Testing and Analysis of Three Plug-in Hybrid Electric Vehicles

2007-01-0283

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Argonne National Laboratory

SAE 2007 World Congress

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PHEV Testing

Vehicles Tested

- Renault Kangoo
- Hymotion Prius
- EnergyCS Prius

Three PHEV's tested on UDDS and HWY cycles for:

- Fuel Economy
- Emissions
- Electrical Energy Consumption

Renault Kangoo

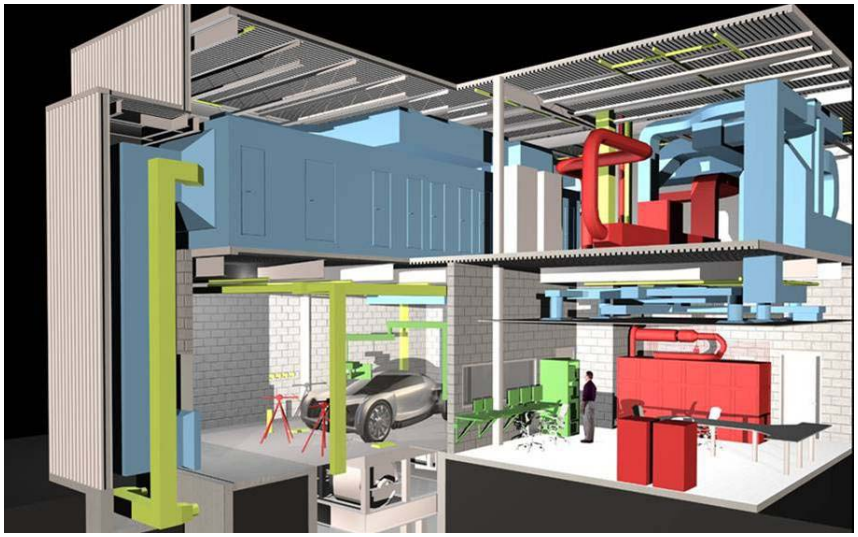
Hymotion Prius

EnergyCS Prius

Chassis Dynamometer Test Facility

Instrumentation

- Burke Porter 4WD Chassis Dynamometer
- Pierburg AMA4000 Emissions Bench
  - Bag and Modal emissions
- National Instruments PXI data acquisition
- Hioki “HiTester” meter
  - Current and Voltage measurement
  - Integrated Ah and kWh



Vehicle Information – Renault Kangoo

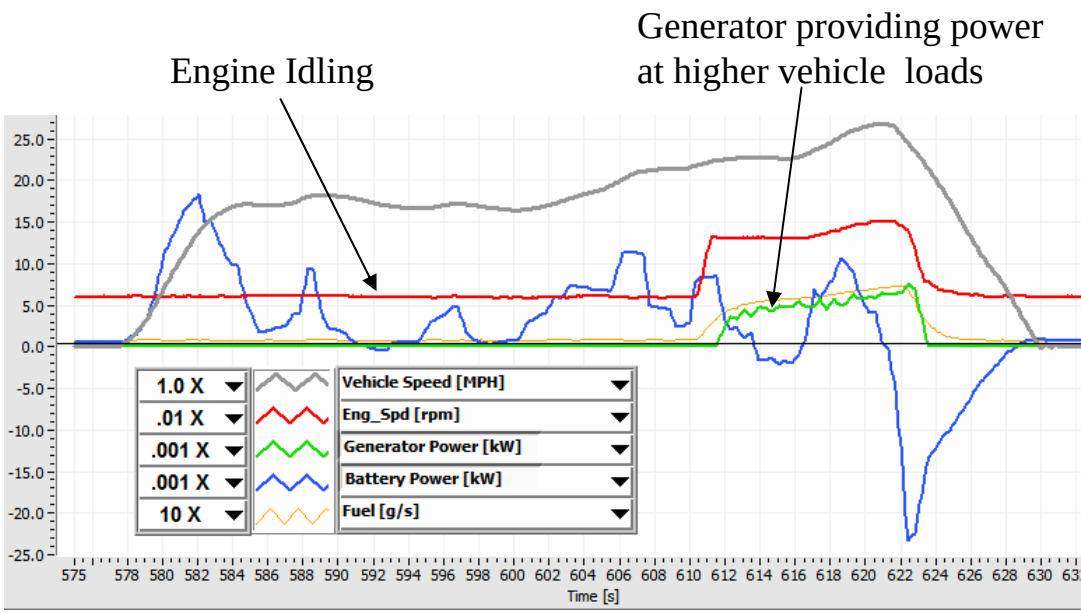
Renault Kangoo – Series PHEV

- 9-kWh NiCd battery pack
- 35-kW electric motor
- Two-cylinder engine/generator set (approx. 15kW)
  - Engine operation is controlled manually by driver
  - Engine/generator only assist battery under high vehicle loads, not used to charge battery pack
- 2 Modes of operation (both are charge depleting)
  - EV mode operation
  - Engine On operation (push-button on dashboard)
    - Battery continues to charge deplete but at a slower rate

Renault Kangoo: Range Extending EV

Not representative of a production PHEV for the North American market

- No charge-sustaining operation
- Manual control system to turn engine on (driver operated, not automatic)



UDDS	EV#1 (Cold)	EV#2 (Hot)	HEV#1 (Cold)	HEV#2 (Hot)
Fuel Economy [mpg]	-	-	42.2	39.3
Elec Consump [DC Wh/mi]	217	217	117	89.2

