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FedEx Express Gasoline Hybrid Electric Delivery Truck Evaluation: 12-Month Report

R. Barnitt

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

Technical Report
NREL/TP-5400-48896
January 2011

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Prepared under Task No. FC08.3000

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Executive Summary

This final report presents results of a technology evaluation of gasoline hybrid electric parcel delivery trucks operated by FedEx Express in and around Los Angeles, California. FedEx Express is a large commercial fleet that operates more than 30,000 motorized vehicles and has hybrid electric (diesel and gasoline) vehicles currently in service. FedEx Express has deployed 20 gasoline hybrid electric vehicles (gHEVs) on parcel delivery routes in the Sacramento and Los Angeles areas. This report presents the results of parcel delivery drive cycle data collection and analysis activities, 12-month in-use fuel economy and maintenance costs, and emissions and fuel economy results of chassis dynamometer testing of a gHEV and a comparative diesel truck at the National Renewable Energy Laboratory's (NREL's) Renewable Fuels and Lubricants (ReFUEL) laboratory.

The drive cycle data collection and analysis effort framed the selection of study vehicles and routes and structured the measurement of vehicle emissions and fuel economy on the chassis dynamometer at NREL's ReFUEL laboratory. Tailpipe emissions from the gHEV were substantially lower across all three tested drive cycles than emissions from the diesel baseline vehicle. Notably, the gHEV exhibited 75–89% lower oxides of nitrogen (NO_x) and over 99% lower particulate matter. Laboratory-measured diesel-equivalent fuel economy was similar between the gHEV (7.3 – 11.4 mpg) and diesel vehicle (6.1 – 11.7 mpg). On the most kinetically intensive drive cycle tested in the laboratory, the hybrid exhibited 21% higher fuel economy than the diesel. There was no statistical difference in calculated on-road diesel equivalent fuel economy for the gHEV (7.5 mpg) and diesel (7.9 mpg) study groups. The fuel economy findings are encouraging considering that gasoline engines in general have lower fuel economy than diesel engines. These gHEV's were able to provide similar or improved fuel economy while also providing significantly reducing emissions.

Six similar trucks were selected for this in-use evaluation project. Three of the trucks are gHEVs, and three are conventional diesel trucks that serve as a control group. Comparison data were collected and analyzed for in-use fuel economy and fuel costs, maintenance costs, total operating costs, and vehicle uptime. Based upon the data collected during this study, there was no statistically significant difference in fuel cost per mile or maintenance cost per mile between the gHEV and diesel groups. As a result, there was no statistically significant difference in total operating cost per mile between the gHEV ($0.63/mile) and diesel ($0.59/mile) groups.

The gHEVs experienced a smooth integration and deployment into commercial service. During the study period, the gHEVs performed as expected, experienced a minimum of unscheduled maintenance, and met the expectations of FedEx Express.

This technology evaluation was part of a collaborative effort co-funded by the U.S. Department of Energy's (DOE's) Vehicle Technologies Program and the South Coast Air Quality Management District (SCAQMD) via CALSTART. The in-use technology evaluation was conducted by NREL and primarily sponsored by DOE. The chassis dynamometer testing was conducted by NREL and primarily funded by SCAQMD via CALSTART.

Acronyms and Abbreviations

AC	alternating current
ATA	American Trucking Association
AZD	Azure Dynamics, Inc.
CAN	Controller Area Network
CO	carbon monoxide
CoV	coefficient of variance
DC	direct current
DOE	U.S. Department of Energy
FE	fuel economy
FT&E	Fleet Test and Evaluation
g	gram
gHEV	gasoline hybrid electric vehicle
GPS	global positioning system
HC	hydrocarbons
HP	horsepower
J	joule
KI	kinetic intensity
lb-ft	foot-pounds
mpg	miles per gallon
NOx	oxides of nitrogen
NREL	National Renewable Energy Laboratory
NYCC	New York City Cycle
OC Bus	Orange County Bus
PM	particulate matter
ReFUEL	Renewable Fuels and Lubricants
RPM	revolutions per minute
SCAQMD	South Coast Air Quality Management District
THC	total hydrocarbons
V	volt
VMT	vehicle miles traveled

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1 Background

The Fleet Test and Evaluation (FT&E) team at the National Renewable Energy Laboratory (NREL) provides unbiased evaluations of alternative fuel and advanced transportation technologies that reduce U.S. dependence on foreign oil while improving the nation's air quality. The FT&E team's role is to bridge the gap between research and development and the commercial availability of alternative fuels and advanced vehicle technologies. FT&E supports the U.S. Department of Energy's (DOE's) Vehicle Technologies Program by examining market factors and customer requirements, evaluating the performance and durability of alternative fuel and advanced technology vehicles, and assessing the performance of these vehicles in fleet applications.

The FT&E team supports vehicle research activities at NREL by conducting medium- and heavy-duty vehicle evaluations. The team's tasks include selecting appropriate technologies to validate, identifying fleets to evaluate, designing test plans, gathering on-site data, preparing technical reports, and communicating results on its Web site and in print publications. NREL has completed numerous medium- and heavy-duty vehicle evaluations based on an established data collection protocol, known as the General Evaluation Plan,[1] developed with and for DOE. This project supports DOE's Advanced Vehicle Testing Activity.

This technology evaluation was part of a collaborative effort co-funded by the DOE's Vehicle Technologies Program and CALSTART via funding from the South Coast Air Quality Management District (SCAQMD). The in-use technology evaluation was conducted by NREL and primarily sponsored by DOE. The chassis dynamometer testing was conducted by NREL and primarily funded by CALSTART via funding from SCAQMD.

2 Introduction

This document presents the final results of a technology evaluation of gasoline hybrid electric parcel delivery trucks operated by FedEx Express in and around Los Angeles, California. FedEx Express is a large commercial fleet that operates more than 30,000 motorized vehicles and has hybrid electric (diesel and gasoline) vehicles currently in service. FedEx Express has deployed 20 gasoline hybrid electric vehicles (gHEVs) on parcel delivery routes in the Sacramento and Los Angeles areas. These gHEVs (Figure 1) are built upon a Ford E-450 strip chassis, and each vehicle is powered by a Ford 5.4L gasoline engine and Azure Dynamics, Inc. (AZD) Balance Hybrid System. Additional vehicle information is discussed in subsequent sections, while the specifics of the hybrid system evaluated are presented in Table 1. FedEx Express was the domestic launch customer for the AZD Balance Hybrid electric product. FedEx Express chose this vehicle platform for several reasons:

1. It represented a gHEV solution for use in California.
2. It provided an engine off at idle feature.
3. It offered a projected improvement in fuel economy over the gasoline engine W700.

[1] Available on the Web at http://www.nrel.gov/docs/fy02osti/32392.pdf.

4. It would provide a platform comparison to the diesel hybrid electric W700 platform.

FedEx Express's expectation for gHEV deployment was a successful launch of the technology.



Figure 1. FedEx Express gHEV (Photo courtesy of Sam Snyder, FedEx Express)

Table 1. AZD Balance Hybrid System

Model Year	2008
Model	Balance Hybrid Electric (parallel hybrid)
Motor	100 kW AC induction w/regenerative braking
Motor Controller	120 kW inverter
Transmission	Elect. 5-spd. Torqshift auto. O/D transmission
Battery	Cobasys 288 V, 60 kW, 8.5 Ah, nickel metal hydride Automatic high-voltage disconnect in case of vehicle collision
System Voltage	288 VDC nominal
Power Steering/Brakes	Engine on – standard engine-driven pump
12V System	Alternator supplemented by DC/DC converter
Cooling	Engine – Ford cooling system with electrified radiator cooling fans Hybrid system – Separate low temp cooling loop

This final report presents the results from a 12-month in-use evaluation comparing in-use fuel economy and maintenance costs of gHEVs and comparative diesel parcel delivery trucks. In addition, this report presents the results of the parcel delivery drive cycle data collection and analysis activities as well as emissions and fuel economy results of chassis dynamometer testing of a gHEV and a comparative diesel truck at NREL's Renewable Fuels and Lubricants (ReFUEL) laboratory.

3 Approach

3.1 Route / Drive-Cycle Selection

Matching gHEV and diesel trucks to similar routes is important for accurate comparison of in-use fuel economy and maintenance costs. In addition, grouping well-matched gHEV and diesel truck routes aids in truck-truck comparisons as well as group-group comparisons. Finally, knowledge of in-use driving characteristics, including intensity, speed, and stops per mile allows for the selection of similar industry drive cycles for chassis dynamometer testing. The relevance of chassis dynamometer-derived emissions and fuel economy is dependent upon selecting test cycles that are similar to drive cycles driven in the field.

Global positioning system (GPS)-based data loggers were used to collect drive cycle information from several FedEx Express parcel delivery trucks. This drive cycle data collection effort was conducted in two phases. First, in order to identify three well-matched gHEVs and routes, eight gHEVs deployed from three FedEx Express depots in southern California were instrumented with GPS-based data loggers, and spatial speed-time data were collected over 61 valid route-days (Table 2). These route data were filtered, visualized using Google Earth, and analyzed according to 58 drive cycle metrics to analyze daily route consistency and to characterize each route. Data

filtering and analysis were performed using the NREL Duty Cycle Analysis and Custom Test Generation Tool.[2]

Table 2. Drive Cycle Data Collection by Truck-Days

Truck	Depot	Days Logged	Days Valid	1	2	3	4	5	6	7	8	9	10	11
D286	EMT	4	3	OFF	ON	ON	ON	NM	NM	NM	NM	NM	NM	NM
D288	EMT	11	8	ON	ON	ON	ON	OFF	OFF	ON	ON	ON	ON	OFF
D289	SPQ	8	6	ON	ON	ON	ON	OFF	OFF	ON	ON	NM	NM	NM
D290	SPQ	10	8	ON	ON	ON	ON	OFF	OFF	ON	ON	ON	ON	NM
H292	POC	10	9	ON	ON	ON	ON	ON	ON	ON	ON	ON	OFF	NM
H293	POC	10	9	OFF	ON	ON	ON	ON	ON	ON	ON	ON	ON	NM
H294	POC	9	9	ON	ON	ON	ON	ON	ON	ON	ON	ON	NM	NM
H295	POC	9	9	ON	ON	ON	ON	ON	ON	ON	ON	ON	NM	NM
	Totals	**71**	**61**											

OFF: Vehicle not in service
ON: Vehicle in service
NM: Data were not measured

Our goal was to assemble a group of three similar routes being driven by gHEVs from a single depot. These three similar gHEV-served routes would be the focus of this 12-month in-use evaluation and would provide average drive cycle metrics to aid in chassis dynamometer test cycle selection. Two depots had been assigned only two gHEVs each. The third depot (POC) was assigned four gHEVs and was subsequently decided upon as the focus of this analysis. Based upon a statistical comparison of key drive cycle characteristics (Table 3), three of the four gHEV-served POC routes were selected as three of the six total study routes for the in-use evaluation. These routes (A1, A2, and A3) were initially served by trucks H292, H294, and H295.

In the absence of initial GPS-derived route data, diesel vehicles driving similar routes in terms of daily vehicle miles traveled (VMT) and traffic patterns were suggested by the POC depot manager. These routes (B1, B2, and B3) were initially served by trucks D670, D896, and D830. In the second phase of drive cycle data collection, the three routes served by diesel vehicles were instrumented with GPS data loggers. Data were collected, filtered, and analyzed using the same process. The key drive cycle characteristics of these routes (A1, A2, A3, B1, B2, and B3), anonymized at the request of FedEx Express, are presented in Table 3 and are visualized in Figure 2.

[2] *NREL Vehicle Drive Cycle Tool, User Guide*. Copyright © 2009 Alliance for Sustainable Energy, LLC. All Rights Reserved.

Table 3. Parcel Delivery Study Routes

Drive Cycle Characteristic	Route and Group Statistics									
	A1	A2	A3	Mean A	CoV A	B1	B2	B3	Mean B	CoV B
Average Driving Speed (mph)	16.8	16.9	16.3	16.7	2%	18.9	20.9	18.8	19.5	6%
Daily VMT (miles)	43.8	47.3	21.4	37.5	37%	38.7	36.1	49.3	41.4	17%
Stops per Mile	3.85	3.79	4.22	3.96	6%	2.97	2.66	3.38	3.00	12%
Average Acceleration (ft/s^2)	2.27	2.11	2.09	2.16	4%	2.26	2.13	2.03	2.14	6%
Average Deceleration (ft/s^2)	-2.59	-2.55	-2.52	-2.55	1%	-2.44	-2.31	-2.56	-2.43	5%
Accelerations per Mile	20.80	20.78	22.82	21.46	5%	21.37	18.12	18.32	19.27	9%
Decelerations per Mile	20.26	19.71	22.63	20.87	7%	20.13	18.21	18.03	18.79	6%
Kinetic Intensity (ft^{-1})	0.00059	0.00055	0.00074	0.00063	16%	0.00037	0.00030	0.00039	0.00035	14%

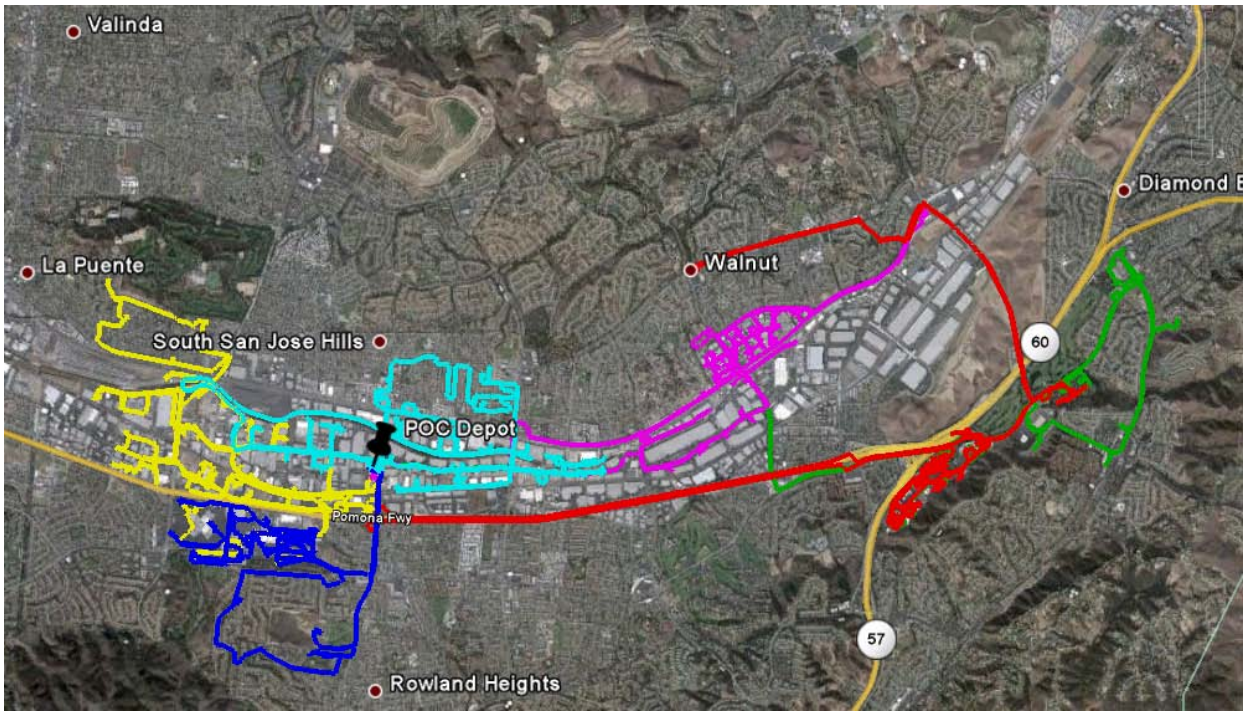


Figure 2. Study routes

While each of the two groups is made up of relatively well-matched routes, there is some variability between A and B groups. While the differences are small for most statistics, there is a larger A versus B difference in kinetic intensity. In order to partially account for this route variability, the vehicle groups exchanged routes after 6 months of evaluation. Thus, the 12-month averages for gHEV and diesel groups are comparable.

