RAV4 GEN IV Hybrid 2.5L Performance Simulation

12-29-19

http://www.vxphysics.com/EV%20Performance/Rav4_Gen_IV_2.5L_Hybrid%20Simulation-WU.xmcd

Macro Model of Hybrid Vehicle Performance: RAV4 Gen IV Hybrid

Procedure to determine Torque for ICE and Motor M2:
First model of the "Recreational Activity Vehicle: 4-wheel drive" RAV4 Internal Combustion Engine's (ICE) and the motor's, torque and power. Define vehicle and road parameters.

RAV4 Hybrid Synergy Drive: MG1 Starter/Generator and Controller Acceleration Protocol

MG1 is the battery initiated starter for the ICE. "Simulate" MG1's spin startup, $\Omega 1init_{m2}$ and $\Omega 1init_{ice}$, as a ramp from 0 to its maximum speed, along with the motor M2 and ICE, respectively, which are also driven by the RAV4 Controller to ramp up. Refer to Startup Curves on bottom of page 6. This is an arbitrary set of conditions just to start the generator turning. Note that this startup is not a function of time, but of corresponding rotations. This startup condition simulates a low gear mode for the ICE.

Evaluate two different RAV4 Control Strategies: Max Acceleration and Nominal. See curves on page 4.

During acceleration, the **largest torque** is from motor/generator **MG2**, which is geared to the axle. The axle determines the vehicle speed. Use the MG2 rotation, ω_{m2}, as our control variable. During acceleration, supply peak electrical power to MG2 from **both the battery** (peak battery power for 10 seconds) and from **MG1**, which is now run as a generator at it's max speed and is mechanically driven by the ICE.

As MG2 speeds up and demands increasing power, throttle back it's peak drive/torque by limiting the MG2's electrical power input to the peak Inverter Output, i.e. the sum of the battery's and MG1 generator's peak power. Refer to the curve of M2 Torque vs.ω_{m2} on page 3. **4th Gen RAV4**: All Wheel drive, AWD. AWD uses 3rd motor (MGR) (50kW) mounted in rear. Operates independently from front motor, drives rear wheels only.

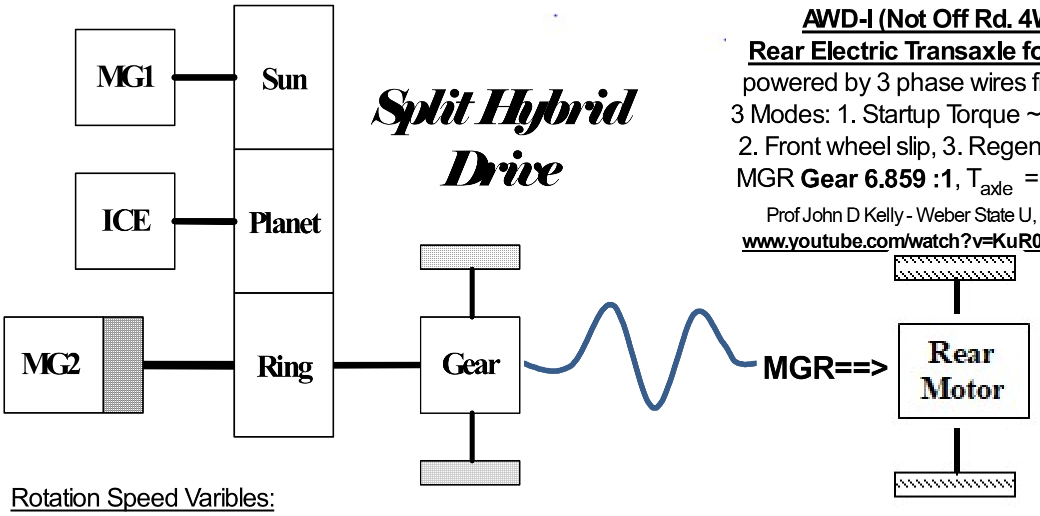
Peak acceleration and 0 - 60 mph is programmed by setting the MG1 max speed: Ωmax_{m1}

Use equations for vehicle dynamics to calculate the time to 60 mph. Plot performance simulation curves. Calculate All Electric Range, AER, miles from a single charge of the battery. Calculate AER using various EPA driving modes.

Basic Description of RAV4
http://en.wikipedia.org/wiki/Toyota_RAV4

Description and Design of Synergy (Planetary Gear) Drive
Refer to: **US Patent: US6005297**

RAV4: Hybrid Synergy 4-Wheel Drive



AWD-I (Not Off Rd. 4WD)
Rear Electric Transaxle for MGR:
powered by 3 phase wires from front.
3 Modes: 1. Startup Torque ~ 0-3 mph,
2. Front wheel slip, 3. Regen braking.
MGR **Gear 6.859 :1**, T_{axle} = 659 lb-ft
Prof John D Kelly - Weber State U, Utah
www.youtube.com/watch?v=KuR0cihFAvQ

Total T_{axle}
2700 lbf-ft

Front T_{axle}
= 2160 lbf-ft

M2 GR
8.88 : 1

$GR_{m2} := 2.636$
Motor M2
Grear
Reduction

$GR_{m2} := 1$

Rotation Speed Varibles:

MG1, MG2, and Engine: ωm1, ωm2, and ωice.

Power Efficiencies:

Inverter, axle to tire, engine to MG1, reduction gear, and engine to axle efficiencies ηinv, ηaxle, ηeng_m1, ηred, and ηaeng_axle

RAV4 Gen IV Hybrid Synergy Specs

Atkinson 4-Cycle Internal Combustion Engine

2.5 L Atkinson 4-cycle

Power: 150 hp (112 kW) @5700 rpm

Torque; 152 fl-lbf (206 N-m)@4400 rpm

Traction Motors M1, M2, M3 - PM Magnet Synchronous

M2 Front Motor: 105 kW (141 hp), 199 ft-lbf, (270 N-m)

M3 Rear Motor, MGR: 50 kW (67 hp), 103 ft-lbf, (139 N-m)

M3 Rear Motor Output can add to MG2 for charged battery

Total 194 hp, 145 kW, **Total T_{axle}:** 2700 lbf-ft (3661 N*m)

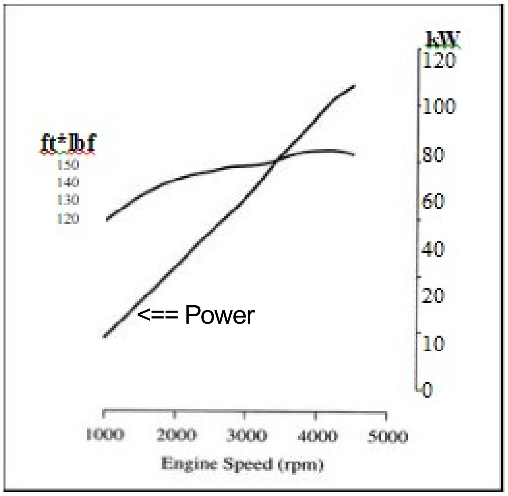
M2: GR 8.88 Front T_{axle} = 2160 lbf-ft,

MGR: GR 6.86 T_{axle} = 659 lbf-ft

Battery: NiMH 24 12-volt cells, 244V, 1.6kW-hr

0-60 mph: 8.1 s Curb Weight: 3950 lbs

Scale Up Prius 1.8L Atkinson ICE to 2.5L
RAV4 Gen IV 2.5L Torque & Power Specs



Toyota Atkinson Gen IV 2.5L ICE Model: Scale the Power and Torque Curves from Above Prius Gen III 1.8L

RAV4 Gen IV ICE Torque and Power Models:

$$k := 1000 \qquad T_{idle} := 85 \qquad \Omega_{idle} := 1000 \qquad P_{idle} := T_{idle} \cdot \left(\frac{2 \cdot \pi \cdot \Omega_{idle}}{60 \cdot k} \right) \qquad P_{slope} := \frac{57 - P_{idle}}{4000} \qquad T_{slope} := \frac{60.23 - P_{idle}}{60 \cdot k}$$

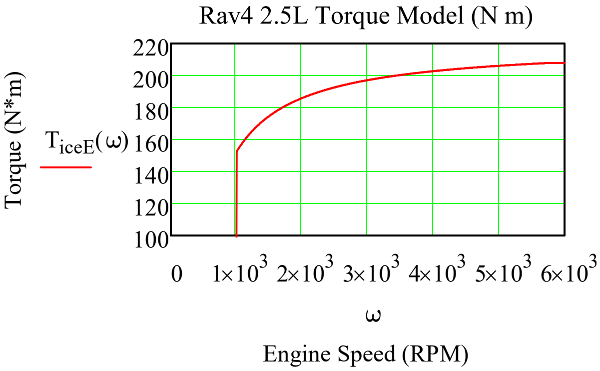
$$PIII_{ice}(\omega) := \text{if}\left[\omega < \Omega_{idle}, 0, P_{idle} + P_{slope} \cdot (\omega - \Omega_{idle})\right] \qquad TIII_{ice}(\omega) := \text{if}\left[\omega < \Omega_{idle}, 0, P_{idle} + T_{slope} \cdot (\omega - \Omega_{idle})\right] \cdot \frac{60 \cdot k}{2 \cdot \pi \cdot \omega}$$

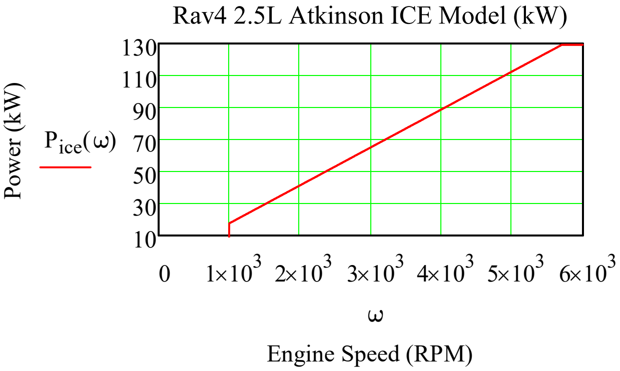
$$TIII_{ice}(\omega) := \text{if}\left(\omega > 5700, TIII_{ice}(5700), TIII_{ice}(\omega)\right) \qquad PIII_{ice}(\omega) := \text{if}\left(\omega > 5700, PIII_{ice}(5700), PIII_{ice}(\omega)\right)$$

