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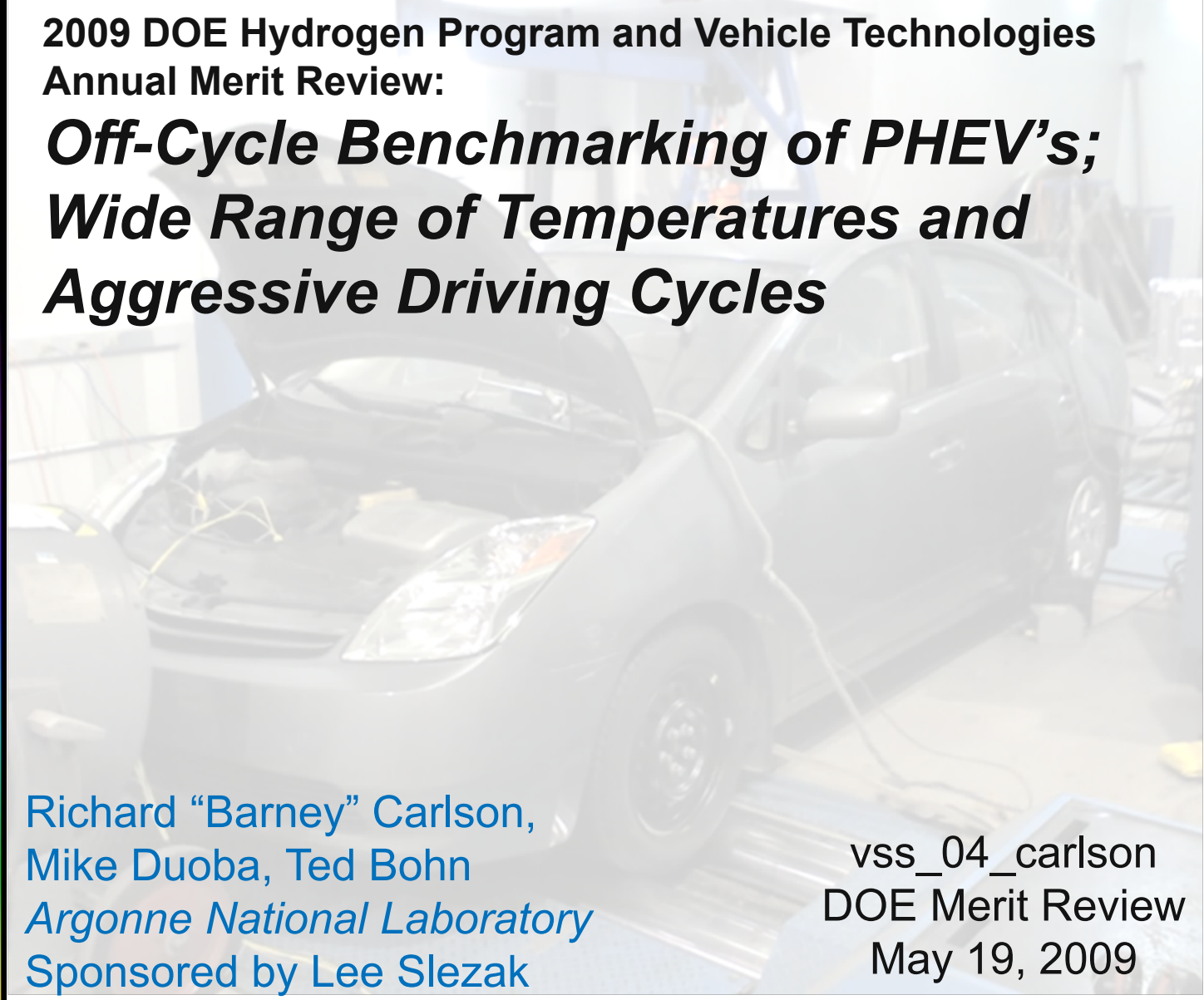
2009 DOE Hydrogen Program and Vehicle Technologies Annual Merit Review:

Off-Cycle Benchmarking of PHEV's; Wide Range of Temperatures and Aggressive Driving Cycles



Richard "Barney" Carlson,
Mike Duoba, Ted Bohn
Argonne National Laboratory
Sponsored by Lee Slezak

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Project Overview

Timeline

- PHEV Cold Dyno Facility testing of Hymotion Prius
  - March to Sept. 2008
- PHEV Fuel Consumption Variability to Driver Aggressiveness
  - Aug. to Nov. 2008

Budget

- PHEV Cold Ambient Testing
  - FY08: $200k
  - FY09: $180k
- PHEV Aggressive driving study
  - FY09: $50k

Barriers

- Dyno facilities with sub-freezing testing capabilities and solar heat load are rare due to cost and upkeep
- Standard drive cycles are less aggressive than typical real world drivers
- HEV fuel economy is more sensitive to aggressive driving (expected similar sensitivity in PHEV's)

Partners

- Environment Canada
  (Cold Dynamometer testing facility)
- Idaho National Lab
  (on-road fleet data and analysis)

Objectives

- Test PHEV operation at sub-freezing temperatures in a dynamometer facility
  - Measure impacts on fuel consumption electrical energy consumption and tailpipe emissions of sub-freezing temperatures to PHEV operation
  - Measure impacts on fuel consumption electrical energy consumption and tailpipe emissions of hot ambient temperatures to PHEV operation with air conditioner utilization
- Benchmark PHEV fuel consumption variability with varying driver aggressiveness

Milestones

- PHEV Full Charge testing completed on Hymotion Prius at several conditions
  - UDDS at 3 temperature ranges (22°C, -7°C, -18°C)
  - HWY
  - US06
  - SC03 with air conditioning on (no solar heat load)
- PHEV Testing was completed over aggressive drive cycles (scaled UDDS)
  - UDDS, UDDSx1.1, UDDSx1.2, UDDSx1.3, UDDSx1.4

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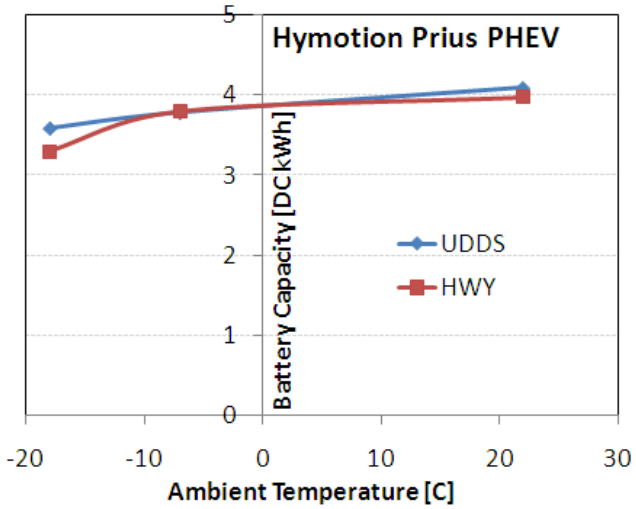
5 Cycle Test

