<u>Macro Model Performance Comparison:</u>

EREV vs. Split Hybrid Dynamics of Extremums vs. Corolla

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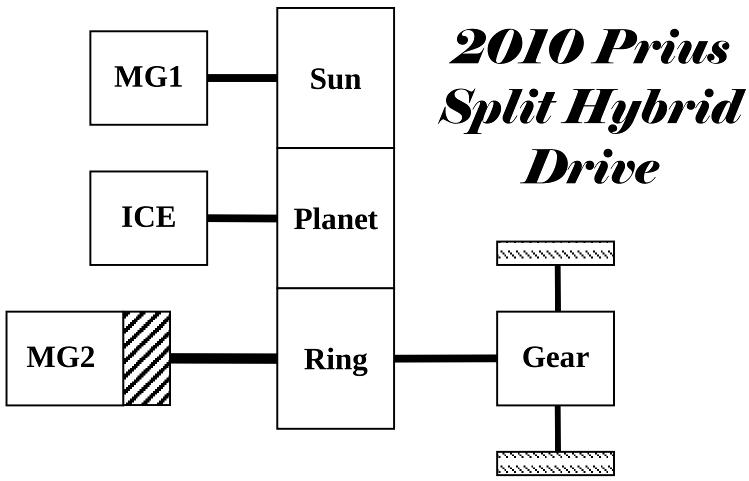
There has been much discussion lately of performance of the GM Volt relative to the 2010 Prius. These vehicles employ very different hybrid strategies (EREV versus Serial-Parallel). To make a more detailed comparison I did macro "toy" models of the dynamics of both the Volt and Prius. The macro models consist of 32 variables and ten equations, but do not include detailed models of the batteries, inverters, engines, motors, their efficiencies, rotational dynamics, weight distributions, **or control strategies**. This is a motor to wheels simulation strategy, i.e. the traction motor's angular velocity is commanded and the corresponding acceleration and velocity are calculated. To minimize the complexity, we will only consider limiting cases, i.e. maximum and minimum scenarios. This approach is not capable of doing design calculations, but with just a few pages of basic physics of power, energy, forces, and motion, this approach can easily give the extremum performance results within a few percent. Details of the models are shown at http://www.leapcad.com/Transportation/Prius_Gen_IV_1.8L_Simulation.pdf and http://www.leapcad.com/Transportation/GM_Volt_Simulation.pdf .
http://www.leapcad.com/Transportation/Corolla_Simulation.pdf
The Prius is a Split Serial-Parallel Hybrid with a planetary gear combination of a tractive ICE and two motor/generators, MG1 and MG2. For some details see Basic Description of Prius. Below are the results of the Macro Model analysis for the Volt in both Charge Depletion and Sustaining Modes versus the Prius. We will evaluate the Volt's Performance for both the Charge Depletion and the extreme limit of the Power Starved Generator-Only-Mode.