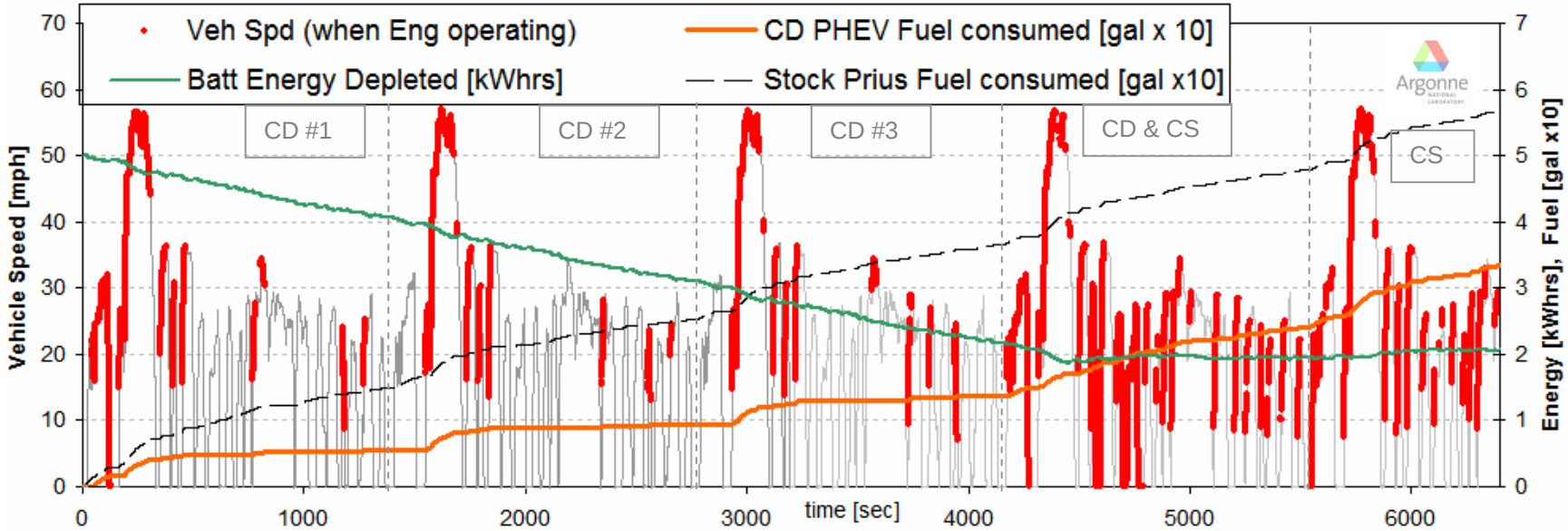
Vehicle information - Hymotion Prius

- 5kWh Li-Ion battery and power converter in parallel with production Prius battery pack
  - Hymotion control system enables charge depletion operation through CAN bus communication and use of the production “EV mode” button
- Charge-depletion operation
  - Single mode of operation
- Charge-Sustaining operation
  - Hymotion system disabled
  - Reverts to production Prius control

Hymotion Prius: UDDS Fuel and Elec. Energy Consumption

Fuel Consumption and Electrical Energy Consumption on UDDS Cycle

- Charge Depleted over three UDDS cycles (approx 25 miles)
- EV operation approx 80% of UDDS cycle time (engine on 20% of time)

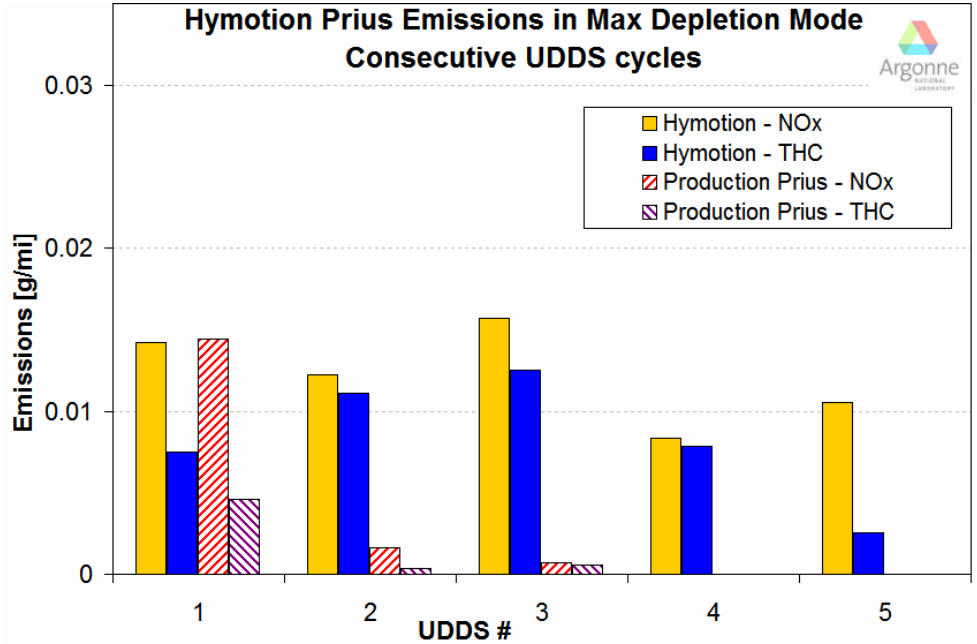


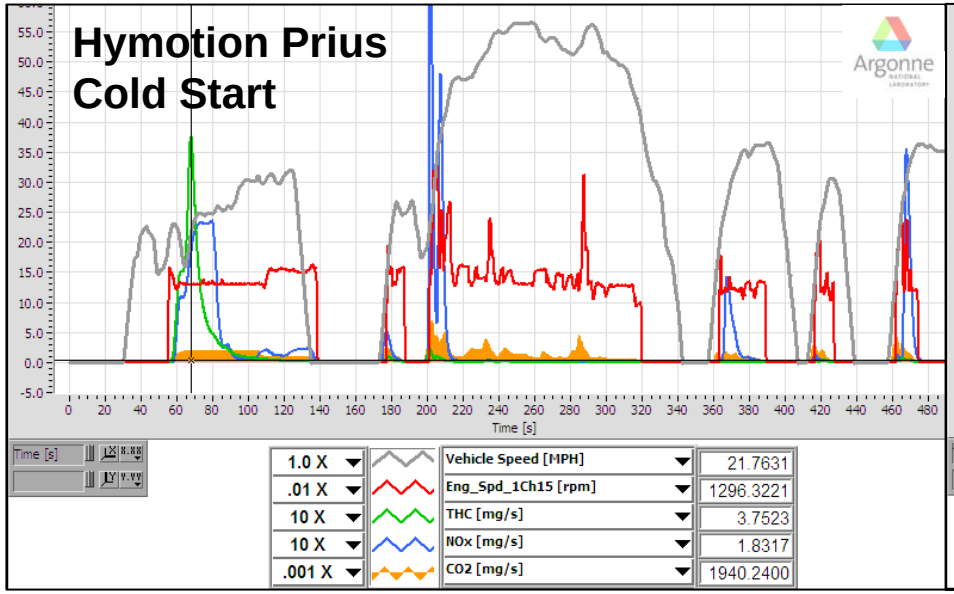
UDDS	#1	#2	#3	#4	#5
Fuel Economy [mpg]	148	200	187	74.3	66.4
Elec Consump [DC Wh/mi]	123	128	125	30.6	-15.9

