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# FedEx Gasoline Hybrid Electric Delivery Truck Evaluation: 6-Month Interim Report

R. Barnitt

*Technical Report*
NREL/TP-540-47693
May 2010

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Prepared under Task No. FC08.3000

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# Executive Summary

This interim report presents partial (six months) results for a technology evaluation of gasoline hybrid electric parcel delivery trucks operated by FedEx in and around Los Angeles, CA. FedEx is a large commercial fleet that operates more than 22,000 motorized vehicles and has hybrid electric (diesel and gasoline) vehicles currently in service. FedEx has deployed 20 gasoline hybrid electric vehicles (gHEVs) on parcel delivery routes in the Sacramento and Los Angeles areas. A 12 month in-use technology evaluation comparing in-use fuel economy and maintenance costs of GHEVs and comparative diesel parcel delivery trucks was started in April 2009.

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 was collected and analyzed for in-use fuel economy and fuel costs, maintenance costs, total operating costs, and vehicle uptime.

In addition, this interim report presents results of parcel delivery drive cycle 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 the National Renewable Energy Laboratory's (NREL) ReFUEL laboratory. The goal of the ReFUEL testing was to quantify the reduction in emissions realized with the gHEV and to compare the fuel economy of a gHEV and a diesel vehicle.

A robust drive cycle data collection and analysis effort framed the selection of study vehicles and routes as well as 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 tested drive cycles than emissions from the diesel baseline vehicle. Fuel economy was similar between the gHEV and diesel vehicle, except for the highest kinetic intensity drive cycle where the hybrid exhibited ~20% higher fuel economy.

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.

This interim report captures only the first six months of study. To account for differences in routes between the gHEV and diesel vehicles, truck routes were exchanged after six months; therefore, the 12-month average fuel economy will be a more accurate comparison between the two vehicle groups. A final report will be issued when 12 months of in-use data have been collected and analyzed.

# Acronyms and Abbreviations

| | |
|---|---|
| AC | Air conditioning |
| AQMD | Air Quality Management District |
| ATA | American Trucking Association |
| AVTA | Advanced Vehicle Testing Activity |
| CAN | Controller Area Networks |
| CI | Compression ignition |
| CO | Carbon monoxide |
| DOE | U.S. Department of Energy |
| DPF | Diesel particulate filter |
| gHEV | Gasoline hybrid electric vehicle |
| GVWR | Gross vehicle weight rating |
| HP | Horsepower |
| HVAC | Heating, ventilation and cooling |
| lb-ft | Foot pounds |
| mpg | Miles per gallon |
| NOx | Oxides of nitrogen |
| NREL | National Renewable Energy Laboratory |
| PM | Particulate matter |
| RPM | Revolutions per minute |
| SI | Spark ignition |
| THC | Total hydrocarbons |
| TWC | Three-way catalyst |

# Table of Contents

# List of Figures

# List of Tables

# 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 (R&D) and the commercial availability of alternative fuels and advanced vehicle technologies. FT&E supports the U.S. Department of Energy's (DOE) 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 (AVTA).

This technology evaluation project with FedEx is supported and primarily sponsored by DOE. This project is also part of a larger effort funded primarily by South Coast AQMD and managed by Calstart, which will assess the potential for electric drive parcel delivery vehicles in southern California.

# 2 Introduction

This document presents interim results for the technology evaluation of gasoline hybrid electric parcel delivery trucks operated by FedEx in and around Los Angeles, CA. FedEx is a large commercial fleet that operates more than 22,000 motorized vehicles and has hybrid electric (diesel and gasoline) vehicles currently in service. FedEx has deployed 20 gasoline hybrid electric vehicles (gHEVs) on parcel delivery routes in the Sacramento and Los Angeles areas. These gHEVs 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.

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

**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<br>Automatic high-voltage disconnect in case of vehicle collision |
| **System Voltage** | 288 V DC 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<br>Hybrid system – Separate low temp cooling loop |

This interim report presents partial (six months) 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 interim report presents results of parcel delivery drive cycle 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 ReFUEL laboratory. A final report will be issued when 12 months of in-use data have been collected and analyzed.

# 3 Approach

## 3.1 Route / Duty-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 stock 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.

In order to identify three well matched gHEVs and routes, eight gHEVs deployed from three FedEx 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 data were used to confirm daily route consistency and to characterize each route over 55 drive cycle metrics.

**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 |
|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|
| 242286 | EMT | 4 | 3 | OFF | ON | ON | ON | NM | NM | NM | NM | NM | NM | NM |
| 242288 | EMT | 11 | 8 | ON | ON | ON | ON | OFF | OFF | ON | ON | ON | ON | OFF |
| 242289 | SPQ | 8 | 6 | ON | ON | ON | ON | OFF | OFF | ON | ON | NM | NM | NM |
| 242290 | SPQ | 10 | 8 | ON | ON | ON | ON | OFF | OFF | ON | ON | ON | ON | NM |
| 242292 | POC | 10 | 9 | ON | ON | ON | ON | ON | ON | ON | ON | ON | OFF | NM |
| 242293 | POC | 10 | 9 | OFF | ON | ON | ON | ON | ON | ON | ON | ON | ON | NM |
| 242294 | POC | 9 | 9 | ON | ON | ON | ON | ON | ON | ON | ON | ON | NM | NM |
| 242295 | 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. 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.

