1999 GM EV-1 NiMH PERFORMANCE SIMULATION

http://www.leapcad.com/Transportation/GM_EV1_Simulation.mcd

VXPhysics.com

GM EV-1 - Vehicle, Motor, Road, and Environmental Parameters:

Gear Ratio: $GR := 10.946$

Nickel Metal Hydride: $85 \cdot A \cdot hr \cdot 343 \cdot volt = 29.155\,kW \cdot hr$

Max Motor Power: $Power_{max} := 137 \cdot hp$

$Power_{max} = 102.161\,kW$

Lead Acid Batt Energy: $60 \cdot A \cdot hr \cdot 312 \cdot volt = 18.72\,kW \cdot hr$

$Energy_{bat} := 29 \cdot kW \cdot hr$ $\quad Energy_{bat} := 29.155 \cdot kW \cdot hr$

Max Motor Torque: $Tm := 110 \cdot ft \cdot lbf$

Tire Radius*: $r_{tire} := 1.05 \cdot ft$

Max Force, Fm: $Fm := GR \cdot \frac{Tm}{r_{tire}}$ $\quad Fm = 1.147 \times 10^3\,lbf$ $\quad RPM := min^{-1}$

Constant Power Motor Torque, ω: $\omega_{CP} := \frac{Power_{max}}{Tm}$ $\quad RPM_{CP} := \frac{\omega_{CP} \cdot min}{2 \cdot \pi}$ $\quad RPM_{CP} = 6.541 \times 10^3$

Constant Power vehicle velocity, v_{CP}: $v_{CP} := \frac{Power_{max}}{Fm}$ $\quad v_{CP} = 44.802\,mph$ $\quad k := 10^3$ $\quad Tm = 149.14\,N \cdot m$

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

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

Frontal Area*: $Afg := 1.89 \cdot m^2$

Shape Correction Factor: $SCF := 0.85$

Frontal Area Corrected: $Af := Afg \cdot SCF$ $\quad Af = 1.606\,m^2$

Drag Coeff: $Cd := 0.19$

Rolling Resistance Per Tire: $RR_{tire} := 0.006$

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

Tire Hysteresis, Th:

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

θ (radians): (Average 0% road grade) $\theta := atan(0.0)$

Road Rolling Resist: $RR_{road} := 0.002$

Curb Weight: $M_{curb} := 2848 \cdot lb$

Rotational Inertia Coeff: $k_m := 1.08$

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

Gross Weight: $M_{gross} := M_{curb} + Passengers2$ $\quad M_{gross} = 3.018 \times 10^3\,lb$ $\quad M_{batt} := 1310lb$

Motor Breaking Force in g: $MotorBrake_g := GR \cdot Tm \cdot \left(k_m \cdot M_{gross} \cdot r_{tire} \cdot g\right)^{-1}$ $\quad MotorBrake_g = 0.352$

$WeightToHP := \frac{M_{curb}}{Power_{max}}$ $\quad WeightToHP = 20.788\,\frac{lb}{hp}$

Vehicle Dynamics Equations:

Velocity at Torque Fall: $v_{maxT} := 6000 \cdot min^{-1} \cdot 2 \cdot \pi \cdot r_{tire} \cdot GR^{-1}$ $\quad v_{maxT} = 41.094\,mph$ $\quad Th := 0 \cdot sec \cdot mi^{-1}$

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

Air Drag Force, 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: $Fo(v) := Fa(v) + Ft(v)$ $\quad Fo(60 \cdot mph) = 56.061\,lbf$

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) $a(v) := \frac{F(v) - Fo(v)}{k_m \cdot M_{gross}}$ $\quad P(v) := F(v) \cdot v$ $\quad Fm \cdot v_{maxT} = 125.664\,hp$

$P_m(\omega) := T_\omega(\omega) \cdot k \cdot 2 \cdot \pi \cdot \omega \cdot RPM$ $\quad P(60 \cdot mph) = 137\,hp$

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

$End := 20$ $\quad$ Given $\quad \frac{d}{dt} v(t) = \frac{F(v(t)) - Fo(v(t))}{k_m \cdot M_{gross}}$ $\quad v(0) = 0$ $\quad velocity := Odesolve(t, End)$

