ELECTRIC VEHICLE PERFORMANCE SIMULATION

GM Volt - Vehicle, Motor, Road, and Environmental Parameters:

Max Motor Power: $Power_{max} := 209 \cdot hp$

$P_{Generator} := 53 \cdot kW$ $\quad Power_{max} := P_{Generator}$

Max Motor Torque: $Tm := 273 \cdot ft \cdot lbf$

Max Force, Fm: $Fm := GR \cdot \frac{Tm}{r_{tire}}$

$Power_{max} = 209\ hp$

Constant Power Motor Torque, ω: $\omega_{CP} := \frac{Power_{max}}{Tm}$

Constant Power vehicle velocity, v_{CP}: $v_{CP} := \frac{Power_{max}}{Fm}$

Time, in seconds: $t := 0, 1 .. 61$

Time unit: $\tau := 1 \cdot sec$

Shape Correction Factor: $SCF := 0.85$

Drag Coeff: $Cd := 0.245$

Cross Wind Drag Coff: $Cd_{cw} := 0.000014$

Air Density: $\rho := 1.3 \cdot \frac{gm}{liter} \frac{m}{er}$

Road Rolling Resist: $RR_{road} := 0.0011 \cdot 0$

Rotational Inertia Coeff: $k_m := 1.06$

Gear Ratio (v_{CP}=60mph): $GR := 12$ $\quad GR_2 := 8$

Battery Energy: $Energy_{bat} := 16 \cdot kW \cdot hr$

Tire Radius*: $r_{tire} := \frac{27.2}{2} \cdot in$ $\quad$ 195/55R21

$Fm = 2.891 \times 10^3\ lbf$ $\quad RPM := min^{-1}$

$\omega_{max} := 12000 \cdot RPM$

$RPM_{CP} := \frac{\omega_{CP} \cdot min}{2 \cdot \pi}$ $\quad RPM_{CP} = 4.021 \times 10^3$

$v_{CP} = 27.114\ mph$ $\quad k := 10^3$ $\quad Tm = 370.138\ N \cdot m$

Average Wind Velocity: $Vw := 0 \cdot mph$

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

Frontal Area*: $Afg := 2.16 \cdot m^2$

Frontal Area Corrected: $Af := Afg \cdot SCF$ $\quad Af = 1.836\ m^2$

Rolling Resistance Per Tire: $RR_{tire} := 0.01$

Tire Hysteresis, Th:

θ (radians):

(Average 0% road grade) $\theta := atan(0)$

Curb Weight: $M_{curb} := 3140 \cdot lb$

Passenger Weight: $Passengers2 := 170 \cdot lb$

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

Motor Breaking Force in g: $MotorBrake_g := GR \cdot Tm \cdot \left(k_m \cdot M_{gross} \cdot r_{tire} \cdot g\right)^{-1}$ $\quad MotorBrake_g = 0.824$

$WeightToHP := \frac{M_{curb}}{Power_{max}}$ $\quad WeightToHP = 15.024 \frac{lb}{hp}$

Vehicle Dynamics Equations:

Velocity at Torque Fall: $v_{maxT} := \omega_{max} \cdot 2 \cdot \pi \cdot r_{tire} \cdot GR_2^{-1}$ $\quad v_{maxT} = 121.38\ mph$ $\quad Th := 0 \cdot sec \cdot mi^{-1}$

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: $Fa(v) := 0.5 \cdot \rho \cdot Af \cdot \left[(v + Vw)^2 \cdot Cd + Cd_{cw} \cdot \left(0.5 \cdot v + V_{cw}\right)^2\right]$

Opposing Force, Fo: $Fo(v) := Fa(v) + Ft(v)$ $\quad Fo(60 \cdot mph) = 80.135\ lbf$

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

$T_{\omega}(\omega) := T\left(\omega \cdot k \cdot 2 \cdot \pi \cdot r_{tire} \cdot GR^{-1} \cdot RPM\right)$

Third Law of Motion: (a is acceleration) $a(v) := \frac{F(v) - Fo(v)}{k_m \cdot M_{gross}}$