Daily route consistency was confirmed by filtering and then visualizing GPS-derived latitude and longitude data. Figure 1 depicts the four routes, each with nine or more overlaid days of operation. Table 3 presents the key drive cycle characteristics of these four routes, listed by truck number.

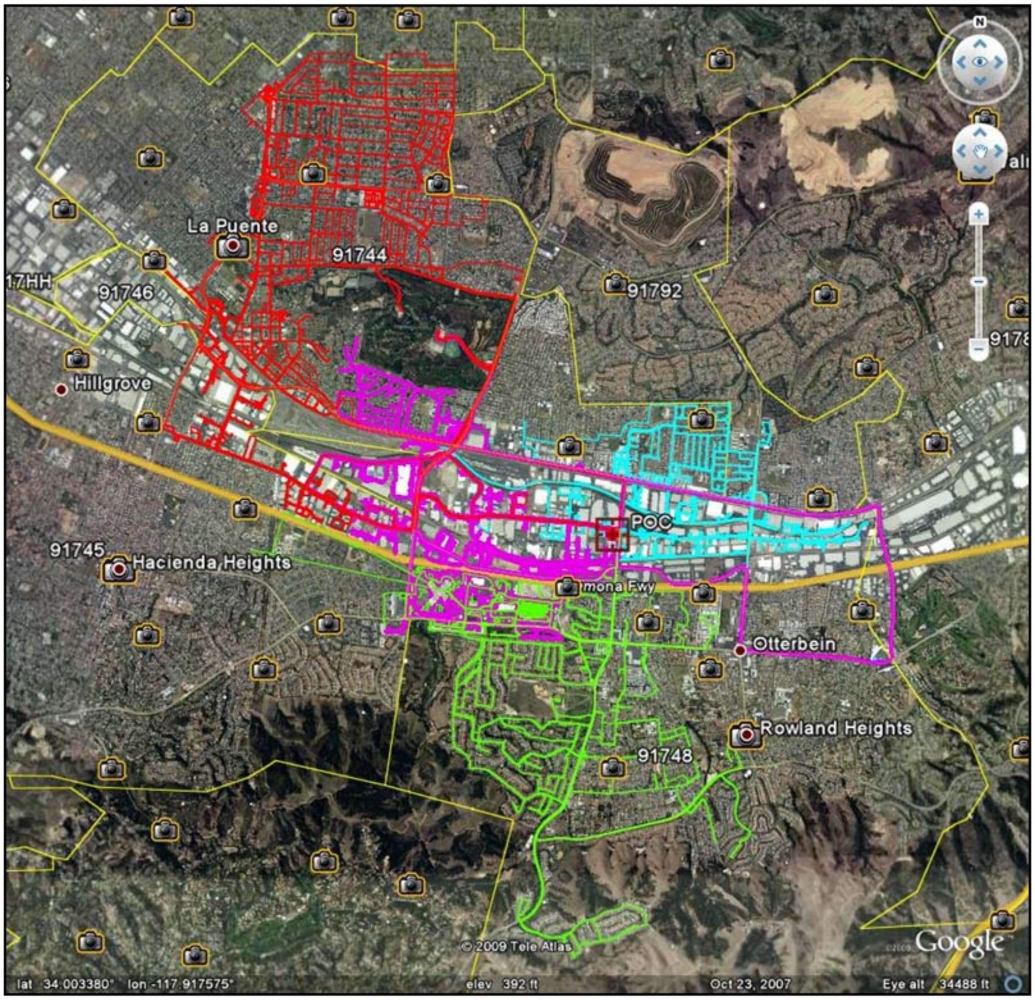

Figure 1. Four gHEV routes at FedEx POC depot

**Table 3. Key Drive Cycle Characteristics – gHEV Routes at POC Depot**

| Drive Cycle Characteristic | Vehicle # | | | |
|---|---|---|---|---|
| | 242292 | 242293 | 242294 | 242295 |
| Average Driving Speed (mph) | 16.8 | 17.3 | 16.9 | 16.2 |
| Daily VMT (miles) | 43.8 | 25.4 | 47.2 | 21.3 |
| Stops per Mile | 3.86 | 5.42 | 3.80 | 4.24 |
| Avg. Acceleration (ft/s$^2$) | 2.27 | 3.63 | 2.11 | 2.10 |
| Avg. Deceleration (ft/s$^2$) | -2.61 | -3.36 | -2.58 | -2.56 |
| Accelerations per Mile | 20.90 | 27.26 | 20.88 | 23.08 |
| Decelerations per Mile | 20.36 | 27.72 | 19.83 | 22.81 |
| Kinetic Intensity (ft$^{-1}$)[1] | 0.00059 | 0.00101 | 0.00055 | 0.00075 |

Based upon a statistical comparison of the drive cycle characteristics listed above, gHEV numbers 242292, 242294, and 242295 had the most similar drive cycles, so they were selected as the three gHEV study vehicles for the in-use evaluation.

In the absence of GPS-derived route data, diesel vehicles driving similar routes in terms of daily VMT and traffic patterns were suggested by the POC depot manager. To best negate the likely differences in the gHEV and diesel vehicle routes, after six months of evaluation the vehicle groups will exchange routes. Thus, the 12-month averages for gHEV and diesel groups should be comparable.

Calculated kinetic intensity[2] was used to compare real drive cycles to existing stock drive cycles, and aid in chassis dynamometer test cycle selection and vehicle simulation activities. Based upon observed drive cycle kinetic intensities, the Orange County Bus cycle was selected as a cycle that best approximated the average of the routes driven by three study vehicles, while the NYCC and HTUF4 cycles were selected as upper and lower boundaries for vocational kinetic intensity (Figure 2).