Scale Up to Gen IV Specs:

$$X_P := \frac{150}{76} \qquad X_T := \frac{206}{115} \qquad P_{ice}(\omega) := PIII_{ice}(\omega) \cdot X_P \qquad T_{iceE}(\omega) := TIII_{ice}(\omega) \cdot X_T$$

2.5L ICE Model Approximations





Model Equations for the Driveshaft, ICE, and Planetary Gears

Simulation of a Series Hybrid Electric Vehicle based on Energetic Macroscopic Representation

W. Lhomme1, A. Bouscayrol1, Member, P. Barrade2

$$J \cdot \frac{d}{dt} \Omega_{shaft} + f \cdot \Omega_{shaft} = T_{ice} - T_{dcg}$$

$$P_{ice} = m_{ice} \cdot k_{ice} \cdot \Omega_{shaft}$$

$$T_{ice} = m_{ice} \cdot k_{ice} \cdot D_{gas}$$

$$k_{ice} = \frac{\eta \cdot \rho \cdot P_c}{\Omega_{ice\_max}}$$

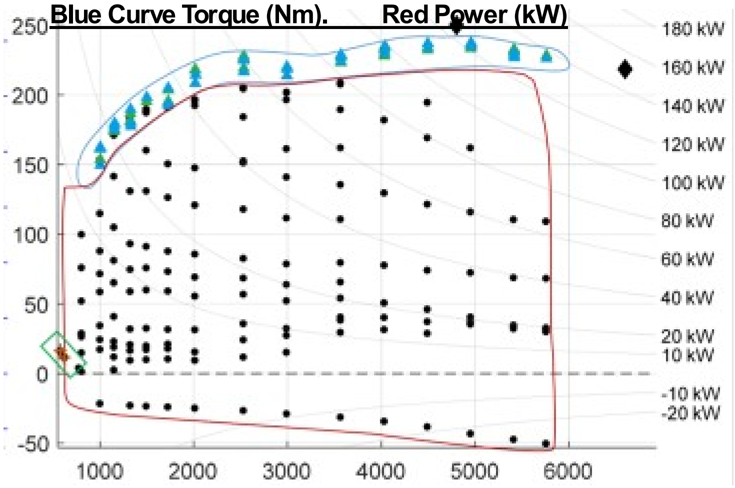
$$\omega_{mg1} + 2.6 \cdot \omega_{mg2} = 3.6 \omega_{ice}$$

J, f, and Ωshaft are the moment of inertia, friction coefficient, and speed of the shaft. Tice and Tdcg are the ICE and generator torques. The ICE pressure, Pice, results from the flow of gasoline. η is the ICE efficiency, ρ the density of gasoline (D_{gas}), P_c the calorific value of gasoline and Ω_{ice_max} the maximum rotation speed of the engine. The control of the machine is ensured by the m_{ice} ratio, which defines the actual flow of gasoline, dgas, through a specific actuator.

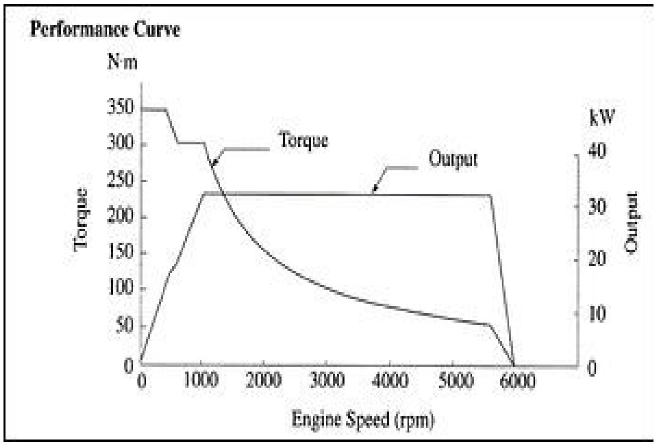
The relation for the shaft rotational velocities, ωice, ωmg1, and ωmg2/axle gear corresponding to Planet, Sun, Ring, describes the action of the Hybrid Synergy Drive *Planetary Gear* (shown in the above illustration).

Planet Gears: ω of sun, ring, planet gears vs. # teeth, N: $\omega_s \cdot N_s + \omega_r \cdot N_r = (N_s + N_r) \omega_p$

2018 Camry (Not-Hybrid) 2.5L A25A-FKS Atkinson
Blue Curve Torque (Nm). Red Power (kW)



Gen III Prius (Not RAV4) MG2 Motor Performance



Toyoto RAV4 Gen IV 2.5L-Vehicle, Motor and Road Parameters: **Specifications for Different RAV4**

Gear Ratio and Efficiencies: $GR := 8.878$ $\eta_{inv} := 0.90$ $\eta_{eng\_axle} := 0.95$ $\eta_{axle} := 0.95$ $\eta_{eng\_m1} := 0.95$ $\eta_{red} := 0.95$

Max Motor Power: $Pmax_{m2} := 105\cdot kW\cdot \eta_{axle}$ $Pmax_{m1} := 50\cdot kW\cdot \eta_{eng\_m1}$ $Pmax_{ice} := 112\cdot kW\cdot \eta_{eng\_m1}$

$Pmax_{m1} = 63.699\cdot hp$ $Pmax_{ice} = 142.685\cdot hp$

Max Motor Torque: $Tmax_{m1} := 139\cdot ft\cdot lbf\cdot \eta_{eng\_m1}$ $Tmax_{ice} := 152\cdot N\cdot m\cdot \eta_{eng\_m1}$

$Tmax_{m2} := 270 N\cdot m\cdot GR_{m2}\cdot \eta_{axle}$

$r_{tire} := 0.362\cdot m$ $RPM := min^{-1}$

Max Motor Speeds: **Max. Acceleration Mode==>** $\Omega max_{m1} := 6700\cdot RPM$ $\Omega max_{ice} := 5700\cdot RPM$

$\Omega max_{m1} := \Omega max_{m1}$ $Tmax_{m1}\cdot \Omega max_{m1} = 19.992\cdot kW$ Note MG1's power is speed (6500 rpm) limited

Set Pmaxbat to 0 for Extremum

$Redline := \Omega max_{ice}\cdot min$ $Tmax_{m2} = 256.5\cdot N\cdot m$ $Energy_{bat} := 1.6\cdot kW\cdot hr$ $Pmax_{bat} := 27\cdot kW$

Chassis and Environmental Parameters

Average Wind Velocity: $Vw := 0\cdot mph$ Frontal Area*: $Afg := 3.1\cdot m^2$

Shape Correction Factor: $SCF := 0.85$ Frontal Area Corrected: $Af := Afg\cdot SCF$ $Af = 2.635\cdot m^2$

Drag Coeff: $Cd := 0.30$ Rolling Resistance Per Tire: $RR_{tire} := 0.007$

Cross Wind Drag Coff: $Cd_{cw} := 0.000014$ (Average 0% road grade) $\theta := atan(0.0)$ θ (radians):

Air Density: $\rho := 1.293\cdot \frac{gm}{liter}$ Average Cross Wind: $V_{cw} := 0\cdot mph$

Road Rolling Resist: $RR_{road} := 0.002$ Curb Weight: $M_{curb} := 3950\cdot lb$

Rotational Inertia Coeff: $k_m := 1.08$ Passenger Weight: $Passengers2 := 170\cdot lb$

Gross Weight: $M_{gross} := M_{curb} + Passengers2$ $M_{gross} = 4120\cdot lb$ $M_{batt} := 9.999\cdot kg\cdot \frac{1.6}{1.3}$

Vehicle Dynamics Equations - Find Velocity and Time for Maximum Acceleration

Road Resistance, Fr: $Fr(v) := M_{gross}\cdot g\cdot\left[\left(RR_{tire} + RR_{road}\right)\cdot cos(\theta) + sin(\theta)\right]$ $Fr(60\cdot mph) = 164.94\cdot N$

Aerodynamic Loss, Fa: $Fa(v) := 0.5\cdot \rho\cdot Af\cdot\left[(v + Vw)^2\cdot Cd + Cd_{cw}\cdot\left(0.5\cdot v + V_{cw}\right)^2\right]$ $Fa(60\cdot mph) = 367.681\cdot N$

Opposing Force, Fo: $Fo(v) := Fa(v) + Fr(v)$ $Fo(60\cdot mph) = 532.621\cdot N$ $Fo(60\cdot mph) = 532.621\cdot N$

Velocity vs Shaft (MG2 Rotaional Speed) and Hybrid Synergy Gearing

$M2rpm\_at\_mph(s) := \frac{GR\cdot s}{\left(2\cdot \pi\cdot r_{tire}\cdot RPM\right)}$ $velMG2\_at\_rpm(\omega) := \frac{2\cdot \pi\cdot r_{tire}\cdot \omega\cdot RPM}{GR}$ $v\_r(\omega) := \frac{2\cdot \pi\cdot r_{tire}\cdot \omega\cdot RPM}{GR\cdot mph}$

Control Strategies (Hybrid Synergy Drive Speed Relationships):
Develop an MG1 Profile and then Find Speed Relationships of MG2(ICE) and ICE(MG2)

ω_{mg2} is not defined. Only specified as an IF xx, --> Then yy condition or range variable.

