CARNEGIE-MELLON EV PERFORMANCE SIMULATION

http://www.leapcad.com/Transportation/Re-simulation_CM_PHEV_Study.mcd

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

Max Motor Power: $Power_{max} := 120 \cdot kW$

4 Cylinder 1.4L

$P_{Generator} := 53 \cdot kW$ $Power_{max} = 160.923\ hp$

Max Motor Torque: $Tm := 370 \cdot N \cdot m$

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

$Power_{max} = 160.923\ hp$

Constant Torque 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: $Cd := 0.215$

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

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

Road Rolling Resist: $RR_{road} := 0.0011$

Rotational Inertia Coeff: $k_m := 1.06$

Gross Weight: $M_{gross} := M_{curb} + Passengers2$

Gear Ratio (v_{CP}=60mph): $GR := 8.2$

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

Tire Radius*: $r_{tire} := \frac{25.9}{2} \cdot in$ 195/55R21 225/45R18

$Fm = 2.074 \times 10^{3}\ lbf$ $RPM := min^{-1}$

$MaxHp := 161$ $\omega_{max} := 12000 \cdot RPM$

$v_{CP} = 29.102\ mph$ $k := 10^{3}$

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: $Af := Afg \cdot SCF$ $Af = 1.836\ m^{2}$

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

Tire Hysteresis, Th:

θ (radians):

(Average 0% road grade) $\theta := atan(0)$ $T_{hys} := 0 \cdot \frac{sec}{m}$

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

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

$M_{gross} = 3.31 \times 10^{3}\ lb$ $M_{batt} := 300lb$

Vehicle Dynamics Equations:

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

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

Opposing Force, Fo: $Fo(v) := Fa(v) + Ft(v)$ Note: Force/Torque Curve is based on Tesla Data

Torque Model (Tesla) Linear Falloff - Match 1- 60 mph Performance

Torque/Force Drop Curve: $Fd_{tire}(v) := Fm \cdot \left[1 - (v - v_{CP}) \cdot \left[\left(110 - \frac{v_{CP}}{mph}\right) \cdot mph\right]^{-1}\right]$ $F_p(v) := \frac{Power_{max}}{v}$

Torque Speed Relation: $F(v) := if(v \le v_{CP}, Fm, Fd_{tire}(v))$ $T(v) := F(v) \cdot \frac{r_{tire}}{GR}$

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

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

$P(v) := F(v) \cdot v$ $P(60 \cdot mph) = 205.059\ hp$

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

$Time := 0 \cdot sec$

$V := 0 \cdot mph$ $velocity(t) := root\left(V - \int_{0}^{t} a(V) \cdot \tau\, dt, V\right)$

$time(v) := root(v - velocity(Time), Time)$

$P_m(\omega) := T_{\omega}(\omega) \cdot k \cdot 2 \cdot \pi \cdot \omega \cdot RPM$