$P(v) := F(v) \cdot v$

$P(60 \cdot mph) = 209\ hp$

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

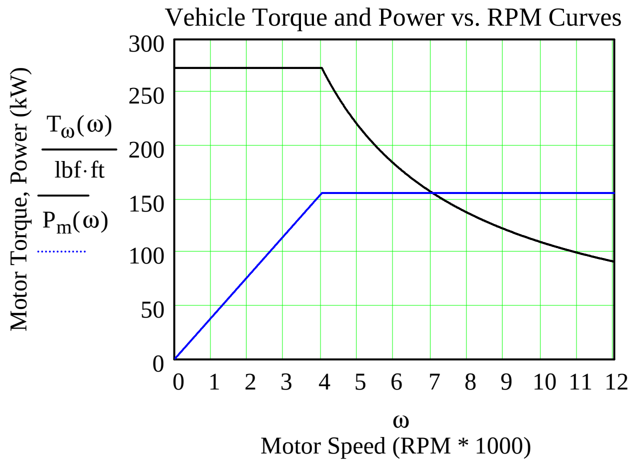
$Time := 0 \cdot sec$ $\quad P_m(\omega) := T_{\omega}(\omega) \cdot k \cdot 2 \cdot \pi \cdot \omega \cdot RPM \cdot kW^{-1}$

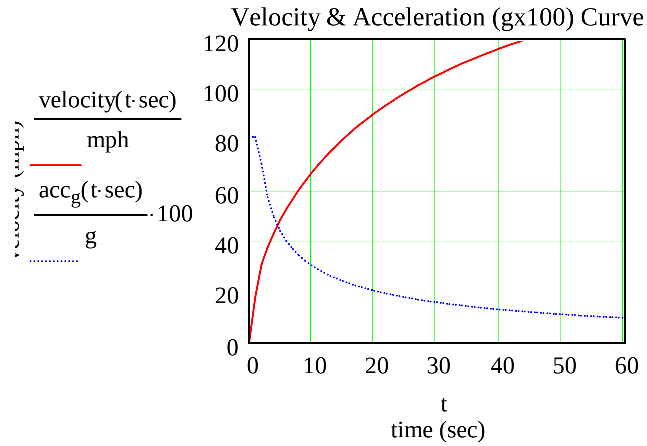
$V := 0 \cdot mph$ $\quad velocity(t) := root\left(V - \int_0^t a(V) \cdot \tau \, dt, V\right)$ $\quad velocity(60 \cdot sec) = 130.228 mph$

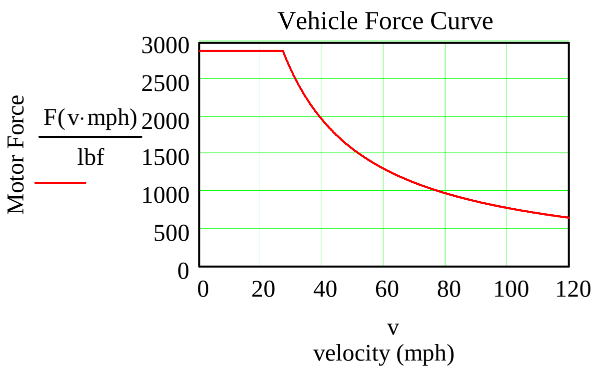
$acc_g(t) := a(velocity(t \cdot sec))$

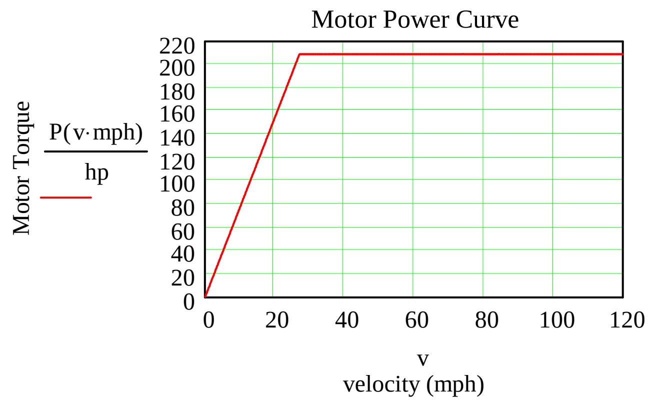
$time(v) := root(v - velocity(Time), Time)$ $\quad time(60 \cdot mph) = 7.827 s$

GM VOLT PEFORMANCE SIMULATION CURVES:









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

Driving Pattern/Profile:

Assume we cruise at constant speed and start, stop, and regen breaking 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