Fuel economy can vary due to driving style. In general, FedEx Express assigns one driver to a given vehicle operating on a given route. However, due to vacations and illness, as well as occasional scheduling needs, other drivers may operate a vehicle on a route for a day or more. As a result, in-use fuel economy results include some uncontrolled driver and driving style variability. Drivers did not follow vehicles when the vehicle-route swaps were conducted but instead continued to serve the same route using a different vehicle.

3.2 Vehicle Descriptions

Based upon the activities outlined in Section 3.1 and based upon the FedEx Express fleet composition and usage of vehicles within their fleet, six similar trucks were selected for this in-use evaluation project. Three of the trucks are gHEVs and three are conventional diesel trucks that serve as a control group. Although these truck groups are not identical, they represented the best possible match for an evaluation based on vocational usage, size, and age. Both groups of trucks provided the same functionality for FedEx Express. Basic vehicle attributes are presented in Table 4.

Table 4. FedEx Express Delivery Truck Basic Information

Vehicle Information	gHEV	Diesel
Asset Numbers	H292, H294, H295	D670, D896, D830
Chassis Manufacturer/Model	Ford E-450 Strip Chassis	Freightliner MT-45
Chassis Model Year	2008	2006
Engine Manufacturer/Model	Ford 5.4L EFI Triton V-8	Cummins 5.9L ISB 200 I-6
Engine Model Year	2008	2006 (EPA 04)
Engine Ratings Max. Horsepower Max. Torque	 255 HP @ 4,500 RPM 350 lb-ft @ 2,500 RPM	 200 HP @ 2,300 RPM 520 lb-ft @ 1,600 RPM
Fuel Capacity	55 gallon - Gasoline	45 gallon - Diesel
Transmission Manufacturer/Model	Ford 5R110 5-spd. auto.	Allison 1000 5-spd. auto.
Curb Weight	9,300 lb	9,700 lb
Gross Vehicle Weight Rating	14,050 lb	16,000 lb
Cabin Air Conditioning	Yes	Yes

3.3 Laboratory Vehicle Emissions and Fuel Economy Measurement

One representative gHEV and one representative diesel vehicle were tested at the ReFUEL laboratory, which is operated by NREL and located in Denver, Colorado. The ReFUEL laboratory utilizes a heavy-duty vehicle (chassis) test cell with emissions and fuel consumption measurement capability. Additional information relative to the ReFUEL laboratory's capabilities and experimental setup is included in the appendix. A gHEV being used by FedEx Express at the POC depot in southern California was transported to ReFUEL, and a representative MY2006 (2004 engine certification) diesel truck was obtained from the Denver FedEx Express fleet for testing. The goal of testing at the ReFUEL laboratory was to quantify the reduction in emissions realized with the gHEV and to compare the fuel economy of a gHEV and a diesel vehicle.

To select the appropriate chassis dynamometer test cycles, calculated kinetic intensity[3] was used to compare real, collected drive cycle data (section 3.1) to industry drive cycles. Drive cycle kinetic intensity is derived from the classic road load equation for power. Kinetic intensity is a calculated "macro-characteristic" that represents the transient intensity (accelerations and decelerations) of a particular drive cycle. At the time chassis dynamometer testing was performed, drive cycle data had only been collected for the A group described in the previous section. Based upon the observed group A drive cycle kinetic intensities, the Orange County Bus cycle (OC Bus) was selected as a cycle that best approximated the average of the routes driven by the initial three routes. The New York City Cycle (NYCC) and HTUF4 cycles were selected as upper and lower boundaries for kinetic intensity with the intention of demonstrating the expected range of fuel economy. NYCC and HTUF4 were also selected based upon usage in previous tests of similar vehicles. Figure 3 presents kinetic intensity values for the industry drive cycles and the measured A and B routes along with the average kinetic intensity of all six study routes. Figure 3 also includes cycle average driving speed, as it is a common basic metric for cycle comparison.

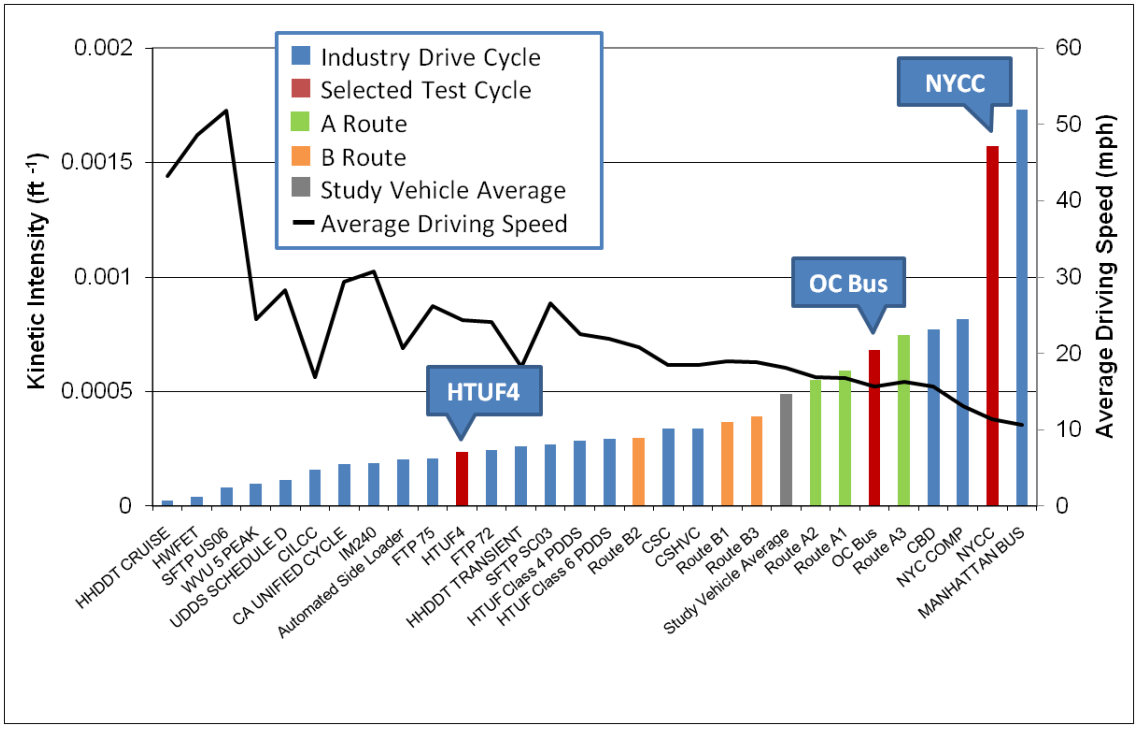


Figure 3. Comparison of drive cycle kinetic intensities

3.4 In-Use Vehicle Refueling Data Collection

The purpose of collecting and analyzing truck in-use fuel records is to calculate and compare in-use fuel economy. Three in-use fuel economy evaluation methods were used for corroboration due to potential reliability and accuracy issues inherent in each. Collection of truck fueling records took two forms:

[3] O'Keefe, M. *Duty Cycle Characterization and Evaluation Towards Heavy Hybrid Vehicle Applications*. Society of Automotive Engineers Paper No. 2007-01-0302, 2007.

1. Fuel logs were located in each truck, and drivers were instructed to fill in fields at each fueling event. Each week, depot management faxed a completed fuel log to NREL.
2. Retail fuel purchases required the entry of mileage and asset number. Although a transaction receipt is an option, a monthly statement associated with the fuel card provided the required data. These fuel records were transmitted electronically to NREL, reviewed for accuracy, and analyzed to compare fuel economy for the gHEV and diesel vehicle groups.

A third method was also implemented:

3. Controller Area Network (CAN) bus-derived fuel consumption was measured with ISAAC brand data loggers. Fuel consumption data were downloaded periodically by AZD personnel and transmitted to NREL. These data were not inclusive of all study vehicles for all study months; they were intended merely as a spot check of methods 1 and 2.

This overlap and cross-indexing will allow for higher confidence in in-use fuel economy calculations.

3.5 Vehicle Maintenance and Data Collection

Scheduled and unscheduled maintenance is performed by FedEx Express personnel at the POC depot. Preventive maintenance is conducted in accordance with the California requirement of 90-day intervals, and the scope is identical for gHEV and diesel trucks.

Repair orders in the form of labor hours and parts costs are cataloged by American Trucking Association code and are captured electronically. Evaluation truck repair orders were transmitted electronically to NREL by FedEx Express, reviewed for accuracy, and analyzed for a maintenance cost per mile comparison of the gHEV and diesel groups. Because several vehicle systems differ between gHEV and diesel groups, or because the common systems may experience different operating conditions, specific maintenance cost per mile figures are calculated and reported for each of these systems.

These systems and specific components of interest include:

- Vehicle systems
    - Engine
    - Hybrid propulsion system
    - Brakes
- Vehicle components
    - Brake rotors, pads
    - Spark plugs
    - Exhaust aftertreatment (three-way catalyst and diesel particulate filter)

3.5.1 Vehicle Warranty Repairs

Data on warranty repairs are collected in a similar manner to data on normal maintenance actions. However, the warranty cost data are not included in the operating cost calculation. Labor costs may be included depending on the mechanic (operator or manufacturer) and on whether those hours were reimbursed under the warranty agreement. (Warranty maintenance information is collected primarily for an indication of reliability and durability.)

The MY2006 diesel trucks and pre-production gHEVs were under warranty during the evaluation period.

3.6 Vehicle Uptime

gHEV availability or uptime is tracked by AZD and reported to FedEx Express in a weekly, monthly, and quarterly format. AZD included NREL in the distribution of this reporting metric. Diesel evaluation truck availability data were transmitted electronically to NREL by FedEx Express, reviewed for accuracy, and analyzed for comparison of the gHEV and diesel vehicle groups.

4 Results

4.1 Laboratory Vehicle Emissions and Fuel Economy Measurement

A detailed description of experimental setup, vehicle coast down curves, test fuels (California certification gasoline and diesel), tested drive cycles, and gHEV battery state of charge considerations are included in the appendix. It is worthwhile to note two things related to the drive cycles tested. First, the NYCC drive cycle is relatively short, so to collect adequate particulate matter (PM) mass this cycle was run three times in sequence. Second, reported results for the HTUF4 cycle are specific to an NREL modification of the *HTUF Class 4 PDDS* drive cycle. The *HTUF Class 4 PDDS* drive cycle has three distinct phases totaling 55 minutes in duration. Due to scheduling and cost constraints, this cycle was shortened to include only phases 1 and 3 and was designated HTUF4. These modifications to HTUF4 are detailed in the appendix.

4.1.1 Vehicle Emissions Comparison

A summary of results is presented in Table 5. Distilled results and discussion are provided in the subsections below.

Table 5. Summary of Emissions Results

Drive Cycle	Vehicle	NOx (g/mile)	CO (g/mile)	THC (g/mile)	PM (g/mile)
NYCC	gHEV	3.24	0.84	ND[a]	0.0016
	Diesel	12.70	7.60	0.80	0.7930
OC Bus	gHEV	1.05	0.29	ND[a]	0.0004
	Diesel	7.60	2.90	0.60	0.3000
HTUF4	gHEV	0.57	1.03	0.04	0.0006
	Diesel	5.20	2.50	0.40	0.2820

[a] Measured below laboratory detection limit. Note error bars in Figure 4.

As expected, tailpipe emissions were considerably lower across all drive cycles for the gHEV than for the diesel vehicle. This hybridized, gasoline-fueled vehicle is equipped with a three-way catalyst, which results in very low tailpipe gaseous emissions. The diesel baseline vehicle was not equipped with a diesel particulate filter. For this project, precise measurement of nitrogen oxides (NO_x) and PM were essential. The laboratory dilution ratio was calibrated to optimize NO_x measurement precision at the expense of some hydrocarbon analyzer precision in measuring carbon monoxide (CO) and total hydrocarbons (THC). Thus, there is higher variability in the CO and THC data than would otherwise occur. Criteria emissions reductions are presented in Table 6.

Table 6. gHEV Criteria Emissions Reductions by Drive Cycle

Drive Cycle	gHEV Emissions Reductions (%)			
	NOx	CO	THC	PM
NYCC	74.5	88.9	100	99.8
OC Bus	86.2	90.0	100	99.9
HTUF4	89.0	58.6	89.9	99.8

Figure 4 visually illustrates the emissions reductions realized with the gHEV. Furthermore, the relationship between drive cycle kinetic intensity and tailpipe emissions is demonstrated. With decreasing kinetic intensity, characterized by fewer stops and accelerations per mile, tailpipe emissions are typically lower.

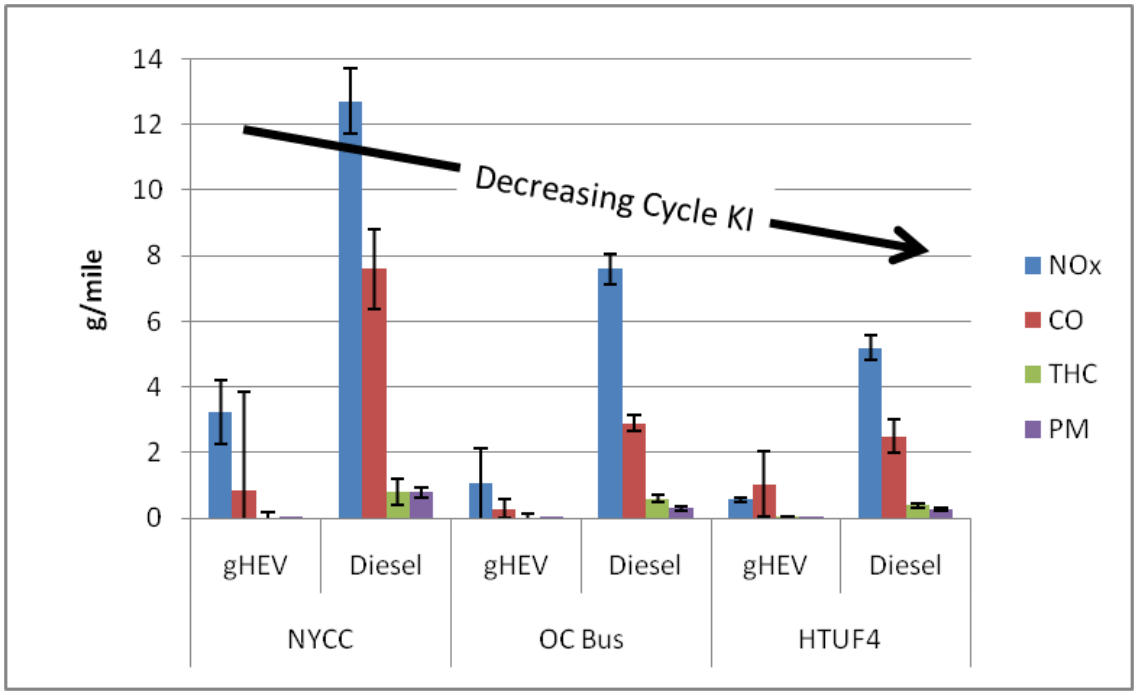


Figure 4. Criteria emissions by drive cycle

4.1.2 Vehicle Fuel Economy Comparison

To allow for normalization of volumetric fuel economy, NREL measured the energy content of both gasoline (42,372 J/g) and diesel (46,048 J/g) fuels. Volumetric fuel economy was measured for each vehicle over three drive cycles. These results, as well as the normalized gHEV fuel economy advantage by drive cycle, are presented in Table 7 and Figure 5.

