

# GM VOLT PERFORMANCE SIMULATION

[http://www.leapcad.com/Transportation/GM\\_Volt\\_Simulation.mcd](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 <sub>max</sub> := 111·kW·0.9	Gear Ratio, Inefficiencies: GR := 8    η <sub>axle</sub> := 0.92
P <sub>Generator</sub> := 53·kW	Power <sub>max</sub> := P <sub>Generator</sub> ·0.9	Battery Energy: Energy <sub>bat</sub> := 16·kW·hr
Max Motor Torque:	T <sub>m</sub> := 273·ft·lbf    T <sub>m</sub> = 370.138 N·m	Tire Radius*: r <sub>tire</sub> := $\frac{27.2}{2}$ ·in    195/55R21
Max Force, F <sub>m</sub>	F <sub>m</sub> := GR·η <sub>axle</sub> · $\frac{T_m}{r_{tire}}$	F <sub>m</sub> = 1.773 × 10 <sup>3</sup> lbf
Power <sub>max</sub> = 133.968 hp		RPM := min <sup>-1</sup>
Constant Power	ω <sub>CP</sub> := $\frac{Power_{max}}{T_m}$	ω <sub>max</sub> := 12000·RPM
Motor Torque, ω:		RPM <sub>CP</sub> := $\frac{\omega_{CP} \cdot \text{min}}{2 \cdot \pi}$
Constant Power	v <sub>CP</sub> := $\frac{Power_{max}}{F_m}$	RPM <sub>CP</sub> = 2.577 × 10 <sup>3</sup>
vehicle velocity, v <sub>CP</sub> :		v <sub>CP</sub> = 28.337 mph    k := 10 <sup>3</sup> T <sub>m</sub> = 370.138 N·m
Average Wind Velocity:	V <sub>w</sub> := 0·mph	Effective Cross Wind V: V <sub>cw</sub> := 0·mph
	Power <sub>max</sub> = 99.9 kW	Frontal Area*: A <sub>fg</sub> := 2.16·m <sup>2</sup>
Shape Correction Factor:	SCF := 0.85	Frontal Area Corrected: A <sub>f</sub> := A <sub>fg</sub> ·SCF    A <sub>f</sub> = 1.836 m <sup>2</sup>
Drag Coeff:	C <sub>d</sub> := 0.28	Rolling Resistance Per Tire: RR <sub>tire</sub> := 0.007
Cross Wind Drag Coff:	C <sub>d</sub> <sub>cw</sub> := 0.000014	Tire Hysteresis, Th: Th := 0·sec·mi <sup>-1</sup>
Air Density:	ρ := 1.3· $\frac{\text{gm m}}{\text{liter er}}$	θ (radians): θ := atan(0)
Road Rolling Resist:	RR <sub>road</sub> := 0.002	(Average 0% road grade)
Rotational Inertia Coeff:	k <sub>m</sub> := 1.08	Curb Weight: M <sub>curb</sub> := 3140·lb
Gross Weight:	M <sub>gross</sub> := M <sub>curb</sub> + Passengers2	Passenger Weight: Passengers2 := 170·lb
Motor Breaking Force in g:	MotorBrake <sub>g</sub> := GR·T <sub>m</sub> ·(k <sub>m</sub> ·M <sub>gross</sub> ·r <sub>tire</sub> ·g) <sup>-1</sup>	M <sub>gross</sub> = 3.31 × 10 <sup>3</sup> lb    M <sub>batt</sub> := 300lb
WeightToHP := $\frac{M_{curb}}{Power_{max}}$		MotorBrake <sub>g</sub> = 0.539

