National Renewable Energy Laboratory
Innovation for Our Energy Future

Emissions and Fuel Consumption Test Results from a Plug-In Hybrid Electric School Bus

DOE Annual Merit Review

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Organization: NREL

June 8, 2010

Project ID: VSS007

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Project Overview

Timeline

- Project funded late in FY08
- Project conducted in FY09
  - July 2009 testing
  - August 2009 data post processing
- Project is 100% complete

Budget

- Total project funding
  - DOE: $59k
- In-kind support received from project partners

Barriers Addressed

- Users and OEMs need 3rd party dynamometer data to benchmark technologies
- Selection of representative drive cycles
- Test cycle-specific PHEV benefit via petroleum reduction

Project Partners

- Enova
- Adams County School District
- Navistar, IC Corp

Project Relevance

Chassis testing is important for electric drive vehicles

- HEVs add a disconnect between engine and vehicle operation
- PHEVs add two more complexities
  - Fuel and electricity consumption
  - Performance dependence on distance

Project Objective

- Measure energy consumption and emissions of PHEV and diesel baseline school buses on relevant drive cycles
  - Benchmark technology
  - Data for dynamic model validation
- Supports the VTP Programs Strategic Goal of: *Support the laboratory and field evaluations of large-scale demonstration fleets of advanced commercial and passenger PHEVs and EVs.*

Project Approach

Test Vehicles

	PHEV School Bus	Diesel School Bus
Chassis / Integrator	2007 IC Corp / Enova	2008 Bluebird
Engine	6.4L MAXXFORCE 149 kW (200 hp)	7.2L Caterpillar 261 kW (350 hp)
Electric Motor	25/80 kW (cont./peak)	NA
Traction Battery	Valence U24-12XP 370 V, 100 Ah, 35.8 kWh	NA
Test mass (lbs)	27,850	24,550
Passenger Capacity	72	72
DPF-equipped	Yes	Yes

Project Approach

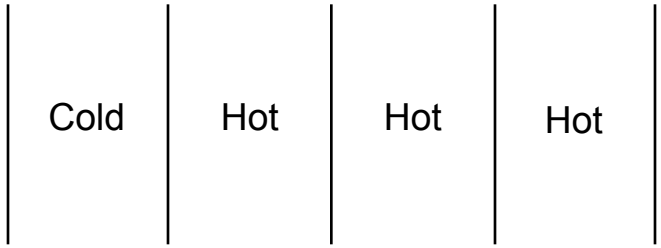
Test Cycle Selection

Drive Cycle Characteristic	Data Avg. (stdev)	UDDSHDV	RUCSBC	OCTA
Average Driving Speed (mph)	25.56 (3.93)	28.23	26.59	15.67
Stops per Mile	1.17 (0.46)	2.52	1.44	4.74
Avg. Acceleration (ft/s^2)	1.71 (0.22)	1.58	2.10	1.49
Avg. Deceleration (ft/s^2)	-1.95 (0.24)	-1.89	-2.44	-2.09
Accelerations per Mile	15.20 (4.57)	17.29	10.62	11.47
Decelerations per Mile	14.96 (4.54)	13.87	10.62	11.47
Kinetic Intensity (km^{-1})	0.83 (0.49)	0.38	1.05	2.23

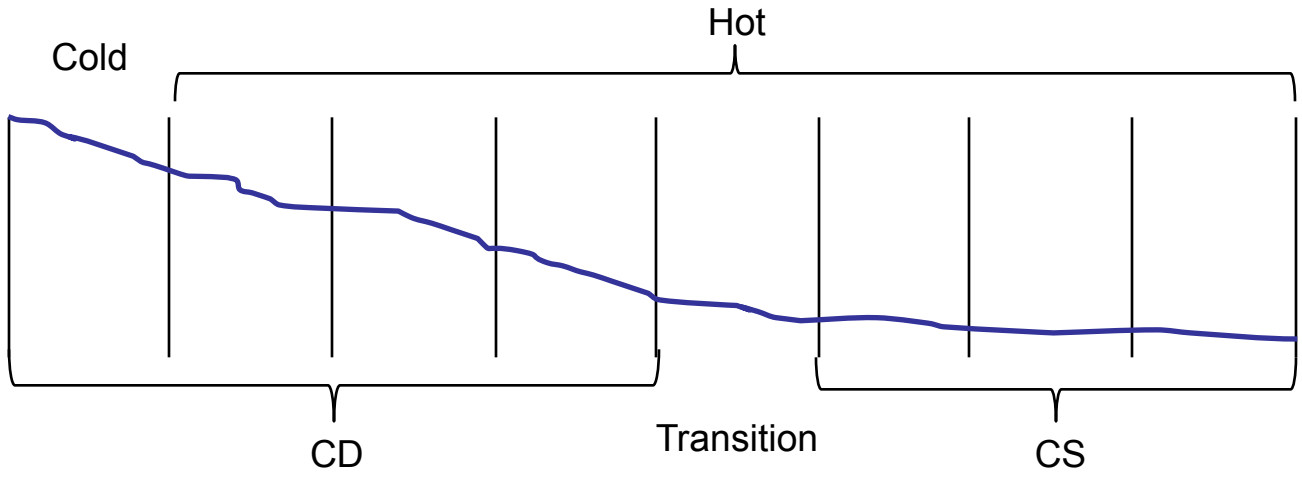
Project Approach

Test Plan

- Three drive cycles: UDDSHDV, RUCSBC, OC Bus
- Baseline (plus PHEV with hybrid system off for UDDSHDV & OC Bus)
  - Hot-start replicates