Table 7. gHEV Fuel Economy Comparison by Drive Cycle

Drive Cycle	gHEV Fuel Economy (mpg)	gHEV Diesel Equivalent Fuel Economy (mpg)	Diesel Fuel Economy (mpg)	gHEV Advantage (diesel equivalent basis) (%)
NYCC	6.75	7.34	6.08	20.6
OC Bus	8.61	9.36	9.52	-1.7
HTUF4	10.45	11.36	11.66	-2.6

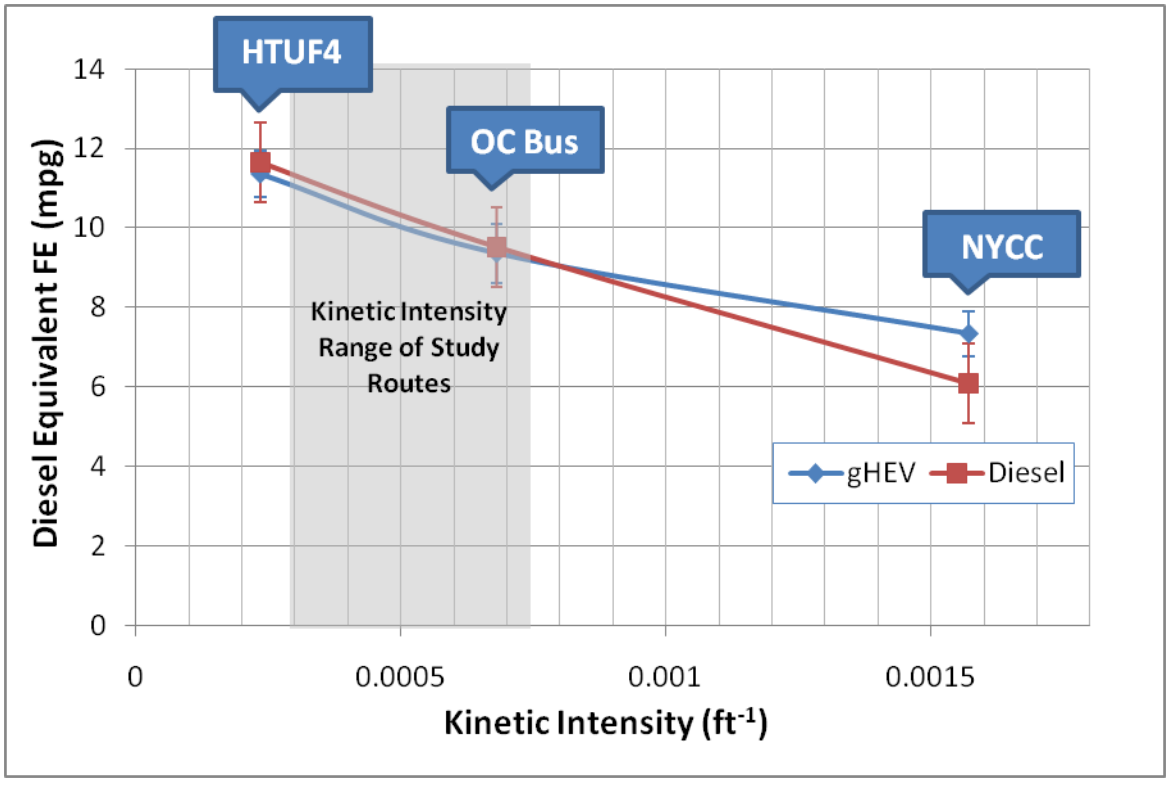


Figure 5. Influence of route kinetic intensity on fuel economy

The gHEV is statistically equivalent to the diesel vehicle with respect to normalized fuel economy for the HTUF4 and OC Bus test cycles. While there is slight overlap in fuel economy error bars for the NYCC test cycle, the average fuel economy difference between gHEV and diesel is more pronounced. While the hybrid electric element imparts higher efficiency, this advantage is offset in part by the lower liquid fuel energy content (gasoline compared with diesel) and lower thermal efficiency (spark ignition compared with compression ignition). The NYCC drive cycle exhibits the highest kinetic intensity, characterized by many acceleration and deceleration events. gHEV acceleration demands are shared by the gasoline engine, the battery, and the electric motor, while the diesel vehicle relies solely on its diesel engine. The electric power train is a higher-efficiency option for these transient events. gHEV deceleration events allow for the recapture of energy via regenerative braking, while this energy is unrecoverable and lost by the diesel vehicle. For these reasons, high kinetic-intensity drive cycles are a better application for gHEVs than for diesel vehicles.

These results highlight the need to match the most appropriate drive cycles to hybrid power train vehicles. Drive cycles with higher kinetic intensity are better candidates for hybrid vehicle application due to the improved fuel economy. In addition, route distance and daily VMT are important metrics to consider in order to maximize hybrid vehicle return on investment.

4.2 In-Use Fuel Economy and Costs

In-use fuel data were collected via retail fuel data supplied by FedEx Express and via on-board fuel logs completed by vehicle drivers and faxed to NREL. Due to occasional gaps in on-board fuel log data, the more comprehensive retail fuel data set was analyzed. Fuel data for the study period are presented below (Table 8, Figure 6, Figure 7). There is no statistically significant difference (two-tailed P value of 0.45) in diesel equivalent fuel economy values for the gHEV and diesel groups.

Table 8. Fuel Economy and Costs from Retail Fueling Records

Vehicle Type	Asset #	Start Date	End Date	Miles	Fuel Volume (gallons)	Fuel Economy (mpg)	Diesel Equivalent FE (mpg)	Fuel Cost ($)[a]	Fuel Cost per Mile ($/mile)
gHEV	H292	04/21/09	04/12/10	10,693	1,540.8	6.94	7.54	4,468	0.42
	H294	04/21/09	04/14/10	11,843	1,744.7	6.79	7.38	5,119	0.43
	H295	04/23/09	04/22/10	7,214	1,001.5	7.20	7.83	3,010	0.42
	Total			**29,750**	**4,287.0**	**6.94**	**7.54**	**12,597**	**0.42**
Diesel	D670	04/21/09	04/23/10	13,099	1,822.43	7.19	7.19	5,254	0.40
	D830	04/22/09	04/26/10	11,344	1,321.50	8.58	8.58	3,893	0.34
	D896	04/28/09	04/26/10	11,124	1,350.82	8.23	8.23	3,899	0.35
	Total			**35,567**	**4,494.8**	**7.91**	**7.91**	**13,046**	**0.37**

[a] Average fuel costs for the study vehicles during the study period were $2.94/gallon (gasoline) and $2.90/gallon (diesel).

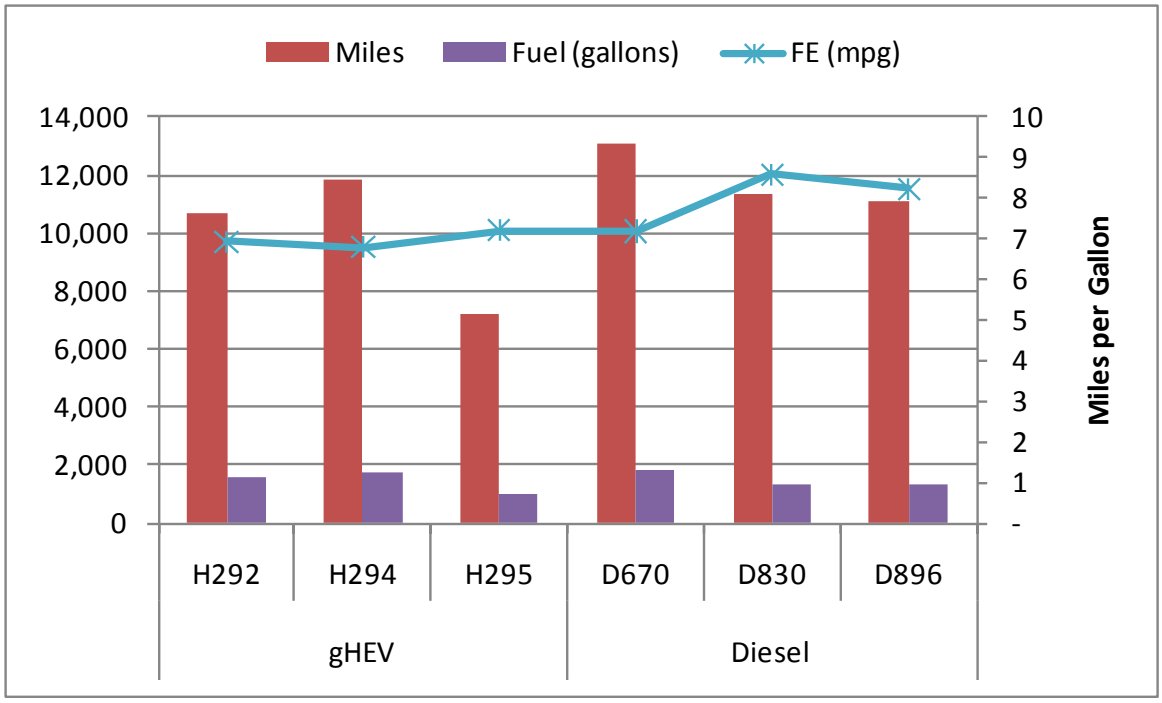


Figure 6. Fuel economy results

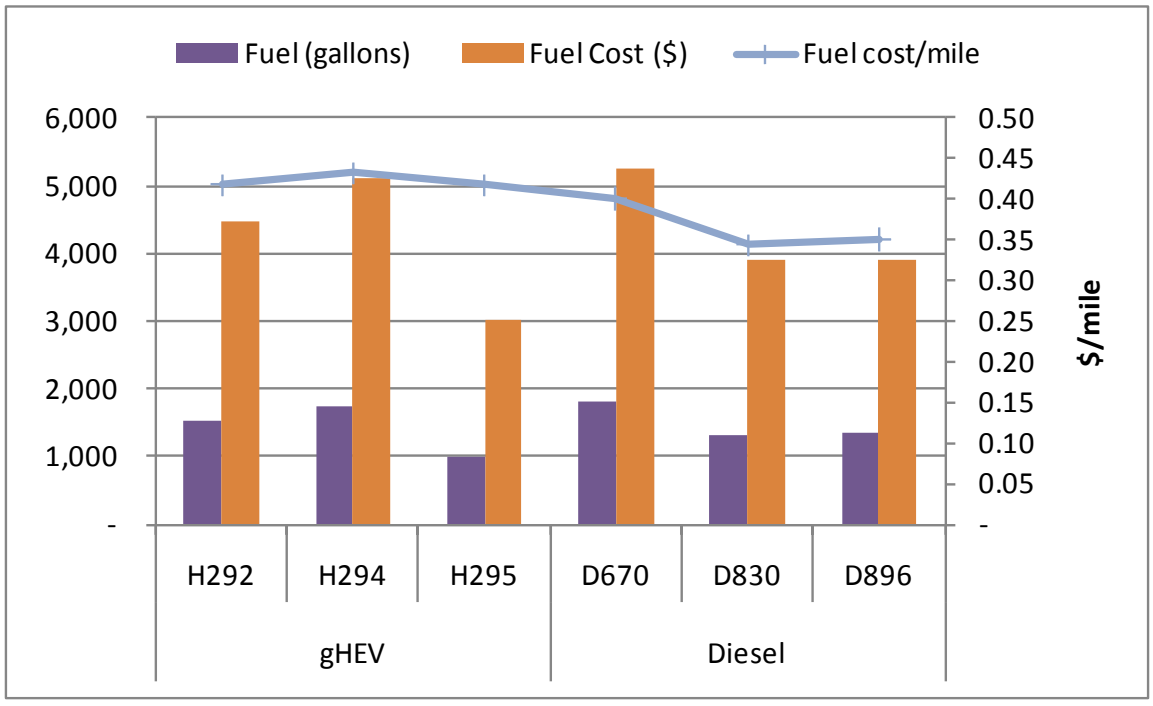


Figure 7. Fuel and fuel cost per mile results

AZD personnel downloaded CAN data from the ISAAC data loggers during scheduled visits to POC. These data, consisting of distance traveled and fuel consumed since the last download, were collected from the gHEVs during the first 6 months of the study period. Table 9 compares fuel economy values calculated using the ISAAC data with values calculated using retail fuel logs during the same 6-month period. AZD reports a ± 3% error in CAN-derived fuel consumption during simultaneous chassis dynamometer testing. A similar difference between CAN-derived and in-use data is shown in the table. The relatively small difference between these types of data imparts confidence to the retail fuel log-derived fuel economy results.

Table 9. CAN Fuel Economy Results

Vehicle Type	Asset #	Start Date	End Date	CAN Miles	CAN Fuel Volume (gallons)	CAN FE (mpg)	Retail Fuel Log FE (mpg)	% Difference
gHEV	H292	04/22/09	09/03/09	4,507	650.0	6.93	6.78	2.2%
	H294	04/22/09	09/03/09	3,180	423.3	7.51	7.29	3.0%
	H295	04/22/09	09/03/09	2,410	345.8	6.97	6.78	2.7%

4.3 Maintenance Costs

Maintenance costs and maintenance costs per mile driven can be a function of vehicle age. Table 10 presents the odometer readings of the study vehicles at the beginning and at the end of this study period.