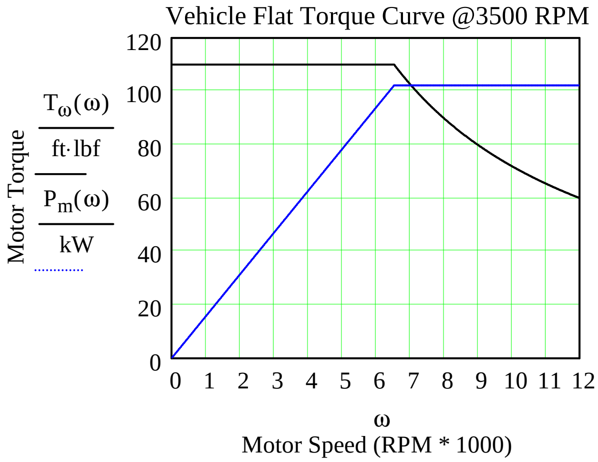
$acc_g(t) := a(velocity(t \cdot sec)) \cdot g^{-1}$

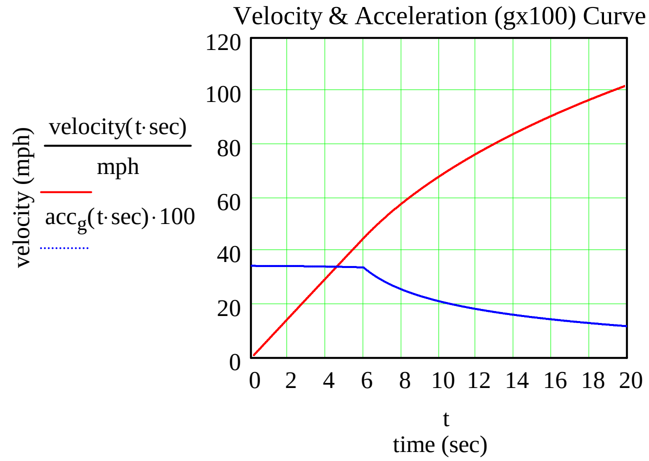
Spec 0-50 mph in 6.5 sec

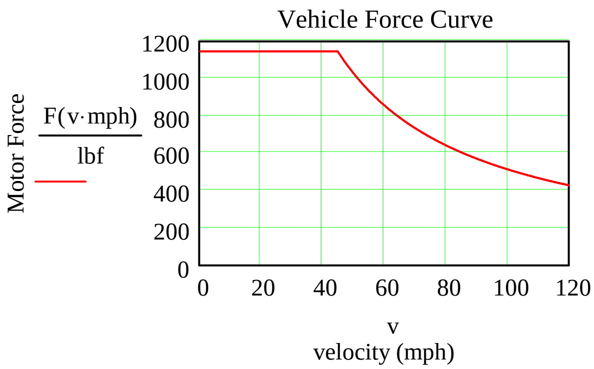
$Time := 0 \cdot sec$ $\quad time(v) := root(v - velocity(Time), Time)$ $\quad time(50 \cdot mph) = 6.704\,s$

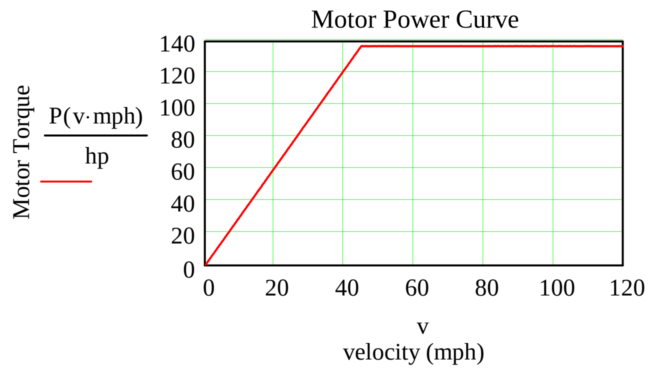
Link to EV1 NiMH Performance Specification Data