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

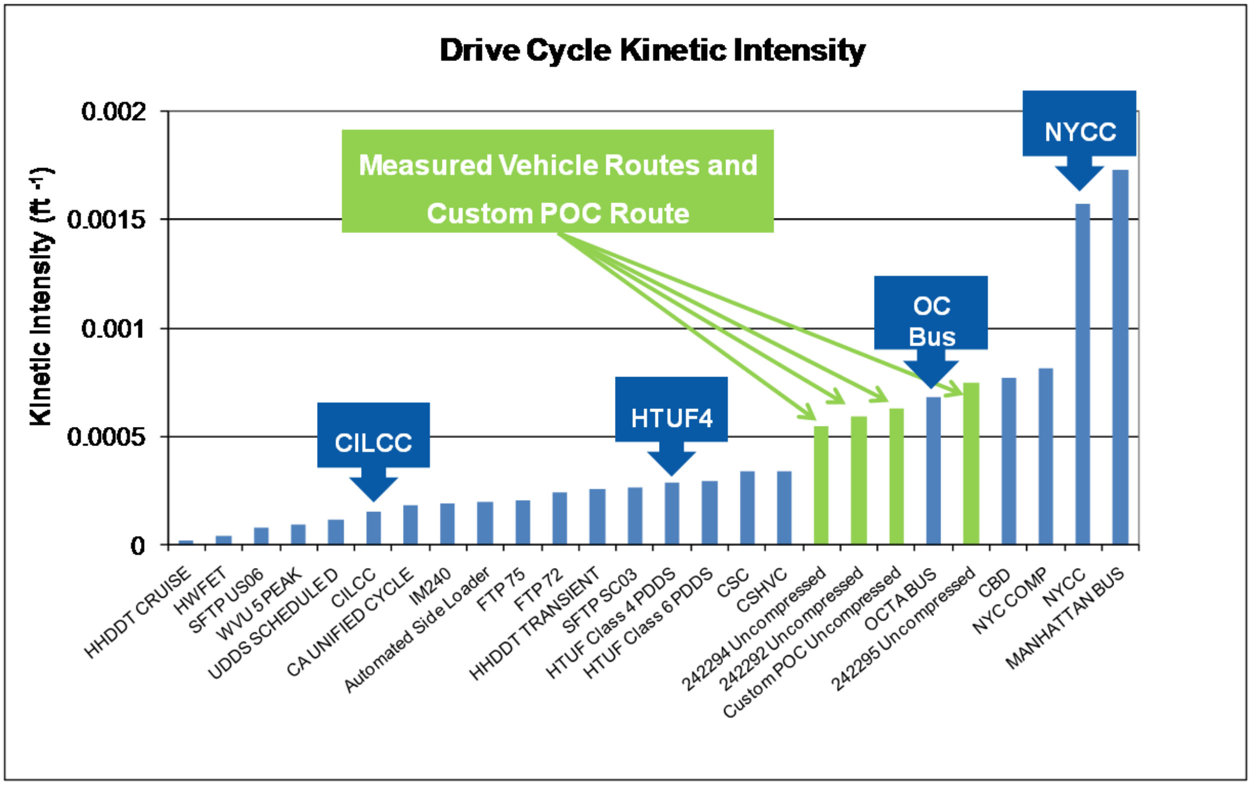

**Figure 2. Comparison of drive cycle kinetic intensities**

### 3.2 Vehicle Descriptions

Based upon the activities outlined in Section 3.1, 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. Basic vehicle attributes are presented in Table 4.

**Table 4. FedEx Delivery Truck Basic Information**

| Vehicle Information | gHEV | Diesel |
|---|---|---|
| Asset Numbers | 242292, 242294, 242295 | 239670, 239896, 239830 |
| 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<br>Max. Horsepower<br>Max. Torque | <br>255 HP @ 4500 RPM<br>350 lb-ft @ 2500 RPM | <br>200 HP @ 2300 RPM<br>520 lb-ft @ 1600 RPM |
| Fuel Capacity | 55 Gallon - Gasoline | 45 Gallon - Diesel |
| Transmission Manufacturer/Model | Ford 5R110 5-Spd. Auto. | Allison 1000 5-Spd. Auto. |
| Curb Weight | 8,235 lb | 9,700 lb |
| Gross Vehicle Weight (GVWR) | 14,050 lb | 16,000 lb |
| Cabin Air Conditioning | No | No |

## 3.3 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, CO. ReFUEL utilizes a heavy-duty vehicle (chassis) test cell with emissions and fuel consumption measurement capability. A gHEV being used by FedEx 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 fleet for testing. By leveraging collected and analyzed drive cycle data (Section 3.2), three stock drive cycles were identified for testing. These drive cycles span the range of vocational usage specific to parcel delivery vehicles tested in the field at the POC depot. The goal of the ReFUEL testing was to quantify the reduction in emissions realized with the gHEV and to compare the fuel economy of a gHEV and a diesel vehicle. Additional information relative to ReFUEL capabilities and experimental setup is included in the Appendix.

## 3.4 Vehicle Fueling and Data Collection

The purpose of collecting and analyzing truck in-use fuel records is to calculate and compare in-use fuel economy. Two 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:

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 #. 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 groups.

