design of the engine, air intake & exhaust systems; and variables including throttle opening, valve timing, car and engine speed, % EGR, turbo boost, and engine vs coolant temperatures. Many of these variables are controlled by car computers. Most drivers are probably content that it works.

There is no evidence that MG1 performs regenerative braking. The computers do not seem to allow the condition where (a) MG1 has +ve rpm and -ve torque and (b) ICE is locked to deliver that torque from MG1 to the wheels. Indeed, the physics of the planetary gear set require that when ICE is off (C stopped) MG1 (S) rotates -ve when the wheels (via R) rotate +ve. Thus MG1 cannot perform regenerative braking (it cannot simultaneously generate electricity and provide -ve torque for braking while spinning with -ve rpm when ICE is stopped during braking).



In this interpretation, regen braking from MG2 was not 100% efficient (as expected). But there were odd moments when the calculated wheel regen torque exceeded (-ve) wheel torque from the same motor. When the throttle was eased at speed, MG2 (but not MGR) sometimes gave regenerative coasting, even while ICE ran and provided torque!



This log shows (with cruise control off): (a) Regeneration without friction while the brake pedal is pressed. (b) Engine braking without regeneration or friction (high SOC, downhill, no pedal press). (c) Friction then regeneration, with gentle engine braking and no pedal press! (d) Various ratios of regeneration to friction depending on SOC, pitch etc. All un-noticed while driving; the car computers take care of it all without fuss.

Regenerative braking is controlled by the car computers based on inputs including traction battery SOC, torque capacity of the motor (in generator mode) and driver demand for braking force (gauged through the brake stroke sensor and regulator pressure sensor). Control of regeneration by the AC motors is not fully explained in TIS. It might involve field-weakening, or current drawn / circuit resistance. In the case of MGR, logs show no regenerative braking: torque is unaltered during braking from the slight -ve levels shown during coasting. A small regenerative current from MGR during coasting (and braking) would be consistent with in-car graphics. In normal driving the car computers never 'request' regenerative braking by MGR. This may be intentional if it is harder to design for safety/stability with regenerative braking by MGR; although it does contradict some claims about the advantages of MGR. In contrast, the 'requested' braking torque from MG2 is often twice that delivered (the balance coming from friction or other braking). At some level, the electricity generated will be less than losses in the system; so the computers will let motor-generators spin without drawing any current from them. This occurs when decelerating from low speed (cooperative braking is deactivated at 5-10 kph).

The explanation below assumes control of regenerative braking through circuit resistance, which is probably an over-simplification; but the broad reasoning holds even if control includes other mechanisms such as field-weakening (just substitute):

- When MGR is not powered and the car is not coasting, the PID for MGR torque is zero. I assume that the stator circuit is open. There must be some negative torque from friction, eddy currents etc in the permanent-magnet, spinning-rotor, MGR; but this may be subtracted from the PID value, or too little to register if Toyota motors are very efficient indeed.
- An EMF is expected across the open-circuit stator wires, but this will not enter the car electrical system and the stator coils do not seem to be harmed.
- When coasting, both MG2 and MGR show a little negative torque, and the car displays show regenerative current flow. If correct, there must be a high load resistance, but some current flows from the stator of each motor during coasting.
- During braking, the resistance of the MGR stator circuit must be kept high, to avoid additional regenerative current and braking torque. In contrast, the car computers must regulate resistance of the MG2 stator circuit, and thus regenerative current and braking torque from MG2, in response to multiple factors including HB SOC and driver demand for braking.

HSD Efficiency

Toyota hybrid vehicles (like the gen5 rav4) are unlike most ICE vehicles in that they are more fuel-efficient around town than on the highway. Some sources indicate that this is because there is more energy recovery through regenerative braking around town. That is nonsense. The efficiency of energy recovered by the regenerative brake system will not exceed 80%. In other words at least 20% of energy is wasted during braking. The vehicle would be more-fuel efficient if it could be driven without braking.

So what are the real causes of reduced fuel-efficiency on the highway? Firstly, drag (friction from air and tyres) increases substantially and in a non-linear manner with speed. (Aerodynamic drag $\propto$ air-velocity^2). Secondly, efficiency of the planetary gearbox and spinning motors decreases at higher speed. The contribution of each factor is not documented. Glance at the trip computer's fuel consumption rate while cruising at 90 kph vs 110 kph on a level highway. There will be a substantial drop in fuel economy at the higher speed. But many drivers care more about travel time than fuel economy, so they travel at the speed limit anyway.

