GM VOLT PERFORMANCE SIMULATION

YXPhysics.com

http://www.leapcad.com/Transportation/GM_Volt_Simulation.mcd

GM Volt - Vehicle, Motor, Road, and Environmental Parameters: Enable Generator Only Mode

Max Motor Power: $Power_{max} := 111 \cdot kW \cdot 0.9$ Gear Ratio, Inefficiencies: $GR := 8$ $\eta_{axle} := 0.92$

$P_{Generator} := 53 \cdot kW$ $Power_{max} := P_{Generator} \cdot 0.9$ Battery Energy: $Energy_{bat} := 16 \cdot kW \cdot hr$

Max Motor Torque: $Tm := 273 \cdot ft \cdot lbf$ $Tm = 370.138\, N \cdot m$ Tire Radius*: $r_{tire} := \frac{27.2}{2} \cdot in$ 195/55R21

Max Force, Fm $Fm := GR \cdot \eta_{axle} \cdot \frac{Tm}{r_{tire}}$ $Fm = 1.773 \times 10^{3}\, lbf$ $RPM := min^{-1}$

$Power_{max} = 133.968\, hp$ $\omega_{max} := 12000 \cdot RPM$

Constant Power Motor Torque, ω: $\omega_{CP} := \frac{Power_{max}}{Tm}$ $RPM_{CP} := \frac{\omega_{CP} \cdot min}{2 \cdot \pi}$ $RPM_{CP} = 2.577 \times 10^{3}$

Constant Power vehicle velocity, v_{CP}: $v_{CP} := \frac{Power_{max}}{Fm}$ $v_{CP} = 28.337\, mph$ $k := 10^{3}$ $Tm = 370.138\, N \cdot m$

Average Wind Velocity: $Vw := 0 \cdot mph$ Effective Cross Wind V: $V_{cw} := 0 \cdot mph$

$Power_{max} = 99.9\, kW$ Frontal Area*: $Afg := 2.16 \cdot m^{2}$

Shape Correction Factor: $SCF := 0.85$ Frontal Area Corrected: $Af := Afg \cdot SCF$ $Af = 1.836\, m^{2}$

Drag Coeff: $Cd := 0.28$ Rolling Resistance Per Tire: $RR_{tire} := 0.007$

Cross Wind Drag Coff: $Cd_{cw} := 0.000014$ Tire Hysteresis, Th: $Th := 0 \cdot sec \cdot mi^{-1}$

Air Density: $\rho := 1.3 \cdot \frac{gm}{liter}$ θ (radians): (Average 0% road grade) $\theta := atan(0)$

Road Rolling Resist: $RR_{road} := 0.002$ Curb Weight: $M_{curb} := 3140 \cdot lb$

Rotational Inertia Coeff: $k_{m} := 1.08$ Passenger Weight: $Passengers2 := 170 \cdot lb$

Gross Weight: $M_{gross} := M_{curb} + Passengers2$ $M_{gross} = 3.31 \times 10^{3}\, lb$ $M_{batt} := 300 lb$

Motor Breaking Force in g: $MotorBrake_{g} := GR \cdot Tm \cdot \left(k_{m} \cdot M_{gross} \cdot r_{tire} \cdot g\right)^{-1}$ $MotorBrake_{g} = 0.539$

$WeightToHP := \frac{M_{curb}}{Power_{max}}$ ***Vehicle Dynamics Equations:*** $WeightToHP = 23.438\, \frac{lb}{hp}$

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

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

Opposing Force, Fo: $Fo(v) := Fa(v) + Ft(v)$ $Fo(60 \cdot mph) = 83.544\, lbf$

Tractive Force: $F(v) := if\left(v \le v_{CP}, Fm, \frac{Power_{max}}{v}\right) \cdot \eta_{axle}$ $T(v) := F(v) \cdot \frac{r_{tire}}{GR}$

Third Law of Motion: (a is acceleration) $a(v) := \frac{F(v) - Fo(v)}{k_{m} \cdot M_{gross}}$ $T_{\omega}(\omega) := T\left(\omega \cdot k \cdot 2 \cdot \pi \cdot r_{tire} \cdot GR^{-1} \cdot RPM\right)$