GM EV-1 ESTIMATED PEFORMANCE CURVES









Find NiH Single Charge (@SOC = 3.5%) Cruise Range for 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 of generator is SOC_{gen}. **SOC_{gen} is 3.5% for recharge.** 320V HV battery idle power is Po. 12V battery gives Accessory Power. The Traction Inverter Efficiency - TInvE, HV Power Electronics at Idle Efficiency - IPEE, and Gear Power Efficiency - GPE are 92.5%, 95%, and 90%, respectively. Brake Regen efficiency of kinetic energy is 60%. Then the number of starts per hour as a function of velocity, NS, NumStarts(v, Po), is

$TInvE := 0.925 \quad IPEE := 0.95 \quad GPE := 0.95 \quad Regen := 0.6 \quad v := 0, 2 .. 80 \quad SOC_{gen} := 0.035$

USABC Round Trip Battery Energy Efficiency

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

$RTEff := 0.92$

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

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

$$\text{Cruise\_Range}(20\cdot\text{mph}, 50, \text{SOC}_{\text{gen}}) = 351.325\,\text{mi}$$

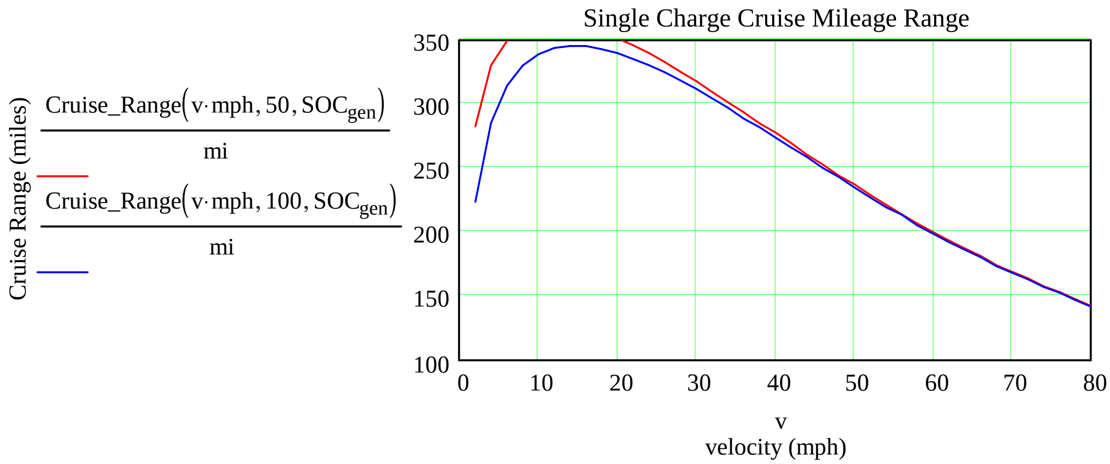
$$\text{Cruise\_Range}(45\cdot\text{mph}, 50, \text{SOC}_{\text{gen}}) = 256.619\,\text{mi}$$

$$\text{Cruise\_Range}(50\cdot\text{mph}, 50, \text{SOC}_{\text{gen}}) = 237.27\,\text{mi}$$

$$\text{Cruise\_Range}(55\cdot\text{mph}, 50, \text{SOC}_{\text{gen}}) = 218.304\,\text{mi}$$

$$\text{Cruise\_Range}(60\cdot\text{mph}, 50, \text{SOC}_{\text{gen}}) = 199.867\,\text{mi}$$

$$\text{Cruise\_Range}(70\cdot\text{mph}, 50, \text{SOC}_{\text{gen}}) = 168.905\,\text{mi}$$



Find the Power to Maintain Constant Velocity

$$\text{Power}_{\text{cruise}}(v, P_o) := \text{Power}_{\text{dissLoss}}(v, P_o) \qquad v := 0, 1 .. 120$$

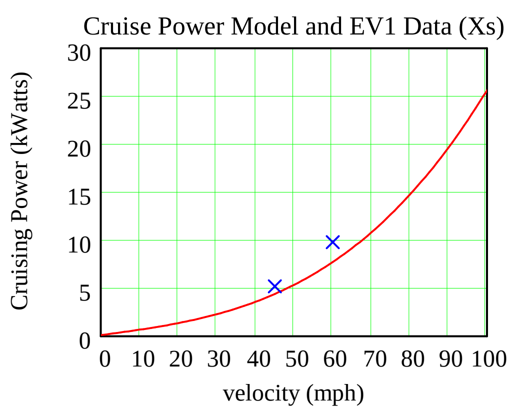
Compare and Validate with INL Lab Test EV1 Cruise Data: http://avt.inel.gov/pdf/fsev/eva/genmot.pdf