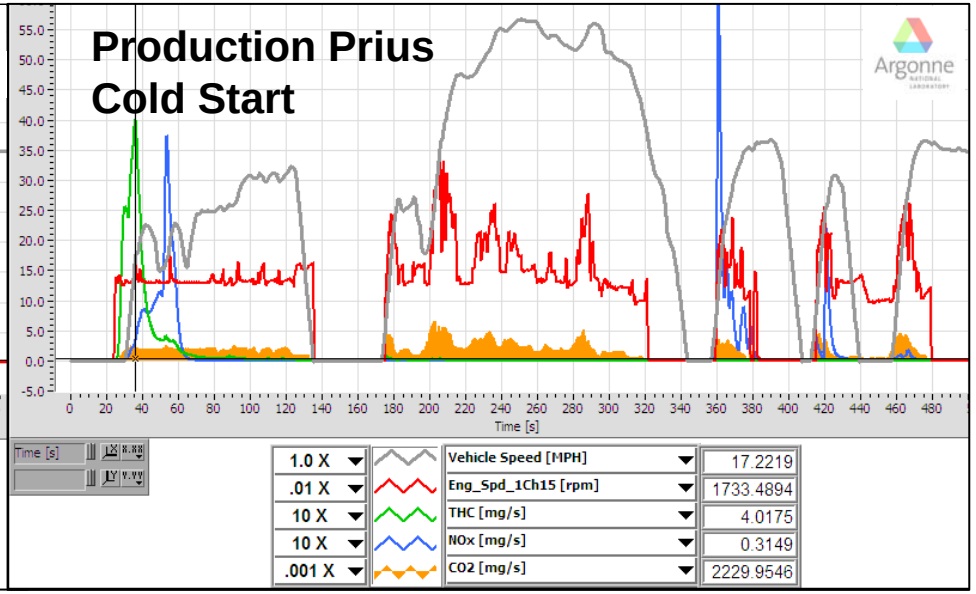
Hymotion Prius: Emissions

Emissions on UDDS Cycle

- Engine operation in 1st hill similar to production Prius
- Following UDDS emissions remain high due to infrequent engine operation



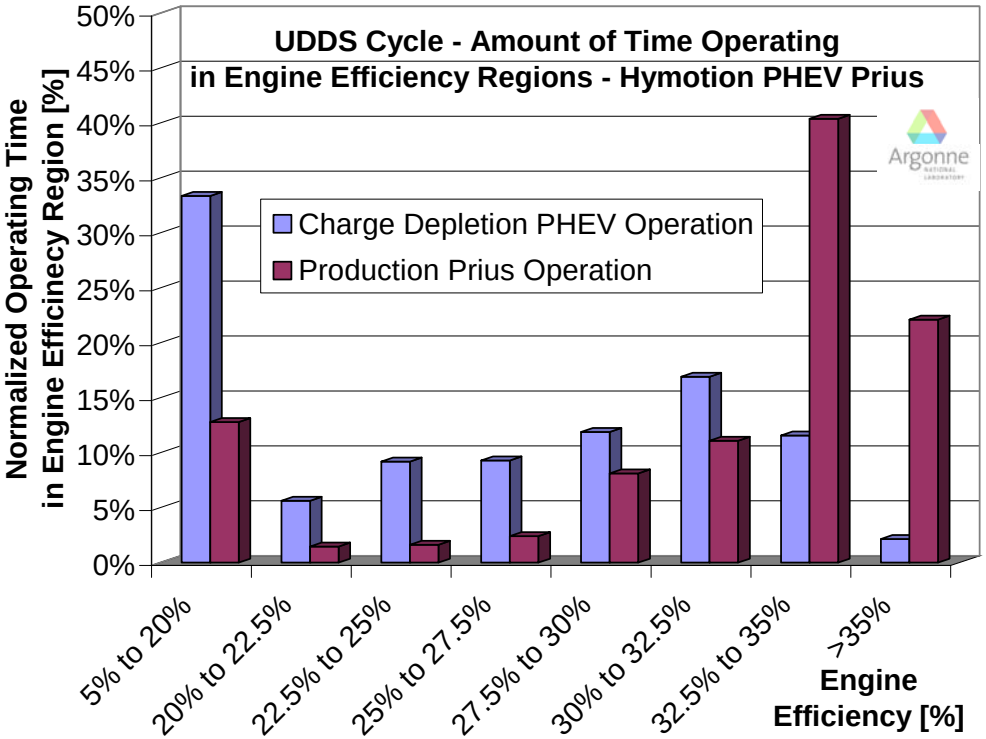


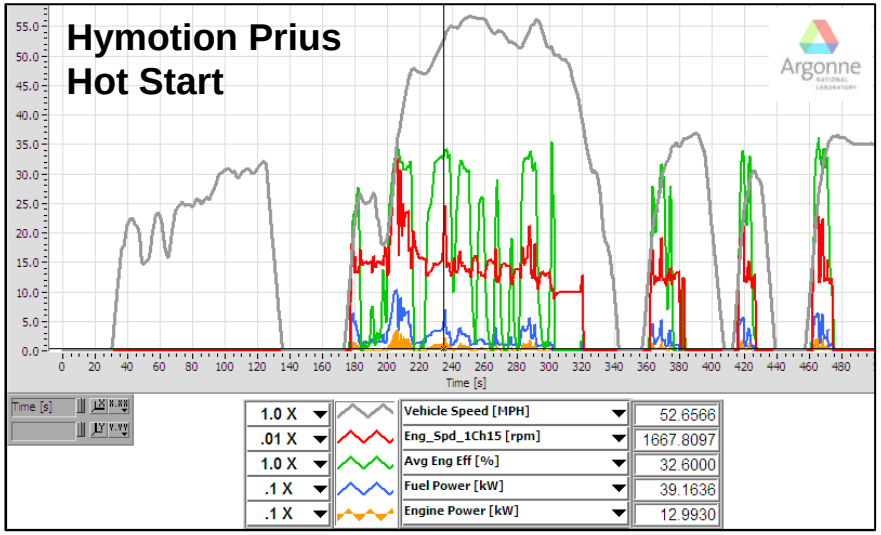


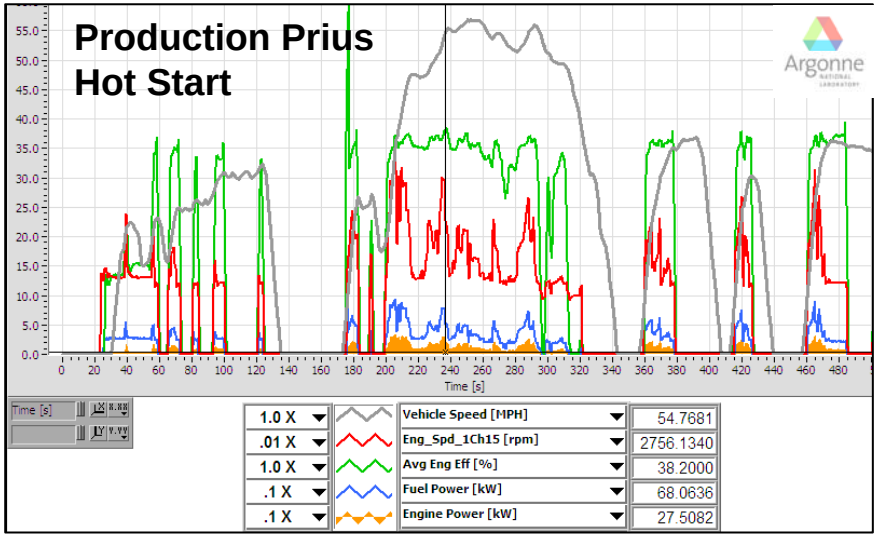
Hymotion Prius: Engine Efficiency

Engine Efficiency on UDDS Cycle

- Engine torque sensor and in-line fuel flow meter used to calculate engine efficiency
- Production Prius engine efficiency is consistently high by charging battery pack during loads (i.e. engine is always at high load)

