PRIUS GEN III 1.5L PERFORMANCE SIMULATION

http://www.leapcad.com/Transportation/Prius_Gen_III_1.5L_Simulation.mcd

Goal: Macro Model the Prius Gen III 1.5L ICE Vehicle Performance

Procedure:
First model the Prius Internal Combustion Engine's (ICE) and motor's, torque and power. Define vehicle and road parameters.
Acceleration Protocol:
Use motor/generator speed, MG2 rpm, ω_{m2}, (axle of planetary gear) as a control variable. Initially, use the high starting torque from motor MG2 to drive the axle. Supply peak electrical power to MG2 from both the battery (peak battery power for 10 seconds) and from MG1 (run as a generator at it's max speed, mechanically driven by the the ICE). This condition simulates a low gear mode for the ICE.

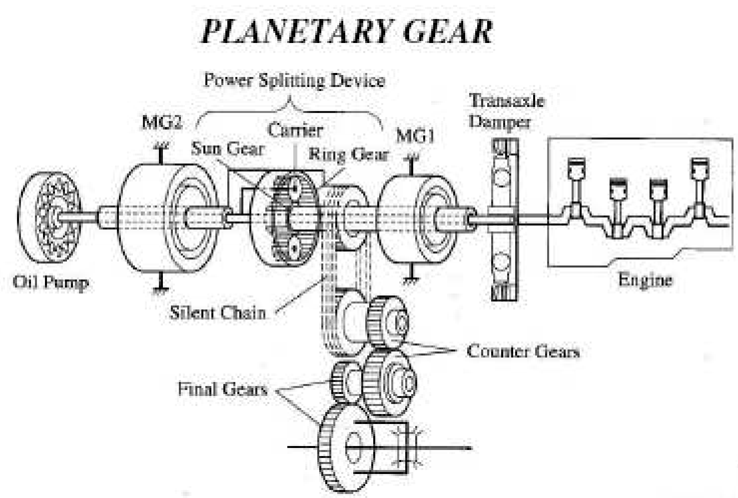
As MG2 speeds up and demands increasing power, throttle back it's drive/torque by limiting its electrical power input to the max Inverter Output, i.e. sum of battery and MG1 generator power. Refer to the curve of M2 Torque vs.ω_{m2} on page 3.

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. Get AER results using various EPA driving modes.

Basic Description of Prius

Modeling and Simulation of Serial Parallel Hybrid EV

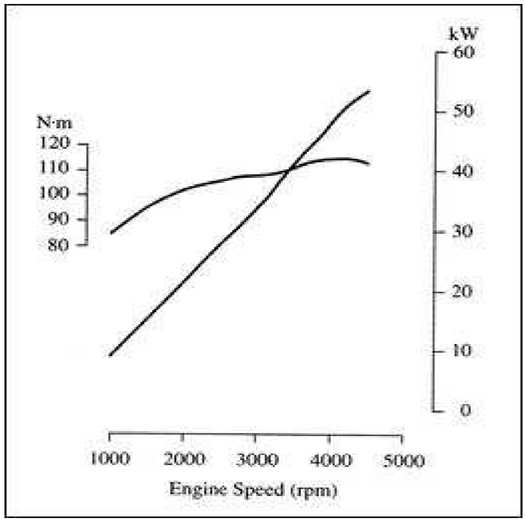
Description of Synergy (Planetary Gear) Drive



Rotation Speed Varibles:
MG1, MG2, and Engine: ωm1, ωm2, and ωice.