A third method will be implemented later in this project:

3. CAN bus-derived fuel consumption will be measured with ISAAC brand data loggers. Fuel consumption data will be collected on-board the vehicles for a limited period (approx. 1-2 weeks) during the evaluation. CAN-derived fuel consumption data reflects the call for fuel under current operating conditions and is not indicative of the actual mass of fuel consumed. Azure reports +/- 3% error in CAN-derived fuel consumption during simultaneous chassis dynamometer testing. This method will be employed 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 personnel at the POC depot. Preventive maintenance is conducted at 84-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 ATA code and are captured electronically. Evaluation truck Repair Orders were transmitted electronically to NREL by FedEx, 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 will be 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 (TWC and DPF)

### *3.5.1 Vehicle Warranty Repairs*

Data on warranty repairs are collected in a similar manner to data on normal maintenance actions. However, the 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 are under warranty. When a vendor (or FedEx) makes a warranty repair, the FedEx technician will close out the Repair Order to allow for reimbursement.

### 3.6 Vehicle Uptime

gHEV availability or uptime is tracked by Azure Dynamics and reported to FedEx in a weekly, monthly, and three-monthly format. The FedEx vehicle uptime target is 98%. Azure included NREL in the distribution of this reporting metric. Diesel evaluation truck availability data was transmitted electronically to NREL by FedEx, reviewed for accuracy, and analyzed for comparison of the gHEV and diesel vehicle groups.

# 4 Results

## 4.1 Vehicle Emissions and Fuel Economy Measurement

A detailed description of experimental setup, vehicle coast down curves, test fuels, 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, and 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.

### *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 and Fuel Economy Results**

| Drive Cycle | Vehicle | NOx (g/mile) | CO (g/mile) | THC (g/mile) | PM (g/mile) | Fuel Economy (mpg) |
|---|---|---|---|---|---|---|
| NYCC | gHEV | 3.24 | 0.84 | ND[a] | 0.0016 | 6.75 |
| | Diesel | 12.70 | 7.60 | 0.80 | 0.7930 | 6.08 |
| OC Bus | gHEV | 1.05 | 0.29 | ND[a] | 0.0004 | 8.61 |
| | Diesel | 7.60 | 2.90 | 0.60 | 0.3000 | 9.52 |
| HTUF4 | gHEV | 0.57 | 1.03 | 0.04 | 0.0006 | 10.45 |
| | Diesel | 5.20 | 2.50 | 0.40 | 0.2820 | 11.66 |

[a] Measured below laboratory detection limit. Note error bars in Figure 3.

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 $NO_x$ and PM were essential. The laboratory dilution ratio was calibrated to optimize for the precise measurement of $NO_x$, at the expense of some hydrocarbon analyzer precision in measuring CO and HC. Thus, there is higher variability in the CO and HC 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 3 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.

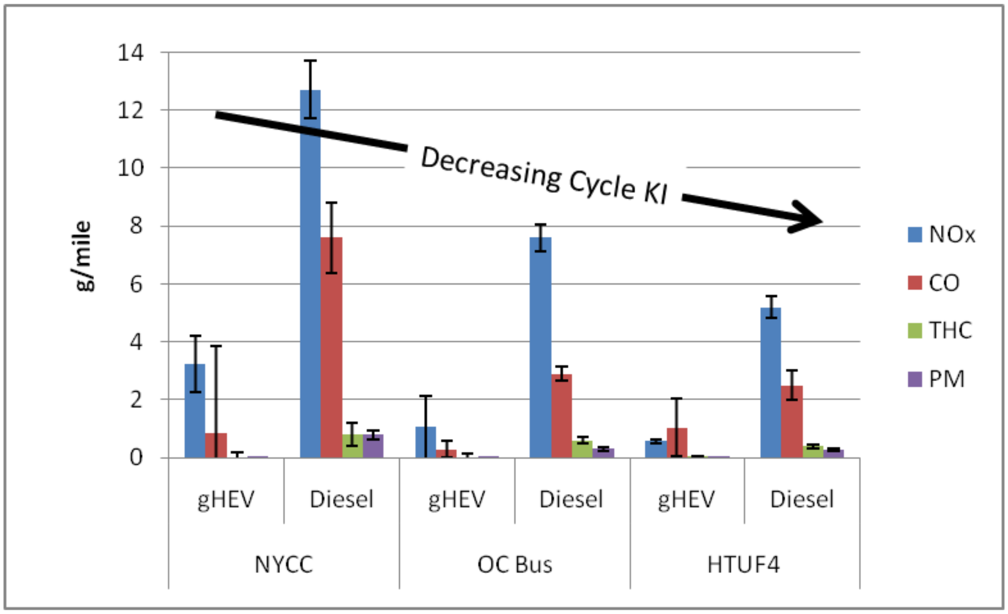

**Figure 3. Criteria emissions by drive cycle**

### *4.1.2 Vehicle Fuel Economy Comparison*

Volumetric fuel economy was measured for each vehicle over three drive cycles. The fuels were analyzed for energy content to enable normalization of volumetric fuel economy. These results, as well as the normalized gHEV fuel economy advantage by drive cycle, are presented in Table 7.

**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 (%) |
|---|---|---|---|---|
| NYCC | 6.75 | 7.34 | 6.08 | 20.65 |
| OCTA Bus | 8.61 | 9.36 | 9.52 | -1.71 |
| HTUF4 | 10.45 | 11.36 | 11.66 | -2.60 |

The gHEV is approximately equal to the diesel vehicle with respect to fuel economy on two of the three test cycles. This parity exists due to the gHEV's lower liquid fuel energy content (gasoline) and the inherently lower thermal efficiency of a spark ignition (SI) engine as compared to a compression ignition (CI) engine. 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 and the battery and 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 wasted 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 calculated kinetic intensity are better candidates for hybrid vehicle deployment, due to the benefits of increased fuel economy.