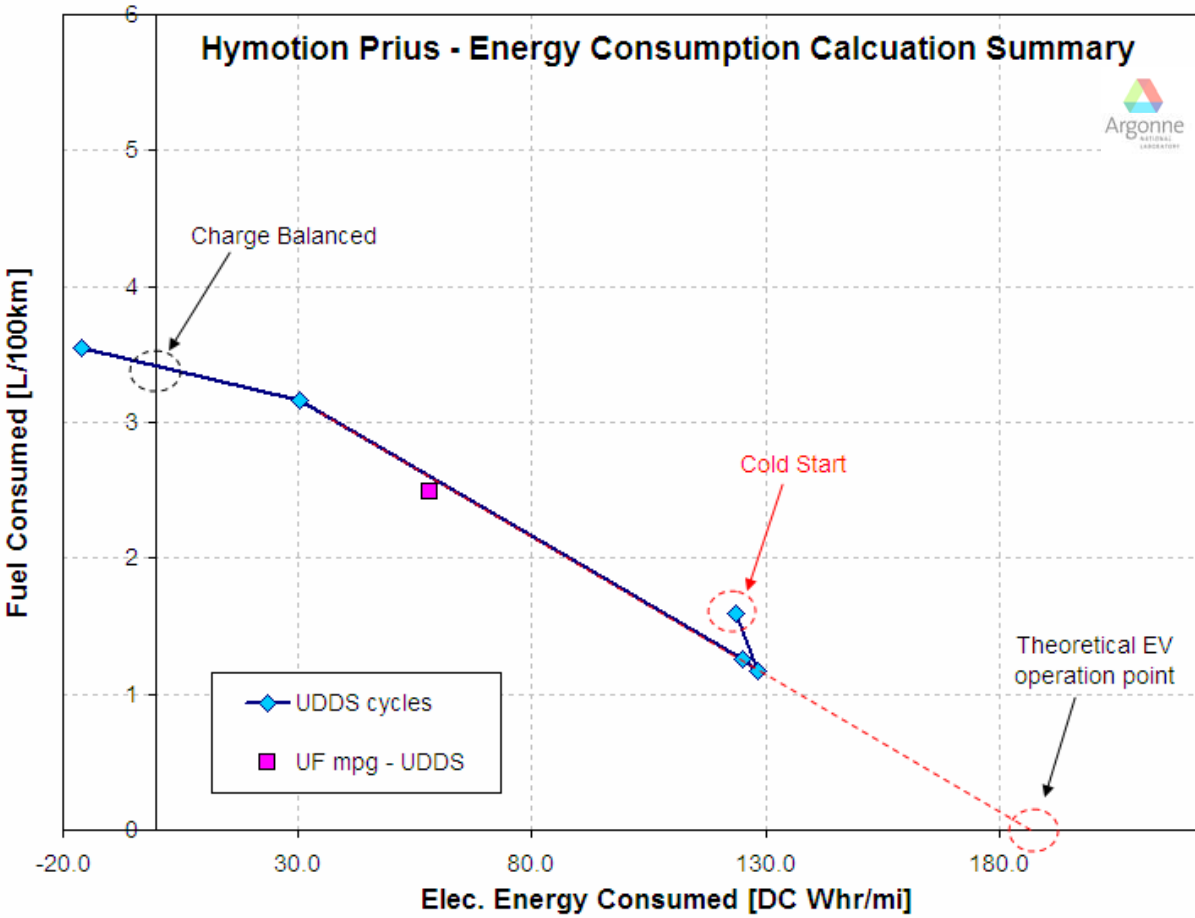






Hymotion Prius: Energy Utilization Plot

- Slope is not constant because engine efficiency is changing
  - increasing engine load from charging more as approaching charge-sustaining operation
- Utility Factor weighted Fuel Economy is calculated in a piece-wise manner

