CAN-View Data Collection and Analysis for a 2005 Prius

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Introduction

The availability of the CAN-View add-on (http://www.hybridinterfaces.ca) for the Prius II enables the driver to see many parameters of the car change with time as it is driven. The CAN-View box is attached to the MFD (Multi-Function Display) and the OBD (On-Board Diagnostics plug under the steering wheel) to collect data from the OBD to display on the MFD.

For a Prius with factory-installed navigation the CAN-View device is easy to install (http://www.roperld.com/science/prius/CanViewInstall.pdf).

CAN-View has a serial port for collecting data on a portable computer (http://www.roperld.com/Science/Prius/CAN-ViewCapture.htm).

A Microsoft Windows program has been written by Gary Morris for analyzing the data (http://mggm.net/prius/candecoder.html). He used the CAN coding information supplied by Attila Vass (http://www.vassfamily.net/ToyotaPrius/CAN/PriusCodes.xls) plus some he discovered himself.

Gary Morris provided many of the ideas used in this work.

Data Collected

The purpose of this web page is to give some examples of collected data and some analysis of the data. The types of data collected are given in Appendix 1.

The examples are:

1. **Stationary**: Readings with the car pointing in the four primary directions in my reasonably flat driveway.
2. **Tight Circle**: Clockwise and counterclockwise movement in the smallest possible circle (tight circle). See appendix 3 for the mathematics of the turning radius.
3. **Motormile Speedway**: Clockwise and counterclockwise laps around the Motormile Speedway (http://www.motormilespeedway.com) **Dimensions:** Straights are 506 feet long, 55 feet wide, and banked seven degrees. Turns are 550 feet long, 70 feet wide, and banked 15 degrees. (Thanks to Mr. Al Shelor and Mr. David Hagen for permission to use the Motormile Speedway.) Laps were run at speeds of approximately 20 mph and 40 mph.
4. **Brush Mountain Trip**: A trip from my home at 1001 Auburn Drive, Blacksburg VA to the top of Brush Mountain on Rt. 460 toward West Virginia, a distance of 9.1 miles, and return. Appendix 2 contains maps of the trip. The trip lasted about 17 minutes (1025 seconds). The average speed was 32.1 mph (including stops).

Data Analysis

There are four quantities that are measured that required considerable effort to figure out exactly what they are. Attila Vass: (http://www.vassfamily.net/ToyotaPrius/CAN/PriusCodes.xls) calls two of them "sideway acceleration" and "acceleration"; there are two of each discovered by Morris.

They are Side Angular Speed1 (S1), Side Angular Speed2 (S2), Forward Acceleration1 (A1) and Forward Acceleration2 (A2). It will be show below for reasonably controlled specific vehicle runs that the following equations hold to a high degree of approximation:

$$a_f = \frac{A1 - A2}{14.5} \text{ and } w = \frac{S1 + S2}{2(72.1)} \text{ where } a_f = \text{forward acceleration and } w = \text{angular speed.}$$

Stationary

Here are the stationary readings for the four primary directions at location (37.209ºN 80.452ºW = reasonably level driveway of LDR):

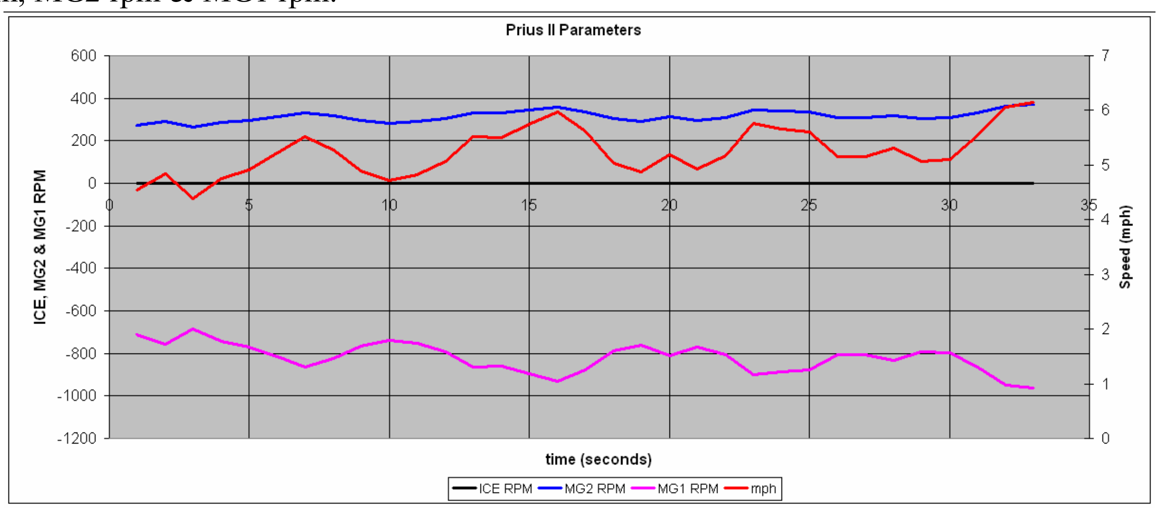
Direction	SideAccel1	SideAccel2	Accel1	Accel2
East	0	-3	5	13
West	0	-3	2	-6
North	0	-3	17	12
South	0	-3	-6	-3

So, the two "side accelerations" do not change with direction, but differ by 3.
And the two "accelerations" vary with direction. Why do these parameters have values for a stationary vehicle?

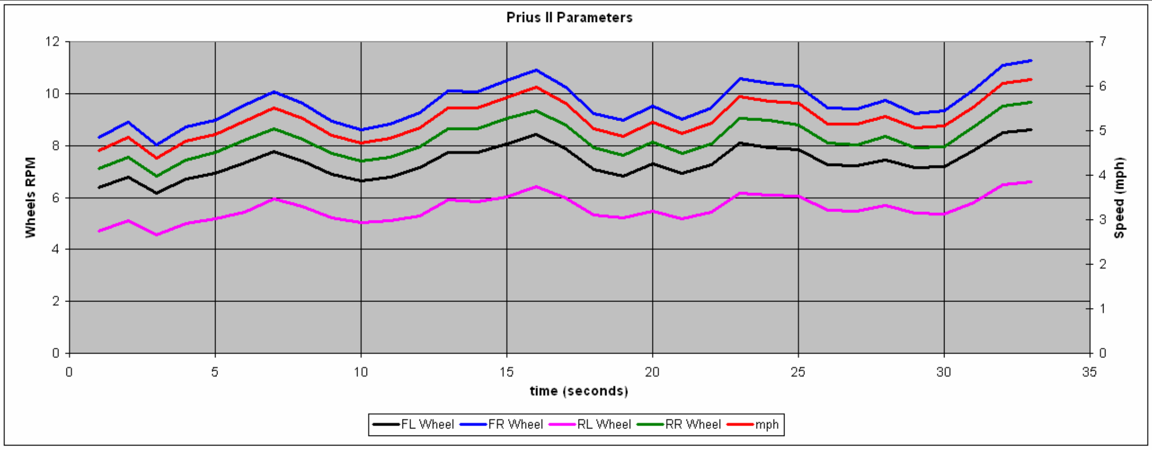
Tight Circle

Counterclockwise Tight Circle

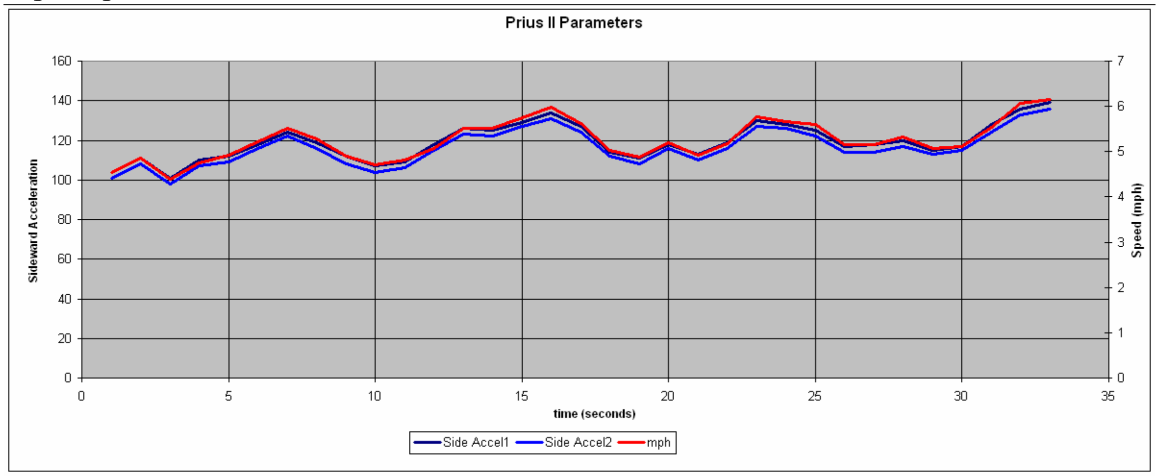
ICE rpm, MG2 rpm & MG1 rpm:



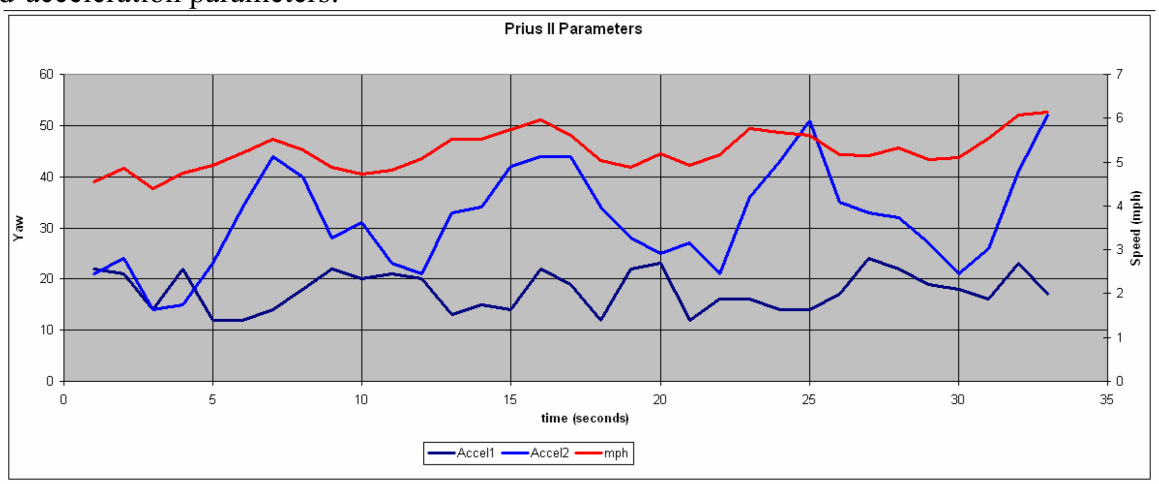
Front-Left, Front-Right, Rear-Left & Rear-Right wheels rpm:



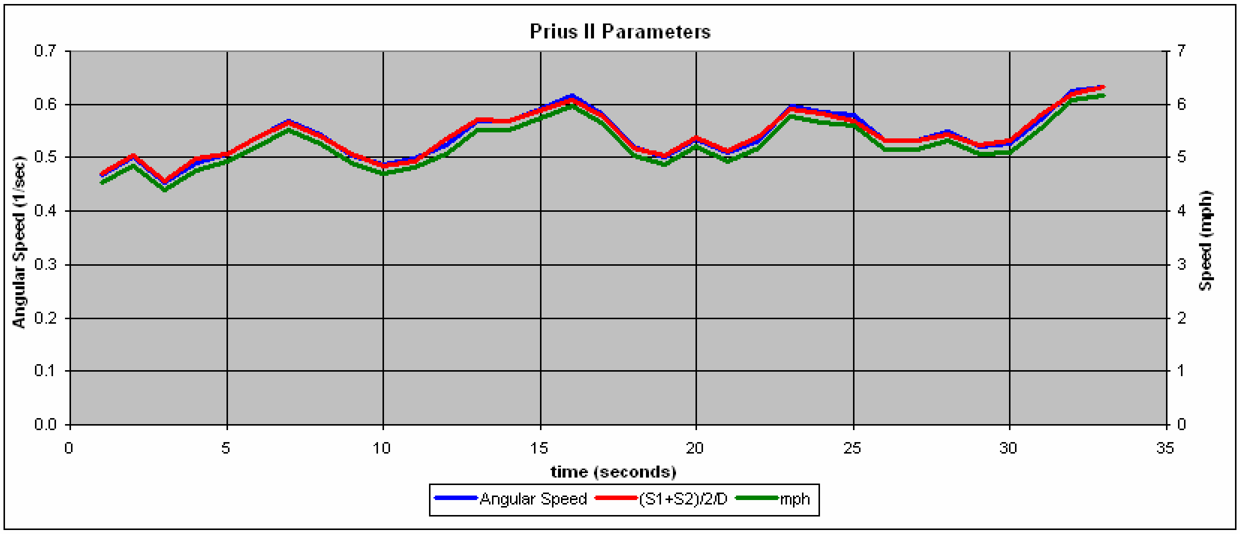
Angular-speed parameters:



Forward-acceleration parameters:



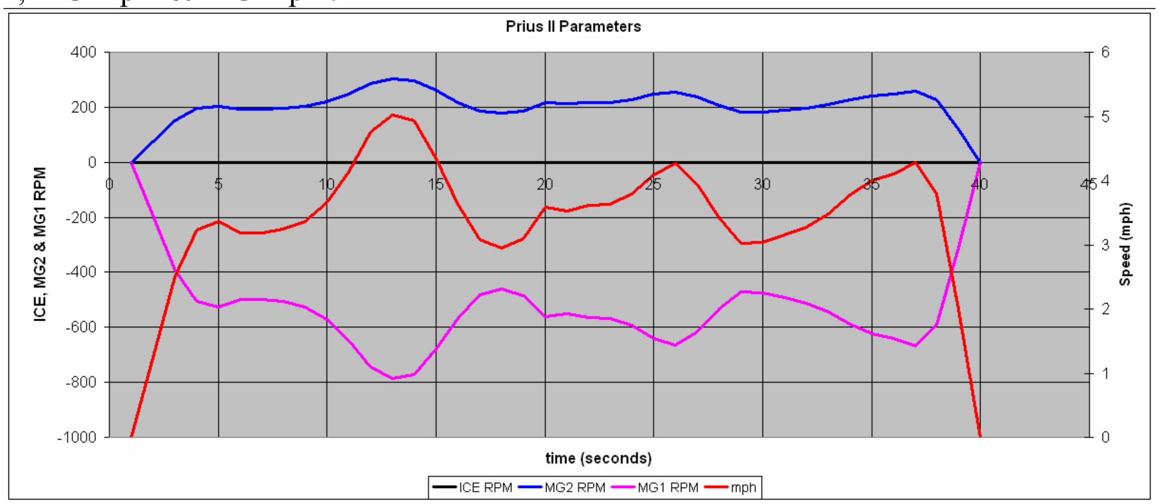
It appears that (S1+S2)/2 is the angular speed, w :



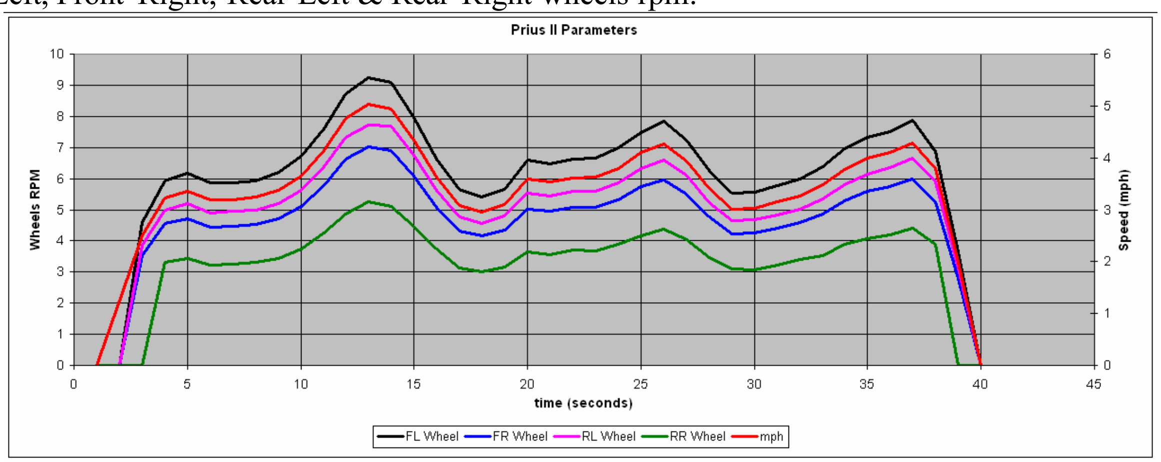
This is a least-squares fit of $(S1+S2)/C$ to the angular speed ($w = v/r$ where $r =$ turn radius=12.6 feet.). C is 192.9 for the best fit.

Clockwise Tight Circle

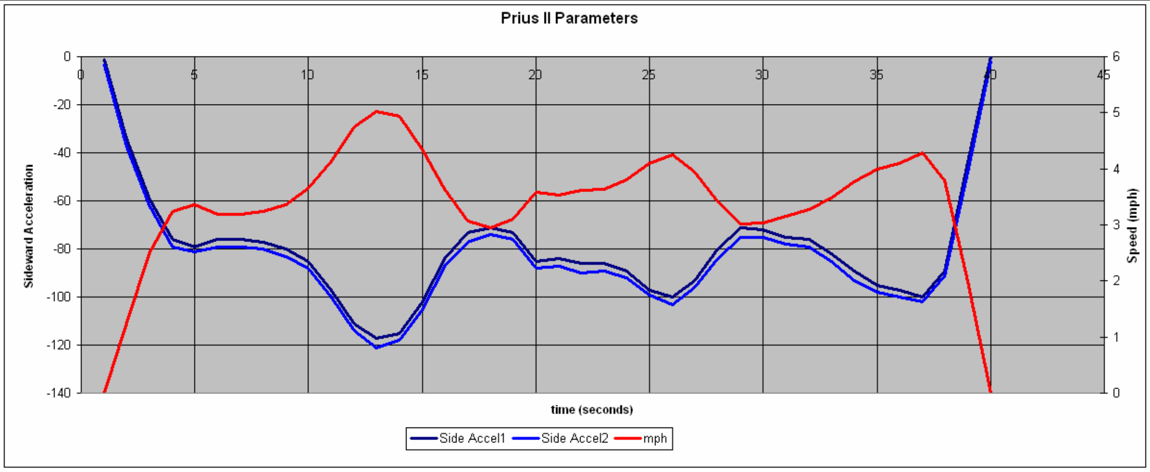
ICE rpm, MG2 rpm & MG1 rpm:



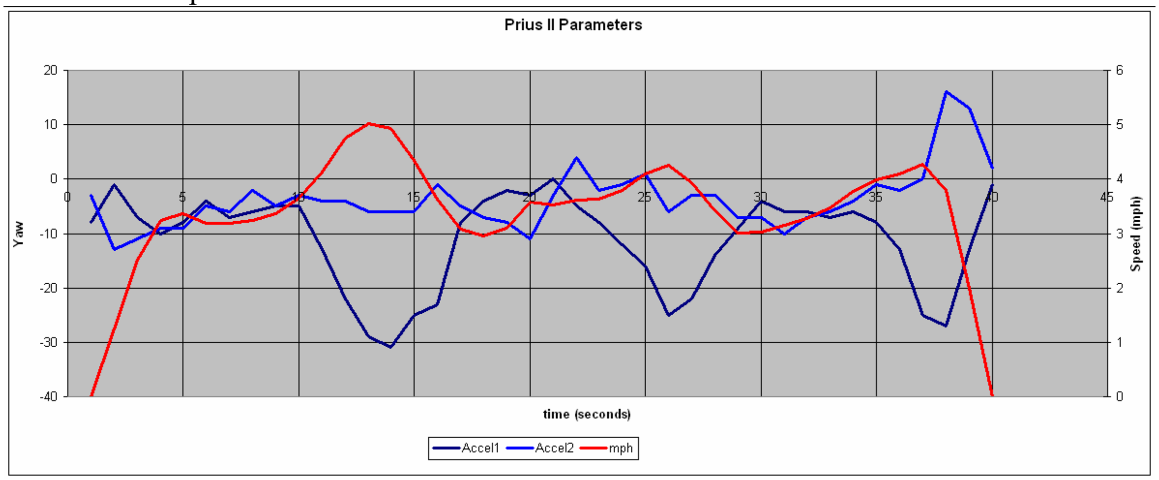
Front-Left, Front-Right, Rear-Left & Rear-Right wheels rpm:



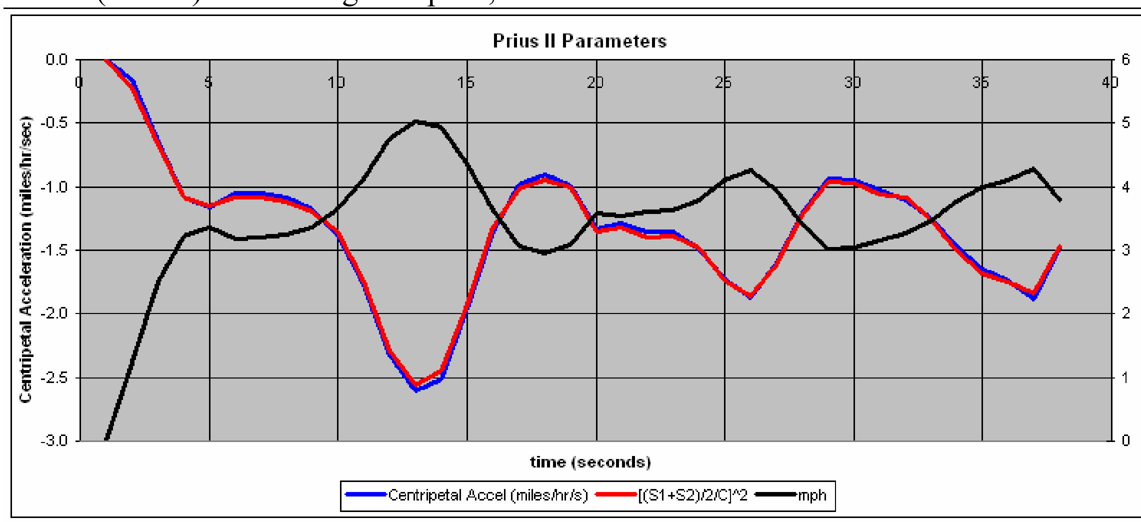
Angular-speed parameters:



Forward-acceleration parameters:



It appears that (S1+S2)/2 is the angular speed, w :



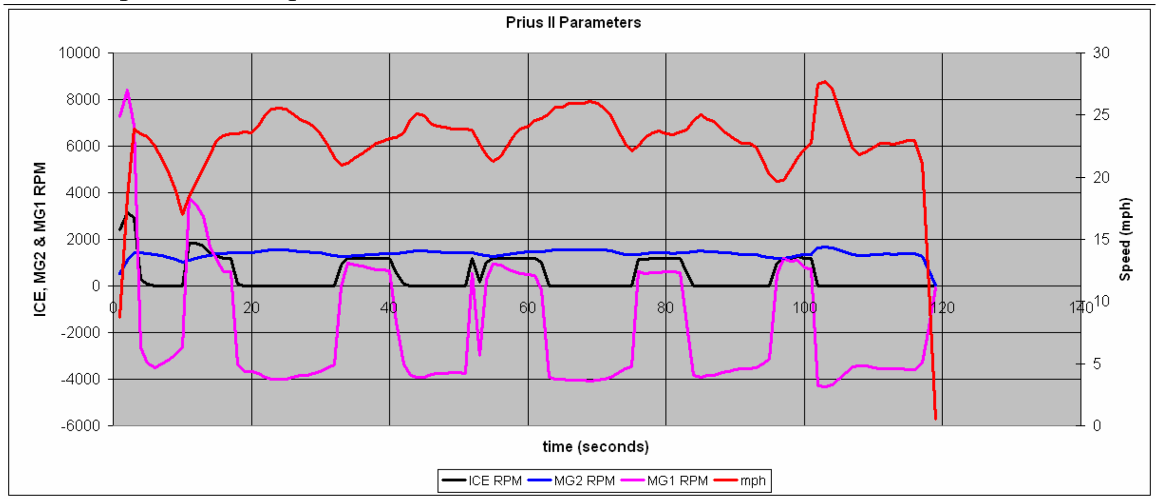
This is a least-squares fit of $(S1+S2)/C$ to the angular speed ($w = v/r$ where $r =$ turn radius=12.6 feet.). C is 198.4 for the best fit.

The average value of C for both counterclockwise and clockwise motion is 195.7 .

Motormile Speedway

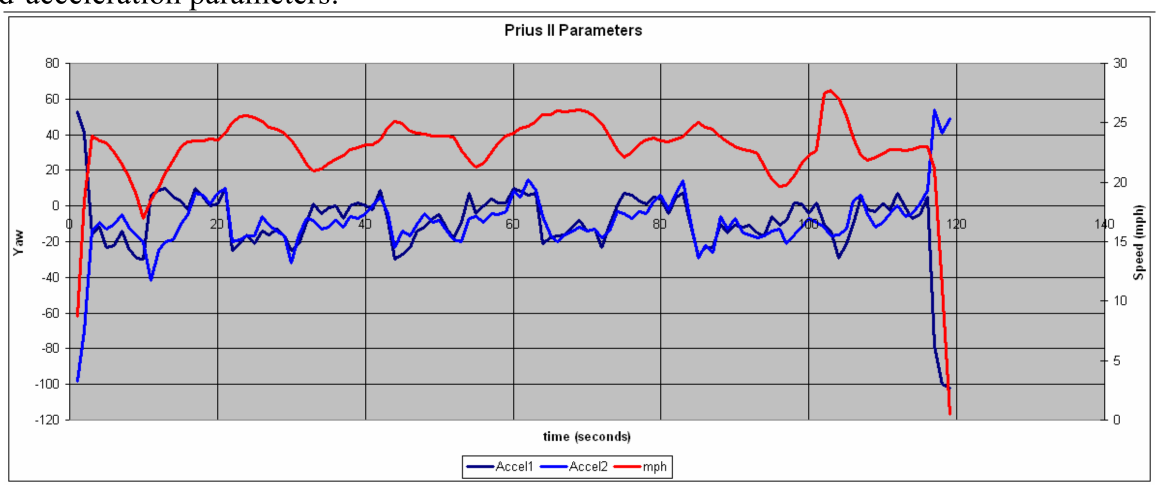
Counterclockwise 20 mph

ICE rpm, MG2 rpm & MG1 rpm:

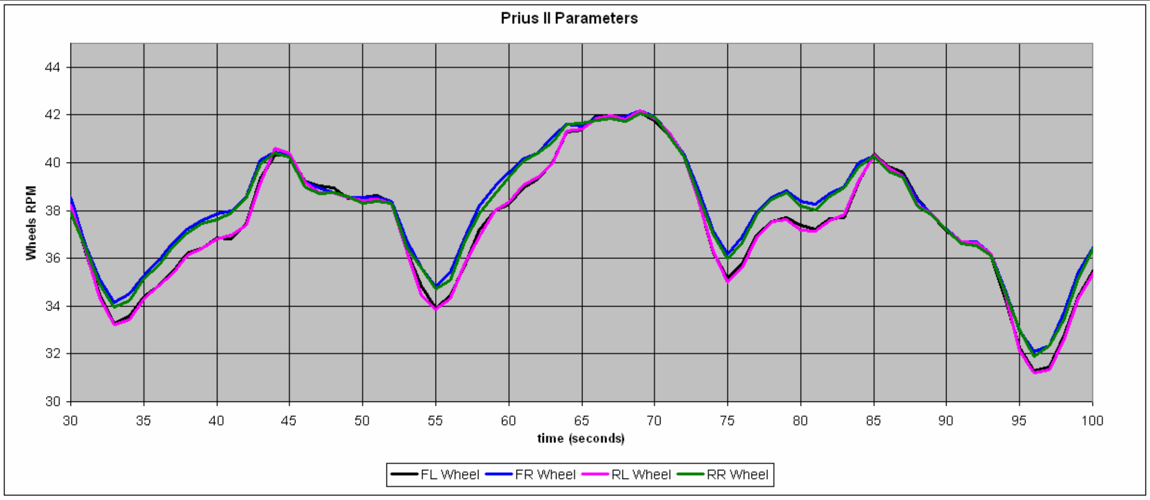


Angular-speed parameters:

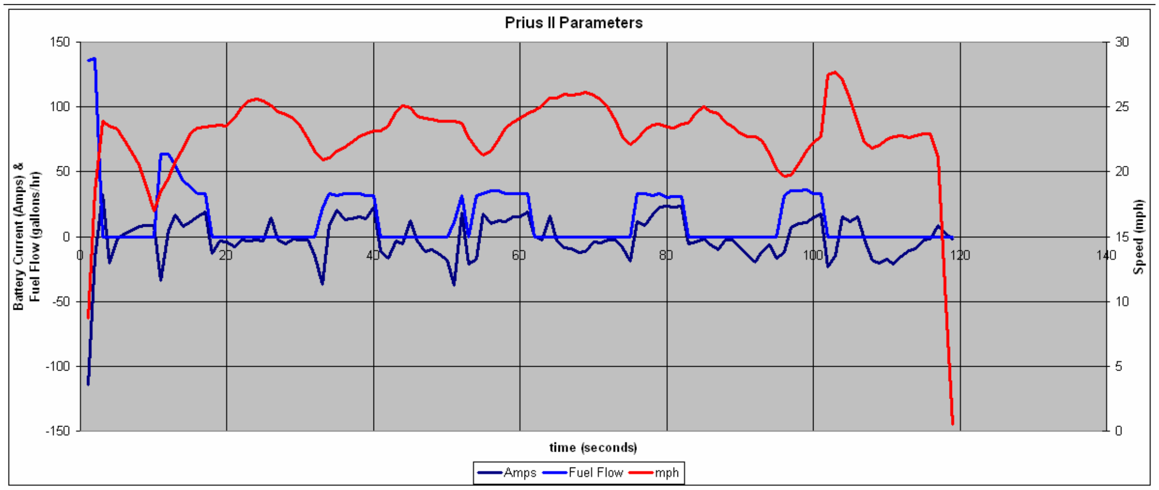
Forward-acceleration parameters:



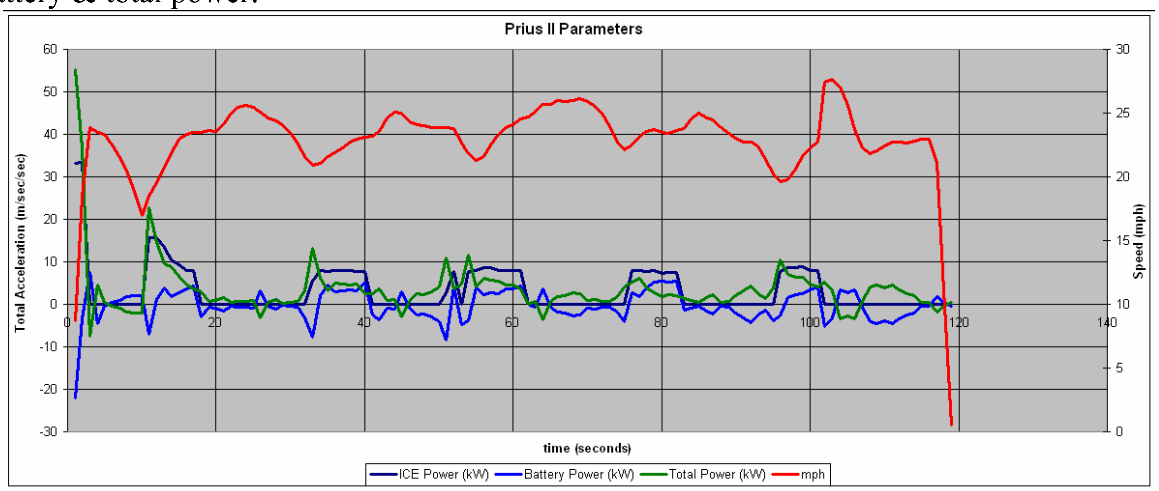
Front-Left, Front-Right, Rear-Left & Rear-Right wheels rpm:



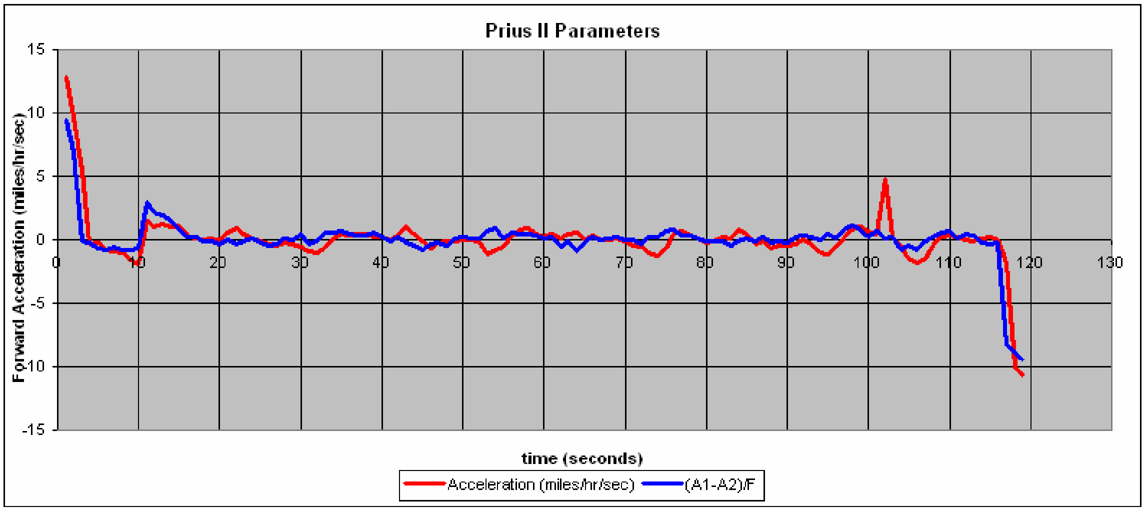
Battery current & fuel flow:



ICE, battery & total power:



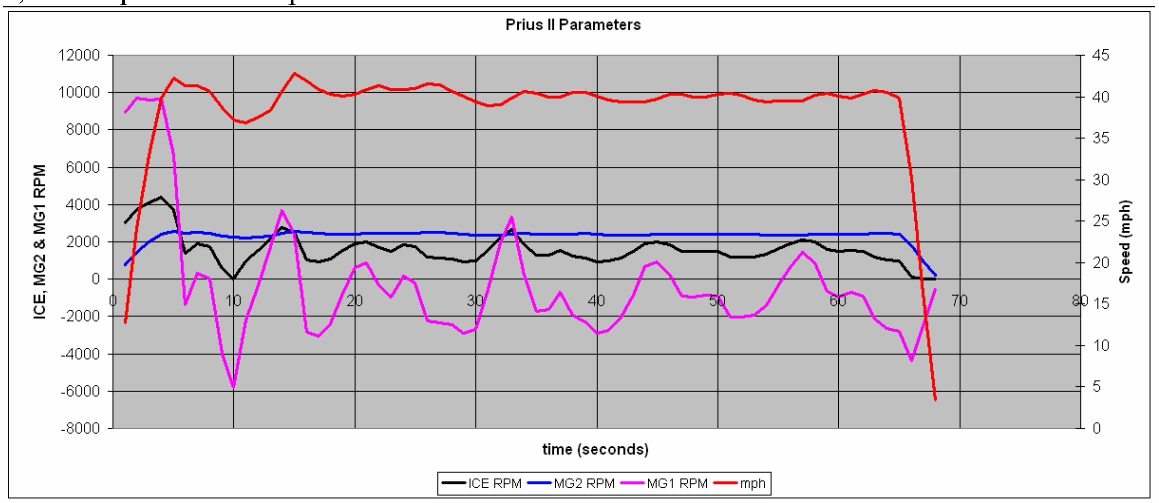
It appears that A1-A2 is approximately the forward acceleration:



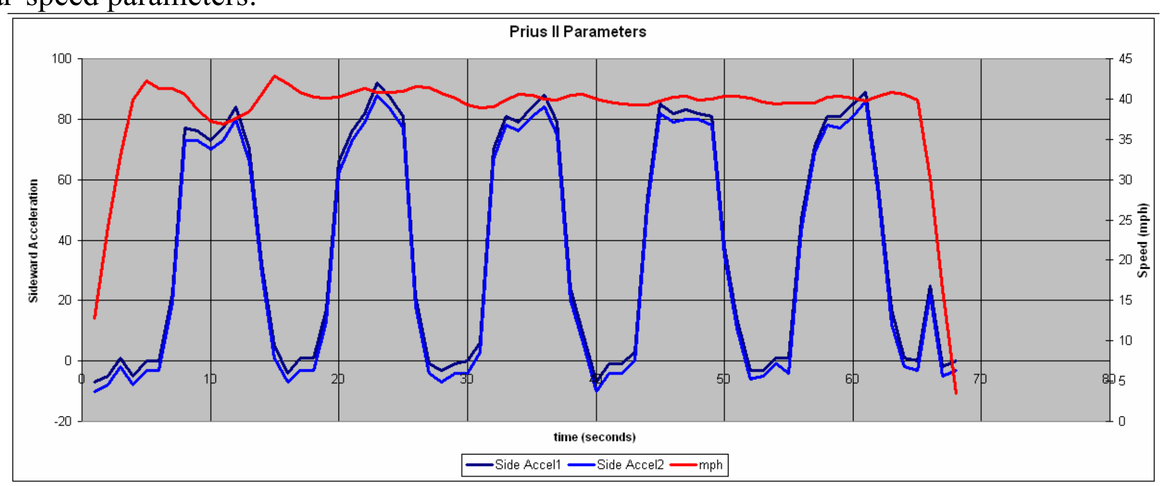
This is a least-squares fit of (A1-A2)/C to the forward acceleration in miles/hr/sec. (The best fit is for C = 15.9 .)

Counterclockwise 40 mph

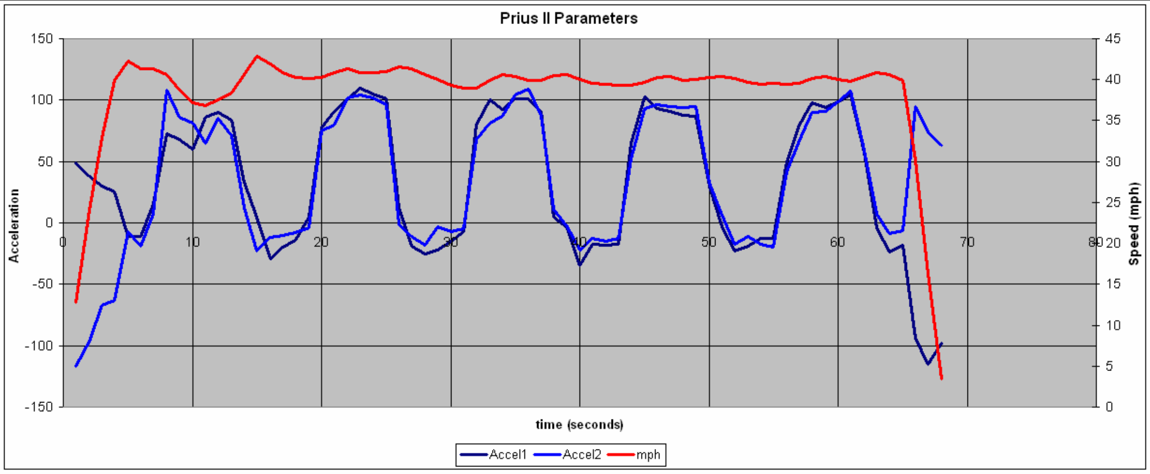
ICE rpm, MG2 rpm & MG1 rpm:



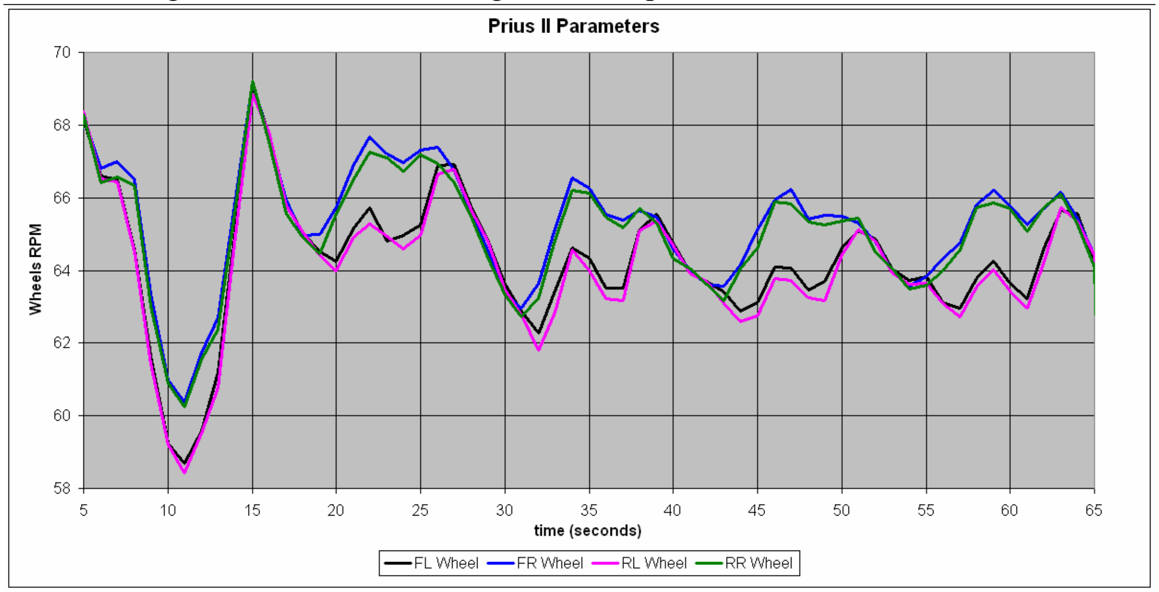
Angular-speed parameters:



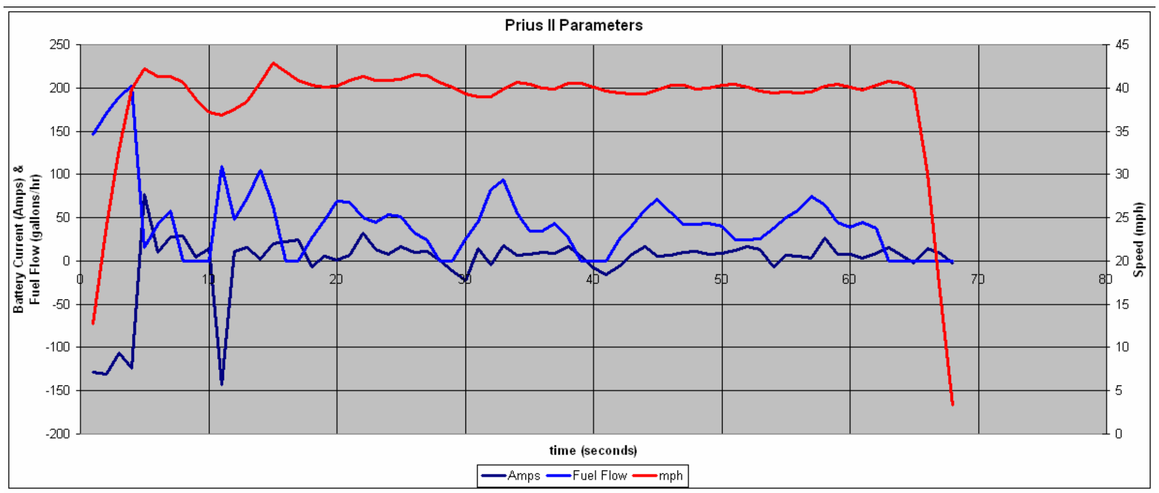
Forward-acceleration parameters:



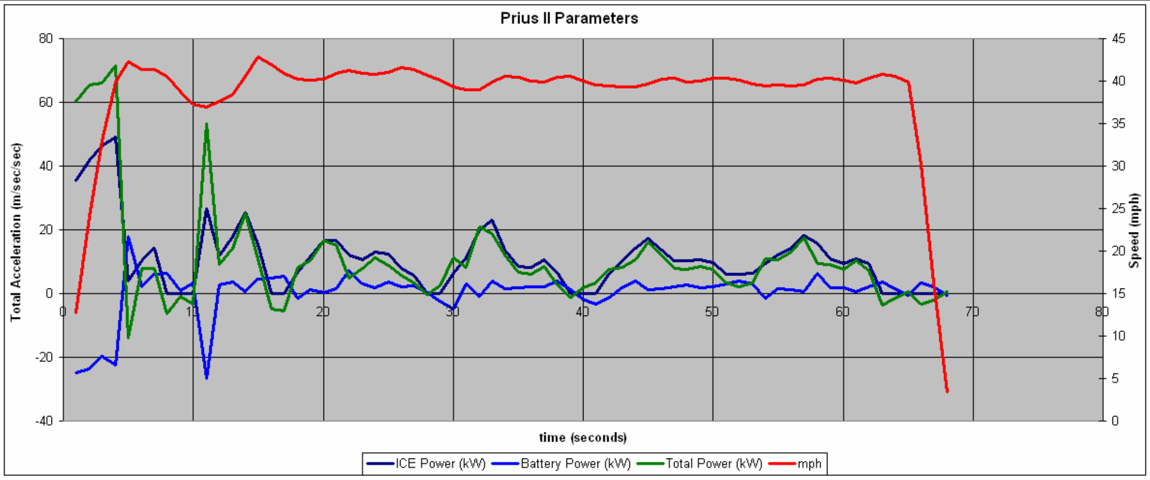
Front-Left, Front-Right, Rear-Left & Rear-Right wheels rpm:



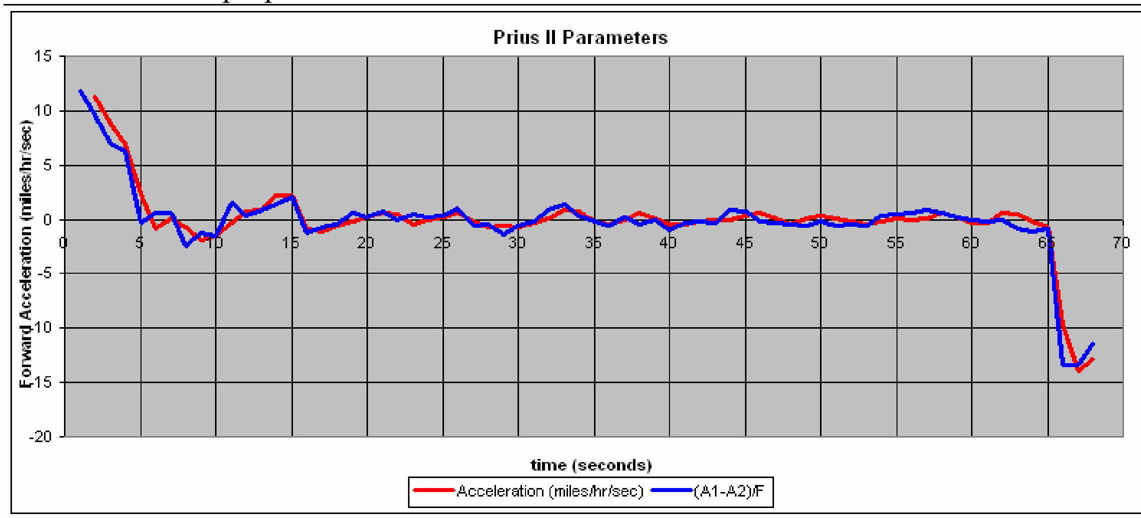
Battery current & fuel flow:



ICE, battery & total power:



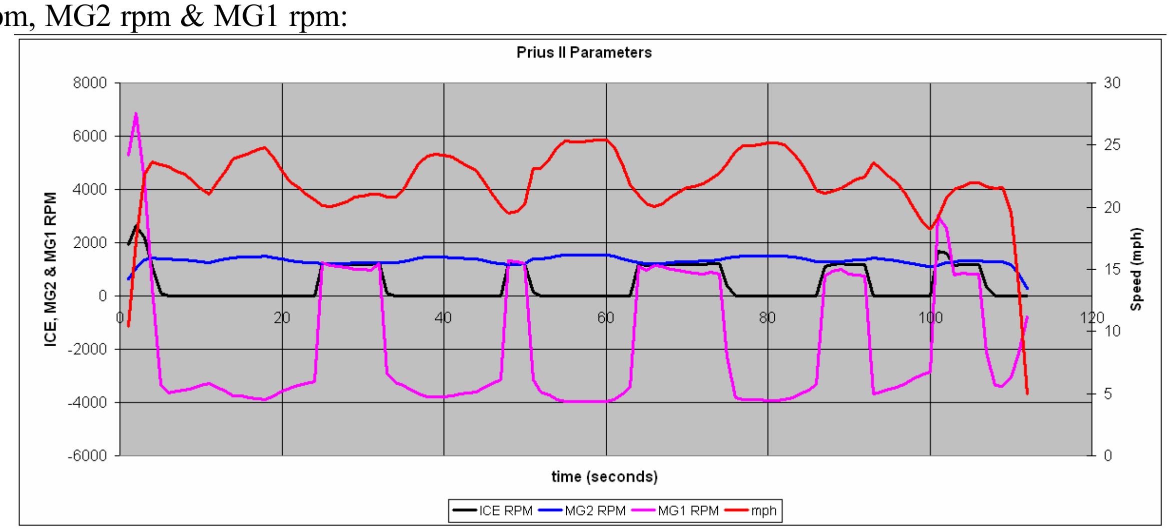
It appears that A1-A2 is proportional to the forward acceleration:



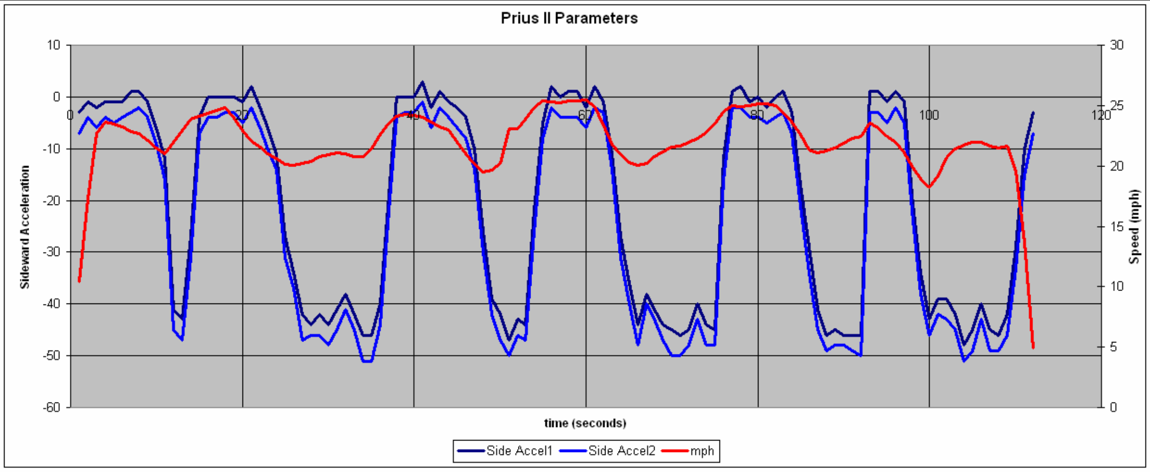
This is a least-squares fit of (A1-A2)/C to the forward acceleration. (The best fit is for C = 14.0 .)

Clockwise 20 mph

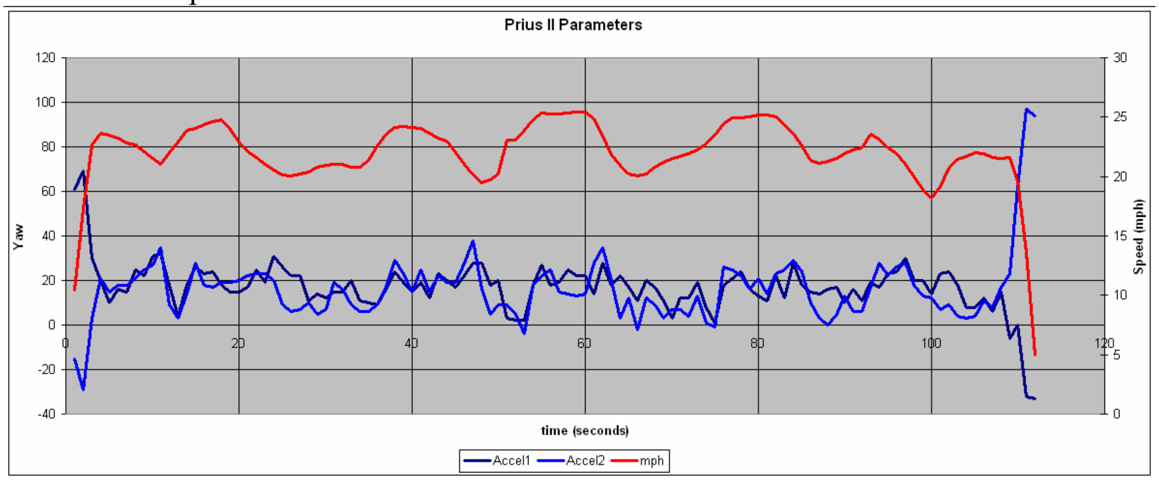
ICE rpm, MG2 rpm & MG1 rpm:



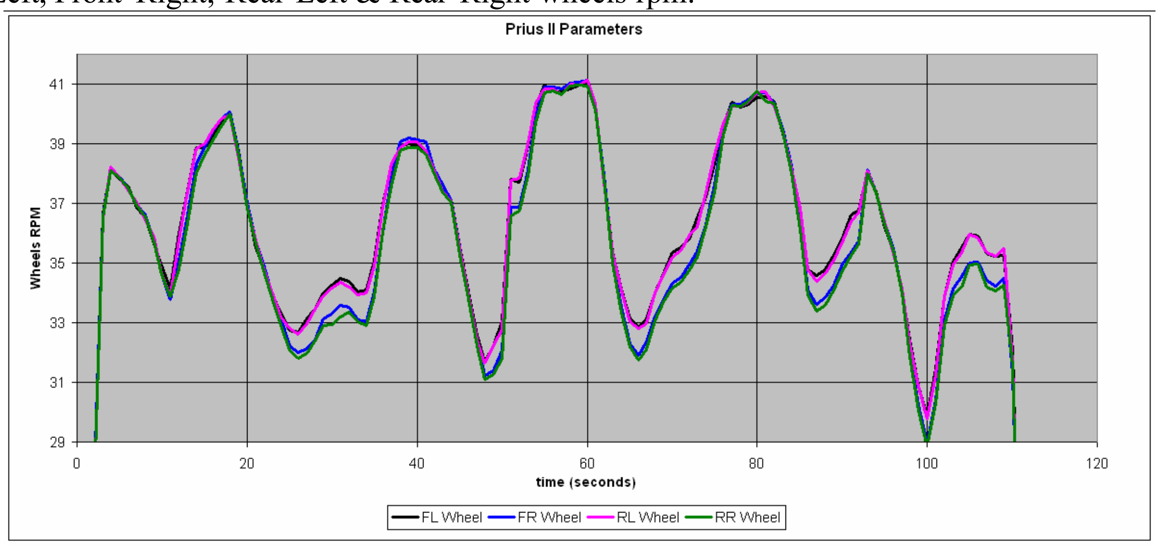
Angular-speed parameters:



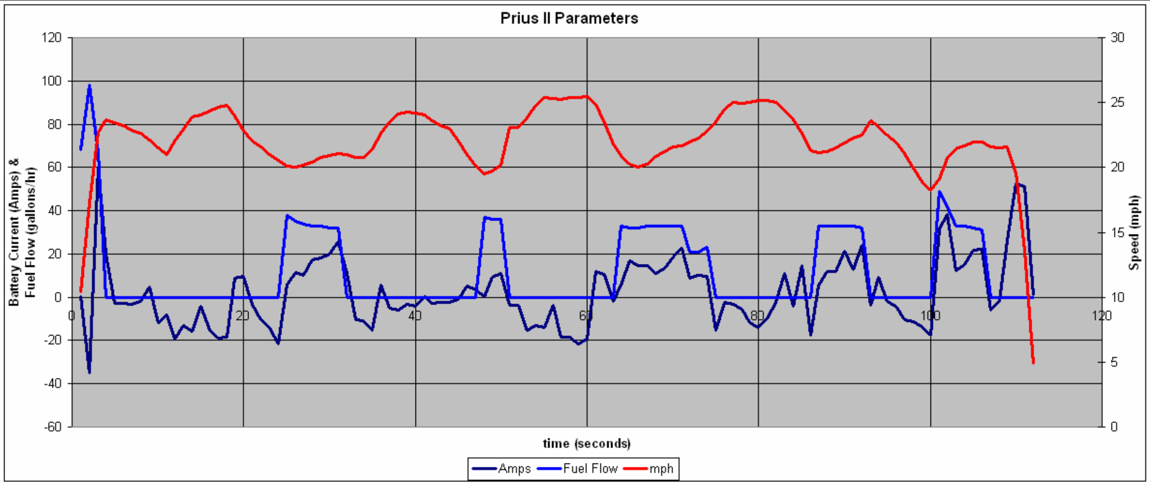
Forward-acceleration parameters:



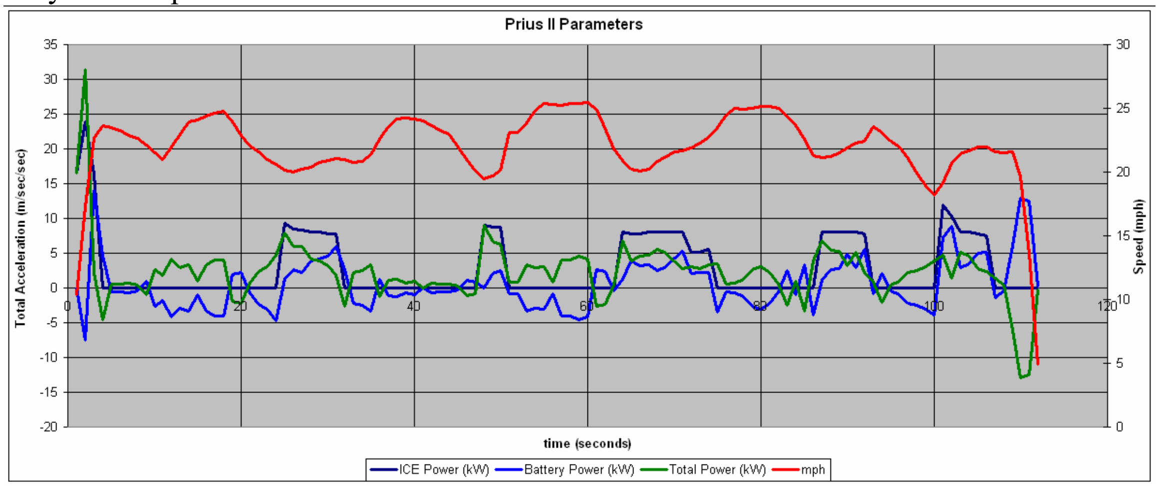
Front-Left, Front-Right, Rear-Left & Rear-Right wheels rpm:



Battery current & fuel flow:



ICE, battery & total power:



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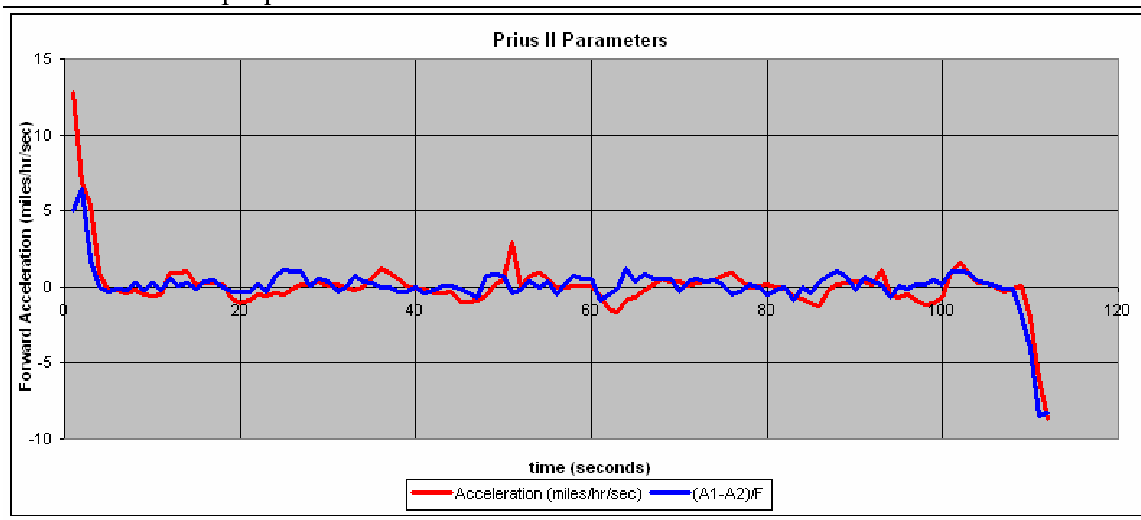
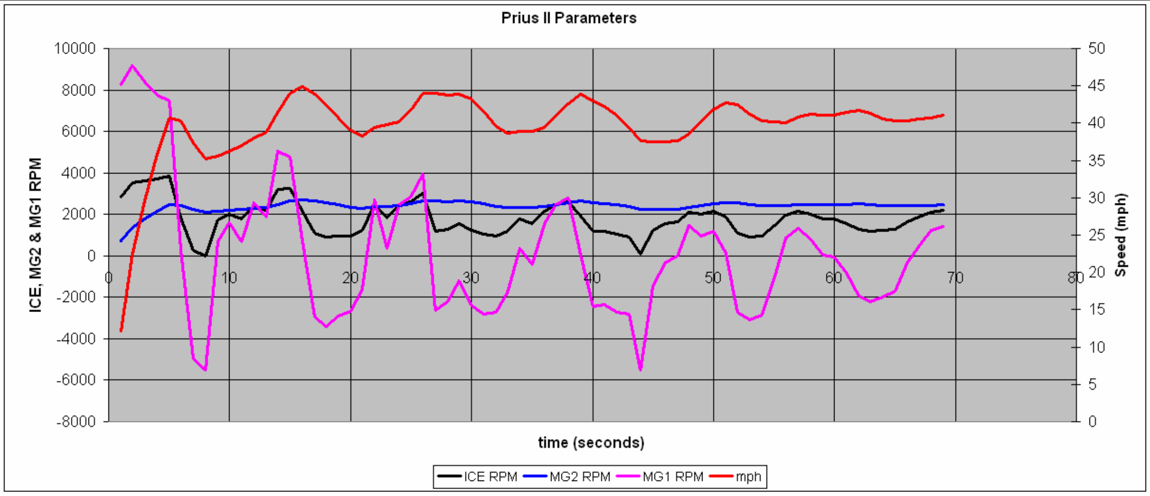


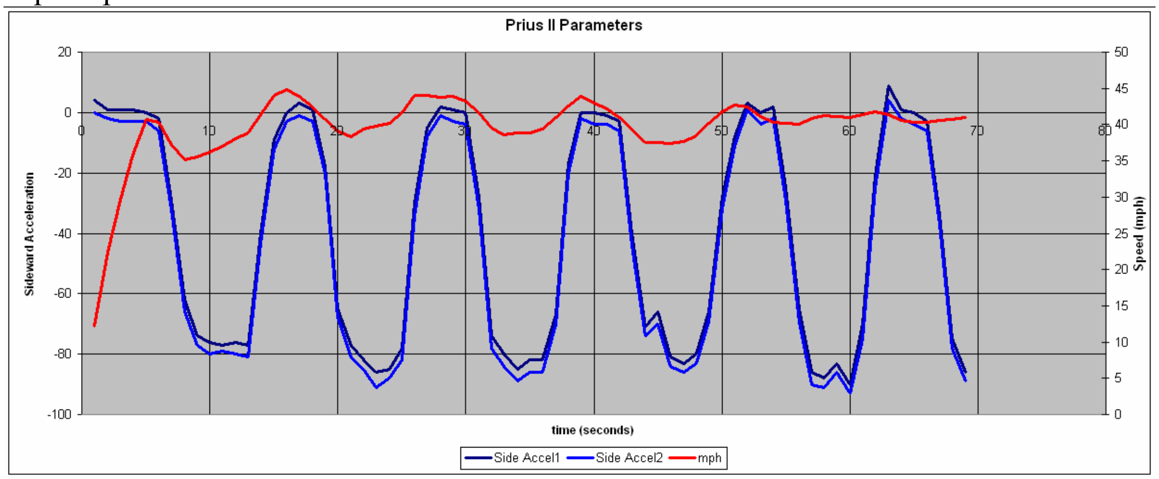
This is a least-squares fit of (A1-A2)/C to the forward acceleration. (The best fit is for C = 15.3 .)

Clockwise 40 mph

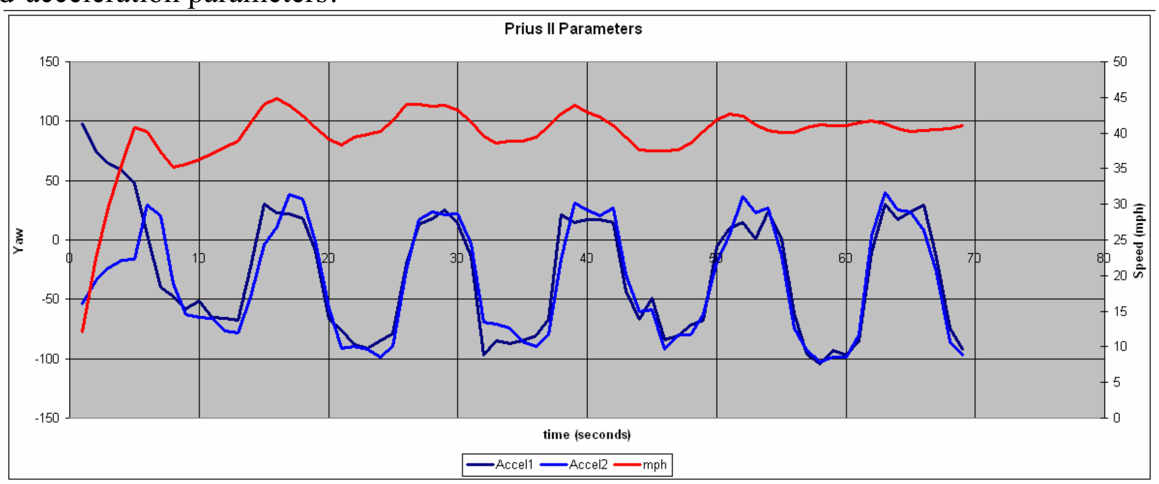
ICE rpm, MG2 rpm & MG1 rpm:



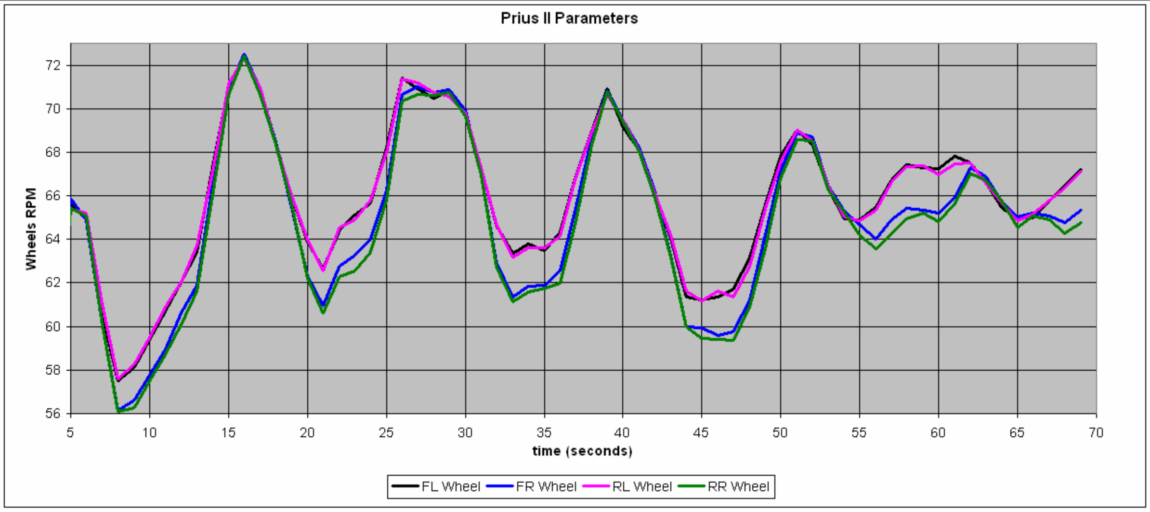
Angular-speed parameters:



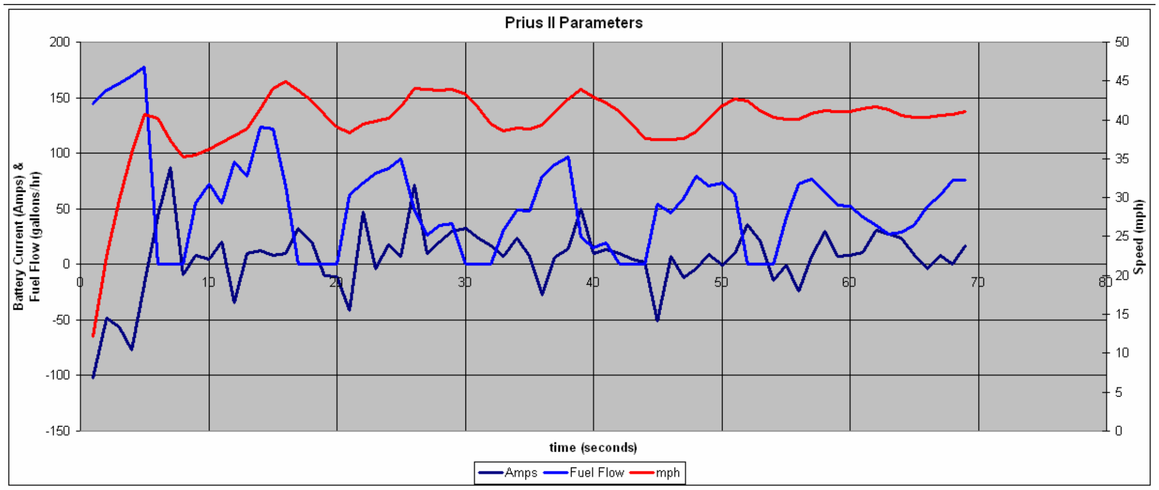
Forward-acceleration parameters:



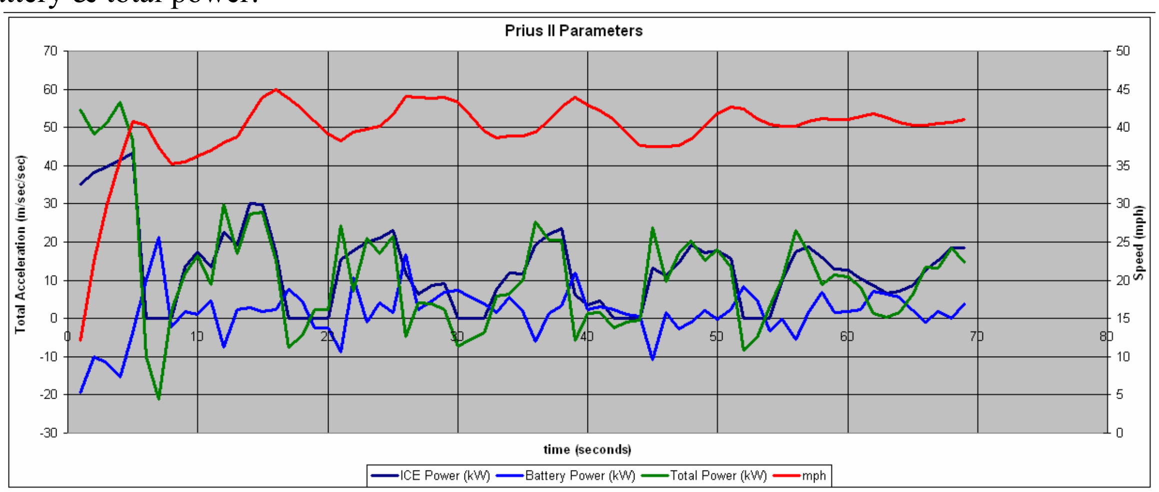
Front-Left, Front-Right, Rear-Left & Rear-Right wheels rpm:



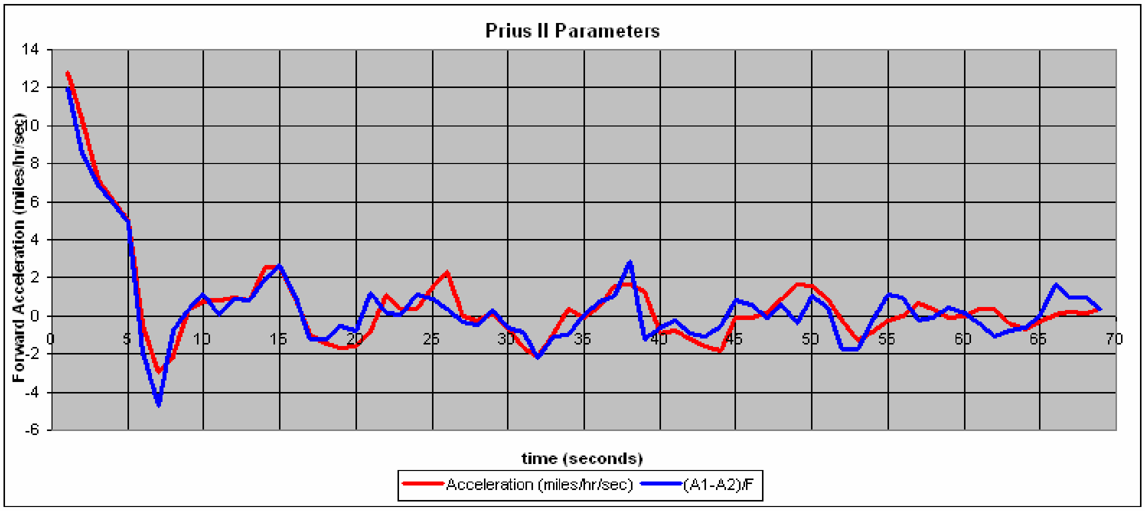
Battery current & fuel flow:



ICE, battery & total power:



It appears that A1-A2 is proportional to the forward acceleration:

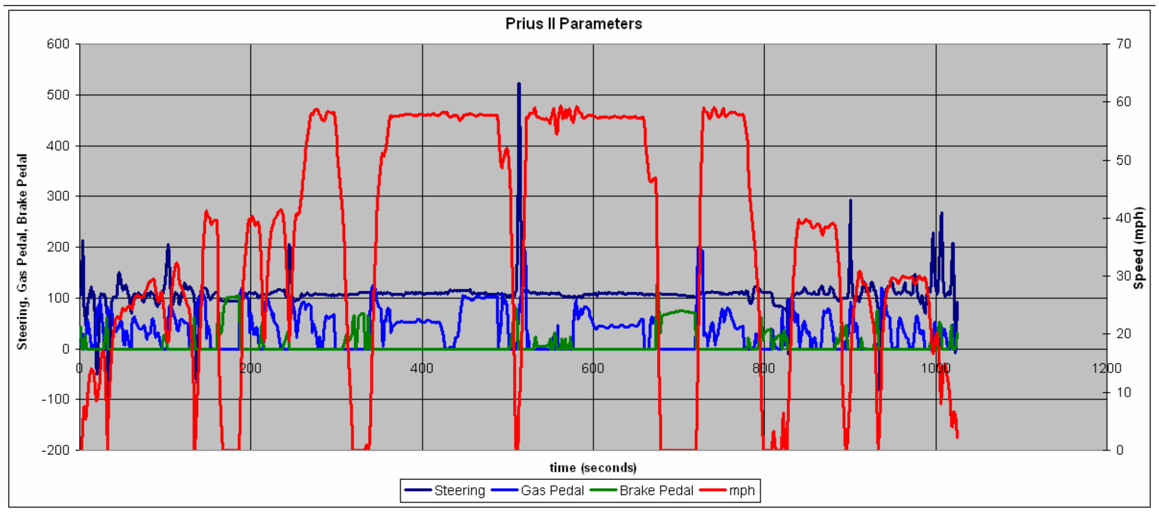


This is a least-squares fit of (A1-A2)/C to the forward acceleration. (The best fit is for C = 12.8 .)

The average value for the four case is C = 14.5 .

Brush Mountain Trip

Steering, Gas Pedal and Brake Pedal

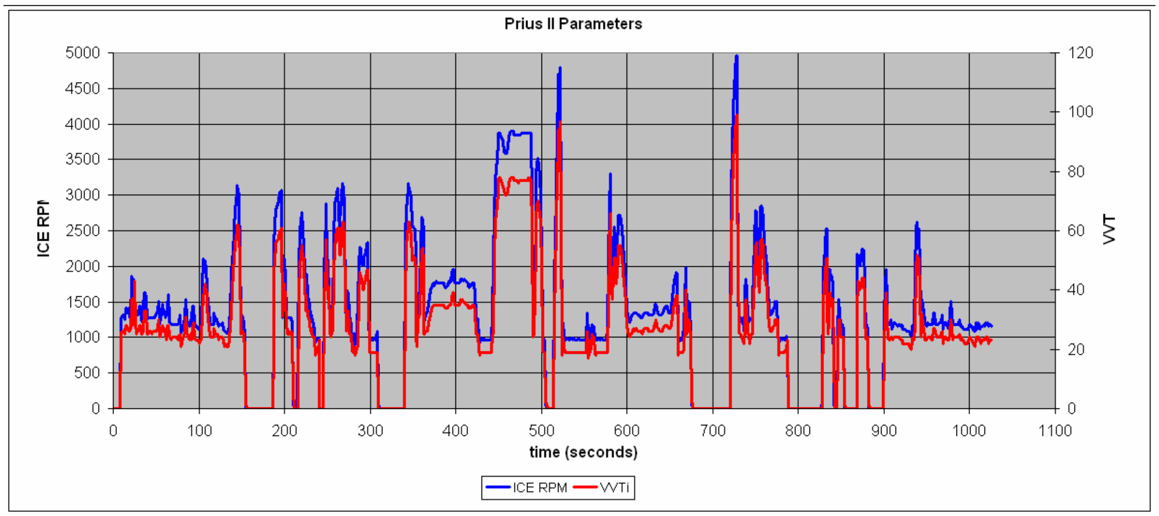


- Steering is about 100 for straight ahead travel and note the large value (over 500) at the 360 degree turn around at the top of the mountain.
- Gas Pedal is high going up the mountain just before the 360 degrees turn around. Just before that there was a short decline, so Gas Pedal was zero. And, of course, the Gas Pedal is zero and there is some Brake Pedal coming down the mountain after the turn around.
- Note the symmetrical stops at four stop lights and stop signs on the outgoing and ingoing legs of the trip. There was an extra stop sign near the beginning of the outgoing leg.

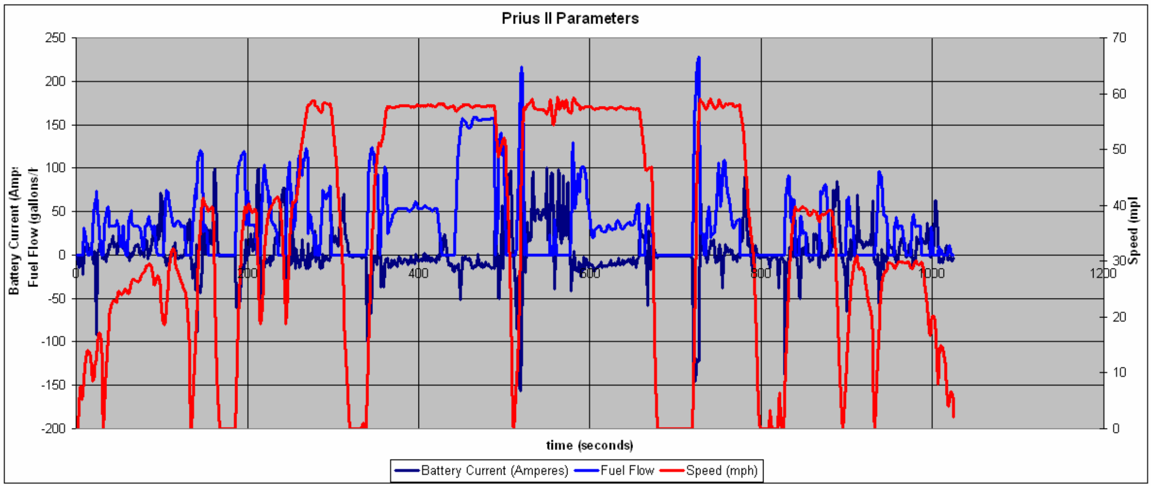
ICE rpm, MG1 rpm and MG2 rpm (rolling wheel radius of 11.5")

- All rpms are zero at the stop signs and lights.
- ICE rpm is high and MG1 rpm is high positive going up the mountain just before the 360 degrees turn around and ICE rpm is low (freely spinning) and MG1 rpm is high negative just before that on a decline. And, of course, the ICE spins freely with high negative MG1 rpm coming down the mountain after the turn around.

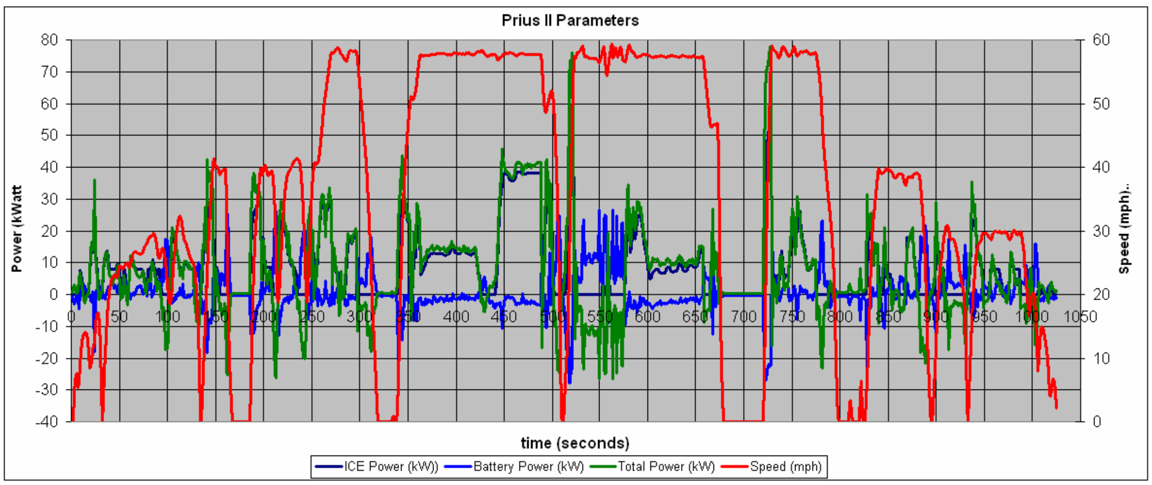
ICE rpm and VVTi



Battery Current and Fuel Flow



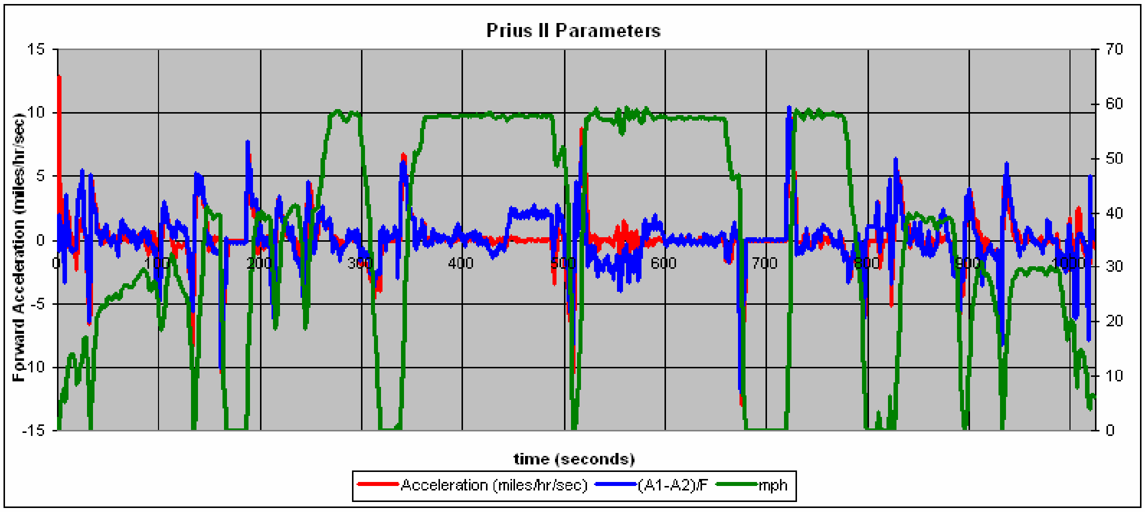
ICE Power, Battery Power and Total Power



ICE (Internal Combustion Engine) power is calculated as prescribed by Norm Dick, the inventor of CAN-View, ascribing 58 kW to 238 in the CAN output for fuel flow and assuming linearity. Of course, battery power is voltage times current, and it is positive going into the battery. So, total power going out of the vehicle is ICE power minus battery power.

Forward Acceleration

One can take the average of the four factors (14.5) used to relate forward acceleration to A1-A2 for the four Motormile Speedway runs to calculate forward acceleration for this Brush Mountain trip:

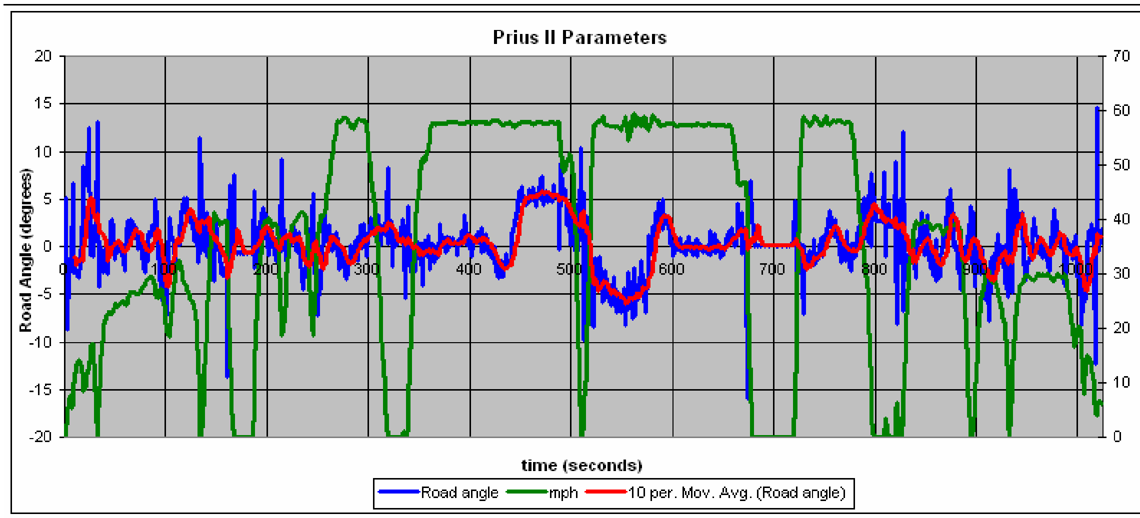


It calculates close to the acceleration except for the times when the Prius is going down and up slopes; then the gravitational acceleration, g, has a component along or opposite the forward direction, respectively. The accelerometers cannot tell the difference between vehicle and gravitational acceleration.

Road Angle

One can use (A1-A2)/14.5 to calculate the road angle: $q = \arcsin\left[\left(\left\{\frac{A1-A2}{14.5}\right\} - a\right)/g\right]$. (See Appendix 3.)

The result is:



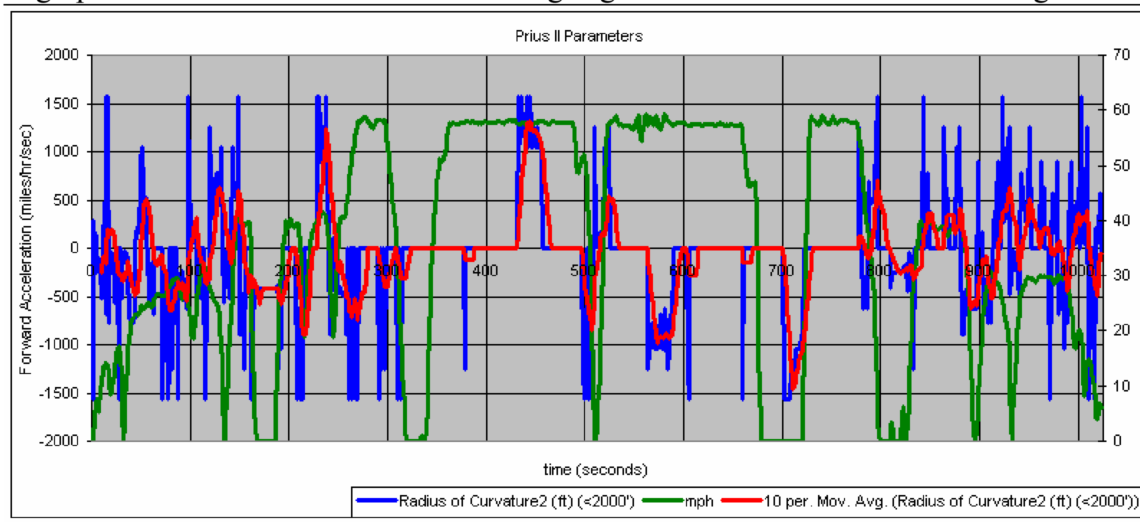
The red curve is a 10-second moving average to smooth out the obvious measurement noise.

Radius of Curvature

One can use the angular speed (S1+S2/2/225 to calculate the radius of curvature $\frac{v}{w}$ with [=IF(ABS(5280v/?/3600)>2000,0,5280v/? /3600) in Excel for v in mph. This eliminates very large radii of curvature (2000 ft) due to small deviations in the vehicle path.]:

The red curve is a 10-second moving average to smooth out the obvious measurement noise.

A similar graph can be calculated from the steering angle as outlined in the section on tight circles:



The two graphs directly above are similar, but not exactly the same.

Template Excel Spreadsheet for CAN Data Analysis

A template Excel Spreadsheet can be downloaded at http://www.roperld.com/science/prius/template.xls and used according to the following instructions:

1. Use the cancoder.exe program (http://mggm.net/prius/candecoder.html) to create a CSV file for a set of recorded CAN data.
2. Load the CSV file into Excel and copy the data excluding the titles row at the top to the clipboard.
3. Open the template.xls file and paste the copied data into the file beginning at position (row 2, column 1). That is, leave the top titles row and the right-hand colored columns as they are in the template.
4. Then some calculations will be automatically done to the right in the colored columns.
5. Some graphs of the data and calculations will automatically be done on the worksheet graphics.
6. The template spreadsheet is set up for 30 minutes of driving (1800 rows = 1800 seconds). It can be extended to longer times by copying the last colored row-columns on the right to more rows. Each row is 1 second of driving.

Other articles by L. David Roper about Hybrid Vehicles

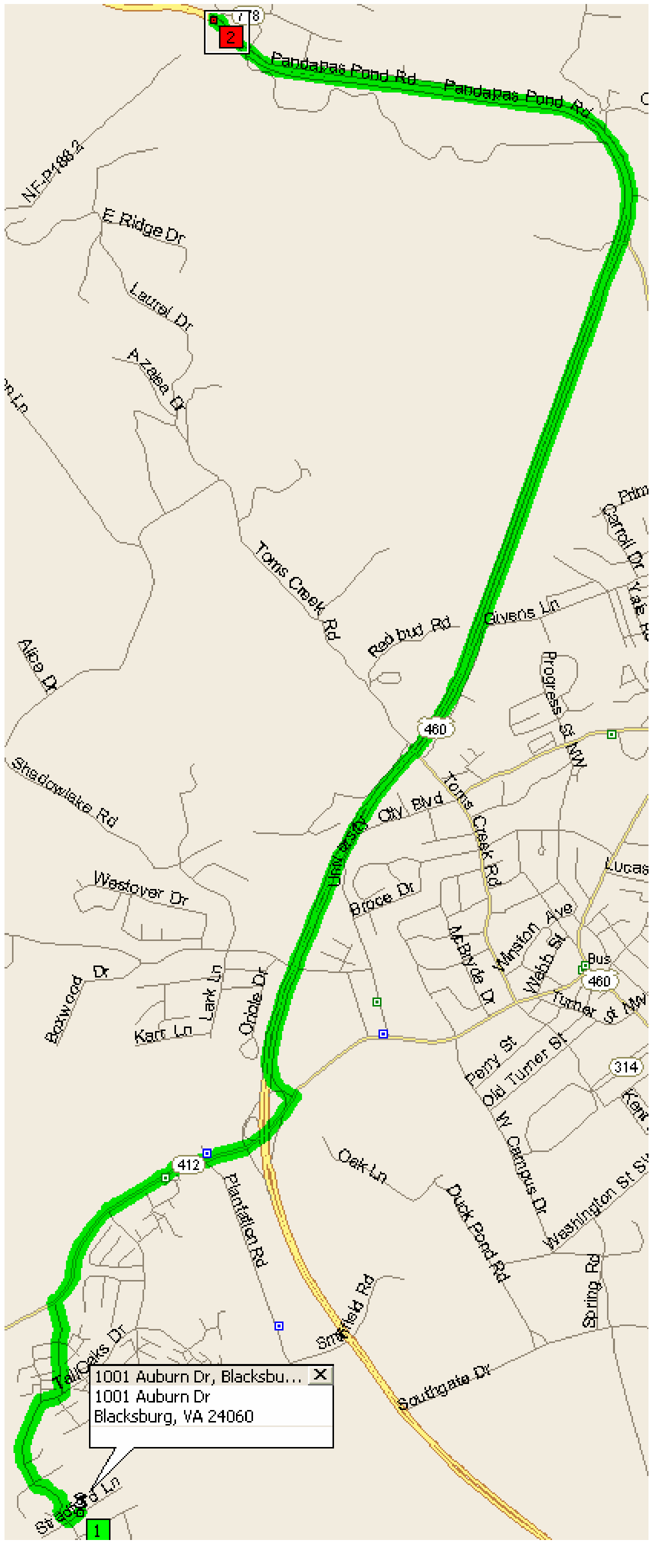
http://www.roperld.com/Science/Prius/HybridVehicles.htm

Appendix 1: List of CAN Parameters Recorded

- Voltage
- State of Charge (SOC)
- Battery Current
- Maximum Charge Current
- Maximum Discharge Current
- Minimum Battery Temp (ºC)
- Maximum Battery Temp (ºC)
- Speed (kph) | Speedometer
- Speed Related
- Front Left Wheel
- Front Right Wheel
- Rear Left Wheel
- Rear Right Wheel
- ICE rpm (See graph directly below for a possible way to find a non-linear relationship between ICE rpm and ICE power.)
- ICE Temp (ºC)
- Coolant Temp (ºC)
- Side Angular Speed1 (S1)
- Side Angular Speed2
- Forward Acceleration1 (A1)
- Forward Acceleration2 (A2)
- Steering (Gary Morris discovered a calibration offset that is subtracted from positive steering values and added to negative steering values.)
- Go Pedal
- Brake Pedal
- Brake Pressed
- EV Mode
- Cruise Control
- Lights
- Fuel Injection [Used to calculate mpg = mph*1100/(fuel inj)]
- Fuel Flow (ICE power can be calculated by multiplying fuel flow by 58 kW and dividing by 238, assuming linearity of ICE power with fuel flow. See graph directly below for a possible way to find a non-linear relationship between ICE rpm and ICE power.)
- VVTi (Variable Valve Timing-Intelligent)
- Gas Gauge

Appendix 2: Maps of the Brush Mountain Trip

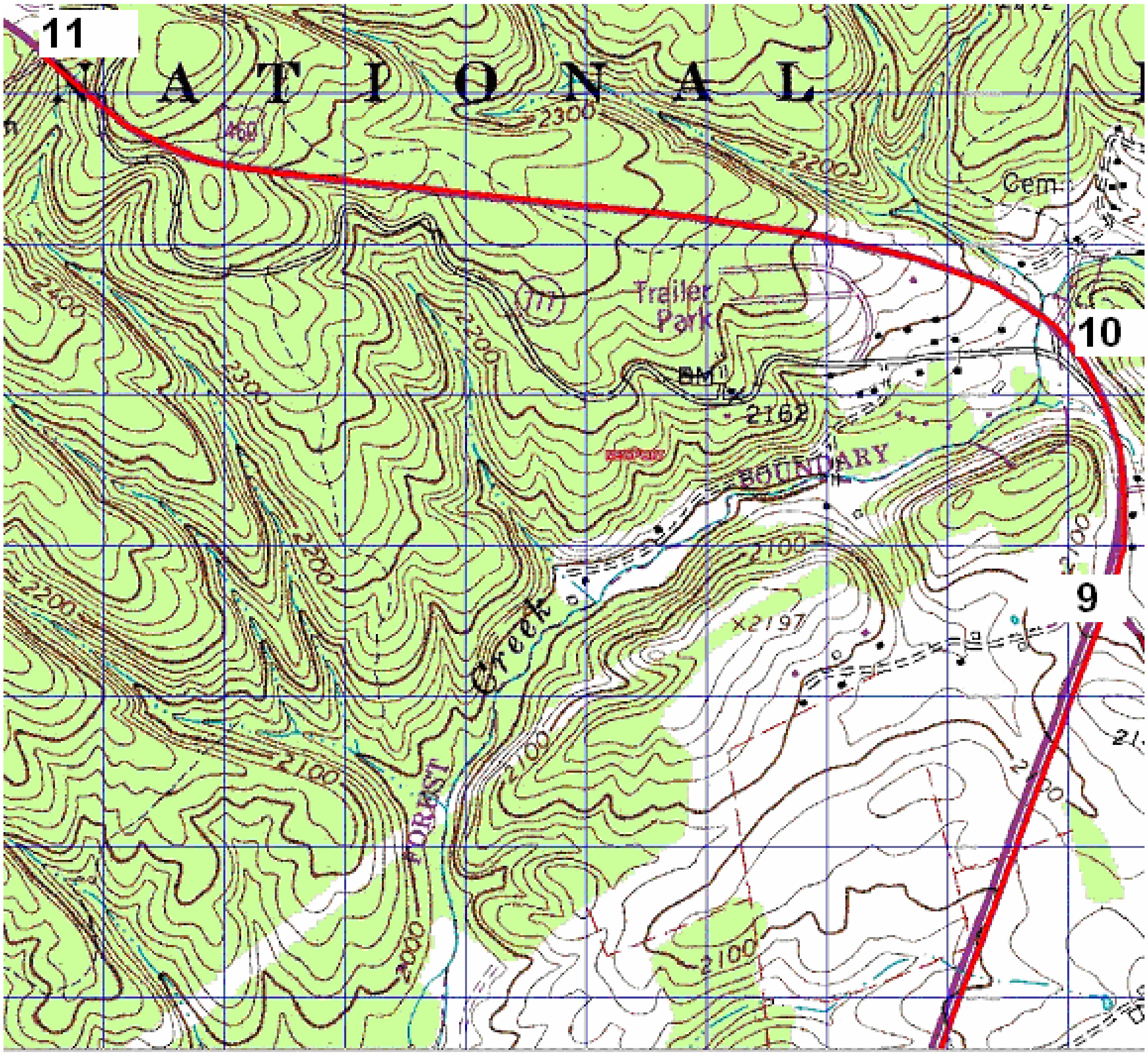
Two-Dimensional Map



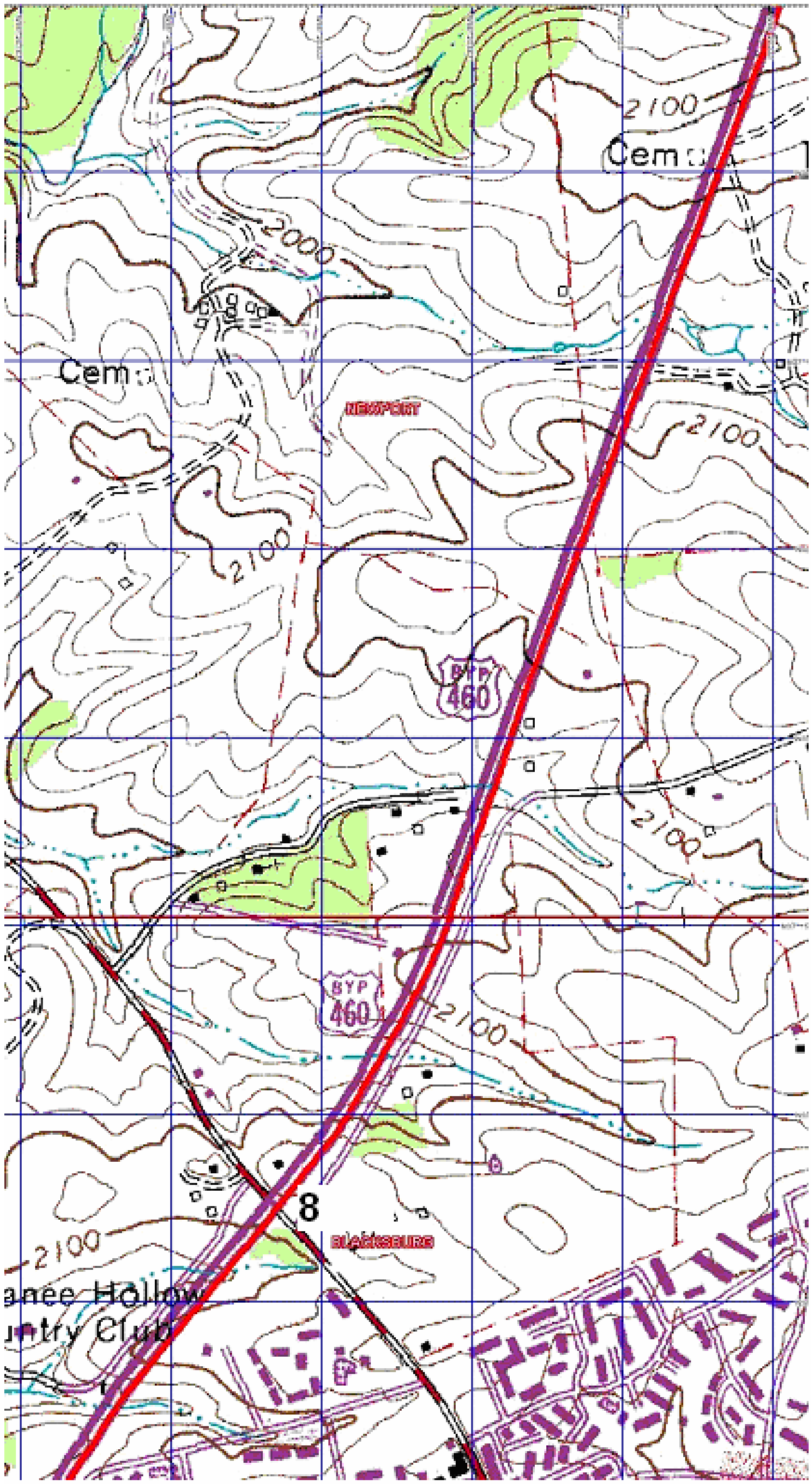
7.1 miles each way.

Topographic Maps

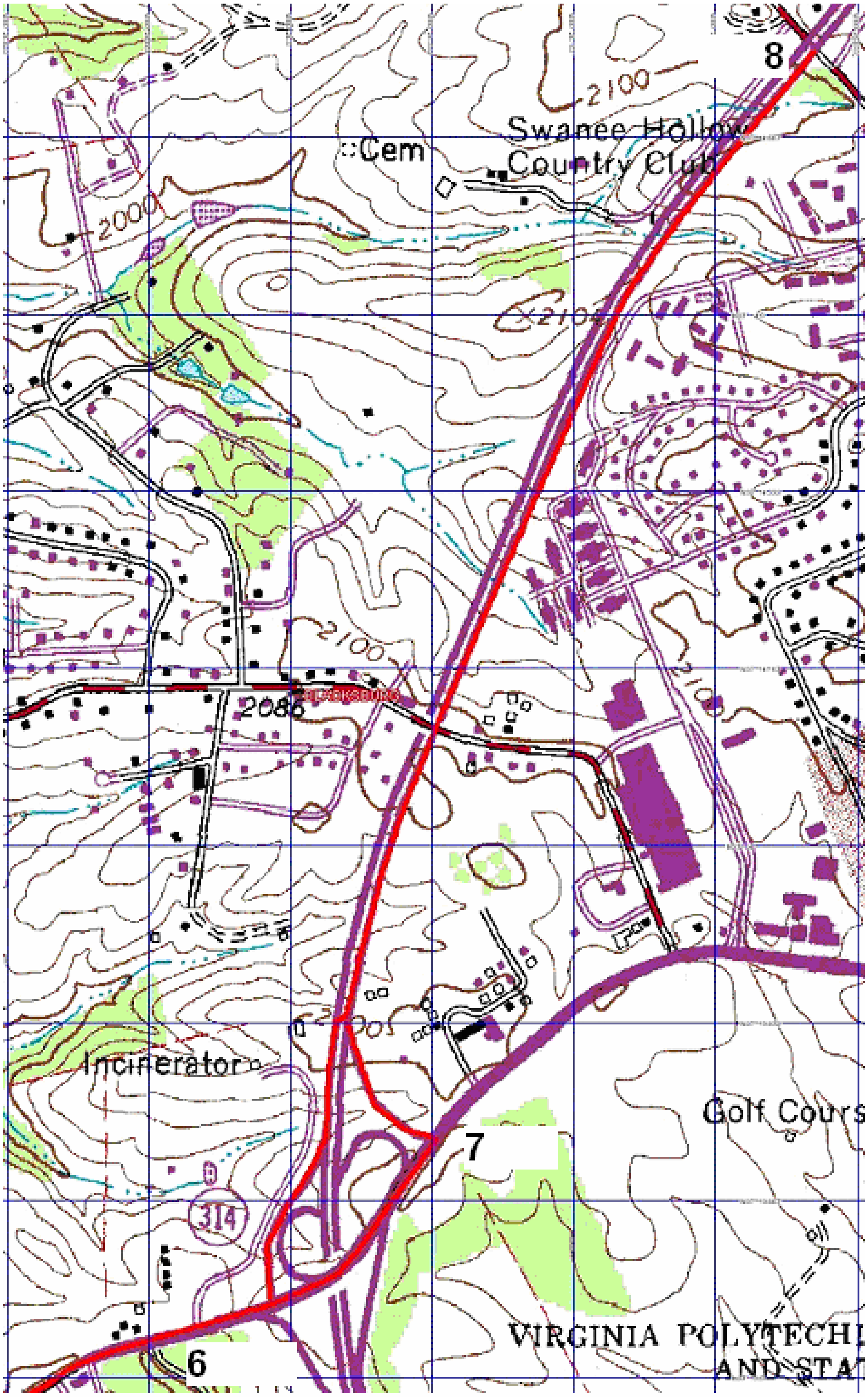
The times for specific locations on the out trip are indicated below each map:



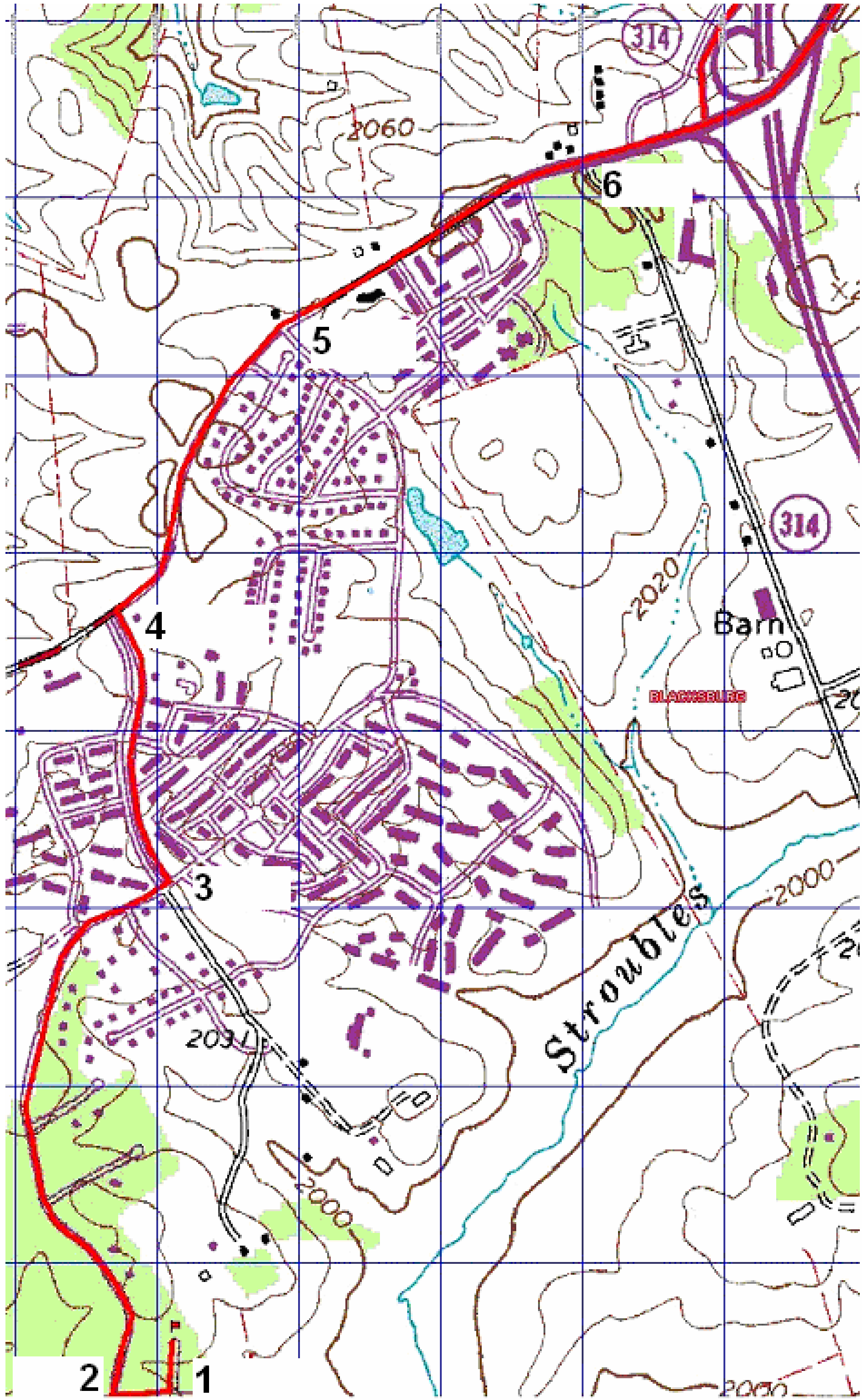
9 = 425 seconds (downhill, beginning of left curve), **10 = 440-460** seconds (uphill, end of curve), **11 = 510-520** seconds (turn around).



8 = 320-340 seconds, (stop light)



6 = 215 seconds (stop light slow down), **7 = 245 seconds** (turn onto US460 bypass), **8 = 320-340 seconds**, (stop light)



1 = 20 seconds (stop sign right turn), **2 = 35 seconds** (stop sign right turn), **3 = 105 seconds** (downhill, then left turn), **4 = 135 seconds** (stop sign right turn), **5 = 170-180** seconds (stop light), **6 = 215 seconds** (stop light slow down)

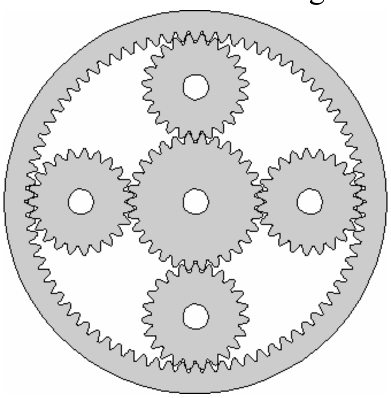
Appendix 3. Equations

Power Split Device

From http://www.ecrostech.com/prius/original/PriusFrames.htm and http://www.engin.umd.umich.edu/vi/w4_workshops/Miller_W04.pdf :

Let

- S = rpm of small generator/motor (MG1)
- L = rpm of large motor/generator (MG2)
- E = rpm of Internal Combustion Engine (ICE)
- V = vehicle speed in mph
- N_r = number of gears in outer (ring) gear (= 78)
- Ns = number of gears in inter (sun) gear (= 30)



Then (S - E)/(L - E) = $-N_r$/Ns or S = (1 + 78/30)E - (78/30)L .

But $L = \frac{4.113(12\,\frac{\text{in}}{\text{ft}})(5280\,\frac{\text{ft}}{\text{mile}})}{2p\,(11.5\text{ in})(60\,\frac{\text{min}}{\text{hr}})} V = 60.1\ V$, where V is in mph, 4.113 is the gear ratio between the ring gear and the wheels for the Prius II and 11.5 in is the rolling radius of the wheels (depends on the tires).

Power and Energy

- **Battery power** for current I (Amperes) and potential V (Volts) is $P_B = IV$ in kW.
- **ICE power** is assumed to be 58(fuel flow)/238 in kW.
- **Kinetic energy** of vehicle of mass m and speed v: $E_k = \frac{1}{2}mv^2$.

Air-Friction Drag Force

Assume that the only external frictional force of consequence is the air-friction drag due to the velocity v of the vehicle. (For high speeds this is a good approximation for the external frictional forces.) Then the **air-friction drag force** is to a good approximation

$F = -\frac{1}{2} c_d A \rho v^2 \equiv -mCv^2$ (http://en.wikipedia.org/wiki/Drag_equation) where

- c_d = drag coefficient (unitless) (0.26 for 2004-5 Toyota Prius II)
- A = projected area perpendicular to the velocity (~2.52 meter² for Toyota Prius II)
- ρ = air density $\approx 1.2 \frac{\text{kg}}{\text{meter}^3}$. (Depends on the temperature, air pressure and the amount of water vapor in the air.)
- m = mass of the vehicle (1311 kg for Toyota Prius II) (The mass is only needed in the equation directly below; it will cancel out in the final equations of interest.)
- $C = \frac{1}{2} c_d A \rho / m =\sim 3.0 \times 10^{-4} \frac{1}{\text{meter}}$ for Toyota Prius II.

(Force in Newtons, mass in kg, velocity in m/sec and acceleration in m/sec^2.)

Thus, the total force acting on a vehicle moving up a hill of angle ? is

$$F = F_d - mg \sin\theta - mCv^2 \text{ where } C = 6 \times 10^{-4} \frac{1}{\text{meter}} \text{ for the Prius II.}$$

The second term is the gravitational force and third term is due to air friction. F_d is the force that propels the vehicle of mass m to accelerate it or keep it moving at a constant speed opposing air friction and the component of gravity. Friction always opposed the direction of motion; so, its sign must be adjusted accordingly.

Road angle

$\theta = \arcsin\left[(A - a)/g\right]$ for the 2003-6 Prius, where A is the accelerometer measurement.

If one uses v in miles/hr, a in miles/hr/sec (true acceleration) and g = 32.2 ft/sec^2, then one must multiply $\frac{a}{g}$ by (5380 ft/mile)/(3600 sec/hr)

Centripetal acceleration

The CAN gives v and ω (angular speed in s^{-1}) $\propto [S1 + S2]$. One can use them to calculate the radius of curvature: $r = v/\omega$. For r in feet and v in miles/hr one must multiply v/ω . by (3600 sec/hr)/(5380 ft/mile).

For speed v and a circle of radius r with bank angle φ : centripetal acceleration is $a_c = \frac{v^2}{r} + g \sin\varphi$.

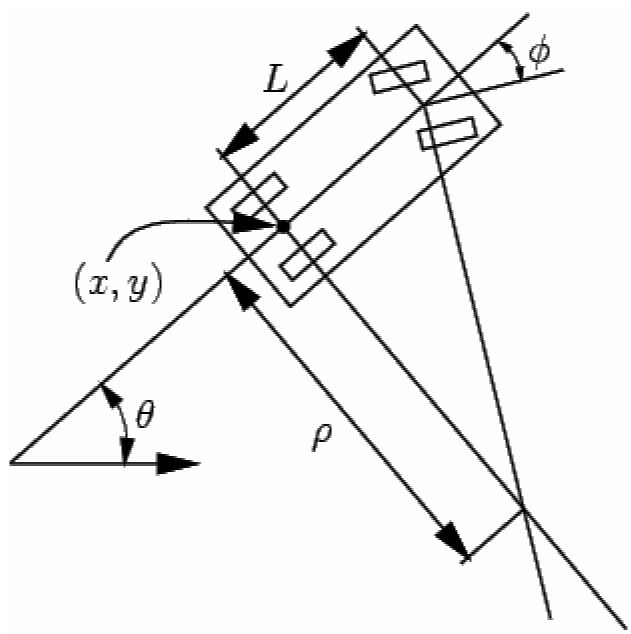
This can be used to calculate the bank angle $\varphi = \arcsin\left(a_c - \frac{v^2}{r}\right)/g$.

Radius of Curvature

The specifications of the Prius II give the turning circle as 34.1 feet, which refers to the outside of the car. For physics analysis the turning circle of the center of mass is what is needed, which is, according to the published 2005 Prius specifications (34.1 – 4.86) feet = 29.24 feet. Thus, the **turning radius** of the center of mass is 14.62 feet.

However, for my Prius the turning circle (between outer edges of back wheels) is 30 ft for counterclockwise motion and 29.1 feet for clockwise motion. The distance between the centers of the back tires is 4.86 feet. Thus, (30-4.86) feet = 25.1 feet and (29.1-4.86) feet = 24.2 feet and the turning radii are 12.6 feet for counterclockwise motion and 12.1 feet for clockwise motion. The steering CAN value (after applying the calibration offset) is 432 for counterclockwise motion and -444 for clockwise motion.

The mathematics of the radius of curvature for a vehicle is given by http://planning.cs.uiuc.edu/node658.html. The following diagram is taken from that web page:



The radius of curvature is represented by r and the wheel base is $L = 8.86$ feet for the 2005 Prius. The equation for the radius of curvature is $r = L/\tan f = L\cot f$ where f = steering angle. If the CAN steering parameter, s, is proportional to the steering angle, then $r = L/\tan(s/a)$ where a is the proportionality constant. Solving this equation for the proportionality constant yields $a = s/\left[\arctan(L/r)\right]$. For counterclockwise motion $a = 705.5$ and for clockwise motion $a = 703.1$. Use the average 704.3.