Max Acceleration Control Strategy P1: Turn on ICE at 15 mph (See Control Plot)

Hybrid Synergy Drive
MG1 Control Stategy:
Max MG1 Rotation
Ωmax_{m1}
Initial M2 Spinup (Ωm1),
$\Omega 1init_{m2}(\omega_{mg2})$
and Driving Profiles,
$\Omega 1Prfl_{m1}$, $\Omega 1Prfl2_{m1}$

Apply maxium MG1 power/speed Ωmax_{m1} = 8500 RPM from Generator MG1 to MG2.

$$\Omega 1init_{m2}(\omega_{mg2}) := \text{if}\left(\omega_{mg2} < 700 \wedge Pmax_{bat} > 1\cdot kW, 1000 + \frac{\Omega max_{m1}}{820}\cdot\frac{\omega_{mg2}}{RPM}, \Omega max_{m1}\cdot min\right)$$

$$\Omega 1init_{ice}(\omega_{ice}) := \text{if}\left(\omega_{ice} < 1700 \wedge Pmax_{bat} > 1\cdot kW, 1000 + \frac{\Omega max_{m1}}{1950}\cdot\frac{\omega_{ice}}{RPM}, \Omega max_{m1}\cdot min\right)$$

$$\Omega 1Prfl_{m1}(\omega_{mg2}) := \Omega 1init_{m2}(\omega_{mg2})$$

Nominal Control Strategy P2: Constant ICE (rpm= 1800) to 60 mph, then ramp up. Profile 2- $\Omega 1Prfl2_{m1}$

Use just $\Omega_{ice\_vel}(vel)$ to find resultant relation between MG1 and Velocity, i.e. MG2

$$Vel_{rev\_up} := 60 \qquad \Omega_{ice\_vel}(vel) := \text{if}\left[vel < Vel_{rev\_up}, 1800, 1800 + (vel - Vel_{rev\_up})\cdot\frac{4000 - 1800}{100 - Vel_{rev\_up}}\right]$$

Calculate Control Point:
Rev up ICE from Cruise at Vehicle Velocity Vel_{rev_up}
See Plot Lower Right

$$\Omega_{iceVel}(\omega_{mg2}) := \Omega_{ice\_vel}\left(\frac{velMG2\_at\_rpm(\omega_{mg2})}{mph}\right) \qquad \Omega_{iceVel}(5000) = 1800$$

$$\Omega 1Prfl2_{m1}(\omega_{mg2}) := 3.6\cdot\Omega_{iceVel}(\omega_{mg2}) - 2.6\omega_{mg2}$$

Examination of above then gives us the form of $\Omega 1Prfl2_{vm1}(v)$

$$\Omega 1Prfl2_{vm1}(v) := \text{if}\left[v < 60, 6500 - \frac{7500}{60}\cdot v, -1000 + (v - 60)\cdot\frac{4000}{60}\right] \qquad xm2 := 1500$$

ICE and MG2 Rotation Profiles From MG1 Profiles Ω1Prfl1m1 (Enabled) or Ω1Pffl2m1 (Disabled):

$$\Omega_{ice}(\omega_{mg2}) := \frac{\left(\Omega 1Prfl_{m1}(\omega_{mg2}) + 2.6\cdot\omega_{mg2}\right)}{3.6} \qquad \Omega_{mg2}(\omega_{ice}) := root\left(xm2 - \frac{\omega_{ice}\cdot 3.6 - \Omega 1Prfl_{m1}(xm2)}{2.6}, xm2\right)$$

$$\Omega_{ice}(\omega_{mg2}) := \frac{\left(\Omega 1Prfl2_{vm1}(v\_r(\omega_{mg2})) + 2.6\cdot\omega_{mg2}\right)}{3.6} \qquad \Omega_{mg2}(\omega_{ice}) := root\left(xm2 - \frac{\omega_{ice}\cdot 3.6 - \Omega 1Prfl2_{vm1}(v\_r(xm2))}{2.6}, xm2\right)$$

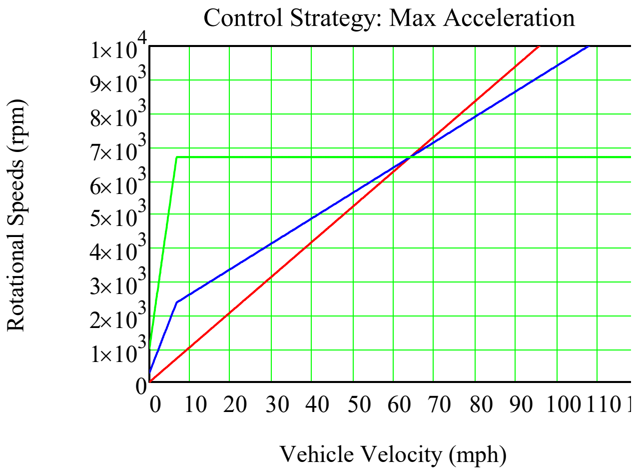
Use these expressions Just for generating plots at bottom of page

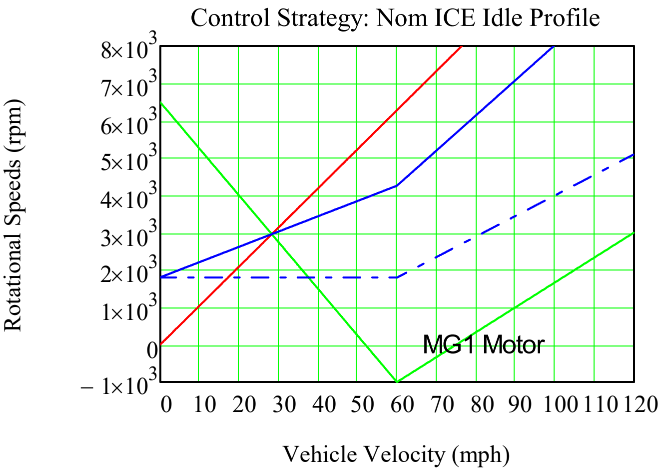
$$\Omega_{iceP1}(\omega_{mg2}) := \frac{\left(\Omega 1Prfl_{m1}(\omega_{mg2}) + 2.6\cdot\omega_{mg2}\right)}{3.6} \qquad \Omega_{iceP2}(\omega_{mg2}) := \frac{\left(\Omega 1Prfl2_{vm1}(v\_r(\omega_{mg2})) + 2.6\cdot\omega_{mg2}\right)}{3.6}$$

$$\Omega_{ice}(M2rpm\_at\_mph(120\cdot mph)) = 1.093\times 10^{4}$$

Control Stategy Plots: Max Acceleration and Nominal Cruise Profiles

Plot Colors: **MG2 Shaft Rotational Speed (Red)**, **ICE RPM (Blue)**, and **MG1 Rotor (Green)**.
Note Max Accel Plot: ICE does not turn on until MG2 propels Vehicle Speed up to 10 mph





Given Control Acceleration Stategy $\Omega 1$Prfl1m1: Calculate Power and Torque

Torque, ICE: $T_{icem2}(\omega_{mg2}) := T_{iceE}(\Omega_{ice}(\omega_{mg2}))\cdot N\cdot m$ $\Omega 1Prfl_{m1}(7000) = 6700$

Torque,MG1: $T_{m1}(\omega_{mg2}) := -T_{icem2}(\omega_{mg2})\cdot 3.6^{-1}\cdot\eta_{eng\_m1}$

$$PinvA_{m2}(\omega_{mg2}) := \eta_{inv}\cdot(Pmax_{bat} - T_{m1}(\omega_{mg2})\cdot 2\cdot\pi\cdot\Omega max_{m1})$$

$$PinvB_{m2}(\omega_{mg2}) := if(PinvA_{m2}(\omega_{mg2}) \ge Pmax_{m2}\cdot\eta_{inv}, Pmax_{m2}\cdot\eta_{inv}, PinvA_{m2}(\omega_{mg2}))$$

Max Power to Inverter: < P2max, P1max + Pbatmax and Pm1< P1max and Pice x 2.6/3.6

MG2 Inverter Power, Pinv:

$$Pinv_{m2}(\omega_{mg2}) := if\left[-(T_{m1}(\Omega 1init_{m2}(\omega_{mg2}))\cdot 2\cdot\pi\cdot\Omega max_{m1}) > Pmax_{m1}, (Pmax_{bat} + Pmax_{m1})\cdot\eta_{inv}, PinvB_{m2}(\omega_{mg2})\right]$$

Torque MG2
Power Limited
Break Point, ω_{inv}

Problem, Find ω_{inv} such that:
$(Tmax_{m2})\ \omega_{inv} = Pinv_{m2}(\omega_{inv})$

Guess for winv, wx: $wx := if(Pmax_{bat} < 1\cdot kW, 8, 800)$

$$\omega_{inv} := root\left[Tmax_{m2} - \frac{Pinv_{m2}(wx)}{(2\cdot\pi\, wx + 1)\cdot RPM}, wx\right]$$

Solution (rpm): $\omega_{inv} = 2143.896$

Torque, MG2: $T_{m2}(\omega_{mg2}) := if\left(\omega_{mg2} \le \omega_{inv}, Tmax_{m2}, \frac{Pinv_{m2}(\omega_{mg2})}{2\cdot\pi\,\omega_{mg2}\cdot RPM}\right)$ $T_{m2}(\omega_{inv})\cdot 2\cdot\pi\,\omega_{inv}\cdot RPM = 57.586\cdot kW$

Tractive Torq, Total: $T_{tot}(\omega_{mg2}) := T_{m2}(\omega_{mg2}) + T_{icem2}(\omega_{mg2})\cdot\frac{2.6}{3.6}\cdot\eta_{eng\_axle}$ $P_{m2}(\omega) := T_{m2}(\omega)\cdot 2\cdot\pi\cdot\omega\cdot RPM$

Tractive Road Force, Total: $Ft\omega(\omega_{mg2}) := \frac{T_{tot}(\omega_{mg2})\cdot GR\cdot\eta_{red}}{r_{tire}}$ $T_{m2}(1000) = 256.5\cdot N\cdot m$

Tractive Road Force, Total: $F_{tot}(v) := \frac{T_{tot}(M2rpm\_at\_mph(v))\cdot GR\cdot\eta_{red}}{r_{tire}}$ $P_{M2}(\omega) := \frac{P_{m2}(\Omega_{mg2}(\omega))}{kW}$

Plot Terms: $P_{tot}(v) := F_{tot}(v)\cdot v$ $P_{tot}(60\cdot mph) = 194.48\cdot hp$

Applying maximum motor torque, find the velocity and time starting from initial velocity = 0 mph.