$TInvE := 0.90 \qquad IPEE := 0.95 \qquad GPE := 0.97 \qquad Regen := 0.69 \qquad v := 0, 2 .. 80 \qquad SOC_{gen} := 0.5$

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

USABC Round Trip Battery Energy Efficiency

$RTEff := 0.92$

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

NSo and NS are iterative converging estimates of NumStarts

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

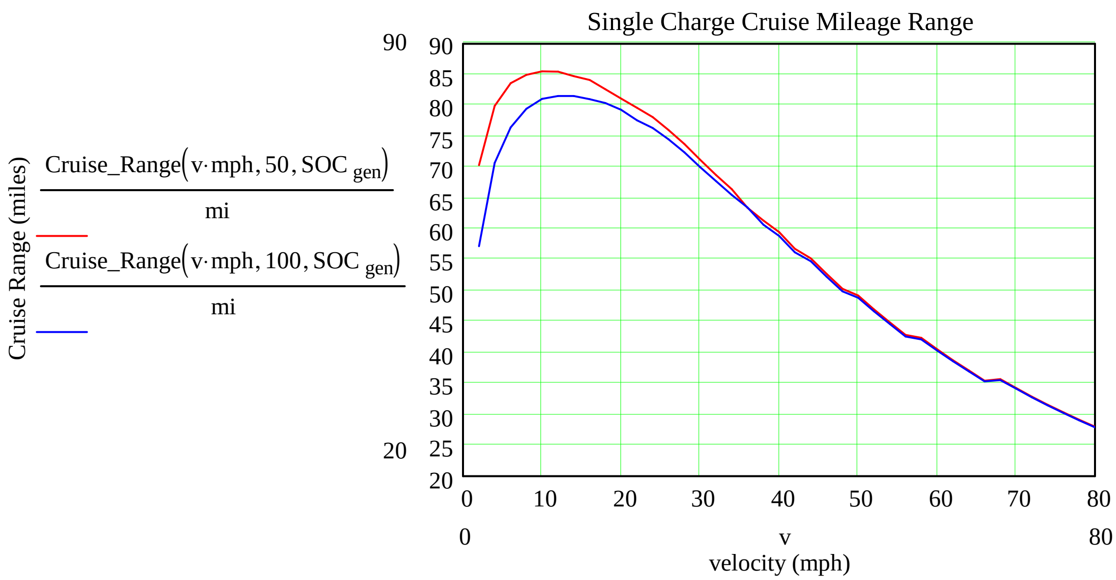
$$NS(v, P_o, S) := \frac{Energy_{bat} \cdot (1 - S) - NS_o(v) \cdot \left(\frac{Energy_{accel}(v)}{TInvE \cdot GPE} - \frac{Regen \cdot M_{gross} \cdot v^2}{2}\right)}{Power_{dissLoss}(v, P_o) \cdot 15 \cdot min}$$

$$NumStarts(v, P_o, S) := floor\left[\frac{Energy_{bat} \cdot (1 - S) - NS(v, P_o, S) \cdot \left(\frac{Energy_{accel}(v)}{TInvE \cdot GPE} - \frac{Regen \cdot M_{gross} \cdot v^2}{2}\right)}{Power_{dissLoss}(v, P_o) \cdot 15 \cdot min}\right]$$

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

Single Charge Highway Cruise Range Estimate

$$\text{Cruise\_Range}(30\cdot mph, 50, SOC_{gen}) = 71.188\ mi$$
$$\text{Cruise\_Range}(40\cdot mph, 50, SOC_{gen}) = 59.5\ mi$$
$$\text{Cruise\_Range}(50\cdot mph, 50, SOC_{gen}) = 49.211\ mi$$
$$\text{Cruise\_Range}(55\cdot mph, 50, SOC_{gen}) = 43.835\ mi$$
$$\text{Cruise\_Range}(60\cdot mph, 50, SOC_{gen}) = 40.515\ mi$$
$$\text{Cruise\_Range}(70\cdot mph, 50, SOC_{gen}) = 34.229\ mi$$
$$\text{Cruise\_Range}(90\cdot mph, 50, SOC_{gen}) = 22.892\ mi$$
$$\text{Cruise\_Range}(100\cdot mph, 50, SOC_{gen}) = 21.418\ mi$$
$$\text{Cruise\_Range}(120\cdot mph, 50, SOC_{gen}) = 15.861\ mi$$



