NREL
NATIONAL RENEWABLE ENERGY LABORATORY

Emissions from Medium-Duty Conventional and Diesel-Electric Hybrid Vehicles

24th CRC Real World Emission Workshop

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San Diego, California

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NREL is a national laboratory of the U.S. Department of Energy, Office of Energy Efficiency and Renewable Energy, operated by the Alliance for Sustainable Energy, LLC.

Background

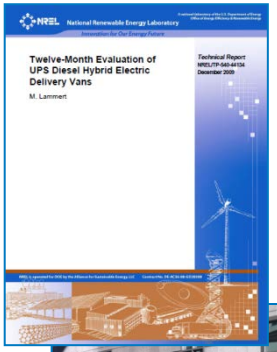
- **National Renewable Energy Laboratory (NREL) Fleet Testing and Evaluation**
  - Primarily funded by the U.S. Department of Energy's (DOE) Vehicle Technologies Office under Lee Slezak
- **Overview**
  - Field evaluation approach
  - Fleet DNA drive cycle database
  - ReFUEL chassis dynamometer
  - Results: fuel economy and tailpipe NO_x emissions
    - Parcel delivery (Class-6 step vans)
    - Beverage delivery (Class-8 tractors)
    - Parcel delivery (Class-7 box trucks)
    - All with intended service class MHDD
  - Summary
  - Next steps: ongoing work between NREL and CARB

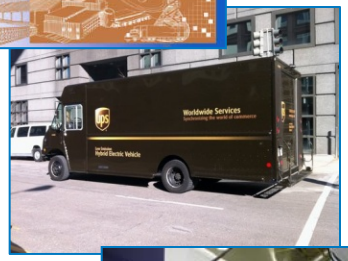
Fleet Evaluation Team - Objectives

- **Test and analyze:** near-term advanced technologies in-service and compare to conventional technologies in similar service

- **Provide unbiased, 3rd party performance data:** to potential vehicle customers and OEMs as needed to make informed decisions on advanced technology vehicle purchases and fleet implementation

- **Provide data, analysis and feedback**: to the R&D community (including other offices and programs within DOE) to guide technology development that will lead to fuel-saving, commercially available products





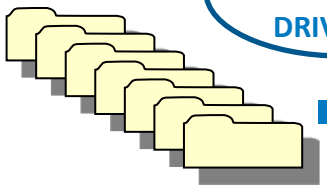
Approach – Data Acquisition and Analysis Tools

1. **Enhanced data collection capabilities:**
   - Controller Area Network (CAN) (standard and proprietary advanced technology parameters)
   - GPS route data collection and analysis for chassis dyno and simulation testing

2. **Analysis Capabilities:** multiple methods to assess performance of new technology in service, automated processes – most analyzed data to be supplied to Fleet DNA (public database on usage)

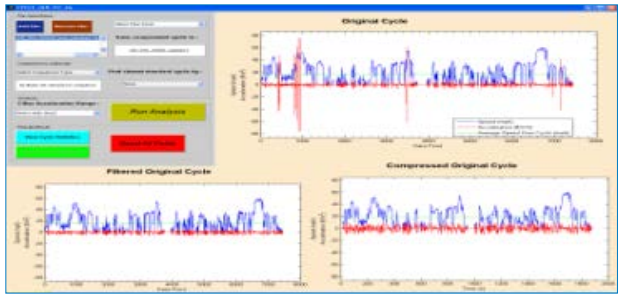
On-Board Data Collection

Data Analysis



Collect sets of GPS, CAN & analog data (per day or per shift)

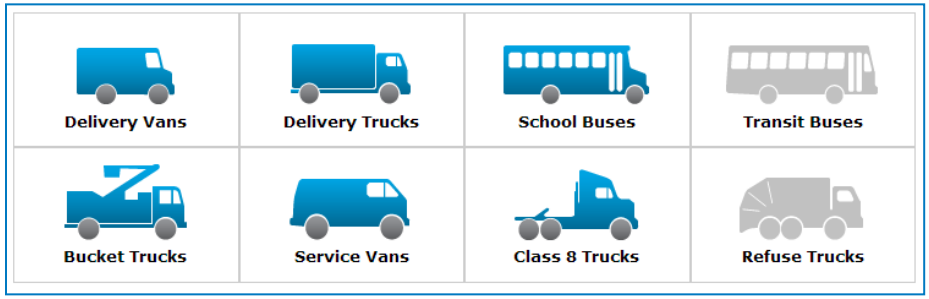
Drive cycle analysis tool = DRIVE



- Full understanding of supplied data: daily variation info; 150 stats for original, filtered and shortened data
- User-specific test cycle generated

Current Fleet DNA Data Summary :

- 620 vehicles
- 4,687 days
- 340,875 miles
- 77 deployments



http://www.nrel.gov/vehiclesandfuels/fleettest/research_fleet_dna.html

Chassis Dynamometer Test Cell

Test Range: 8,000–80,000 lb (Class 3-8)

- Twin 40” rolls (adjustable wheelbase)
- 380 hp DC motor

Features

- Programmable driver’s aid
- Electrical / mechanical inertia simulation
- Augmented braking
- Grade simulation
- Automated warm-up & coast-downs
- CVS emissions tunnel

Data Acquisition

- Emissions: Regulated emissions measurement for 2010 HD on-road engine technology (CFR, Part 1065)
- Fuel Economy: High accuracy (+/- 0.5% reading) fuel metering, gravimetric and carbon balance

Drive Cycle Data Collection

Data Collected Using Isaac Instruments GPS+CAN data logging devices

- 25+ vehicle parameters
  - 1Hz sampling rate
  - GPS Route Capture
  - CAN signals collected using J1939 protocols

- **Vehicle selection**
  - Advanced technologies
  - Comparison vehicles
    - MY / make / model / GVWR
    - Engine / emissions
    - VMT
- **Depot refueling records**

UPS Diesel HEV Class-6 Walk-In Step Vans

In-service Field Testing:

- Minneapolis, MN
- 18 month evaluation
- 11 second-generation diesel HEV
- 11 conventional diesel vehicles

Data collected:

- Fuel economy and maintenance records
- 1Hz J1939 ECU data
- GPS route data logging
- Drive cycle characterization
- NREL-ReFUEL dynamometer testing

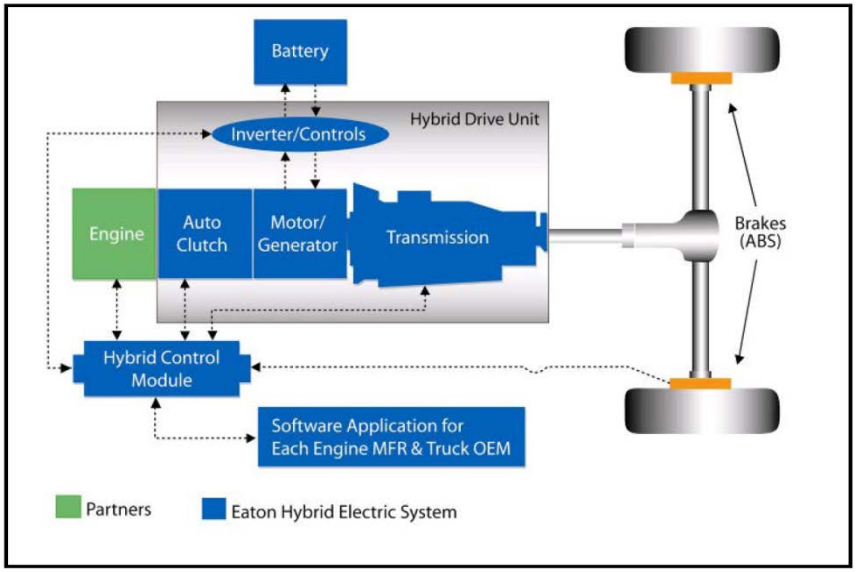
Details:

- 338 driving days of diesel HEV operation
- 252 driving days of conventional diesel operation
- Eaton Hybrid System
- Engine off at idle technology