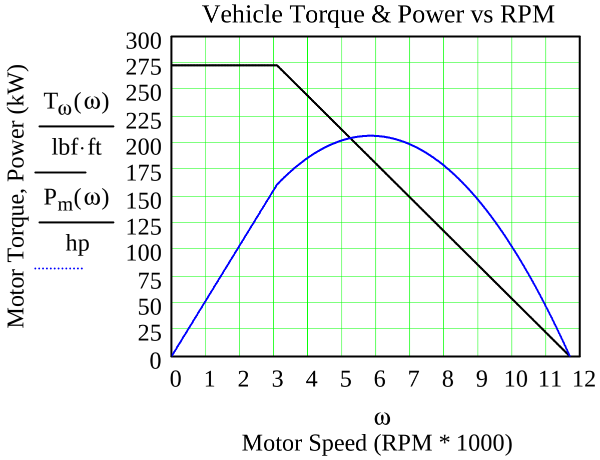
$velocity(60 \cdot sec) = 95.177\ mph$

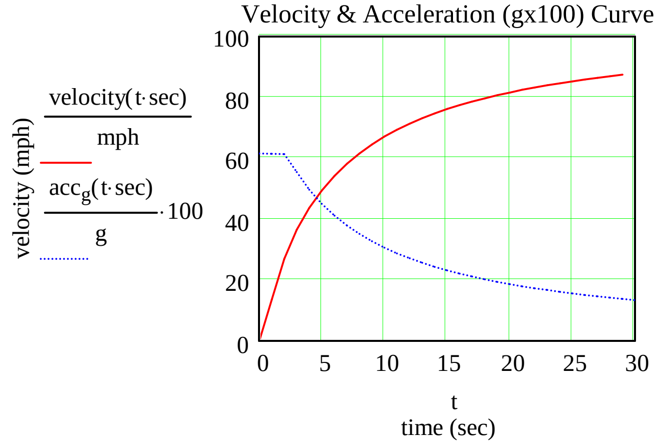
$acc_g(t) := a(velocity(t \cdot sec))$

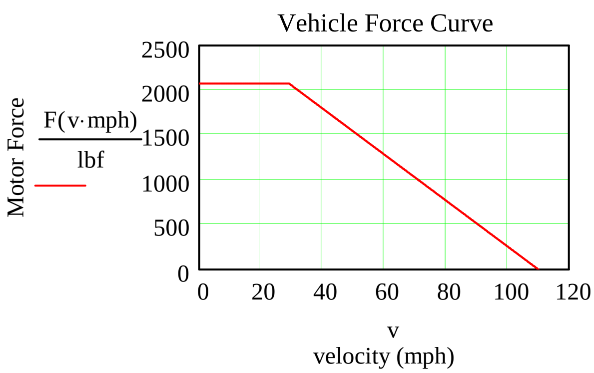
$time(60 \cdot mph) = 7.522\ s$

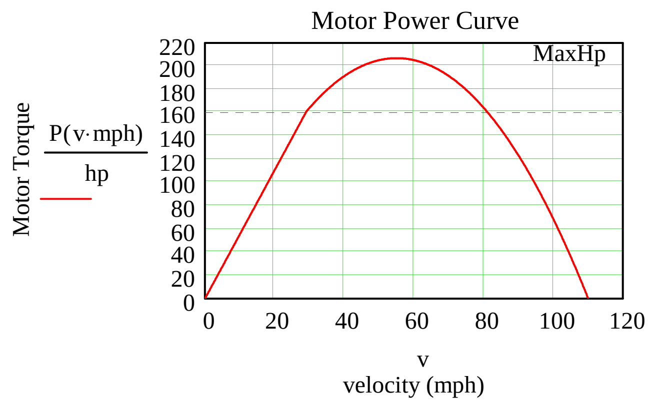
$P_m(5.5) = 206.015\ hp$

GM VOLT 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

$RTEff := 0.92$

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

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")

All Electric Range, AER: 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.

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

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

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

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

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

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

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

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

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

$AER_{US06} := AER(US06, 1) \quad AER_{FTP} := AER(FTP, 1) \quad AER_{HWY} := AER(HWY, 1) \quad AER(UDDS, 1) = 39.646$

EPA 2008 Cycle MPG Fuel Economy Least Squares Fit Regression for AER

$$MPG_{city} := \frac{1}{\left(0.003259 + \frac{1.18053}{AER_{FTP}}\right)} \qquad MPG_{hwy} := \frac{1}{0.001376 + \frac{1.3466}{AER_{HWY}}}$$