Other things that will reduce fuel efficiency to various extents (from ICE, hybrid, battery-electric or any other known power source) include:
(1) increased drag from accessories such as roof racks;
(2) increased drag from driving with the windows down;
(3) increased drag from incorrect tyre inflation;
(4) increased weight from passengers or accessories such as mats, tool kits or tow bars;

(5) towing, which increases both drag and weight, and requires more friction braking;
(6) tweaking the system so that a cooling fan (eg the HB cooling fan) runs continuously;
(7) using any power-consuming accessory, such as a portable refrigerator;
(8) driving in hilly terrain, because more energy is used going up than recovered coming down;
(9) driving in very hot or cold conditions (or setting the cabin temperature further from ambient); because more energy is consumed to cool or heat the cabin;
(10) driving under conditions that involve more wheel slip, such as gravel or icy roads;
(11) driving in normal or sport or trail, instead of eco mode;
(12) a driving style with harder acceleration and/or braking.

If it is any consolation, alternative hybrid drive train arrangements used by other vehicle manufacturers, such as computer-controlled clutches to engage ICE and motors independently, are so far less fuel-efficient that the Toyota HSD (with VVT, simulated Atkinson-cycle engine).

The A25A-FXS engine variant in the gen5 rav4 hybrid uses variable intake and exhaust valve timing (VVT) and cooled exhaust gas recirculation (EGR). It is said by Toyota to achieve up to 41% thermal efficiency (compared with about 25% for older Otto-cycle engines). It delays closing of the intake valve until the piston has completed part of its upward travel on the compression stroke. Some of the fresh charge is thus pushed back into the intake manifold. The cylinder is not completely filled, so there is a power reduction; which is more than compensated by the electric motor(s). The payoff comes after ignition when the piston descends on the expansion (power) stroke. The shortened intake stroke combined with a full-length expansion stroke results in increased thermal efficiency. Exhaust pressure is also affected by VVT and EGR.

rav4: 4WD?

The model designation stood for recreational active vehicle 4WD, but the rav4 hybrid AWD is NOT designed or suited for use on rough tracks or off road. There are several limitations, and exceeding any of these will result in inconvenience for recovery, and probably cost for repairs:

- Specified ground clearance of hybrid variants is lower than some ICE-only variants (190 vs 217 mm), which are already lower than typical high-clearance 4WDs (≥220 mm). International specs vary.
    - I measure only 160 mm of ground clearance when the car is fuelled but otherwise unladen.
    - Clearance, approach angle (17.5º) and departure angle (20º) are specified for unladen cars. Given that the rav4 has independent suspension, these numbers will be less with a load (including fuel).
    - Many Australian secondary roads (like the 'Muttaburra Highway', Morella-Muttaburra Rd) are deeply rutted at times, depending on when they were last levelled by a 'grader' (heavy earthmover). The rav4 hybrid AWD does not have sufficient ground clearance for deeply rutted roads.
- Wheel articulation is less than that in high-clearance 4WDs, exacerbating the adverse effects of low clearance, approach and departure angles, and the likelihood of wheel slip, on rough tracks.
- The rear motor is air-cooled and only intended for intermittent operation. Excessive use will result in high-temperature shut down of the motor, and thus loss of drive to the rear axle.
    - Trail mode increases use of the rear motor, and is only intended for short-term and low-speed use.
- Both the front and rear differentials are open: that is they lack any diff lock or limited slip diff mechanism. The gen5 rav4 has improved the implementation of automatic braking of any spinning wheel as a kind of virtual limited-slip differential. But this mechanism is still slow to operate.
    - It risks excessive wear and heating of the brakes under conditions where a wheel frequently looses traction.
    - It may eventually allow you to extricate the car from a position where a wheel spins, but it is not suitable to 'walk' the car through a long series of such obstacles.
- There is no downhill descent mitigation.
    - Engine braking from S mode / low gear alone is not enough for steep off-road use.
- Many components are not engineered for the stresses imposed by rough off-road driving.

However, the rav4 hybrid AWD system is very well suited to well-formed roads that may allow occasional wheel slip (eg due to snow, rain or gravel). It seamlessly engages the rear motor for extra torque when moving from stationary, and any time slip of a front wheel is detected. Otherwise, the car uses FWD. It is a 'soft roader', more than capable on well-formed dirt roads.