Table 10. Relative Ages of Study Vehicles

Vehicle Type	Asset #	Start Miles	End Miles
gHEV	H292	10,807	21,500
	H294	11,190	23,033
	H295	7,868	15,082
	Average	**9,955**	**19,872**
Diesel	D670	37,643	50,742
	D830	40,130	51,474
	D896	42,245	53,369
	Average	**40,006**	**51,862**

The diesel group is generally older and has been driven farther than the gHEV group, which suggests that maintenance costs could be higher. These diesel vehicles were chosen for the study because they were the newest comparable vehicles available from this fleet at the time of the study. However, the gHEV group represents a new technology, and additional maintenance procedures and/or lack of familiarity on the part of the maintenance personnel could lead to higher maintenance costs. Regardless, in their current usage pattern of approximately 10,000 miles/year per vehicle, the diesel vehicles are on average three truck-years older than the gHEVs.

In-use maintenance data were supplied by FedEx Express and transmitted to NREL for analysis. NREL removed warranty items and associated costs from this comparison. During the study period, the gHEVs had labor and parts warranted, while the diesel vehicles did not. Had warranty costs been included, the total gHEV maintenance costs for the study period would have been $6,815, or $0.229/mile. Maintenance data for the study period are presented below (Figure 8 and Table 11). There is no statistically significant difference (two-tailed P value of 0.637) in maintenance cost per mile between the gHEV and diesel groups.

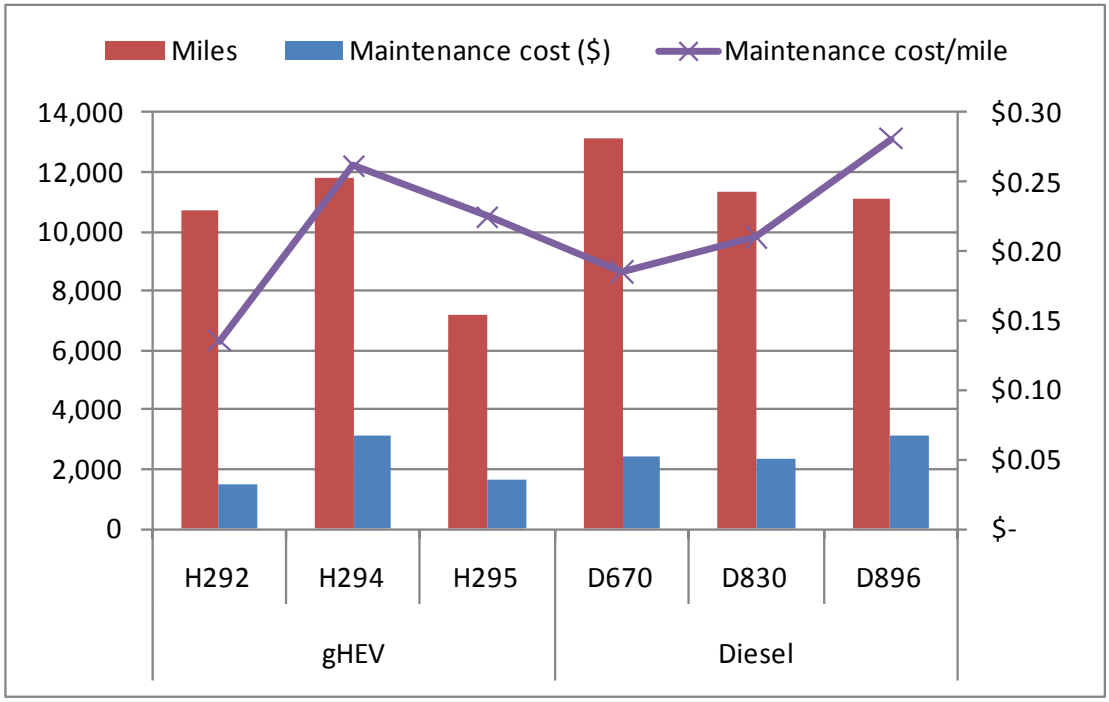


Figure 8. Total maintenance cost and maintenance cost per mile results

Table 11. Maintenance Costs by System

ATA Code(s)	Description	gHEV		Diesel	
		Total Cost ($)	Cost per Mile ($/mile)	Total Cost ($)	Cost per Mile ($/mile)
000	Preventive Maintenance	1,416.37	0.048	2,580.71	0.073
001	Air Conditioning, Heating, and Ventilation	258.46	0.023	71.67	0.002
002	Cab	274.22	0.009	328.88	0.009
003	Instruments, Gauges, Meters	82.26	0.003	246.01	0.007
013	Brakes	-	-	220.04	0.006
014	Frame	46.28	0.002	-	-
017	Tires	1,520.25	0.051	1,458.70	0.041
031, 032	Charging System	127.30	0.007	442.12	0.012
034	Lighting System	151.37	0.005	27.43	0.001
035	Multi-Function Electronic	67.03	0.002	491.94	0.014
041	Air Intake System	-	-	35.69	0.001
042	Cooling System	-	0.002	360.63	0.010
043	Exhaust	51.79	0.002	81.52	0.002
044	Fuel System	-	-	830.20	0.023
045	Power Plant	30.46	0.001	54.84	0.002
048	Electric Propulsion System	252.88	0.012	-	-
053	Expendable Items	613.03	0.021	18.28	0.001
066, 071, 072	Body, Doors	524.54	0.018	202.57	0.006
075	Manholes	18.28	0.001	-	-
078	Trim	70.88	0.002	-	-
092	Bulk Product Transfer (Compressor)	-	-	9.14	0.000
102	Special Body Codes	161.48	0.005	109.69	0.003
153	Misc. Shop Supplies	107.26	0.004	169.71	0.005
156	Back-Up Camera	362.12	0.012	193.61	0.005
Total		**6,136.26**	**0.206**	**7,933.38**	**0.223**

Maintenance costs are dominated by preventive maintenance activities and tire replacements (Figure 9 and Figure 10). These two dominant maintenance categories are removed in Figure 11, allowing for better visualization of lower-tier maintenance costs for each study group.

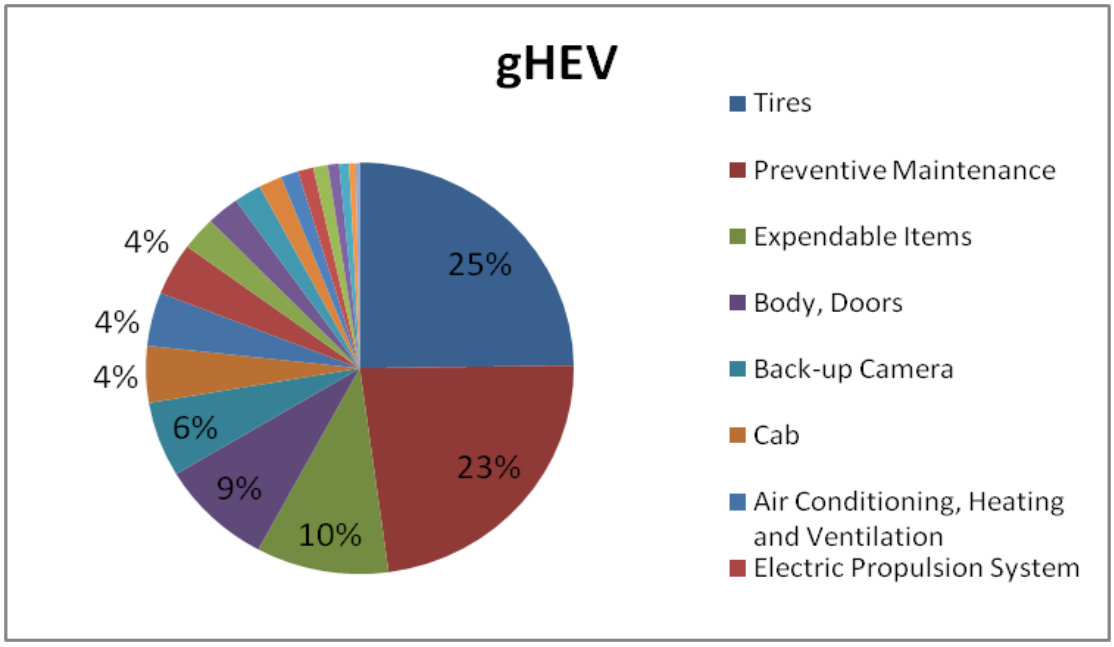


Figure 9. gHEV maintenance costs by system

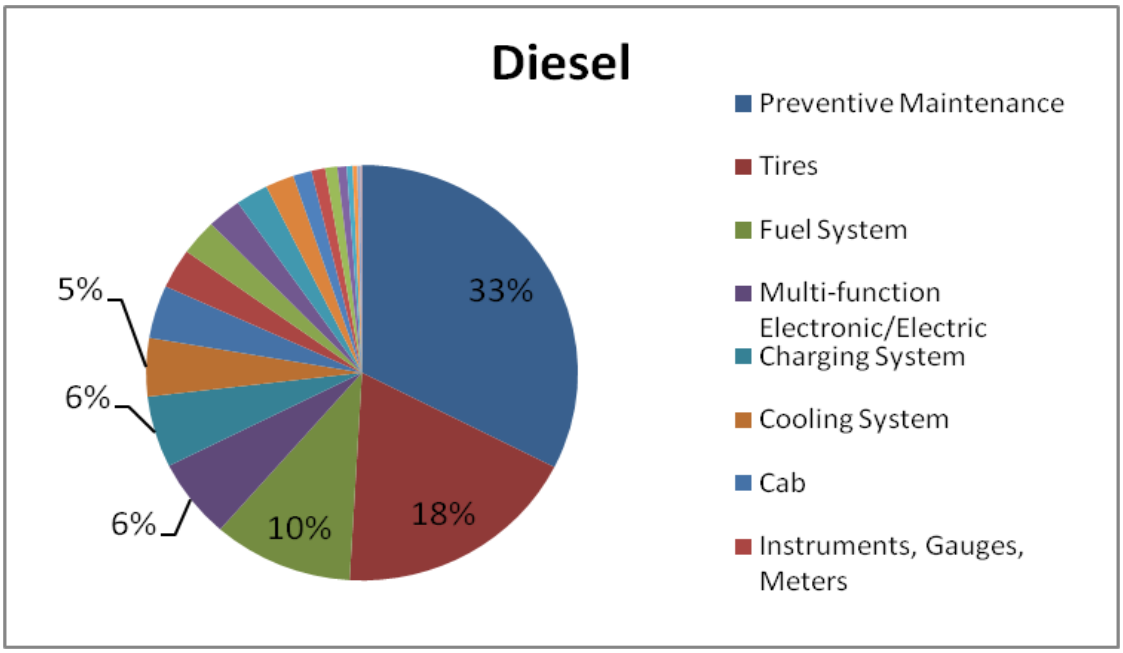


Figure 10. Diesel maintenance costs by system

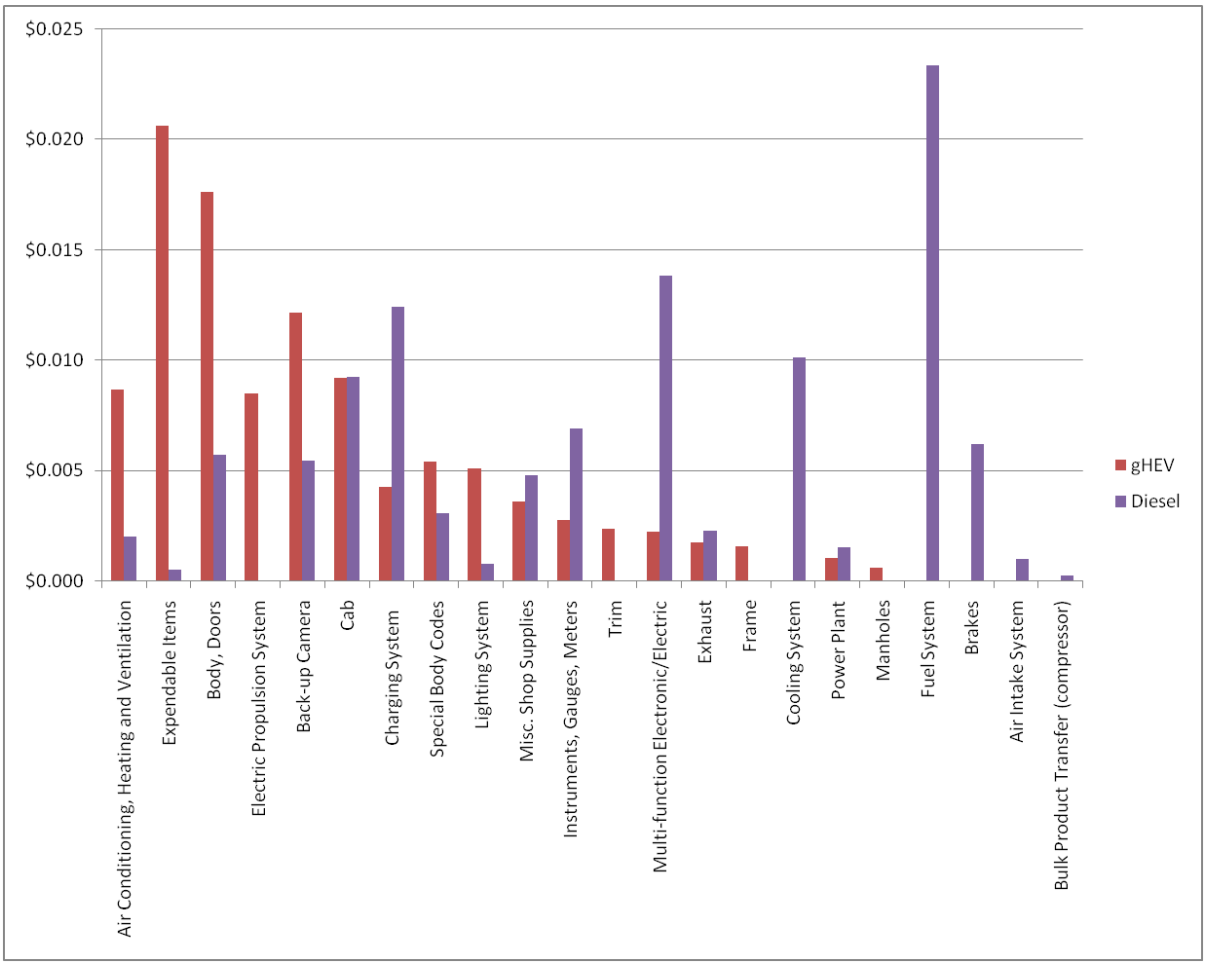


Figure 11. Lower-tier maintenance costs per mile by system

Upon examination of Figure 11, there are several obvious differences between the gHEV and diesel groups. Some of them (air conditioning and heating, ventilation and cooling, body, lighting, and various expendable items used to engineer solutions to minor problems) are likely due to "shakedown" activities when integrating the pre-production gHEVs. Key vehicle systems for comparison are the electric propulsion system, exhaust, power plant, brakes, and fuel system; these systems exhibit design or usage differences between the study groups.

During the study period, there were records of electric propulsion system maintenance for each of the gHEVs. This non-warranty maintenance was limited to inspections and road tests. Warranty events involving the electric propulsion systems are discussed in Section 4.3.1 below.