<u>Planetary Gears</u>

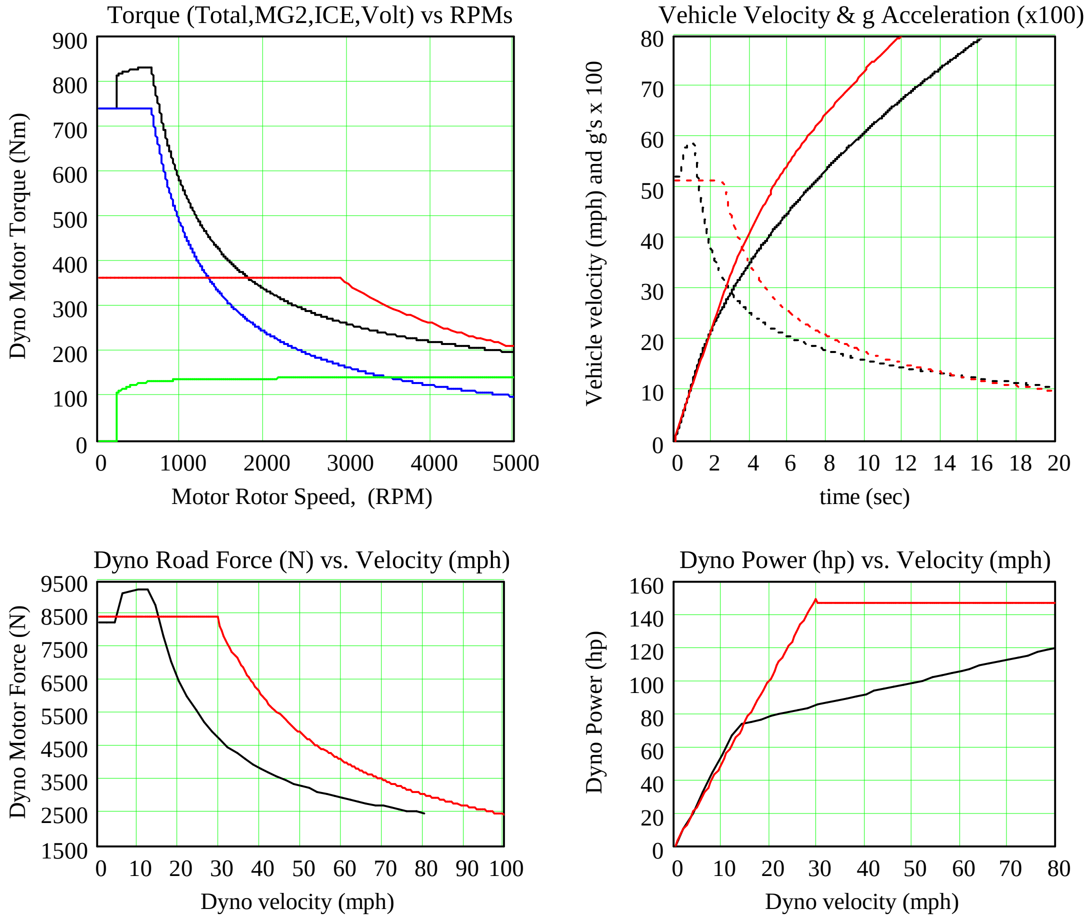


<u>Details of Acceleration Performance Models of Prisus vs. Volt (Charge Depletion Mode):</u>
This 2010 Prius model uses a 9000 rpm max MG1 speed. An earlier model used 6500 rpm.
Refer to Charge Depletion Mode plots on next page. The upper left plots show the Prius and Volt Torques versus rotor speed. The black, blue, and green curves show the Prius Total, Motor/Generator2, and ICE torques. The Prius "Total" is the sum of Motor/Genertor1, Motor/Genertor2, and ICE torques. The initial break in the Prius Total and ICE curves results from the delay of the ICE turning on until the motor has the vehicle up to about 15 mph. In the acceleration mode, Motor/Gen1 is used as a generator so it does not contribute directly to traction.

The red curve is the Volt motor torque. For both plots on the left we see that the Prius (black/blue motor curves) has a much higher initial torque and road force, but that the Volt (red curves) sustains it longer. The reason for this is shown in the Power vs. velocity curves on the lower right. The Prius ramps up power a bit quicker, but beyond 15 mph, the Volt's much larger battery and motor power can sustain the higher peak power much longer.
The final result is shown on the curve on the upper right. This curve shows the g force (dotted line with a scaling of one g = 100) on the vehicle and the resulting velocity (solid lines) versus time in seconds. The traction power on the Prius accelerates it at about 0.6 g for 1 second. The Volt sees ½ g, but it sustains it for 3 seconds, and continues to maintain a larger g force during the remaining acceleration.

The calculated 0 to 60 mph acceleration time for the Prius is 9.7 second and 7 seconds for the Volt. The published spec for the Prius is also 9.8 seconds, which validates the more complicated Prius model. When the Volt was first announced in 2007, Bob Lutz stated that the Volt would do 0 to 60 in less than 6 seconds. In 2008 the number was raised to 7 seconds and now it is 8.5 seconds. Why this change? The Volt battery pack by itself can supply the rated peak power to the motor for only about 4 minutes before discharging to the 50% SOC condition. I suspect that a more conservative design approach is now being used and thus after a few seconds the 100kW of power is throttled back to keep the controller and motor from over heating. It would be interesting to know the cost savings between the original 6 second and the production model 8.5 second acceleration performance.

2010 Prius (Black) vs. Charge Depletion Mode Volt (Red) Acceleration Performance



<u>The ICE/Generator Power Sizing Dilemma for the Volt Extended Range Serial Hybrid</u>
Tony Posawatz, the Volt's vehicle line engineer has stated "*Many people ask us why there aren't others following us in droves in developing EREVs. It's a **very hard configuration to make work. Once an engine is burning** it changes the game.*" "*Therein lies the challenges associated with it and why maybe some companies never made the leap, because it's hard. In an absolute technical sense it's hard because of its overall complexity, and the **balance** and interface and integration of all these things together add to the challenge*."

From what is quoted above, one can infer that one hard aspect of the EREV is balance when the engine is "burning." This is the dilemma of sizing and optimizing the ICE/Generator. But the ICE is only used during the charge sustaining mode. The rest of the time it just takes up space, adds weight, added structural materials, and cost. Obviously, you want to minimize this space, weight, and cost. On the other hand, you want maximum performance in the charge sustaining mode, which requires as much power as possible. This is not a problem for parallel operation where ICE usage is optimized.