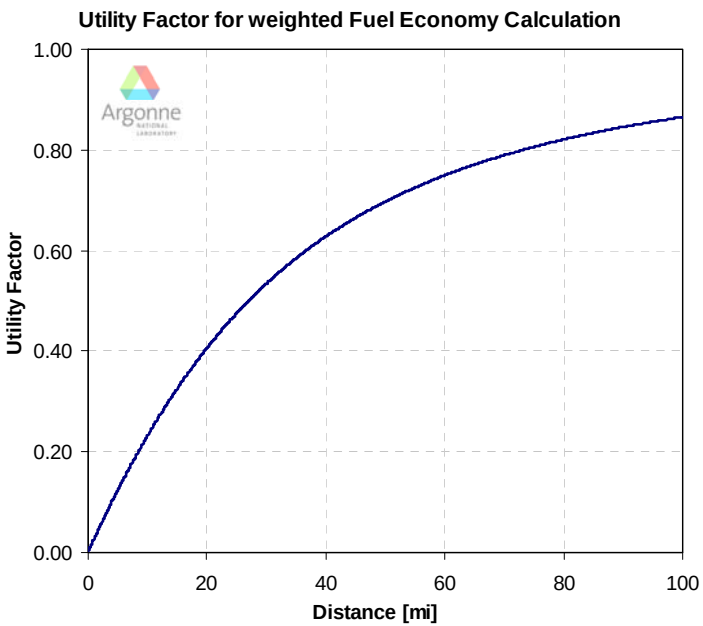


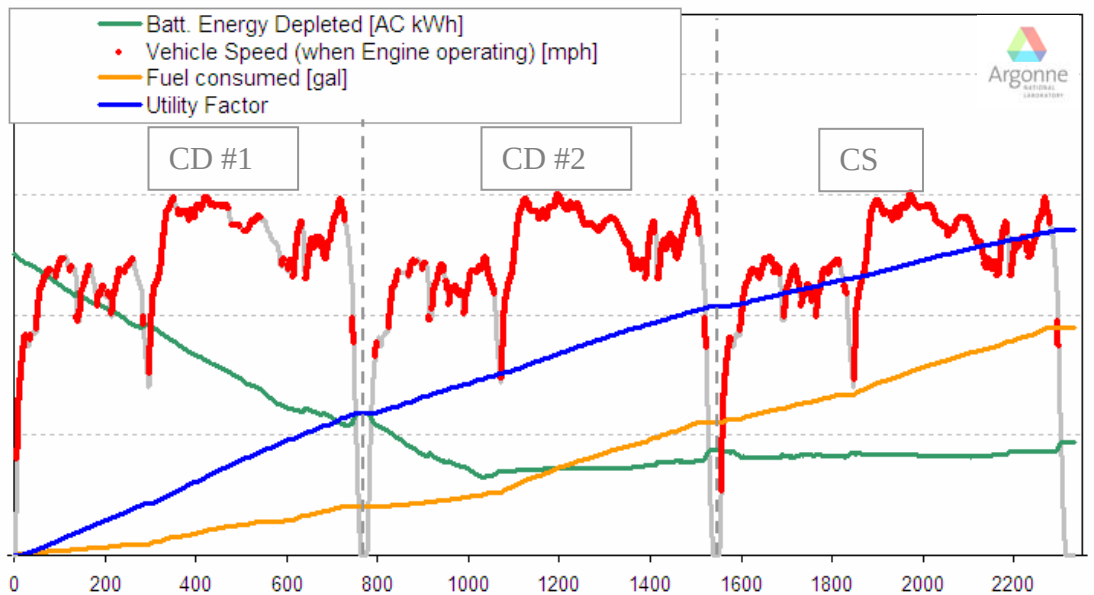
Utility Factor Weighted Fuel Economy and Energy Consumption Calculations

- Each cycle has UF weighting factor
- Charge-sustaining region begins with first full charge-sustaining cycle

$$MPG = \frac{1}{\sum_{i=1}^{maxCD} UF_i \left(1/MPG_{CD} \right)_i + \left(1 - \sum_{i=1}^{maxCD} UF_i \right) \left(1/MPG_{CS} \right)}$$

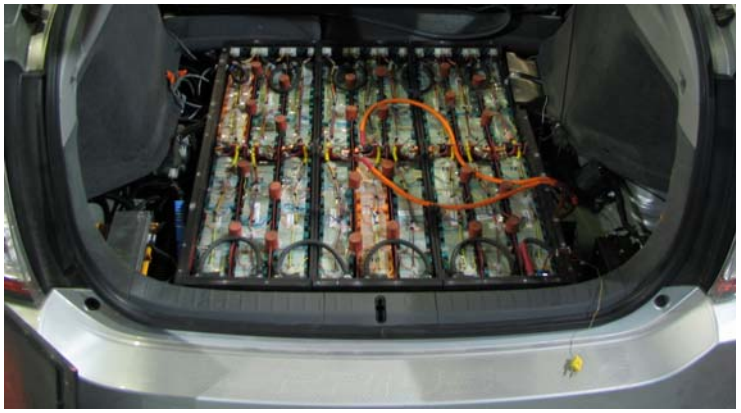
$$\frac{Whrs_{PHEV}}{miles} = \sum_{i=1}^{maxCD} UF_i \left(\frac{Whrs_{CD}}{miles_{CD}} \right)$$





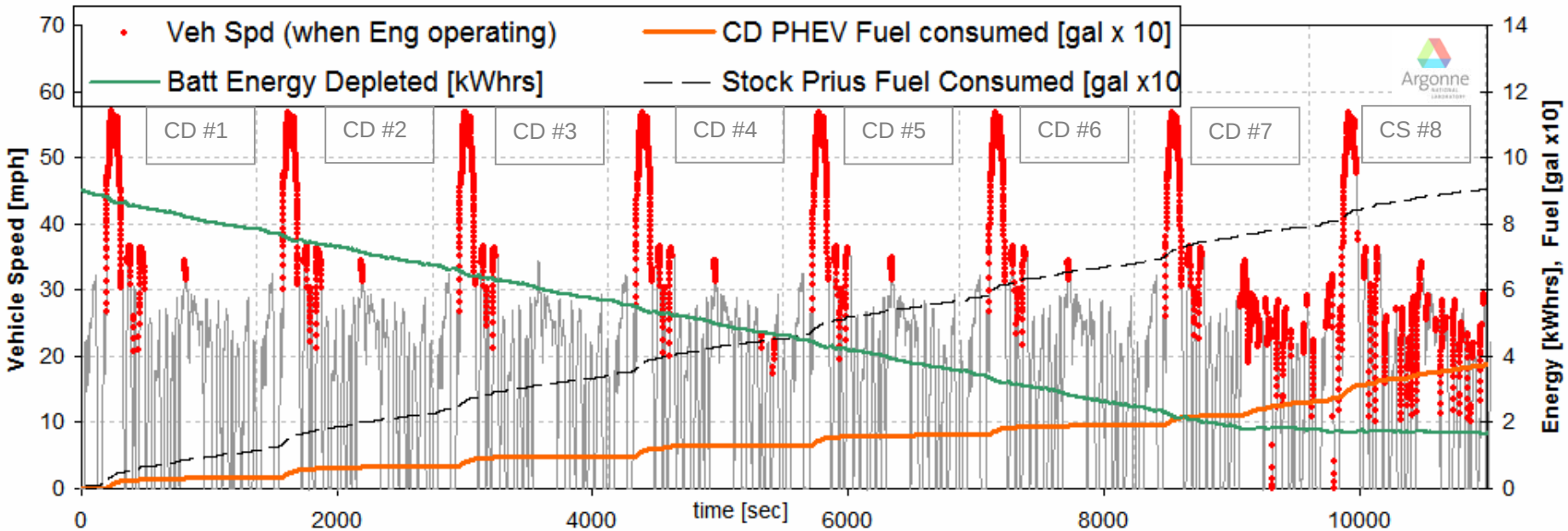
Vehicle Information – EnergyCS Prius

- 9kWh Li-Ion battery replaces production Prius battery pack
- EnergyCS control system enables charge-depletion operation
  - CAN bus communication to Prius Hybrid ECU
  - use of the production “EV mode” button
- Two Modes of Charge Depletion Operation
  - Maximum Charge-Depletion Mode
  - “California” Mode for best emissions



EnergyCS Prius : Max Depletion Mode UDDS Fuel and Elec. Energy Consumption

- Charge Depleted over seven UDDS cycles (approx 50 miles)
- EV operation over 85% of UDDS cycle time (engine on 15% of time)