UPS Diesel HEV Class-6 Walk-In Step Vans

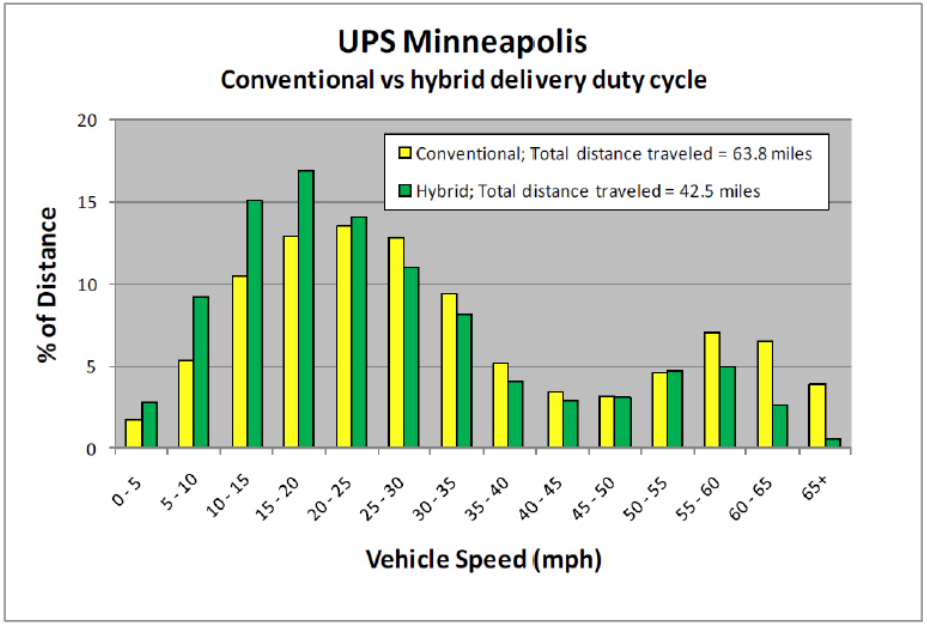
	Hybrid Electric	Conventional Diesel
Chassis manufacturer/model	Utilimaster P100H	Morgan Olson Freightliner P100D
Chassis model year	2010	2010
Engine manufacturer/model	Cummins ISB	Cummins ISB
Engine model year	2009	2009
Engine emissions certifications	EPA and CARB	EPA and CARB
Engine ratings Maximum horsepower Maximum torque	 200 hp @ 2,300 rpm 520 ft-lbs @ 1,600 rpm	 200 hp @ 2,300 rpm 520 ft-lbs @ 1,600 rpm
Diesel fuel capacity	30 gal	30 gal
Transmission manufacturer/ model	Eaton automated manual	Allison Auto HS 2200 Series
Curb weight (lb)	12,000	10,800
Gross vehicle weight rating (lb)	23,000	23,000
Retarder/regenerative braking	Regenerative brakes	N/A
Advanced emission-control equipment	DPF	DPF
Cabin air conditioning	No	No
Rear axle ratio	4.10	4.10

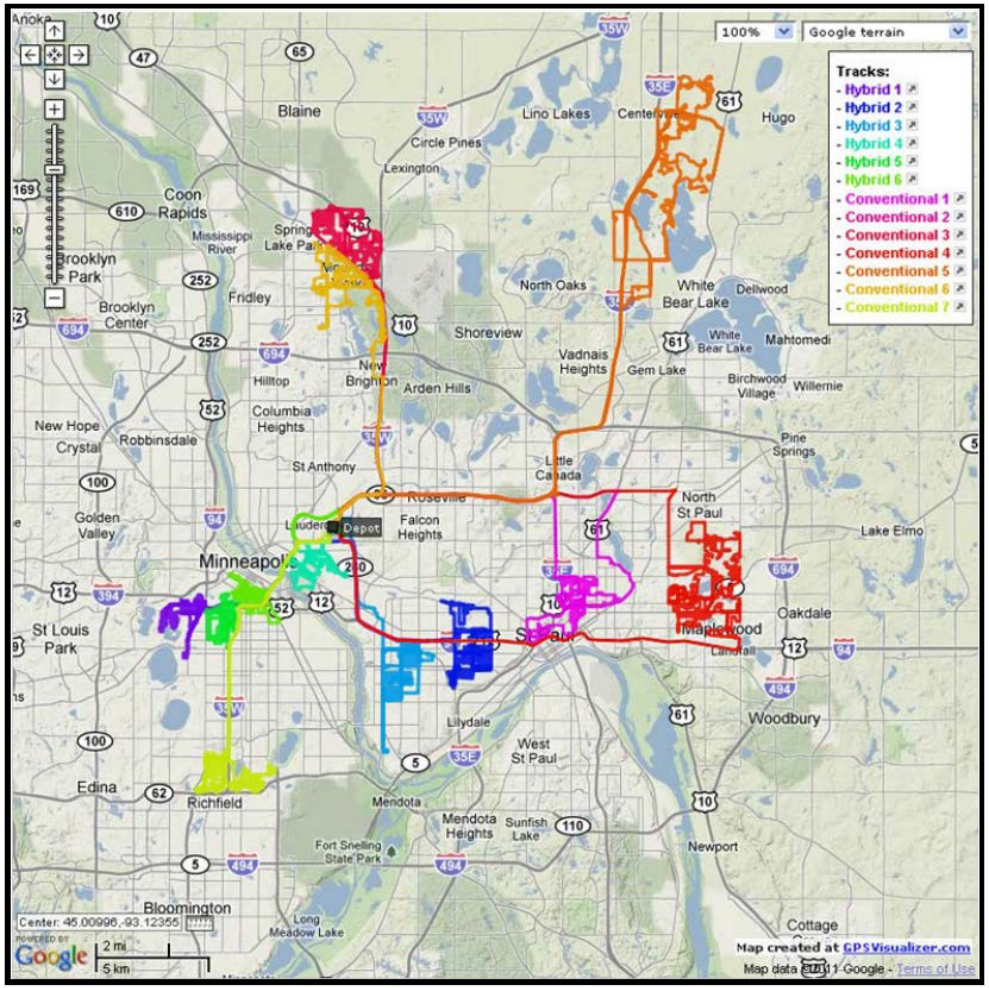
Category	Hybrid System Description
Manufacturer/integrator	Eaton Corporation
Transmission	Fuller medium-duty automated 6-speed manual
Electric Motor	Synchronous brushless with permanent magnet
	26 kW continuous power
	44 kW peak power
Energy storage	Lithium ion batteries
	340 VDC
	1.8 kWh total storage



UPS Diesel HEV Class-6 Walk-In Step Vans

- Hybrid vans drove 44% of distance below 20 mph, conventional vans drove only 30.5%
- Hybrid vans drove 13% of distance above 50 mph, while conventional vans drove 22%