Hymotion Prius @ 22°C, -7°C, and -18°C

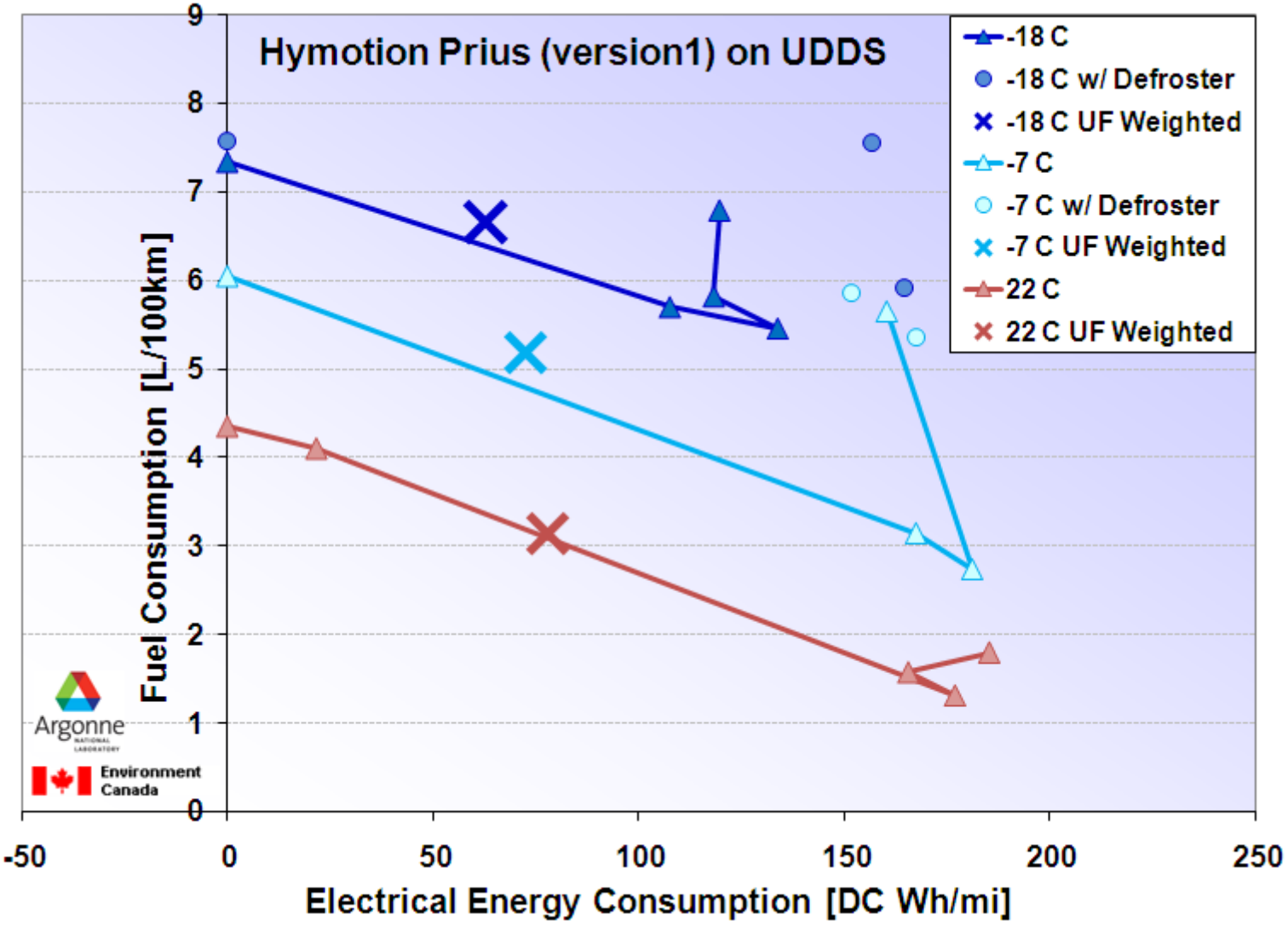
- With Decreasing ambient temperature:
  - Fuel Economy and Electrical Consump. Decreases
  - Equivalent All-Electric Range Decreases
  - The Round-Trip Efficiency Decreases



	HWFET			UDDS		
Ambient Temperature [°C]	22	-7	-18	22	-7	-18
UF weighted Fuel Economy [mpg]	97.2	83.5	70.1	74.9	45.4	35.3
UF weighted Elec. Consump. [AC Wh/mi]	90.3	89.5	76.3	98.4	96.7	92.4
Electric Range Fraction (ERF) [%]	60.8%	52.9%	35.1%	49.4%	36.6%	19.2%
Charge Depletion Distance [mi]	30.3	30.0	30.8	23.3	22.1	28.0
Equiv All-Electric Range (EAER) [mi]	18.7	16.3	14.4	14.7	8.2	5.7

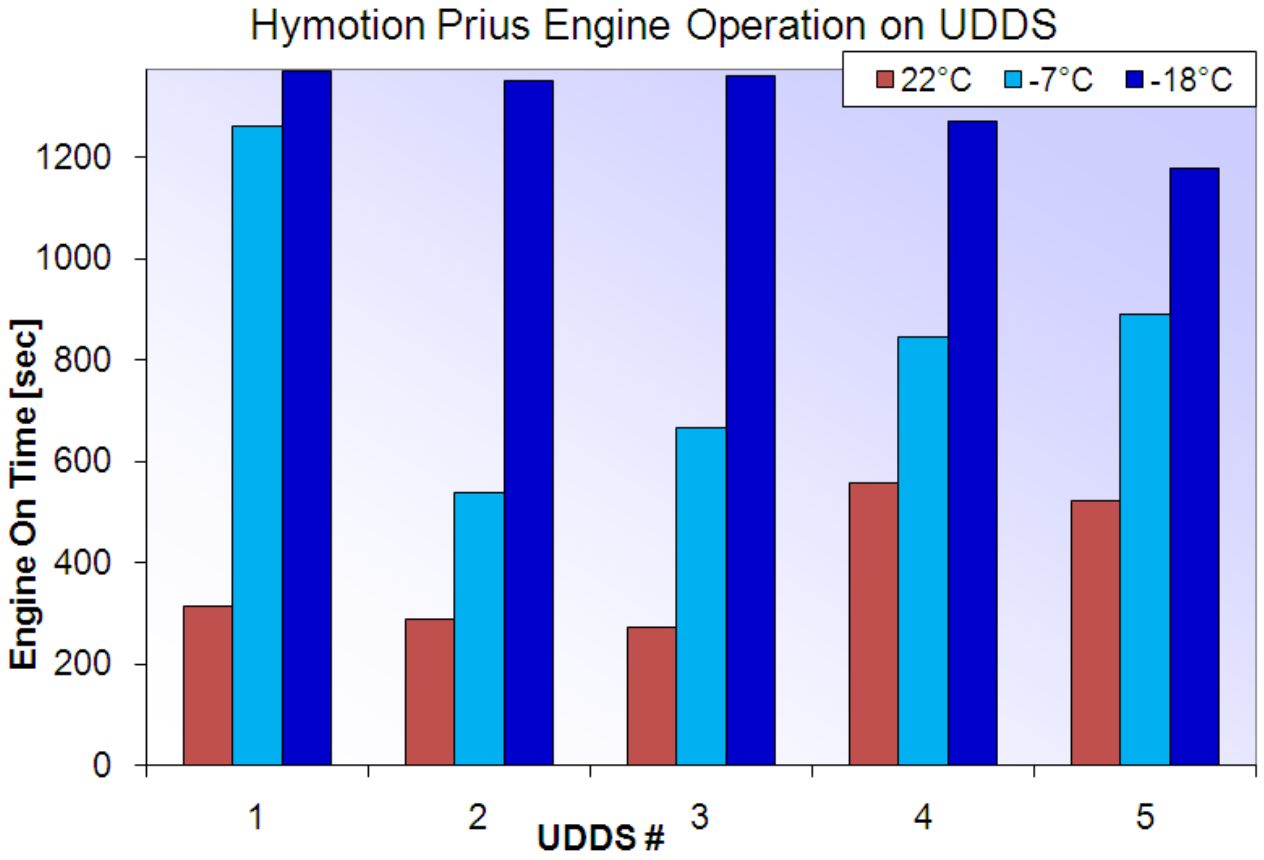
	HWFET			UDDS		
Ambient Temperature [°C]	22	-7	-18	22	-7	-18
Hymotion Electrical Energy Use [DC kWh]	4.0	3.8	3.3	4.1	3.8	3.5
Charging Energy [AC kWh]	5.1	5.2	4.7	5.2	5.1	5.3
Round Trip Efficiency [%]	78%	73%	71%	79%	75%	67%
Charging Time [Hours]	5.1	5.4	6.0	5.2	5.0	6.3