$P(v) := F(v) \cdot v$ $P(60 \cdot mph) = 123.251\, hp$

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

$End := 30$ Given $\frac{d}{dt} v(t) = \frac{F(v(t)) - Fo(v(t))}{k_{m} \cdot M_{gross}}$ $v(0) = 0$ $velocity := Odesolve(t, End)$

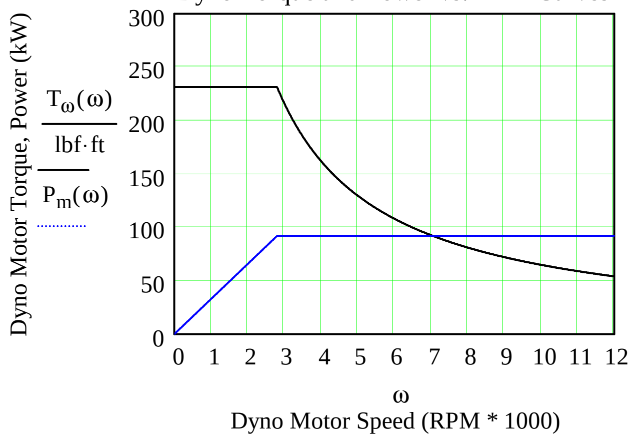
$acc_{g}(t) := a(velocity(t \cdot sec))$ $P_{m}(\omega) := T_{\omega}(\omega) \cdot k \cdot 2 \cdot \pi \cdot \omega \cdot RPM \cdot kW^{-1}$ $velocity(30) = 110.208\, x \cdot mph$

$Time := 0 \cdot sec$ $time(v) := root(v - velocity(Time), Time)$ $time(60 \cdot mph) = 8.167\, s$

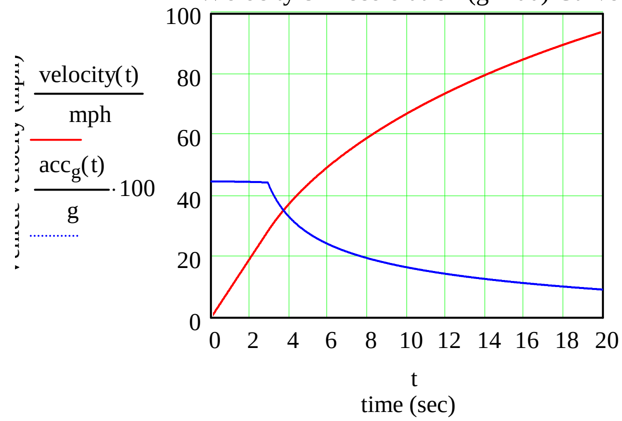
Time to Accelerate from 40 to 60 mph: $time(60 \cdot mph) - time(40 \cdot mph) = 3.818\, s$

G M V O L T P E F O R M A N C E S I M U L A T I O N C U R V E S:

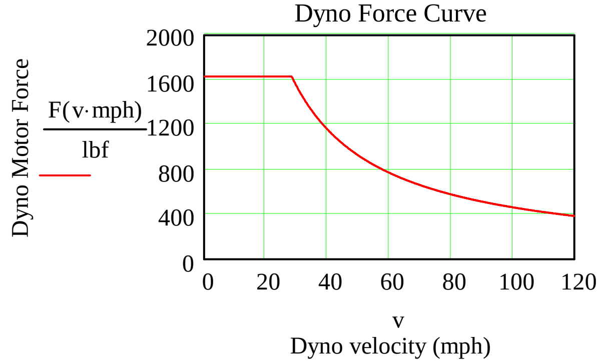
Dyno Torque and Power vs. RPM Curves



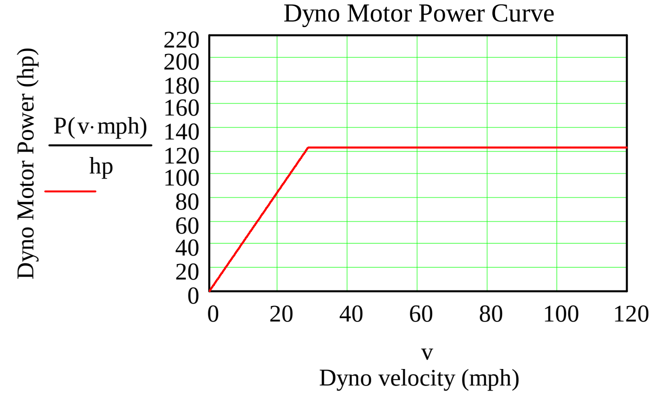
\Velocity & Acceleration (gx100) Curve



Dyno Force Curve



Dyno Motor Power Curve



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

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

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

NSo and NS are iterative converging estimates of NumStarts

USABC Round Trip Battery Energy Efficiency

$RTEff := 0.92$

$Energy_{accel}(v) := Power_{max}\cdot time(v)$

$$NS_o(v) := 2\cdot\left(\frac{50\cdot mph}{v}\right)^2$$

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

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

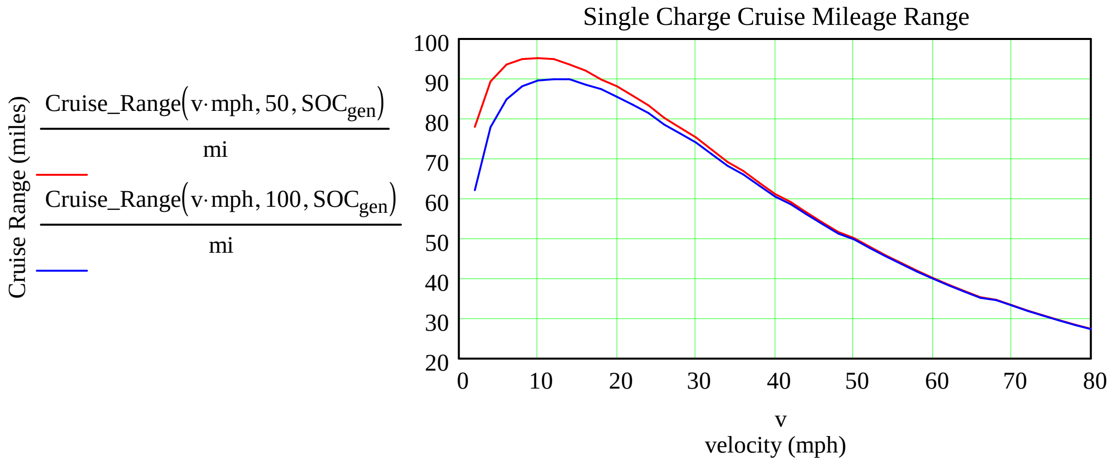
$$Cruise\_Range(v, P_o, S) := \frac{\left[Energy_{bat}\cdot(1-S) - NumStarts(v, P_o, S)\cdot\left(\frac{Energy_{accel}(v)}{TInvE\cdot GPE} - \frac{Regen\cdot M_{gross}\cdot v^2}{2}\right)\right]\cdot v}{Power_{dissLoss}(v, P_o)}$$

Single Charge Highway Cruise Range Estimate

Velocity Range

$v := 0, 2 .. 80$

$\text{Cruise\_Range}(55\cdot\text{mph}, 50, \text{SOC}_{gen}) = 44.83\,\text{mi}$