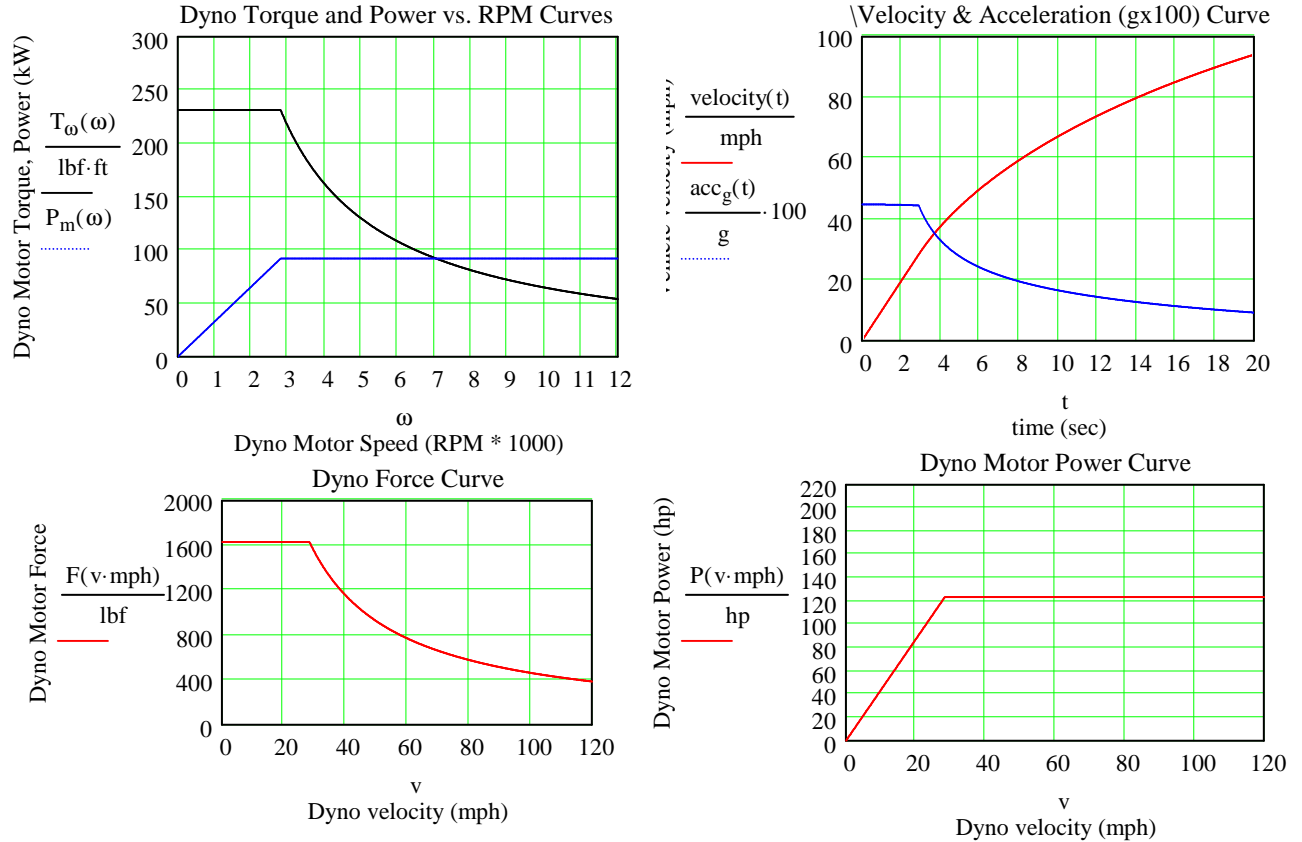
## Vehicle Dynamics Equations:

Road Resistance, Ft:	F <sub>t</sub> (v) := M <sub>gross</sub> ·g·[Th·v·sin(θ) + (RR <sub>tire</sub> + RR <sub>road</sub> )·cos(θ) + sin(θ)]	
Aerodynamic Loss, Fa:	F <sub>a</sub> (v) := 0.5·ρ·A <sub>f</sub> ·[(v + V <sub>w</sub> ) <sup>2</sup> ·C <sub>d</sub> + C <sub>d</sub> <sub>cw</sub> ·(0.5·v + V <sub>cw</sub> ) <sup>2</sup> ]	x := $\frac{s}{m}$
Opposing Force, Fo:	F <sub>o</sub> (v) := F <sub>a</sub> (v) + F <sub>t</sub> (v)	F <sub>o</sub> (60·mph) = 83.544 lbf
Tractive Force:	F(v) := if(v ≤ v <sub>CP</sub> , F <sub>m</sub> , $\frac{Power_{max}}{v}$ )·η <sub>axle</sub>	T(v) := F(v)· $\frac{r_{tire}}{GR}$
Third Law of Motion:	a(v) := $\frac{F(v) - F_o(v)}{k_m \cdot M_{gross}}$	T <sub>ω</sub> (ω) := T(ω·k·2·π·r <sub>tire</sub> ·GR <sup>-1</sup> ·RPM)
(a is acceleration)		P(v) := F(v)·v    P(60·mph) = 123.251 hp