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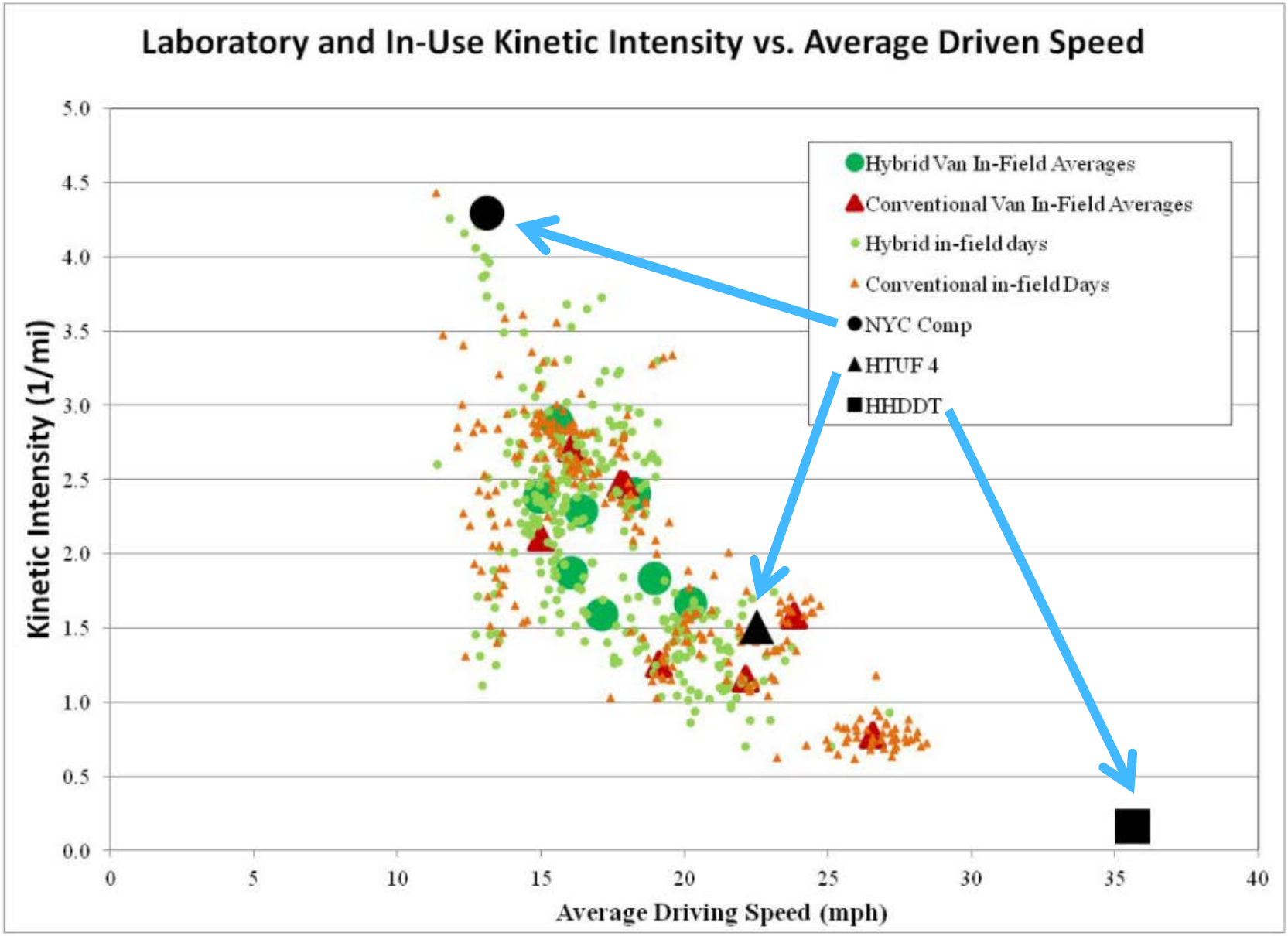
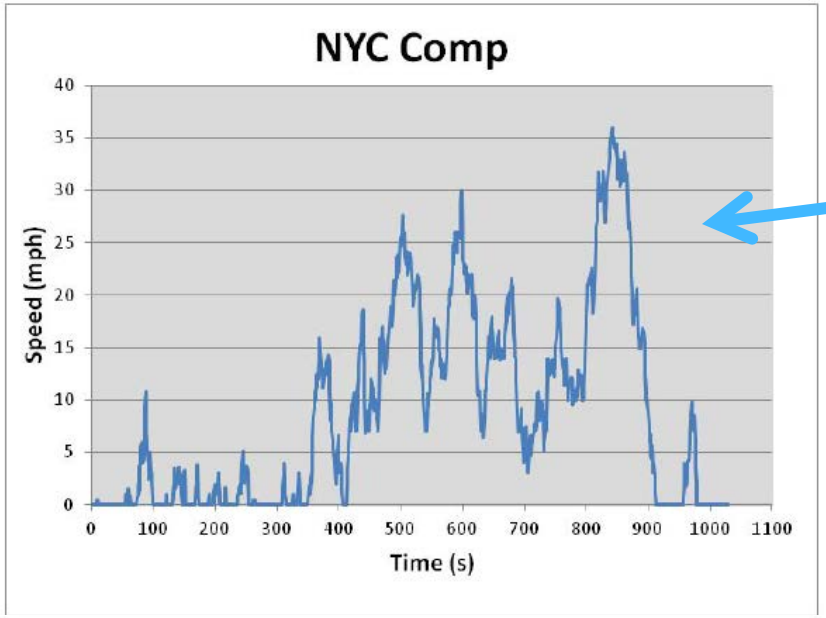
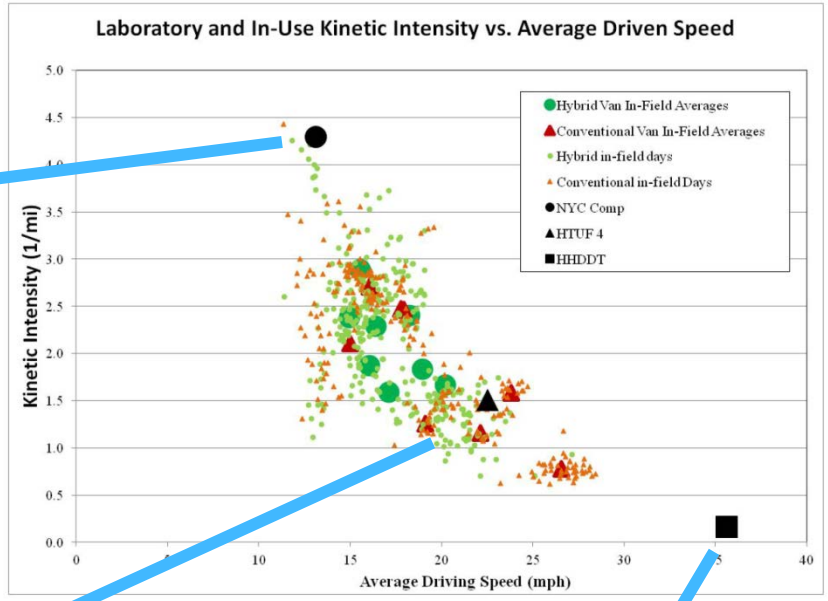
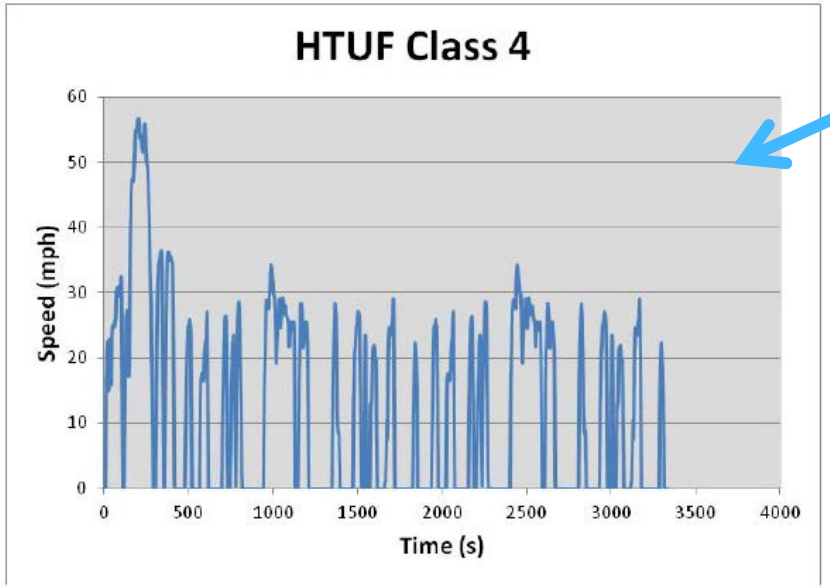
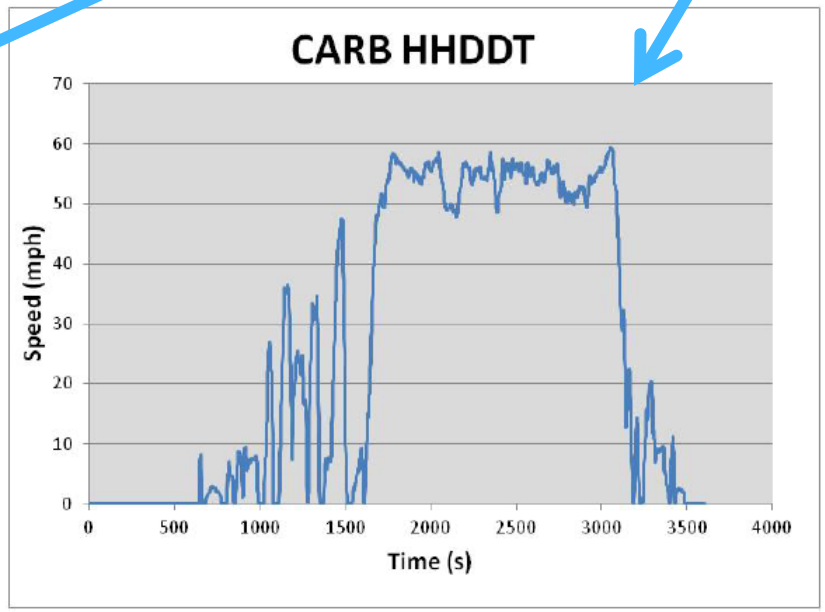


UPS Diesel HEV Class-6 Walk-In Step Vans





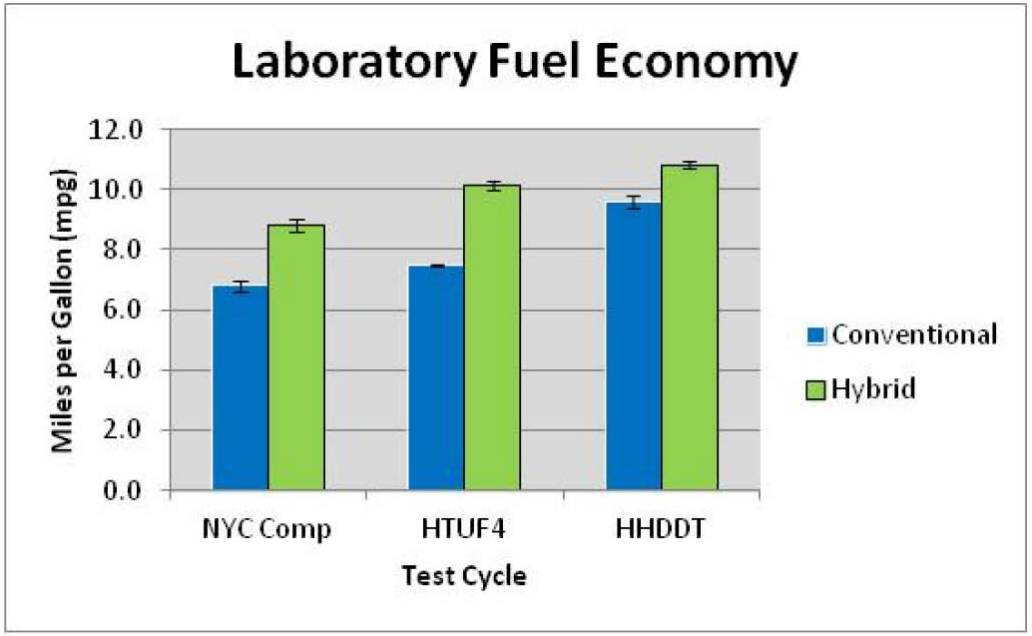




UPS Diesel HEV Class-6 Walk-In Step Vans

- **Fuel Economy Increase (13% to 36%)**
- **Annual Fuel Savings (176 to 610) gal/Veh**