During the study period, no brake repairs were performed on the hybrid vehicles; this was an expected result due to their low mileage and regenerative braking capability. Diesel trucks D670 and D830 had two-wheel brake replacements during the study period, for a total cost of $220.04. FedEx Express examines brakes every time preventive maintenance is performed and replaces them as necessary. Quantifying any differences in brake maintenance costs between the gHEV and diesel vehicle groups may require a study period in excess of 12 months. At the time of this study, FedEx Express did not provide a brake life metric for their W700 fleet.

Exhaust and power plant system maintenance cost differences between the two groups were insignificant during the study period. The diesel group exhibited a higher fuel system cost per mile. Vehicle D896 had on-road fuel system problems, requiring a tow, fuel-water separator maintenance, and fuel tank cleaning, which totaled $821.06. The diesel group exhibited a higher multifunction electronic/electric system cost per mile. Vehicle D896 had two incidents in five days during December 2009; each required an inspection and tow, which totaled $491.94. No additional information was available in the FedEx Express maintenance data provided. The diesel group also exhibited a higher cooling system cost per mile. Vehicle D830 experienced a cracked radiator, and required a tow and radiator replacement.

4.3.1 Vehicle Warranty Repairs

There were several warranty repairs for the gHEVs during the study period and none for the diesel group. These warranty repairs were mainly related to the heating, ventilating, and air conditioning; cooling; and electric propulsion systems. The electric propulsion system repairs included a campaign to replace the 200A traction battery fuses in each gHEV and the replacement of the integrated starter generator and digital motor operational controller in vehicle H295. These warranty repairs with associated costs (reimbursed by AZD) are summarized in Table 12.

Table 12. Vehicle Warranty Repairs

Asset #	Mileage	System	Assembly	Part	Item	Description	Warranted Cost ($)
H292	11,334	001	001	049	Valve Assembly	Expansion Inspection	18.28
H292	11,596	031	000	000	Charging System	Inspection	36.56
H292	11,596	031	001	000	Generator/Alternator	Other Maintenance	6.09
H292	11,596	031	001	000	Generator/Alternator	Other Maintenance	24.37
H292	11,596	032	000	000	Cranking System	Inspection	9.14
H292	11,858	048	001	000	Power Train Assembly	Hybrid Exchange New	36.56
H292	11,858	048	001	000	Power Train Assembly	Hybrid Burned Out	–
H292	18,280	042	004	031	Pulley - Idler, Water Pump	Inspection	15.23
H294	19,597	042	004	031	Pulley - Idler, Water Pump	Inspection	15.23
H294	20,036	048	001	000	Power Train Assembly - Hybrid	Exchange New	18.28
H294	20,036	048	001	000	Power Train Assembly - Hybrid	Burned Out	–
H294	20,036	048	001	000	Power Train Assembly - Hybrid	Road-Test	12.19
H294	20,101	048	000	000	Hybrid Power Train	Exchange New	45.70
H294	20,101	048	000	000	Hybrid Power Train	Worn	–
H294	20,911	001	001	052	Core - Evaporator	Exchange New	48.75
H294	20,911	001	001	000	Air Conditioning Assembly	Other Maintenance	42.65
H294	20,911	001	001	000	Air Conditioning Assembly	Other Maintenance	67.03
H294	20,911	001	001	052	Core - Evaporator	Broken	176.55
H294	20,911	001	001	049	Valve Assembly - Expansion	Standard Practice	29.44
H294	20,911	001	001	065	Receiver - Dehydrator Assembly	Standard Practice	36.00
H294	20,911	053	999	021	Refrigerant - Air Conditioner	Standard Practice	13.00
H294	20,911	153	997	000	Misc. Shop Supplies	Standard Practice	12.75
H295	12,161	042	004	031	Pulley - Idler, Water Pump	Inspection	15.23
Total							**679.03**

4.4 Total Operating Costs

Total operating costs include fuel and maintenance costs. These costs for the study period are summarized and presented in Table 13 and Figure 12.

Table 13. Total Operating Costs

Vehicle Type	Asset #	Miles	Fuel Cost ($)	Maintenance Cost ($)	Total Operating Cost ($)	Total Operating Cost per Mile ($/Mile)
gHEV	H292	10,693	4,468	1,451	5,919	0.55
	H294	11,843	5,119	3,065	8,218	0.69
	H295	7,214	3,010	1,620	4,630	0.64
	Total	29,750	**12,597**	6,136	18,767	**0.63**
Diesel	D670	13,099	5,254	2,422	7,676	0.59
	D830	11,344	3,893	2,386	6,279	0.55
	D896	11,124	3,899	3,126	7,024	0.63
	Total	35,567	**13,046**	7,933	20,979	**0.59**

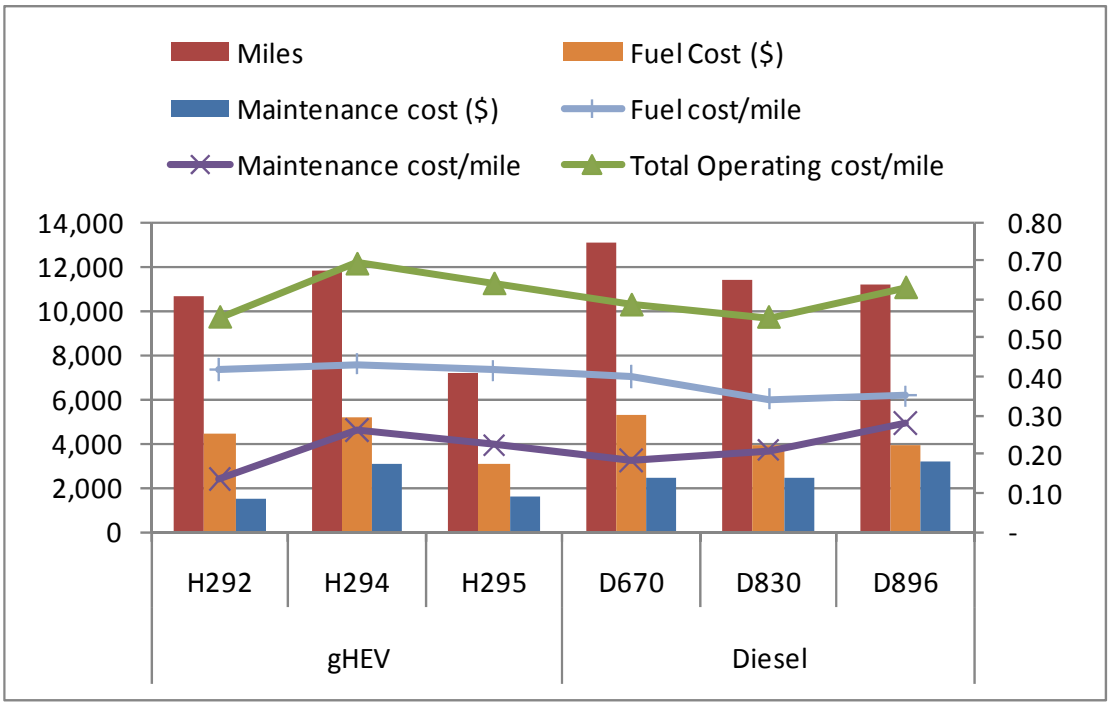


Figure 12. Total operating costs

4.5 Vehicle Uptime

Vehicle uptime is calculated as:

$$[Days\ in\ Service]/[Days\ in\ Service + Unplanned\ Days\ Out\ of\ Service]$$

Vehicle and study group uptime percentages for the study period are presented in Table 14 and Figure 13 and represent both warranty and non-warranty related maintenance. The uptime goal of 98% is shown as a red dashed line in Figure 13.

Table 14. Vehicle Uptime

Vehicle Type	Asset #	Unplanned Days Out of Service	Total Days in Period	Days in Service	Uptime %
gHEV	H292	4	366	362	98.9
	H294	23	366	343	93.7
	H295	19	366	347	94.8
	Total	**46**	**1098**	**1052**	**95.8**
Diesel	D670	3	366	363	99.2
	D830	5	366	361	98.6
	D896	10	366	356	97.3
	Total	**18**	**1098**	**1080**	**98.4**

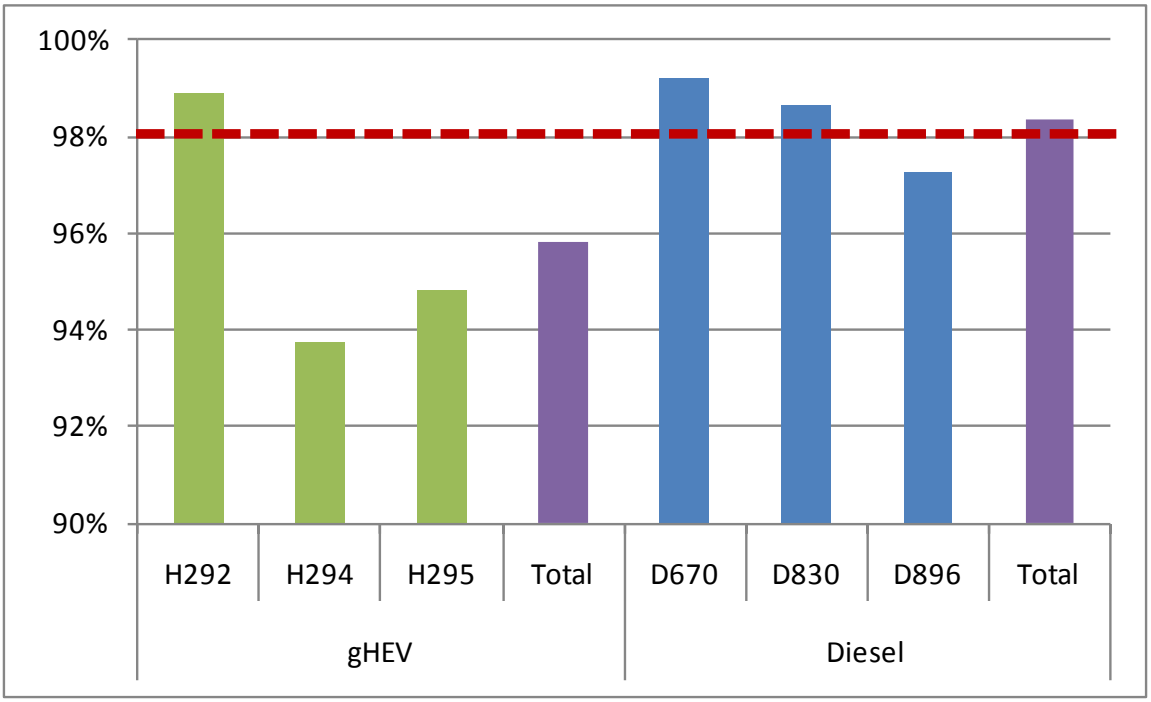


Figure 13. Vehicle uptime

It is important to note that only four of the 46 unplanned days out of service for the gHEVs were related to hybrid propulsion system-related maintenance issues. These four days were specific to vehicle number H295, due to the replacement of an integrated starter generator and digital motor operational controller. Thus, the vehicle uptime related to hybrid system performance was 99.6%.

5 Summary

A robust drive cycle data collection and analysis effort framed the selection of study vehicles and routes and provided the data to accurately select test cycles for the measurement of vehicle emissions and fuel economy on the chassis dynamometer at NREL's ReFUEL laboratory. The testing completed on the chassis dynamometer proved to be an accurate assessment of the range of fuel economy that could be expected during on-road operation, as the 12-month, on-road fuel economy averages were shown to fall within the tested range documented in the lab. Realizing the primary goal of this gHEV deployment in the FedEx Express fleet, tailpipe emissions from the tested gHEV were proven to be substantially lower across all tested drive cycles than emissions from the diesel baseline vehicle. Fuel economy results observed both in the lab and on the road were similar between the gHEV and the diesel vehicle, except for the highest kinetic intensity drive cycle tested in the laboratory, where the hybrid exhibited ~20% higher fuel economy. These results highlight the need to match the most appropriate drive cycles to hybrid power train vehicles. As observed, drive cycles with higher kinetic intensity are better candidates for hybrid vehicle application due to the improved fuel economy. In addition, route distance and daily VMT are important metrics to consider in order to maximize hybrid vehicle return on investment.

Based upon the data collected during this study, there was no statistically significant difference in fuel cost per mile or maintenance cost per mile between the gHEV and diesel groups. As a result, there was no statistically significant difference in total operating cost per mile between the gHEV and diesel groups.

The gHEVs experienced a smooth integration and deployment into commercial service. During the study period, the gHEVs performed well, experienced a minimum of unscheduled maintenance, and met the expectations of FedEx Express.

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- Jim Mancuso, Dave Alef – **Azure Dynamics, Inc.**
- Jeff Cox – **South Coast Air Quality Management District**
- Jasna Tomic – **CALSTART**
- Adam Duran, John Ireland, Robert Moore, Kevin Walkowicz, Scott Walters – **NREL**

Appendix: ReFUEL Test Report

This appendix provides additional information related to the ReFUEL Laboratory capabilities and experimental setup.

PROJECT SUMMARY REPORT

Dynamometer Testing of FedEx Express Fleet Hybrid Electric Vehicle

October 2, 2009

ReFUEL Laboratory
National Renewable Energy Laboratory
1980 31st Street
Denver, CO 80216

Test Participants:

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Jasna Tomic	CALSTART
Sam Snyder	FedEx Express

Objectives

This work comprises chassis dynamometer testing of two medium-duty FedEx Express delivery vehicles, a gasoline hybrid electric vehicle (GHEV) and a conventional diesel (baseline) vehicle. Testing was performed to compare the benefits of the GHEV with the baseline vehicle as well as to gather data for model validation, with the primary focus on fuel economy. The remainder of this report serves to describe the experimental setup, outline the test procedures, present the data, and summarize the results from dynamometer testing of each vehicle.

General Lab Description and Methods

The vehicles were tested at the ReFUEL laboratory, operated by NREL and located in Denver, Colorado. The lab includes a heavy-duty vehicle (chassis) test cell and an engine dynamometer test cell with emissions measurement capability. The laboratory is designed for the challenge of measuring a variety of engines and vehicles with a range of emissions levels. Regulated emissions measurements are performed using procedures consistent with the Code of Federal Regulations applicable to heavy-duty engine certification for 2007. Extensive data acquisition and combustion analysis equipment can be used to relate the effects of different fuel properties and engine settings to performance and emissions. Other capabilities of the laboratory include power analyzer equipment to perform hybrid-electric research, systems for sampling and analyzing unregulated emissions, on-site fuel storage and fuel blending equipment, high-speed data acquisition hardware and software to support in-cylinder measurements, altitude simulation system, and fuel ignition quality testing. Instrumentation and sensors at the laboratory are maintained with NIST-traceable calibration.

Chassis Dynamometer

The ReFUEL Chassis Dynamometer is installed in the main high-bay area of the laboratory. The roll-up door to the high bay is 14 ft x 14 ft, high enough to accept all highway-ready vehicles without modification. The dynamometer is installed in a pit below the ground level, such that the only exposed part of the dynamometer is the top of the 40-in. diameter rolls. Two sets of rolls are used so that twin-axle tractors can be tested. The distance between the rolls can be varied between 42 in. and 56 in. The dynamometer will accommodate vehicles with a wheelbase between 89 in. and 293 in. The dynamometer can simulate up to 80,000 lb vehicles at speeds up to 60 mph.