<u>Comparison of Hybridization Ratios, Series vs. Parallel:</u>
To get performance in the Generator-Only-Mode comparable to the Charge Depletion Mode, the ICE/Generator must be sized to match the battery peak power, that is, for some specified road power requirement, Proad, the Series Design needs ICE Power x Coupling Efficiency x Generator Efficiency + Pmotor = 2X Proad, i.e. <u>Pmotor = Proad</u> (drives are chained –> weakest link). There is an obvious cost in weight, efficiency, and sticker price. The ICE Extended Range is still a good strategy for a BEV. Why? Because the energy density of the ICE/generator/gas tank (~ 3,600 Whr/kg) is about 20 X greater than the Li-Ion battery.

Thus the Series can never be as efficient as the Parallel Hybrid where the motor and ICE power can be ½ Pice + ½ Pmotor = Proad, i.e. <u>Pmotor = ½ Proad</u> (parallel hybrid drives are additive) and the ICE has a gear train directly to the axle.

<u>Volt Performance Limits of the Sustaining Mode:</u>
<u>What are the Applicable Statistics of Rare Low Probability Events where SOC ~ 20%?</u>
Statistically, for an AER of 40 miles, 22% of the Volt's miles will be in the Charge Sustaining Mode. In this mode the Volt draws power from the generator and from a battery Buffer Zone (SOC = 30% - Buffer Zone). The Volt probably uses some strategy of throttling back the motor's power as the SOC drops increasingly within the Buffer Zone.

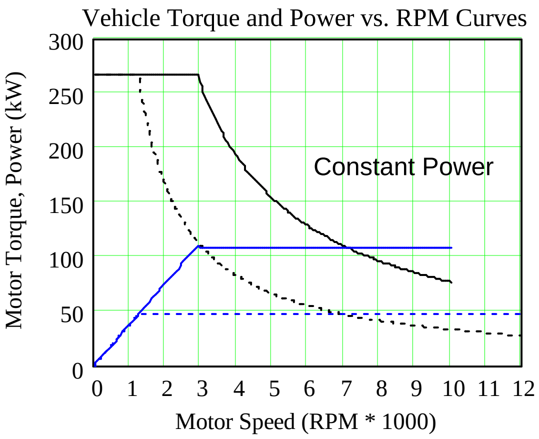
To ensure warranty life, we assume that battery operation below some absolute minimum SOC (25%?) is not permitted. There may be some rare occasions (i.e. when SOC < 25%) in which only the Generator will be used to power the motor. The probability of rare events is governed by Poisson statistics. (If we think of the battery as a reservoir, then Hurst statistics may also apply.) Clearly, this probability increases rapidly with increased distance between recharging, driving in windy, hilly terrain, driving aggressively, and at high speeds, all of which result in greater individual risk. The extreme, low probability, throttle back limit occurs if only the Generator supplies power to the motor and the power is thus reduced to Gen Power x 95% x 95% = 47.7 kW. What is the probability of this occurring with 100 miles between charging, 10 mph headwind, median road grade of 9% for 4 miles, and with aggressive driving? My guess is greater than 5%. *It's a **very hard configuration to make work.***

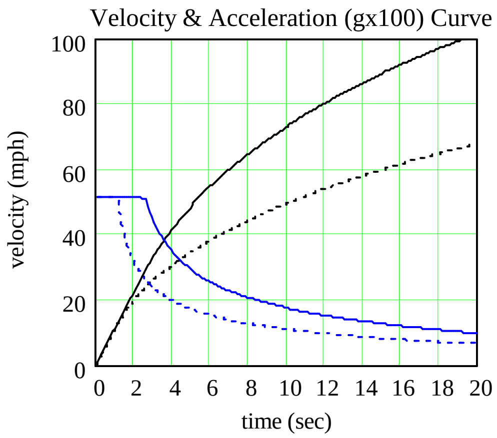
<u>Prius Performance Limit of ICE Only (no battery) Power to Motor M2:</u>
We examine the condition where only the ICE and not the battery + ICE supply power to motor MG2. The simulation plots below show that there may be an occasional degradation in 40 to 60 mph passing speed of 2.5X for the Volt in Generator Only and 1.8X for Prius in ICE Only Mode.

Acceleration Performance Power Starved Limit

Extreme Limit of Volt Generator-Only Simulation Performance: 2010 Volt Sustaining (Sold) vs. Generator-Only-Mode (Dotted)

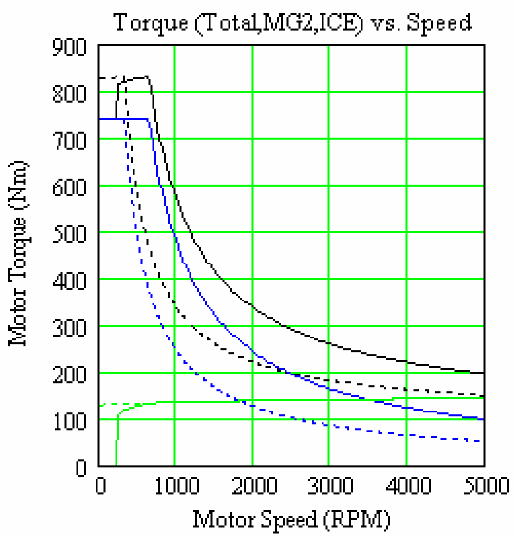
Volt 0 to 60 mph time increases from 8.5 to 15 secs.
Volt 40 mph to 60 mph passing time increased from **3.3 to 8.5 seconds**. **Factor of 2.5X**