UDDS Fuel Economy and Electrical Consumption Decrease with Decreasing Ambient Temperature



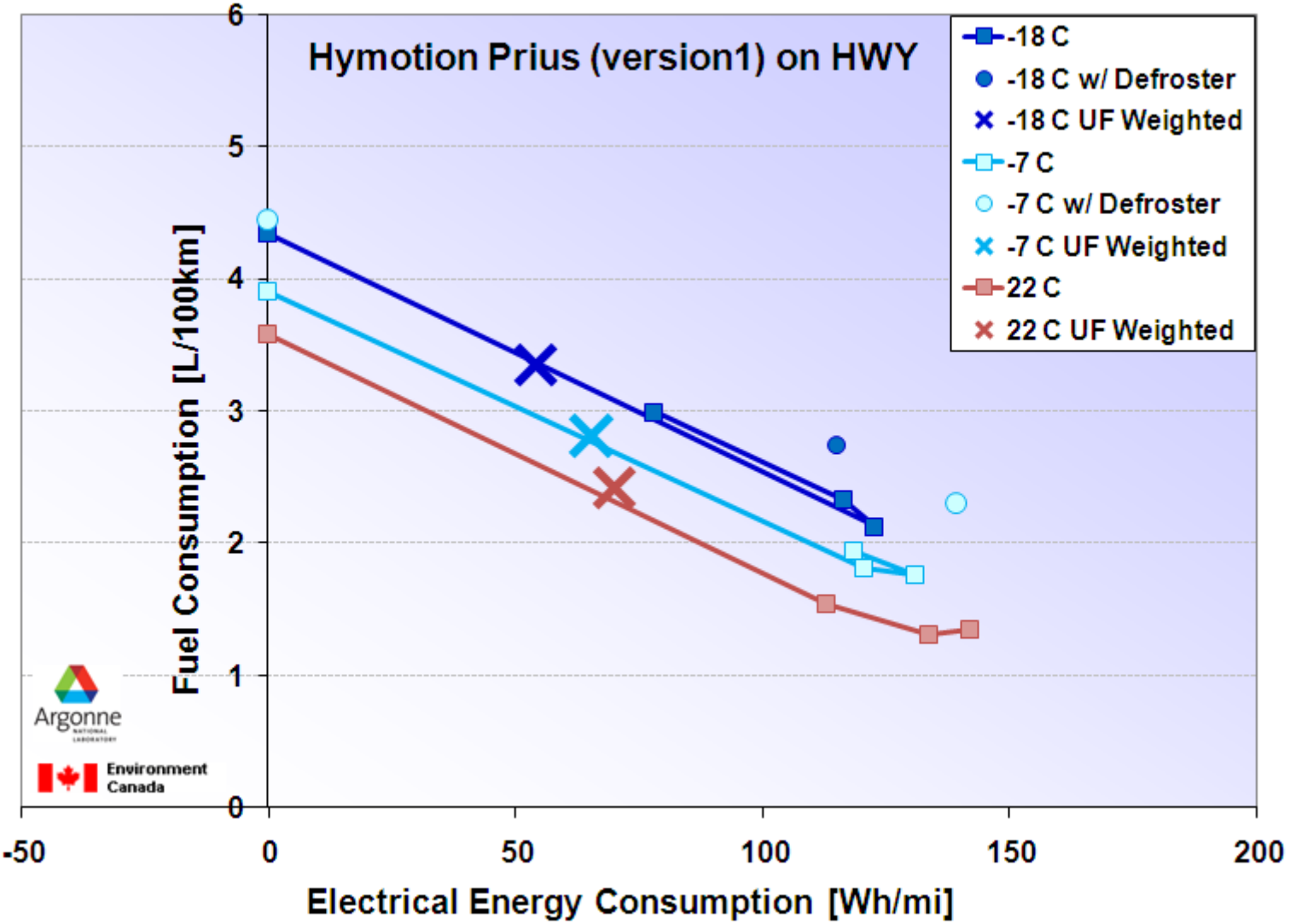
Engine Operating Time Increases at Lower Ambient Temperatures

- Engine warm-up after key start increases engine on time
- At lower ambient temperature the engine is utilized more due to reduced battery system power
- Engine doesn't reach peak operating temperature until Charge Sustaining operation

