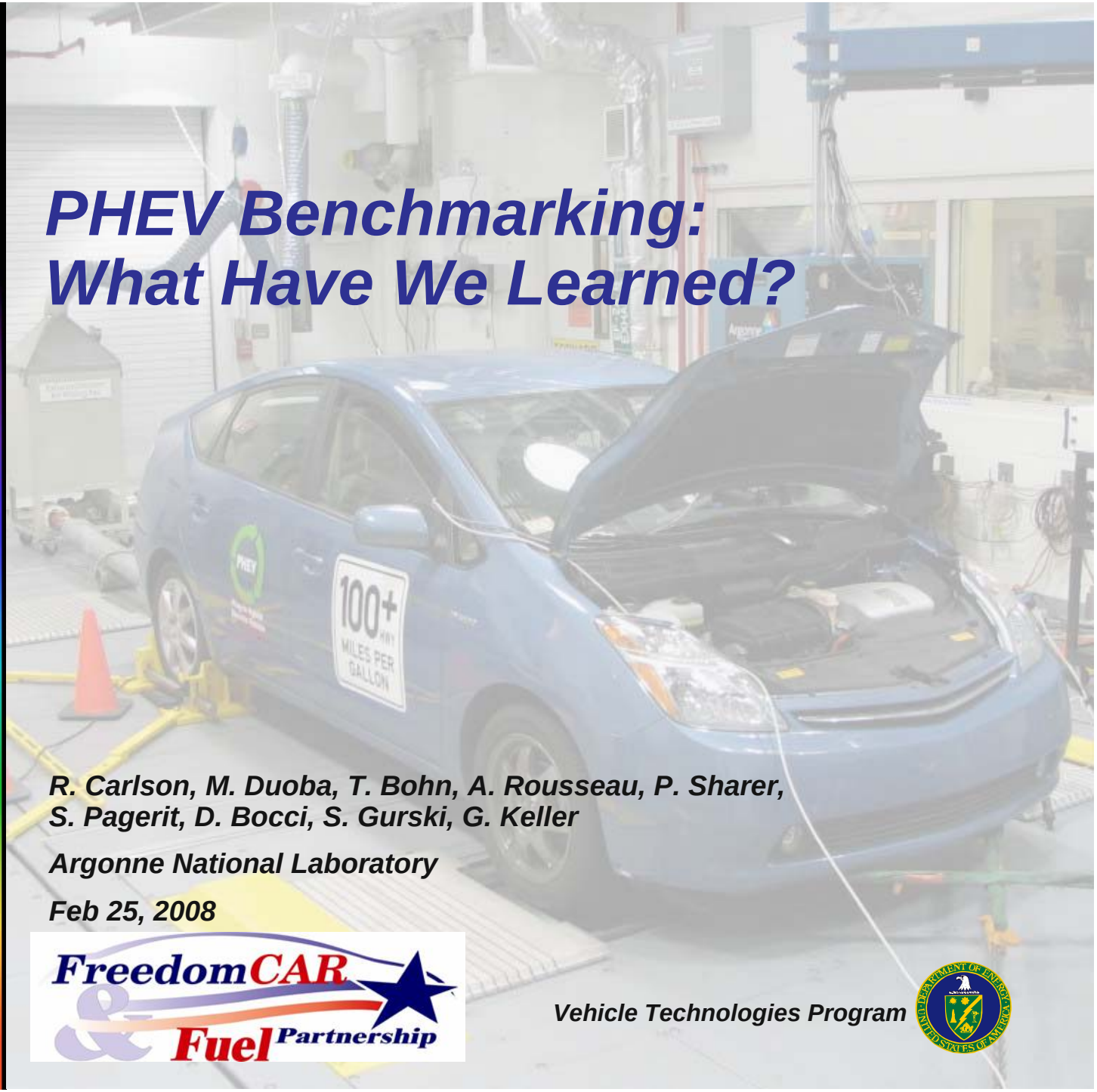
Argonne NATIONAL LABORATORY

… for a brighter future

PHEV Benchmarking: What Have We Learned?



R. Carlson, M. Duoba, T. Bohn, A. Rousseau, P. Sharer, S. Pagerit, D. Bocci, S. Gurski, G. Keller

Argonne National Laboratory

Feb 25, 2008

U.S. Department of Energy

UChicago ▶ Argonne LLC

A U.S. Department of Energy laboratory managed by UChicago Argonne, LLC

FreedomCAR & Fuel Partnership

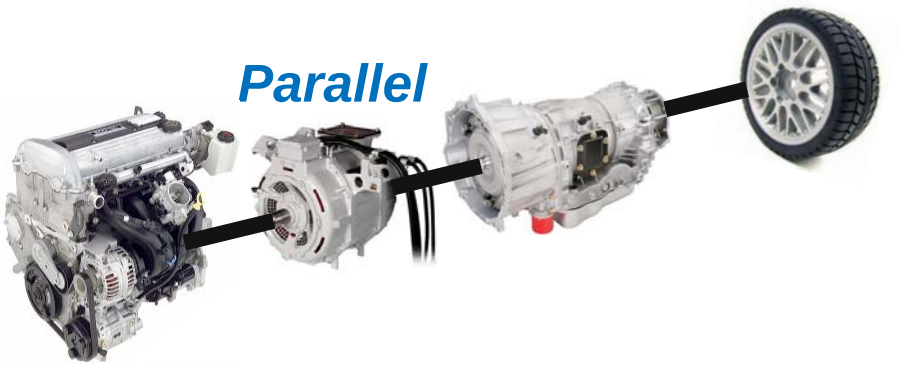
Vehicle Technologies Program

Hybrid Electric Vehicle (HEV)

- Vehicle that contains more than one propulsion Technology
  - Typically an Internal Combustion Engine (ICE) and an Electric Motor (EM)
- Three configurations of HEV's
  - Parallel
  - Series
  - Power-Split
- HEV's reduce fuel consumption by:
  - No engine idle
  - Utilize the ICE engine in higher efficiency region
  - The electric motor can recover some energy during braking