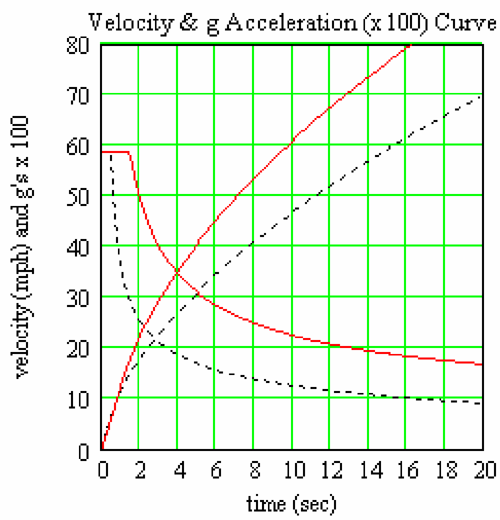


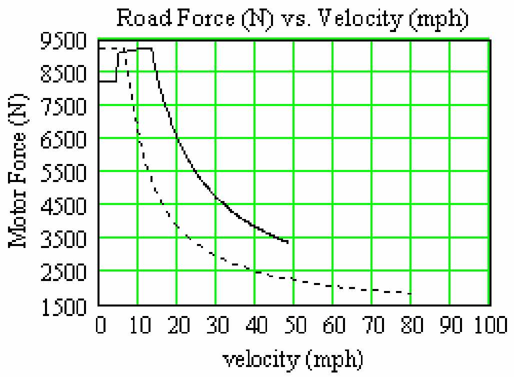


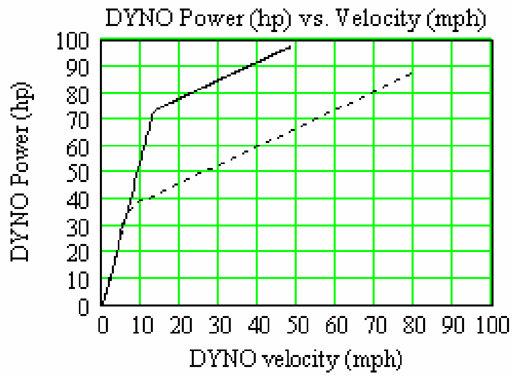
Extreme Limit of Prius: Battery + ICE (Solid) vs. ICE Only (Dotted) Simulation

Prius 0 – 60 mph time increases from 9.7 to 15.3 seconds
Passing time increases from 4.8 to 7.6 seconds. **Factor of 1.6X**





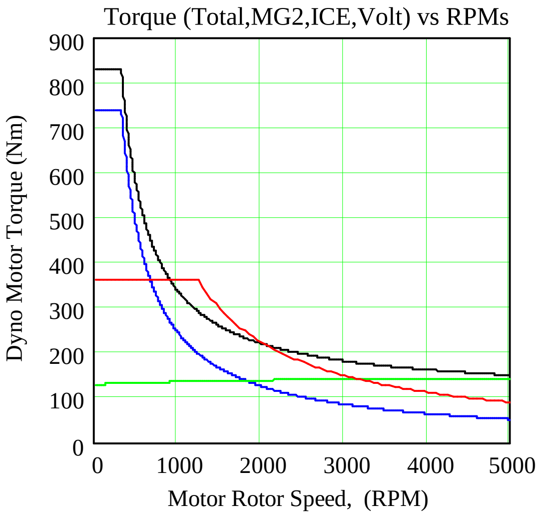


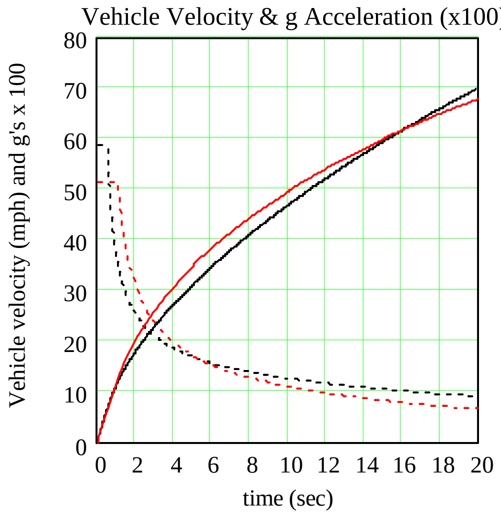


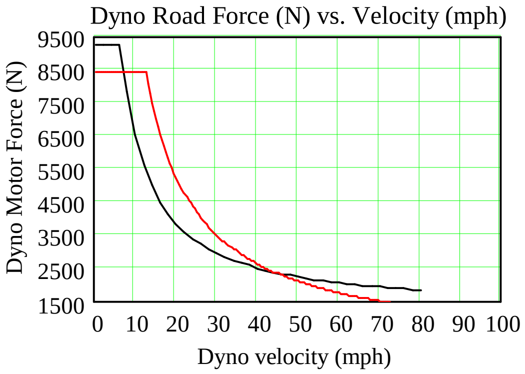
Acceleration Performance Power Starved Limit