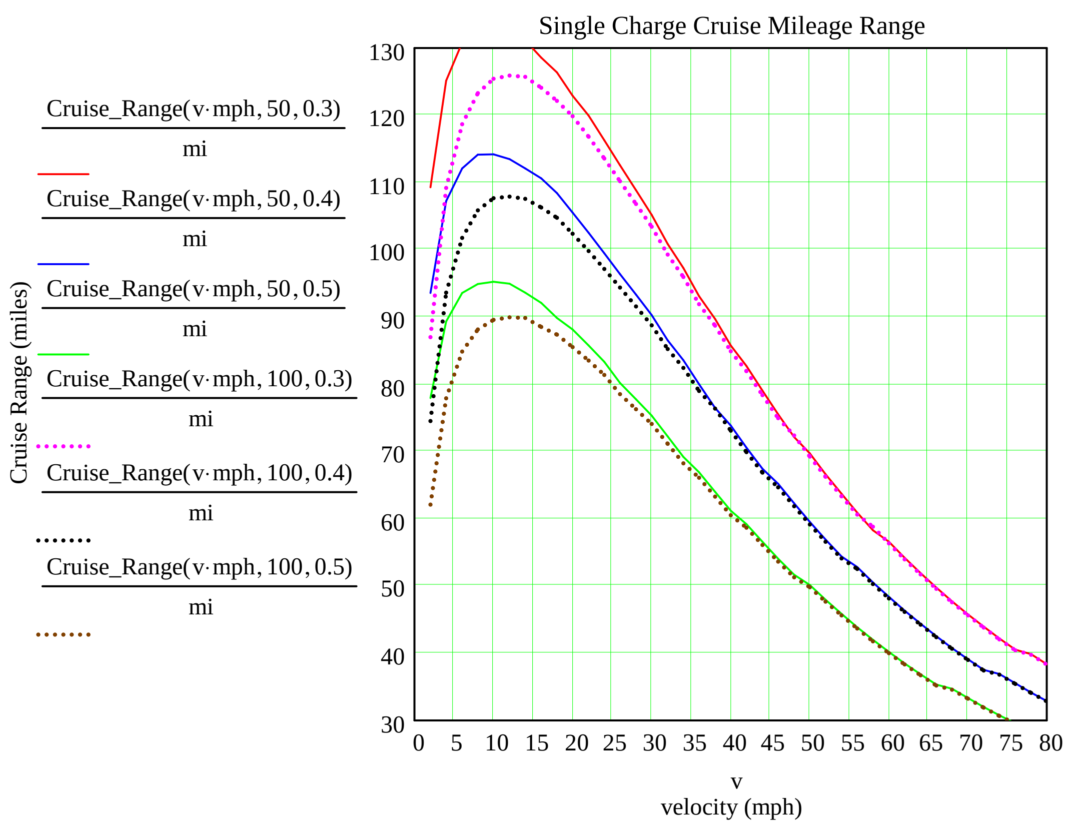


Specsmanship: Twice as much range at 30 mph than 70 mph.
Conclusion: I need a bigger or a better battery!

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

$\text{Cruise\_Range}(15\cdot\text{mph}, 50, 0.3) = 129.854\,\text{mi}$

$\text{Cruise\_Range}(55\cdot\text{mph}, 50, 0.5) = 44.83\,\text{mi}$



Find the Power to Maintain Constant Velocity at Road Grades

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

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

$$v_n := \frac{n}{2} \qquad P_{cruise_n} := Power_{cruise}(v_n \cdot mph, 100)\left[(k \cdot watt)^{-1}\right]$$

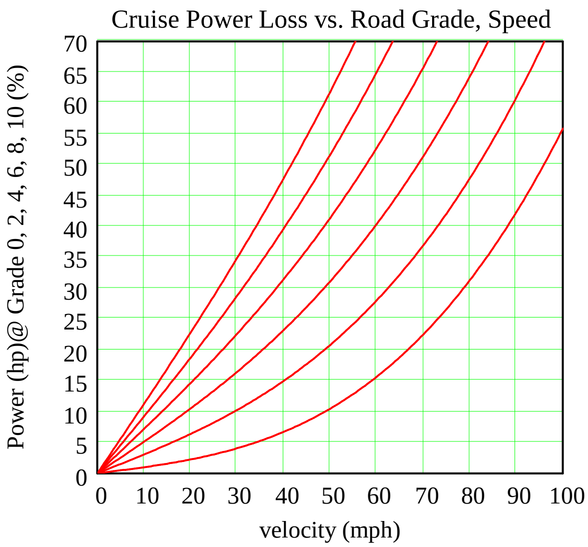
$$i := 0..5$$

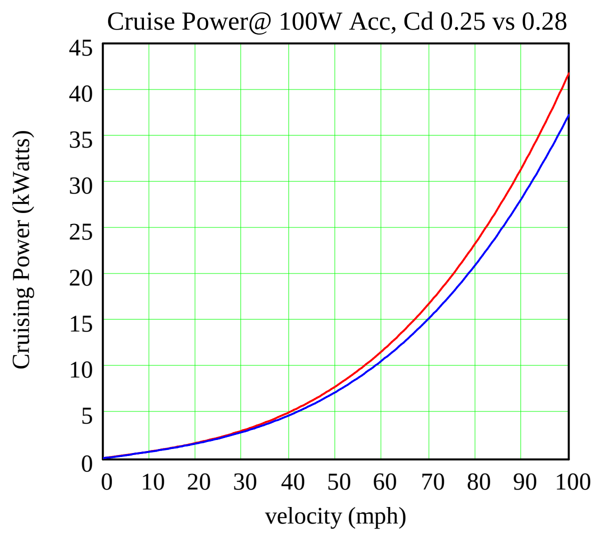
$$\theta_i := 0.02 \cdot i$$

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

$$Phill(v, \theta) := \frac{(Ftg(v, \theta) + Fa(v)) \cdot v}{TInvE \cdot GPE}$$

$$P_{hill_{n,i}} := Phill(v_n \cdot mph, \theta_i)$$





AER Given Three Different Driving Schedules

Read US06 and FTP Driving Profile Files

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

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")

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.