Third Law of Motion:
(dv/dt is acceleration)

Given $a(v) := \frac{F_{tot}(v) - Fo(v)}{k_m\cdot M_{gross}}$ $End := 40$

$V := 0\cdot mph$ $vel(t) := root\left(t\cdot sec - \int_0^V \frac{mph}{a(V\cdot mph)}\,dV, V\right)\cdot mph$ $time(v) := \int_0^v \frac{1}{a(v)}\,dv$ $time(60mph) = 8.022\,s$

$vel(8.022) = 60.001\cdot mph$

$velocity(t) := vel(t)$

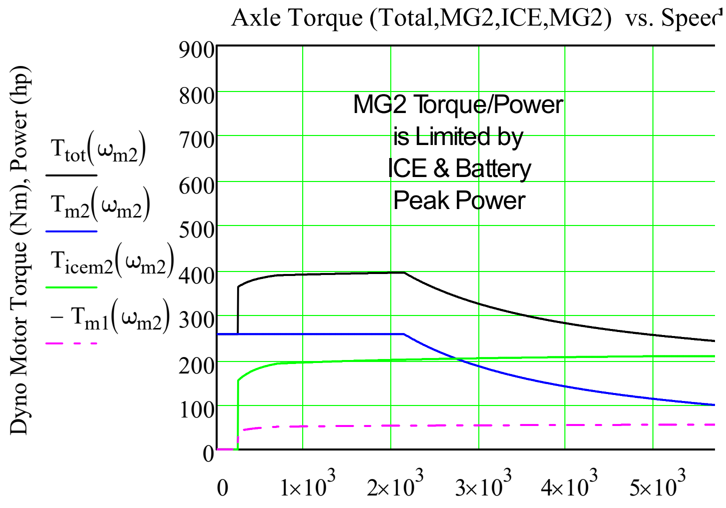
$a(85mph) = 0.197\cdot g$ $v_{gfall} := 85$ $time(60mph) = 8.022\,s$

$$accel(t) := \frac{F_{tot}(velocity(t)) - Fo(velocity(t))}{k_m\cdot M_{gross}}$$ $P_t(\omega_{m2}) := T_{tot}(\omega_{m2})\cdot 2\cdot\pi\cdot\omega_{m2}\cdot RPM\cdot kW^{-1}$

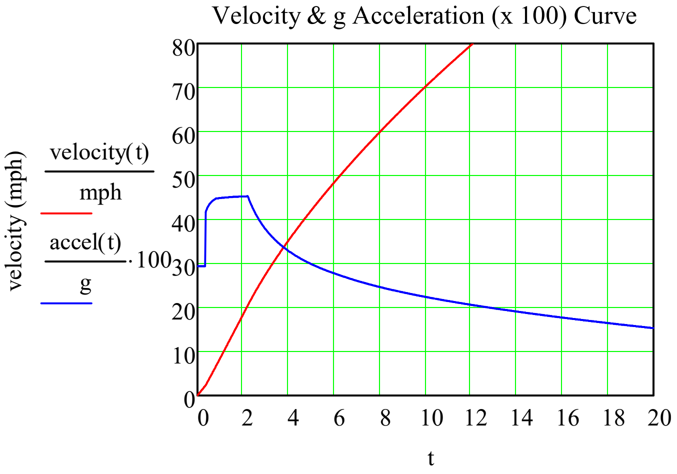
$Time := 0\cdot sec$ $time(v) := root(v - velocity(Time), Time)$

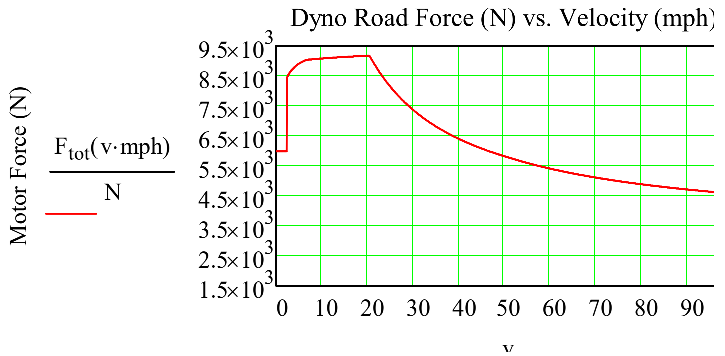
Passing 40 to 60 mph: $Passing := time(60\cdot mph) - time(40\cdot mph) = 3.342\,s$

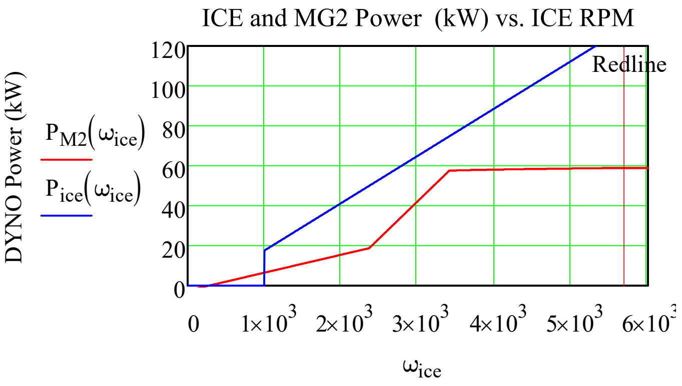
RAV4 GEN IV PEFORMANCE SIMULATION CURVES

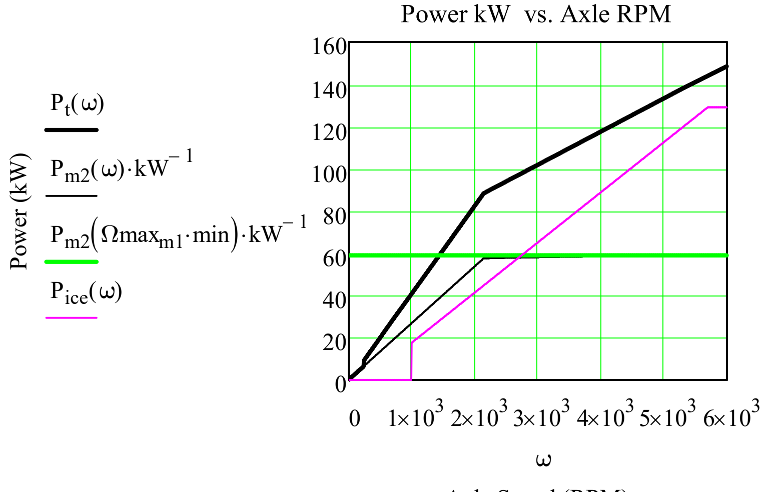

Axle Torque (Total,MG2,ICE,MG2) vs. Speed

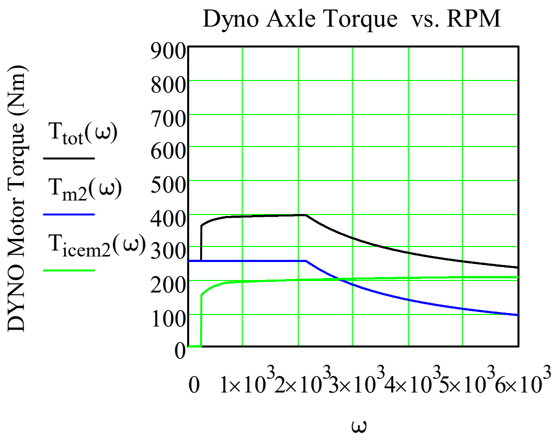
MG2 Torque/Power is Limited by ICE & Battery Peak Power

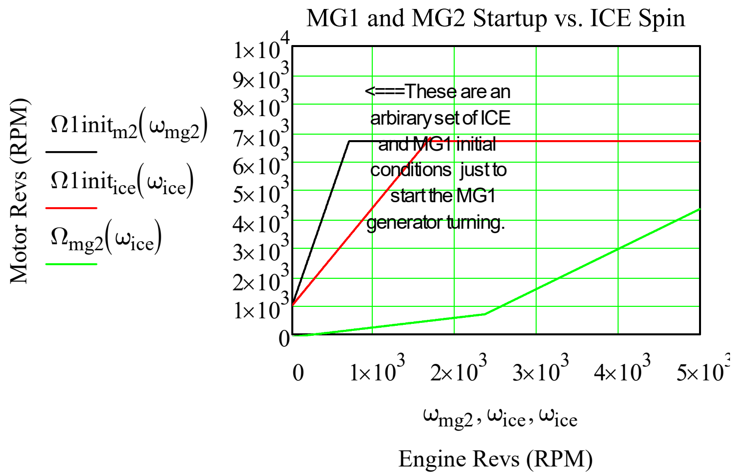

Velocity & g Acceleration (x 100) Curve


Dyno Road Force (N) vs. Velocity (mph)


ICE and MG2 Power (kW) vs. ICE RPM

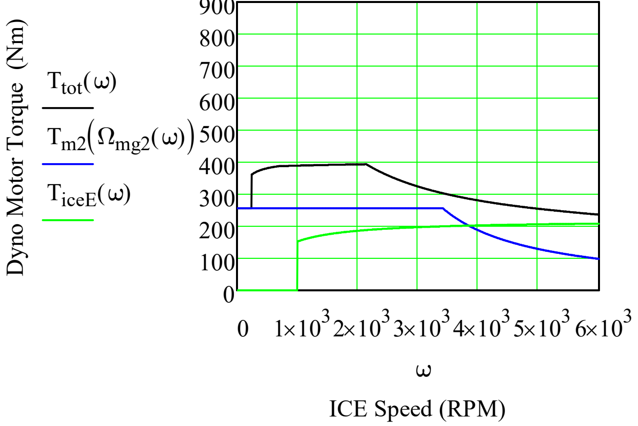

Power kW vs. Axle RPM


Dyno Axle Torque vs. RPM


MG1 and MG2 Startup vs. ICE Spin

<===These are an arbirary set of ICE and MG1 initial conditions just to start the MG1 generator turning.