## 4.2 In-Use Fuel Economy and Costs

In-use fuel data were collected via retail fuel data supplied by FedEx 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 4, Figure 5).

**Table 8. Fuel Economy and Costs from Retail Fueling Records**

| Vehicle Type | Asset # | Start Date | End Date | Miles | Fuel Volume (gallons) | Fuel Economy (mpg) | Fuel Cost ($) | Fuel Cost per Mile ($/mile) |
|---|---|---|---|---|---|---|---|---|
| gHEV | 242292 | 04/21/09 | 10/29/09 | 6,057 | 892.9 | 6.78 | 2,513 | 0.41 |
| | 242294 | 04/21/09 | 10/27/09 | 5,978 | 820.2 | 7.29 | 2,347 | 0.39 |
| | 242295 | 04/23/09 | 10/27/09 | 3,340 | 492.6 | 6.78 | 1,483 | 0.44 |
| | **Total** | | | **15,375** | **2,205.7** | **6.97** | **6,343** | **0.41** |
| Diesel | 239670 | 04/21/09 | 10/26/09 | 6,569 | 984.3 | 6.67 | 2,665 | 0.41 |
| | 239830 | 04/22/09 | 10/26/09 | 5,271 | 595.3 | 8.85 | 1,715 | 0.33 |
| | 239896 | 04/28/09 | 10/29/09 | 5,231 | 672.0 | 7.78 | 1,836 | 0.35 |
| | **Total** | | | **17,071** | **2,251.5** | **7.58** | **6,217** | **0.36** |

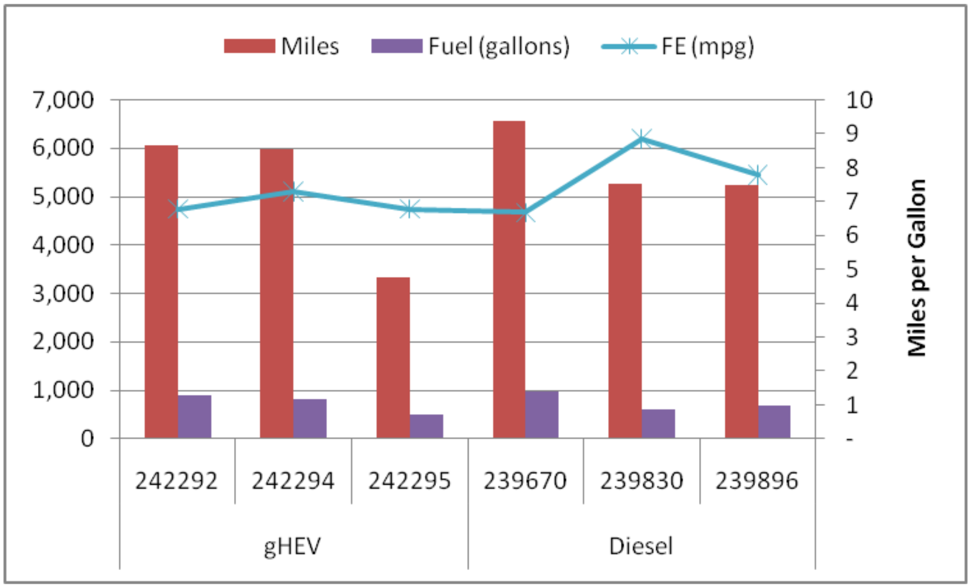

**Figure 4. Fuel economy results**

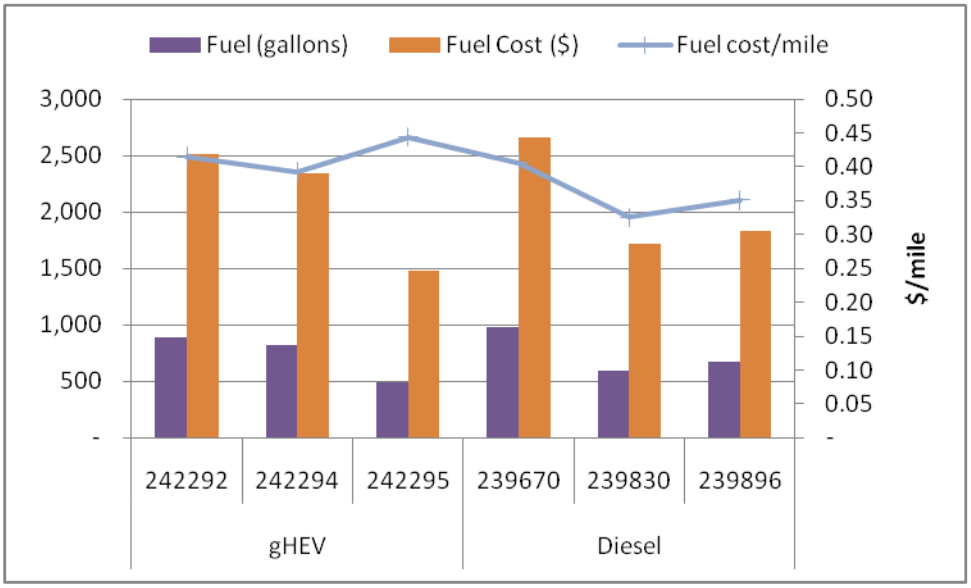

**Figure 5. Fuel and fuel cost/mile results**

CAN-based fuel economy will be measured later in the project and included in the Final Report.