At 45 mph = Power: 5.19 kW, Efficiency: 115 w-hr/mi (8.7 mi/kw-hr)
At 60 mph = Power: 9.79 kW, Efficiency: 164 w-hr/mi (6.1 mi/kw-hr)

$$\text{Speed} := \begin{pmatrix} 45 \\ 60 \end{pmatrix} \qquad \text{Pwr} := \begin{pmatrix} 5.19 \\ 9.79 \end{pmatrix}$$

Model Projection at 70 mph

At 70 mph: $\text{Power}_{\text{cruise}}(70\cdot\text{mph}, 50) = 10.759\,\text{kW}$ $\qquad \dfrac{70\cdot\text{mi}}{\text{Power}_{\text{cruise}}(70\cdot\text{mph}, 50)\cdot\text{hr}} = 6.506\,\dfrac{\text{mi}}{\text{kW}\cdot\text{hr}}$



$$n := 0 .. 120 \qquad \text{CPDat}_{n} := n$$

$$\text{CPDat}_{n,1} := \frac{\text{Power}_{\text{cruise}}(n\cdot\text{mph}, 100)}{\text{k}\cdot\text{watt}}$$

$$\text{WRITEPRN}(\text{"EV1Cpwr.txt"}) := \text{CPDat}$$

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("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")

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

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

EbatDrivingCycle_Whr := 25.14

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

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

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

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

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

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

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

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

Data: Range per SAE J1634: 140.3 miles

$AER(US06, 1) =$ ▪ $AER(FTP, 1) = 156.568$ $AER(HWY, 1) = 168.298$ $AER(HWY10, 10) =$ ▪

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

$MPG_{city} := \frac{1}{\left(0.003259 + \frac{1.18053}{AER(FTP,1)}\right)}$ $MPG_{city} = 92.601$ $MPG_{hwy} := \frac{1}{0.001376 + \frac{1.3466}{AER(HWY,1)}}$ $X := \frac{1}{40}$

$MPG_{epa} := 0.55\cdot MPG_{city} + 0.45\cdot MPG_{hwy}$ $MPG_{epa} = 98.919$

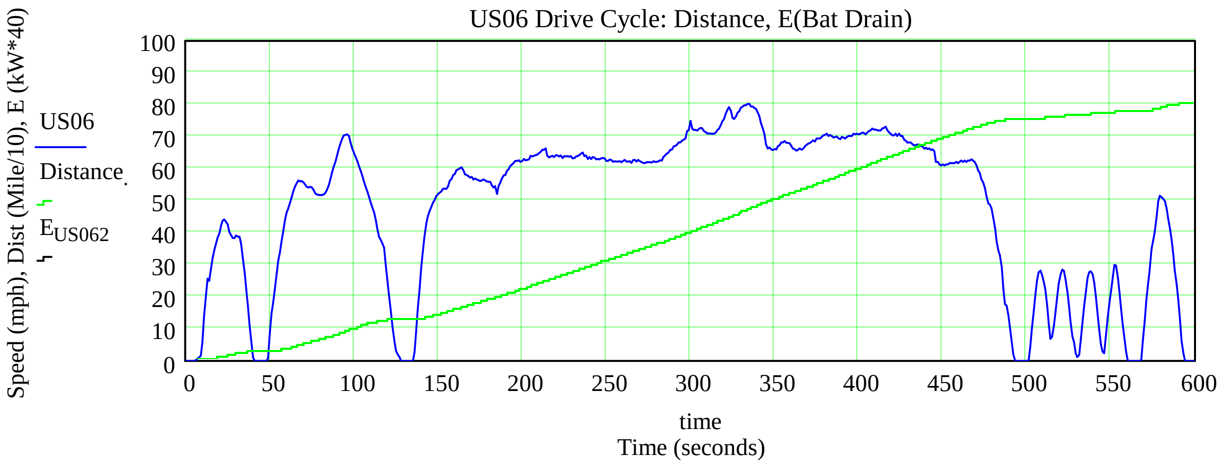
$r := 0 .. rows(FTP) - 1$ $Distance_r := \sum_{r=0}^{r} FTP_r\cdot\frac{10}{60\cdot 60}$ $rr := 0 .. rows(US06) - 1$ $Distance\__{rr} := \sum_{rr=0}^{rr} US06_{rr}\cdot\frac{10}{60\cdot 60}$