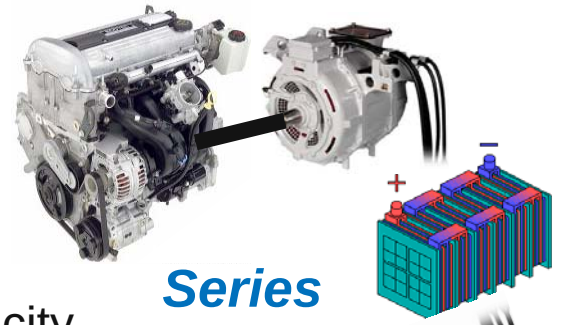
Hybrid Electric Vehicle (HEV)

- Parallel
  - Both the ICE engine and Electric Motor directly propel the vehicle (connected to wheel through transmission)



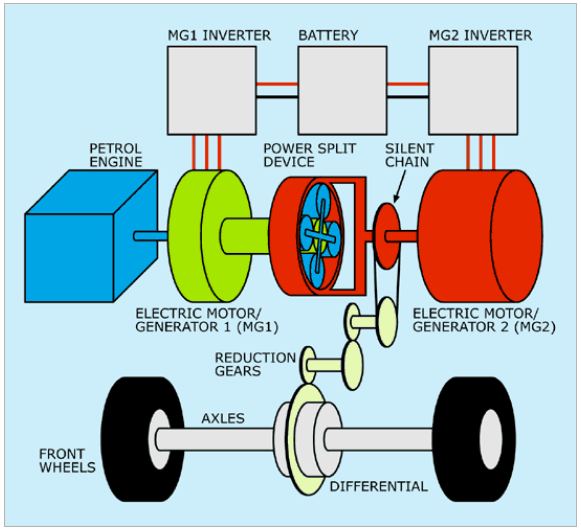
Parallel

- Series
  - Electric motor propels the vehicle
  - ICE engine drives a generator to create electricity



Series

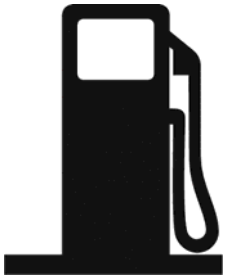
Power-Split



- Power-Split
  - Combination of Parallel and Series
  - Some benefits from both
  - Unique limitations

Plug-In Hybrid Electric Vehicle (PHEV)

- A PHEV is a special type of HEV that uses Two Energy Sources



  - Fuel
    - *typically liquid fuel such as Gasoline*

  - Electricity
    - *stored on board the vehicle in a battery system*
    - *Recharged from the wall plug*

- Main benefits of PHEV over HEV
  - Petroleum Displacement (energy diversification)
    - *Renewable Energy or Domestic Energy Sources*

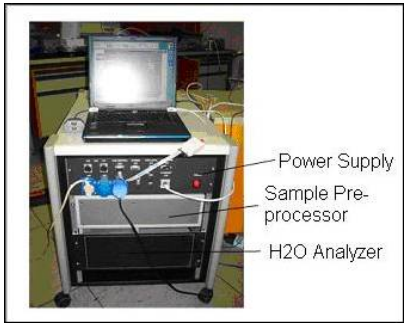
ARGONNE'S OBJECTIVE: Provide to DOE and Partners the Best Advanced Vehicle Test Data

"Be the eyes and ears of technology development"

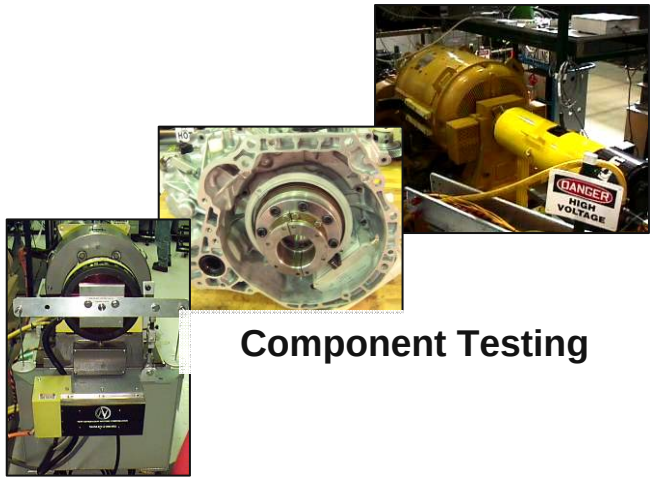
- **Advanced Powertrain Research Facility (APRF)**
  - Purpose built for DOE benchmarking
  - State-of-the-art 4WD chassis dynamometer
  - Custom multi-input data acquisition specific to hybrid vehicle instrumentation
- Staff at cutting edge of test procedures for new advanced vehicles
- Inventing new and novel instrumentation techniques

APRF's Unique Combination of Facilities

Hydrogen Test Capability
gaseous and liquid H_2



H_2O Analyzer



Component Testing

Comprehensive Database Hybrids since 2000

Linking Models to Hardware

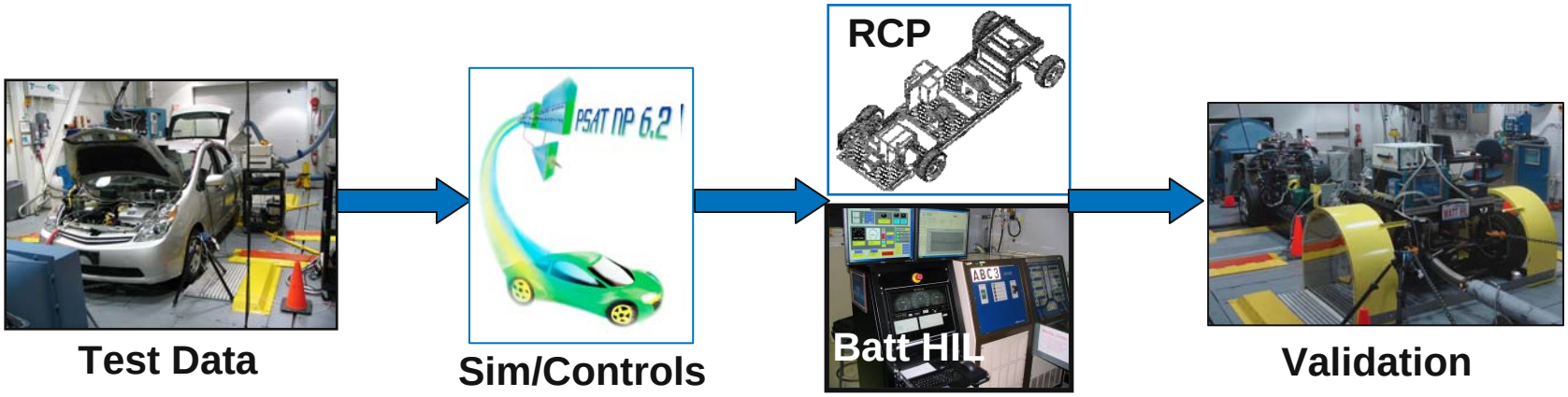
In-House Data Acquisition

Vehicle Benchmarking

Technology Development Is "Data Driven"