$GR_{m2} = 1$


Dyno Torque vs. ICE RPM

Find the Single Charge (@SOC = 50%) Cruise Range for a given Velocity

Driving Pattern/Profile:

Given we **cruise at constant speed** and Time for start, stop, and regen breaking, **Time_{ssr}= every 15 minutes**.

Drive Train Power Efficiency - Battery Loss to Force Commanded Vehicle Velocity:

State of Charge for generator is SOC_{gen}. **SOC_{gen} is 70% for recharge.** 201V HV battery **idle power is Po**. 12V battery gives Accessory Power. The Traction Inverter x motor Efficiency - TInvE, HV Power Electronics at Idle Efficiency - IPEE, and Gear Power Efficiency - GPE are 90%, 95%, and 97%, respectively. Brake Regen efficiency of kinetic energy is 60% @ deacceleration = 0.315g. Then the number of starts per hour as a function of velocity, NS, NumStarts(v, Po), is3

$NS_o(v) := 1$ $\quad TInvE := 0.90$ $\quad IPEE := 0.95$ $\quad GPE := 0.97$ $\quad Regen := 0.6$ $\quad SOC_{gen} := 0.7$

$$\text{Power}_{dissLoss}(v, P_o) := \frac{Fo(v)\cdot v}{TInvE\cdot GPE} + \frac{P_o\cdot watt}{IPEE}$$

USABC Round Trip Battery Energy Efficiency

$$RTEff := 0.92$$

$$\text{Energy}_{accel}(v) := \text{Pmax}_{m2}\cdot time(v)$$

NSo, NS are iterative converging estimates of total NumStarts per charge

$$NS_o(v) := 2\cdot\left[\frac{65mph}{(v + 0.1\cdot mph)}\right]^2$$

$$NS(v, P_o, SOC_f) := \frac{\text{Energy}_{bat}\cdot(1 - SOC_f) - NS_o(v)\cdot\left[\left[\frac{M_{gross}\cdot(v)^2}{2}\cdot(1 - Regen)\right]\right]}{\text{Power}_{dissLoss}(v, P_o)\cdot 15\cdot min}$$

$$\text{NumStarts}(v, P_o, SOC_f) := \text{floor}\left[\frac{\text{Energy}_{bat}\cdot(1 - SOC_f) - NS(v, P_o, SOC_f)\cdot\left[\frac{M_{gross}\cdot(v)^2}{TInvE\cdot GPE}\cdot(1 - Regen)\right]}{\text{Power}_{dissLoss}(v, P_o)\cdot 15\cdot min}\right]$$

$$\text{Cruise\_Range}(v, P_o, SOC_f) := \frac{\left[\text{Energy}_{bat}\cdot(1 - SOC_f) - \text{NumStarts}(v, P_o, SOC_f)\cdot\left[\frac{Regen\cdot M_{gross}\cdot(v)^2}{TInvE\cdot GPE}\cdot(1 - Regen)\right]\right]\cdot v}{\text{Power}_{dissLoss}(v, P_o)}$$

Highway Cruise Range with Four Stops per Hour Estimate

$\text{Cruise\_Range}(30\cdot mph, 200, SOC_{gen}) = 3.464\cdot mi$

$\text{Cruise\_Range}(40\cdot mph, 200, SOC_{gen}) = 2.768\cdot mi$

$\text{Cruise\_Range}(50\cdot mph, 200, SOC_{gen}) = 2.188\cdot mi$

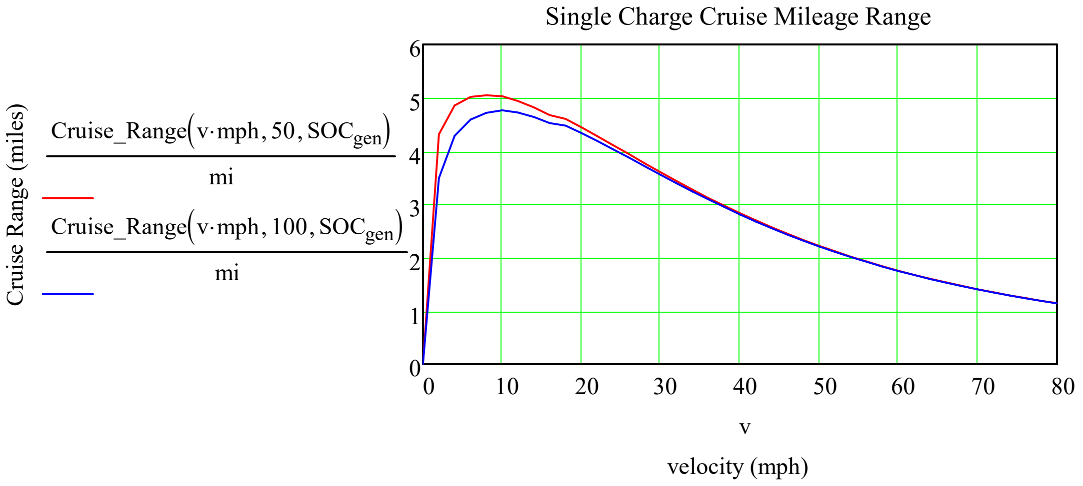
$\text{Cruise\_Range}(60\cdot mph, 200, SOC_{gen}) = 1.738\cdot mi$

$\text{Cruise\_Range}(70\cdot mph, 200, SOC_{gen}) = 1.396\cdot mi$

$\text{Cruise\_Range}(60\cdot mph, 200, SOC_{gen}) = 1.738\cdot mi$

$v := 0, 2 .. 80$

$\text{Cruise\_Range}(70\cdot mph, 50, 0.7) = 1.406\cdot mi$



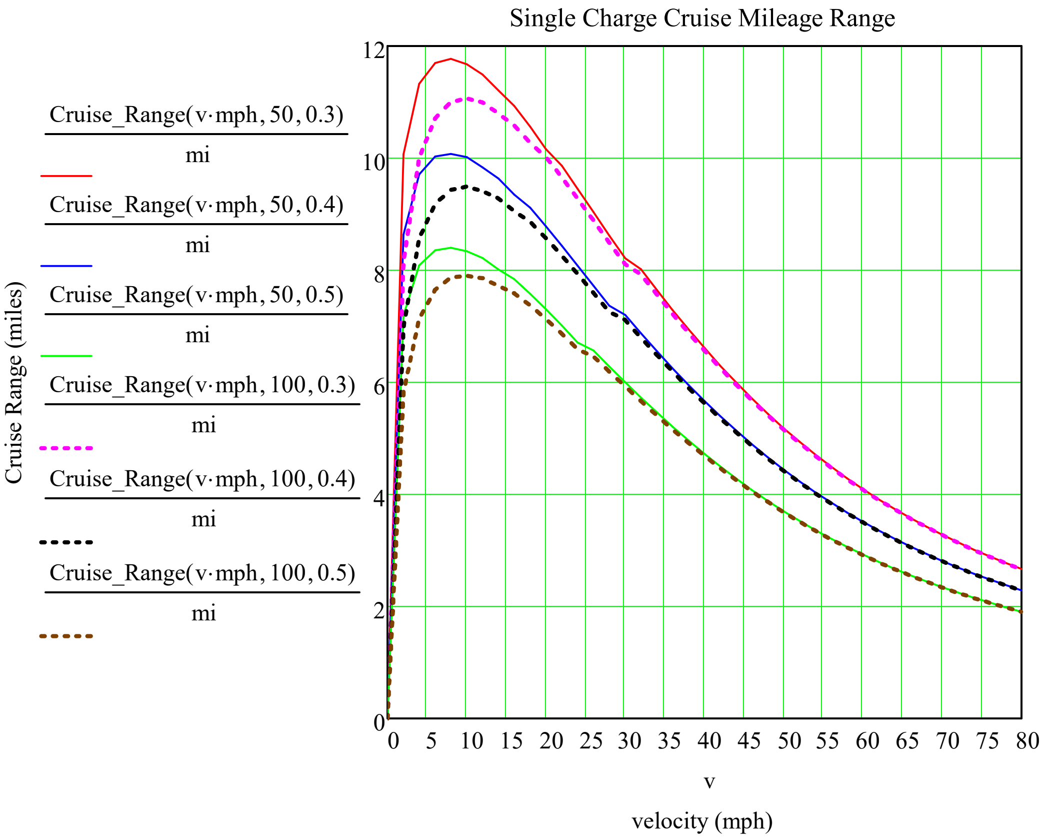
Cruise Range as a Function of Traction Battery Idle Power, Po

$$\mathrm{Cruise\_Range}(15\cdot\mathrm{mph}, 50, 0.3) = 11.101\cdot\mathrm{mi}$$

$$\mathrm{Cruise\_Range}(55\cdot\mathrm{mph}, 50, 0.5) = 3.284\cdot\mathrm{mi}$$

$$180\cdot\frac{\mathrm{km}}{\mathrm{hr}} = 111.847\cdot\frac{\mathrm{mi}}{\mathrm{hr}}$$

$$\frac{0.5 - 0.25}{0.5} = 0.5 \qquad \frac{\mathrm{Cruise\_Range}(55\cdot\mathrm{mph}, 100, 0.25) - \mathrm{Cruise\_Range}(55\cdot\mathrm{mph}, 100, 0.5)}{\mathrm{Cruise\_Range}(55\cdot\mathrm{mph}, 100, 0.5)} = 0.5$$



Find the Power to Maintain Constant Velocity

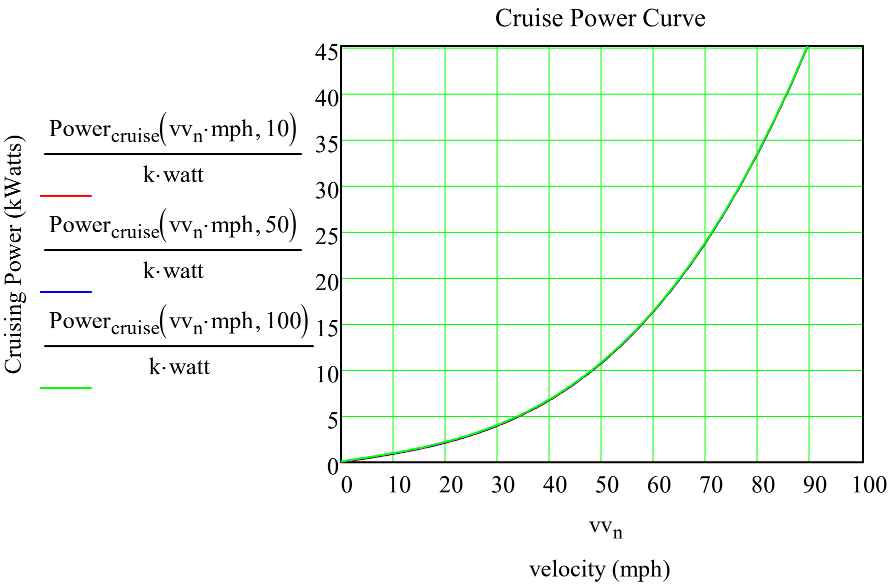
Note: The generator's output is 54 kW. This allows it produce a net charge up to 80 mph cruise.

$$\mathrm{Power_{cruise}}(v, P_o) := \mathrm{Power_{dissLoss}}(v, P_o)$$

$$\mathrm{Power_{cruise}}(60\cdot \mathrm{mph}, 100) = 16.47\cdot \mathrm{kW}$$

$$n := 0..200 \quad \tau_n := \frac{n}{10} \quad w_n := \frac{n}{20} \quad vv_n := \frac{n}{2}$$

$$P_{\mathrm{cruise}_n} := \frac{\mathrm{Power_{cruise}}(vv_n\cdot \mathrm{mph}, 100)}{k\cdot \mathrm{watt}}$$



FTPF := READPRN("http://www.leapcad.com/Transportation/FedTestProc.TXT")

UDDSF := READPRN("http://www.leapcad.com/Transportation/uddscol.txt")

HWYF := READPRN("http://www.leapcad.com/Transportation/hwycol.txt")

FP10 := READPRN("http://www.leapcad.com/Transportation/FTP10Hz.TXT")

HY10 := READPRN("http://www.leapcad.com/Transportation/HWY10Hz.txt")

US06F := READPRN("http://www.leapcad.com/Transportation/US06PROFILE.TXT")

AER Given Three Different Driving Schedules

Read US06 and FTP Driving Profile Files

http://www.epa.gov/nvfel/testing/dynamometer.htm

The US06 cycle represents an 8.01 mile (12.8 km) route with an average speed of 48.4 miles/h (77.9 km/h), maximum speed 80.3 miles/h (129.2 km/h), and a duration of 596 seconds.
The Federal Test Procedure(FTP) is composed of the UDDS followed by the first 505 seconds of the UDDS. It is often called the EPA75. FP10 is a 10 Hz Sampling. HY10 is the 10 Hz Highway schedule.

$$tx := FTPF^{\langle 0\rangle} \quad FTP := FTPF^{\langle 1\rangle} \quad \mathrm{rows}(FTP) = 1875$$

$$UDDS := UDDSF^{\langle 1\rangle} \quad \mathrm{rows}(UDDS) = 1370$$

$$HWY := HWYF^{\langle 1\rangle} \quad R_{hwy} := \mathrm{rows}(HWY)$$

$$FTP10V := \mathrm{submatrix}(FP10, 0, \mathrm{rows}(FP10) - 1, 1, \mathrm{cols}(FP10) - 1)$$

$$HWY10V := \mathrm{submatrix}(HY10, 0, \mathrm{rows}(HY10) - 1, 1, \mathrm{cols}(HY10) - 1)$$

$$time := US06F^{\langle 0\rangle} \quad US06 := US06F^{\langle 1\rangle} \quad n_6 := 0..598$$

All Electric Range, AER, for Driving Profile Velocity/Time File, P Sampling Rate, Hz, and SOC = 0

Regen Efficiency Curve vs Decel (g): $\mathrm{REff}(g) := \frac{85}{77}\cdot 0.01\cdot\left[\left(1-e^{-27.129\cdot g}\right)\cdot 91.235 - 28.408\right]$ $\quad Gg := \frac{\mathrm{mph}}{\mathrm{sec}\cdot g}$

```
$\mathrm{AER}(P, Hz) :=$
    $Ebat \leftarrow E_{diss} \leftarrow v_{old} \leftarrow 0$
    $n \leftarrow -1$
    $N \leftarrow \mathrm{rows}(P) - 1$
    while $E_{diss} < \frac{Energy_{bat}}{kW\cdot hr}$
        $n \leftarrow n + 1$
        $t \leftarrow \mathrm{mod}(n, N)$
        $v \leftarrow P_t$
        $v_{avg} \leftarrow (v + v_{old})\cdot 0.5$
        $P_{accel} \leftarrow \frac{k_m\cdot M_{gross}\cdot(v - v_{old})\cdot\frac{mph\cdot Hz}{sec}\cdot v_{avg}\,mph}{TInvE\cdot GPE}$ if $v > v_{old}$
        $P_{accel} \leftarrow k_m\cdot M_{gross}\cdot(v - v_{old})\cdot\frac{mph\cdot Hz}{sec}\cdot v_{avg}\,mph\cdot \mathrm{REff}\left[(v_{old} - v)\cdot Hz\cdot Gg\right]$ otherwise
        $E_{diss} \leftarrow E_{diss} + \frac{\left(Power_{dissLoss}(v\cdot mph, 100) + P_{accel}\right)\cdot sec}{kW\cdot hr\cdot Hz}$
        $v_{old} \leftarrow v$
        $Ebat_n \leftarrow E_{diss}$
    $R \leftarrow \sum_{m=0}^{n}\frac{\left(P_{\mathrm{mod}(m,N)} + P_{\mathrm{mod}(m+1,N)}\right)\cdot mph\cdot sec}{2\cdot mi\cdot Hz}$
    $R$
```

$r1 := 0 .. \mathrm{rows}(HY10)\cdot 10 - 1 \qquad HWY10_{r1} := HWY10V_{\mathrm{ceil}\left(\frac{r1+1}{10}\right)-1,\ \mathrm{mod}(r1, 10)}$

$\mathrm{AER}(US06, 1) = 3.714 \qquad \mathrm{AER}(FTP, 1) = 6.231 \qquad \mathrm{AER}(HWY, 1) = 5.439 \qquad \mathrm{AER}(HWY10, 10) =$

EPA 20085 Cycle MPG Fuel Economy Least Squares Fit Regression for AER to SOC = 0

$MPG_{city} := \frac{1}{\left(0.003259 + \frac{1.18053}{\mathrm{AER}(FTP, 1)}\right)} \qquad MPG_{city} = 5.189 \qquad MPG_{hwy} := \frac{1}{0.001376 + \frac{1.3466}{\mathrm{AER}(HWY, 1)}} \qquad X := \frac{1}{40}$

$MPG_{epa} := 0.55\cdot MPG_{city} + 0.45\cdot MPG_{hwy} \qquad MPG_{epa} = 4.661$

$r := 0 .. \mathrm{rows}(FTP) - 1 \qquad Distance_r := \sum_{r=0}^{r} FTP_r\cdot\frac{10}{60\cdot 60}$

$\max(Distance) = 110.414$

$rr := 0 .. \mathrm{rows}(US06) - 1 \qquad Distance_{.rr} := \sum_{rr=0}^{rr} US06_{rr}\cdot\frac{10}{60\cdot 60}$

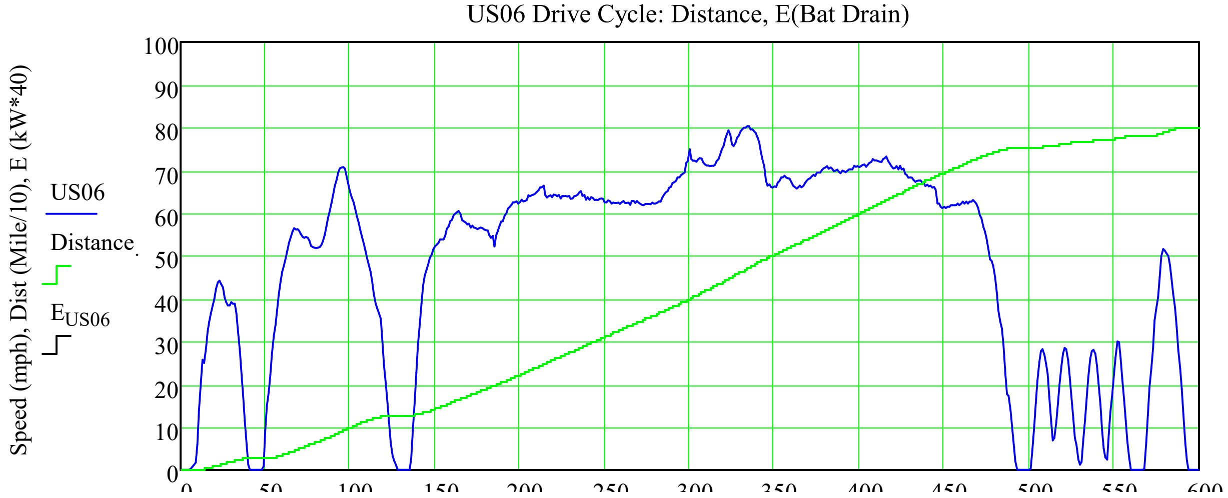
$\max(Distance_{.}) = 80.08$

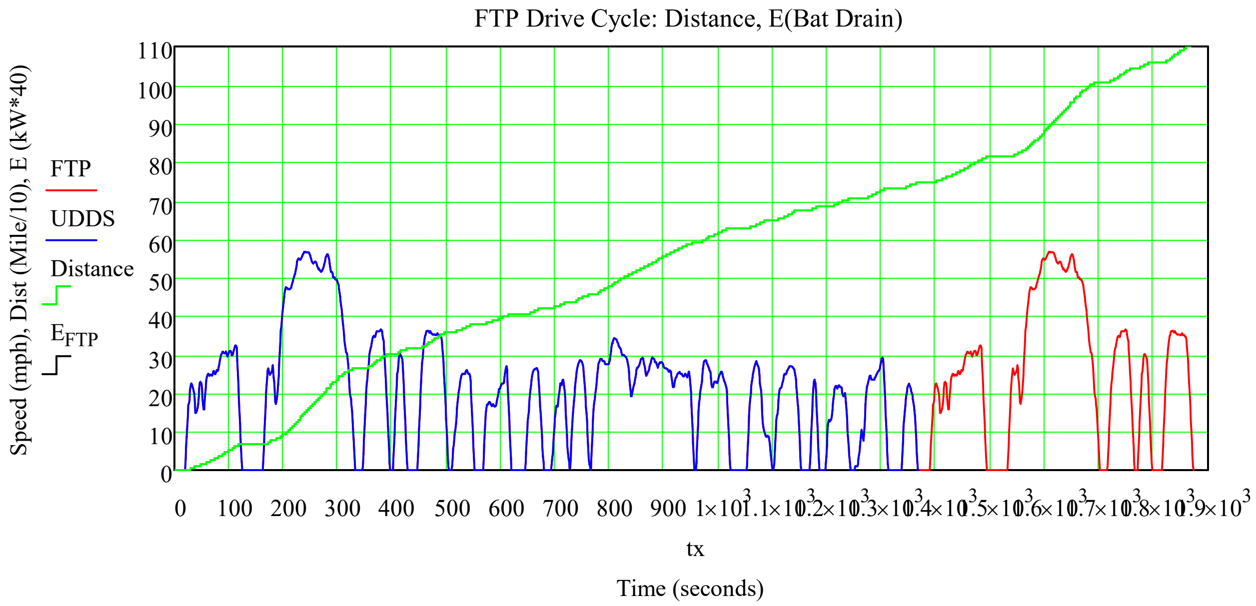
SAVE PROFILES

WRITEPRN("EFTP.PRN") := AER(FTP, 1)·40 E_{FTP} := READPRN("EFTP.PRN") $\max(E_{FTP})\cdot X = 6.23$

WRITEPRN("EUS06.PRN") := AER(US06, 1)·40 E_{US06} := READPRN("EUS06.PRN") $\max(E_{US06})\cdot X = 3.715$

WRITEPRN("EHWY.PRN") := AER(HWY, 1)·40 E_{HWY} := READPRN("EHWY.PRN") $\max(E_{HWY})\cdot X = 5.438$





Compare 2017 RAV4 (Black) vs. Sustaining Mode Volt (Red) Acceleration Performance

Read Charge Depletion Mode Data

Read Charge Sustaining Mode Data (**Disabled**)

Data Format in File: Time, Vel, Angular Speed, MPH, Accel(g), Torque(rpm), Power (rpm), Force(v), P(v)

Volt := READPRN("http://www.leapcad.com/Transportation/Volt_tVelwMAgTPmFP.prn")

Volt := READPRN("VoltGenOnly_tVelwMAgTPmFP.prn")

$\mathrm{cols}(\mathrm{Volt}) = 10 \qquad \mathrm{time}_v := \mathrm{Volt}^{\langle 0 \rangle} \qquad n := 0..300 \qquad P_{tot}(v) := F_{tot}(v \cdot \mathrm{mph}) \cdot v \cdot \mathrm{mph} \cdot \mathrm{hp}^{-1}$

$PT(v) := \dfrac{P_{tot}(v \cdot \mathrm{mph})}{\mathrm{hp}} \qquad v_v := \mathrm{Volt}^{\langle 1 \rangle} \qquad \omega_v := \mathrm{Volt}^{\langle 2 \rangle} \cdot k \qquad \mathrm{mph}_v := \mathrm{Volt}^{\langle 3 \rangle} \qquad g_v := \mathrm{Volt}^{\langle 4 \rangle} \qquad tz_n := \dfrac{n}{10}$

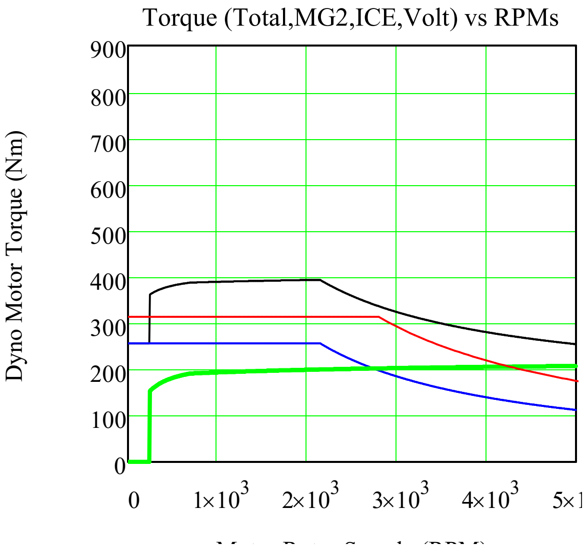
$q := (N \cdot m)^{-1} \qquad T_v := \mathrm{Volt}^{\langle 5 \rangle} \qquad P_v := \mathrm{Volt}^{\langle 6 \rangle} \qquad F_v := \mathrm{Volt}^{\langle 7 \rangle} \qquad Pv_v := \mathrm{Volt}^{\langle 8 \rangle} \qquad P_{cruiseV} := \mathrm{Volt}^{\langle 9 \rangle}$

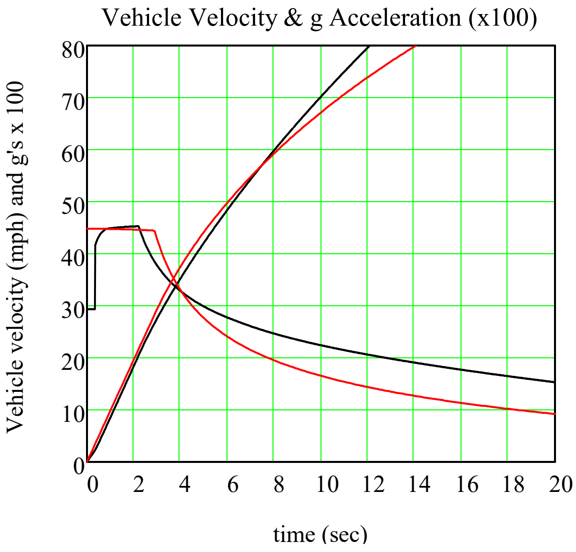
$\omega_{x_n} := \dfrac{6000 \cdot n}{200} \qquad Ttot_n := T_{tot}\left(\omega_{x_n}\right) \cdot q \qquad Tm2_n := T_{m2}\left(\omega_{x_n}\right) \cdot q \qquad Tice_n := T_{icem2}\left(\omega_{x_n}\right) \cdot q \qquad Vx_n := \mathrm{velocity}\left(tz_n\right)$

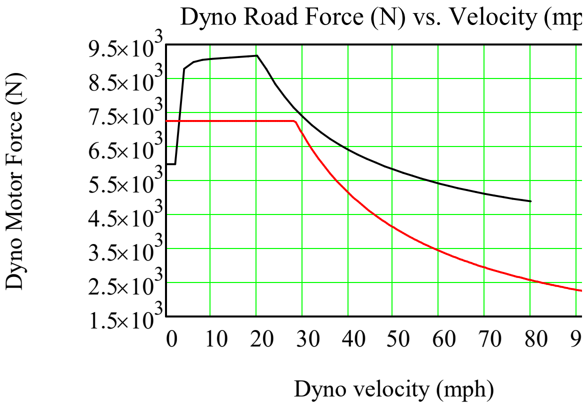
$Ax(Vx) := \dfrac{\left(F_{tot}(Vx \cdot \mathrm{mph}) - Fo(Vx \cdot \mathrm{mph})\right) \cdot 100}{k_m \cdot M_{gross} \cdot g} \qquad ax_n := Ax\left(Vx_n\right) \qquad Ft_n := \dfrac{F_{tot}\left(Vx_n \cdot \mathrm{mph}\right)}{N} \qquad Pt_n := \dfrac{P_{tot}\left(Vx_n \cdot \mathrm{mph}\right)}{\mathrm{hp}}$

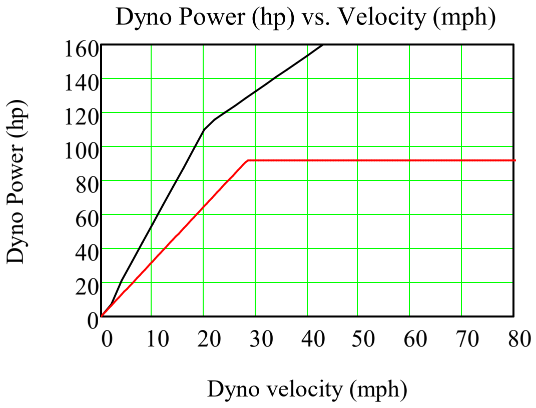
$PreWtTotM2ICVA := \mathrm{augment}\left(\omega_x, tz, Ttot, Tm2, Tice, Vx, ax, Ft, Pt\right) \qquad \mathrm{WRITEPRN}(\text{"Pre3PB0.txt"}) := PreWtTotM2ICVA$

Volt Power reduced from 111 kW to Generator Power x 90% = 47.7 kW in Sustaining Mode.
Volt 0 to 60 mph time increases from 8.5 to 15 seconds.
Volt 40 mph to 60 mph Sustaining passing time increased from 3.3 seconds to **8.5 seconds**.