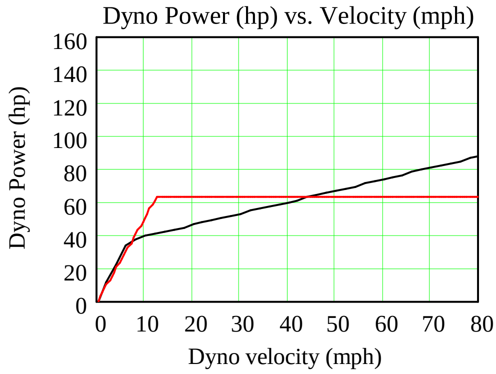
2010 Prius ICE Only (Black) vs. Volt Generator Only (Red) Acceleration Performance

For the Prius and Volt Sustaining Mode, we see that the performance velocity curves for the Volt and Prius start to converge after 15 seconds at 60 mph. Road force above 60 mph has dropped off drastically and acceleration drops below 0.1g. Power is an interesting contrast. In the lower right curve, we observe that the Volt reaches peak motor power after only 12 seconds while the Prius ICE total power continues to rise up to 80 mph. The first break in the Prius power results from the max power limit of the smaller MG1, which is applying power to the larger MG2.





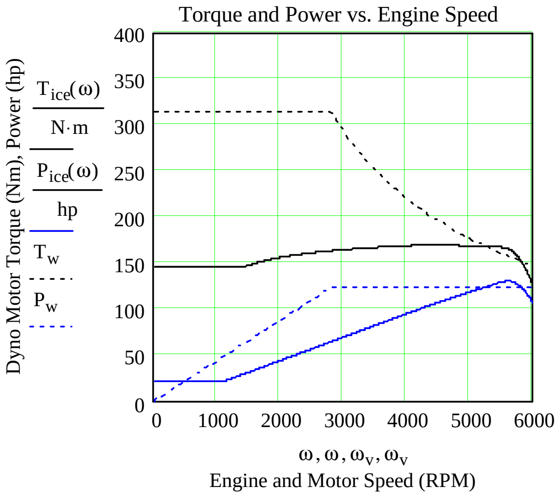


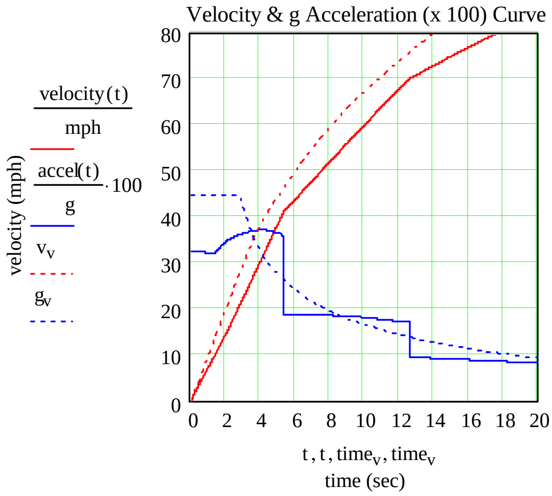


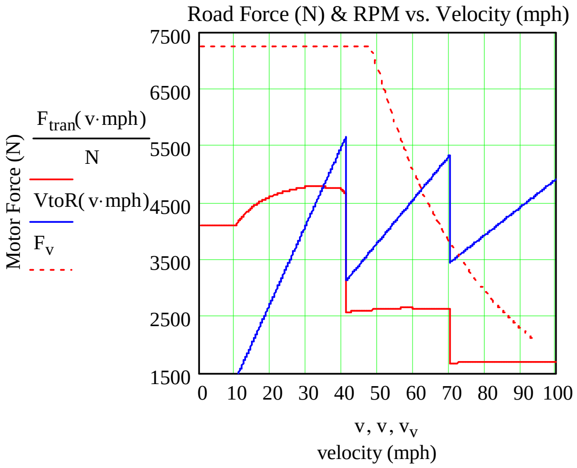
Acceleration Performance Volt vs. Corolla