## 4.3 Maintenance Costs

Maintenance costs and maintenance costs per mile driven can be a function of vehicle age. Table 9 presents the odometer readings of the study vehicles at the beginning of and at the end of this study period.

**Table 9. Relative Ages of Study Vehicles**

| Vehicle Type | Asset # | Start Miles | End Miles |
|---|---|---|---|
| gHEV | 242292 | 10,807 | 16,864 |
| | 242294 | 11,190 | 17,168 |
| | 242295 | 7,868 | 11,208 |
| | **Average** | **9,955** | **15,080** |
| Diesel | 239670 | 37,643 | 44,212 |
| | 239830 | 40,130 | 45,401 |
| | 239896 | 42,245 | 47,476 |
| | **Average** | **40,006** | **45,696** |

The diesel group is generally older than the gHEV group, which suggests that maintenance costs could be higher. 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 and transmitted to NREL for analysis. Maintenance data for the study period are presented below (Figure 6 and Table 10).

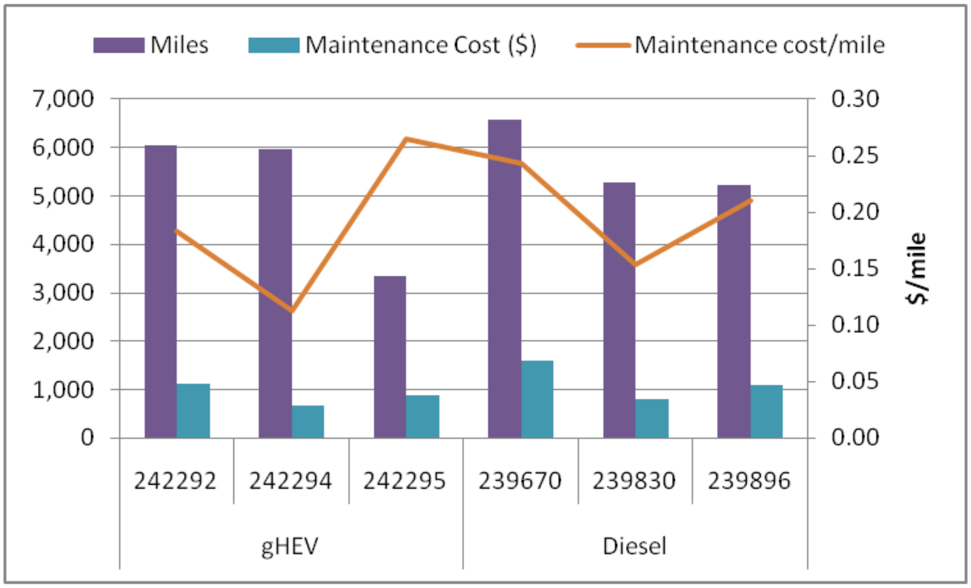

**Figure 6. Total maintenance cost and maintenance cost/mile results**

### Table 10. 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 | 858.90 | 0.056 | 1,546.44 | 0.091 |
| 001 | Air Conditioning, Heating, and Ventilation | 91.39 | 0.006 | - | - |
| 002 | Cab | 241.20 | 0.016 | 203.98 | 0.012 |
| 003 | Instruments, Gauges, Meters | 9.14 | 0.001 | 111.96 | 0.007 |
| 013 | Brakes | - | - | 192.62 | 0.011 |
| 017 | Tires | 947.75 | 0.062 | 923.03 | 0.054 |
| 031, 032 | Charging System | 136.44 | 0.009 | 36.56 | 0.002 |
| 034 | Lighting System | 9.14 | 0.001 | 8.28 | 0.000 |
| 041 | Air Intake System | - | - | 35.69 | 0.002 |
| 043 | Exhaust | 9.14 | 0.001 | 3.05 | 0.000 |
| 044 | Fuel System | - | - | 18.28 | 0.001 |
| 045 | Power Plant | 6.09 | 0.000 | 18.28 | 0.001 |
| 048 | Electric Propulsion System | 18.28 | 0.001 | - | - |
| 053 | Expendable Items | 29.67 | 0.002 | 18.28 | 0.001 |
| 066, 071, 072 | Body, Doors | 118.82 | 0.008 | 39.60 | 0.002 |
| 092 | Bulk Product Transfer (compressor) | - | - | 9.14 | 0.001 |
| 102 | Special Body Codes | 149.29 | 0.010 | 60.94 | 0.004 |
| 153 | Misc. Shop Supplies | 47.59 | 0.003 | 91.70 | 0.005 |
| 156 | Back-up Camera | - | - | 193.61 | 0.011 |
| **Total** | | **2,672.84** | **0.174** | **3,511.44** | **0.206** |

Maintenance costs are dominated by preventive maintenance (PM) activities, tire replacements, and cab repairs (Figure 7 and Figure 8). These three dominant maintenance categories are removed in Figure 9, allowing for better visualization of lower-tier maintenance costs for each study group.