Power Efficiencies:
Inverter, axle to tire, engine to MG1, and engine to axle efficiencies
ηinv, ηaxle, ηeng_m1, and ηaeng_axle

Prius Gen III ICE Performance Curves

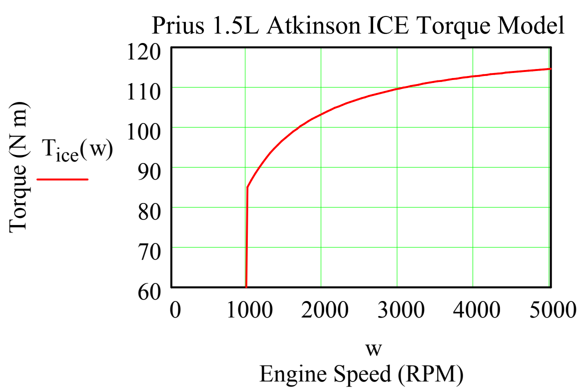


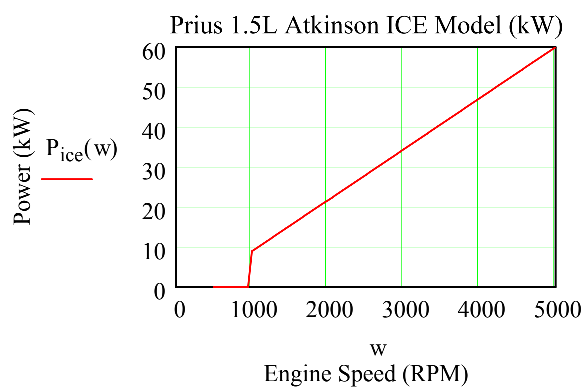
Power and Torque vs. RPM Models of Toyota Atkinson Gen III 1.5L ICE

Match Model Parameters to: **Specifications for Different Prius Models**

$k := 1000$ $\quad w := 500, 550 .. 5000$ $\quad T_{idle} := 85$ $\quad \Omega_{idle} := 1000$ $\quad P_{idle} := T_{idle} \cdot \left(\frac{2 \cdot \pi \cdot \Omega_{idle}}{60 \cdot k} \right)$ $\quad P_{slope} := \frac{57 - 9}{4000}$

$P_{ice}(w) := \text{if}\left[w < \Omega_{idle}, 0, P_{idle} + P_{slope} \cdot (w - \Omega_{idle}) \cdot \frac{115}{108} \right]$ $\quad T_{ice}(w) := (P_{ice}(w)) \cdot \frac{60 \cdot k}{2 \cdot \pi \cdot w}$ $\quad T_{ice}(5000) = 114.615$





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

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

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

$$T_{ice} = m_{ice} \cdot k_{ice} \cdot dgas$$

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

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

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, 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 describes the action of the Hybrid Synergy Drive *Planetary Gear* (shown in the above illustration).

Fuel_Use := READPRN("http://www.leapcad.com/Transportation/Prius%201_5L%20Atkinson%20Fuel%20Use.TXT")^T

Toyota Prius GIII 1.5L-Vehicle, Motor and Road Parameters:

Max Motor Power:	$Pmax_{m2} := 50 \cdot kW$	$Pmax_{m1} := 25 \cdot kW$	$Pmax_{ice} := 57 \cdot kW$
Max Motor Torque:	$Tmax_{m2} := 400 \cdot N \cdot m$	$Tmax_{m1} := 207 \cdot N \cdot m$	$Tmax_{ice} := 115 \cdot N \cdot m$
Max Motor Speeds:	**Max. Acceleration Mode==>**	$\Omega max_{m1} := 6500 \cdot RPM$	$\Omega max_{ice} := 5000 \cdot RPM$

Gear Ratio and Efficiencies: $GR := 3.905$ $\eta_{inv} := 0.95$ $\eta_{eng\_axle} := 0.95$ $\eta_{axle} := 0.98$ $\eta_{eng\_m1} := 0.98$ $r_{tire} := 0.287 \cdot m$

Motor M2 Constant Power Torque, rpm: $Tstep_{m2} := Tmax_{m2}$ $\quad \Omega CP_{m2} := \dfrac{Pmax_{m2}}{2 \cdot \pi Tstep_{m2}}$