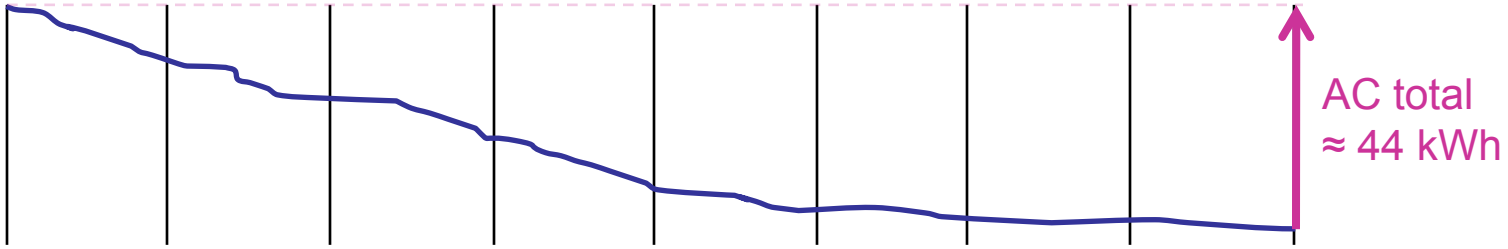
- PHEV
  - Hot-start charge-depleting (CD) and hot-start charge-sustaining (CS) replicates