Read Comparison Files Either for GenIV No Battery Power or Full Power Gen IV RAV4

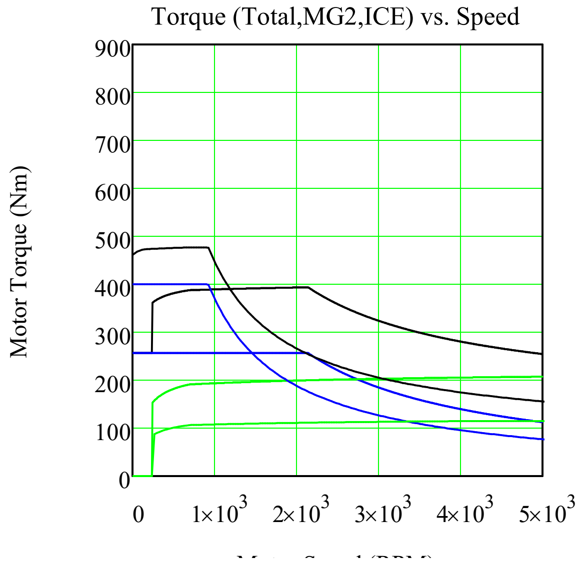
$\mathrm{Pre} := \mathrm{READPRN}(\text{"Pre3PB0.txt"})$ $\mathrm{Pre} := \mathrm{READPRN}(\text{"PreGenIII.txt"})$ PreWtTotM2ICVA

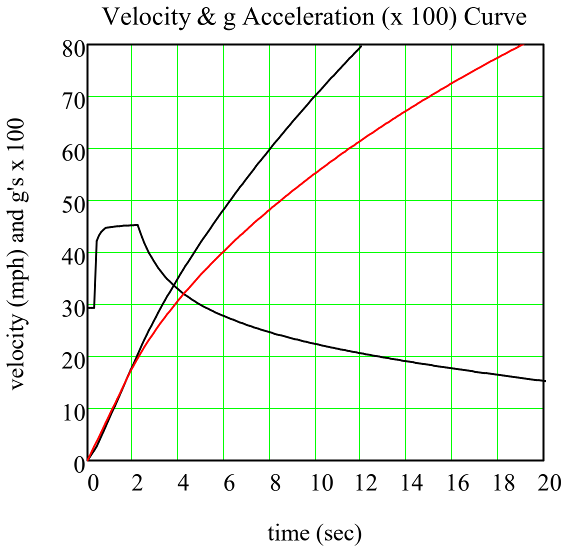
$\omega_z := \mathrm{Pre}^{\langle 0 \rangle}$ $\mathrm{time}_z := \mathrm{Pre}^{\langle 1 \rangle}$ $\mathrm{Ttotz} := \mathrm{Pre}^{\langle 2 \rangle}$ $\mathrm{Tm2z} := \mathrm{Pre}^{\langle 3 \rangle}$ $\mathrm{Ticez} := \mathrm{Pre}^{\langle 4 \rangle}$ $\mathrm{Vz} := \mathrm{Pre}^{\langle 5 \rangle}$ $\mathrm{az} := \mathrm{Pre}^{\langle 6 \rangle}$

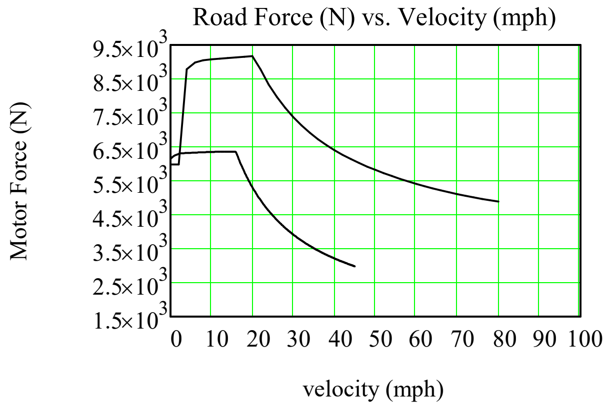
$\mathrm{Fz} := \mathrm{Pre}^{\langle 7 \rangle}$ $\mathrm{Pz} := \mathrm{Pre}^{\langle 8 \rangle}$ $\mathrm{Agx}(t) := \dfrac{\mathrm{accel}(t)}{g}$

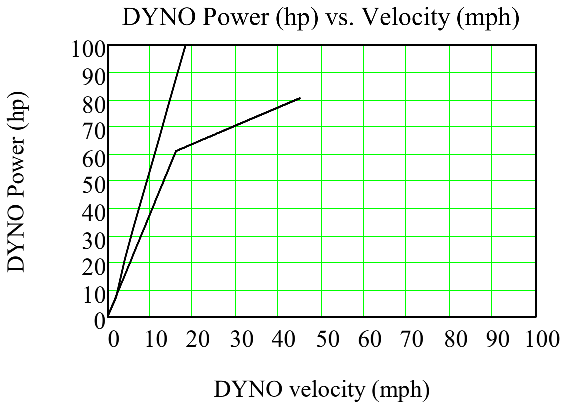
Comparison RAV4 Gen IV (Sold) vs. RAV4 Gen IV (Dotted)

Comparison RAV4 No Battery (Solid) vs. Battery (Dotted)

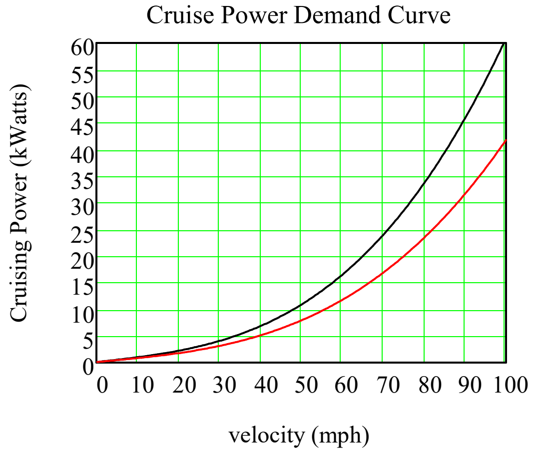








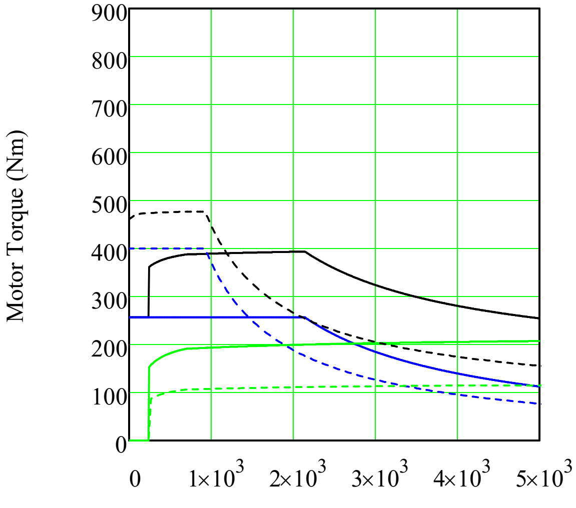
$\mathrm{Fuel\_Use} := \mathrm{READPRN}(\text{"http://www.leapcad.com/Transportation/Prius\%201\_5L\%20Atkinson\%20Fuel\%20Use.TXT"})^{T}$

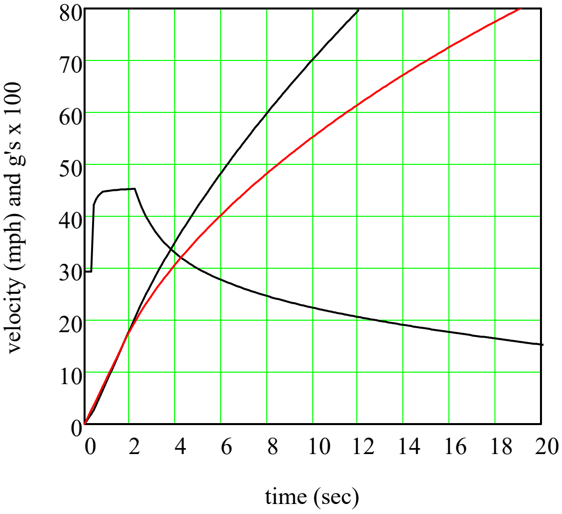


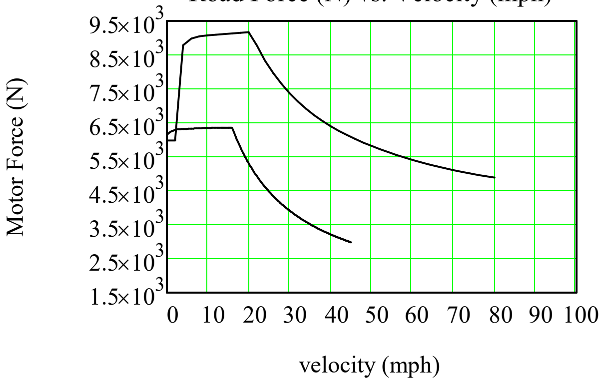
Switch Solid and Dotted Curves

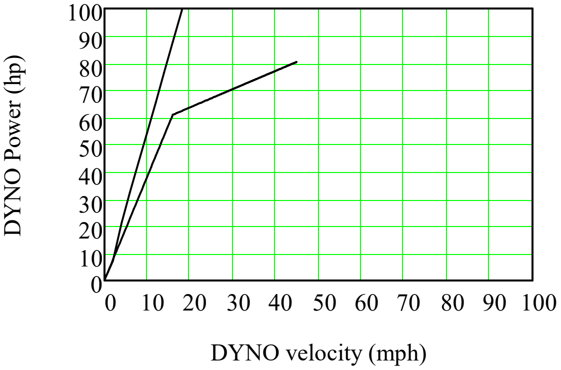
Comparison RAV4 No Battery (Dotted) vs. Battery (Solid)

Comparison RAV4 Gen IV (Dotted) vs. Prius Gen IV (Solid)


Torque (Total,MG2,ICE) vs. Speed


Velocity & g Acceleration (x 100) Curve


Road Force (N) vs. Velocity (mph)


DYNO Power (hp) vs. Velocity (mph)