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

End := 30	Given	$\frac{d}{dt} v(t) = \frac{F(v(t)) - F_o(v(t))}{k_m \cdot M_{gross}}$	v(0) = 0	velocity := Odesolve(t, End)
	acc <sub>g</sub> (t) := a(velocity(t·sec))	P <sub>m</sub> (ω) := T <sub>ω</sub> (ω)·k·2·π·ω·RPM·kW <sup>-1</sup>		velocity(30) = 110.208 x·mph
Time := 0·sec	time(v) := root(v - velocity(Time), Time)			time(60·mph) = 8.167 s
	Time to Accelerate from 40 to 60 mph:			time(60·mph) - time(40·mph) = 3.818 s

# GM VOLT PERFORMANCE 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 braking,  $Time_{ssr} =$  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  $P_o$** . 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% @ deceleration = 0.315g. Then the number of starts per hour as a function of velocity,  $NS$ ,  $NumStarts(v, P_o)$ , is

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

**USABC Round Trip Battery Energy Efficiency**

$$RTEff := 0.92$$

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

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

$NS_o$  and  $NS$  are iterative converging estimates of  $NumStarts$

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

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

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

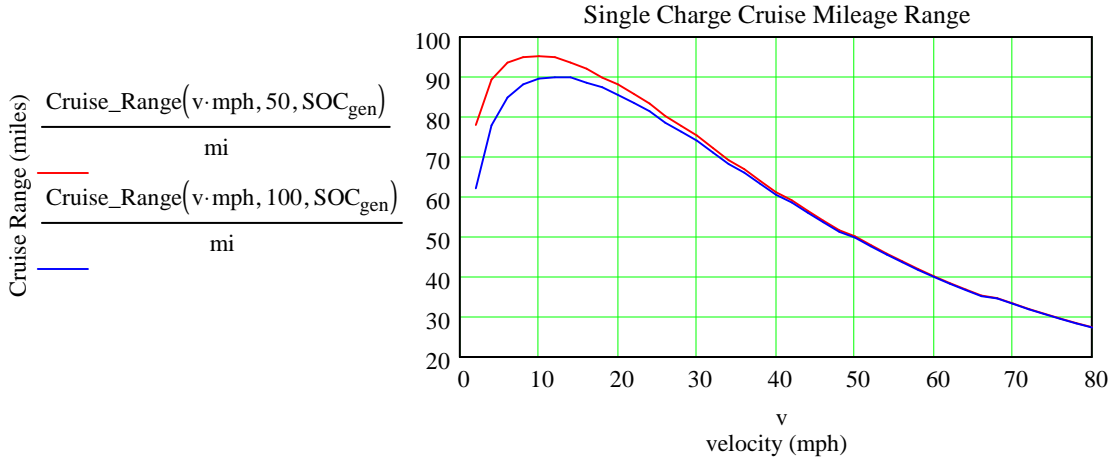
$$Cruise\_Range(v, P_o, S) := \frac{Energy_{bat} \cdot (1 - S) - NumStarts(v, P_o, S) \cdot \left( \frac{Energy_{accl}(v)}{TInvE \cdot GPE} - \frac{Regen \cdot M_{gross} \cdot v^2}{2} \right)}{Power_{dissLoss}(v, P_o)} \cdot v$$