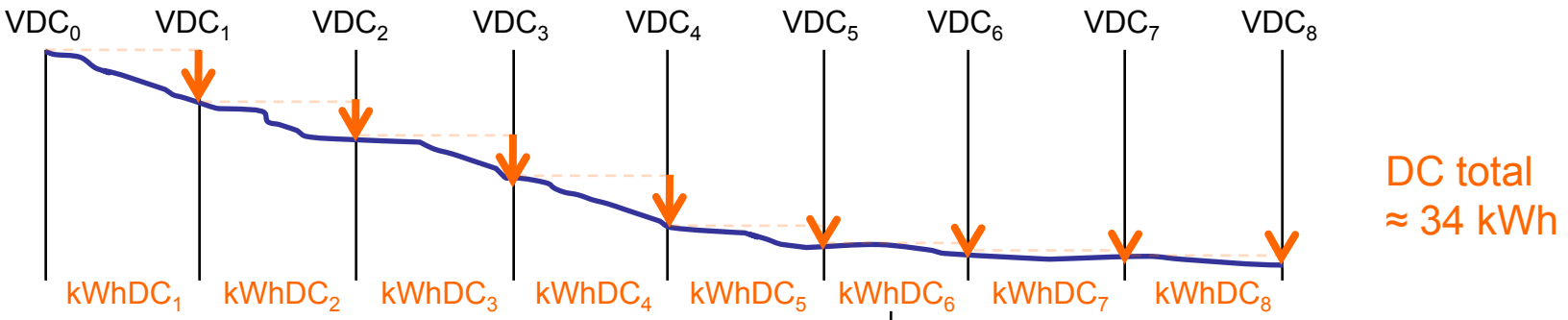
Project Approach

Electrical Charging test methods and charge accounting

- Measure AC recharge kWh at end of each complete test



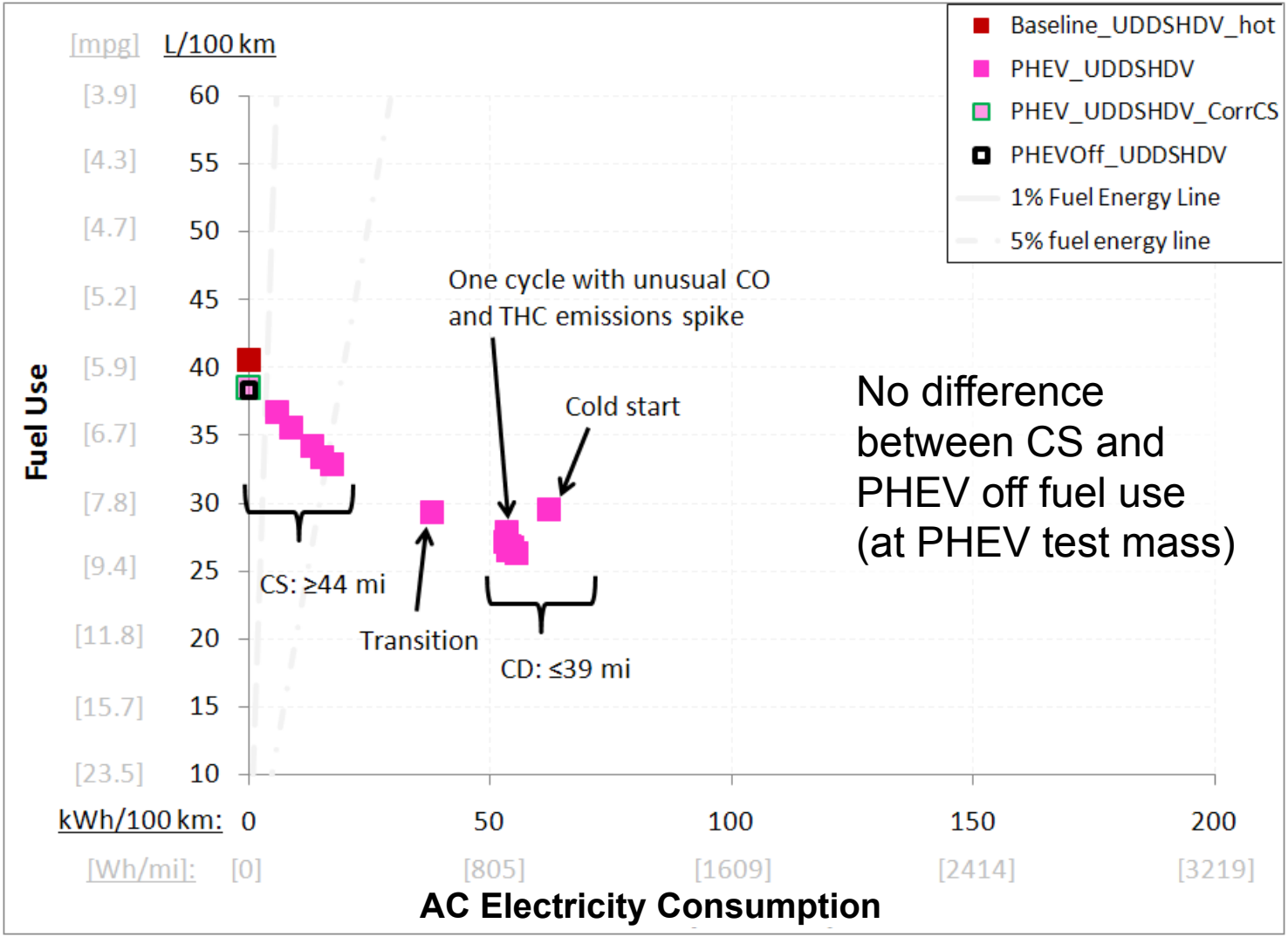
- Determine per-cycle and total DC kWh
  - DC Ah during, CAN-reported voltage before and after each cycle



- Calculate per-cycle AC kWh, e.g.: $kWhAC_6 = kWhDC_6 * \frac{\text{AC total}}{\text{DC total}}$