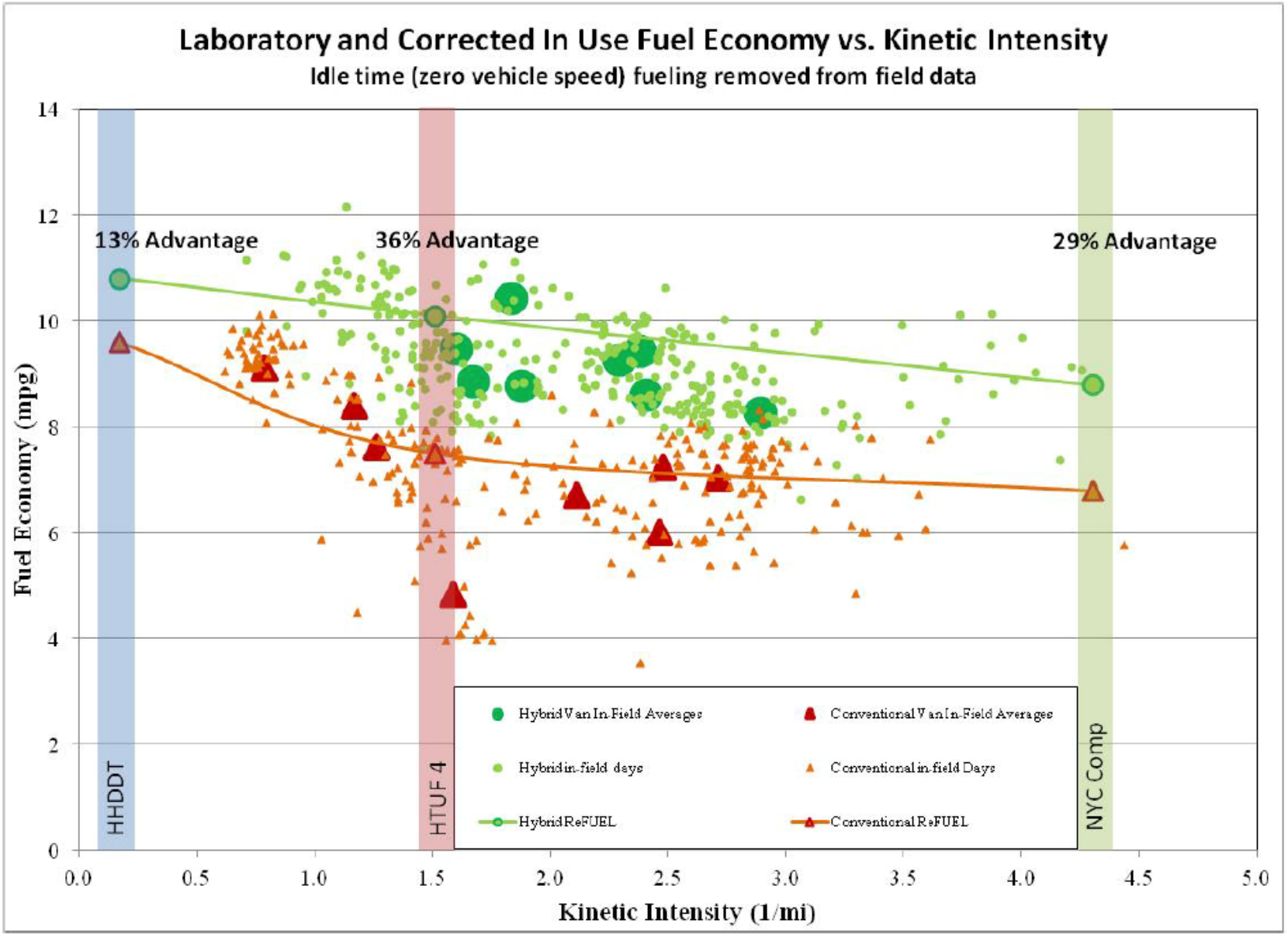
Gravimetric Fuel Economy	NYC Comp	HTUF4	HHDDT
Conventional P100D	6.8	7.5	9.6
Hybrid P100H (mpg)	8.8	10.2	10.9
Hybrid Advantage	29%	36%	13%
T test P Value	0.0001	0.0000	0.0002



Gallons Saved per Van Year of Operation								
Miles per Day	30	40	50	60	70	80	90	100
NYC Comp	254.7	339.6	424.5					
HTUF 4	261.5	348.7	435.9	523.1	610.3			
HHDDT				176.4	205.8	235.2	264.6	294.0

* Based on 254 delivery days a year as with this study period

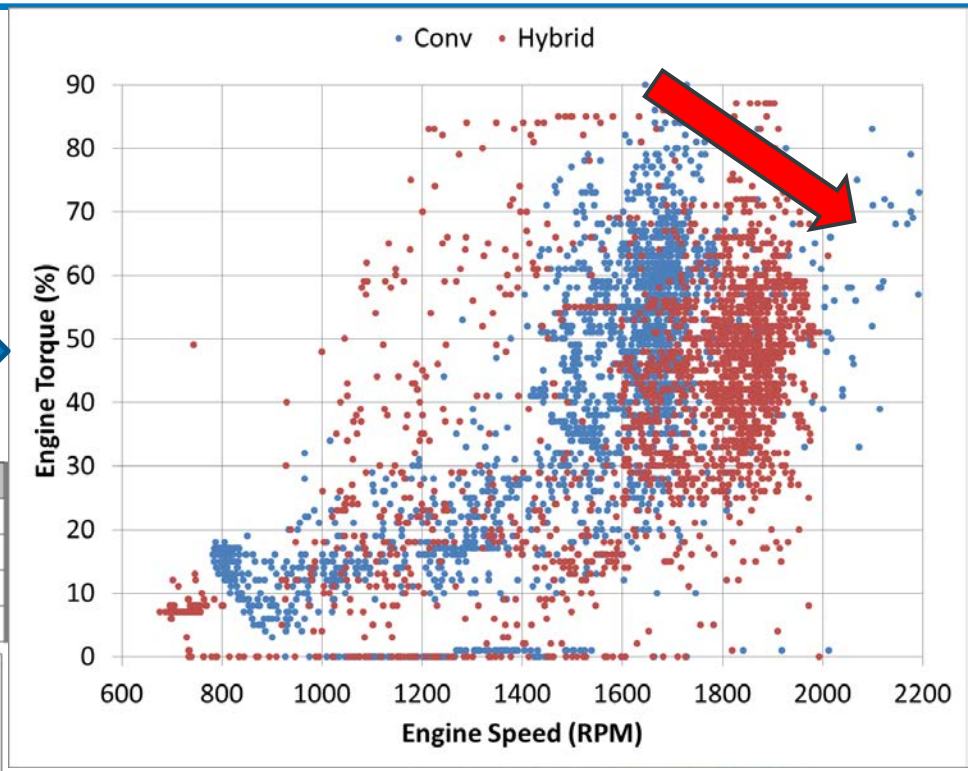
UPS Diesel HEV Class-6 Walk-In Step Vans