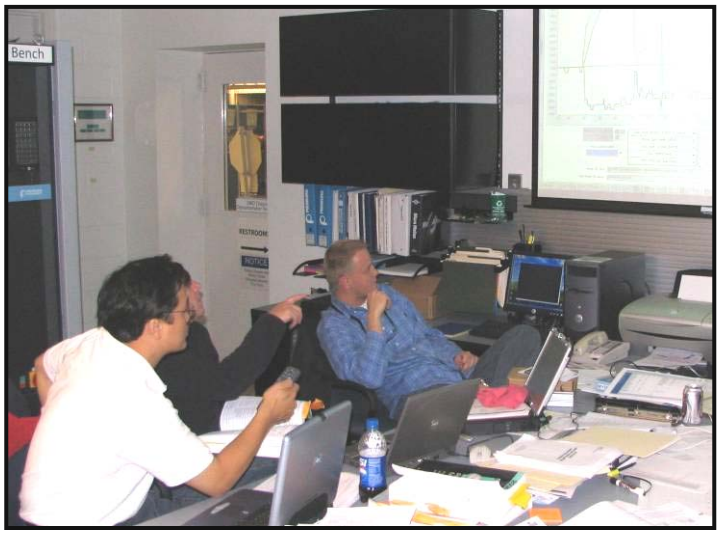
Vehicle Benchmarking Addresses the Following Needs

- Simulation Models (PSAT): only as good as the data fed into the model
- Component Tech Teams: Set targets in system perspective
- DOE and Partners: Compare current technology to overall goals, prioritize funding
- New Technology Requires Evaluation of Test Standards:
  - Hybrids
  - Regen Braking
  - 4WD vs. 2WD
  - SOC Measurement
  - Coast-Down Procedures, PHEVs



OEM's: On-site Collaboration at APRF

OEM HEV Engineer Adding Sensors



OEM Engineers Review Data in APRF Control Room After Data Was Taken

- Now working with three (3) major OEMs in proprietary testing of PHEVs
- OEMs appreciate the unique APRF design and its capabilities for prototype testing and analysis

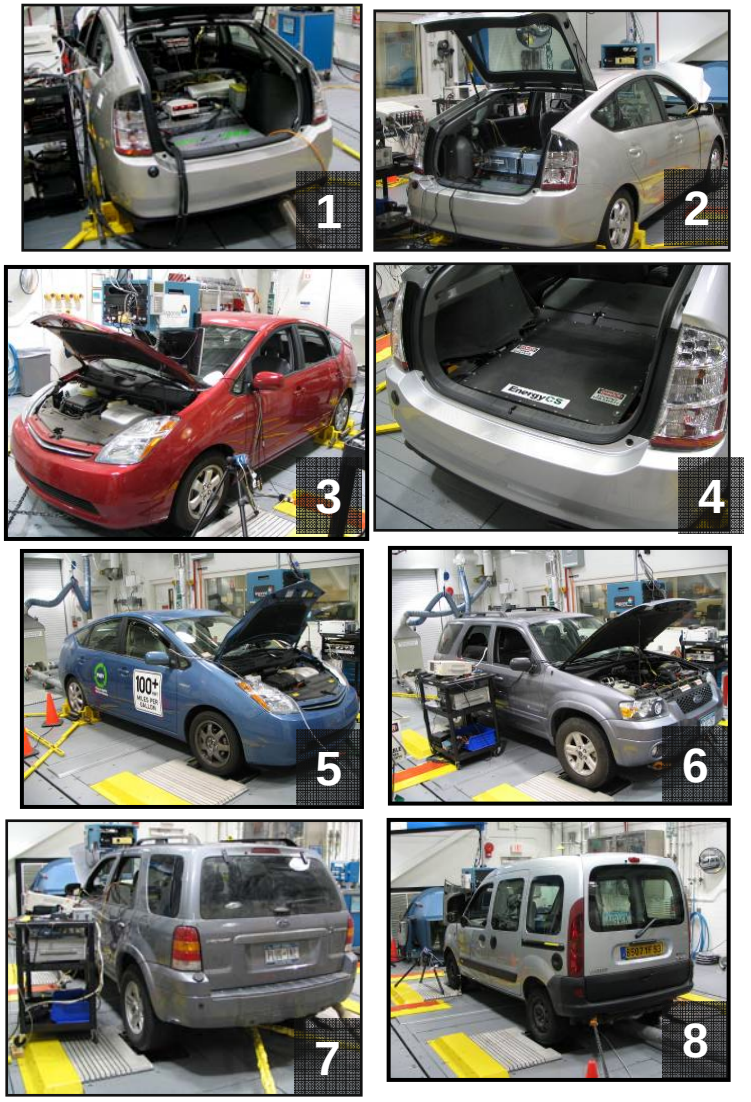
First Available Data from Blended PHEV (Hymotion Prius)

- Blended Mode PHEV(5kWh)
- Li-Ion battery pack added to stock NiMH pack
- Installed in ANL, highly instrumented Prius