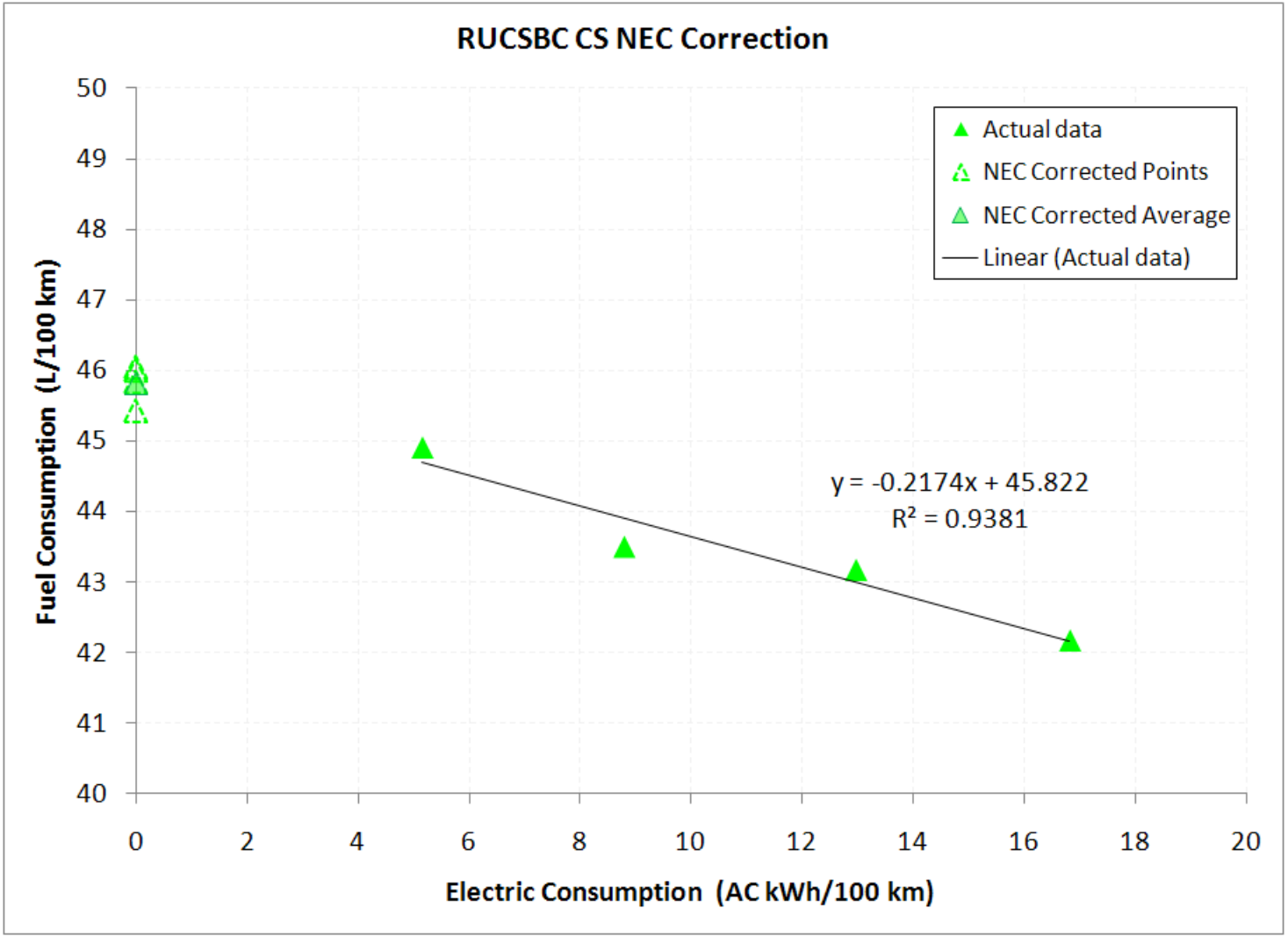
Technical Accomplishments

UDDSHDV Test Results



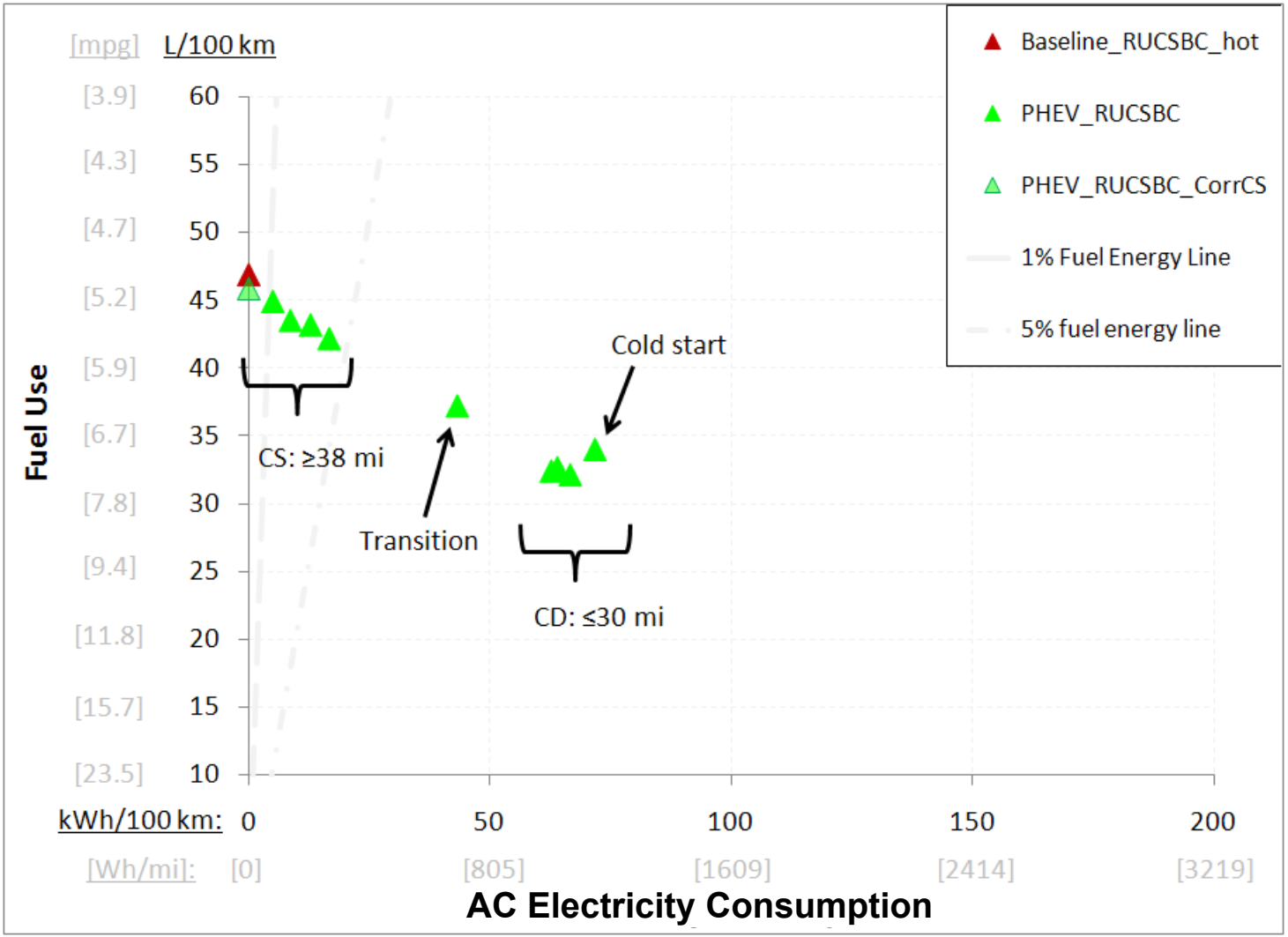
Technical Accomplishments