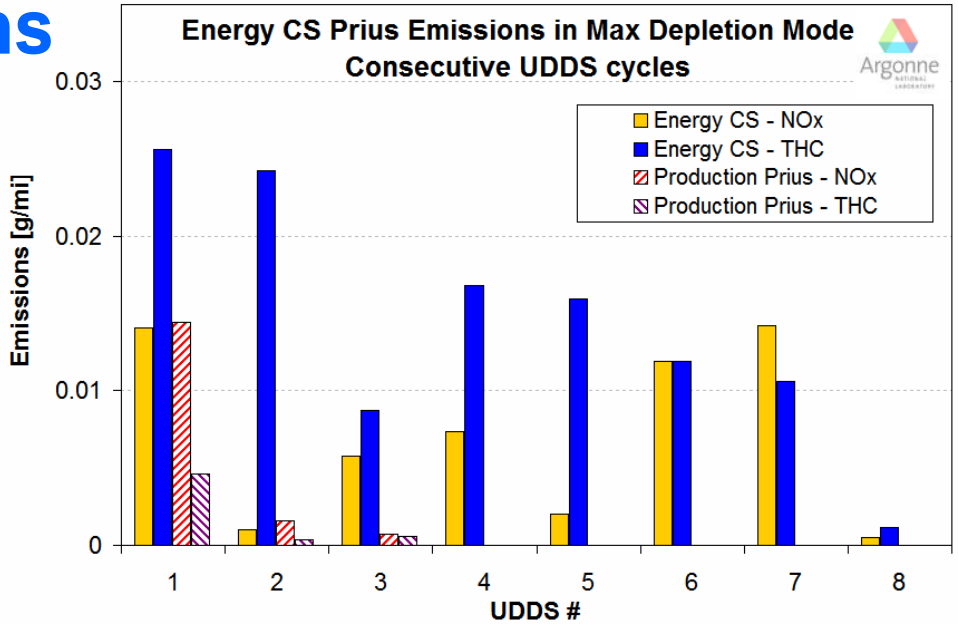


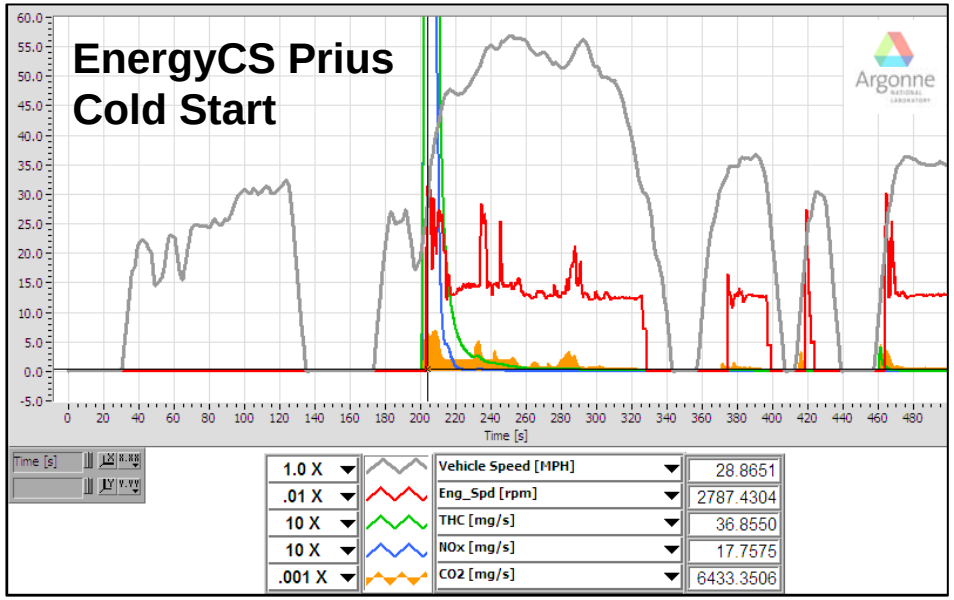
UDDS	#1	#2	#3	#4	#5	#6	#7	#8
Fuel Economy [mpg]	215	221	242	223	240	239	104	69.7
Elec Consump [DC Wh/mi]	159	147	146	143	145	147	92.4	16.6

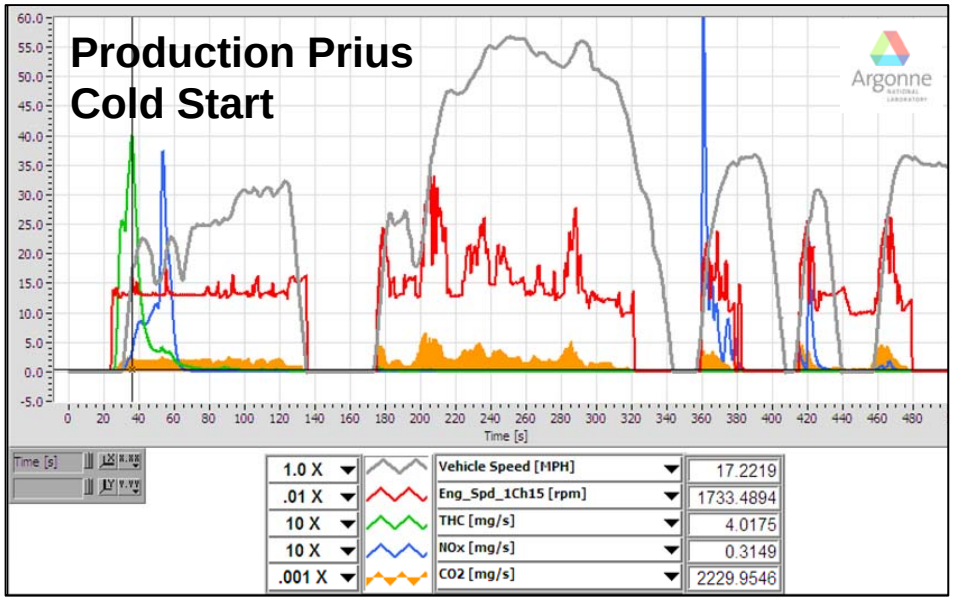
EnergyCS Prius: Emissions Max Depletion Mode