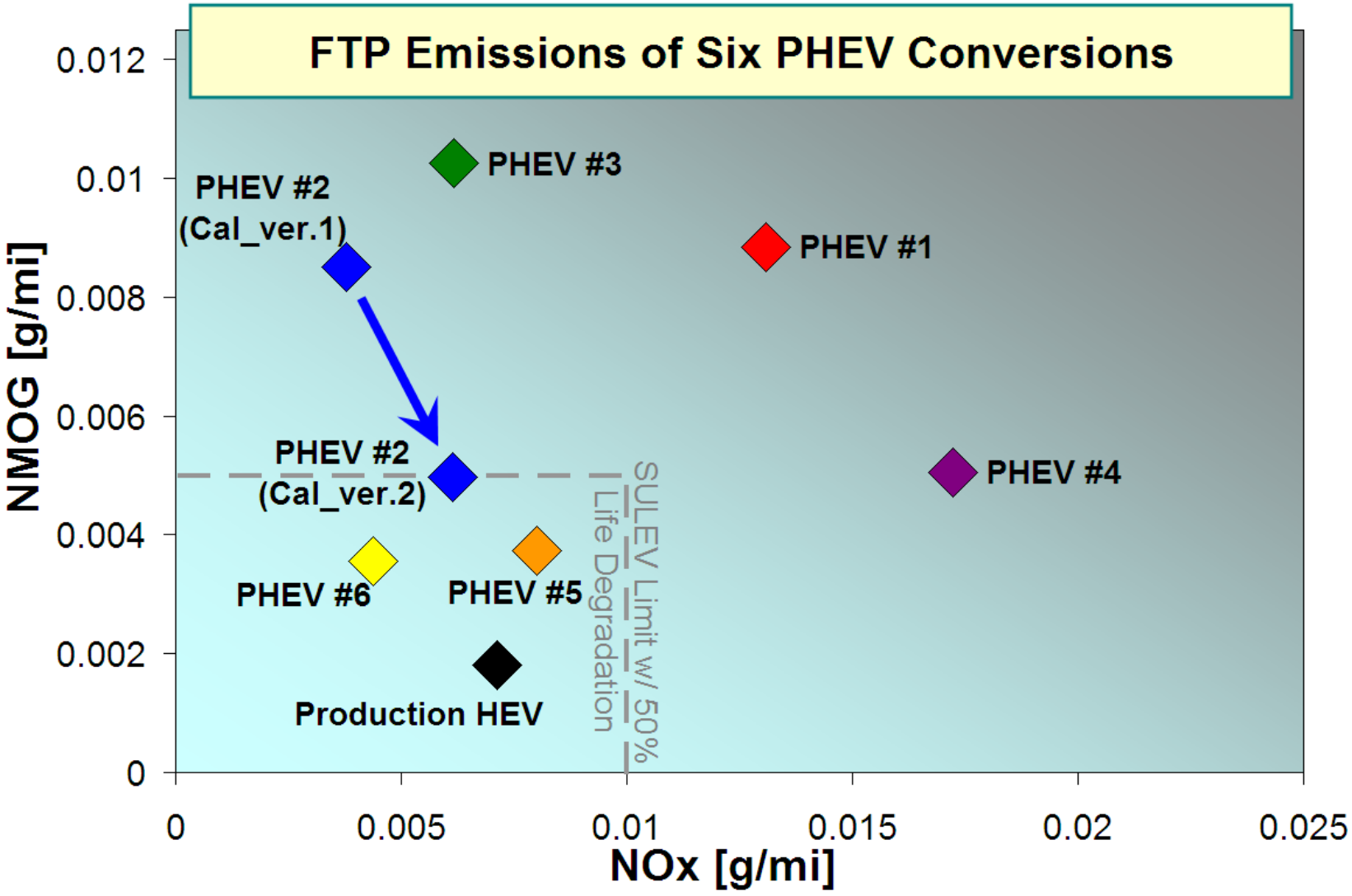
September 2006

Accomplishments: PHEVs Tested from 2007-08

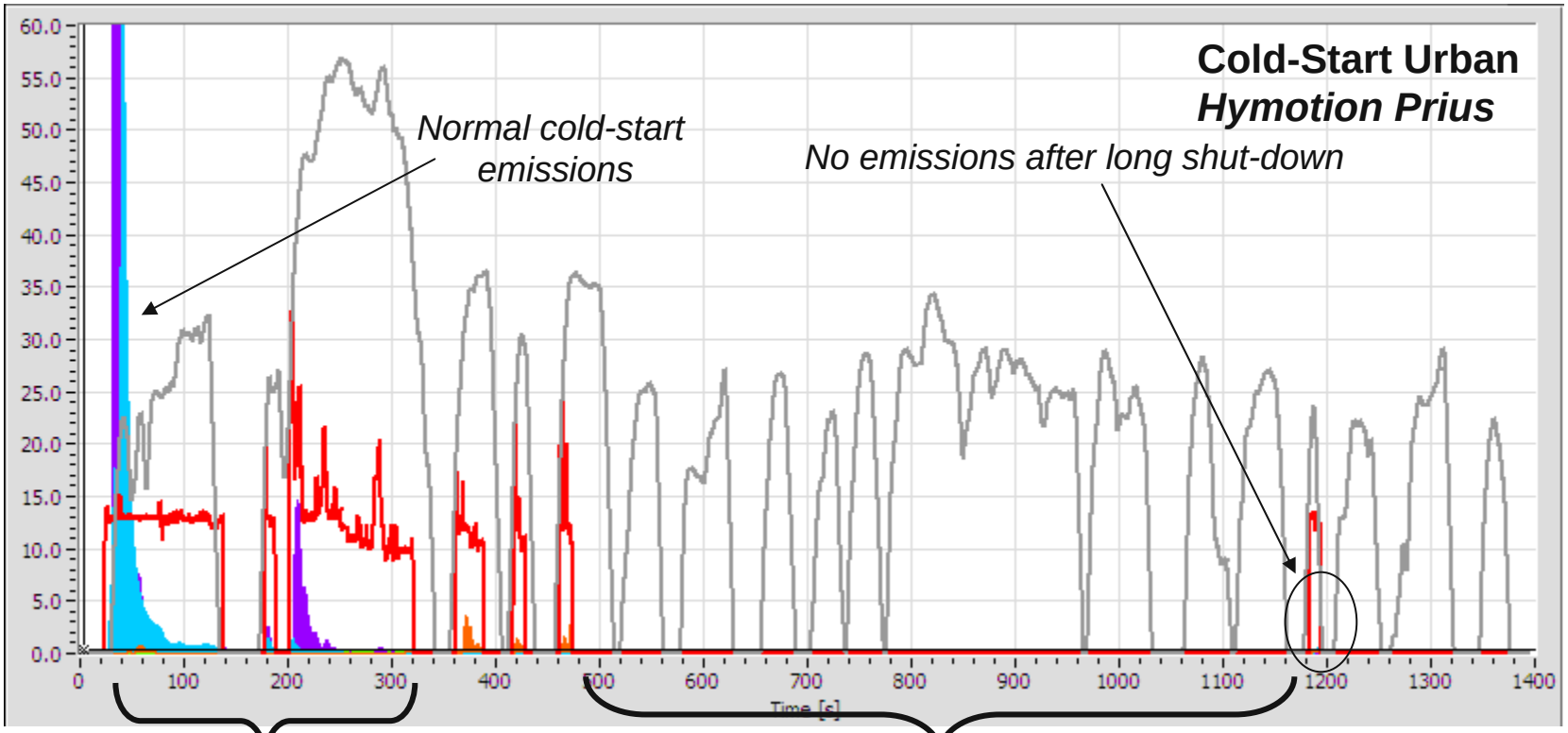
- **Prius Conversions**
  1. Hymotion (1st gen) Prius (highly instrumented)
  2. HybridsPlus Prius (highly instrumented)
  3. Hymotion (2nd gen) Prius (AVTA)
  4. EnergyCS Prius ver.1 and ver.2 (AVTA)
  5. Hymotion (3nd gen) Prius (owned by A123)
- **Escape Conversions**
  6. Electrovya Escape (AVTA / NYSERDA)
  7. Hymotion Escape (AVTA / NYSERDA)
- **OEMs**
  8. Renault Kangoo
  9. OEM PHEV Mule (NDA-protected)
  10. **Extensive instrum/testing of OEM– June08**
  11. **More OEM PHEVs – Summer08**