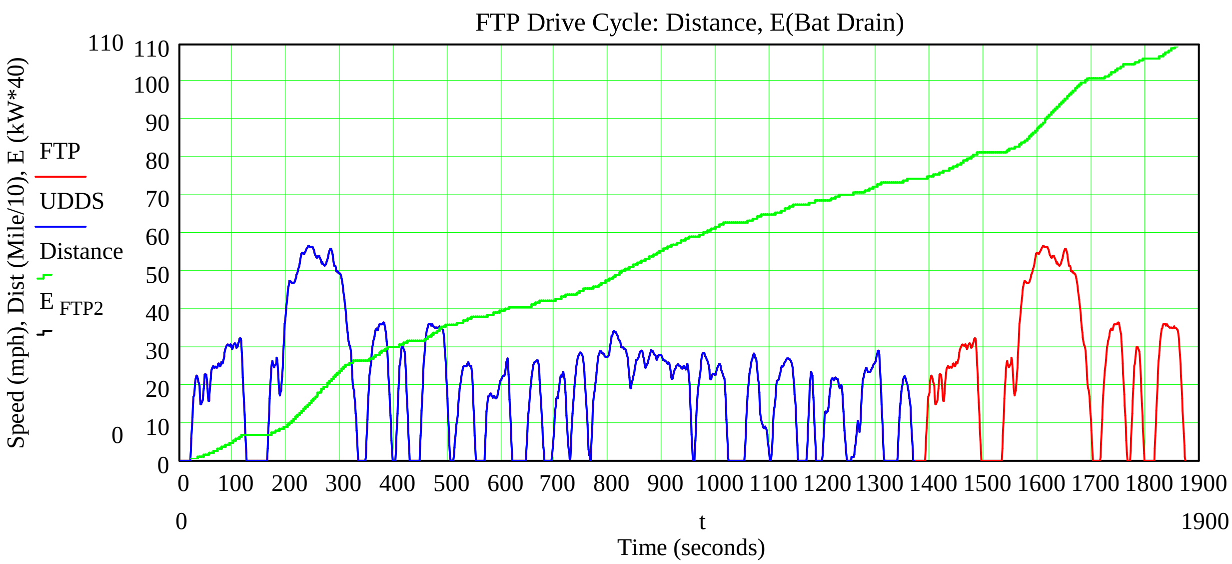
$max(Distance) = 110.414$ $max(Distance\_) = 80.08$

$WRITEPRN("EFTP2.PRN") := AER(FTP,1)\cdot 40$ $E_{FTP2} := READPRN("EFTP2.PRN")$ $max(E_{FTP2})\cdot X = 153.875$

$WRITEPRN("EUS062.PRN") := AER(US06,1)\cdot 40$ $E_{US062} := READPRN("EUS062.PRN")$ $max(E_{US062})\cdot X = 111.875$

$WRITEPRN("EHWY2.PRN") := AER(HWY,1)\cdot 40$ $E_{HWY2} := READPRN("EHWY2.PRN")$ $max(E_{HWY2})\cdot X = 166$


US06 Drive Cycle: Distance, E(Bat Drain)
Speed (mph), Dist (Mile/10), E (kW*40)
US06
Distance
E US062
100
90
80
70
60
50
40
30
20
10
0
0 50 100 150 200 250 300 350 400 450 500 550 600
time
Time (seconds)


FTP Drive Cycle: Distance, E(Bat Drain)
Speed (mph), Dist (Mile/10), E (kW*40)
FTP
UDDS
Distance
E FTP2
110
0
110
100
90
80
70
60
50
40
30
20
10
0
0 100 200 300 400 500 600 700 800 900 1000 1100 1200 1300 1400 1500 1600 1700 1800 1900
0
t
1900
Time (seconds)