$Redline := \Omega max_{ice} \cdot min$

Motor M2 Power Starved rpm: $\Omega PS_{m2} := 400 \cdot RPM$

Average Wind Velocity:	$Vw := 0 \cdot mph$	Average Cross Wind:	$V_{cw} := 0 \cdot mph$
Shape Correction Factor:	$SCF := 0.85$	Frontal Area*:	$Afg := 2.33 \cdot m^2$
Drag Coeff:	$Cd := 0.26$	Frontal Area Corrected:	$Af := Afg \cdot SCF$ $\;Af = 1.98\,m^2$
Cross Wind Drag Coff:	$Cd_{cw} := 0.000014$	Rolling Resistance Per Tire: (Average 0% road grade)	$RR_{tire} := 0.008$ $\;\theta := atan(0)$ $\;\theta$ (radians):
Air Density:	$\rho := 1.293 \cdot \dfrac{gm}{liter}$	$Energy_{bat} := 6.5 \cdot kW \cdot hr$	$Pmax_{bat} := 21 \cdot kW$
Road Rolling Resist:	$RR_{road} := 0.007$	Curb Weight:	$M_{curb} := 1317 \cdot kg$
Rotational Inertia Coeff:	$k_m := 1.08$	Passenger Weight:	$Passengers2 := 170 \cdot lb$
Gross Weight:	$M_{gross} := M_{curb} + Passengers2$	$M_{gross} = 3.073 \times 10^3\,lb$	$M_{batt} := 68 \cdot kg$

Vehicle Dynamics Equations (We don't know specifics of Prius Control Strategy):

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

Aerodynamic Loss, Fa: $Fa(v) := 0.5 \cdot \rho \cdot Af \cdot \left[(v + Vw)^2 \cdot Cd + Cd_{cw} \cdot \left(0.5 \cdot v + V_{cw} \right)^2 \right]$ $\qquad x := \dfrac{s}{m}$

Opposing Force, Fo: $Fo(v) := Fa(v) + Fr(v)$ $\qquad Fo(60 \cdot mph) = 444.58\,N$

Hybrid Synergy Drive, Max. ICE Acceleration: $\Omega_{ice}(\omega_{mg2}) := \dfrac{\left(\Omega max_{m1} \cdot min + 2.6 \cdot \omega_{mg2} \right)}{3.6}$ $\qquad \Omega_{mg2}(\omega_{ice}) := \dfrac{\omega_{ice} \cdot 3.6 - \Omega max_{m1} \cdot min}{2.6}$

Torque, ICE: $T_{ice}(\omega_{mg2}) := if\left[T_{ice}\left(\Omega_{ice}(\omega_{mg2})\right) \cdot N \cdot m \le Tmax_{ice}, T_{ice}\left(\Omega_{ice}(\omega_{mg2})\right) \cdot (N \cdot m), Tmax_{ice} \right]$

Torque,MG1: $T_{m1}(\omega_{mg2}) := -T_{ice}(\omega_{mg2}) \cdot 3.6^{-1} \cdot \eta_{eng\_m1}$ $\qquad Pinv_{m2}(\omega_{mg2}) := \eta_{inv} \cdot \left(Pmax_{bat} - T_{m1}(\omega_{mg2}) \cdot 2 \cdot \pi \cdot \Omega max_{m1} \right.$

MG2 Inverter Power, Pinv:

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

Solution: $Tmax_{m2}$ => $Pinv_{m2}(\omega_{inv})$ $\qquad \omega_{inv} = 926.013$

Tractive Torq, Total: $T_{tot}(\omega_{mg2}) := T_{m2}(\omega_{mg2}) + T_{ice}\left(\Omega_{ice}(\omega_{mg2})\right) \cdot \dfrac{2.6}{3.6} \cdot \eta_{eng\_axle}$ $\qquad P_{m2}(\omega) := T_{m2}(\omega) \cdot 2 \cdot \pi \cdot \omega \cdot RPM$

Tractive Road Force, Total: $Ft\omega(\omega_{mg2}) := \dfrac{T_{tot}(\omega_{mg2}) \cdot GR \cdot \eta_{axle}}{r_{tire}}$ $\qquad rpm\_to\_mph(s) := \dfrac{GR \cdot s}{\left(2 \cdot \pi \cdot r_{tire} \cdot RPM \right)}$