### Single Charge Highway Cruise Range Estimate

#### Velocity Range

$v := 0, 2.. 80$

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



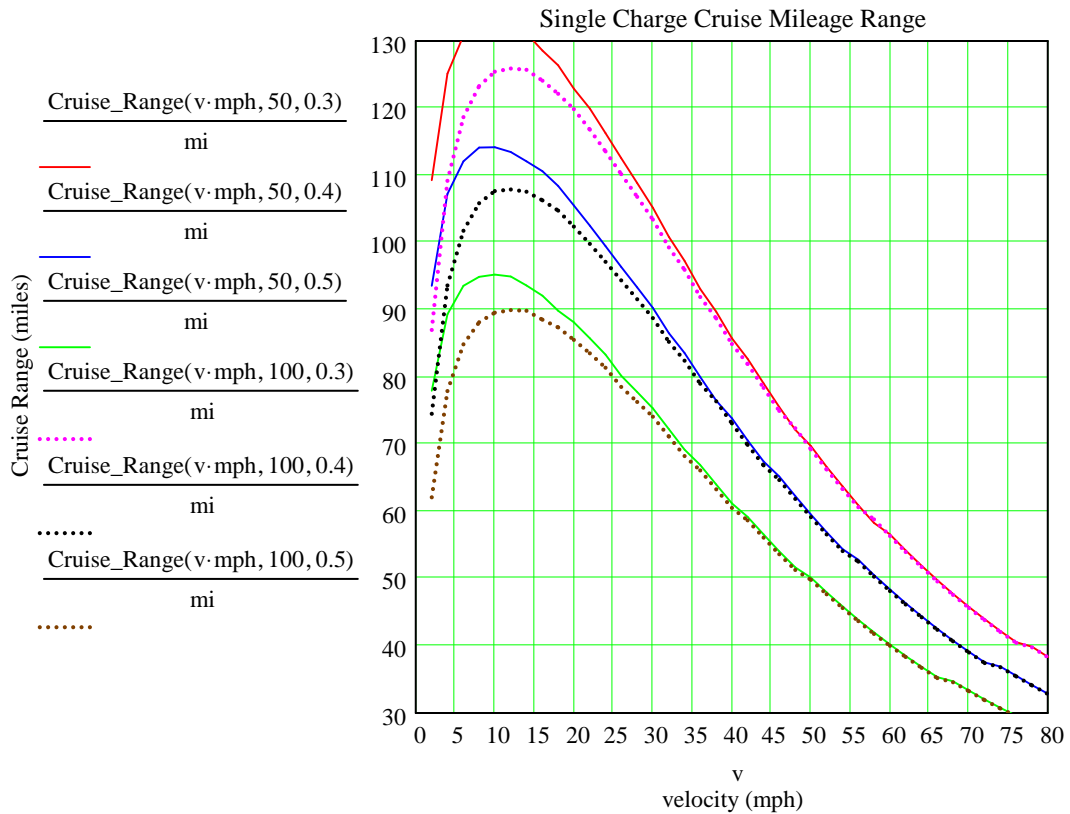
**Specsmanship: Twice as much range at 30 mph than 70 mph.**

**Conclusion: I need a bigger or a better battery!**

### Cruise Range as a Function of Traction Battery Idle Power, $P_o$

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

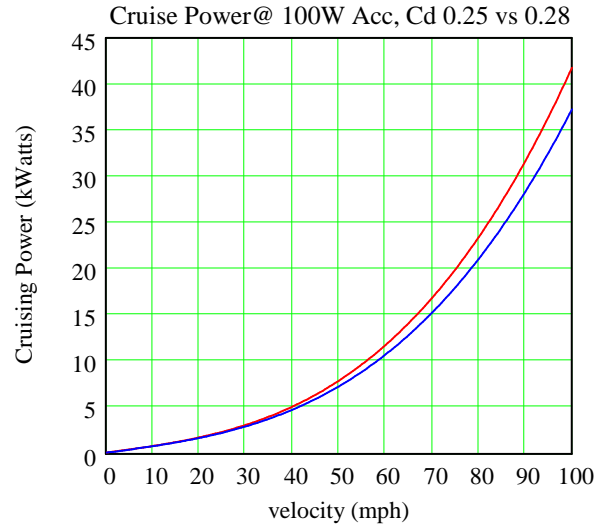
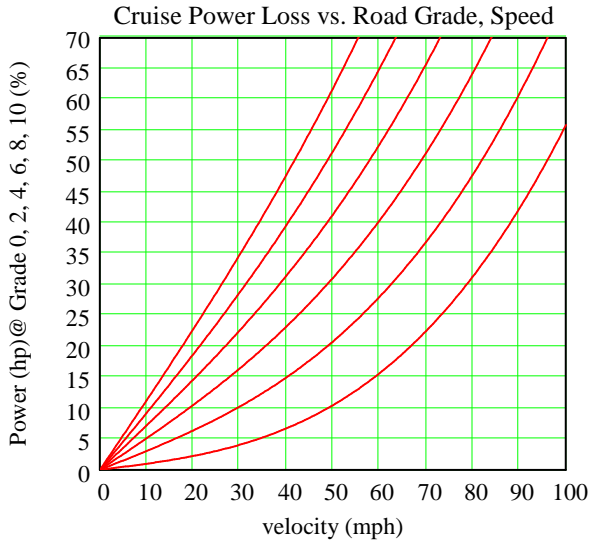
$$\text{Cruise\_Range}(55 \cdot \text{mph}, 50, 0.5) = 44.83 \text{ mi}$$