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

$\text{Cruise\_Range}(15\cdot mph, 50, 0.3) = 118.09\, mi$

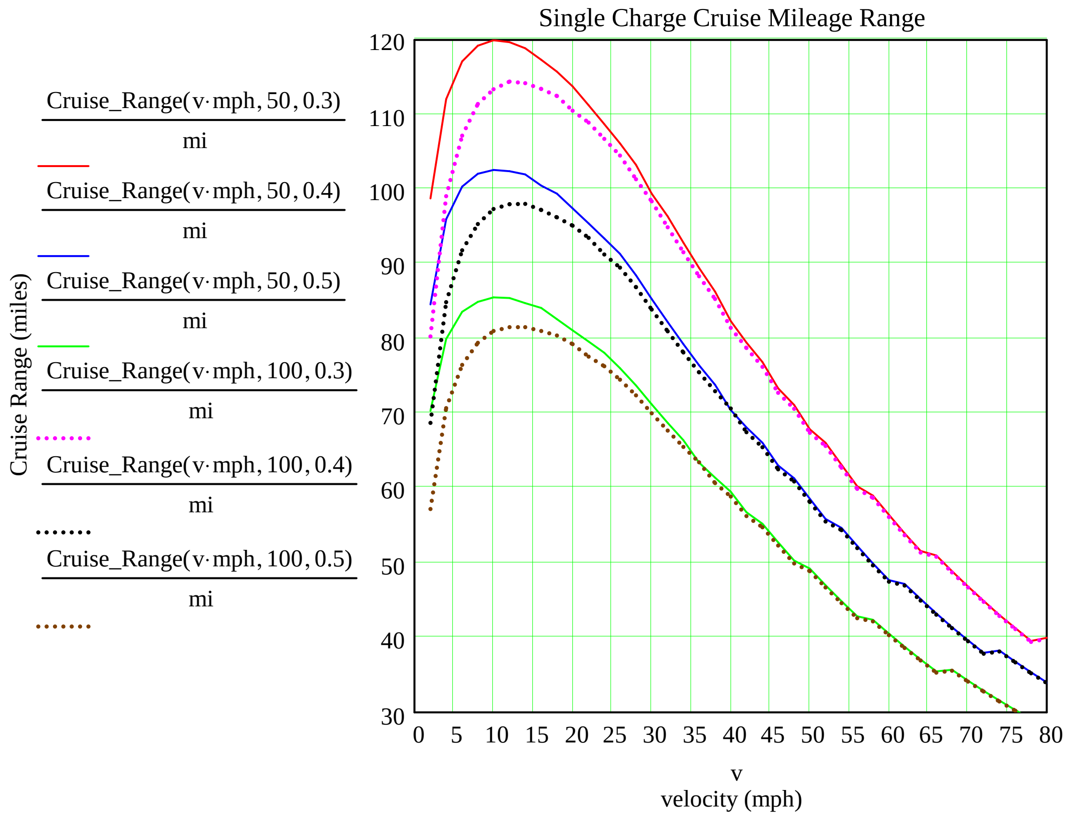
$\text{Cruise\_Range}(55\cdot mph, 50, 0.5) = 43.835\, mi$

$v := 0, 2 .. 80$

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

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

$$\frac{\text{Cruise\_Range}(55\cdot mph, 100, 0.25) - \text{Cruise\_Range}(55\cdot mph, 100, 0.5)}{\text{Cruise\_Range}(55\cdot mph, 100, 0.5)} = 0.516$$



A123 Systems NanoPhosphate m1 Cell Characterization / GM Volt Battery:

$SpecificEnergy_{A123m1} := \frac{3.3\cdot volt\cdot 2.3\cdot amp\cdot hr}{70\cdot gm}$ $SpecificEnergy_{A123m1} = 108.429\frac{watt\cdot hr}{kg}$

Weight Aux: Case, Blower, Cooler, Relays, Electronics $Weight_{Aux} := 25\cdot lb$ $Weight_{bat} := 350\cdot lb$

$Energy_{A123Bat} := Weight_{bat}\cdot SpecificEnergy_{A123m1}$ $Energy_{A123Bat} = 17.214\, k\cdot watt\cdot hr$