Tractive Road Force, Total: $F_{tot}(v) := \dfrac{T_{tot}(rpm\_to\_mph(v)) \cdot GR \cdot \eta_{axle}}{r_{tire}}$ $\qquad P_{M2}(\omega) := \dfrac{P_{m2}\left(\Omega_{mg2}(\omega)\right)}{kW}$

Plot Terms: $P_{tot}(v) := F_{tot}(v) \cdot v$ $\qquad P_{tot}(60 \cdot mph) = 90.146\,hp$ $\qquad \xi := \dfrac{1}{(N \cdot m)}$ $\qquad End := 20$

Third Law of Motion: (dv/dt is acceleration) $\quad$ Given $\dfrac{d}{dt} v(t) = \dfrac{F_{tot}(v(t)) - Fo(v(t))}{k_m \cdot M_{gross}}$ $\qquad v(0) = 0$ $\qquad velocity := Odesolve(t, End)$

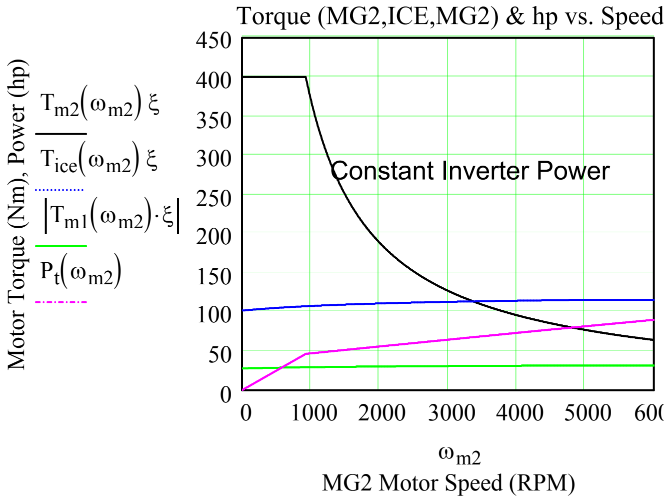
Applying maximum motor torque, find the velocity starting from initial velocity = 0 mph.

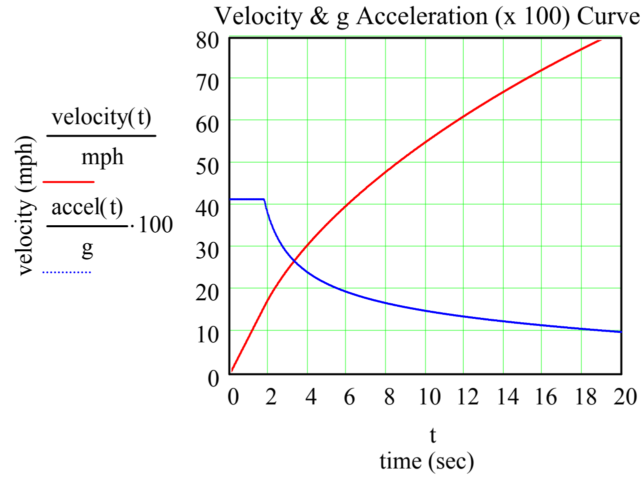
$accel(t) := \dfrac{F_{tot}(velocity(t)) - Fo(velocity(t))}{k_m \cdot M_{gross}}$ $\qquad P_t(\omega_{m2}) := T_{tot}(\omega_{m2}) \cdot 2 \cdot \pi \cdot \omega_{m2} \cdot RPM \cdot kW^{-1}$