The chassis dynamometer is composed of three major components: the rolls, which are in direct contact with the vehicle tires during testing; the direct current (DC) electric motor (380 hp absorbing/360 hp motoring) dynamometer; and the flywheels.

The rolls are the means by which power is absorbed from the vehicle. The rolls are attached to gearboxes that increase the speed of the central shaft by a factor of 5. The flywheels, mounted on the back of the dynamometer, provide a mechanical simulation of the vehicle inertia.

The electric motor is mounted on trunnion bearings and therefore is used to measure the shaft torque from the rolls. The absorption capability of the dynamometer is used to apply the “road load,” which is a summation of the aerodynamic drag and friction losses that the vehicle experiences in use, as a function of speed. The road load may be determined experimentally, if

data are available, or estimated from standard equations. The electric dynamometer is also used to adjust the simulated inertia, either higher or lower than the 31,000-lb base dynamometer inertia, as the test plan requires. The inertia simulation range of the chassis dynamometer is 8,000–80,000 lb. The electric motor may also be used to simulate grades and provide braking assist during decelerations.

The truck is secured with the drive axles over the rolls. A driver's aid monitor in the cab is used to guide the vehicle operator in driving the test trace. A large fan cools the vehicle radiator during testing. The chassis dynamometer is supported by 72 channels of data acquisition in addition to the emissions measurement, fuel metering, and combustion analysis subsystems.

The dynamometer is capable of simulating vehicle inertia and road load during drive cycle testing. With the vehicle jacked up off of the rolls, an automated dynamometer warm-up procedure is performed daily, prior to testing, to ensure that parasitic losses in the dynamometer and gearboxes have stabilized at the appropriate level to provide repeatable loading. An unloaded coast down procedure is also conducted to confirm that inertia and road load is being simulated by the dynamometer control system accurately.

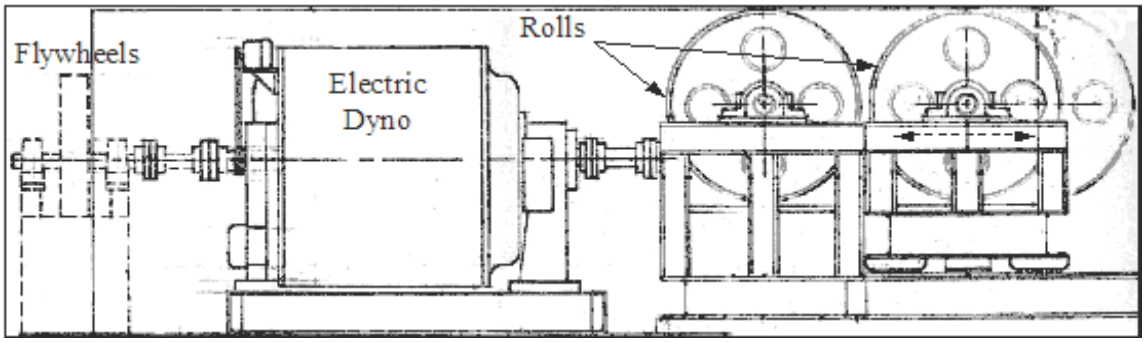


Figure A-1. Chassis dynamometer schematic

Fuel Storage and Blending

Buildings designed specifically for safely storing and handling fuels are installed at the ReFUEL facility. The fuel storage shed is 8 ft x 26 ft and holds 48 drums (55 gal each). Features include heating/cooling, secondary containment to 25% of its capacity, continuous ventilation, explosion-proof wiring/lighting, and a dry chemical fire suppression system.

The fuel blending shed is 8 ft x 14 ft, and it has a nominal storage capacity of 24 drums. It has all of the features of the storage shed, with the addition of an explosion-proof electrical outlet for powering accessories. The fuel blending may be performed on a gravimetric or a volumetric basis and may involve both large-scale (L/kg) and small-scale (cc/g) measurements. A fuel line inside of a sealed conduit delivers the fuel from the supply drum to the fuel metering/conditioning system inside the ReFUEL laboratory, eliminating the need for bulk fuel storage inside the laboratory. Another fuel line in the same conduit delivers waste fuel back to the fuel blending shed for storage (waste fuel is generated only when a fuel changeover requires a flush of the system).

Fuel Metering & Conditioning

The fuel metering and conditioning system supports both engine and chassis dynamometers. The meter measures volumetric flow to an accuracy of +/- 0.5% of the reading, with a reproducibility of 0.2%. A sensor measures the density at an accuracy of +/- 0.001 g/cc, allowing an accurate mass measurement in real time even if the density of the fuel blend is not known prior to testing.

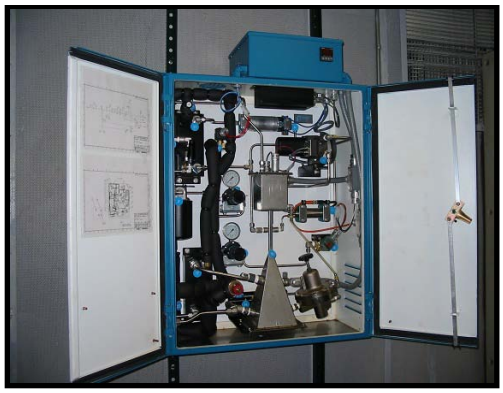


Figure A-2. Pierburg fuel metering system

Air Handling & Conditioning

Dilution air and the air supplied to the engine or vehicle for combustion are derived from a common source, a roof-mounted system that conditions the temperature of the air and humidifies as needed to meet desired specifications. This air is then passed through a HEPA filter, in accordance with the (2007) CFR specifications, to eliminate background particulate matter as a source of uncertainty in measurements.

Engine intake air flow is metered with a Laminar Flow Element (LFE) that measures air flow to within +/- 0.72% of reading. Inlet and exhaust restrictions can be adjusted with inline valves to meet manufacturers' specifications or testing requirements.

Emissions Measurement

The ReFUEL laboratory's emissions measurement system supports both the chassis and engine dynamometers. It is based on the full-scale dilution tunnel method with a Constant Volume Sampling (CVS) system for mass flow measurement. The system is designed to comply with the requirements of the 2007 Code of Federal Regulations, title 40, part 86, subpart N. Exhaust from the engine or vehicle flows through insulated piping to the full-scale 18-in. diameter stainless steel dilution tunnel. A static mixer ensures thorough mixing of exhaust with conditioned, filtered, dilution air prior to sampling of the dilute exhaust stream to measure gaseous and particulate emissions.

A system with three Venturi nozzles is employed to maximize the flexibility of the emissions measurement system. Featuring 500 cfm, 1,000 cfm, and 1,500 cfm Venturi nozzles and gas-tight valves, the system flow can be varied from 500 cfm to 3,000 cfm flow rates in 500 cfm increments. This allows the dilution level to be tailored to the engine size being tested (whether on the engine stand or in a vehicle), maximizing the accuracy of the emissions measurement equipment.

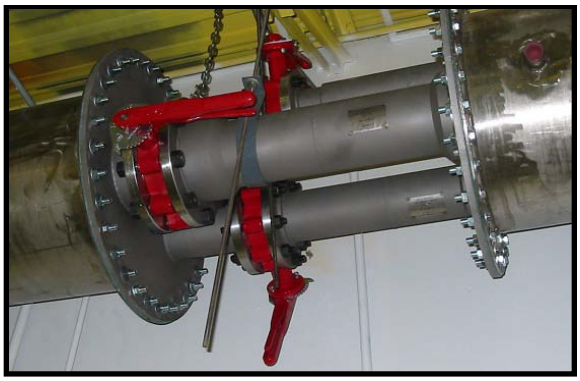


Figure A-3. Venturi nozzles

The gaseous emissions bench is a Pierburg model AMA-2000. It features continuous analyzers for total hydrocarbons (HC), oxides of nitrogen (NO_x), carbon monoxide (CO), carbon dioxide (CO_2), and oxygen (O_2). The system features auto-ranging, automated calibration, zero check, and span check features as well as integrating functions for calculating cycle emissions. It communicates with the ReFUEL data acquisition systems through a serial interface. There are two sample trains for gaseous emissions measurement: one for HC/NO_x and another for the other gaseous emissions. The HC and NO_x sample train is heated to prevent sample loss and water condensation. Both sample probes are in the same plane of the dilution tunnel.



Figure A-4. Gaseous and PM sampling benches

The particulate matter sample control bench is managed by the ReFUEL data acquisition system through a serial connection. It maintains a desired sample flow rate through the particulate matter (PM) filters in proportion to the overall CVS flow, in accordance with the CFR. Stainless steel filter holders, designed to the 2007 CFR requirements, house 47-mm diameter Teflon membrane filters through which the dilute exhaust sample flows. The PM sampling system is capable of drawing a sample directly from the large full-scale dilution tunnel or utilizing secondary dilution to achieve desired temperature, flow, and concentration characteristics. A cyclone separator, as

described in the CFR requirements, may be employed for ultra-clean vehicles equipped with PM aftertreatment.

A dedicated clean room/environmental chamber is installed inside the ReFUEL facility. It is a Class 1000 clean room with precise control over the temperature and humidity (+/- 1°C for temperature and dew point). This room is used for all filter handling, conditioning, and weighing.

The microbalance for weighing PM filters features a readability of 0.1 µg (a CFR requirement) and features static control, a barcode reader for filter identification and tracking, and a computer interface for data acquisition. The microbalance is installed on a specially designed table to eliminate variation in the measurement due to vibration. The microbalance manufacturer (Sartorius) was consulted on the design of the clean room to ensure that the room air flow would be compatible with the microbalance.



Figure A-5. Class 1000 clean room, filter housing, and microbalance

Project Specific Setup and Methods

The test vehicles were installed on the chassis dynamometer as shown in Figure A-6. A process and instrumentation diagram of the test setup is included in Appendix A along with detailed information regarding sensor description and placement. All sensors shown were monitored and recorded continuously by the ReFUEL data acquisition system throughout each test cycle run, unless otherwise noted. Additional data from the engine control unit, including state of charge details for the HEV, were also recorded using a data logger connected via CAN interface.



Figure A-6. Chassis cell with test vehicle

Test Vehicles

The hybrid electric and baseline vehicles were both tested for fuel economy and emissions on the chassis dynamometer. The baseline vehicle incorporated a 5.9 Liter, 6 cylinder diesel engine. The hybrid vehicle featured a 5.4 Liter, V8 gasoline engine with a 100 kW electric motor. Other vehicle information is outlined in Table A-1.

Table A-1. Test Vehicle Information

Vehicle Information	gHEV Trucks	Diesel Trucks
Chassis Manufacturer/Model	Ford E-450 Strip. Chassis	Freightliner MT-45
Chassis Model Year	2008	2006
Engine Manufacturer/Model	Ford 5.4L EFI Triton V-8	Cummins 5.9L ISB 200 I-6
Engine Model Year	2008	2006 (EPA 04)
Engine Ratings Max. Horsepower Max. Torque	 255 HP @ 4,500 RPM 350 lb-ft @ 2,500 RPM	 200 HP @ 2,300 RPM 520 lb-ft @ 1,600 RPM
Fuel Capacity	55 Gallon - Gasoline	45 Gallon - Diesel
Transmission Manufacturer/Model	Ford 5R110 5-Spd. Auto.	Allison 1000 5-Spd. Auto.
Curb Weight (Mfg.)	9,300 lb	9,700 lb
Gross Vehicle Weight Rating	14,050 lb	16,000 lb

Fuel

Tests run on the conventional diesel were run using a California certification diesel. The hybrid gasoline vehicle was tested on CARB phase II certification gasoline. Certificates of analysis for both fuels are included in Appendix B. The fuel supplied to the engine of each test vehicle was conditioned and metered. All fuel measurements for reported fuel economy were from the Pierburg fuel meter.

Air and Exhaust

Intake air was conditioned and supplied to each test vehicle by the ReFUEL system with continuous recorded measurements of ambient pressure, inlet restriction, air flow rate, humidity, and temperature of the inlet air.

Approximately 20 ft of 6-in. diameter, insulated, stainless steel tubing connected the test vehicle exhaust pipe to the dilution tunnel, with temperatures measured at the outlet of the vehicle exhaust pipe, at the entrance to the dilution tunnel, and at the plane of the emissions sampling probes.

Vehicle Simulation

The simulated vehicle inertia test weight for the conventional vehicle was set at 11,500 lb. The 11,500-lb test weight was calculated from the vehicle curb weight plus one half of the usual FedEx Express payload of 2,000 lb. Since no coast down data for the conventional vehicle was available, ReFUEL conducted crude coast down tests locally to compare the two vehicles (see Figure A-8b in Appendix C). Note: the coast downs provide by Azure and those taken at ReFUEL are not directly comparable due to road surface and grade differences. These data, along with previously published coefficients for this vehicle type, were compared to data for similar vehicles in the ReFUEL software from previous tests and used to derive the road load curve and the following coefficients:

$$A = 147.70 \text{ lb}$$

$$B = -1.35 \text{ lb/mph}$$

$$C = 0.100 \text{ lb/mph}^2.$$

Simulated test weight for the hybrid vehicle was also curb weight plus 1,000 lb (half of the 2,000 lb payload). This sum yielded a 10,860 lb test weight for the hybrid vehicle. Coast down data was delivered with the vehicle (Appendix C, Figure A-8a) and road load curves were generated from this data. The coefficients of the road load curve for the hybrid vehicle are the following:

$$A = 198.55 \text{ lb}$$

$$B = -3.9389 \text{ lb/mph}$$

$$C = 0.13690 \text{ lb/mph}^2.$$

The appropriate chassis dynamometer road load settings were then derived to simulate the road load for both test vehicles on the rolls to match the track data.

Test Description and Results

Initially, on each test day the chassis dynamometer was run through a standard automated warm-up procedure to ensure that dynamometer parasitics had stabilized. Periodic unloaded and loaded coast downs were also performed to ensure that inertia and road load were being simulated correctly according to the set inputs.

Each vehicle was driven through a variety of test cycles, including repeated hot-start runs: 1) New York City Cycle, 2) Orange County Bus, and 3) HTUF Class 4 Parcel Delivery drive cycles (shown in Appendix D, figures A-9, A-10, and A-11). Both trucks were keyed off during predetermined idle portions of the HTUF Class 4 drive cycle.

The hybrid electric vehicle (HEV) was tested from April 16–24, 2009. The conventional (baseline) vehicle was tested from May 12–18, 2009. Tables A-5 and A-6 in Appendix D

summarize the results for testing both vehicles on the New York City (NYCC X3), Orange County Bus, and HTUF Class 4 drive cycles.

The data demonstrates better fuel economy on the Orange County and HTUF Class 4 cycles for the conventional vehicle and a fuel economy penalty on the more aggressive New York City Cycle. Due to the hybrid's gasoline engine with three-way catalyst, NO_x and particulate matter emissions were significantly lower for the hybrid than for the diesel powered vehicle. These values are in comparison to a representative vehicle from the FedEx Express diesel fleet. However, it is important to note that diesel vehicles built following the 2007 and 2010 model years will have additional emissions equipment and will have significantly lower PM and NO_x emissions, respectively.