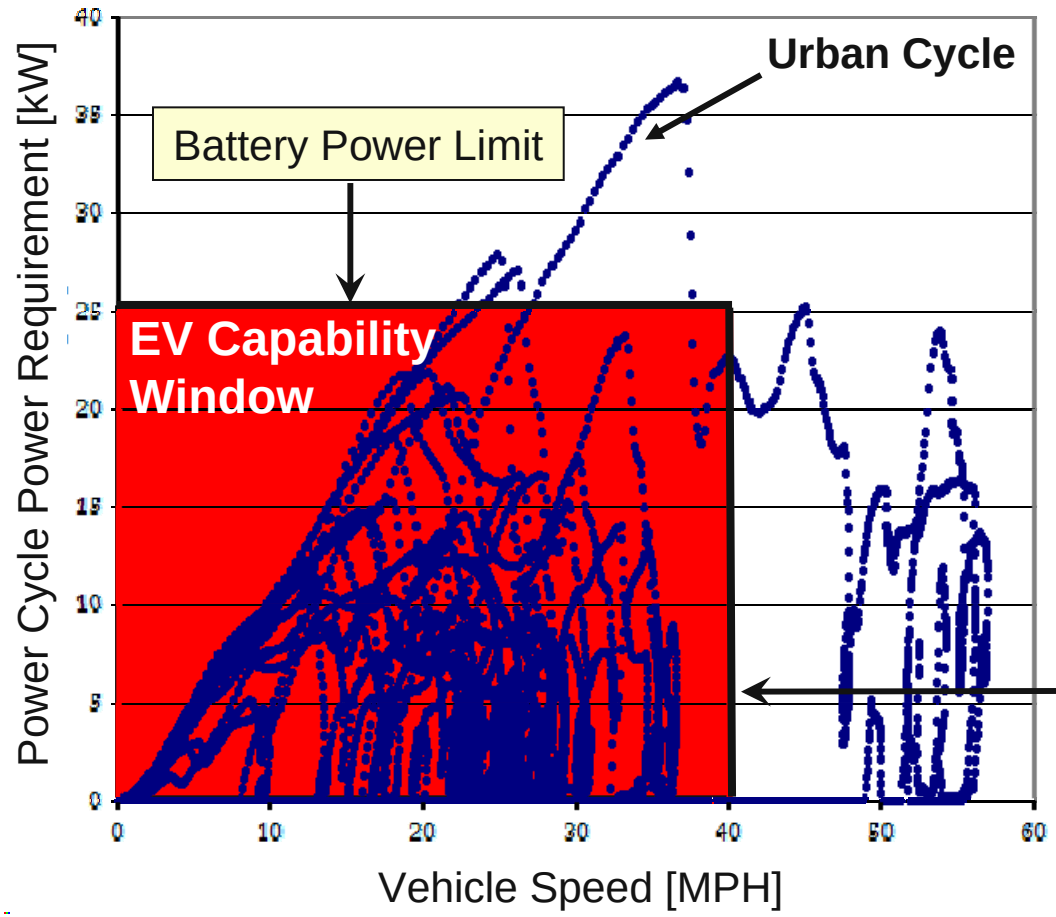
Latest Calibration from Prius PHEV Conversion Demonstrates SULEV Attainment



Emissions: Blended PHEVs Have Demonstrated Low Emissions – (Calibration Performed at ANL)