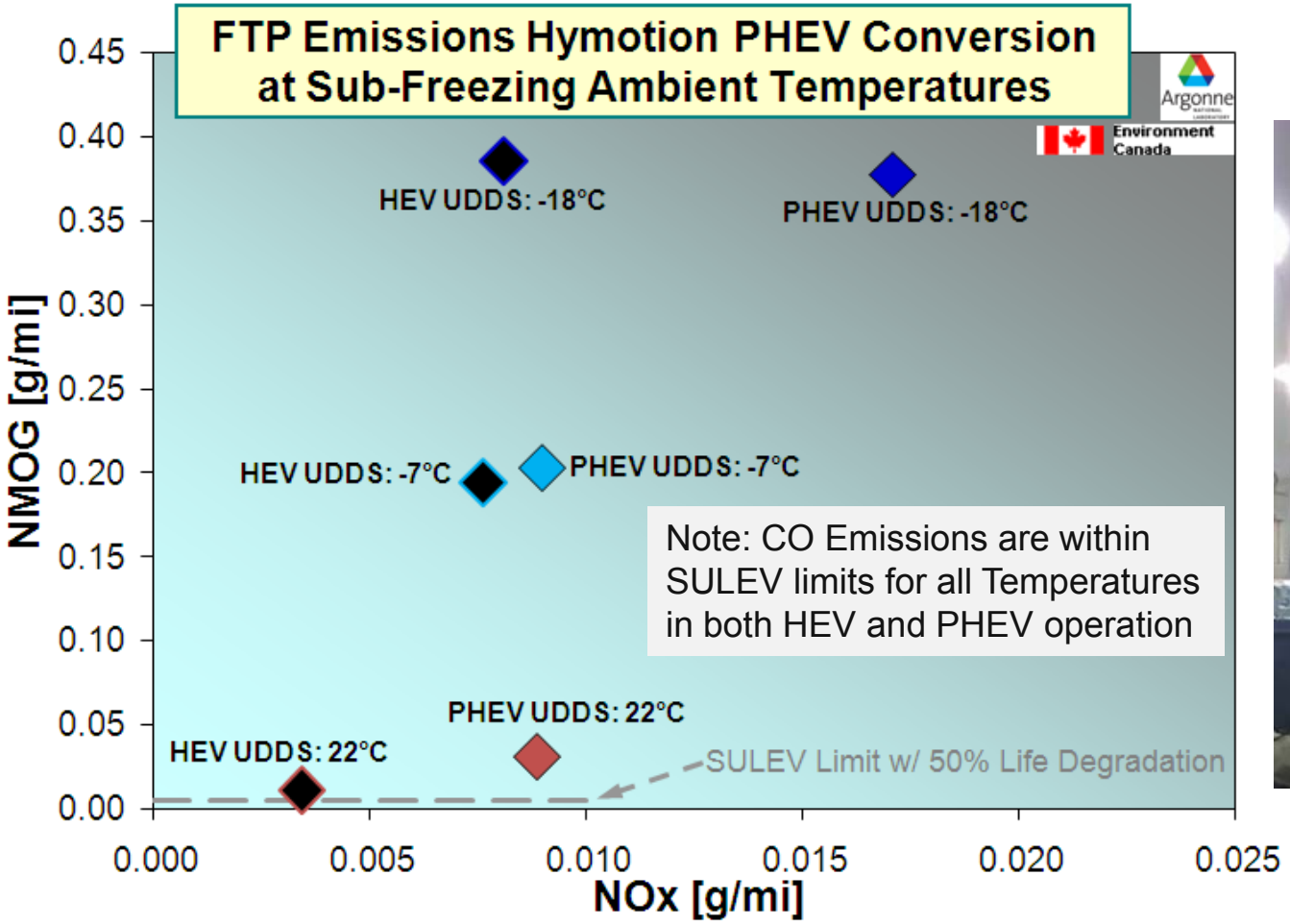


HWY Fuel Economy and Electrical Consumption Decrease with Decreasing Ambient Temperature

(but less than impact on UDDS cycle)

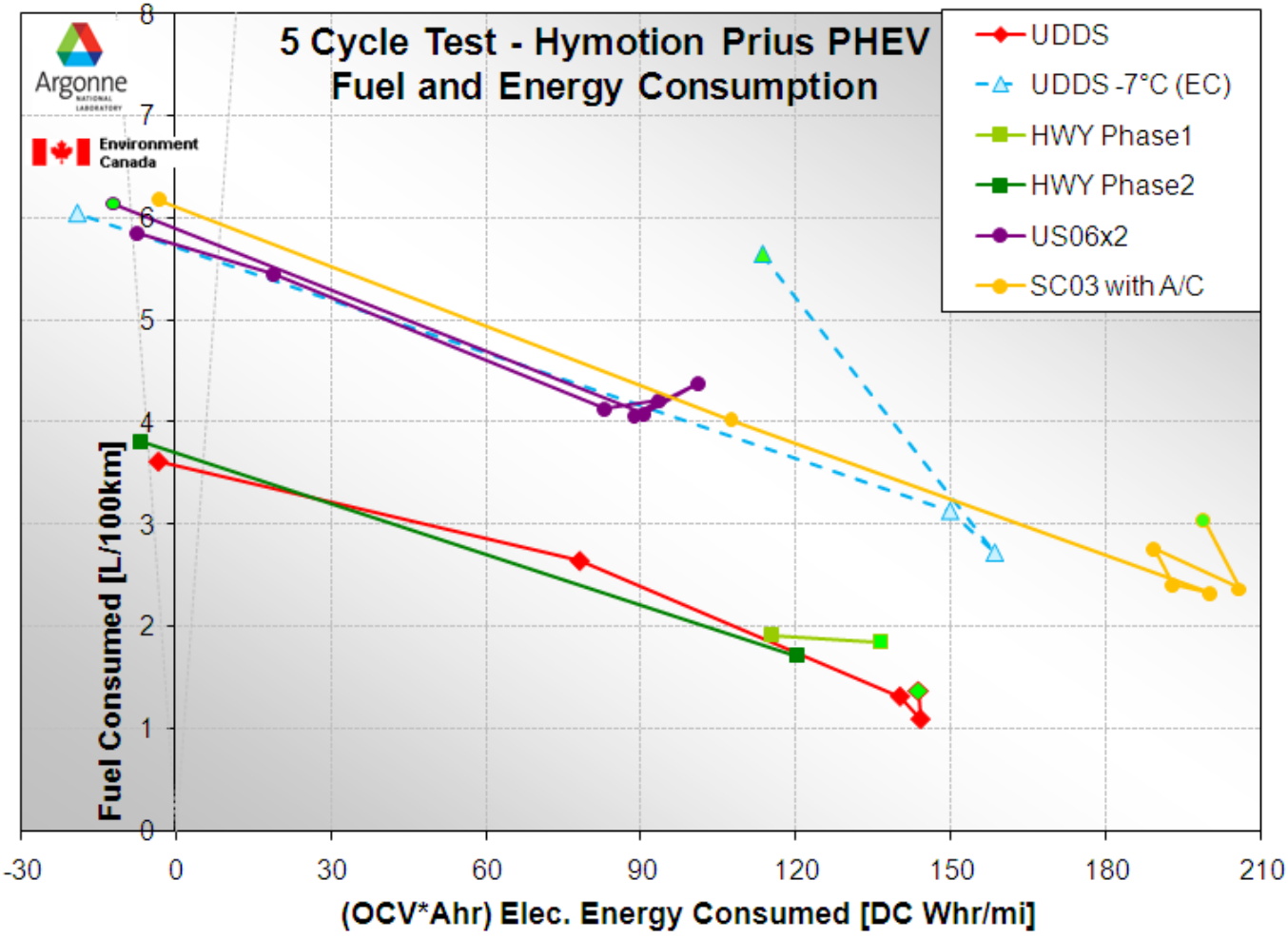


Hymotion Prius PHEV – Tailpipe HC Emissions are Affected by Sub-Freezing Ambient Temperature