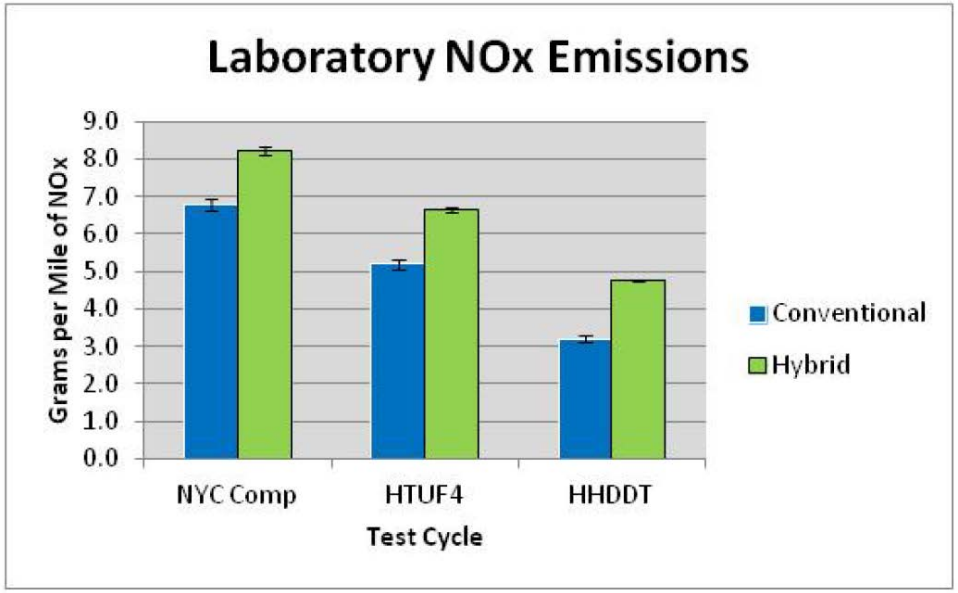


UPS Diesel HEV Class-6 Walk-In Step Vans

- **Engine Out NO_x Increase For All Cycles (21% to 49%)**
- **Hybrid Engine Operates in a Different Region**

NOx Emissions	NYC Comp	HTUF4	HHDDT
Conventional P100D (g/mile)	6.8	5.2	3.2
Hybrid P100H (g/mile)	8.2	6.6	4.8
Hybrid Increase (%)	21%	28%	49%
t-test P Value	0.0001	0.0001	0.0000





Coca-Cola Diesel HEV Class-8 Tractors

In-service Field Testing:

- Miami, Florida
- 12 month evaluation
- 5 class-8 diesel HEV tractors
- 5 conventional diesel tractors

Data collected:

- Fuel economy and maintenance records
- 1Hz J1939 ECU data
- GPS route data logging
- Drive cycle characterization
- NREL-ReFUEL dynamometer testing

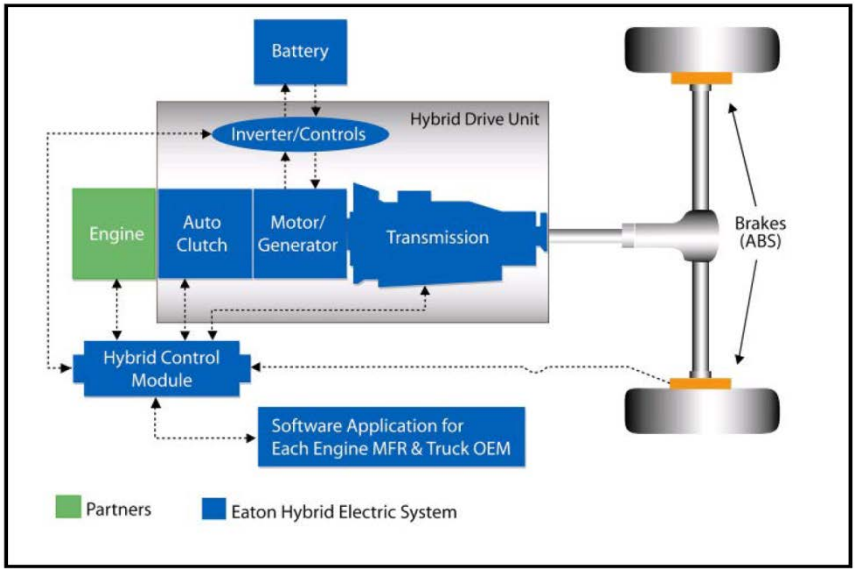
Details:

- Eaton Hybrid System

Coca-Cola Diesel HEV Class-8 Tractors

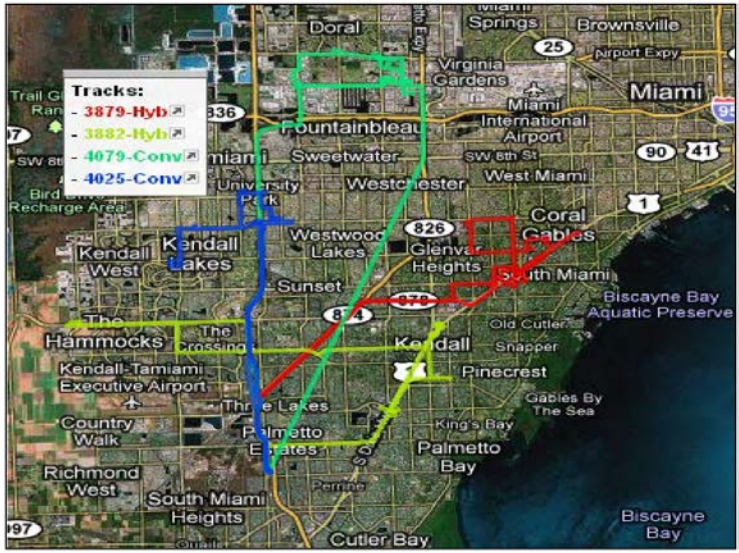
	Hybrid Electric	Conventional Diesel
Chassis manufacturer/model	Kenworth T370	Freightliner M2106
Chassis model year	2010	2009
Engine manufacturer/model	PACCAR PX-6 280	Cummins ISC-285
Engine model year	2009	2008
Engine emissions certifications	EPA 2007, CARB 2008 (Clean Idle)	EPA 2007, CARB 2008 (Clean Idle)
Engine ratings Maximum horsepower Maximum torque	 280 hp @ 2,300 rpm 660 lb-ft @ 1,600 rpm	 285 hp @ 2,000 rpm 800 lb-ft @ 1,300 rpm
Fuel capacity	56 gal	80 gal
Transmission manufacturer/ model	Eaton Fuller UltraShift automatic	Eaton Fuller T-14607 seven-speed manual
Curb weight	11,600 lb	11,140 lb
Gross vehicle weight rating	34,700 lb	34,700 lb
Retarder/regenerative braking	Regenerative braking	None
Advanced emission-control equipment	Diesel particulate filter	Diesel particulate filter
Cabin air conditioning	Yes	Yes

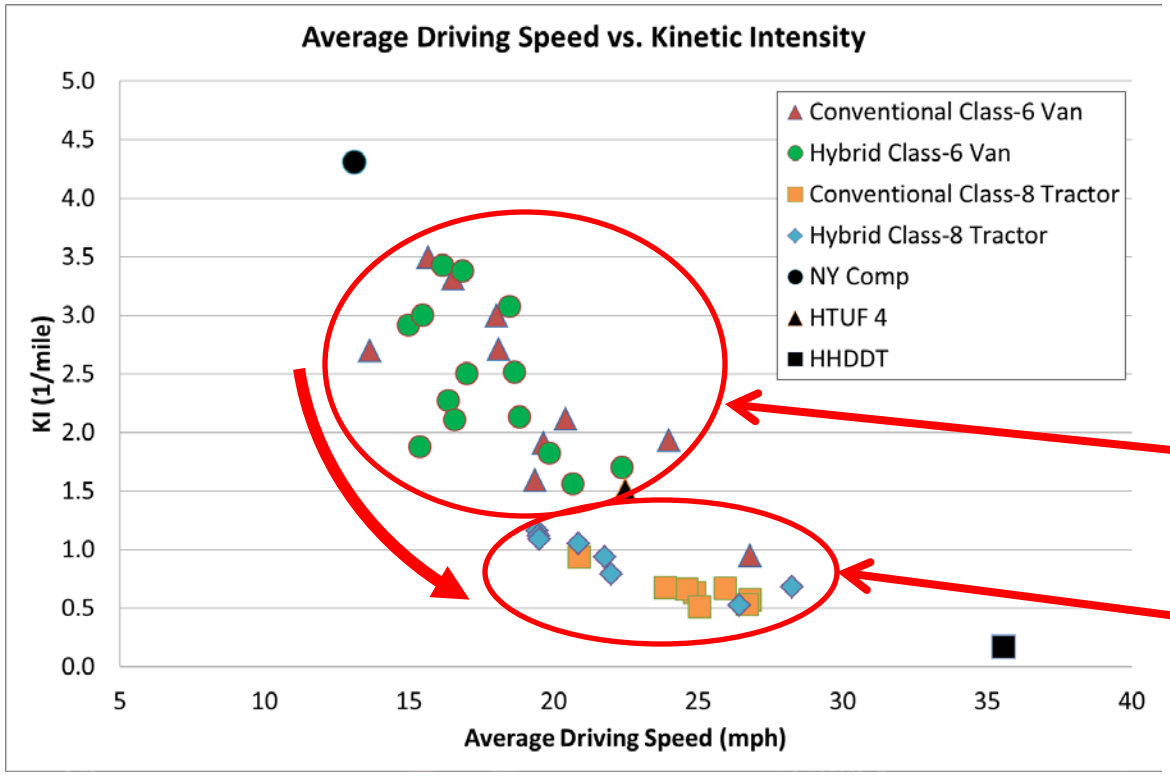
Category	Hybrid System Description
Manufacturer/integrator	Eaton Corporation
Transmission	Fuller medium-duty automated 6-speed manual
Electric Motor	Synchronous brushless with permanent magnet
	26 kW continuous power
	44 kW peak power
Energy storage	Lithium ion batteries
	340 VDC
	1.8 kWh total storage