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

AER Results

$$X := \frac{1}{40}$$

$AER_{FTP} = 39.374$ $\qquad AER_{HWY} = 40.254$ $\qquad AER_{US06} = 28.001$

$MPG_{city} = 30.083$ $\qquad MPG_{hwy} = 28.712$ $\qquad MPG_{epa} = 29.466$

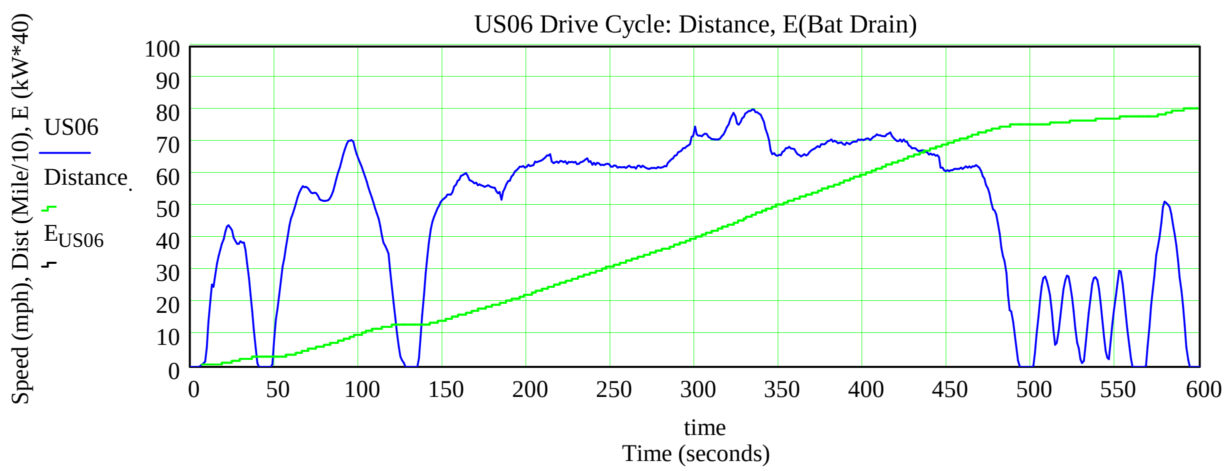
$$r := 0 .. \text{rows}(FTP) - 1 \qquad Distance_r := \sum_{r=0}^{r} FTP_r \cdot \frac{10}{60 \cdot 60} \qquad rr := 0 .. \text{rows}(US06) - 1 \qquad Distance._{rr} := \sum_{rr=0}^{rr} US06_{rr} \cdot \frac{10}{60 \cdot 60}$$

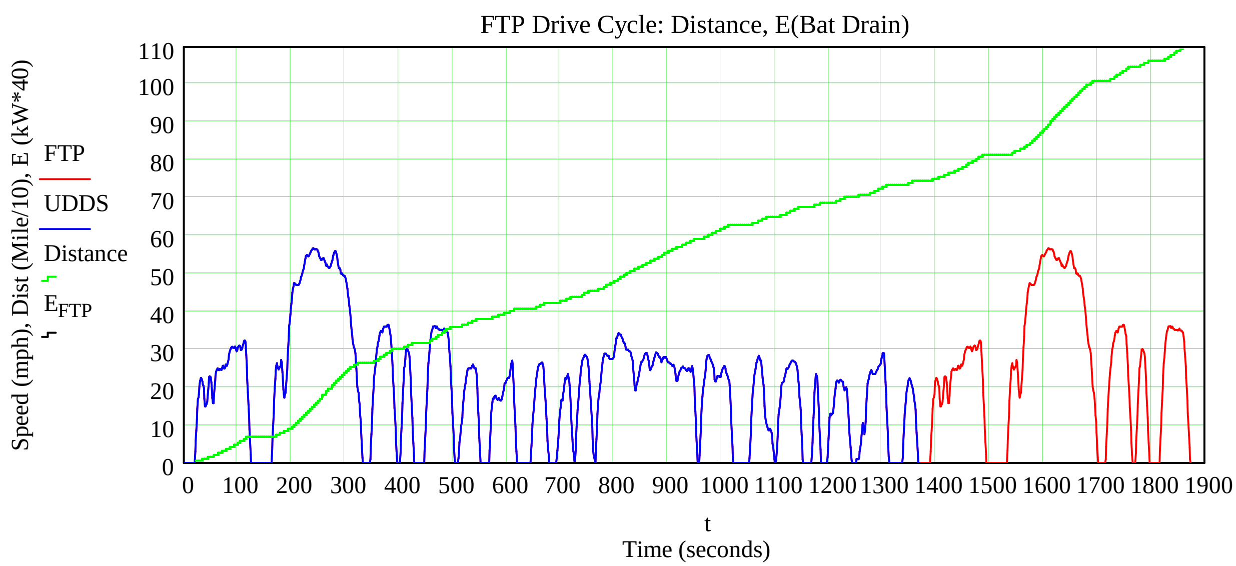
$\max(Distance) = 110.414$ $\qquad \max(Distance.) = 80.08$

$WRITEPRN(\text{"EFTP.PRN"}) := AER(FTP, 1) \cdot 40 \qquad E_{FTP} := READPRN(\text{"EFTP.PRN"}) \qquad \max(E_{FTP}) \cdot X = 39.375$