## 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.

$$\begin{aligned}
 \text{Power}_{\text{cruise}}(v, P_0) &:= \text{Power}_{\text{dissLoss}}(v, P_0) \\
 v_n &:= \frac{n}{2} & P_{\text{cruise}_n} &:= \text{Power}_{\text{cruise}}(v_n \cdot \text{mph}, 100) \left[ (\text{k watt})^{-1} \right] \\
 i &:= 0..5 & F_{t_g}(v, \theta) &:= M_{\text{gross}} \cdot g \cdot \left[ Th \cdot v \cdot \sin(\text{atan}(\theta)) + (RR_{\text{tire}} + RR_{\text{road}}) \cdot \cos(\text{atan}(\theta)) + \sin(\text{atan}(\theta)) \right] \\
 \theta_i &:= 0.02 \cdot i & \text{Phill}(v, \theta) &:= \frac{(F_{t_g}(v, \theta) + F_a(v)) \cdot v}{T_{\text{InvE}} \cdot \text{GPE}} & P_{\text{hill}_{n,i}} &:= \text{Phill}(v_n \cdot \text{mph}, \theta_i)
 \end{aligned}$$



## 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.

$$\begin{aligned}
 t_{ft} &:= \text{FTPF}^{\langle 0 \rangle} & \text{FTP} &:= \text{FTPF}^{\langle 1 \rangle} & \text{rows(FTP)} &= 1.875 \times 10^3 \\
 & & \text{UDDSF} &:= \text{UDDSF}^{\langle 1 \rangle} & \text{rows(UDDSF)} &= 1.37 \times 10^3 \\
 \text{time} &:= \text{US06F}^{\langle 0 \rangle} & \text{US06} &:= \text{US06F}^{\langle 1 \rangle} & n_6 &:= 0..598 & \text{HWY} &:= \text{HWYF}^{\langle 1 \rangle} & R_{\text{hwy}} &:= \text{rows(HWY)} \\
 \text{mean(FTP)} &= 21.2 & \text{FTP10V} &:= \text{submatrix}(\text{FP10}, 0, \text{rows}(\text{FP10}) - 1, 1, \text{cols}(\text{FP10}) - 1) \\
 & & \text{HWY10V} &:= \text{submatrix}(\text{HY10}, 0, \text{rows}(\text{HY10}) - 1, 1, \text{cols}(\text{HY10}) - 1)
 \end{aligned}$$