State Of Charge Considerations

State of charge was recorded and noted at the start and end of each test drive cycle for the HEV runs. The SAE Recommended Practice J2711 is established to provide an accurate, uniform, and reproducible procedure for simulating use of heavy-duty hybrid-electric vehicles (HEVs) and conventional vehicles on dynamometers for the purpose of measuring emissions and fuel economy. The recommended practice provides a description of state of charge (SOC) correction for charge-sustaining HEVs.

The basic premise of the procedure is to ensure that fuel economy and emissions data for a hybrid-electric vehicle are not unduly increased or decreased due to significant changes in energy storage levels over a single drive cycle. The procedure determines the percent change in state of charge (or energy storage) over each individual test cycle run. The basis for this is the net energy change (change in stored energy) divided by the total energy used during the test cycle run, calculated from the fuel calorific content. If the percentage is < 1% no correction factor is applied; if the percentage is > 5% the results are deemed invalid; and for percentage changes between 1% and 5% a correction factor may be applied to provide the corrected figures for fuel economy and emissions through basic interpolation. The recommendation is to perform this correction if the interpolation relationship can be described by linear regression with an $R^2 > 0.8$.

A current clamp was used to measure current during all cycles at 1 Hz. When the total energy was calculated it was found that all cycles had a less than 1% change in the state of charge, so no correction was required. All calculations were done per SAE J2711.

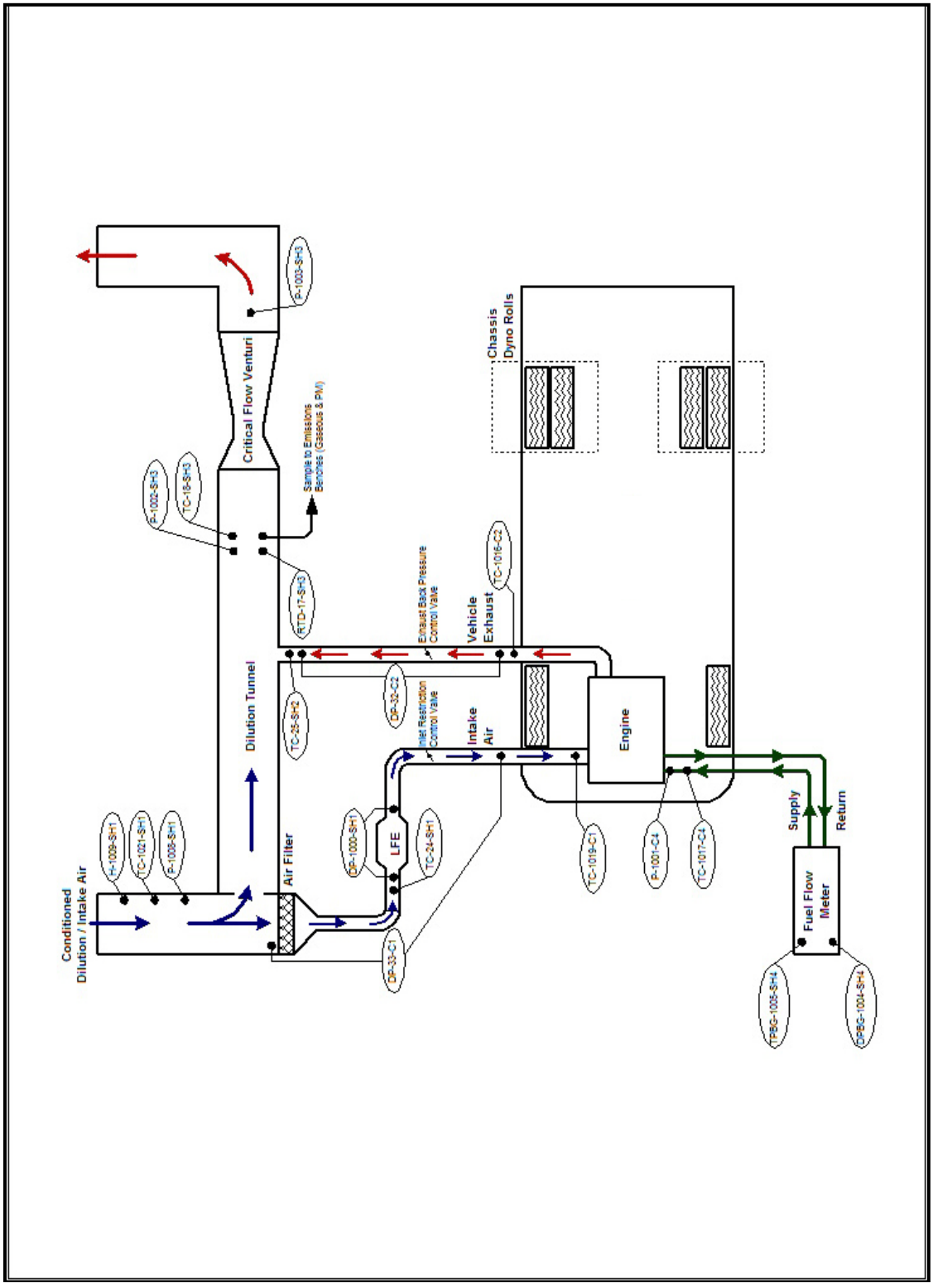


Figure A-7. Process and instrumentation diagram

Table A-2. Instrumentation List

Temperatures	
TC-1021-SH1	Dilution / Intake Air Temp
TC-24-SH1	Pre-LFE Temp
TC-1019-C1	Engine Intake Air Temp
TC-1016-C2	Engine Exhaust Temp
TC-25-SH2	Engine Exhaust Temp at Dilution Tunnel
TC-18-SH3	CVS Temp
RTD-17-SH3	Sample Location Temperature
TC-1017-C4	Fuel Temp at Engine
TPGG-1005-SH4	Fuel Temp at Fuel Flow Meter
Pressures	
P-1008-SH1	Ambient Pressure
DP-1000-SH1	LFE Differential Pressure
DP-33-C1	Inlet Air Restriction
P-1002-SH3	CVS Pressure
P-1003-SH3	CVS Pressure After Venturi
DP-32-C2	Exhaust Back Pressure
P-1001-C4	Fuel Pressure
Other	
DPBG-1004-SH4	Fuel Density
H-1009-SH1	Dilution / Intake Air Humidity

Table A-3. CARB Diesel Fuel Analysis

PRODUCT INFORMATION

Haltermann PRODUCTS

T (800) 969-2542 F (281) 457-1469

RESPONSIBLE CARE
ISO 9001 CERTIFIED

Johann Haltermann Ltd.

PRODUCT: CARB REFERENCE DIESEL
Title 13, CCR 2281-2285

PRODUCT CODE: HF0128

Batch No.: XD0121GP01
TMO No.: 800178
Tank No.: Tote
Analysis Date: 4/13/2009
Shipment Date:

TEST	METHOD	UNITS	SPECIFICATIONS			RESULTS
			MIN	TARGET	MAX	
Distillation - IBP	ASTM D86	°F	340		420	362
5%		°F				397
10%		°F	400		490	415
20%		°F				440
30%		°F				460
40%		°F				478
50%		°F	470		560	493
60%		°F				508
70%		°F				525
80%		°F				546
90%		°F	550		610	575
95%		°F				598
Distillation - EP		°F	580		660	624
Recovery		vol %		Report		98.2
Residue		vol %		Report		1.0
Loss		vol %		Report		0.8
Gravity	ASTM D4052	°API	33.0		39.0	38.0
Specific Gravity 60/60 °	ASTM D4052		0.830		0.860	0.8349
Cloud Point	ASTM D2500	°F		Report		-26
Flash Point	ASTM D93	°F	130			166
Viscosity, 40°C	ASTM D445	cSt	2.00		4.20	2.50
Sulfur	ASTM D5453	ppm wt			15	0
Nitrogen	ASTM D4629	ppm			4.0	<0.3
Total Aromatic	ASTM D5186	vol %			10.0	9.6
Polycyclic Aromatics	ASTM D5186	vol %			1.4	0.7
Cetane Number	ASTM D613		48.0			48.1
High Frequency Recip. Rig	ASTM D6079	microns			520	269

APPROVED BY:

ANALYST GP/PLI/INS

Table A-4. CARB Phase II Gasoline

PRODUCT INFORMATION

Haltermann PRODUCTS

RESPONSIBLE CARE
ISO 9001 CERTIFIED

T (281) 457-2768 F (281) 457-1469

Johann Haltermann Ltd.

PRODUCT: CARB Phase II Certification Fuel

PRODUCT CODE: HF004

Batch No.: W12321GP10
Shipment No: MTS
Tank No.: TK8
Analysis Date: 10/22/2008

TEST	METHOD	UNITS	CARB SPECIFICATIONS			RESULTS
			MIN	TARGET	MAX	
Distillation - IBP	ASTM D86	°F		Report		103
5%		°F				128
10%		°F	130		150	140
20%		°F				154
30%		°F				168
40%		°F				184
50%		°F	200		210	202
60%		°F				222
70%		°F				239
80%		°F				259
90%		°F	290		300	293
95%		°F				316
Distillation - EP		°F			390	355
Recovery		vol %		Report		97.2
Residue		vol %			2.0	0.7
Loss		vol %		Report		2.1
Gravity	ASTM D4052	°API		Report		60.3
Density	ASTM D4052	kg/l		Report		0.7377
Reid Vapor Pressure	ASTM D5191	psi		Report		6.77
Carbon	ASTM E191	wt fraction		Report		83.46
Hydrogen	ASTM E191	wt fraction		Report		13.38
Hydrogen/Carbon ratio	ASTM E191	mole/mole		Report		1.910
Oxygen(other than MTBE)	ASTM D4815	wt %			0.05	<0.01
Sulfur	ASTM D5453	ppmw	30		40	37
Lead	ASTM D3237	g/gal			0.01	<0.001
Phosphorous	ASTM D3231	g/gal			0.005	<0.0001
MTBE	ASTM D4815	vol %	10.80		11.20	10.98
Composition, aromatics	ASTM D1319	vol %	22.0		26.0	22.5
Composition, olefins	ASTM D1319	vol %	4.0		6.0	4.3
Composition, saturates	ASTM D1319	vol %		Report		62.2
Multisubstituted Alkyl Aromatics	ASTM D5769	vol %	12.0		14.0	13.0
Benzene	ASTM D3606	vol %	0.80		1.00	0.87
Particulate matter	ASTM D5452	mg/l			5	0.5
Oxidation Stability	ASTM D525	minutes	1000			>1000
Copper Corrosion	ASTM D130				1	1a
Gum content, washed	ASTM D381	mg/100mls			3	1.0
Research Octane Number	ASTM D2699			Report		97.2
Motor Octane Number	ASTM D2700			Report		88.2
Sensitivity	D2699/2700		7.5			9.0
R+M/2	D2699/2700		91.0			92.7
Net Heat of Combustion	ASTM D240	btu/lb		Report		18194
Deposit Control Additive	Calculated	ppm active		200		200