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

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

$$time := US06F^{\langle 0 \rangle} \qquad US06 := US06F^{\langle 1 \rangle} \qquad n_6 := 0..598 \qquad HWY := HWYF^{\langle 1 \rangle} \qquad R_{hwy} := rows(HWY)$$

$$mean(FTP) = 21.2$$

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

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

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

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

$$
\begin{aligned}
AER(P, Hz) := \; & Ebat \leftarrow E_{diss} \leftarrow v_{old} \leftarrow 0 \\
& n \leftarrow -1 \\
& N \leftarrow rows(P) - 1 \\
& \text{while } E_{diss} < 8 \wedge n = n \\
& \quad n \leftarrow n + 1 \\
& \quad t \leftarrow mod(n, N) \\
& \quad v \leftarrow P_t \\
& \quad v_{avg} \leftarrow \left(v + v_{old}\right) \cdot 0.5 \\
& \quad P_{accel} \leftarrow \frac{k_m \cdot M_{gross} \cdot \left(v - v_{old}\right) \cdot \frac{mph \cdot Hz}{sec} \cdot v_{avg} \, mph}{TInvE \cdot GPE} \quad \text{if } v > v_{old} \\
& \quad P_{accel} \leftarrow k_m \cdot M_{gross} \cdot \left(v - v_{old}\right) \cdot \frac{mph \cdot Hz}{sec} \cdot v_{avg} \, mph \cdot REff\left[\left(v_{old} - v\right) \cdot Hz \cdot Gg\right] \quad \text{otherwise} \\
& \quad E_{diss} \leftarrow E_{diss} + \frac{\left(Power_{dissLoss}(v \cdot mph, 100) + P_{accel}\right) \cdot sec}{kW \cdot hr \cdot Hz} \\
& \quad v_{old} \leftarrow v \\
& \quad Ebat_n \leftarrow E_{diss} \\
& R \leftarrow \sum_{m=0}^{n} \frac{\left(P_{mod(m, N)} + P_{mod(m+1, N)}\right) \cdot mph \cdot sec}{2 \cdot mi \cdot Hz} \\
& R
\end{aligned}
$$

$r1 := 0 .. rows(HY10) \cdot 10 - 1$

Calculated AER(Miles): EPA Federal Test Procedure and Highway Driving Profiles

$AER(FTP, 1) = 39.093$ $AER(HWY, 1) = 38.416$ $AER(US06, 1) = 25.648$

EPA 20085 Cycle MPG Fuel Economy Least Squares Fit Regression for AER

$MPG_{city} := \frac{1}{\left(0.003259 + \frac{1.18053}{AER(FTP, 1)}\right)}$ $MPG_{city} = 29.889$ $MPG_{hwy} := \frac{1}{0.001376 + \frac{1.3466}{AER(HWY, 1)}}$ $X := \frac{1}{40}$