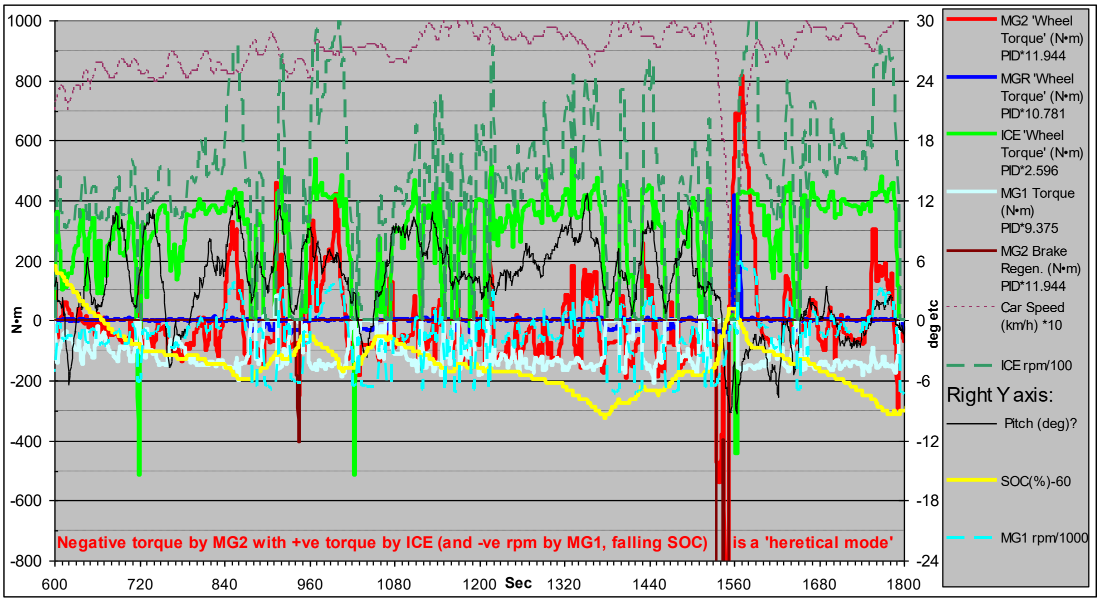
Modes of Driver Amusement

Because the car computer uses a complex algorithm with input from many sensors, small changes in a few parameters can have substantial effects on HSD behaviour. Discovery of new 'modes' of operation is limited only by imagination, and attention to detail in logs of car operations. For example, based on his analysis of prius physics Graham Davies long ago (pre-OBDII logs) deduced that there should be a 'heretical mode' in which MG2 uses torque from ICE to generate electricity while MG1 is consuming electricity to spin 'backwards' and control ICE rpm (maybe even to power R and the wheels??). This was controversial. In postulating that MG1 could drive the wheels while cruising with ICE on, it ignored the effect of counter-torque from ICE to MG1, probably because quantified torques were at that time unavailable. Also, MG1 could be powered from other sources, and the computer could intervene. My logs seem to preclude this postulated effect. But 'hypermilers' wondered if it could improve fuel economy.

In reality, it is probably largely irrelevant for fuel economy under most circumstances, because:

(i) Power to spin MG1 must still come ultimately from ICE; if SOC is low, ICE has to work harder.
(ii) The car uses -ve rpm of MG1 a lot, but usually not for long continuous periods.
(iii) MG1 can run for a long time on HB power at high initial SOC.
(iv) ICE can start or speed up as needed to charge HB (via +ve rpm in MG1).
(v) ICE rpm commonly increases for uphill grades, and MG1 may then generate.
(vi) Even on the highway, there is commonly some (downhill) coasting or braking. These activate generator function of MG2 (and MGR) without drawing directly from ICE.
(vii) It is necessary to quantify all torques, not just rpm, to predict power flows and fuel economy.
(viii) The method and precision of 'torque mapping' for Toyota PIDs is unknown.
(ix) Other factors such as drag (eg tyre inflation) and amount of fuel injected also alter fuel economy.

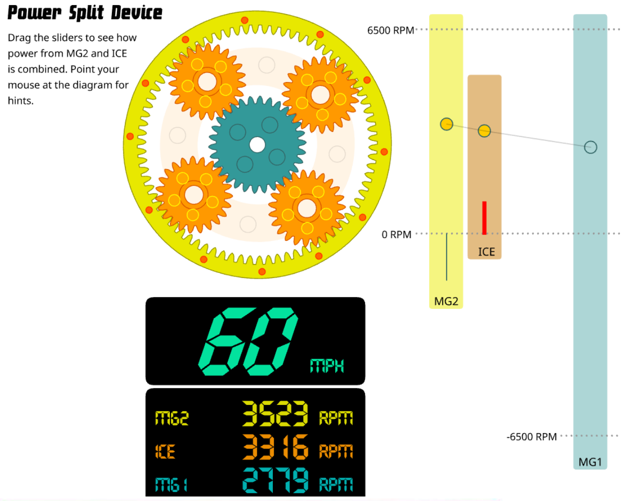
Nevertheless, close examination of rav4 hybrid logs will reveal that during long highway drives there are periods with uphill grades when MG1 rpm and torque remain -ve (motor function with no generation), ICE is on and MG2 gives predominantly -ve torque (electricity generation) without increasing SOC. The best explanation is that under these conditions, MG2 is in fact powering MG1 (via inverters or HB). You can find brief examples of this in the graph below, though there is no evidence that MG1 ever transmits power to R and the wheels.



No doubt you can discover (or imagine) other transient 'modes' of HSD operation by looking carefully at logs under various driving conditions. For the most part, it does not matter: the system is remarkably effective under a wide range of driving conditions. It does serve as a reminder that the in-car energy-flow displays are probably designed more for amusement than for information, as they do not reflect these (heretical) modes.