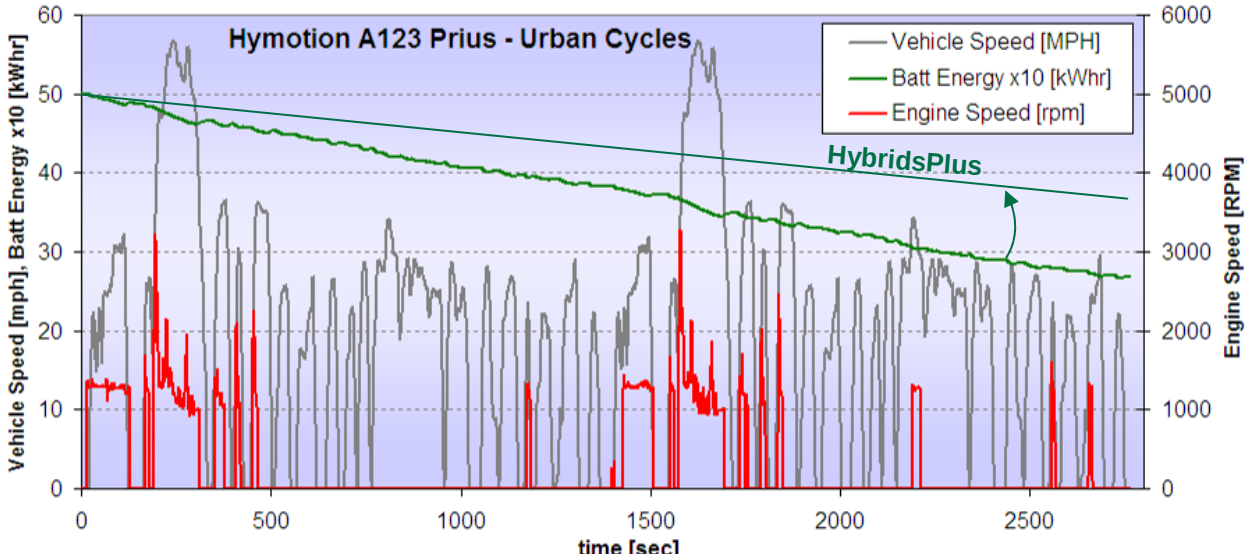
Blended Mode: Significant Petroleum Displaced – Even With Stock Prius Limitations

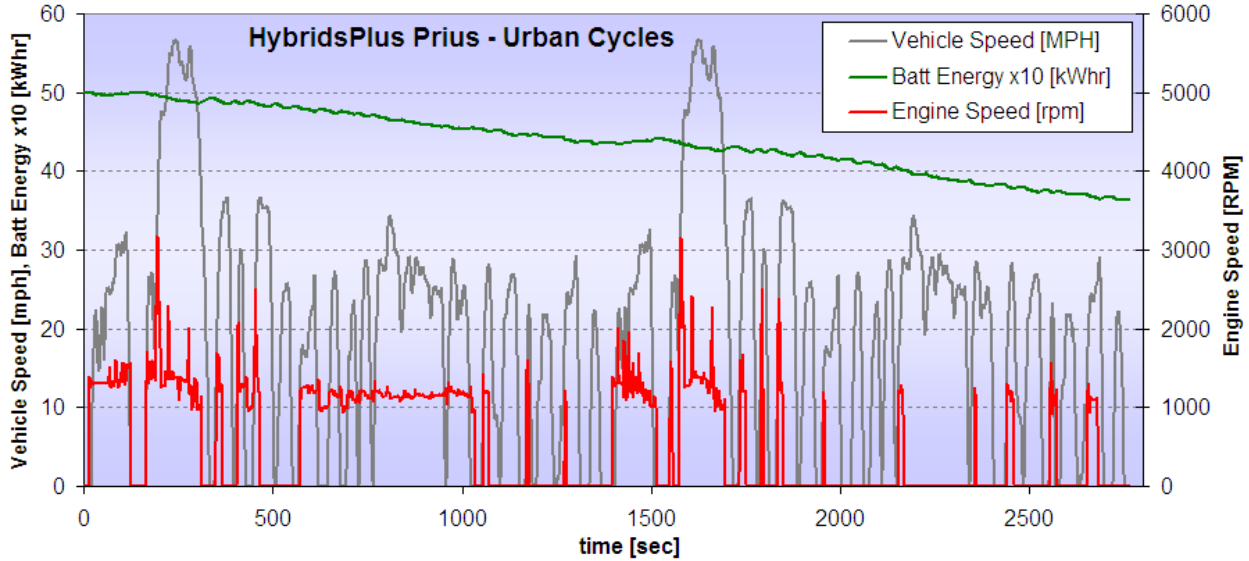


- **69%** of time Prius operated within EV capability window
- **78%** within energy window!!
- i.e., 100% displacement in EV mode, up to 78% petroleum displacement possible in a blended Prius