CS Net Energy Change (NEC) Correction Procedure



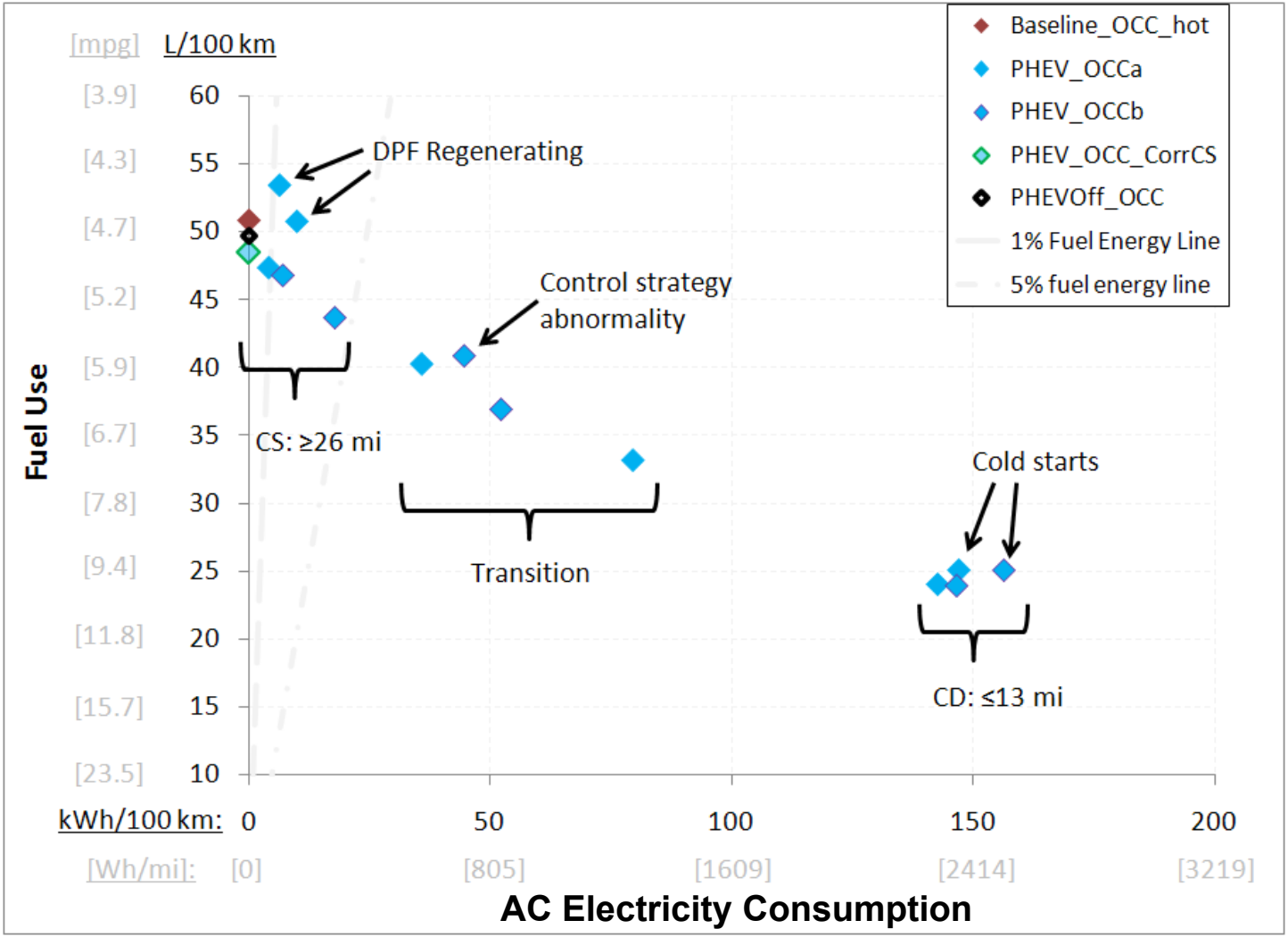
Technical Accomplishments

RUCSBC Test Results