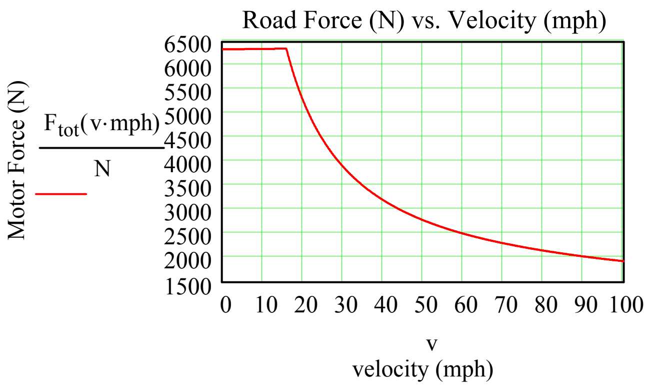
This agrees with Prius Specs

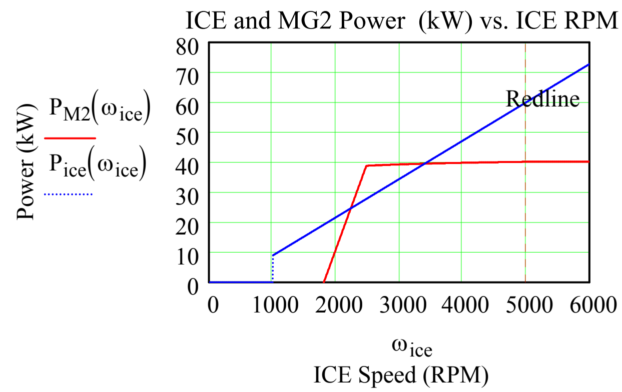
$Time := 0 \cdot sec$ $\qquad time(v) := root(v - velocity(Time), Time)$ $\qquad time(60 \cdot mph) = 11.505\,s$

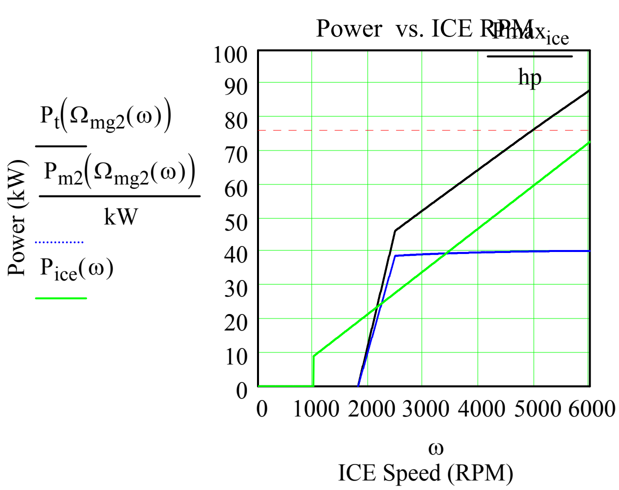
PRIUS GEN III PEFORMANCE SIMULATION CURVES

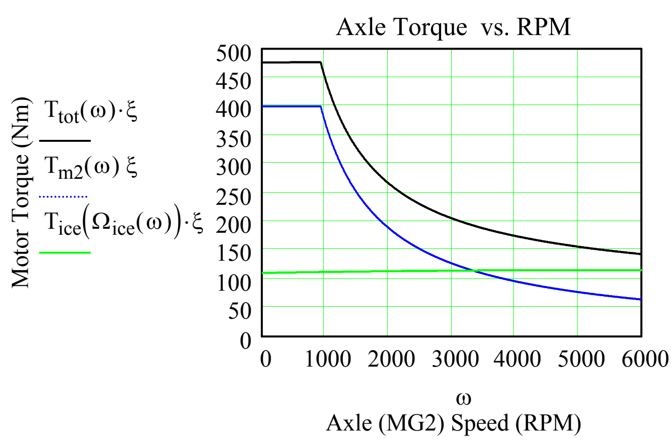


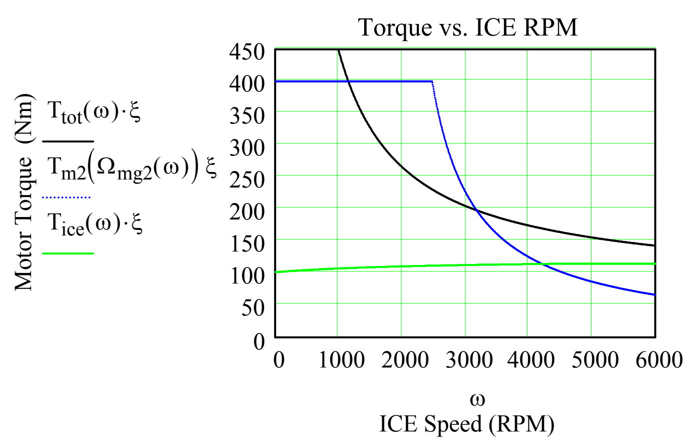












Find the Single Charge (@SOC = 50%) Cruise Range for a given Velocity

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 50% for recharge.** 320V 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 69% @ deacceleration = 0.315g. Then the number of starts per hour as a function of velocity, NS, NumStarts(v, Po), is