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

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

```

AER(P, Hz) :=
  Ebat ← E_diss ← v_old ← 0
  n ← -1
  N ← rows(P) - 1
  while E_diss < 8 ^ n == n
    n ← n + 1
    t ← mod(n, N)
    v ← P_t
    v_avg ← (v + v_old) · 0.5
    P_accel ←  $\frac{k_m \cdot M_{gross} \cdot (v - v_{old}) \cdot \frac{mph \cdot Hz}{sec} \cdot v_{avg} \cdot mph}{T_{InvE} \cdot GPE}$  if v > v_old
    P_accel ←  $k_m \cdot M_{gross} \cdot (v - v_{old}) \cdot \frac{mph \cdot Hz}{sec} \cdot v_{avg} \cdot mph \cdot REff\left[\frac{(v_{old} - v) \cdot Hz \cdot Gg}{1}\right]$  otherwise
    E_diss ← E_diss +  $\frac{(Power_{dissLoss}(v \cdot mph, 100) + P_{accel}) \cdot sec}{kW \cdot hr \cdot Hz}$ 
    v_old ← v
    Ebat_n ← E_diss
  R ←  $\sum_{m=0}^n \frac{(P_{mod(m, N)} + P_{mod(m+1, N)}) \cdot mph \cdot sec}{2 \cdot mi \cdot Hz}$ 
  R
  r1 := 0..rows(HY10)·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**

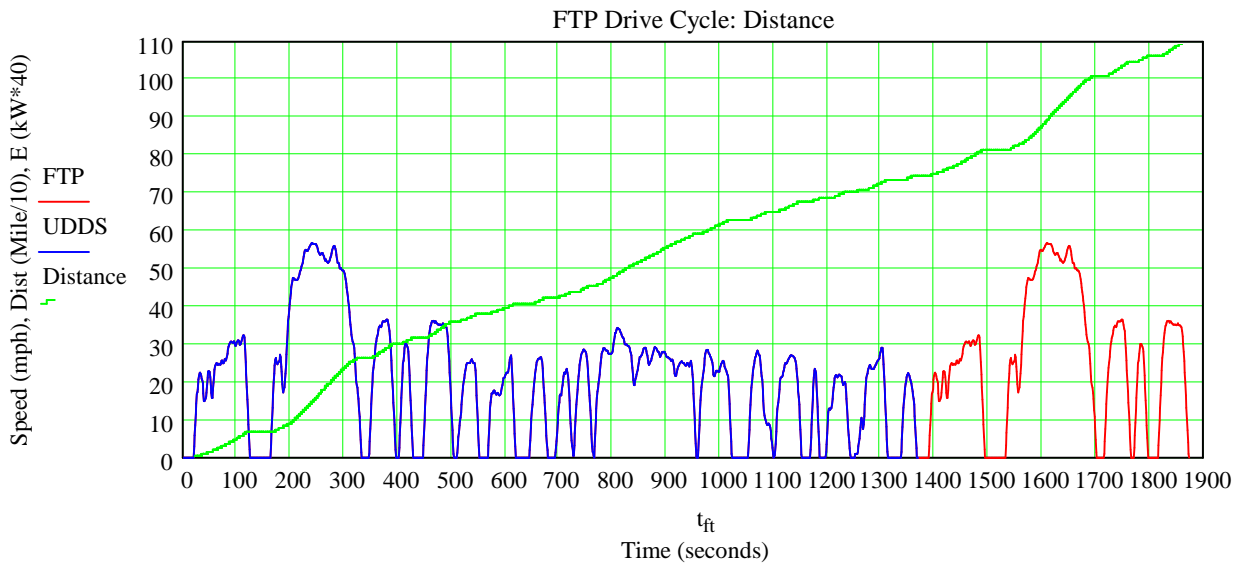
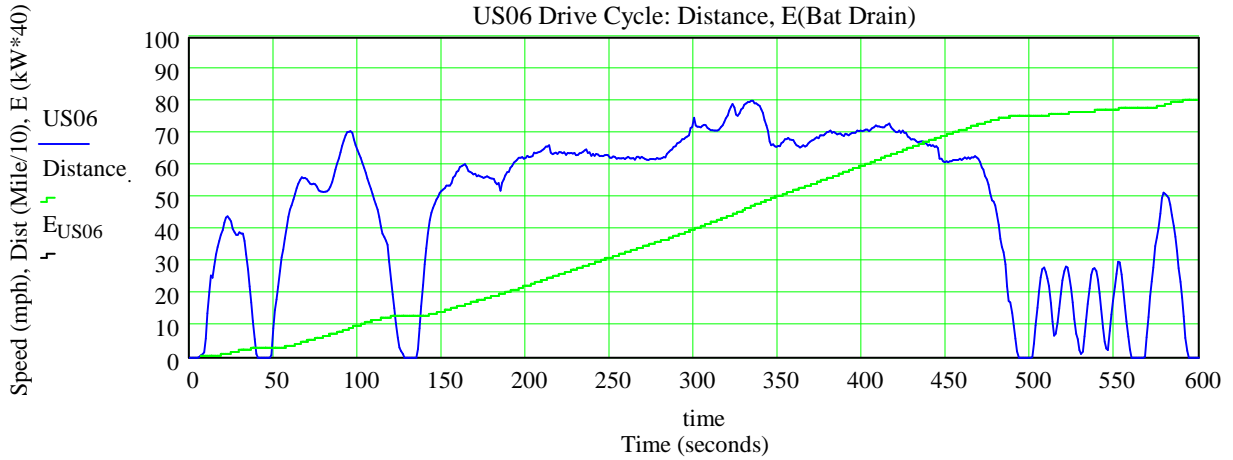
$MPG_{city} := \frac{1}{\left( 0.003259 + \frac{1.18053}{AER(FTP, 1)} \right)}$   $MPG_{city} = 29.889$      $MPG_{hwy} := \frac{1}{0.001376 + \frac{1.3466}{AER(HWY, 1)}}$      $X := \frac{1}{40}$

$MPG_{epa} := 0.55 \cdot MPG_{city} + 0.45 \cdot MPG_{hwy}$     **MPG<sub>epa</sub> = 28.792**

$r := 0..rows(FTP) - 1$      $Distance_r := \sum_{r=0}^r FTP_r \cdot \frac{10}{60 \cdot 60}$      $max(Distance) = 110.414$      $rr := 0..rows(US06) - 1$      $Distance_{rr} := \sum_{rr=0}^{rr} US06_{rr} \cdot \frac{10}{60 \cdot 60}$      $max(Distance) = 80.08$