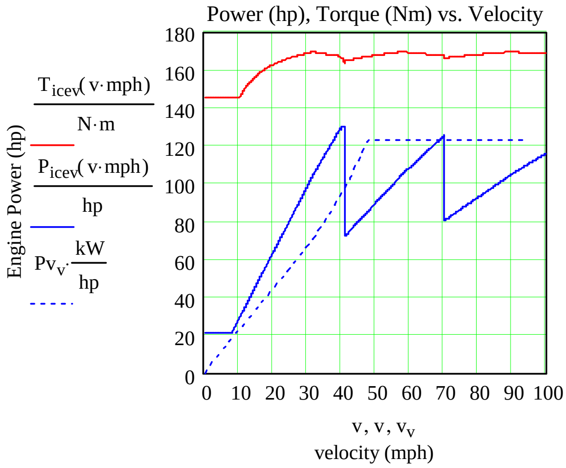
The Corolla has a 0 to 60 mph time comparable to the Volt. Let's examine the dynamics. Refer to the following curves. The curves show that the Volt motor has a quicker initial response than the ICE. The Corolla ICE transmission allows us to keep high 1st gear torque and acceleration up to 42 mph (5 seconds) and then the engine redlines at 5600 rpm. The Volt motor applies twice the torque initially and then peak power limitations drops the motor torque beyond 3000 rpm.

Compare Corolla (Solid) vs. Volt (Dotted) Performance:







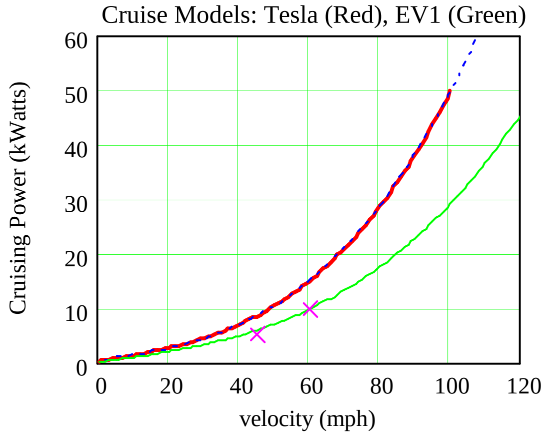


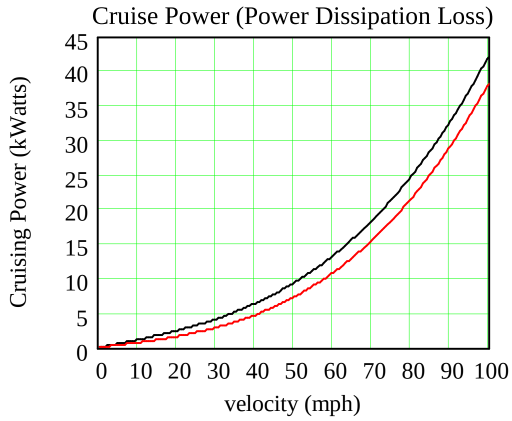
Cruise Mode Models for EV1 and Tesla Roadster– Data Validation
Power dissipation losses in the constant velocity Cruise Mode are the losses from Tire and Road Resistance, Road Grade, Aerodynamic Drag, static losses from Inverter Efficiency, and static losses from total Gear Efficiency. The Cruise mode model was validating by comparing the Macro Model for the EV1 with EV1 data (see page 3 of http://www.leapcad.com/Transportation/GM_EV1_Simulation.pdf) and also the Model for the Tesla Roadster with data published by Tesla (see page 7 of http://www.leapcad.com/Transportation/Tesla_Simulation.pdf). The plots are shown at the left on the following page. They show good matching. The blue dotted line is Tesla data and the two X's are EV1 data points. The Tesla model also includes a dynamic force for Drive Train Drag, DTD, which was determined by solving for an exact match of the DTD coefficient at 54 mph.

<u>Cruise Mode</u>
The Power Dissipation Loss plot below shows that at least 30 kW at the road is needed to cruise at 90 mph. The Charge Sustaining Mode Acceleration curves show that with the present ICE power and generator, Volt passing performance from 40 to 60 mph is marginal. Instantaneous power from the ICE has to go through the fuel – ICE – Coupling (97%) – Generator (95%)-Inverter (94%) loss chain (coupling electrical loss total = 87%). The tire and road resistance dominate the curve below 60 mph. The aerodynamic drag is the major component above 60 mph. The Prius has a slightly larger frontal area. Consequently, it has a greater Power Loss.

Comparison of Cruise Power (Power Dissipation Loss)

Tesla and EV1 Models vs. Data | **Prius (Black) vs. Volt (Red)**



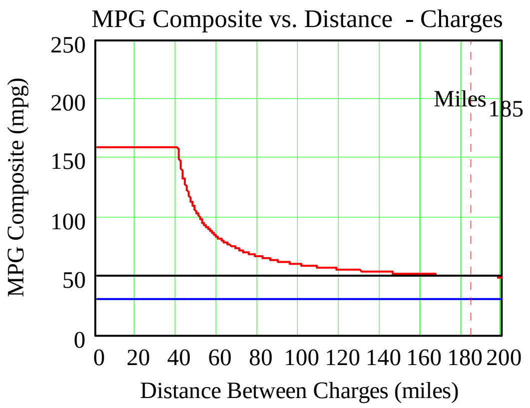


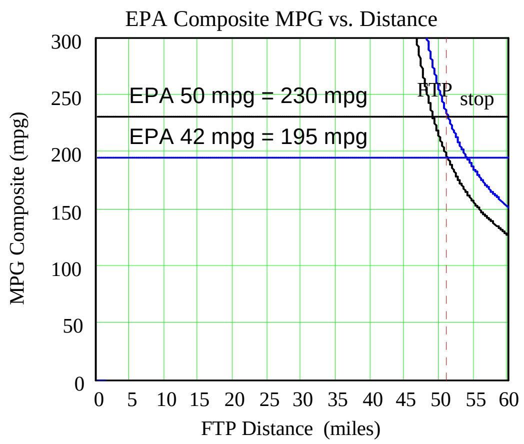
Beyond 40 Un-recharged Miles, Charge Sustaining Mode Performance:

Our model gives an AER for the Volt of 40.6 miles. Beyond this the Volt is in the charge sustaining mode. In the charge sustaining mode the Volt is limited to 53 kW continuous power. Because the Prius is series/parallel it has 100 kW of traction power in its charge sustaining mode. With 88% more charge sustaining power, we expect the Prius to be much better at sustained accelerating, climbing hills, and driving into the wind.

Beyond 200 Un-recharged Miles, Charge Sustaining Mode Fuel and EPA Composite MPG:

If the Volt is not recharged, then after 40.6 miles the Volt's ICE turns on and the generator keeps the battery charged. Assume the ICE gets 30 mpg and the composite Volt Charge Sustaining Mode gets **42 mpg**. (Plot created November 2009. No data for the Volt Sustaining mpg.) There are many ways to calculate a hybrid's fuel economy. We will use the equivalent cost electric power \$0.11/kWhr vs. gasoline (\$3.50/gal) method. Using the amount of gas consumed, beyond 185 un-recharged miles the Volt's composite mpg (red curve) becomes poorer than the 50 mph of the Prius (black) and approaches the ICE mpg of 42 (black) as non recharging miles increase.





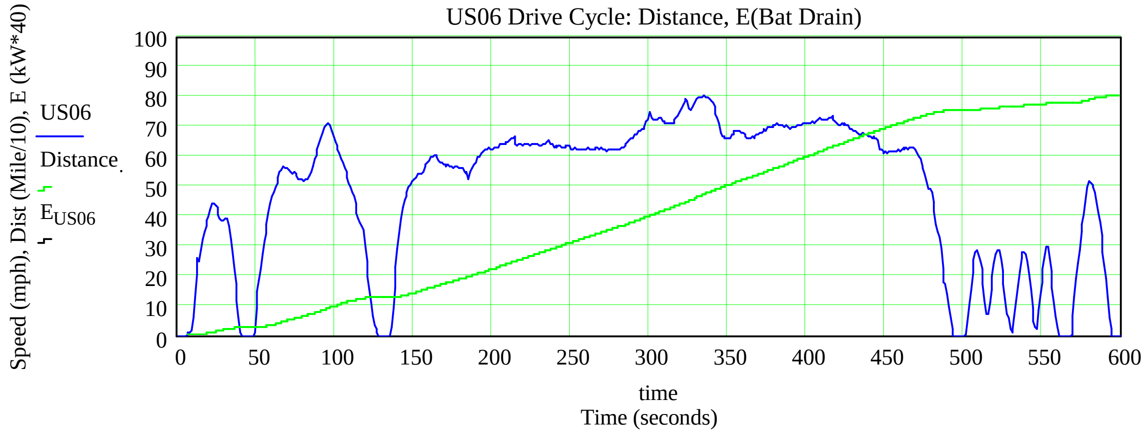
EPA – Volt All Electric Range, AER, Simulation

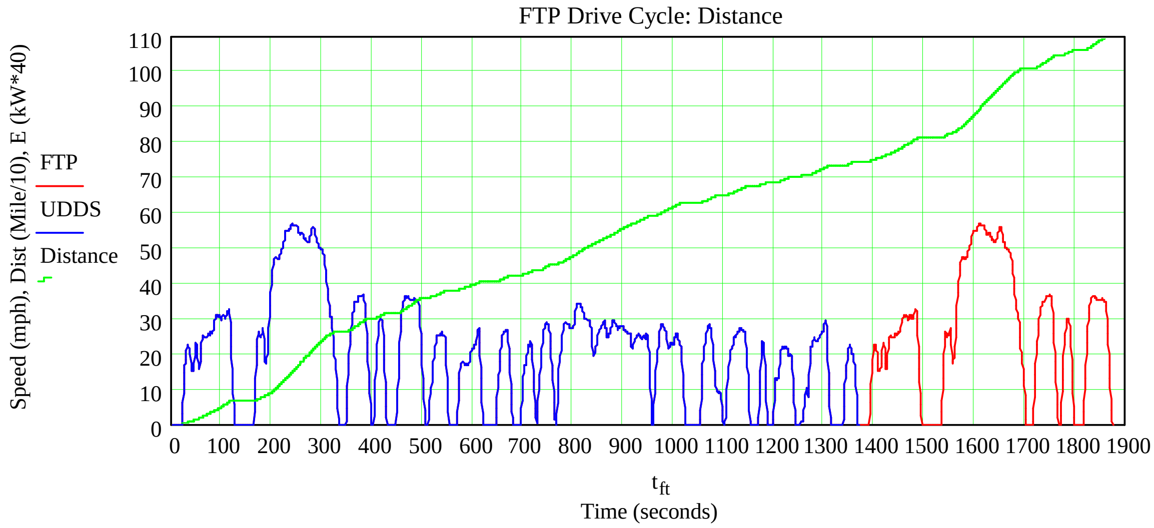
What is your normal driving profile? It will have a huge effect on the Volt's Average Electric Range, AER. Compare three common driving profiles the EPA75, HWY, and US06. We note that these profiles are dynamometer profiles. They are not done in the wind, rough roads, or on road grades, all of which lower AER. Nor are they done with max power (209 motor hp) to simulate passing. The goal of these profiles was to check and compare emissions, not evaluate EV performance, such as AER.

The EPA Federal Test Procedure, EPA75, is called the City Cycle. It consists of the Urban Driving Cycle, UDDS, followed by the first 505 seconds of the UDDS. It has a top speed of 56.7 mph. It uses a maximum of 37 hp road power. The EPA Federal Test Highway Procedure, HWY, has a top speed of 59.9 mph. It uses a maximum of 30 hp road power.

The US06 Supplemental Federal Test Procedure (SFTP) was developed to address the shortcomings with the FTP-75 test cycle in the representation of aggressive, high speed and/or high acceleration driving behavior, rapid speed fluctuations, and driving behavior following startup. It represents an 8.01 mile (12.8 km) route with an average speed of 48.4 mph, maximum speed 80.3 mph, and a duration of 596 seconds. It uses a maximum of 89 hp road power.

I did a detailed second by second Volt simulation with these three profiles. **The results were an AER of 41, 40, and 30 miles for the EPA75/UDDS, HWY, and US06 profiles, respectively.** The Distance (green) plot is the USO6 and FTP Distance multiplied by 10 to make it fit better on the graph.

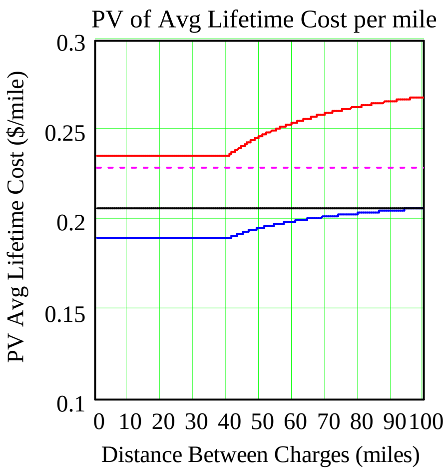




Total Cost of Ownership for a 12 Year Life:
Compare the cost-of-ownership over the vehicle lifetime. The comparison includes the retail cost of the vehicle and the cost of its annual energy (fuel and plug-in power) consumption, but does not account for possible differences in maintenance costs. We assume travel of 12,500 miles per year to be consistent with the assumptions of the EPA. For a 12 year life this gives a total of 150,000 lifetime miles. The cost of retail electricity is held constant at $0.11 per kWh. The Net Present Value of lifetime costs was calculated with a 5% rate. We use a $40,000 Volt cost minus a $7,500 rebate versus a 2010 Prius MSRP of $24,000. We assume a 30 mpg ICE/generator and an 88% charging/discharge efficiency for the Volt. The EPA mileage for the Prius is 48mpg. The plots show that for gas at $3.00/gal the Prius is 14% less expensive than the Volt and the cost of ownership for a Volt is more than an ICE. For gas at $5.00/gal Ownership costs of the Volt and Prius are the same as long as the Volt is always recharged before its ICE turns on. The solid Red, Black, and Blue curves correspond to the Volt, Prius, and PHEV Prius with 40 kWH Li-Ion Battery. The dotted curve is for an ICE rated at 35 mpg. The bottom line is that because of high capital costs, long range BEVs are not cost effective. The typical buyer will not pay the premium for extended battery range.

Comparison of Total Cost of Ownership (12 Years)

Price of Gas: $3.00 per Gal



Price of Gas: $5.00 per Gal