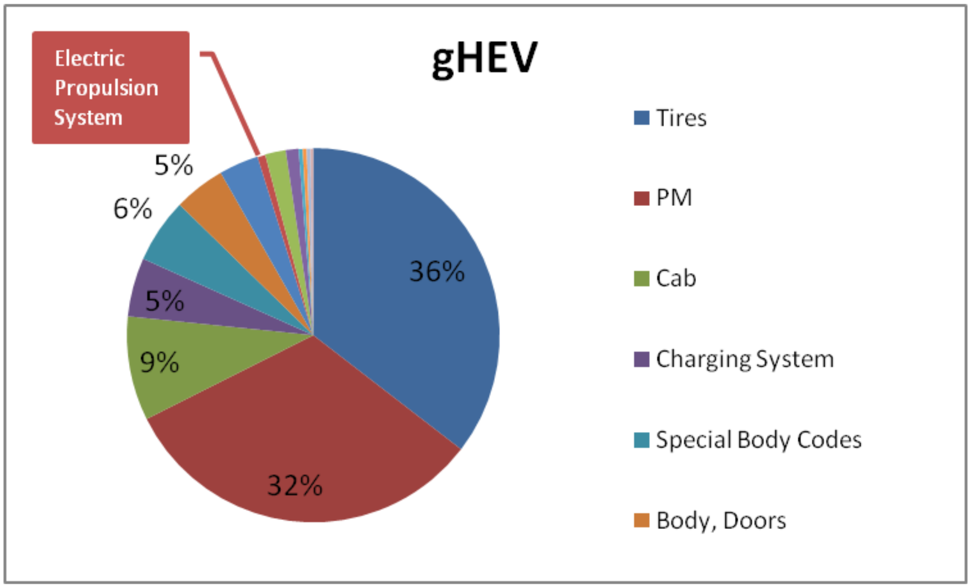

Figure 7. gHEV maintenance costs by system

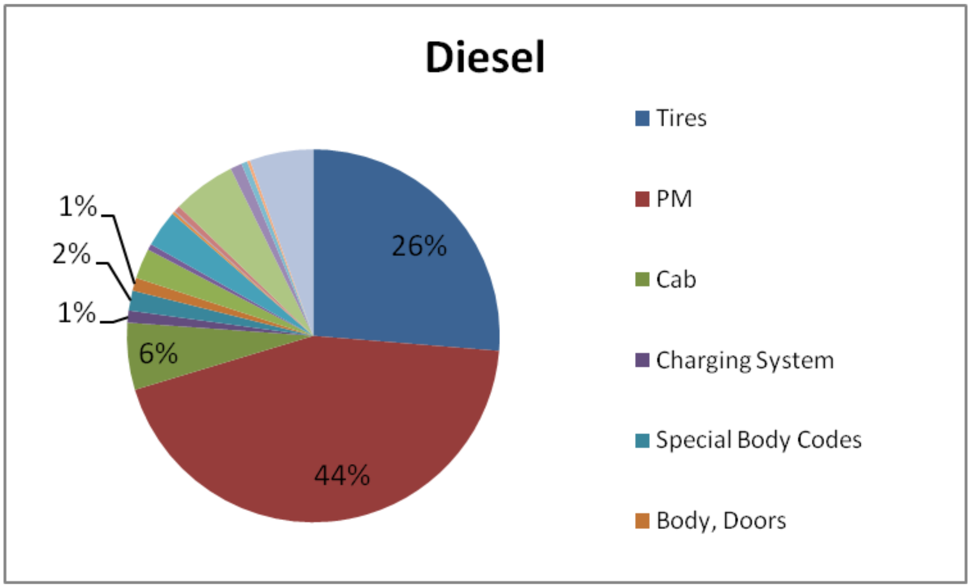

Figure 8. Diesel maintenance costs by system

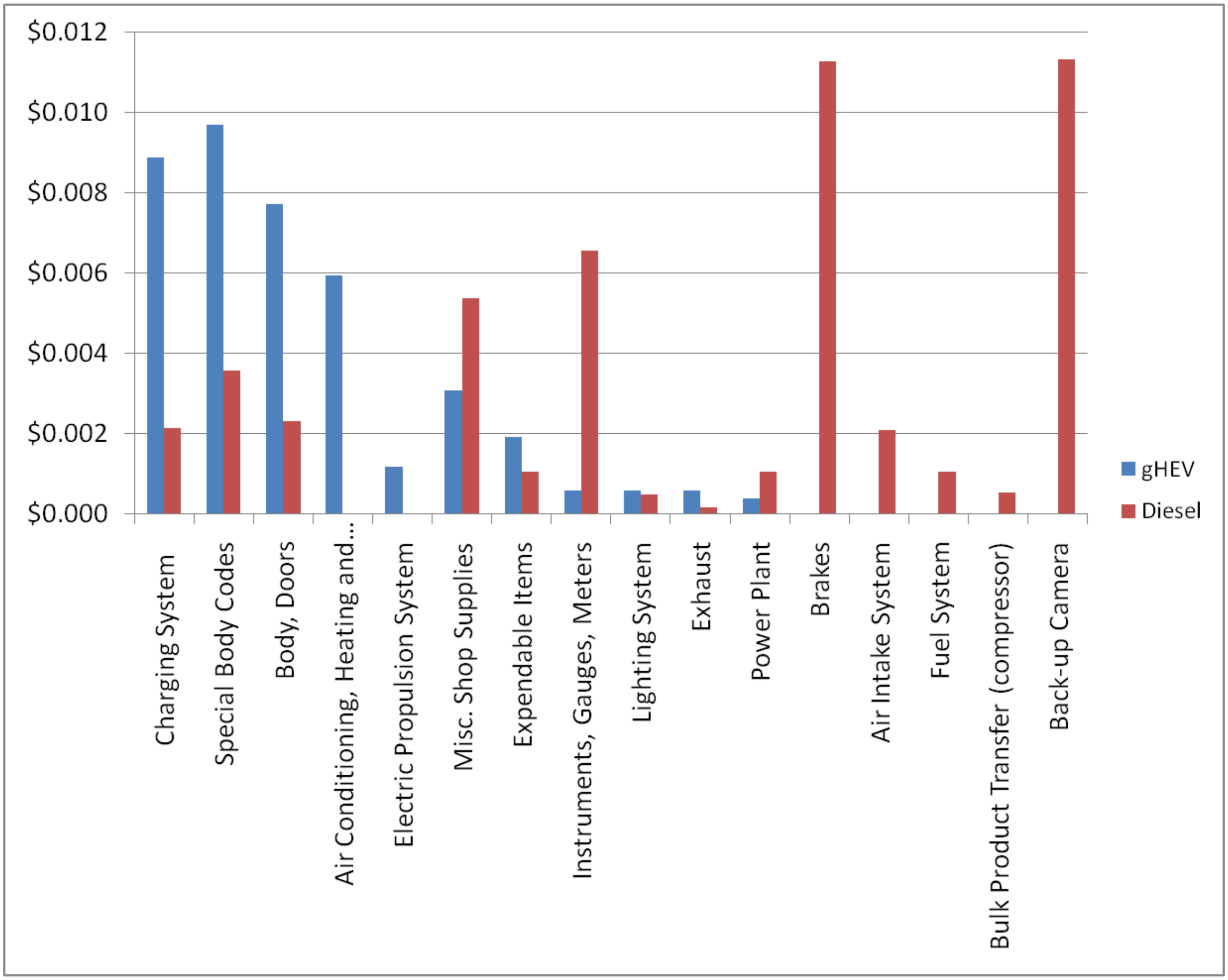

**Figure 9. Lower tier maintenance costs per mile by system**

Upon examination of Figure 9, there are several obvious differences between the gHEV and diesel groups. Several of them (charging system, special body codes, AC and HVAC) are likely due to "shakedown" activities when integrating the new 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.

Over the six-month study period, there were three records of electric propulsion system maintenance for vehicle 242292 totaling $54.84. These included an inspection following reports of the hybrid system not functioning, followed by the replacement of a fuse by Azure Dynamics personnel. Ultimately, two of the three records were identified as warranty replacements, and FedEx was not charged for replacement parts and was reimbursed for some diagnostic labor. The adjusted labor cost for electric propulsion system maintenance was reduced to one routine inspection event at $18.28.

During the study period, no brake repairs were performed on the hybrids; this was an expected result due to their low mileage over six months. Diesel truck 239670 had a two-wheel brake replacement during the study period, for a total cost of $165.20. FedEx examines brakes at every preventive maintenance occurrence 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 the 12 months currently scheduled. Exhaust, power plant, and fuel system maintenance cost differences between the two groups were insignificant during the study period.