Emissions on UDDS Cycle

- No engine start in 1st hill
- Large emissions spike at first engine start

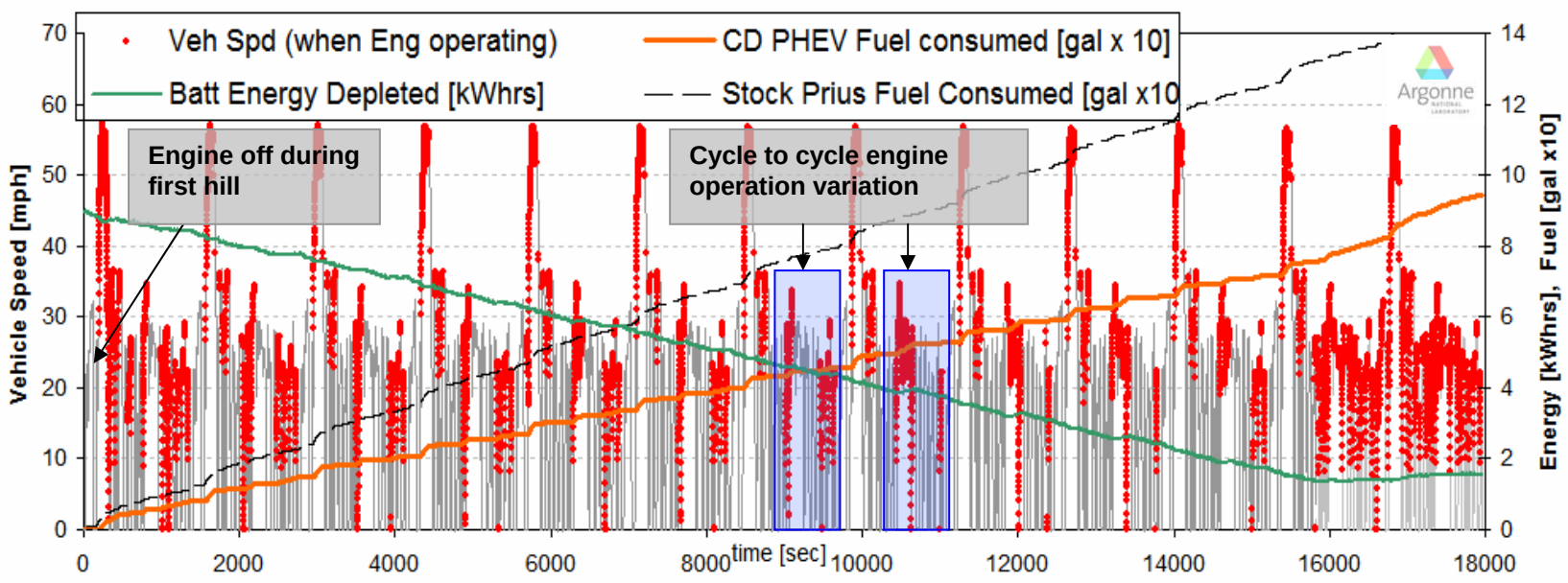






EnergyCS Prius : "California" Mode UDDS Fuel and Elec. Energy Consumption

- Charge Depleted over twelve UDDS cycles (approx 90 miles)
- EV operation over 75% of UDDS cycle time (engine on 25% of time)

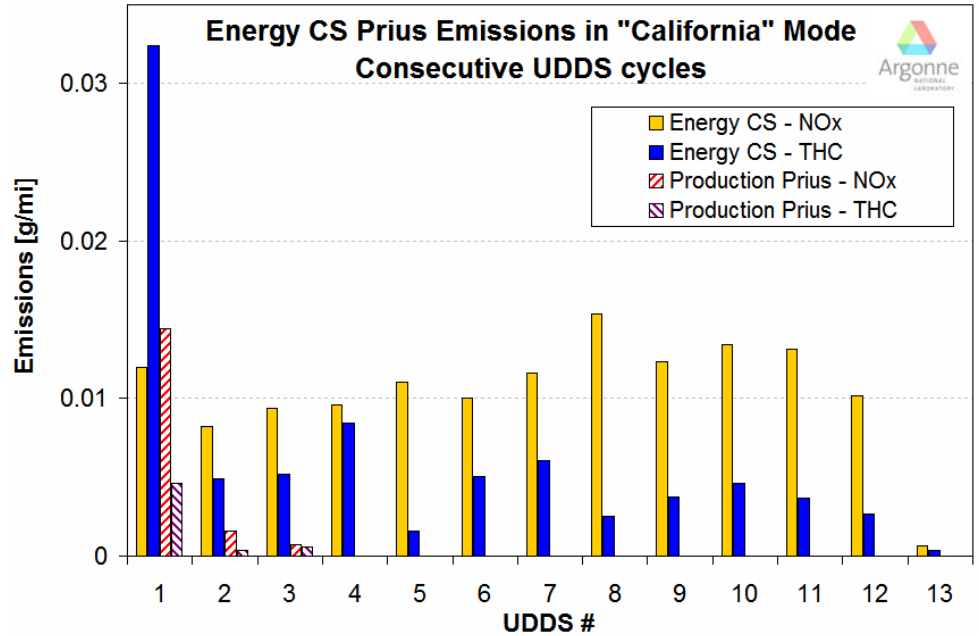


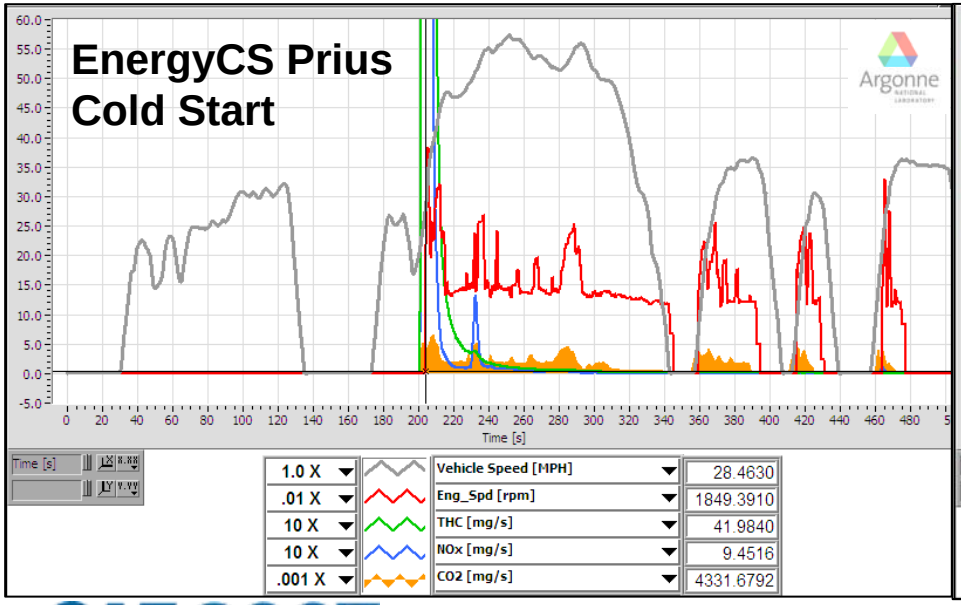
UDDS	#1	#2	#3	#4	#5	#6	#7	#8	#9	#10	#11	#12	#13
Fuel Economy [mpg]	85.8	114	122	128	114	126	122	112	119	117	123	83.7	58.4
Elec Usage [DC Wh/mi]	77.2	88.9	91.9	97.4	86.4	93.6	91.7	85.7	91.6	88.9	92.3	46.2	-18.3