$SpecificEnergy_{GoalBat} := \frac{150\cdot k\cdot watt\cdot hr}{kg}$ $Energy_{Goal} := Weight_{bat}\cdot SpecificEnergy_{GoalBat}$

$Energy_{Goal} = 2.381\times 10^{4}\, k\cdot watt\cdot hr$

Series Parallel Arrangment of A123 Systems ANR26650M1 Cells:

$NumberCells := \frac{Weight_{bat}}{70 \cdot gm}$ $NumberCells = 2.268 \times 10^{3}$ $SeriesCells := \frac{363 \cdot volt}{3.3volt}$ $SeriesCells = 110$

$ParallelCells := \frac{NumberCells}{SeriesCells}$ $ParallelCells = 20.618$ $ContinuousDischargeCell := 70 \cdot amp$

$ContinuousDischargeCell \cdot 20 = 1.4 \times 10^{3}\, A$ $ContinuousPower := 363 \cdot volt \cdot ContinuousDischargeCell \cdot 20$

$ContinuousPower = 508.2\, k \cdot watt$ $Capacity := 2.3 \cdot A \cdot hr \cdot 20 \cdot 363 \cdot volt$ $Capacity = 16.698\, k \cdot watt \cdot hr$

$CostCellDollars := \frac{110}{6}$ $CostBattery := CostCellDollars \cdot 20 \cdot 110$ $CostBattery = 4.033 \times 10^{4}$

Goals for 2010 USABC

$CostBatteryGoal2010 := \frac{500 \cdot Capacity}{k \cdot watt \cdot hr}$ $CostBatteryGoal2010 = 8.349 \times 10^{3}$

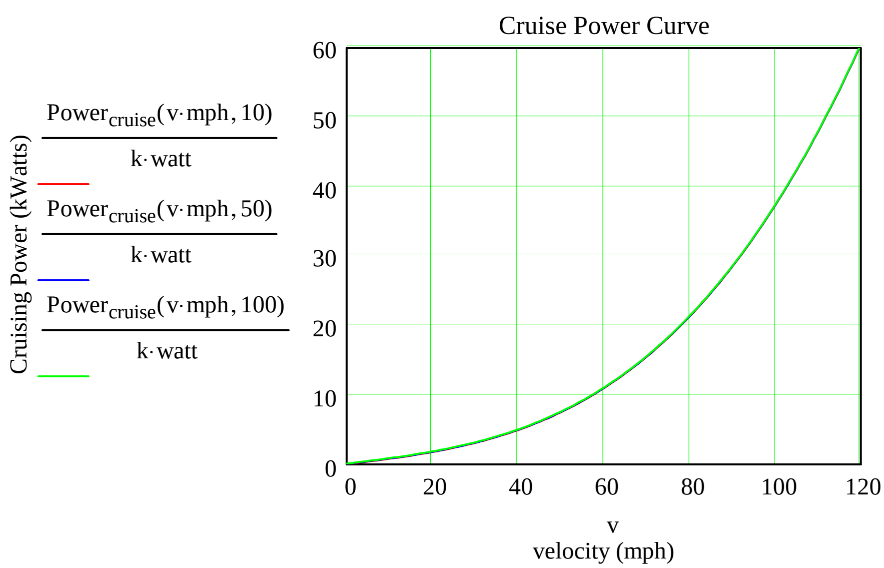
$PeakMotorCurrent := \frac{Power_{max}}{363 \cdot volt}$ $PeakMotorCurrent = 429.342\, A$ $16k \cdot watt$

$MotorStallCurrent :=$ ▮

Find the Power to Maintain Constant Velocity

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

$Power_{cruise}(60 \cdot mph, 100) = 11.057\, kW$ $v := 0, 1 .. 120$



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

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.