Powertrain Speed Limit *(power-split limitation)*

Varying Depletion Rates vs. Fuel Displacement



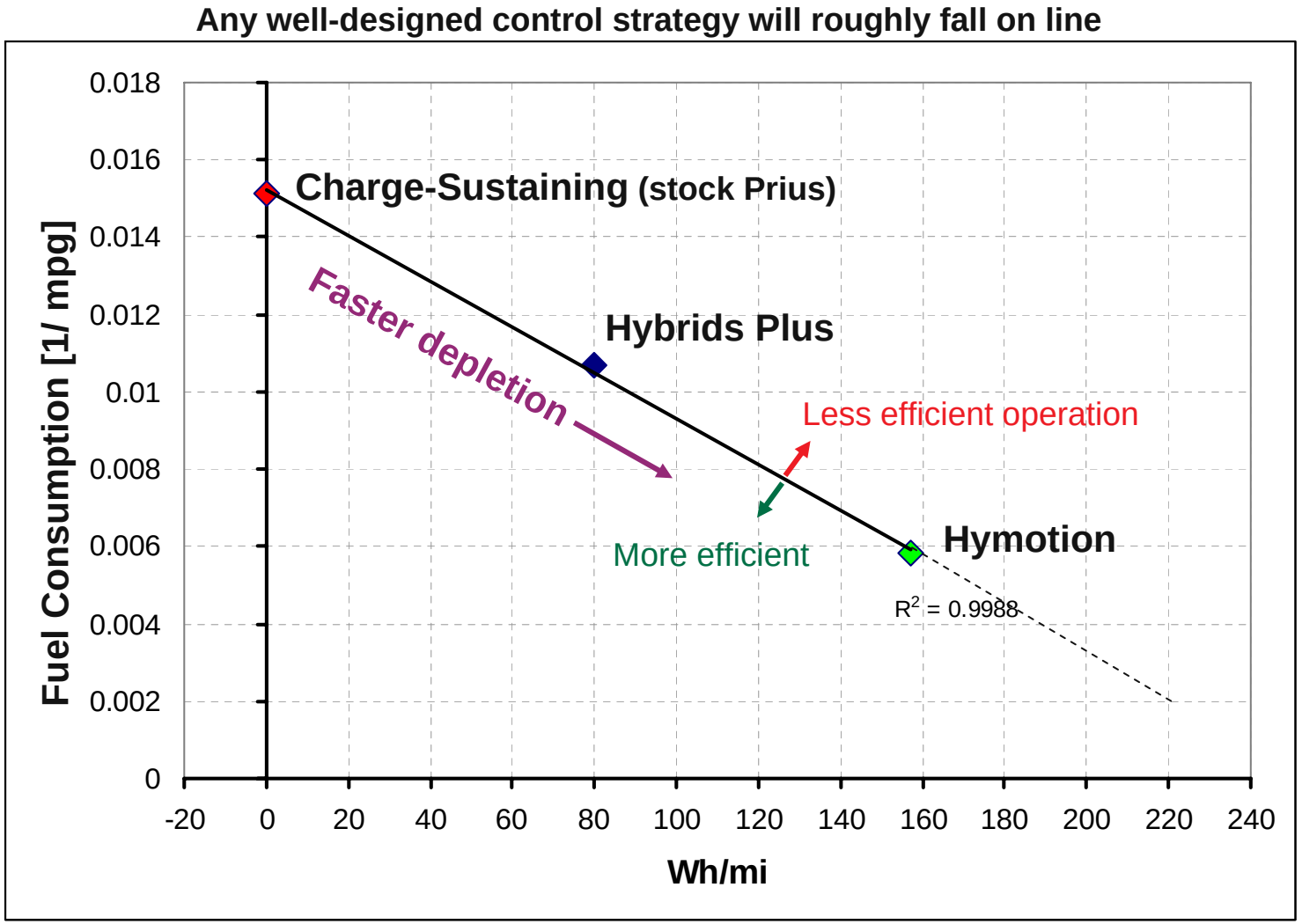


Hymotion
MPG = 172
Wh/mi = 157
Petroleum Displacement = 62%
Depleting Range = 31 miles (4.5kWh)

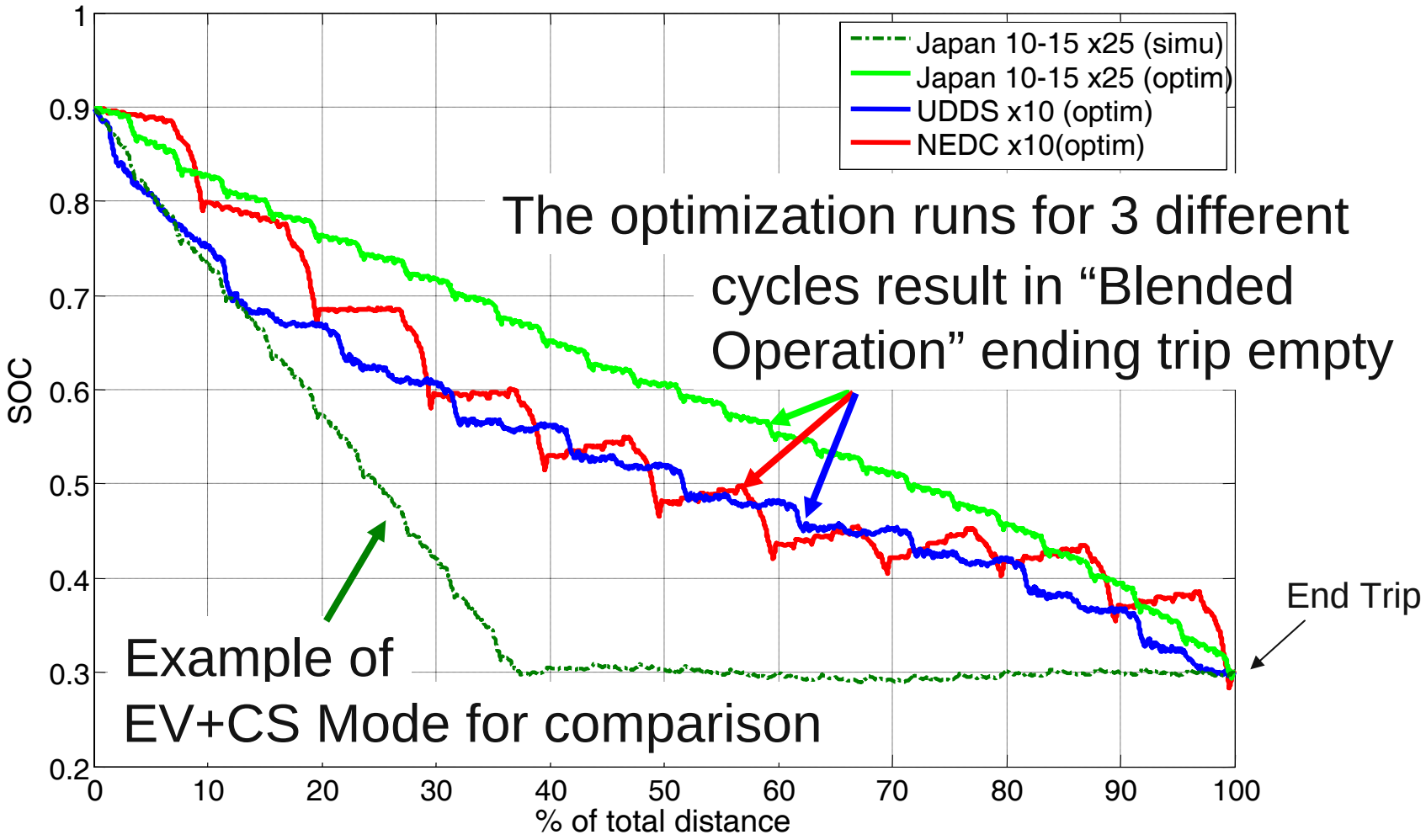
Recall, 78% potential to displace fuel from drive cycle analysis

HybridsPlus
MPG = 93.6
Wh/mi = 79.7
Petroleum Displacement = 29%
Depleting Range = 87 miles (9kWh)
= 43.5 miles if 4.5kWh

Energy Management: Depletion Rate is a Tradeoff of Fuel and Electricity



Computer Simulations Has Shown Best Depletion Rate Is Blended → End Trip Depleted