$WRITEPRN(\text{"EUS06.PRN"}) := AER(US06, 1) \cdot 40 \qquad E_{US06} := READPRN(\text{"EUS06.PRN"}) \qquad \max(E_{US06}) \cdot X = 28$

$WRITEPRN(\text{"EHWY.PRN"}) := AER(HWY, 1) \cdot 40 \qquad E_{HWY} := READPRN(\text{"EHWY.PRN"}) \qquad \max(E_{HWY}) \cdot X = 40.25$





Economic and Environmental Benefits of PHVs

Load the Carnegie Mellon Design Matrix, Design:

Design := READPRN("IBWEBF.txt") **Cols:** 0X, 1X, 2X of 7 20 40 60 & HEV, CV rows(Design) = ▮

Rows: AER (mi), PE (kW), WtE (kg), PM(kW), WtM (kg),WtC (kg),WtS (kg), WtTot (kg), #Mod, #Cells, BatV(m3), Bat (Wh), BW (kg), BSW(kg), BTW(kg), VW (kb), ECD(Wh/mi), CD AER(mi), ECS(gal/100mi), 0-60 (sec),Op$CD($/mi), Op$CS($/mi), GHG CD(kg/mi), GHG C/s(kg/mi)

$M_{Prius} := 824 \cdot kg \qquad M_{Prius} = 1.817 \times 10^{3}\, lb$

Given:
We use the default MY04 Prius configuration. The vehicle body weight is 824 kg, drag coefficient is 0.26, frontal area is 2.25 m2, tire specification is P175/65 R14, and front/rear weight ratio is 0.6/0.4.3 The performance map and motor and controller weight are scaled linearly with peak power.

The PHEV operation costs in this study are evaluated based on an electricity charging cost of $0.11 per kWh and retail gasoline price $3.00 per gallon ($0.80 per liter). In order to calculate the vehicle cost, we estimated the vehicle base cost, excluding the Li-ion battery, using the Prius MSRP less its NiMH battery cost of $3,900 (Naughton, 2008), resulting in a vehicle base cost of $17,600. The base battery cost is assumed to be $1,000 per kWh (Lemoine et al., 2008), and a future low cost $250/kWh case.

The battery model is based on a Saft Li-ion battery package, where each module is comprised of three cells in series with a specific energy adjusted to 100 Wh/kg (Kalhammer et al., 2007). The weight of each cell is 0.173 kg, and its capacity is 6 Ah with a nominal output voltage of 3.6 volts. Accounting for the weight of packaging using a factor of 1.25, the weight of one 3-cell module is 0.65 kg. number of Li-ion battery modules is adjusted to match the original NiMH battery capacity of 1.3 kWh.

We used the Environmental Protection Agency (EPA) Urban Dynamometer Driving Schedule (UDDS) (EPA, 1996) driving cycle. To compare equivalent-performance vehicles, motor size (power) was then adjusted to achieve a 0-60 mph acceleration time specification of 10.5 +0.0/-0.5 seconds, which is approximately the acceleration performance of a Toyota Prius.

The relationships are fairly linear in this range; increasing the target AER of a given PHEV by 10 miles results in an additional ~95 kg of vehicle weight. This additional weight reduces CD-mode and CS-mode efficiencies by 0.10 mile/kWh and 0.68 mile/gal, respectively. These efficiency reductions cause an increase in vehicle operating costs of $0.40-$0.80 per 1000 miles in CD-mode and CS-mode, respectively, and an increase in operation-associated GHG emissions of 3.0-3.2 kg CO2-eq per 1000 miles in CD-mode and CS-mode, respectively.

The linear regression functions for the +1x structural weight case are:

Efficiencies (1X)

$\eta_{CD}(d_{AER}) := (-0.010 \cdot d_{AER} + 5.67) \cdot \frac{mi}{kW \cdot hr} \qquad \eta_{CD}(40) = 5.27 \frac{mi}{kW \cdot hr} \qquad \frac{1000}{Design_{16,6}} = ▮$

$\eta_{CS}(d_{AER}) := (-0.068 \cdot d_{AER} + 51.7) \cdot \frac{mi}{gal} \qquad \eta_{CS}(40) = 48.98 \frac{mi}{gal}$