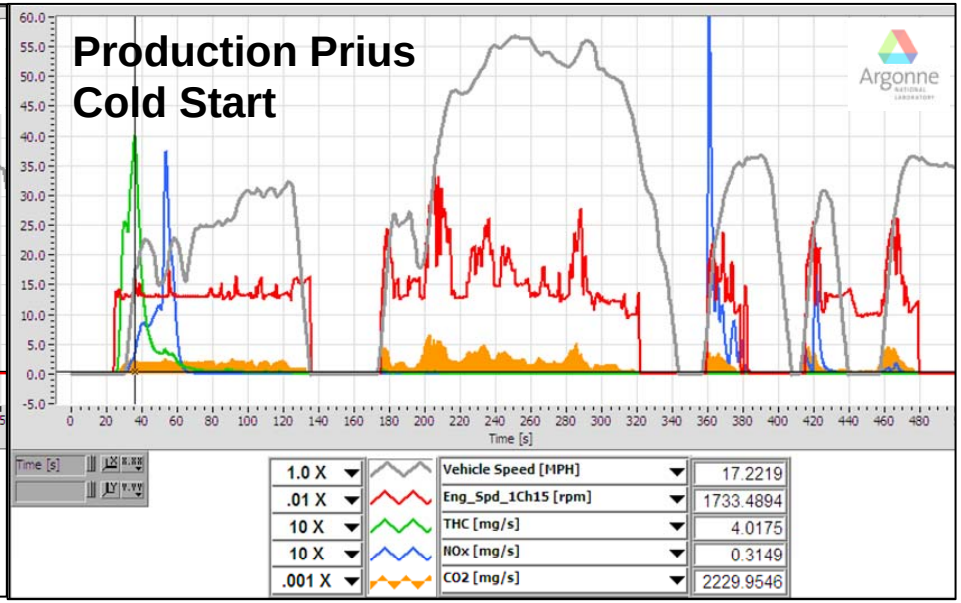
EnergyCS Prius: Emission in "CA Mode"

Emissions on UDDS Cycle

- Engine operation is not as expected
- Large emissions spike at first engine start (similar to Max Depletion Mode)

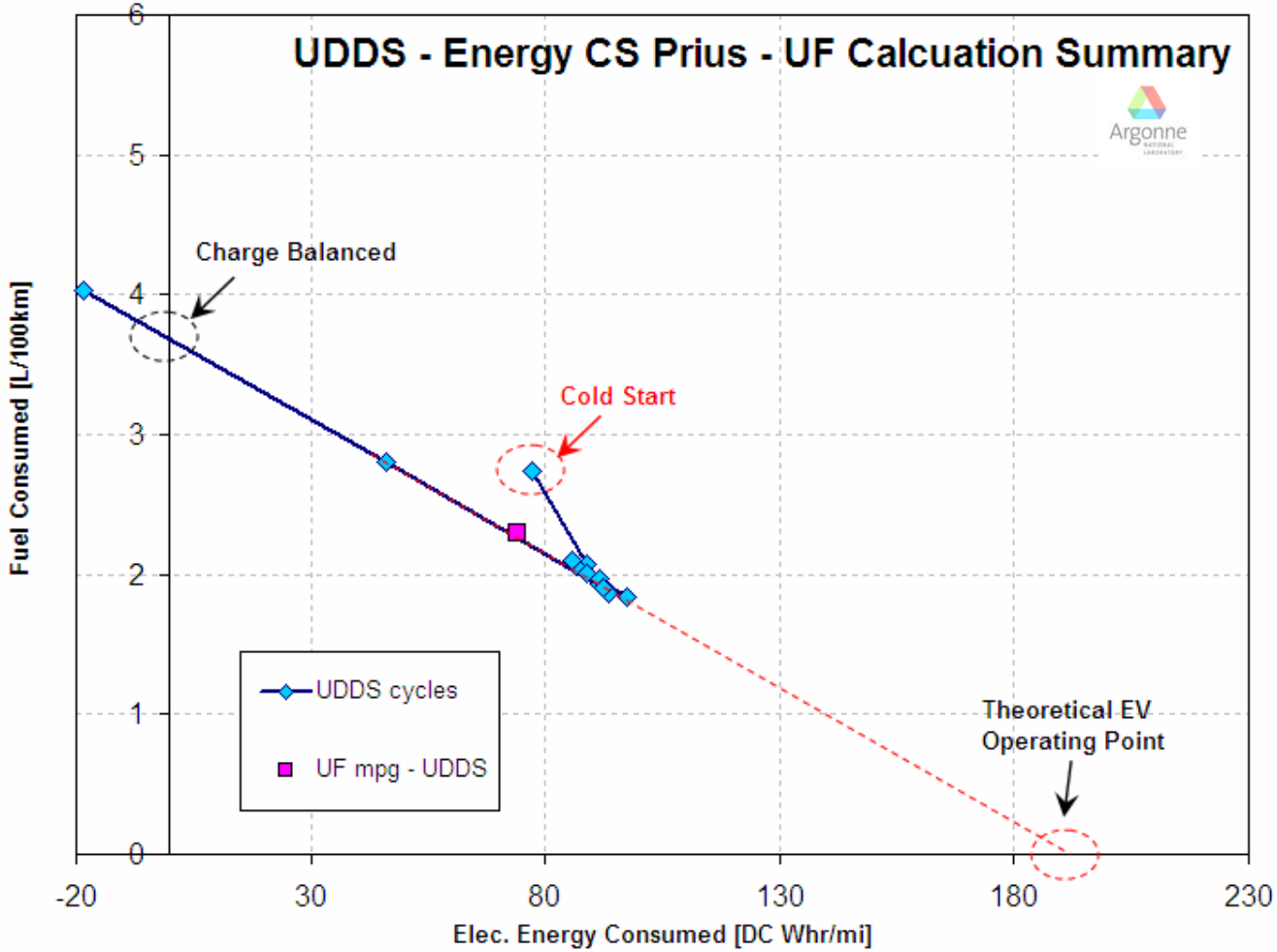






EnergyCS Prius: Energy Utilization

- Slope remains constant at varying rates of depletion unless powertrain system efficiency greatly changes
- Utility Factor weighted Fuel Economy is calculated in a piece-wise manner



Summary

- PHEV's provide significant petroleum displacement (2 to 3 times less petroleum consumed compared to production HEV)
- Emissions controls with PHEV's requires more development and calibration
  - Multiple engine restarts with extended time not operating
  - Catalyst temperature control
  - Controlling engine load and speed during restarts