$Time_{ssr} := 30min \quad TInvE := 0.90 \quad IPEE := 0.95 \quad GPE := 0.97 \quad Regen := 0.69 \quad SOC_{gen} := 0.5$

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

NSo and NS are iterative converging estimates of NumStarts

USABC Round Trip Battery Energy Efficiency

$RTEff := 0.92$

$Energy_{accel}(v) := Pmax_{m2}\cdot time(v)$

$$NS_o(v) := 2\cdot\left(\frac{50\cdot mph}{v}\right)^2 \qquad NS(v, P_o, S) := \frac{Energy_{bat}\cdot(1 - S) - NS_o(v)\cdot\left(\frac{Energy_{accel}(v)}{TInvE\cdot GPE} - \frac{Regen\cdot M_{gross}\cdot v^2}{2}\right)}{Power_{dissLoss}(v, P_o)\cdot Time_{ssr}}$$

$$NumStarts(v, P_o, S) := floor\left[\frac{Energy_{bat}\cdot(1 - S) - NS(v, P_o, S)\cdot\left(\frac{Energy_{accel}(v)}{TInvE\cdot GPE} - \frac{Regen\cdot M_{gross}\cdot v^2}{2}\right)}{Power_{dissLoss}(v, P_o)\cdot Time_{ssr}}\right]$$

$$Cruise\_Range(v, P_o, S) := \frac{\left[Energy_{bat}\cdot(1 - S) - NumStarts(v, P_o, S)\cdot\left(\frac{Energy_{accel}(v)}{TInvE\cdot GPE} - \frac{Regen\cdot M_{gross}\cdot v^2}{2}\right)\right]\cdot v}{Power_{dissLoss}(v, P_o)}$$

Single Charge Highway Cruise Range Estimate

$Cruise\_Range(30\cdot mph, 50, SOC_{gen}) = 23.38\ mi$

$Cruise\_Range(40\cdot mph, 50, SOC_{gen}) = 20.207\ mi$

$Cruise\_Range(50\cdot mph, 50, SOC_{gen}) = 16.995\ mi$

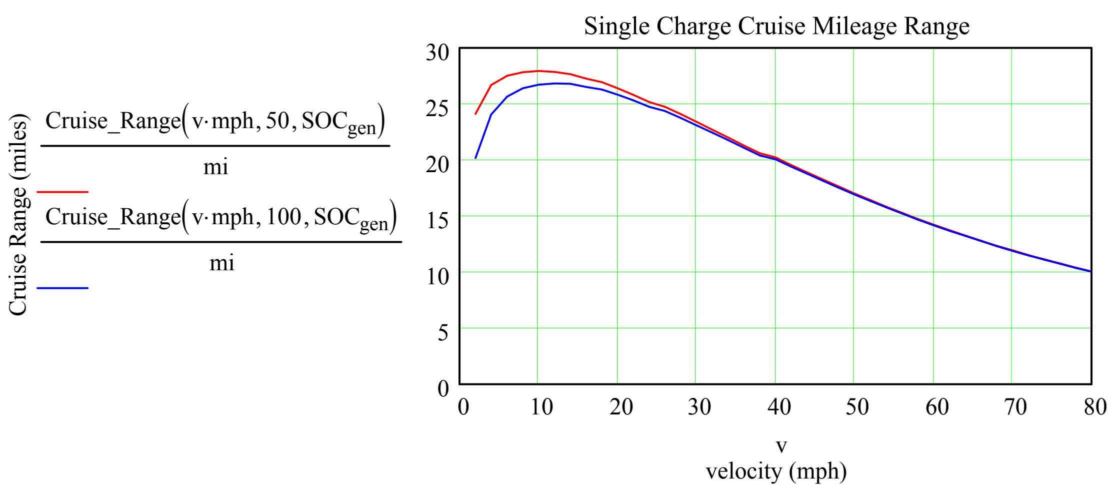
$Cruise\_Range(55\cdot mph, 50, SOC_{gen}) = 15.548\ mi$