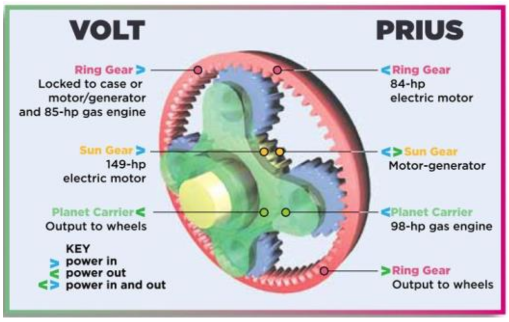
Inherent Limitations in the HSD

- In **neutral**, circuits to all motors are open (to prevent unintended drive to the car). All energy consumed by ICE operation is wasted (as heat) and HB will be drained by car electronics.
  - ➢ Running ICE then delivers power only into the path of low resistance: freely spinning / open circuit motors. The car computers also enforce low ICE torque. This gives almost the same effect as neutral in a conventional car (it pushes easily in either direction, even with ICE running).
- There is inefficiency from **spinning motors** while they are not generating or driving wheels.
  - o MG2 and MGR are connected by gears to the wheels, without any clutch, so the rotors must spin whenever the wheels move. The AWD is slightly less fuel-efficient than the 2WD.
  - o ICE-only cars suffer greater inefficiency by dissipating all brake energy as heat (and by running ICE while the car is gliding). ICE is also much less efficient at energy conversion.
    - ➢ ICE may achieve 14-40% BTE vs ≥90% from motors, and brake regeneration may reach 60-80% (depending on car, speed, driving style & conditions). Less losses in energy transmission.
- **MG1** has to perform competing tasks:
  - o It can not work optimally (sometimes it can not work at all) as a generator while it is intervening to regulate the speed of the ICE.
    - ➢ MG1 cannot generate electricity when rotating + and applying + torque to S in order to speed up ICE. When rotating + MG1 consumes electricity to apply + torque.
    - ➢ When the rotation of MG1 is − {typically when ICE is off, or the car is at highway speed}, it does not for more than a few seconds apply the + torque it would need to generate electricity. Rather it spins freely {wasting mechanical power from MG2 or wheels} or acts as a motor {to regulate ICE}.
  - o But it works effectively as a generator when rotation is + and it can apply − torque. In these (common) circumstances, MG1 converts energy from ICE into electricity.
    - ➢ In theory from the planetary gear formula, in a 2019 rav4 hybrid (ignoring slip by the damper or tyres), MG1 rotation will be + up to 50 kph whenever the ICE is on (>1000 rpm); and at 100 kph if ICE is >2000 rpm. Car computers can control the amount of regenerative current from MG1.
- Electric motor-generators generally become less efficient at high torque and low rpm.
  - ➢ Toyota aims to minimize this, and adjusting voltage etc to stay in an optimal torque band can help.
  - ➢ Jackrabbit starts consume a lot of battery power and reduce the HEV efficiency advantage.
- Perhaps it is worth mentioning that HB, not the auxiliary battery, is used to start ICE.
  - o The HSD hybrid car cannot run without some HB charge and some electronics.
    - ➢ But a modern conventional car cannot run without ICE and some electronics.



This model from eahart is based on an early prius, so the RPM values are not correct for a 2019 rav4, but the general principle is the same: MG1 is computer-controlled to regulate ICE speed, but when conditions permit it can serve as a generator of electricity.

In theory for a 2019 rav4 HV AWD:
R : Differential (wheels) = 49/53 * 78/20 = 3.606
MG2 : Diff. (wheels) = 49/16 * 78/20 = 11.944
MGR : Rear wheels = 41/15 * 71/18 = 10.781
MG2 : R = 49/16 * 53/49 = 3.313
MG1: R (C stopped) = -78/30 = -2.6
MG1 : ICE (R locked) = 1 + 78/30 = 3.6
kph ≈ Differential (wheel) rpm / 7.50
kph ≈ R rpm / 27.05
kph ≈ MG2 rpm / 89.58
kph ≈ MGR rpm / 80.86



There is more than one way to use a planetary gear set in a hybrid car.

In the GM Volt, the planetary gear set that drives the wheels operates mainly to combine power from 2 electric motors (one of which can also generate electricity from ICE power). It facilitates use as a series hybrid.