Technical Accomplishments

OC Bus Test Results



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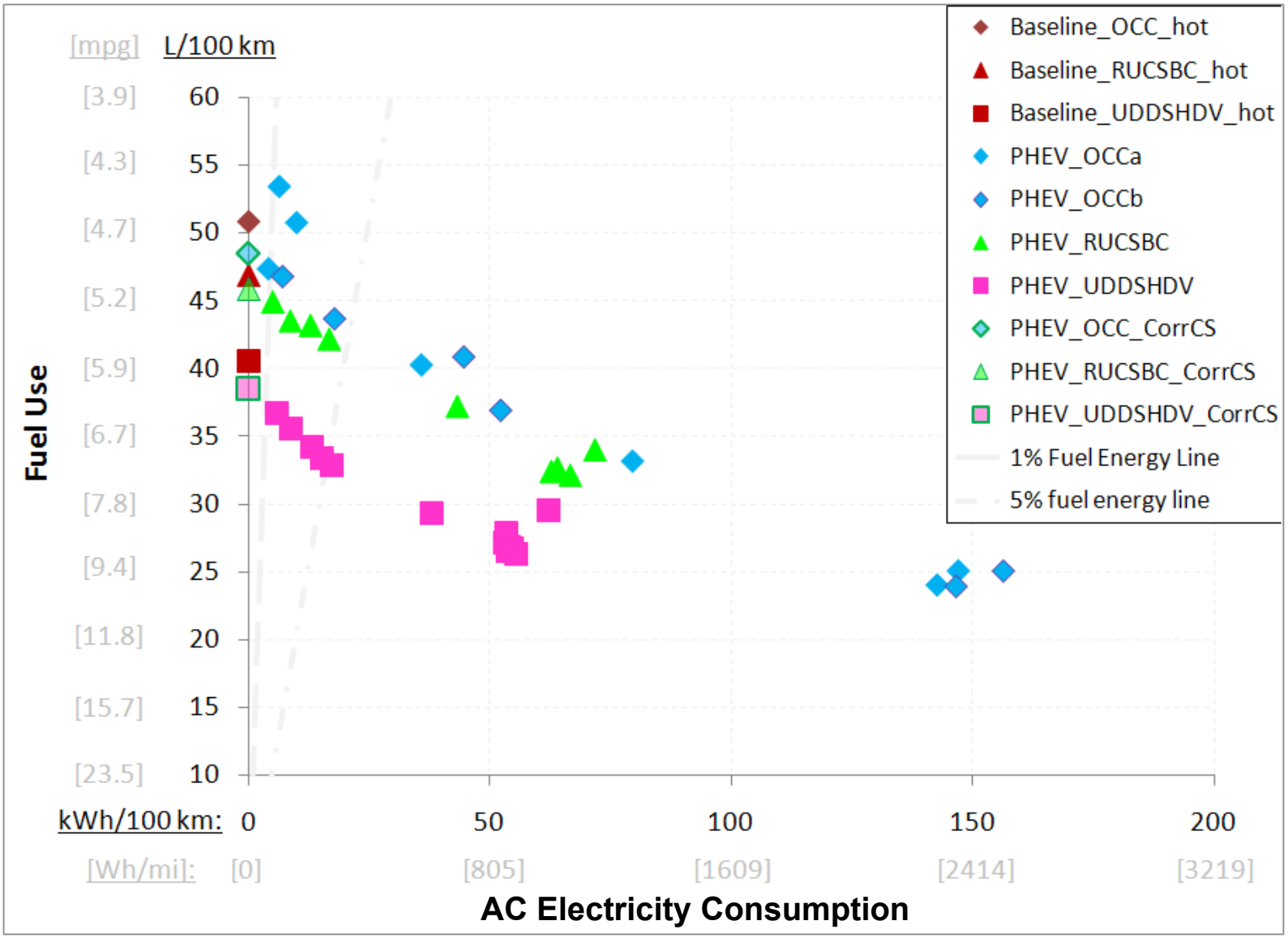