5 Cycle - Hymotion Prius PHEV - SCO3 Air Conditioner Testing Shows Similar Energy Consumption to US06 and Cold UDDS

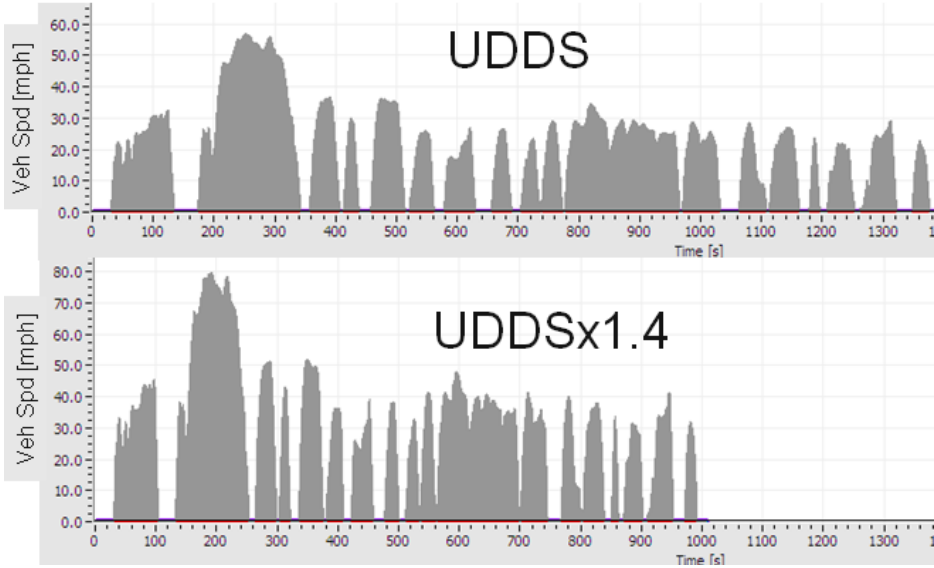
- Test Cell Conditions
  - 35°C Ambient
  - 40% Humidity
  - No Solar Heat Load
  - Vehicle Fan air flow matches vehicle speed
- Vehicle Conditions
  - Hood closed
  - Windows down (since no solar heat load)
  - A/C set to 72°C
- Note Electrical Consumption is greatest on SC03



Drive Cycle Fuel Consumption Variability of PHEV's due to Driving Aggressiveness

- Dynamometer testing conducted over:
  - Standard cycles (UDDS, LA92, US06)
  - Scaled UDDS cycle (UDDSx1.1, UDDSx1.2, UDDSx1.3, UDDSx1.4)

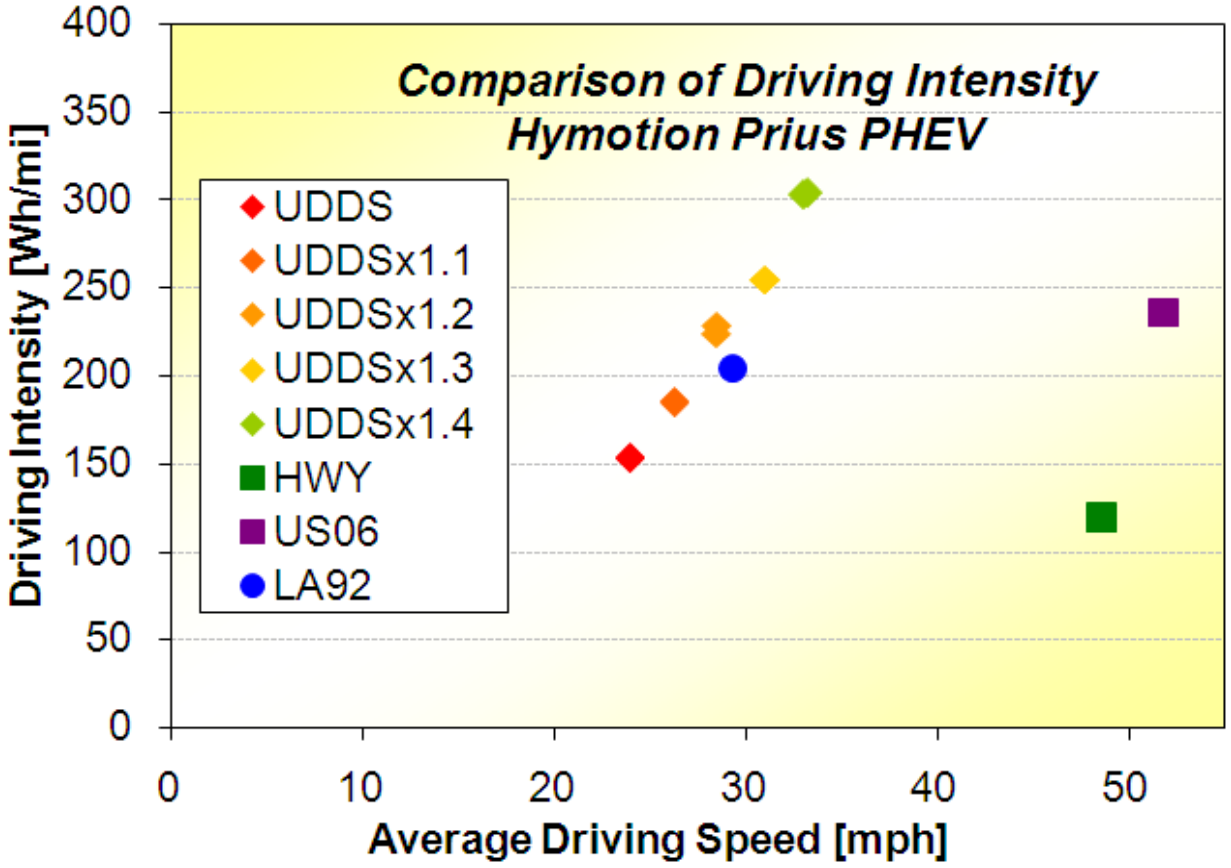
- Vehicles Tested:
  - Blended PHEV
    - *Hymotion Prius*
      - Must start engine on UDDS due to power and speed constraints
  - All-Electric UDDS Capable PHEV
    - *MATT*
      - Able to drive UDDS all electric at high battery SOC



	Hymotion Prius	MATT PHEV
EV Capability	Blended on UDDS	EV on UDDS
Usable Battery Energy [kWh]	3.5 kWh	5.0 kWh
Max. Power [kW]	25 kW	50 kW
Other EV Constraints	Engine On above 40 mph	None