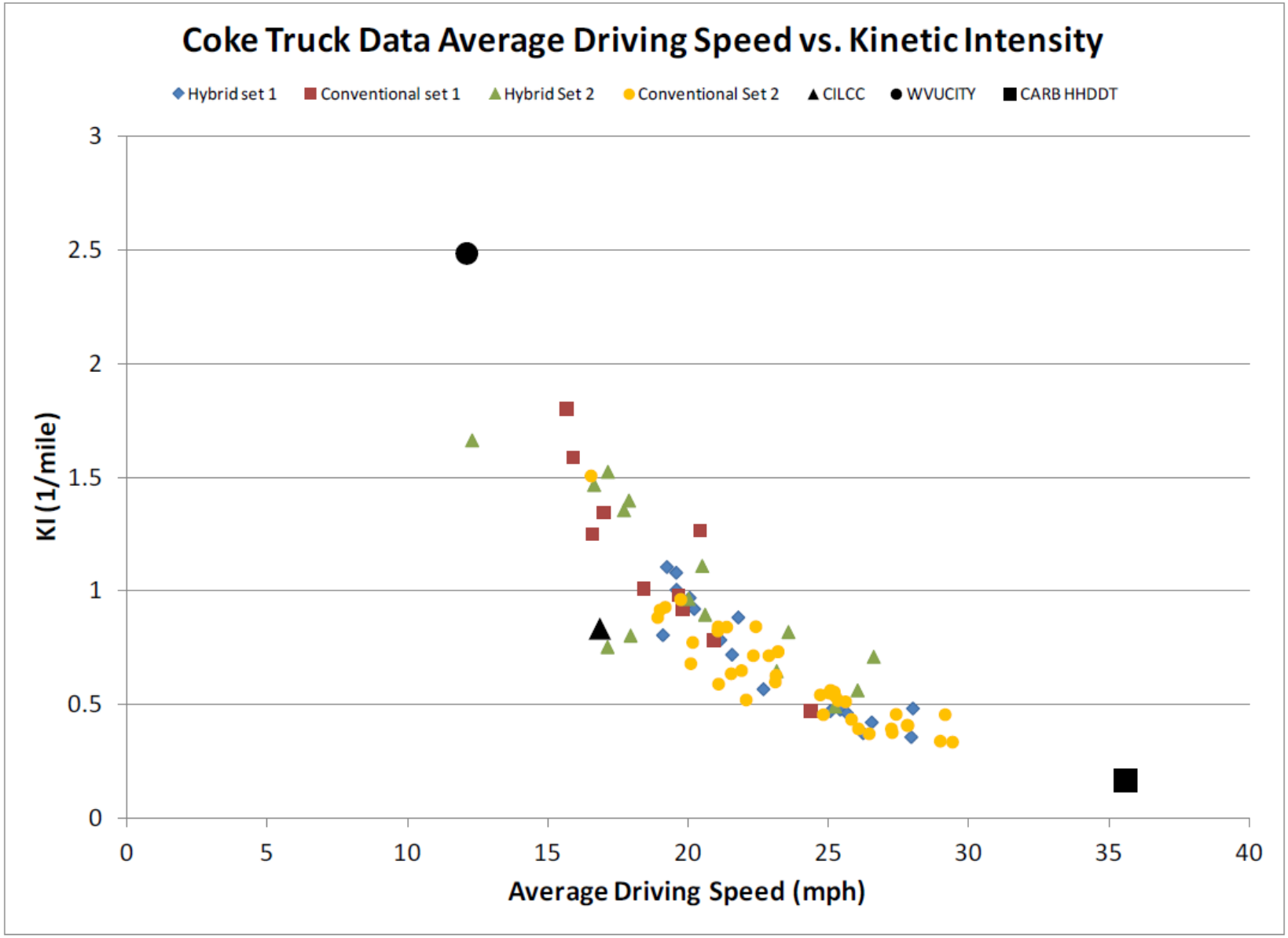
Coca-Cola Diesel HEV Class-8 Tractors

- **As Expected Class-8 Tractors**
  - Lower Kinetic Intensity
  - Higher Average Driving Speed



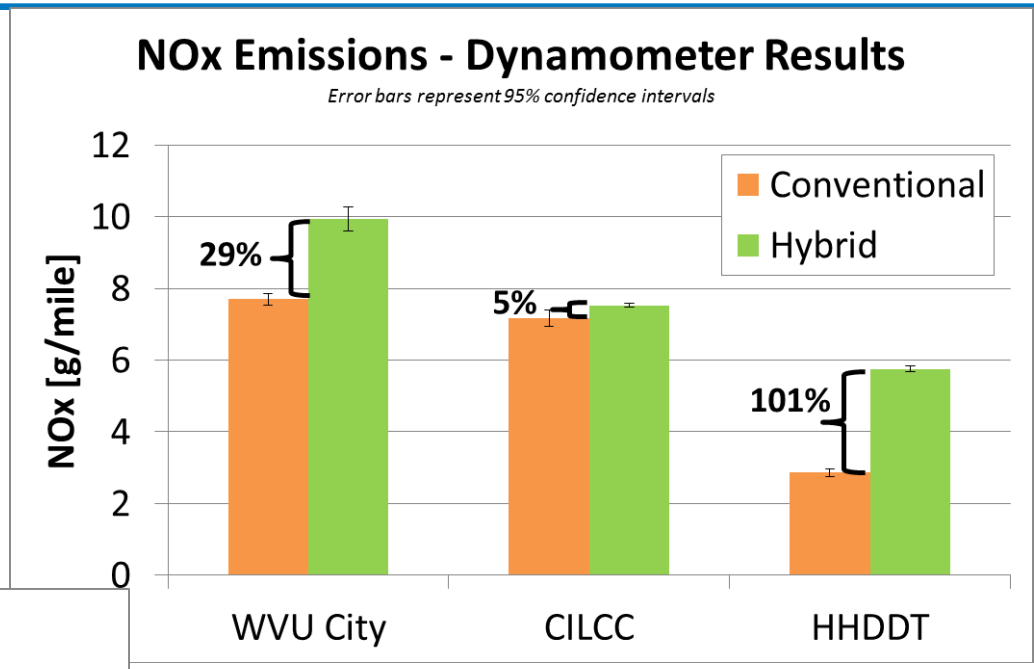


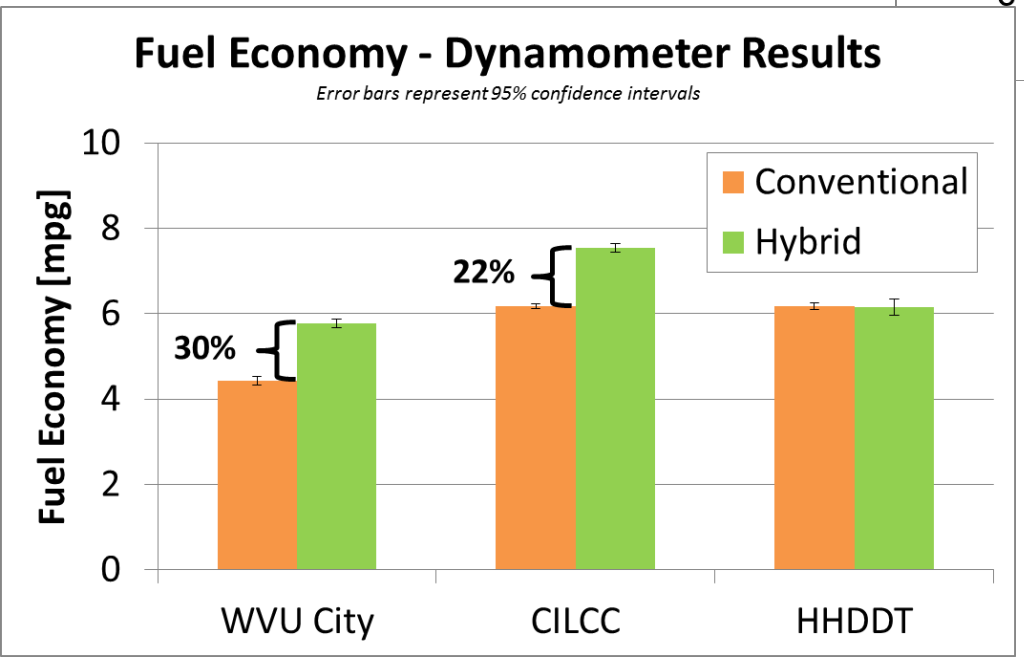
Coca-Cola Diesel HEV Class-8 Tractors



Coca-Cola Diesel HEV Class-8 Tractors

- **Fuel Economy Increase**
  - 0% to 30%
- **Hybrid NO_x Increase**
  - 5% to 101%