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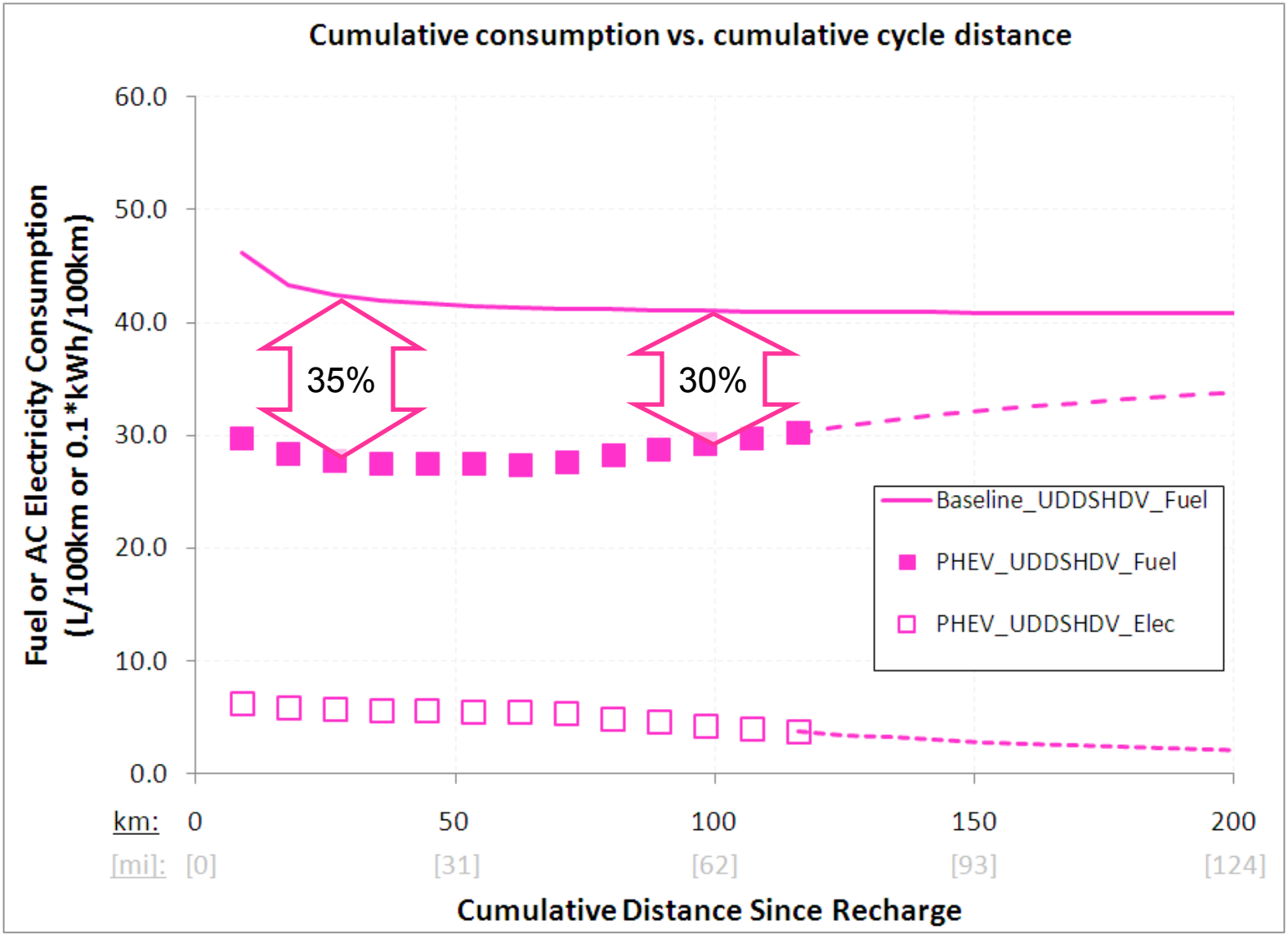

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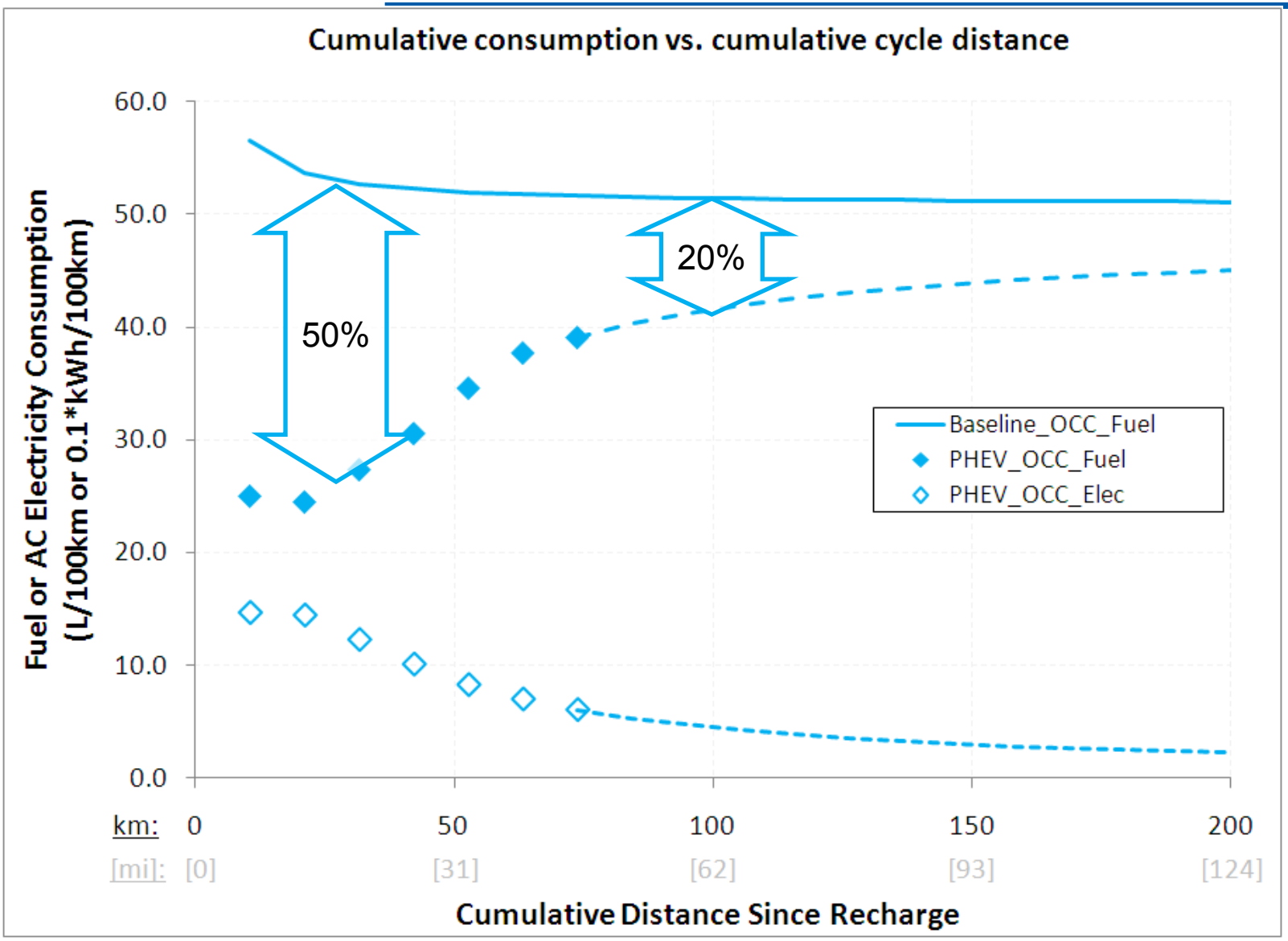