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

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

HWYF := READPRN("hwycol.txt") $\quad HWY := HWYF^{\langle 1 \rangle} \quad R_{hwy} := rows(HWY)$

FP10 := READPRN("FTP10Hz.TXT") $\quad FTP10V := submatrix(FP10, 0, rows(FP10) - 1, 1, cols(FP10) - 1)$

HY10 := READPRN("HWY10Hz.TXT") $\quad HWY10V := submatrix(HY10, 0, rows(HY10) - 1, 1, cols(HY10) -$

US06F := READPRN("US06PROFILE.TXT") $\quad time := US06F^{\langle 0 \rangle} \quad US06 := US06F^{\langle 1 \rangle} \quad n_6 := 0..598$

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

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

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

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

$AER(US06,1) = ■$ $\quad AER(FTP,1) = 40.138$ $\quad AER(HWY,1) = 40.095$ $\quad AER(HWY10,10) = ■$

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

$MPG_{city} := \dfrac{1}{\left(0.003259 + \dfrac{1.18053}{AER(FTP,1)}\right)}$ $\quad MPG_{city} = 30.608$ $\quad MPG_{hwy} := \dfrac{1}{0.001376 + \dfrac{1.3466}{AER(HWY,1)}}$ $\quad X := \dfrac{1}{40}$

$MPG_{epa} := 0.55 \cdot MPG_{city} + 0.45 \cdot MPG_{hwy}$ $\quad MPG_{epa} = 29.706$

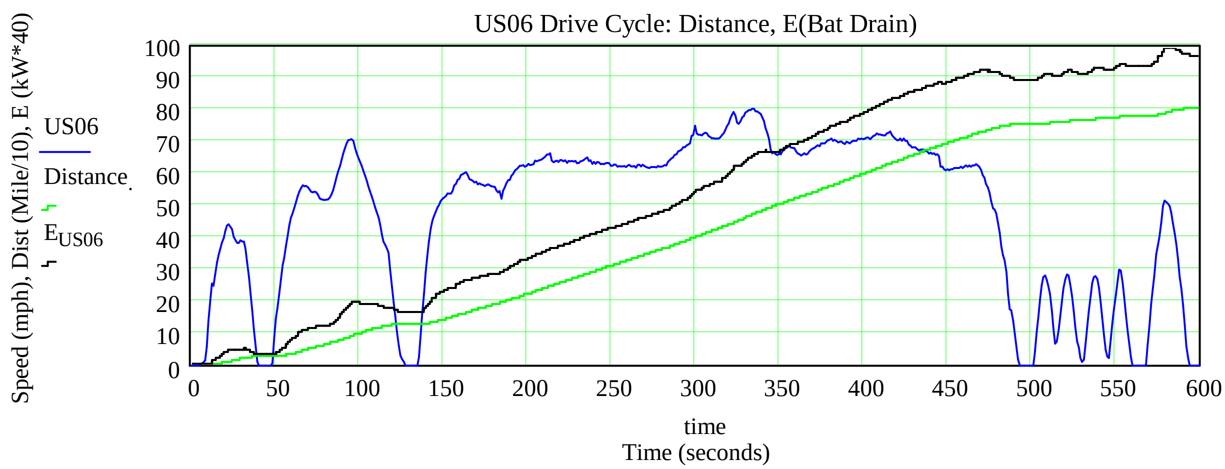
$r := 0..\text{rows}(FTP) - 1$ $\quad Distance_r := \sum_{r=0}^{r} FTP_r \cdot \dfrac{10}{60 \cdot 60}$ $\quad rr := 0..\text{rows}(US06) - 1$ $\quad Distance._{rr} := \sum_{rr=0}^{rr} US06_{rr} \cdot \dfrac{10}{60 \cdot 60}$