EV: Electric Only CS: Charge Sustaining

What We Have Learned from PHEV Testing

- Blended is a viable option for PHEV (early research focused on EV-capable PHEVs)
- Conversion modifications only to Battery and Controls (same powertrain)
- Conversion quality ranges from good, to very poor
- Best conversions utilize Prius “EV Button” to effectively deplete
- Conversion company's batteries are sized from 4-9 kWh
- Depleting range from 30-90mi depleting range
  - Not all designs have optimal depleting rates
- Conversions up to ~70% petroleum displacement (UDDS) with stock limitations
  - Highly dependent upon driving speeds and acceleration rates!
- Several systems show good efficiencies in depleting mode
  - (fall on similar consumption x-y plot line)

Announced: OEM bring PHEV's to the Market in the Near Future

- Series
  - GM Volt
    - *Large Electric motor ~ 160hp (FWD)*
    - *1.0L Engine / Generator*

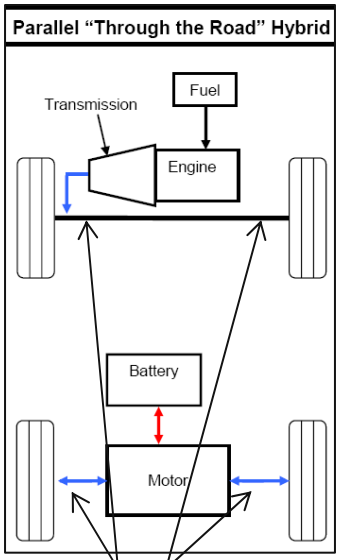
- Power-Split
  - Ford Escape PHEV
    - *Same powertrain as HEV*
  - Toyota Prius PHEV
    - *Same powertrain as HEV*

- Parallel
  - none

ANL Builds Its Own Through-the-Road (TTR) Parallel PHEV

• Through-the-road parallel hybrid electric vehicle with axle torque sensors front and rear to measure power 'through-the-road'.

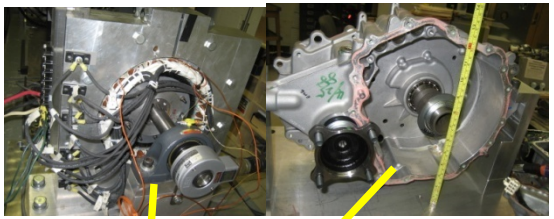
• Additional electric drive powertrain in the rear of the vehicle; interchangeable 120kW air cooled AC induction machine, or 75 kW liquid cooled permanent magnet motor; ~8:1 fixed gear ratio.



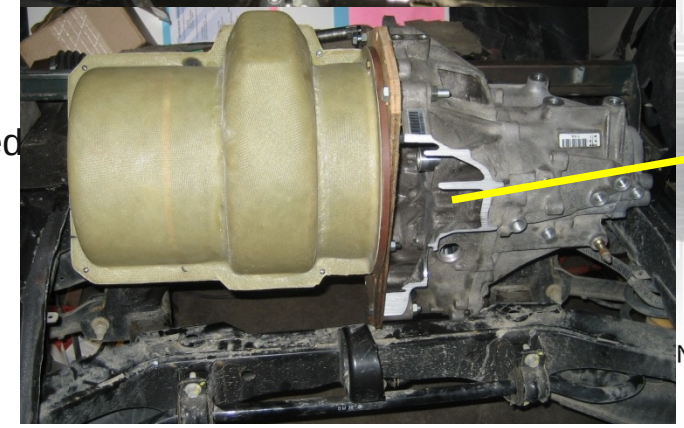
Axle Torque sensors on all 4 ½-shafts to measure "through the road" power

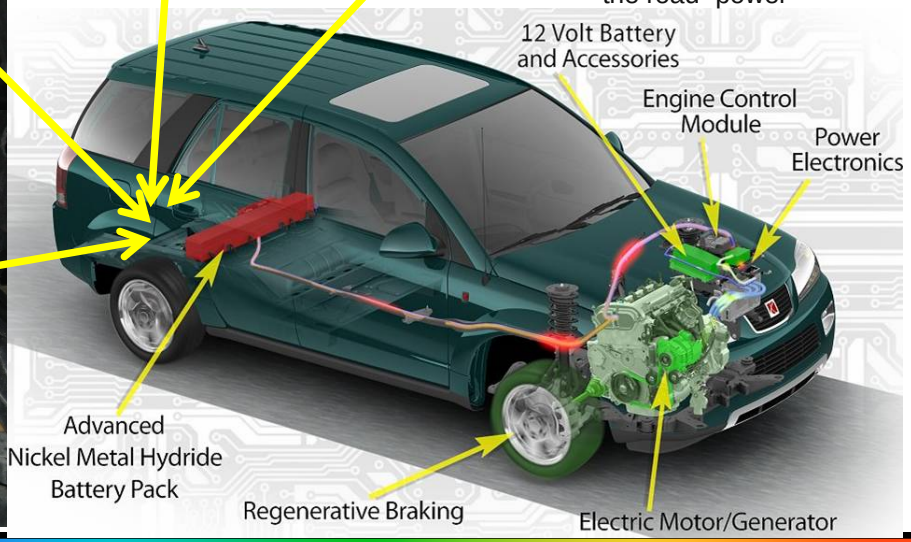
75 kW liquid cooled PM motor

55kW Prototype, OEM motors



120kW air cooled AC induction machine





Dynamometer Testing and Development of TTR

- Control System development and calibration
- Dyno testing fuel consumption electrical energy consumption, and emissions
- Evaluate all-electric operation on battery requirements and overall vehicle operation

Future Plans

- Continue to be the world leader in PHEV dynamometer testing
- Lab upgrades
  - More capacity
  - Accurate testing at elevated temp (A/C very important for PHEV's)
  - Cold temperature testing to evaluate impact on battery system requirements
- Feed critical information, data, and experience to the test procedure / evaluation efforts (J1711 – PHEV Test Procedures)
- Feed updates of newest systems-level information, data to Tech Teams, OEMs, simulation models
- Evaluate ANL-designed PHEV platforms
  - More investigation of energy management and oil displacement
  - Investigate PHEV design space not available from conversions
    - *All-electric range*
    - *Varying controls*

Thank You

We would like to gratefully acknowledge the sponsorship of Ed Wall, Program Manager and Lee Slezak, Manager, Advanced Vehicle Systems Simulation & Evaluation Team, Office of Vehicle Technologies Program, U.S, Department of Energy.

Vehicle Technologies Program