Technical Accomplishments

Vehicle, Cycle	Operating Mode	Fuel Consumption L/100 km Avg, Stdev (mpg Avg)		% Change vs. Base	Electric Consumption AC kWh/100 km Avg, Stdev		NOx g/mi Avg, Stdev		% Change vs. Base	Cyc Energy/Dist bhp-h/mi Avg	% Chg. vs. Base
Baseline, UDDSHDV	N/A	40.5 (5.8)	0.4	N/A	0	0	4.3	0.05	N/A	1.30	N/A
PHEV, UDDSHDV	CD (<39 mi)	26.8 (8.8)	0.3	-34%	53.9	0.6	5.0	0.15	17%	1.62	25%
PHEV, UDDSHDV	CS (>44 mi)	38.6 (6.1)	0.1	-5%	0.0	0.0	5.7	0.08	32%	1.58	21%
Baseline, RUCSBC	N/A	46.9 (5.0)	0.6	N/A	0.0	0.0	5.0	0.07	N/A	2.03	N/A
PHEV, RUCSBC	CD (<30 mi)	32.4 (7.3)	0.3	-31%	64.5	2.0	4.8	0.01	-4%	2.41	19%
PHEV, RUCSBC	CS (>38 mi)	45.8 (5.1)	0.3	-2%	0.0	0.0	5.6	0.12	12%	2.33	15%
Baseline, OCC	N/A	50.8 (4.6)	0.2	N/A	0.0	0.0	4.2	0.05	N/A	1.67	N/A
PHEV, OCC	CD (<13 mi)	24.0 (9.8)	0.1	-53%	144.6	2.6	5.9	0.02	39%	2.02	21%
PHEV, OCC	CS (>26 mi)	48.6 (4.8)	0.1	-4%	0.0	0.0	9.6	0.17	128%	1.94	16%

From hot start replicates; cycles with DPF regeneration or abnormal behavior have been excluded
PM ≤0.01 g/mi for all cycles
PHEV bus power capability in CS mode was reduced, resulting in some trace miss

Summary

- Comparison testing of two school buses
  - Baseline: 7.2 L engine, ≈25k lb test mass
  - PHEV: 6.4 L engine, ≈ 28k lb test mass
- PHEV technology can save a significant amount of fuel
  - Savings magnitude depends on both **driving type** and **distance between charging**
- Improvement opportunities for tested PHEV school bus for fuel and emissions benefit
  - Implement a lower-NOx engine calibration (at Denver's altitude)
  - Improve CS (HEV) mode implementation (further reduce NOx and fuel use)

Collaborations

- Hybrid system specifications, data acquisition support
- Engine and drivetrain specifications
- Chassis specifications
- Drive cycle data
  - Adams County School District
  - Austin Independent School District
  - North Carolina school districts

Future Work

While this project is complete, related work continues and will leverage results:

- NREL's Advanced Vehicle Test Activity (AVTA) is supporting Navistar 'Next Gen' PHEV School Bus development
  - Drive cycle data collection
- NREL's Vehicle Systems Analysis group will utilize measured fuel consumption and SOC data to validate dynamic model of school bus
- Assess design tradeoffs with varied architectures, component sizes
- Leverage real world drive cycle data to optimize design for performance (intensity and range), fuel consumption and cost

Special thanks to:

- Lee Slezak, DOE Vehicle Technologies Program

NREL contacts:

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Questions?

Extra slides

Test Facility: Heavy-duty vehicle (chassis) and two engine dynamometers with emissions measurement capability

- Chassis test range: Class 3 - 8
  - 8,000 - 80,000 lb vehicle testing through combination of mechanical (flywheels) and electrical (DC motor) inertia
  - Twin 40” rolls (adjustable wheelbase)
- Regulated emissions measurement for 2010 heavy-duty on-road engine technology (2007 CFR)
  - Emissions equipment includes Horiba Mexa bench with additional NOx analyzers, FTIR, PEMS, Particulate mass and size (using FMPS)
- High accuracy (+/- 0.5% reading) fuel metering
  - Used for fuel consumption reporting
- Variable altitude testing capability (sea level to mile high)
  - School bus tests conducted at local (Denver) altitude

ReFUEL Laboratory

Relationship between PHEV fuel and electricity consumption