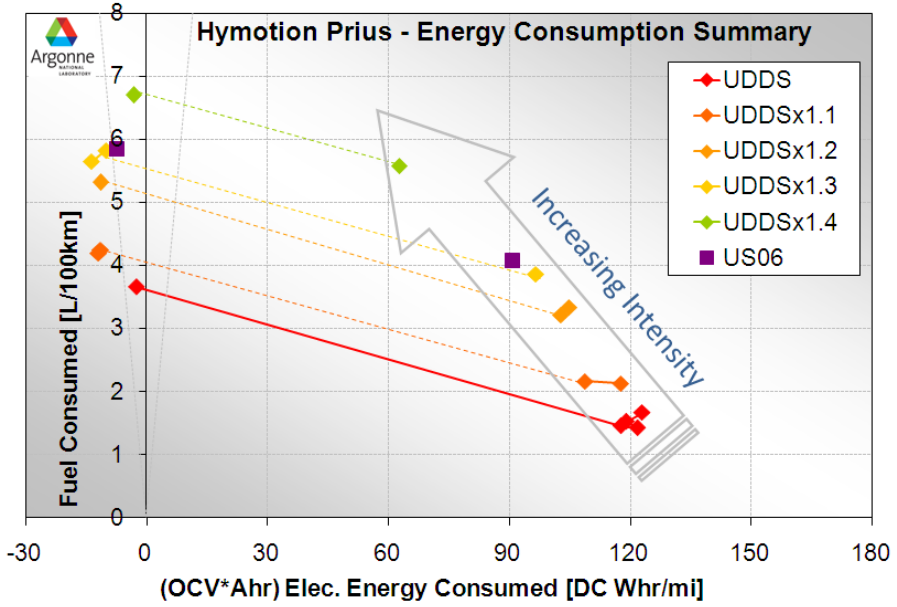
Driving Intensity is a Metric to Measure Driving Aggressiveness

- Speed and Acceleration
  - Both are factors in Aggressive driving
  - Both influence Fuel Economy
- **Driving Intensity** is the vehicle energy required to drive at the desired speed and accelerations (Whr/mi)

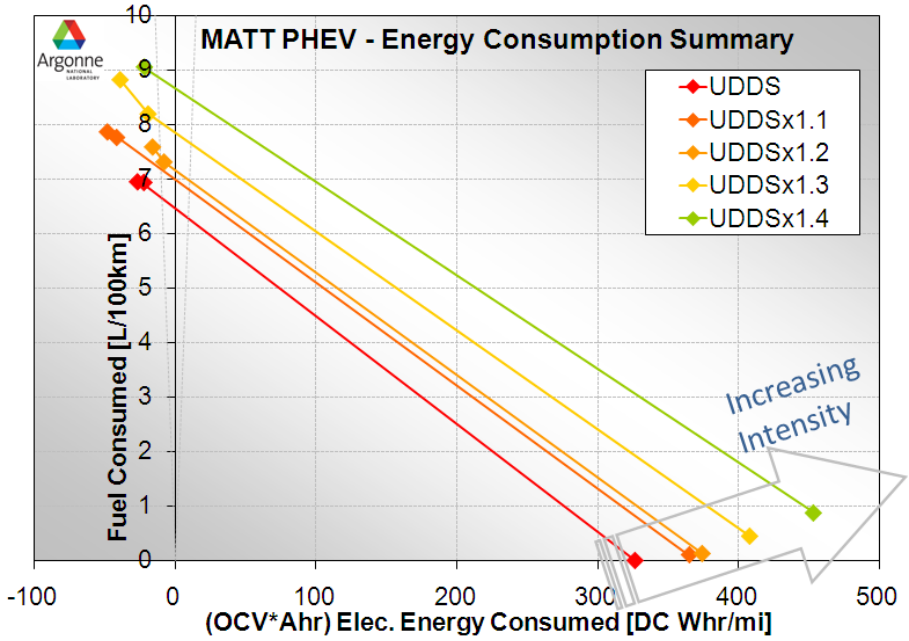


Affect of Driving Intensity on Energy Consumption Differs for Vehicle EV Capability

- Blended PHEV (Hymotion Prius)
  - As Driving Intensity increases, fuel consumption increases but electrical energy consumption decreases

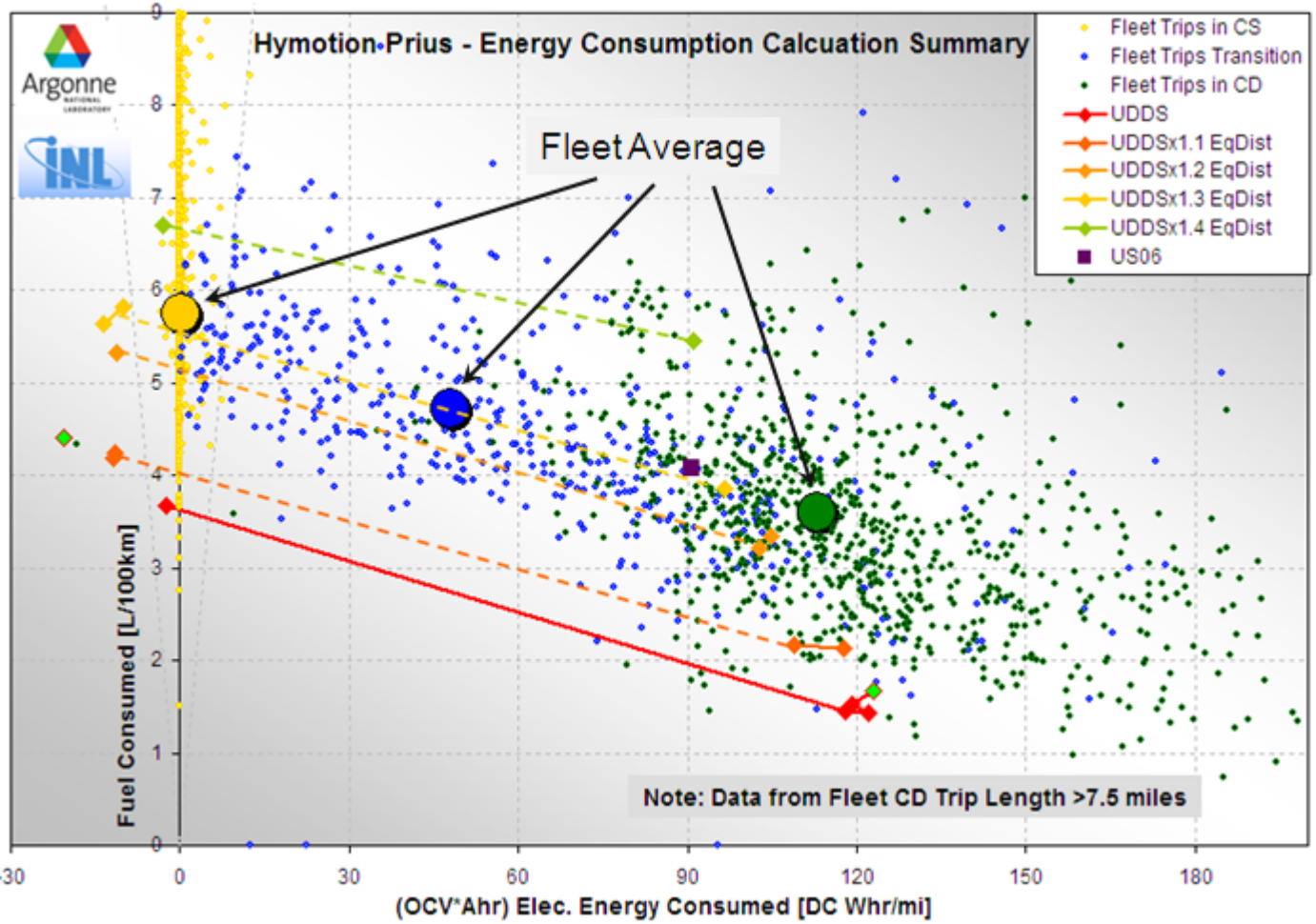


- All-Electric UDDS Capable (MATT)
  - As Driving Intensity increases, fuel consumption and electrical energy consumption increases