### Plot EPA Driving Profiles

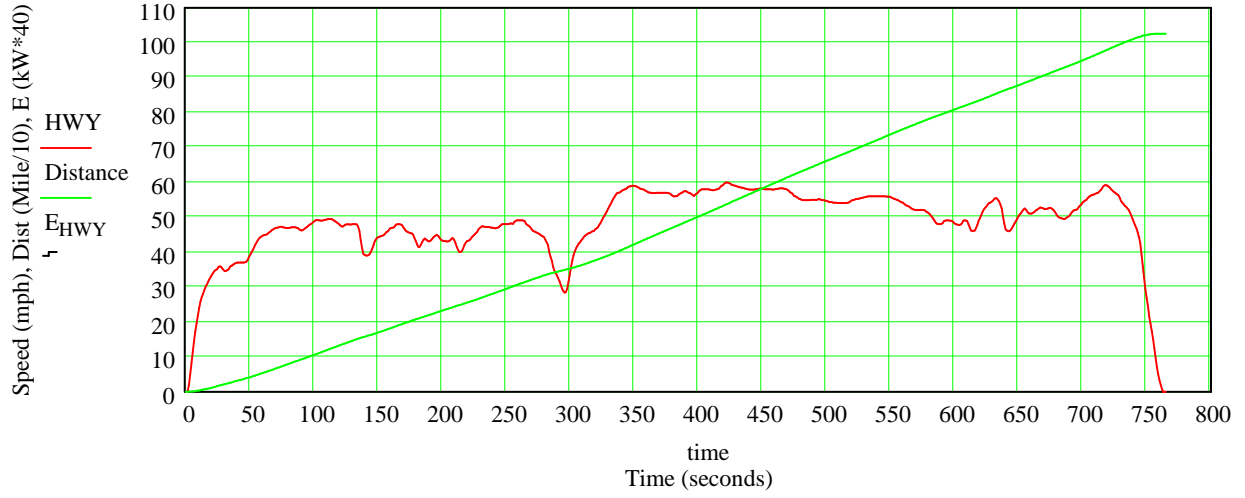
WRITEPRN("EFTP.PRN") := AER(FTP, 1)·40      E<sub>F<sub>FTP</sub></sub> := READPRN("EFTP.PRN")      max(E<sub>F<sub>FTP</sub></sub>)·X = 39.1  
 WRITEPRN("EUS06.PRN") := AER(US06, 1)·40      E<sub>US06</sub> := READPRN("EUS06.PRN")      max(E<sub>US06</sub>)·X = 25.65  
 WRITEPRN("EHWY.PRN") := AER(HWY, 1)·40      E<sub>HWY</sub> := READPRN("EHWY.PRN")      max(E<sub>HWY</sub>)·X = 38.42



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

$$\text{max}(HWY) = 59.9$$

HWY Drive Cycle: Distance, E(Bat Drain)



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

**For Comparison to Prius See:**

<http://www.leapcad.com/Transportation/Macro%20Model%20Performance%20Comparison%20-%20Volt%20EREV%20vs%20Prius.pdf>

**For Comparison to Corolla See (Page 5):**

[http://www.leapcad.com/Transportation/Corolla\\_Simulation.pdf](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<sub>v</sub> := Volt<sup><0></sup>    v<sub>v</sub> := Volt<sup><1></sup>    ω<sub>v</sub> := Volt<sup><2></sup>    mph<sub>v</sub> := Volt<sup><3></sup>    g<sub>v</sub> := Volt<sup><4></sup>  
 $T_w := \frac{\text{Volt}^{<5>}}{\text{lb}\cdot\text{ft}}$     P<sub>w</sub> := Volt<sup><6></sup>    F<sub>v</sub> := Volt<sup><7></sup>    P<sub>v</sub> := Volt<sup><8></sup>    P<sub>cruiseV</sub> := Volt<sup><9></sup>

$$TW(\omega) := \frac{T_{\omega}(\omega)}{\text{lb}\cdot\text{ft}}$$

$$VV(t) := \frac{\text{velocity}(t)}{\text{mph}}$$

$$AG(t) := \frac{\text{acc}_g(t)}{g} \cdot 100$$

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