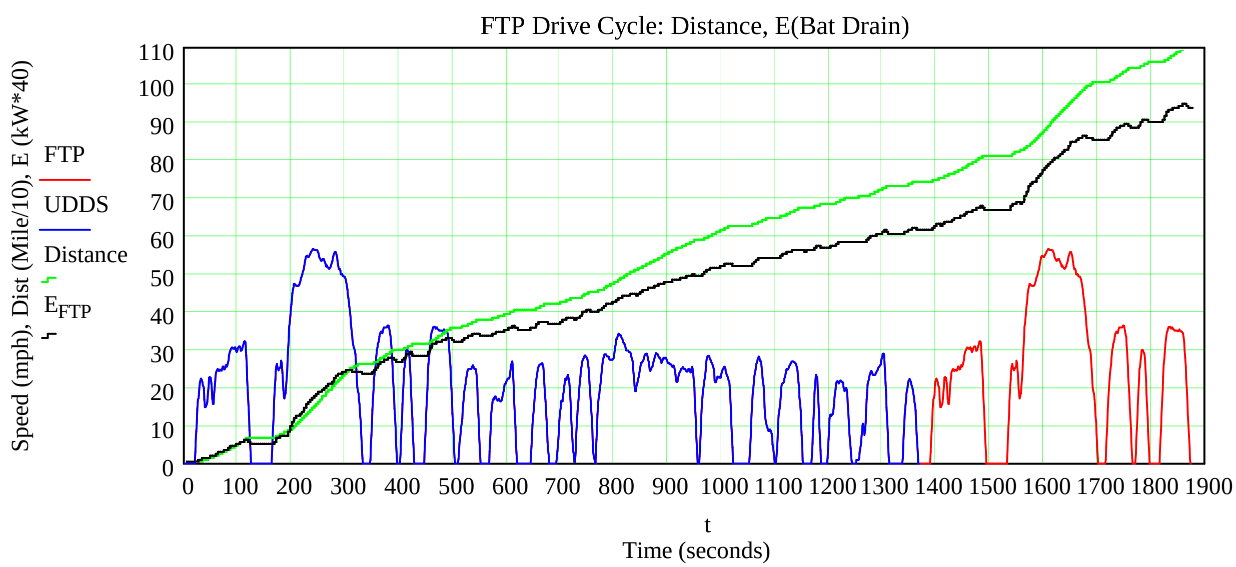
$\max(Distance) = 110.414$ $\quad \max(Distance.) = 80.08$

$WRITEPRN("EFTP.PRN") := AER(FTP,1) \cdot 40$ ■ $\quad E_{FTP} := READPRN("EFTP.PRN")$ $\quad \max(E_{FTP}) \cdot X = 2.369$

$WRITEPRN("EUS06.PRN") := AER(US06,1) \cdot 40$ ■ $\quad E_{US06} := READPRN("EUS06.PRN")$ $\quad \max(E_{US06}) \cdot X = 2.487$

$WRITEPRN("EHWY.PRN") := AER(HWY,1) \cdot 40$ $\quad E_{HWY} := READPRN("EHWY.PRN")$ $\quad \max(E_{HWY}) \cdot X = 40.1$





Profile: Max Acceleration, ads, Max Power Dissipation, Pds, Estimate of AER (#Charges x Distance)

$a_{ds_{n6}} := \left(US06_{n_6+1} - US06_{n_6}\right)\cdot mph\cdot(1\cdot sec)^{-1}$

$P_{ds_{n6}} := k_m\cdot M_{gross}\cdot a_{ds_{n6}}\cdot US06_{n_6}\cdot mph$

$\min(a_{ds}) = -0.315\,g$ $\quad n_h := 0 .. R_{hwy} - 2$

$\max(P_{ds}) = 94.045\,hp$ $\quad \max(US06) = 80.3$

$REff(0.315) = 0.693$

$a_{ds_{nh}} := \left(HWY_{n_h+1} - HWY_{n_h}\right)\cdot mph\cdot(1\cdot sec)^{-1}$

$P_{ds_{nh}} := k_m\cdot M_{gross}\cdot a_{ds_{nh}}\cdot HWY_{n_h}\cdot mph$

$\max(a_{ds}) = 0.146\,g$ $\quad \dfrac{8\cdot 11.04\cdot 40}{\max(E_{FTP})} = 37.278$

$\max(P_{ds}) = 31.34\,hp$ $\quad \dfrac{8\cdot 8.008\cdot 40}{\max(E_{US06})} = 25.762$

$\sum_{r=0}^{1380} FTP_r\cdot\dfrac{1}{60\cdot 60} = 7.45$ $\quad E_{FTP_{1380}} = 61.72$

$\dfrac{8\cdot 7.45\cdot 40}{E_{FTP_{1380}}} = 38.626$

PayOff Battery Lease

$M := 8000$ $\quad num := 12$ $\quad term := 4$ $\quad nper := num\cdot term$ $\quad R_M := 0.05$

$PMT_M := pmt\left(\dfrac{R_M}{num}, nper, M\right)$ $\quad PMT_M = -184.234$ $\quad PMT_M\cdot 12 = -2.211\times 10^3$

Cost of Gas vs. Electric for Months Driving

$Miles\_Yr := 12000\cdot mi$ $\quad GasCost\_Month := \dfrac{Miles\_Yr}{20\cdot mi}\cdot\dfrac{4.2}{12}$ $\quad GasCost\_Month = 210$