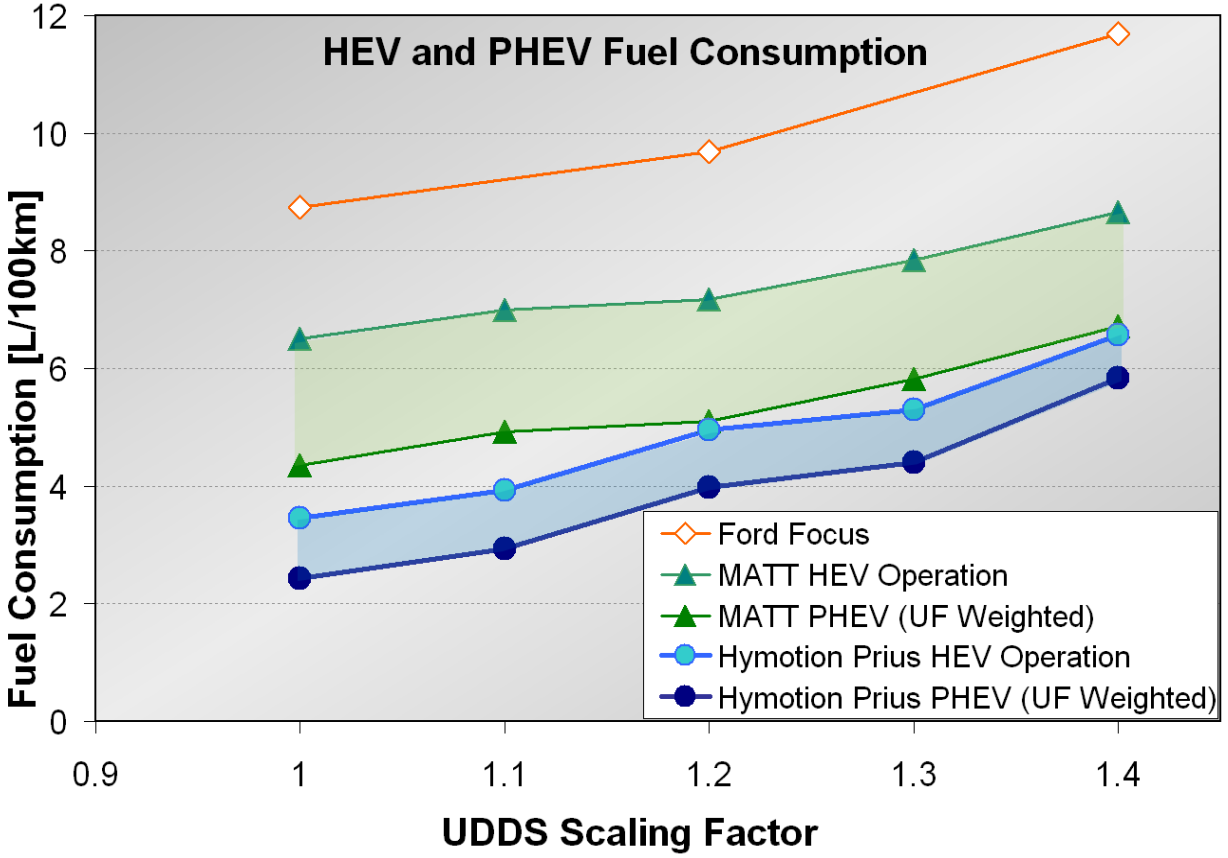
Real PHEV Drivers are Not Well Represented by UDDS; More Representative is US06 (or UDDSx1.3)

- Fleet Average CD Operation shows greater Elec. Consumption than Dyno cycle testing
  - More investigation needed:
  - Accessory loads?
  - Ambient Temperature?
  - Most stop time? (traffic light, etc.)



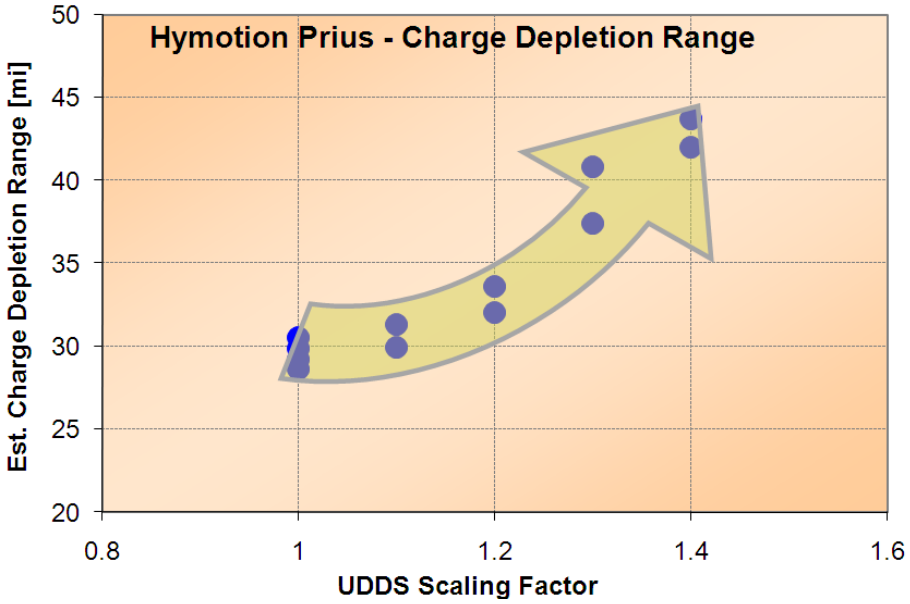
Petroleum Displacement is a Function of Battery Power and Capacity