$MPG_{epa} := 0.55 \cdot MPG_{city} + 0.45 \cdot MPG_{hwy}$ $MPG_{epa} = 28.792$

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

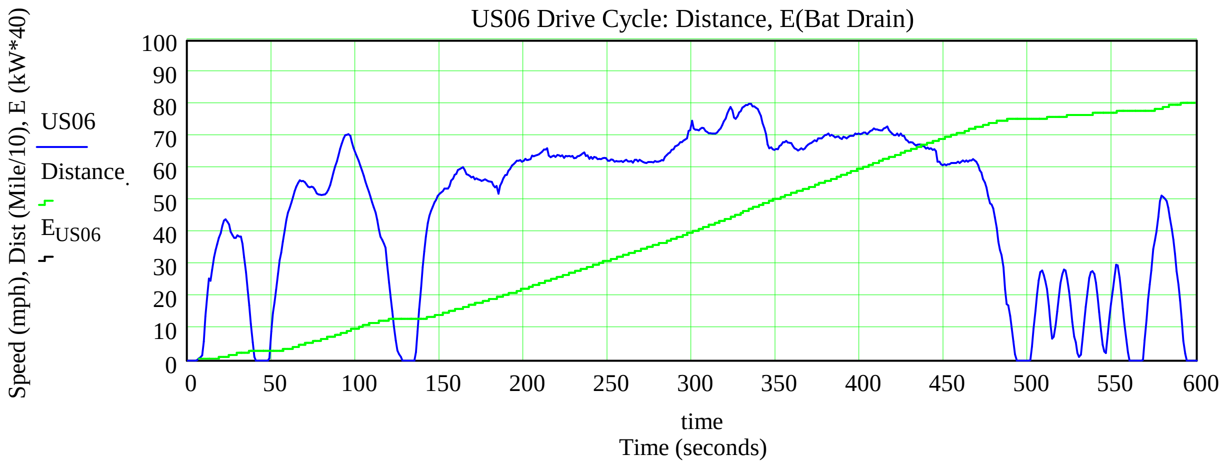
$max(Distance) = 110.41$ $max\left(Distance_{\cdot}\right) = 80.08$

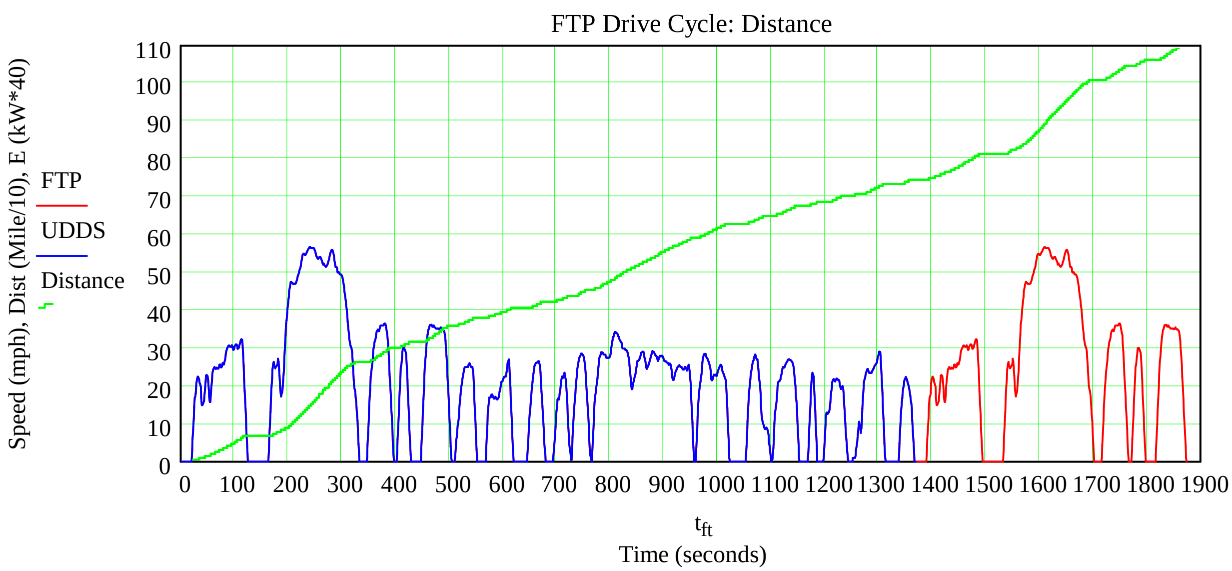
Plot EPA Driving Profiles

$WRITEPRN("EFTP.PRN") := AER(FTP,1)\cdot 40$ $E_{FTP} := READPRN("EFTP.PRN")$ $\max(E_{FTP})\cdot X = 39.1$

$WRITEPRN("EUS06.PRN") := AER(US06,1)\cdot 40$ $E_{US06} := READPRN("EUS06.PRN")$ $\max(E_{US06})\cdot X = 25.65$