$Cruise\_Range(60\cdot mph, 50, SOC_{gen}) = 14.221\ mi$

$Cruise\_Range(62.5\cdot mph, 50, SOC_{gen}) = 13.602\ mi$

Velocity Range $\quad SOC_{gen1} := 0.42 \quad Cruise_Range(70\cdot mph, 50, 0.5) = 11.918\ mi$325 mi

$v := 0, 2 .. 80$



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

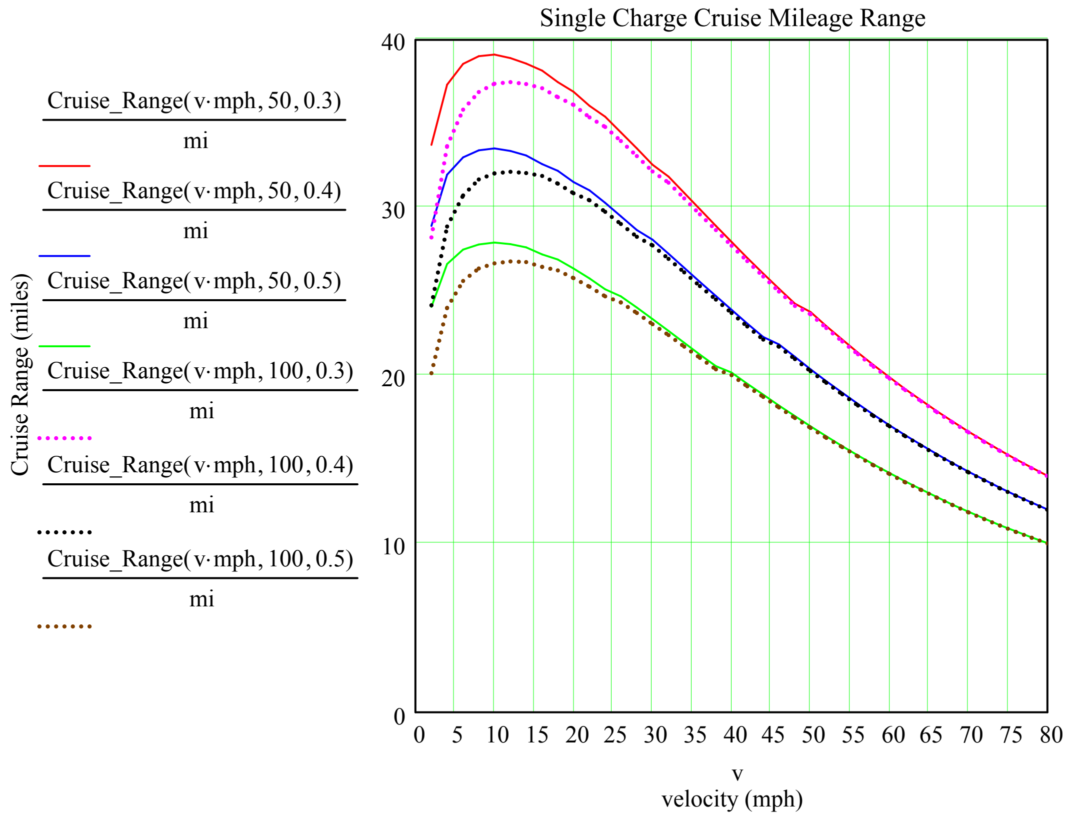
$$\text{Cruise\_Range}(15\cdot \text{mph}, 50, 0.3) = 38.294\ \text{mi}$$