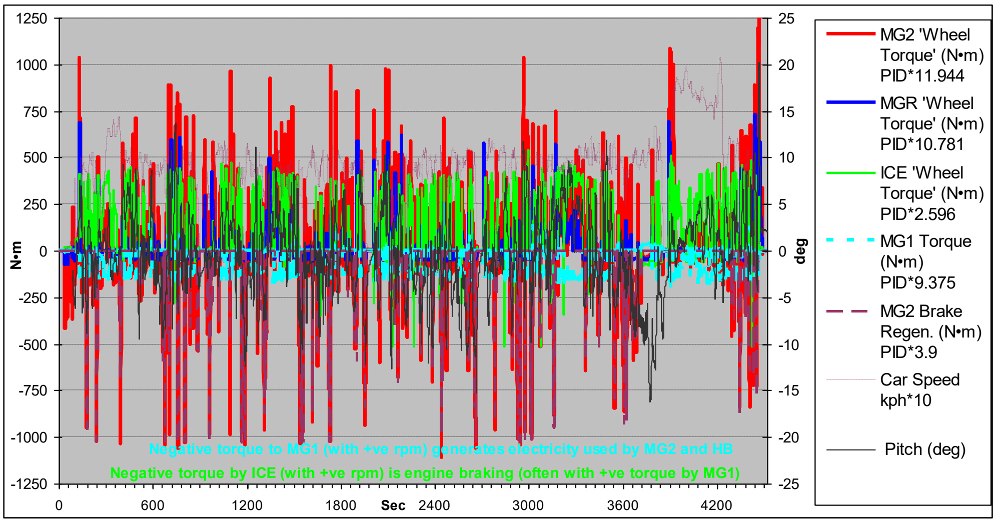
The Toyota HSD splits ICE power to the generator and wheels, facilitating use as a parallel hybrid.

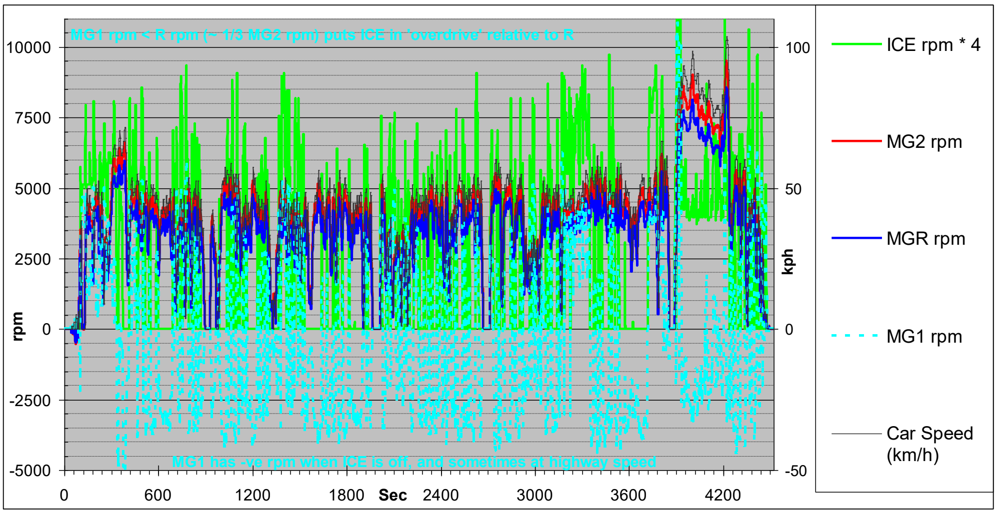
Figure history is uncertain, but it resembles an illustration by Eric Pierce. The 2019 rav4 has only 3 planet gears on the carrier.

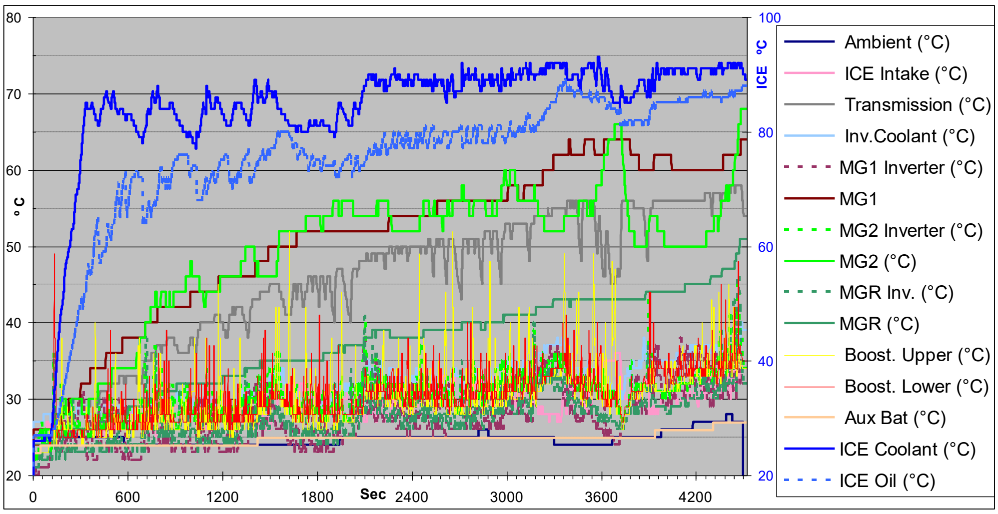
More Real-World Logs

Here is a set of graphs showing PID outputs during one journey in a 2019 rav4 hybrid AWD. Another journey is elsewhere. PIDs were logged every second. Although some graphs seem spiky, the experience is very smooth.