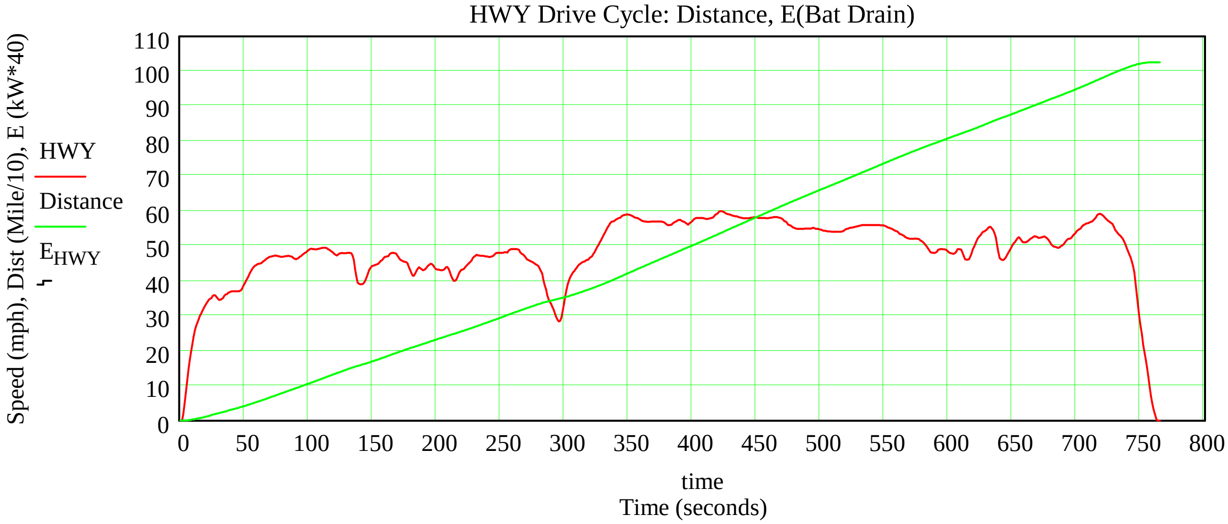
$WRITEPRN("EHWY.PRN") := AER(HWY,1)\cdot 40$ $E_{HWY} := READPRN("EHWY.PRN")$ $\max(E_{HWY})\cdot X = 38.425$





$r := 0..rows(HWY)-1$ $\quad Distance_r := \sum_{r=0}^{r} HWY_r\cdot\frac{10}{60\cdot 60}$ $\quad time := HWYF^{\langle 0\rangle}$ $\quad mean(HWY) = 48.204$

$max(HWY) = 59.9$


HWY Drive Cycle: Distance, E(Bat Drain)
Speed (mph), Dist (Mile/10), E (kW*40)
HWY
Distance
E_HWY
110
100
90
80
70
60
50
40
30
20
10
0
0
50
100
150
200
250
300
350
400
450
500
550
600
650
700
750
800
time
Time (seconds)

Compare Volt Sustaining (Dotted) vs. Generator Only (Solid) Mode:

For Comparison to Prius See:
http://www.leapcad.com/Transportation/Macro%20Model%20Performance%20Comparison%20-%20-Volt%20EREV%20vs%20Prius.pdf
For Comparison to Corolla See (Page 5):
http://www.leapcad.com/Transportation/Corolla_Simulation.pdf

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)

$Volt := READPRN("VoltGenOnly\_tVelwMAgTPmFP.prn")$ $Volt := READPRN("VoltSus\_tVelwMAgTPmFP.prn")$

Store Variables

$n := 0..300$ $time_v := Volt^{\langle 0 \rangle}$ $v_v := Volt^{\langle 1 \rangle}$ $\omega_v := Volt^{\langle 2 \rangle}$ $mph_v := Volt^{\langle 3 \rangle}$ $g_v := Volt^{\langle 4 \rangle}$

$T_w := \frac{Volt^{\langle 5 \rangle}}{(lbf \cdot ft)}$ $P_w := Volt^{\langle 6 \rangle}$ $F_v := Volt^{\langle 7 \rangle}$ $Pv_v := Volt^{\langle 8 \rangle}$ $P_{cruiseV} := Volt^{\langle 9 \rangle}$

$TW(\omega) := \frac{T_\omega(\omega)}{lbf \cdot ft}$ $VV(t) := \frac{velocity(t)}{mph}$ $AG(t) := \frac{acc_g(t)}{g} \cdot 100$

Plot Compare Sustaining (Dotted) vs. Generator Only (Solid) Mode: