Vehicle Validation using PSAT/Autonomie

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Argonne National Laboratory
Outline

- Validation Process
- Light Duty
  - Conventional Vehicles
  - Mild Hybrids
  - Full Hybrids
  - Plug-in Hybrids
- Heavy Duty
  - Line Haul Class 8
  - Additional Classes
Generic Methodology: From Test to Validation

1- Import Test Data into PSAT
2- Individual Sensor Evaluation
3- Sensor Comparison
4- Calculate Effort/Flow From Sensors
5- Sensor & Calculation Comparison
6- Control Strategy
7- Model Validation

Quality Analysis (QA)

Analysis & Validation
Test Data are Renamed, Rescaled and Imported into the same environment as simulation.
Individual Sensor are Evaluated to Find Major Issues (Range, Sign...)

Electric Motor Temperatures

2004 Prius APRF Data
Redundant Sensors are Compared

Direct Fuel Measurement vs. Bench

2004 Prius APRF Data
### Summary Table Highlights the Main Results of the Comparison

<table>
<thead>
<tr>
<th>Component / Range</th>
<th>Compared to... / Range</th>
<th>Absolute Difference</th>
<th>Relative Difference</th>
<th>Correlation Coefficient</th>
</tr>
</thead>
<tbody>
<tr>
<td>Sensor (Dyno Spd Front) / [-0.989912,13.9334] [m/s]</td>
<td>OBD (VEHICLE SPD) / [0.128.0917] [m/s]</td>
<td>71.7453 [m/s]</td>
<td>7.9419 [m/s]</td>
<td>0.99971</td>
</tr>
<tr>
<td>Sensor (Eng Spd 1Ch15) / [-0.32968,3016.4307] [rpm]</td>
<td>OBD (ENGINE SPD) / [0.2976] [rpm]</td>
<td>20.1937 [rpm]</td>
<td>-0.26785 [rpm]</td>
<td>0.99032</td>
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<tr>
<td>Direct Measurement (Fuel) / [-9e-007,0.0016963] [kg/s]</td>
<td>Emission Calculated from density and volume flow / [3.745e-007,0.0019567] [kg/s]</td>
<td>1.0226e-005 [kg/s]</td>
<td>-0.26594 [kg/s]</td>
<td>0.99234</td>
</tr>
<tr>
<td>Boost voltage in(OBD - VL) / [192.238] [volt]</td>
<td>Battery Voltage out(Batt_V_1Ch02) / [198.4637,244.6311] [volt]</td>
<td>7.1356 [volt]</td>
<td>0.032908 [volt]</td>
<td>0.98596</td>
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<tr>
<td>Sensor(Boosted_V_1Ch03) / [206.9615,506.3051] [volt]</td>
<td>OBD(VH) / [204.498] [volt]</td>
<td>3.8596 [volt]</td>
<td>-0.915229 [volt]</td>
<td>0.90283</td>
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</tbody>
</table>
Additional Efforts/Flows are Calculated
Calculated and Measured Signals are Compared

2004 Prius APRF Data
Using Sensors from Different Sources may Lead to Added Uncertainties

Planetary Gear Equation Reveals Problem during Transients (different sampling rate, delay…)

2004 Prius APRF Data
Data Quality Analysis

21-Nov-2005 15:07:01

Abstract

The intent of this report is to assess the data quality of the Prius 2004 vehicle test data performed at Argonne National Laboratory Advanced Powertrain Research Facility (APRF).

Table of Contents

1. Introduction
2. QA Level 1 - Individual Sensor Evaluation
   - Driver
   - Engine
   - Motor Controller 1
   - Motor Controller 2
   - Energy Storage System
electrical Accessory
   - Wheel
   - Vehicle
3. QA Level 2 - Sensor Comparison
   - Vehicle
   - Engine
   - Driver
Parameters are Selected Based on Detailed QA

• Signals with low correlation coefficients or that appeared suspicious from the visual check are scrutinized.
• Sensors installed by test engineers are preferred to OBD or dynamometer signals.
• Ensure consistency in the mathematical relationships.
• Signals from the OBD were not recognized (issue with units or with meaning).
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  - Additional Classes
<table>
<thead>
<tr>
<th>Vehicle</th>
<th>Source</th>
<th>UDDS PSAT (mpg)</th>
<th>HWFET PSAT (mpg)</th>
<th>UDDS Adjusted (mpg)</th>
<th>HWFET Adjusted (mpg)</th>
<th>UDDS Delta EPA (%)</th>
<th>HWFET Delta EPA (%)</th>
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</thead>
<tbody>
<tr>
<td>Civic DX</td>
<td>EPA</td>
<td>29.00</td>
<td>38.00</td>
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<tr>
<td></td>
<td>Adjusted Values</td>
<td>34.62</td>
<td>49.35</td>
<td>31.16</td>
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<td>1.3</td>
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<td>Focus ZTW auto</td>
<td>EPA</td>
<td>25.00</td>
<td>31.00</td>
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<td>24.70</td>
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<td>-1.2</td>
<td>-1.7</td>
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<td>EPA</td>
<td>24.00</td>
<td>34.00</td>
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<td></td>
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<tr>
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<td>Adjusted Values</td>
<td>27.62</td>
<td>44.09</td>
<td>24.86</td>
<td>34.39</td>
<td>3.6</td>
<td>1.1</td>
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<td>Taurus</td>
<td>EPA</td>
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<td>27.00</td>
<td></td>
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<tr>
<td></td>
<td>Adjusted Values</td>
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<td>39.01</td>
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<td>Equinox</td>
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<td>25.00</td>
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<td>-0.2</td>
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<td>F150</td>
<td>EPA</td>
<td>15.00</td>
<td>19.00</td>
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<td></td>
<td>Adjusted Values</td>
<td>17.63</td>
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<td>15.87</td>
<td>20.15</td>
<td>5.8</td>
<td>6.0</td>
</tr>
</tbody>
</table>

Vehicle test data was not available except for the Equinox
Outline

- Validation Process
- Light Duty
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  - Full Hybrids
  - Plug-in Hybrids
- Heavy Duty
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  - Additional Classes
Ford P2000 Validation Results

<table>
<thead>
<tr>
<th>Cycle</th>
<th>Cons test mpg</th>
<th>Cons simul mpg</th>
<th>Diff in %</th>
<th>SOC init</th>
<th>SOCf test</th>
<th>SOCf simul</th>
<th>Diff in %</th>
</tr>
</thead>
<tbody>
<tr>
<td>Japan 10-15</td>
<td>50.31</td>
<td>51.77</td>
<td>2.91</td>
<td>73</td>
<td>74</td>
<td>75</td>
<td>1.35</td>
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<tr>
<td>NEDC</td>
<td>52.45</td>
<td>52.89</td>
<td>0.85</td>
<td>74</td>
<td>76</td>
<td>77.5</td>
<td>1.97</td>
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</tbody>
</table>

Fuel Rate Comparison on NEDC
Honda Insight Validation

Motor used to compensate 12V load
Honda Insight Validation

Japan 10-15
Honda Insight Validation

Japan 10-15 SOC Comparison

![Graph showing measured and simulated SOC over time.](image-url)
## Honda Insight Validation Results

<table>
<thead>
<tr>
<th>Cycle</th>
<th>Cons test mpg</th>
<th>Cons simul mpg</th>
<th>Diff in %</th>
<th>SOC init</th>
<th>SOCf test</th>
<th>SOCf simul</th>
<th>Diff in %</th>
</tr>
</thead>
<tbody>
<tr>
<td>Japan 10-15</td>
<td>57.9</td>
<td>58.8</td>
<td>1.5</td>
<td>0.596</td>
<td>0.610</td>
<td>0.611</td>
<td>0.4</td>
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<tr>
<td>NEDC</td>
<td>60.6</td>
<td>60.2</td>
<td>0.6</td>
<td>0.600</td>
<td>0.602</td>
<td>0.583</td>
<td>3.6</td>
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<tr>
<td>HWFET</td>
<td>74.2</td>
<td>75.3</td>
<td>1.4</td>
<td>0.590</td>
<td>0.588</td>
<td>0.589</td>
<td>0.2</td>
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<td>UDDS</td>
<td>58.3</td>
<td>57.8</td>
<td>0.8</td>
<td>0.728</td>
<td>0.706</td>
<td>0.720</td>
<td>2.0</td>
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</tbody>
</table>
Outline

- Validation Process
- **Light Duty**
  - Conventional Vehicles
  - Mild Hybrids
  - Full Hybrids
  - Plug-in Hybrids
- **Heavy Duty**
  - Line Haul Class 8
  - Additional Classes
GM Precept Correlation

Combined

Test/Simulated Consumptions: 79.6 / 76 mpg

Small SOC difference in Simulation
Japan Prius Validation

![Engine Speed Graph](image)

- Engine Speed
- Rd/s
- Engine Torque
- Nm

- Measured
- Simulated
## Japan Prius Validation Results

<table>
<thead>
<tr>
<th>Cycle</th>
<th>Cons test mpg</th>
<th>Cons simul mpg</th>
<th>Diff in %</th>
<th>SOC init</th>
<th>SOCf test</th>
<th>SOCf simul</th>
<th>Diff in %</th>
</tr>
</thead>
<tbody>
<tr>
<td>Japan 10-15</td>
<td>44.9</td>
<td>45.1</td>
<td>0.4</td>
<td>0.600</td>
<td>0.580</td>
<td>0.583</td>
<td>0.5</td>
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<tr>
<td>Japan 10-15</td>
<td>48.8</td>
<td>50.7</td>
<td>3.9</td>
<td>0.610</td>
<td>0.575</td>
<td>0.561</td>
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<tr>
<td>EUDC</td>
<td>44.0</td>
<td>43.8</td>
<td>0.4</td>
<td>0.610</td>
<td>0.605</td>
<td>0.593</td>
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<tr>
<td>HWFET</td>
<td>48.2</td>
<td>46.7</td>
<td>3.2</td>
<td>0.550</td>
<td>0.571</td>
<td>0.573</td>
<td>0.3</td>
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</tbody>
</table>
2004 Prius - Boost Converter Output Voltage Follows Test Trends

Boost Converter Output

![Graph showing boost converter output voltage trends over time with measurement and simulation data.](image-url)
2004 Prius - Example of SOC Comparison with Final Model

Battery SOC

SOC

0.55
0.6
0.65
0.7
0.75
0.8

Simu
Meas

time (sec)

0
500
1000
1500
2000
2500
3000

UDDS Cycle
## 2004 Prius Fuel Economy Comparison

<table>
<thead>
<tr>
<th>Drive Cycle</th>
<th>APRF Test(^{(1)})</th>
<th>PSAT</th>
</tr>
</thead>
<tbody>
<tr>
<td>UDDS</td>
<td>71</td>
<td>73</td>
</tr>
<tr>
<td>HWFET</td>
<td>67</td>
<td>66.2</td>
</tr>
<tr>
<td>US06</td>
<td>42</td>
<td>45.3</td>
</tr>
<tr>
<td>Japan1015</td>
<td>75</td>
<td>78.1</td>
</tr>
<tr>
<td>NEDC</td>
<td>69</td>
<td>68.5</td>
</tr>
</tbody>
</table>

\(^{(1)}\) Several averaged test results
Outline

- Validation Process
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  - Additional Classes
Plug-in Prius Hymotion - Vehicle Configuration and Specification

<table>
<thead>
<tr>
<th></th>
<th>Value</th>
</tr>
</thead>
<tbody>
<tr>
<td>Vehicle Mass</td>
<td>1586 kg</td>
</tr>
<tr>
<td>High Capacity Battery</td>
<td>5 kWh, Li-ion</td>
</tr>
<tr>
<td>A, B, C (SI Unit)</td>
<td>88.6, 0.14, 0.36</td>
</tr>
<tr>
<td>Test of date</td>
<td>10/30/2006</td>
</tr>
</tbody>
</table>

**Low Capacity Battery**

**Prius** 1.3 kWh NiMH 230 VDC Battery Pack

**High Capacity Battery**

**Hymotion 5kWh System**

- Power Converter to 230VDC
- 115 VDC Li-Ion
Engine Torque Comparison

UDDS

Copyright PSAT 6.1
High Capacity Battery Power
## Charge Depleting Mode Comparison - UDDS

<table>
<thead>
<tr>
<th></th>
<th>Unit</th>
<th>Test</th>
<th>Simulation</th>
<th>Absolute Difference</th>
<th>Relative Difference</th>
</tr>
</thead>
<tbody>
<tr>
<td>Fuel Economy</td>
<td>mile/gallon</td>
<td>176.7</td>
<td>192.3</td>
<td>15.2</td>
<td>8.8%</td>
</tr>
<tr>
<td>Elec. Consumption</td>
<td>Wh/km</td>
<td>86.3</td>
<td>83.8</td>
<td>2.5</td>
<td>2.8%</td>
</tr>
<tr>
<td>SOC Init</td>
<td>%</td>
<td>62</td>
<td>62</td>
<td>0</td>
<td>0</td>
</tr>
<tr>
<td>SOC Final</td>
<td>%</td>
<td>62</td>
<td>62.8</td>
<td>0.8</td>
<td>1.3%</td>
</tr>
<tr>
<td>System Efficiency</td>
<td>%</td>
<td>56.0</td>
<td>55.2</td>
<td>0.8</td>
<td>1.4%</td>
</tr>
</tbody>
</table>
# Charge Sustaining Mode Comparison - UDDS

<table>
<thead>
<tr>
<th></th>
<th>Unit</th>
<th>Test</th>
<th>Simulation</th>
<th>Absolute Difference</th>
<th>Relative Difference</th>
</tr>
</thead>
<tbody>
<tr>
<td><strong>Fuel Economy</strong></td>
<td>mile/gallon</td>
<td>64.5</td>
<td>65.6</td>
<td>1.1</td>
<td>1.7%</td>
</tr>
<tr>
<td><strong>SOC Init</strong></td>
<td>%</td>
<td>62</td>
<td>62</td>
<td>0</td>
<td>0</td>
</tr>
<tr>
<td><strong>SOC Final</strong></td>
<td>%</td>
<td>62</td>
<td>61.8</td>
<td>0.2</td>
<td>0.3%</td>
</tr>
<tr>
<td><strong>System Efficiency</strong></td>
<td>%</td>
<td>41.6</td>
<td>39.1</td>
<td>2.5</td>
<td>6%</td>
</tr>
</tbody>
</table>

Test 60610106
Outline

- Validation Process
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  - Line Haul Class 8
    - Peterbuilt Truck w/ West Virginia
    - Navistar Truck w/EPA
  - Additional Classes
PSAT Validation: Details of Tractor Truck Data from Chassis Dynamometer Tests and On-Road Tests

Vehicle Model Year | 1996
Test weight (lb.) | 56000
Odometer Reading | 441097
Transmission Type | Manual
Transmission Model | RTLO 20918, 18 speed
Engine Type | Caterpillar 3406E
Engine Model Year | 1996
Engine Disp. (Liter) | 14.6
Number of Cylinders | 6

UDDS Used for Chassis Dynamometer Testing
Modeling and Validation of Peterbilt Truck

Component data development

- Engine map
- Auxiliary loads, including fan load.
- Vehicle losses developed to match chassis dynamometer.
- The transmission ratios and efficiencies were documented.

- This vehicle was also simulated on a road route, PA43, as well as chassis dynamometer cycles.
Comparison of Actual and Predicted Results

On-road result variability can be attributed in part to lack of knowledge of real rolling resistance and aerodynamic factors. For the chassis UDDS these factors were known.

PSAT Validation With Chassis (Test weight 56000 lb)

<table>
<thead>
<tr>
<th>Parameters</th>
<th>Measured</th>
<th>PSAT Simu.</th>
<th>Relative % Error</th>
</tr>
</thead>
<tbody>
<tr>
<td>UDDS Cycle (mile)</td>
<td>5.44</td>
<td>5.37</td>
<td>1.29</td>
</tr>
<tr>
<td>Fuel Econ. (MPG)</td>
<td>3.82</td>
<td>3.82</td>
<td>0.00</td>
</tr>
<tr>
<td>Fuel Mass (kg)</td>
<td>4.58</td>
<td>4.52</td>
<td>1.31</td>
</tr>
<tr>
<td>Eng. Fuel Rate (g/s)</td>
<td>4.40</td>
<td>4.30</td>
<td>1.27</td>
</tr>
<tr>
<td>CO₂ (g/mile)</td>
<td>2639.8</td>
<td>2685.5</td>
<td>-1.73</td>
</tr>
</tbody>
</table>

PSAT On-road Test Results (Test weight 79700 lb)

<table>
<thead>
<tr>
<th>Parameters</th>
<th>Measured</th>
<th>PSAT Simu.</th>
<th>Relative % Error</th>
</tr>
</thead>
<tbody>
<tr>
<td>P 43 Route (mile)</td>
<td>19.54</td>
<td>19.44</td>
<td>0.61</td>
</tr>
<tr>
<td>Fuel Econ. (MPG)</td>
<td>4.26</td>
<td>4.20</td>
<td>1.41</td>
</tr>
<tr>
<td>Fuel Mass (kg)</td>
<td>14.42</td>
<td>14.88</td>
<td>-3.19</td>
</tr>
<tr>
<td>Eng. Fuel Rate (g/s)</td>
<td>9.40</td>
<td>9.80</td>
<td>-4.26</td>
</tr>
<tr>
<td>CO₂ (g/mile)</td>
<td>2180.7</td>
<td>2445.4</td>
<td>-12.13</td>
</tr>
</tbody>
</table>