$CostDollar_{elect} := \dfrac{0.1}{kW\cdot hr}$ $\quad charge := \dfrac{8\cdot kW\cdot hr}{40\cdot mi}$ $\quad Cost\_mile_{elect} := CostDollar_{elect}\cdot charge$

$CostDollarsMonthEV_{elect} := Cost\_mile_{elect}\cdot\dfrac{Miles\_Yr}{12}$ $\quad CostDollarsMonthEV_{elect} = 20$

$LeasePlusElect\_Month := -PMT_M + CostDollarsMonthEV_{elect}$ $\quad LeasePlusElect\_Month = 204.234$

$GasCost\_Month = 210$

$charge = 447.387\,kg\,m\,s^{-2}$

$\dfrac{1000\cdot mi}{charge} = 3.597\times 10^3\,s^2\,kg^{-1}$

$\dfrac{Miles\_Yr}{20\cdot mi}\cdot\dfrac{CostGas}{12} = 299 + 24$

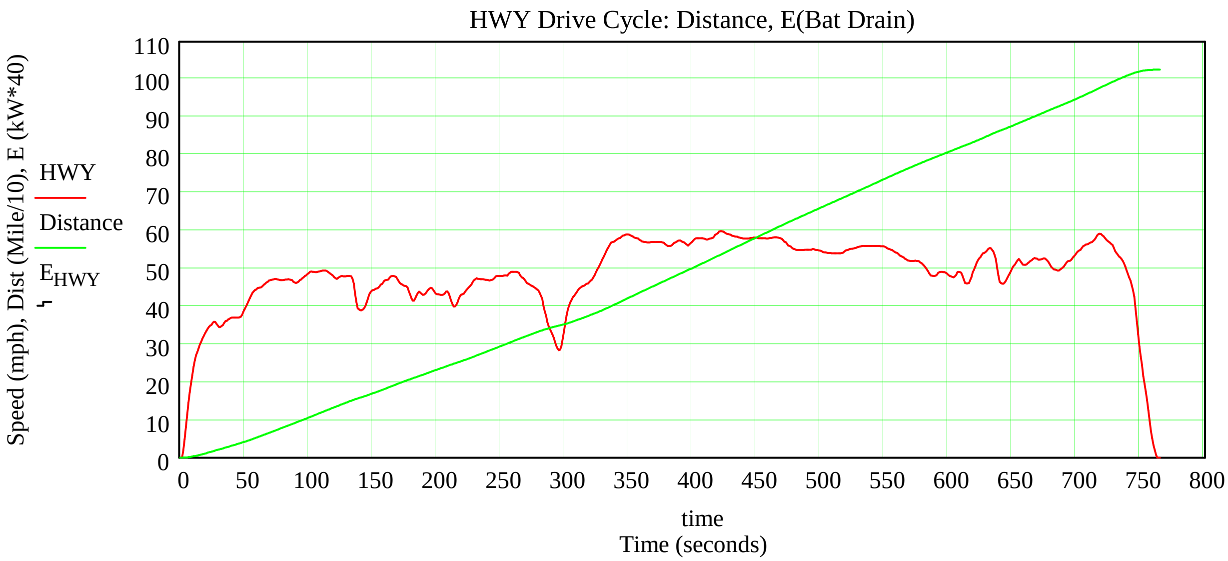
$8\cdot kW\cdot hr\cdot CostDollar_{elect}\cdot 30 = 24$

$r := 0 .. rows(HWY) - 1$

$$Distance_r := \sum_{r=0}^{r} HWY_r \cdot \frac{10}{60 \cdot 60} \qquad time := HWYF^{\langle 0 \rangle}$$

mean(HWY) = 48.204

max(HWY) = 59.9



$$D(SW, AR, RD) := \frac{SW \cdot AR \cdot 2}{25.4 \cdot 100} + RD$$

$$D(195, 55, 21) = 29.445$$

$$D := 0 \cdot mi$$

$$QMile(d) := root\left(d - root\left(D - \int_0^{Time} velocity(Time) \cdot \tau \, dTime, D\right), Time\right)$$

$QMile(0.25 \cdot mi) =$ ▪ ▮ 23 sec

$$0.95 \cdot 0.95 = 0.903$$