$$\text{Cruise\_Range}(55\cdot \text{mph}, 50, 0.5) = 15.548\ \text{mi}$$

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

$$\frac{0.5 - 0.25}{0.5} = 0.5$$

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



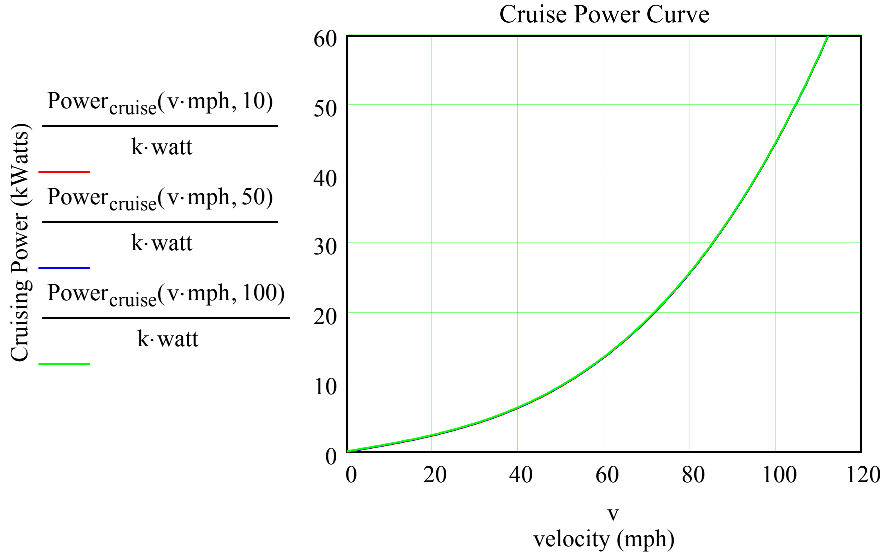
$$k := 1000$$

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.

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

$$Power_{cruise}(60\cdot mph,100) = 13.765\,kW \qquad v := 0,1..120$$



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.

$$t := FTPF^{\langle 0\rangle} \quad FTP := FTPF^{\langle 1\rangle} \quad rows(FTP) = 1.875\times 10^{3}$$

$$UDDS := UDDSF^{\langle 1\rangle} \quad rows(UDDS) = 1.37\times 10^{3}$$

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

$$FTP10V := submatrix(FP10,0,rows(FP10)-1,1,cols(FP10)-1)$$

$$HWY10V := submatrix(HY10,0,rows(HY10)-1,1,cols(HY10)-1)$$

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

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

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

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

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

$AER(US06, 1) = \blacksquare \qquad AER(FTP, 1) = 28.232 \qquad AER(HWY, 1) = 27.23 \qquad AER(HWY10, 10) = \blacksquare$

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

$MPG_{city} := \frac{1}{\left(0.003259 + \frac{1.18053}{AER(FTP, 1)}\right)} \quad MPG_{city} = 22.186 \qquad MPG_{hwy} := \frac{1}{0.001376 + \frac{1.3466}{AER(HWY, 1)}} \qquad X := \frac{1}{40}$

$MPG_{epa} := 0.55 \cdot MPG_{city} + 0.45 \cdot MPG_{hwy} \qquad MPG_{epa} = 21.055$

$r := 0 .. rows(FTP) - 1 \qquad Distance_r := \sum_{r=0}^{r} FTP_r \cdot \frac{10}{60 \cdot 60} \qquad rr := 0 .. rows(US06) - 1 \quad Distance._{rr} := \sum_{rr=0}^{rr} US06_{rr} \cdot \frac{10}{60 \cdot 60}$

$max(Distance) = 110.414 \qquad max(Distance.) = 80.08$

WRITEPRN("EFTP.PRN") := AER(FTP, 1)·40 $\quad E_{FTP}$:= READPRN("EFTP.PRN") $\quad \max(E_{FTP})\cdot X = 28.4$

WRITEPRN("EUS06.PRN") := AER(US06, 1)·40 $\quad E_{US06}$:= READPRN("EUS06.PRN") $\quad \max(E_{US06})\cdot X = 19.66$

WRITEPRN("EHWY.PRN") := AER(HWY, 1)·40 $\quad E_{HWY}$:= READPRN("EHWY.PRN") $\quad \max(E_{HWY})\cdot X = 27.4$