*Note: Engine fuel rate, engine torque, engine speed, engine power and vehicle speed are all average values
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    - Peterbuilt Truck w/ West Virginia
    - Navistar Truck w/EPA
  - Additional Classes
### Truck Specifications

- A Navistar Prostar line haul class 8 truck was tested at SWRI by EPA

<table>
<thead>
<tr>
<th>Year model</th>
<th>2008</th>
</tr>
</thead>
<tbody>
<tr>
<td>Mass</td>
<td>31203.6 kg</td>
</tr>
<tr>
<td>Gearbox</td>
<td>10 Speed Eaton Fuller FRM-15210B</td>
</tr>
<tr>
<td>Engine</td>
<td>Cummins ISX ST400</td>
</tr>
<tr>
<td>Final Drive</td>
<td>Arvin Meritor RT-40-145 (ratio 2.64)</td>
</tr>
</tbody>
</table>

- 3 Drive Cycle traces corresponding to the CARB cycles were used

![Graphs showing various drive cycles](image-url)
The graphs illustrate the comparison between simulation and test results for Trace and Gear number during Cycle 5D.

- **Trace and gear number are very close for all cycles.**
- **Main differences come from the test truck which does not follow the trace very closely.**

The graphs show:

- **Simulation truck is able to start in 2nd or 3rd gear.**
- **Neutral requested early for Test Truck.**
- **Test overshoots the Target.**
HHDDT Cruise (Cycle 7D) - Engine Speed & Fuel Rate

Cycle 7D

Engine Speed (rad/s)

Fuel Rate

Simulation
Test
Fuel Consumption Comparison Using One Test Iteration

<table>
<thead>
<tr>
<th></th>
<th>Cycle 5D Test</th>
<th>Cycle 5D Simu</th>
<th>Cycle 7D Test</th>
<th>Cycle 7D Simu</th>
<th>Cycle 8D Test</th>
<th>Cycle 8D Simu</th>
</tr>
</thead>
<tbody>
<tr>
<td>Distance (miles)</td>
<td>11.92</td>
<td>11.68</td>
<td>45.27</td>
<td>46.12</td>
<td>41.21</td>
<td>42</td>
</tr>
<tr>
<td>Fuel Economy (mpg)</td>
<td>3.69</td>
<td>3.89</td>
<td>7.67</td>
<td>7.60</td>
<td>6.48</td>
<td>6.3</td>
</tr>
<tr>
<td>Fuel Consumption (gal/100mi)</td>
<td>27.04</td>
<td>25.71</td>
<td>13.04</td>
<td>13.16</td>
<td>15.42</td>
<td>15.87</td>
</tr>
<tr>
<td>Delta Fuel Consumption (Simu vs Test)</td>
<td>-4.91%</td>
<td>+0.91%</td>
<td>+2.92%</td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>Delta Distance (Simu vs Test)</td>
<td>-1.99%</td>
<td>+1.88%</td>
<td>+1.92%</td>
<td></td>
<td></td>
<td></td>
</tr>
</tbody>
</table>

- A positive delta fuel consumption value means the Simulation consumes more than the Test
- A positive Delta distance value means the Simulation travels further than the Test
Comparison with All Test Data

- The histograms show the volume of fuel consumed for the iteration of test recordings selected by EPA (used for fuel consumption calculations in slide 18).
- The black error bar shows the range of fuel volumes for all the test iterations.
- The red cross shows the volume of fuel consumed in simulation.

- For the three cycles, the Simulation is within 5% of the Test fuel consumption which is within the test-to-test repeatability.
- The discrepancy is greater for the low speed transient cycle than for high speed highway cycles.
- During each cycle, the simulation and test trucks did NOT drive the exact same distances and at the same average speed, which most likely explain part of the fuel consumption discrepancies.
Outline

- Validation Process
- Light Duty
  - Conventional Vehicles
  - Mild Hybrids
  - Full Hybrids
  - Plug-in Hybrids
- Heavy Duty
  - Line Haul Class 8
  - Additional Classes
**PSAT Has Been Correlated for Several Additional Vehicle Classes**

Other correlated vehicle classes include, but not limited to:

* Data provided by Herbert Fox (NYIT)