The logs confirm that in this car: (1) MG2 and MGR give most 'wheel torque' at low car speed, and ICE dominates at high speed. (2) MG1 probably has little direct effect on wheel torque. MG1 controls ICE speed and (given +ve rpm, -ve torque) it generates electricity used by MG2 and HB. There are intervals of low +ve torque from MG1, but usually only when ICE and traction motor torques are -ve.





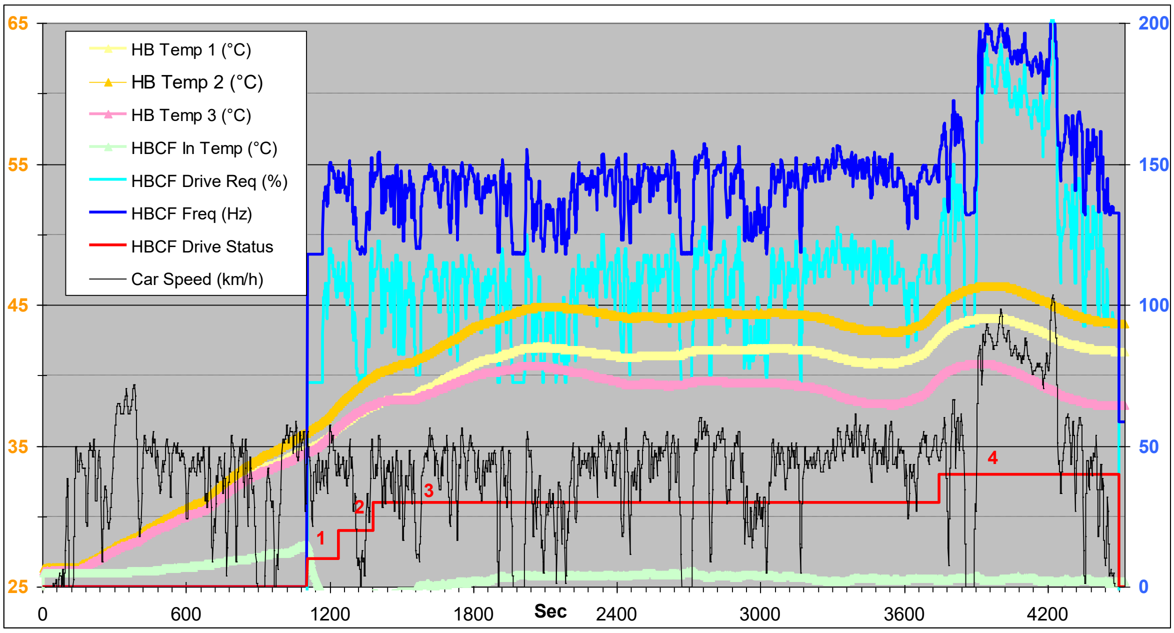


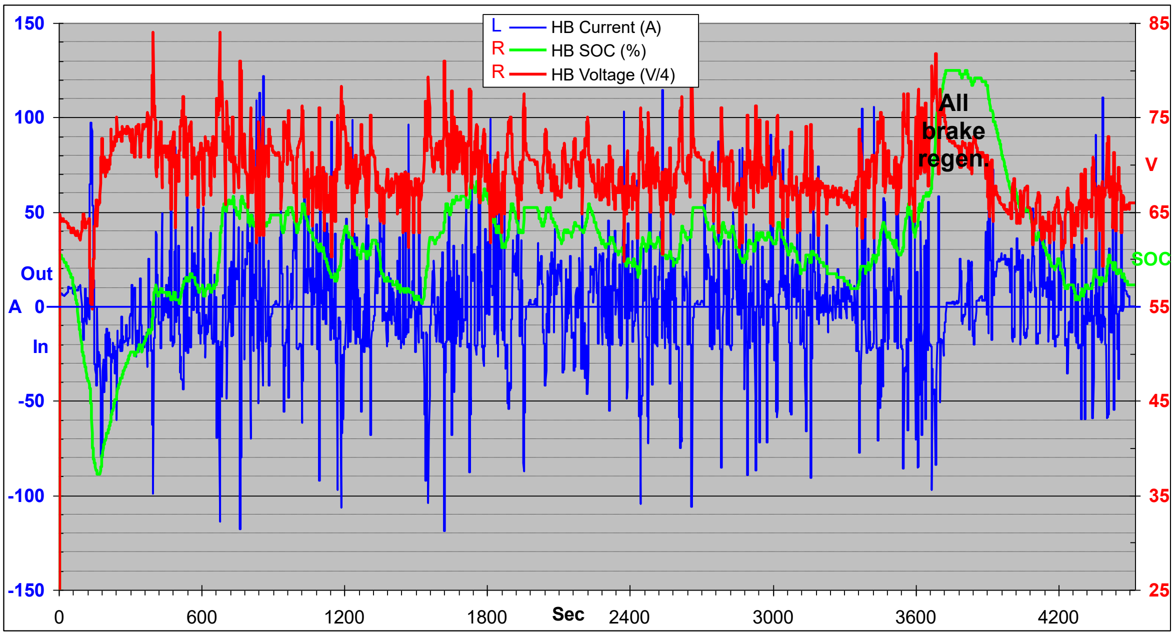
In subdued driving, friction brakes are applied only near stop. MG2 brake regen PID may be specified at the counter-driven gear (* 3.9 for wheel torque)? MGR brake regen and MGR requested brake regen PIDs are always zero.

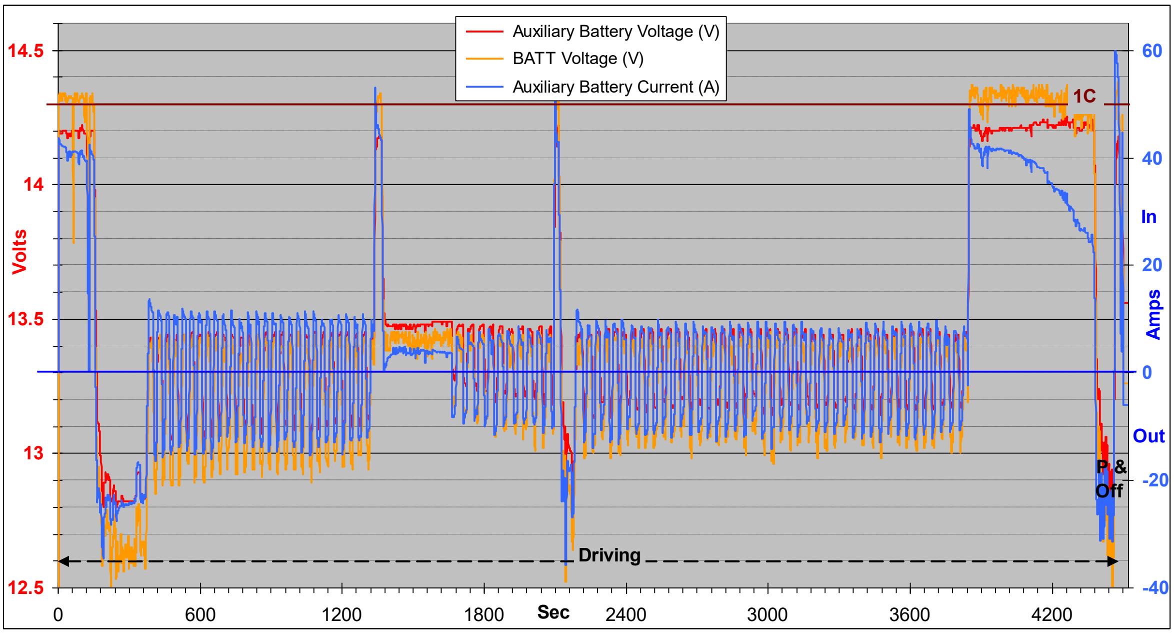
Ratios of logged rpms do not fit the HSD formula, maybe due to logging delays or slip in the ICE damper.

Despite these uncertainties, the results show many relationships; and debunk published nonsense such as:
(i) 'MG2 and MGR rotate backwards for regenerative braking' (never true); and
(ii) 'MG2 must run as a generator using torque from ICE to keep MG1 at -ve rpm' (not necessarily).

Regenerative braking in long down-hills is very effective at HB charging. Near 80% SOC, the car automatically uses engine braking to help the friction brakes. Then higher HB capacity would have value.


HB Temp 1 (°C)
HB Temp 2 (°C)
HB Temp 3 (°C)
HBCF In Temp (°C)
HBCF Drive Req (%)
HBCF Freq (Hz)
HBCF Drive Status
Car Speed (km/h)
1
2
3
4
Sec


L HB Current (A)
R HB SOC (%)
R HB Voltage (V/4)
All brake regen.
Out
A
In
V
SOC
Sec


Auxiliary Battery Voltage (V)
BATT Voltage (V)
Auxiliary Battery Current (A)
1C
Volts
Amps
In
Out
P & Off
Driving
Sec

What About That HSI?

In addition to the information in the Owner's Manual, there are several useful collations of observations about the HSI dash display (at left in the rav4 GX display above):
https://priuschat.com/threads/hybrid-system-indicator-and-stealth.63093/
http://techno-fandom.org/~hobbit/cars/HSI/
https://www.toyotanation.com/threads/chg-portion-of-hybrid-system-indicator.409233/

The indicator varies in appearance between models. It is an attempt to integrate multiple functions related to 'eco-friendly driving'. Contrast this with a tachometer, which shows just one thing (engine rpm). HSI may be too complex for safe use at a glance when driving. I assume that data from the HSI PID is an input, but it must be heavily smoothed and somehow integrated with other data to drive the HSI display on the dashboard. It may be a clue that engine rpm is a PID in the 2019 rav4 Combination Meter module, though no tachometer is displayed. Or maybe not, as some overseas rav4 variants display a tachometer rather than HSI. Other parameters that are certainly used by HSI (like contributors to stored energy regeneration) are not listed as PIDs for this module. As usual (and unfortunately) Toyota gives only the 'explanation for Dummies' and does not reveal the parameters used, or the algorithm used to integrate them in the HSI display.