FedEx Diesel HEV Class-7 Box Trucks

Accomplishment:

- Ontario, CA
- 6 month evaluation
- 6 FedEx HEV Class 7 trucks
- 6 conventional 2010 diesel trucks

Data collected:

- Fuel economy and maintenance records
- 1Hz J1939 ECU data
- GPS route data logging
- Drive cycle characterization
- NREL-ReFUEL dynamometer testing

Details:

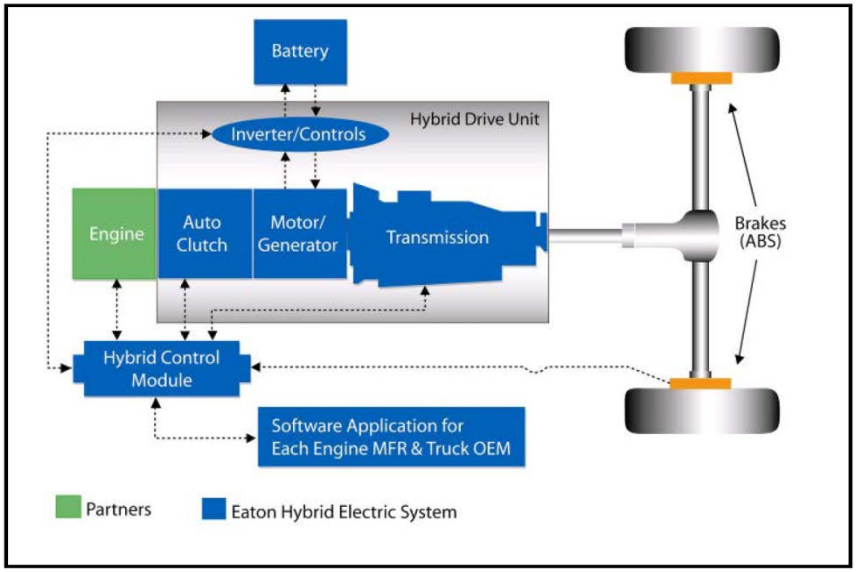
- Eaton Hybrid System

FedEx Diesel HEV Class-7 Box Trucks

	Conventional Truck	Hybrid Electric Truck
Truck Manuf.	Freightliner	Freightliner
Truck Model	M2-106	M2-106
Truck Model Year	2010	2010
Engine Manuf.	Cummins	Cummins
Engine Model	ISB 6.7 220	ISB 6.7 200
Engine Power (HP)	220 @ 2300 rpm	250*
Engine Date of Manuf.	2010	2009
NO_x EPA FEL (g/bhphr)	0.33	0.40*
Emissions Aftertreatment	DOC, DPF, SCR	DOC, DPF, SCR
Transmission	Allison automatic	Eaton auto-shift hybrid
Gross Vehicle Weight (lbs.)	32,000	32,000
Curb Vehicle Weight (lbs.) (empty)	18,220	18,900
Max Payload (lbs.)	13,780	13,100

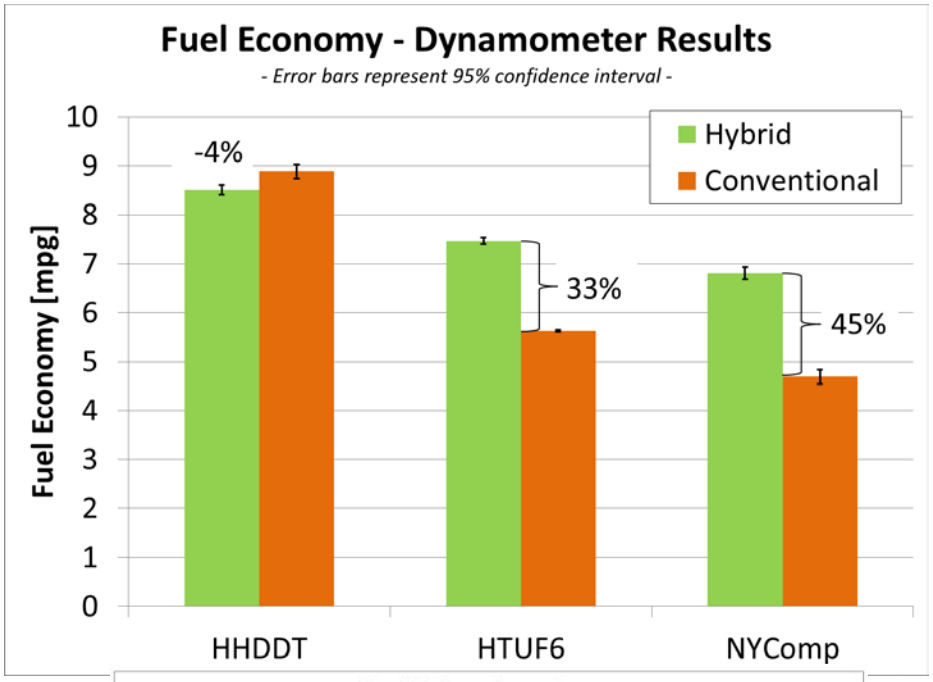
*The original calibration of the HEVs engines were 200 HP @2300 rpm but were changed to 250 HP after delivery of vehicles to FedEx. It is unknown what the FEL of the updated calibration is so the original 0.40 level could be incorrect. The HEV transmission calibrations were also switched to "performance" mode at this same time to help improve overall acceleration of the vehicles by adjusting shift timing.

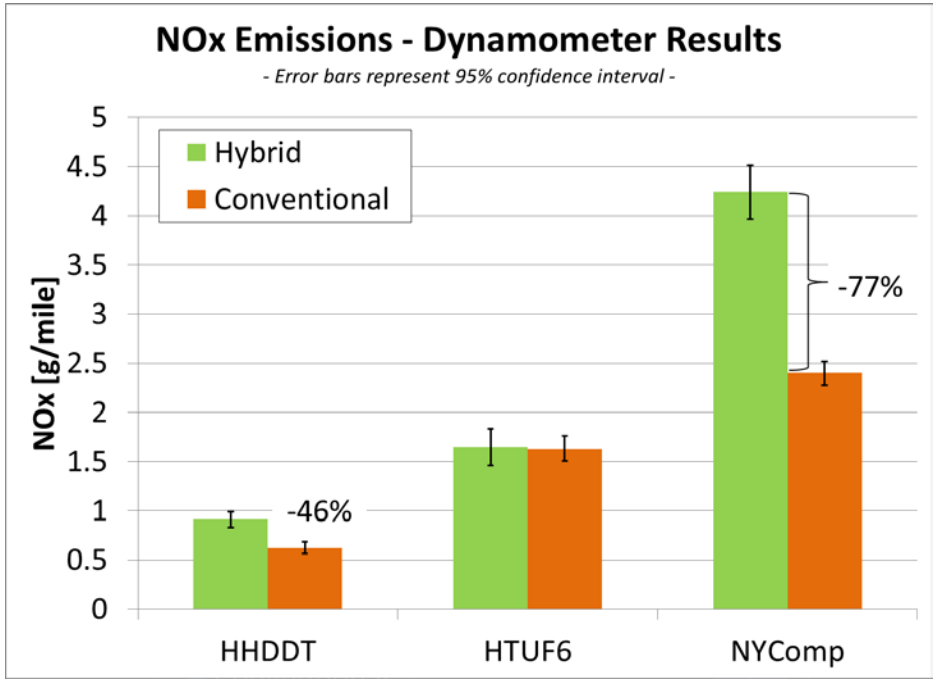
Category	Hybrid System Description
Manufacturer/integrator	Eaton Corporation
Transmission	Fuller medium-duty automated 6-speed manual
Electric Motor	Synchronous brushless with permanent magnet
	26 kW continuous power
	44 kW peak power
Energy storage	Lithium ion batteries
	340 VDC
	1.8 kWh total storage