APPROVED BY: Kevin T. Dunn

ANALYST PLI/PH/CL/GP

ReFUEL Test Report Appendix C. Coast Down Data

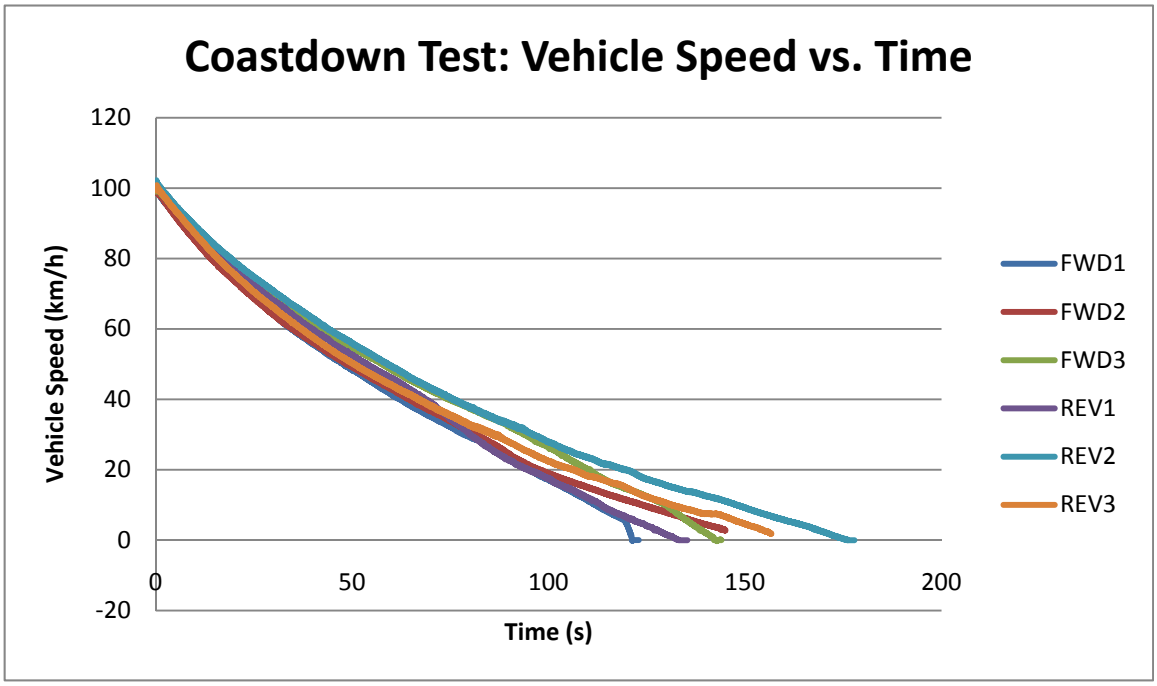


Figure A-8a. HEV track coast down curves

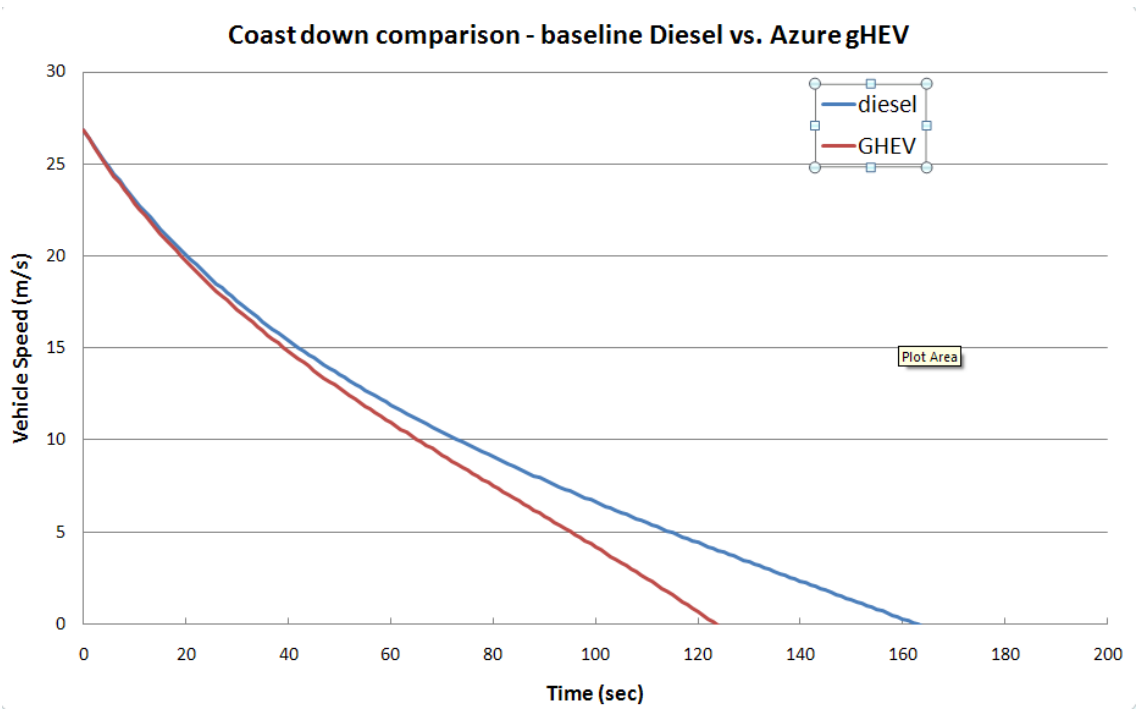


Figure A-8b. Coast down comparison – conducted at ReFUEL

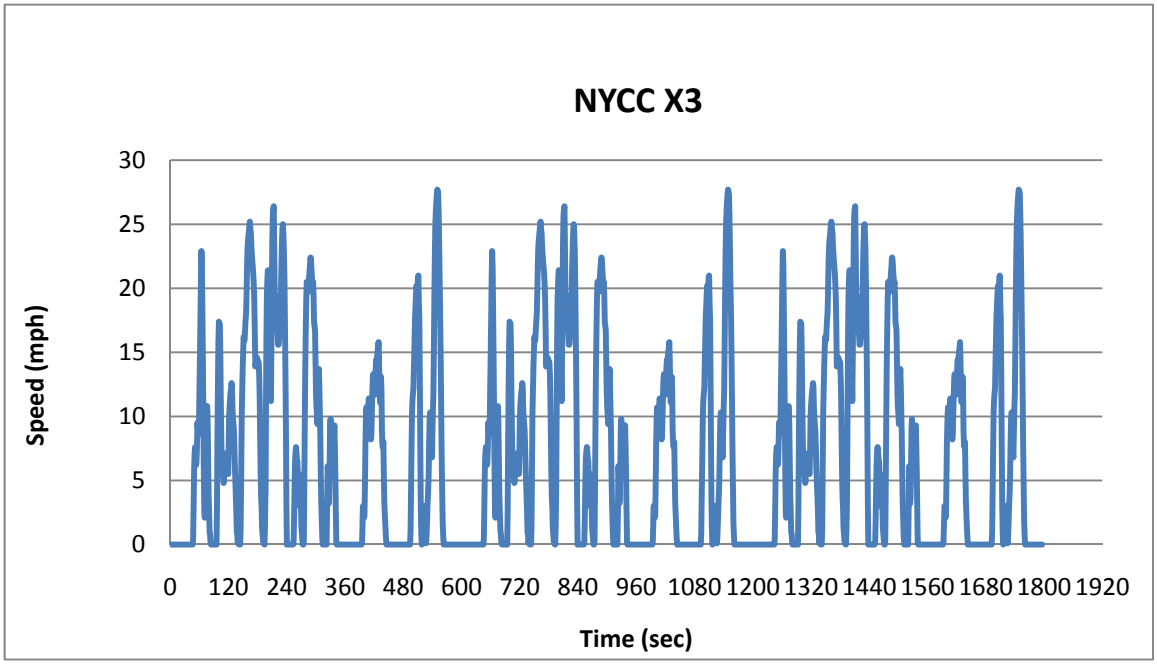


Figure A-9. NYCC drive cycle

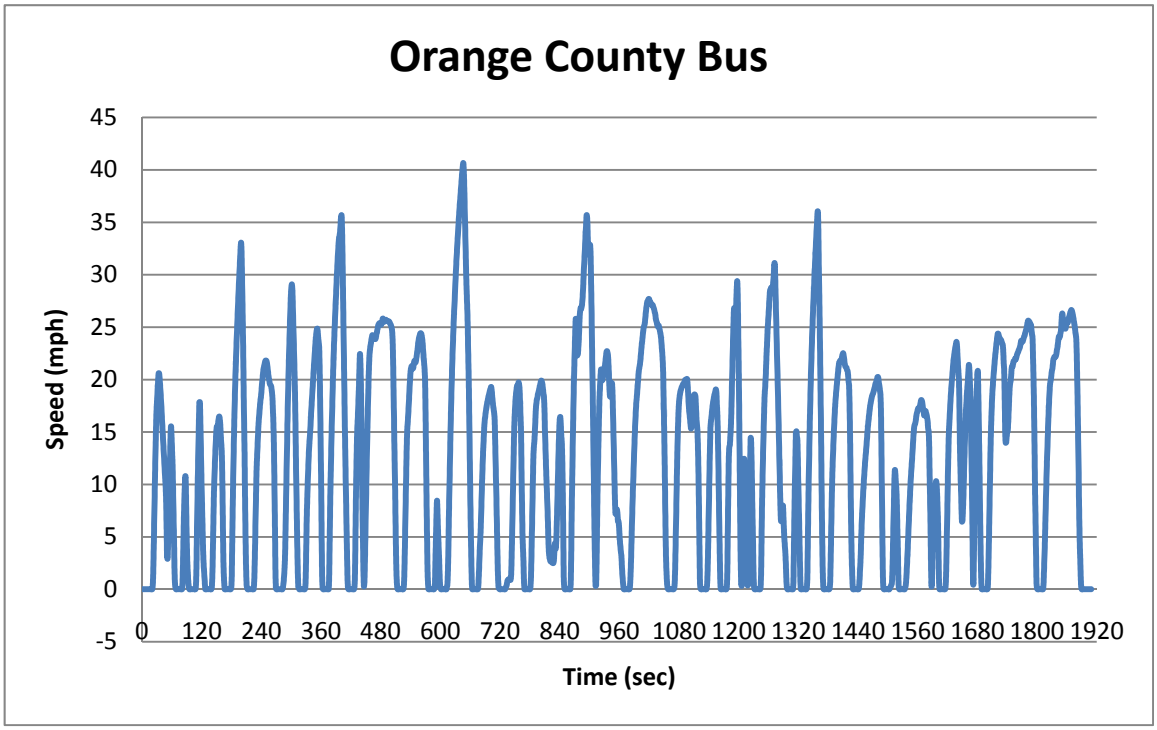


Figure A-10. Orange County Bus drive cycle

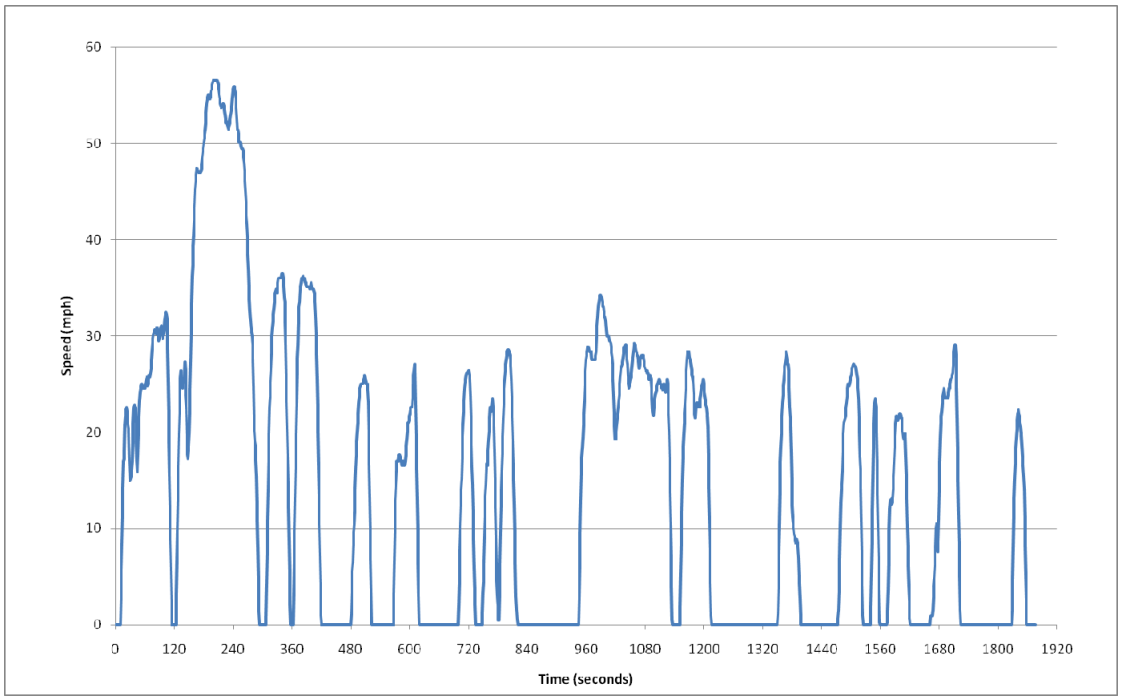


Figure A-11. HTUF4 drive cycle

Table A-5. Conventional Test Results

Date	Cycle	Run #	NOx g/mile	CO g/mile	THC g/mile	CO2 g/mile	PM g/mile	Fuel Economy mpg	Distance miles
05/13/09	NYCC X3	2056	12.3	7.08	0.94	1430	0.719	6.18	3.55
05/18/09	NYCC X3	2065	13.1	8.01	0.57	1507	0.821	5.93	3.53
05/18/09	NYCC X3	2066	12.6	7.77	0.75	1470	0.839	6.13	3.53
		avg	**12.7**	**7.6**	**0.8**	**1468.9**	**0.793**	**6.08**	**3.5**
		stdev	*0.42*	*0.48*	*0.19*	*38.92*	*0.064*	*0.13*	*0.01*
		cov	*3%*	*6%*	*25%*	*3%*	*8%*	*2.2%*	*0%*

Date	Cycle	Run #	NOx g/mile	CO g/mile	THC g/mile	CO2 g/mile	PM g/mile	Fuel Economy mpg	Distance miles
05/14/09	OC Bus	2059	7.4	2.87	0.52	956	0.275	9.59	6.57
05/14/09	OC Bus	2060	7.5	3.03	0.60	955	0.319	9.45	6.60
05/14/09	OC Bus	2061	7.8	2.85	0.60	952	0.305	9.53	6.58
		avg	**7.6**	**2.9**	**0.6**	**954**	**0.300**	**9.52**	**6.6**
		stdev	*0.18*	*0.10*	*0.05*	*2*	*0.022*	*0.07*	*0.02*
		cov	*2%*	*3%*	*9%*	*0%*	*7%*	*0.8%*	*0%*

Date	Cycle	Run #	NOx g/mile	CO g/mile	THC g/mile	CO2 g/mile	PM g/mile	Fuel Economy mpg	Distance miles
05/13/09	HTUF4	2057	5.2	2.38	0.43	759	0.273	11.86	7.34
05/13/09	HTUF4	2058	5.4	2.43	0.40	781	0.292	11.42	7.34
05/13/09	HTUF4	2053	5.1	2.74	0.43	761	N/M	11.68	7.34
		avg	**5.2**	**2.5**	**0.4**	**767**	**0.282**	**11.66**	**7.3**
		stdev	*0.14*	*0.20*	*0.02*	*13*	*0.01*	*0.22*	*0.00*
		cov	*3%*	*8%*	*4%*	*2%*	*5%*	*1.9%*	*0%*

Table A-6. Hybrid Test Results

Date	Cycle	Run #	NOx g/mile	CO g/mile	THC g/mile	CO2 g/mile	PM g/mile	Fuel Econ mpg	Distance miles	SOC %
04/22/09	NYCC X3	2037	NM	0.81	NM	1114	N/M	7.03	3.49	-0.64
04/22/09	NYCC X3	2038	3.5	2.25	0.127	1219	0.0016	6.43	3.53	0.96
04/22/09	NYCC X3	2039	3.4	0.16	0.042	1190	0.0017	6.61	3.54	-0.54
04/22/09	NYCC X3	2040	2.8	0.16	0.057	1122	0.0014	6.92	3.51	-0.27
		avg	**3.2**	**0.8**	**0.0**	**1160.9**	**0.0016**	**6.75**	**3.5**	
		stdev	*0.39*	*0.99*	*0.21*	*51.39*	*0.0002*	*0.28*	*0.02*	
		cov	*12%*	*117%*	*-800%*	*4%*	*9%*	*4.1%*	*1%*	

Date	Cycle	Run #	NOx g/mile	CO g/mile	THC g/mile	CO2 g/mile	PM g/mile	Fuel Econ mpg	Distance miles	SOC %
04/23/09	OC Bus	2041	1.2	0.29	NM	928	0.0003	8.40	6.54	0.33
04/23/09	OC Bus	2042	0.6	0.17	NM	912	0.0006	8.51	6.49	0.55
04/23/09	OC Bus	2043	1.4	0.41	0.016	872	0.0004	8.92	6.50	-0.47
		avg	**1.0**	**0.3**	**0.0**	**903.8**	**0.0004**	**8.61**	**6.5**	
		stdev	*0.44*	*0.12*	*0.08*	*28.57*	*0.0002*	*0.28*	*0.03*	
		cov	*42%*	*42%*	*-189%*	*3%*	*37%*	*3.2%*	*0%*	

Date	Cycle	Run #	NOx g/mile	CO g/mile	THC g/mile	CO2 g/mile	PM g/mile	Fuel Econ mpg	Distance miles	SOC %
04/23/09	HTUF4	2045	0.6	0.58	0.053	770	0.0005	10.22	7.27	0.44
04/23/09	HTUF4	2046	0.5	1.28	0.036	760	0.0008	10.46	7.32	-0.04
04/23/09	HTUF4	2047	0.6	1.24	0.032	745	0.0005	10.66	7.34	-0.25
		avg	**0.6**	**1.0**	**0.0**	**758.6**	**0.0006**	**10.45**	**7.3**	
		stdev	*0.02*	*0.40*	*0.01*	*12.44*	*0.0002*	*0.22*	*0.04*	
		cov	*4%*	*38%*	*28%*	*2%*	*25%*	*2.1%*	*0%*	

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13. SUPPLEMENTARY NOTES

14. ABSTRACT *(Maximum 200 Words)*

This report summarizes the data obtained in a 12-month comparison of three gasoline hybrid electric delivery vehicles with three comparable diesel vehicles. The data show that there was no statistical difference between operating cost per mile of the two groups of vehicles. As expected, tailpipe emissions were considerably lower across all drive cycles for the gHEV than for the diesel vehicle.

15. SUBJECT TERMS
Gasoline hybrid electric truck; gHEV; Evaluation; ReFUEL; fuel economy; diesel

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