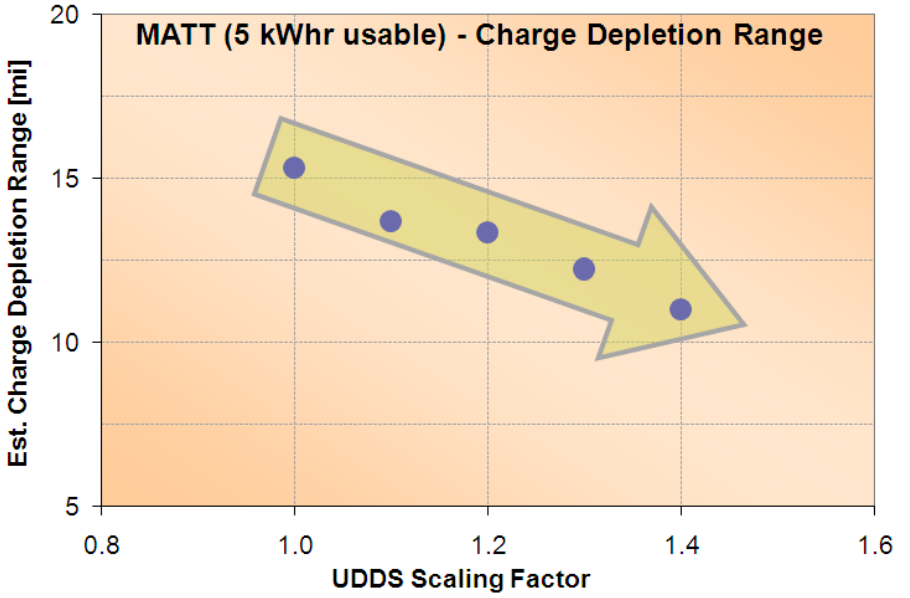
- Shaded area shows petroleum displacement of PHEV compared to same HEV
- Slope of MATT PHEV results are less showing less fuel consumption sensitivity to driver aggressiveness



Charge Depletion Range is Dependant on Driving Intensity

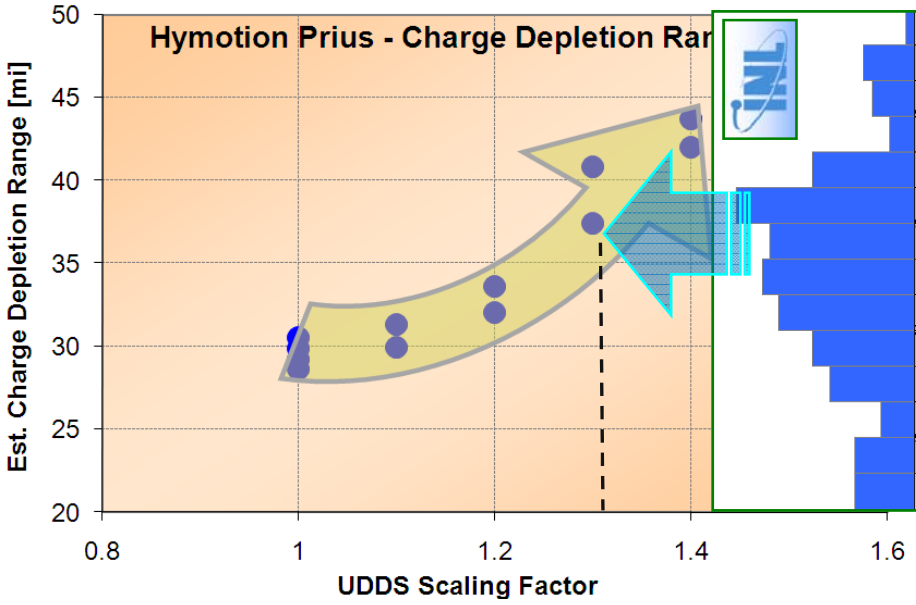
- Battery Power is also influential to Charge Depletion Range
  - Blended PHEV: Range increases with increasing driving intensity
  - All-Electric Capable: Range decreases with increasing driving intensity

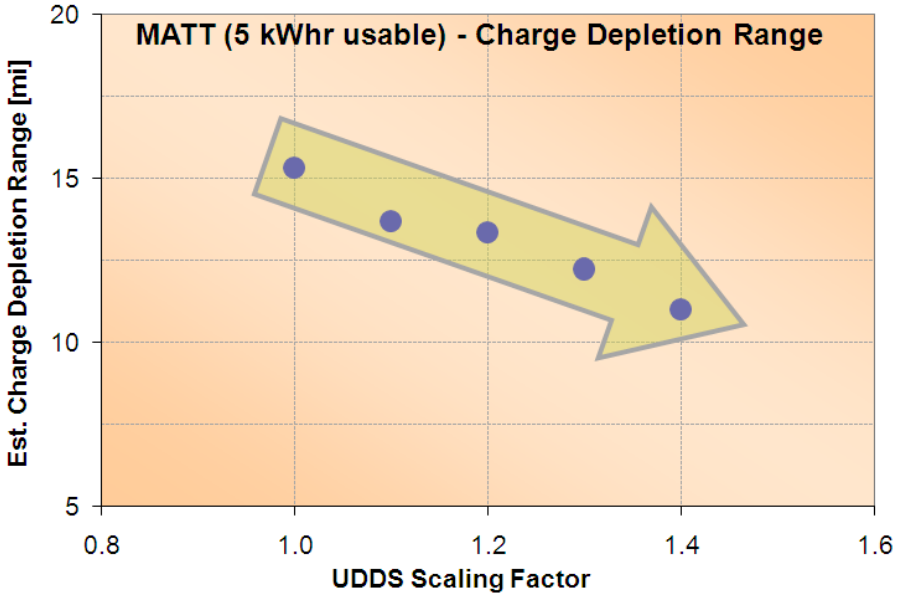




Charge Depletion Range is Dependant on Driving Intensity

- Battery Power is also influential to Charge Depletion Range
  - Blended PHEV: Range increases with increasing driving intensity
  - Average fleet data CD range is between 35-40 miles which roughly correlates to the UDDSx1.3
  - All-Electric Capable: Range decreases with increasing driving intensity





Future Work

- Evaluate Li-Ion “battery replacement” style PHEV in sub-freezing conditions to determine extent of impact / robustness on Li-Ion performance in PHEV system

- Continue to support J1711 Test Procedures and Standard committee:
  - Data and support for validating proposed test procedures (5 cycles)
  - Support with determining correlation between dynamometer testing fuel consumption and on road expected fuel consumption

- Upgrade APRF to include Sub-Freezing and Hot A/C capabilities
  - Expansion of Refrigeration System to enable -15°C Dynamometer Testing
  - Auxiliary equipment modification / upgrade for use in sub-freezing conditions
  - Humidity control and Vehicle Frontal Air Flow control as required by SC03
  - Addition of Solar Heat Load lamps and necessary controls

Summary

- Cold Ambient Temperature Operation of the Hymotion Prius
  - Fuel Consumption significantly increases with lower temperatures
    - *Engine operating time significantly increases*
    - *HC emissions increases*
    - *Battery usable capacity decreases*

- Impact of Driver Aggressiveness on PHEV Fuel Consumption
  - With Increasing Driving Intensity:
    - *Generally fuel consumption increases*
      - magnitude of increase is highly dependant on battery power and capacity
    - *Petroleum Displacement is also dependant on battery power and capacity*
    - *Charge Depletion Range can decrease, increase, or remain constant depending on battery power and capacity*