Operation Costs per 100 Miles

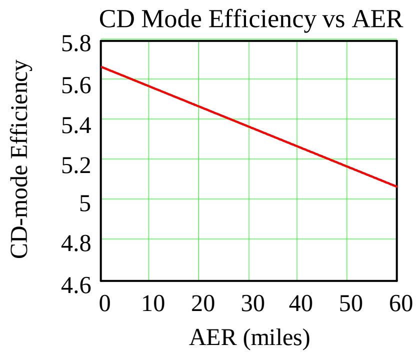
$c_{op\_CD}(d_{AER}) := 0.004 \cdot d_{AER} + 2.20$

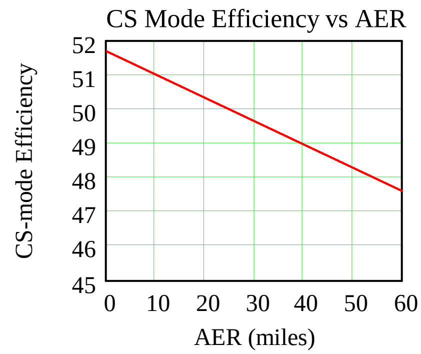
$c_{op\_CS}(d_{AER}) := 0.008 \cdot d_{AER} + 5.79$

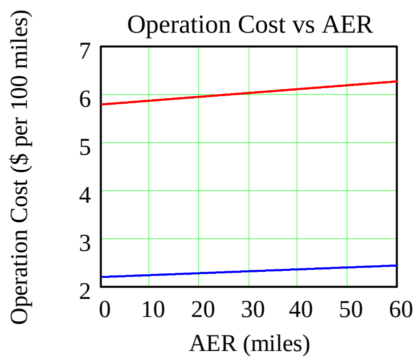
GHG Emissions in kg of CO2

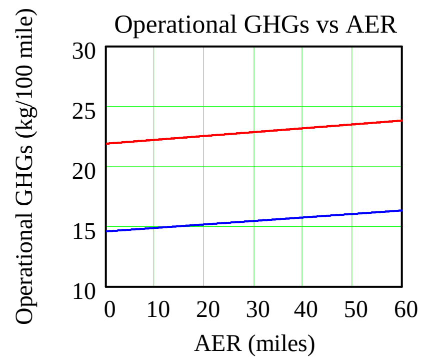
$\nu_{op\_CD}(d_{AER}) := 0.029 \cdot d_{AER} + 14.6$

$\nu_{op\_CS}(d_{AER}) := 0.032 \cdot d_{AER} + 21.9$









Operational Performance

To compare the operational performances of different vehicle configurations, we examine three PHEV characteristics: fuel consumptions (i.e. fuel economy), operational costs and operational GHG emissions. Because these three performance criteria depend on the distance traveled between charges, two key quantities are needed.

For a distance d traveled between charges in a vehicle with an all-electric range of dAER, the **distance traveled in CD-mode d_{CD} and the distance traveled in CS-mode d_{CS} are calculated as:**

$$d_{cd}(d, d_{AER}) := \text{if}(d \le d_{AER}, d, d_{AER})$$

$$d_{cs}(d, d_{AER}) := \text{if}(d \le d_{AER}, 0, d - d_{AER})$$

The results of fuel economy (CS-mode efficiency) in Table 1 indicate that as the target AER increases from 7 miles to 60 miles, the modeled urban driving fuel economy decreases 7.4% from 51.5 miles per gallon (mpg) to 47.7 mpg in the +1x base case due to increased weight. This effect is reduced under lower structural weight assumptions and amplified for larger structural weight. The average fuel consumption per mile g is calculated by, where ηCS is the fuel efficiency in CS-mode.