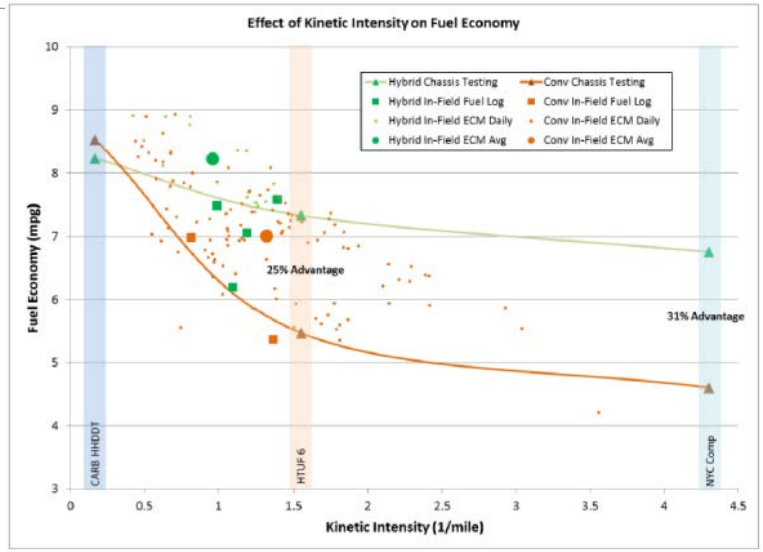


FedEx Diesel HEV Class-7 Box Trucks

- **Fuel Economy Increase**
  - -4% to 45%
- **Hybrid NO_x Increase**
  - 0% to 77%

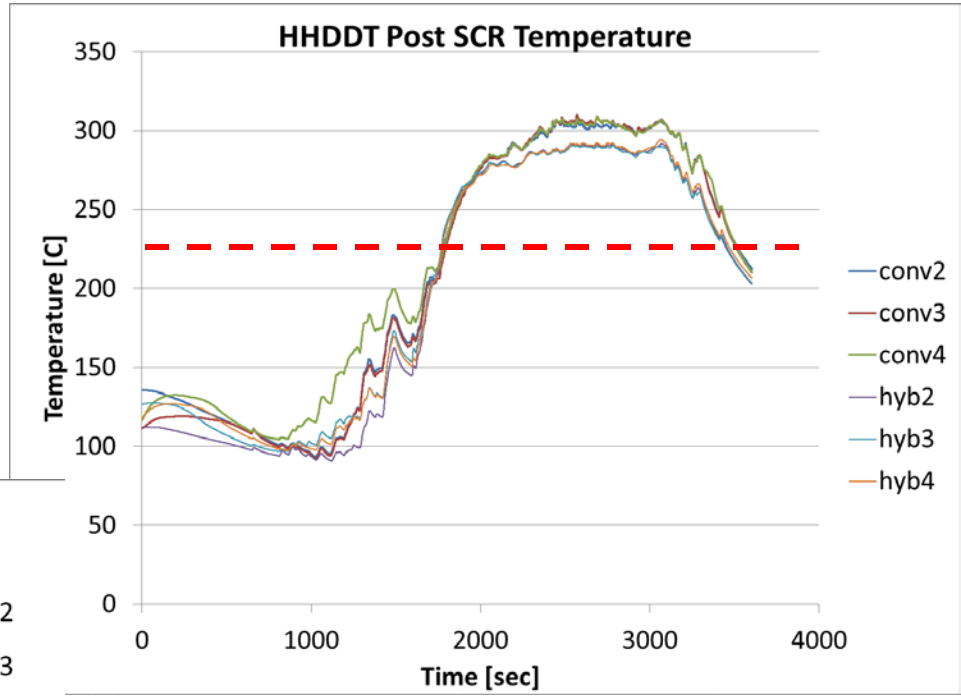


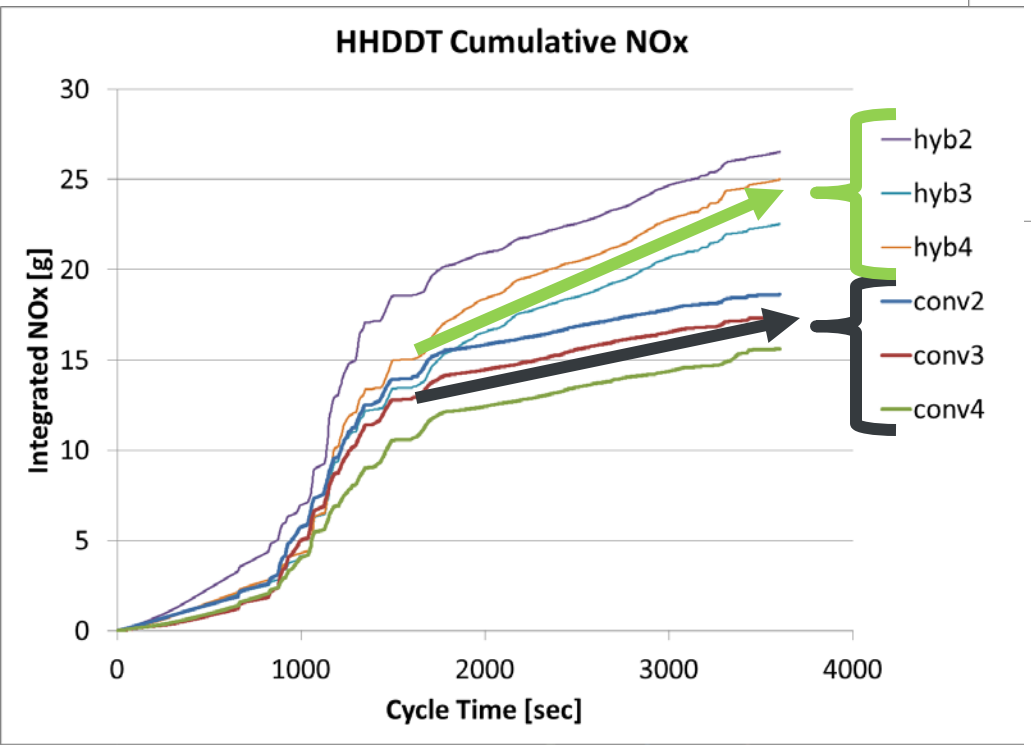


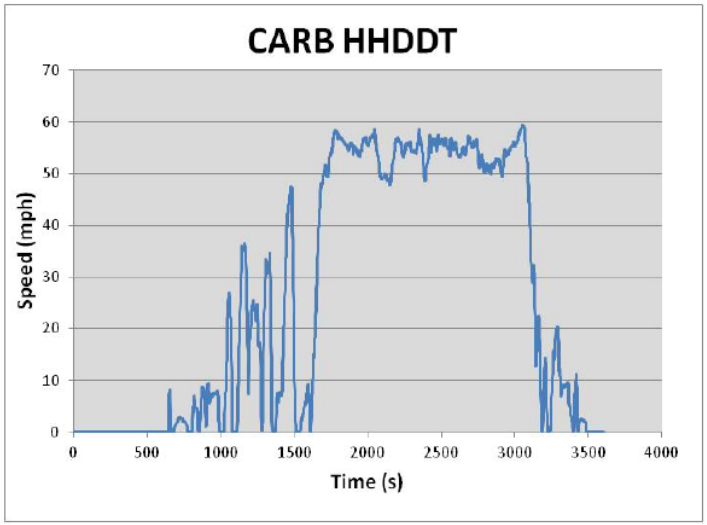


FedEx Diesel HEV Class-7 Box Trucks

- **SCR system becomes active**
  - NOx emission rate reduced from both vehicles
  - However, hybrid NOx emissions continue to exceed the conventional diesel







Results Summary

- **Diesel HEVs average fuel economy advantage on identified test cycles**
  - Class-6 Step Vans: 26%
  - Class-7 Box Trucks: 24.7%
  - Class-8 Tractors: 17.3%
  - VMT is an important factor in determining total petroleum and CO_2 displacement
- **Higher NO_x emissions were observed over some test cycles**
  - Highly drive cycle dependent
  - Engine out differences may result from different engine operating point
  - SCR temperature may play a role, but does not explain the whole story

Next Steps: In-Depth NO_x Analysis

- **Expand field data collection and lab tests to provide better understanding of hybrid vs conventional**
  - Current NREL and CARB collaborative work
    - Target MY 2010+ SCR equipped vehicles
    - In-use field evaluation with OEM NOx sensors recording (100+ vehicles)
    - PEMS testing of select vehicles
    - Chassis testing of select vehicles
- **Investigate vertically integrated solutions**
  - Hino 195 vs. 195h COE box trucks
- **Investigate 2014+ GHG engines**
  - Improved control of SCR with NH_3 feedback?
- **Engine operating region interaction**
  - Transmission, rear axle, tires
  - Catalyst space velocity, temperatures, secondary emissions
  - Talk with industry stakeholders
- **Engine Downsizing**
  - Engine load
  - Deterioration factor (DF)
  - Under powered
- **Testing and implication for GHG phase 2**
  - Model validation

Thank You!

- **NREL Team**
  - Matthew Thornton, Kevin Walkowicz, Jonathan Burton, Petr Sindler, Jon Cosgrove, Adam Duran, Michael Lammert
- **Partners**
  - United States Department of Energy's (DOE) Vehicle Technologies Office
  - California Air Resources Board (CARB)
  - United States Environmental Protection Agency (EPA)
  - UPS, FedEx, Coca-Cola
  - Cummins, Eaton, Navistar

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Questions?

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