In the 2019 Australian rav4 and camry hybrids, the HSI is a large dial displayed where you might expect to see a tachometer. But in the Australian 2019 corolla hybrid this location has a tachometer, and the HSI is available as a smaller (prius-like) linear display. Go figure.

I do not think the HSI alone is a reliable indicator of when the ICE will be used. Probably the ICE is always used when the HSI is in the PWR range, but it is also called upon to charge the traction battery as needed whenever the car is in READY mode. In my experience, the ICE sometimes starts before I can reverse (very slowly) out of my garage; but at other times it does not start until the car reaches a certain speed, far down the road (unless it is accelerated harder before that). It probably depends in part on where the traction battery SOC happened to be at the end of the previous drive, and on multiple other factors including what accessories were on to drain the auxiliary battery while parked (which causes a drain from the traction battery as soon as READY mode is engaged). Some overseas models (not the Australian rav4) even have a predictive system that uses GPS and route features to anticipate when to arrange for high SOC.

So I would not worry if the ICE starts at a low reading on the HSI, especially if the car has been parked for a few days (e.g. during COVID lockdowns). At least I would want to dig deeper into factors such as traction battery SOC that can trigger the ICE. Remember that the Toyota traction battery SOC display is also configured 'for Dummies'. It displays only the range in which Toyota aims to keep the traction battery (40% - 80% of actual SOC?), it is not linear across this range, and the car apparently uses a complex (and undisclosed) algorithm to decide when (and how much) to increase the SOC within this range.

Toyota: Reveal Our Car Control Algorithms

There are very few things I would change about my rav4 hybrid, and if I could understand it better there might be even fewer things I would change. Of course, Toyota is reasonably entitled to keep some secrets. As a manufacturer, I think it is entitled to keep trade secrets about manufacturing methods. Personally, I am happy for now to have the car serviced by a Toyota dealership, but I do not believe that owners should be compelled to have their cars serviced by such a dealership.

I think that no seller of products is entitled to keep secrets about how those products work, if such secrets interfere with the rights of the owners to safely operate, maintain and modify the product according to their personal preferences, in ways permitted by law. For example, in my view traction battery chemistry is a safety issue for hybrid car owners (some lithium complexes are safer than others). Toyota discloses a little more to emergency workers than to owners, but still too little in my view. I also think that owners are reasonably entitled to understand the algorithms used to control the operation of the cars they own. Many of these algorithms affect safety, and safety will be improved if drivers understand the algorithms. In many cases, for safety, it is appropriate to prevent owners from altering the algorithms. In other cases (eg auxiliary battery chemistry and charging) owners are reasonably entitled to understand and adjust the default settings, at their own risk under fair warranty conditions, just as they are entitled to select their own seatcovers, tyres, or dashcams. Fair disclosure may even increase sales to discerning buyers!

I appreciate the need for IP protection to reward and drive innovation. A great deal of innovation goes into hybrid car mechanical features and control algorithms (eg Liu 2008, Najem 2021). IP can be protected by various means that do not restrict the reasonable rights of purchasers. 'Trade secrets' are not effective to protect car control algorithms from use by competitors (who can decipher them using a purchased car). Keeping car control algorithms 'secret' merely harms ordinary customers, who lack the resources to decipher them. In contrast, patents exclude competitors from using a technology for 20 years (by which time a better technology will have been developed in this field) while making the knowledge available to anyone who is interested. Similarly, a competitor can discover mechanical innovations by stripping down a car, but they can not copy patented innovations. The process of innovation actually works faster when competitors can see, and improve on, each other's innovations.

Control algorithms, like mechanical features, are integral to the car. The owner has purchased the car. Toyota's position appears to be that owners are entitled to use, but not to know, control algorithms integral to the cars they have purchased. In my view, the purchase of a car gives the owner an implicit licence to know and use the car control algorithms according to the owner's interests in the purchased car, but not to use them for other purposes.

It does not matter what proportion of owners chooses to understand or adjust such things. It matters a great deal that owners are entitled to understand and adjust such things by free choice; and that manufacturers are not entitled, for commercial interest, to secrets that remove such free choice by owners. Personally I am unlikely to make the effort to understand the complex algorithms controlling planetary gearbox operation or regenerative braking. But every owner is entitled to know those algorithms if so desired, because without them they can not hope to understand, troubleshoot or maintain those features of the vehicle that they own. At present, even with a paid subscription to Toyota TIS, a car owner is denied access to this information.

In my opinion if a manufacturer sells (as distinct from leases) products, there need to be very strong reasons (beyond claimed commercial advantage) to restrict the freedom of owners to understand and maintain according to their own interests the products that they have purchased.