$$g = \frac{1}{d}\left(\frac{d_{CS}}{\eta_{HEV}}\right)$$

where ηCD is CD-mode vehicle electrical efficiency, ηC is the charging efficiency, cELEC is the cost of electricity, and cGAS is gasoline cost. Table 1 shows the average operation cost per mile for CD-mode and CS-mode under the three structural weight multiplier cases assuming cELEC = $0.11 per kWh, ηC = 88% and cGAS = $3.00 per gallon

$$\eta_C := 0.88 \qquad c_{ELEC} := \frac{0.11}{kW\cdot hr} \qquad c_{GAS} := \frac{5}{gal} \qquad \eta_{CS\_ICE} := 27\cdot\frac{mi}{gal}$$

$$c_{op}(d, d_{AER}) := \frac{1}{d\cdot mi}\cdot\left(\frac{d_{cd}(d, d_{AER})\cdot mi}{\eta_{CD}(d_{AER})}\cdot\frac{c_{ELEC}}{\eta_C} + \frac{d_{cs}(d, d_{AER})\cdot mi}{\eta_{CS}(d_{AER})}\cdot c_{GAS}\right)$$

$$c_{op\_ICE} := \frac{1}{100\cdot mi}\cdot\left(\frac{100\cdot mi}{\eta_{CS\_ICE}}\cdot c_{GAS}\right) \qquad c_{op\_ICE} = 0.185\frac{1}{mi}$$

The equation for the net present value of lifetime cost per mile is given by:

$$\nu_{Bat} := 100\cdot\frac{W\cdot hr}{kg} \qquad c_{Bat} := \frac{700}{kW\cdot hr} \qquad c_{Volt} := 28800 \qquad c_{VEH} := 17600 \qquad c_{ICE} := 22000$$

$$d_{ANUL} := 12500\cdot mi \qquad N_{yr} := 12 \qquad d_{LIFE} := 150000\cdot mi \qquad E_{volt} := 16\cdot kW\cdot hr$$

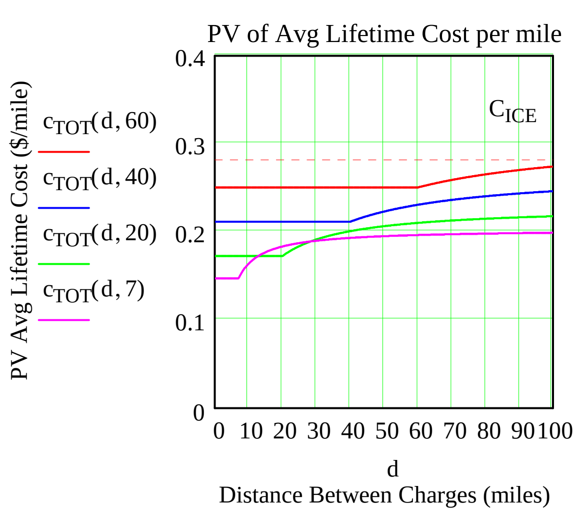
$$\kappa(d_{AER}) := 8.2\cdot\frac{d_{AER}}{20}\cdot kW\cdot hr \qquad r := 0.05 \qquad \rho := 0 \qquad \nu_{OP} := \frac{0}{mi} \qquad c_{Volt} + c_{Bat}\cdot E_{volt} = 4\times 10^4$$

$$C_{ICE} := \frac{mi}{d_{LIFE}}\cdot\left[c_{ICE} + \sum_{n=1}^{N_{yr}} \frac{c_{op\_ICE}\cdot d_{ANUL}}{(1+r)^n}\right] \qquad C_{ICE} = 0.283$$

$$c_{TOT}(d, d_{AER}) := \frac{mi}{d_{LIFE}}\cdot\left[c_{VEH} + c_{Bat}\cdot\kappa(d_{AER}) + \sum_{n=1}^{N_{yr}} \frac{\left(c_{op}(d, d_{AER}) + \rho\cdot\nu_{op\_CD}(d_{AER})\right)\cdot d_{ANUL}}{(1+r)^n}\right]$$

Conclusion:

At $3.00/gal, the Lifetime costs of a 40 and 60 mile AER Prius are greater than an ICE vehicle. Note: Because of the added battery weight and reduced traction power, a high AER EV, must use expensive materials for the vehicle structure to reduce the total weight of the EV. The above calculations do not consider the extra power needed for heating and A/C. Thus, with gas at $3.00/gal, REEVs above 20 miles are not a viable economic alternative to ICEs.



$$\nu_{TOT} = \nu_{OP} + \frac{1}{d_{LIFE}}\left(\nu_{VEH} + \nu_{BAT}\kappa\right) \qquad \nu_{VEH\_C02} := 8500\cdot kg \qquad \nu_{BAT} := 120\cdot\frac{kg}{kW\cdot hr}$$