### *4.3.1 Vehicle Warranty Repairs*

Vehicle warranty repairs during the study period were few. Only gHEV 242292 experienced vehicle warranty repairs, which are summarized in Table 11.

**Table 11. Vehicle Warranty Repairs**

| Asset # | Mileage | System | Assembly | Part | Item | Description | Warranted Cost ($) |
|---|---|---|---|---|---|---|---|
| 242292 | 11,334 | 001 | 001 | 049 | Valve Assembly | Expansion Inspection | 18.28 |
| 242292 | 11,596 | 031 | 000 | 000 | Charging System | Inspection | 36.56 |
| 242292 | 11,596 | 031 | 001 | 000 | Generator/ Alternator | Other Maintenance | 6.09 |
| 242292 | 11,596 | 031 | 001 | 000 | Generator/ Alternator | Other Maintenance | 24.37 |
| 242292 | 11,596 | 032 | 000 | 000 | Cranking System | Inspection | 9.14 |
| 242292 | 11,858 | 048 | 001 | 000 | Power Train Assy | Hybrid Exchange New | 36.56 |
| 242292 | 11,858 | 048 | 001 | 000 | Power Train Assy | Hybrid Burned Out | 36.56 |

## 4.4 Total Operating Costs

Total operating costs include fuel and maintenance costs. These costs for the study period are summarized and presented below (Table 12, Figure 10).

**Table 12. Total Operating Costs**

| Vehicle Type | Asset # | Miles | Fuel Cost ($) | Maintenance Cost ($) | Total Operating Cost ($) | Total Operating Cost per Mile ($/Mile) |
|---|---|---|---|---|---|---|
| gHEV | 242292 | 6,057 | 2,513 | 1,109 | 3,623 | 0.60 |
| | 242294 | 5,978 | 2,347 | 671 | 3,018 | 0.50 |
| | 242295 | 3,340 | 1,483 | 885 | 2,368 | 0.71 |
| | **Total** | **15,375** | **6,343** | **2,796** | **9,139** | **0.59** |
| Diesel | 239670 | 6,569 | 2,665 | 1,598 | 4,263 | 0.65 |
| | 239830 | 5,271 | 1,715 | 811 | 2,527 | 0.48 |
| | 239896 | 5,231 | 1,836 | 1,102 | 2,939 | 0.56 |
| | **Total** | **17,071** | **6,217** | **3,511** | **9,729** | **0.57** |

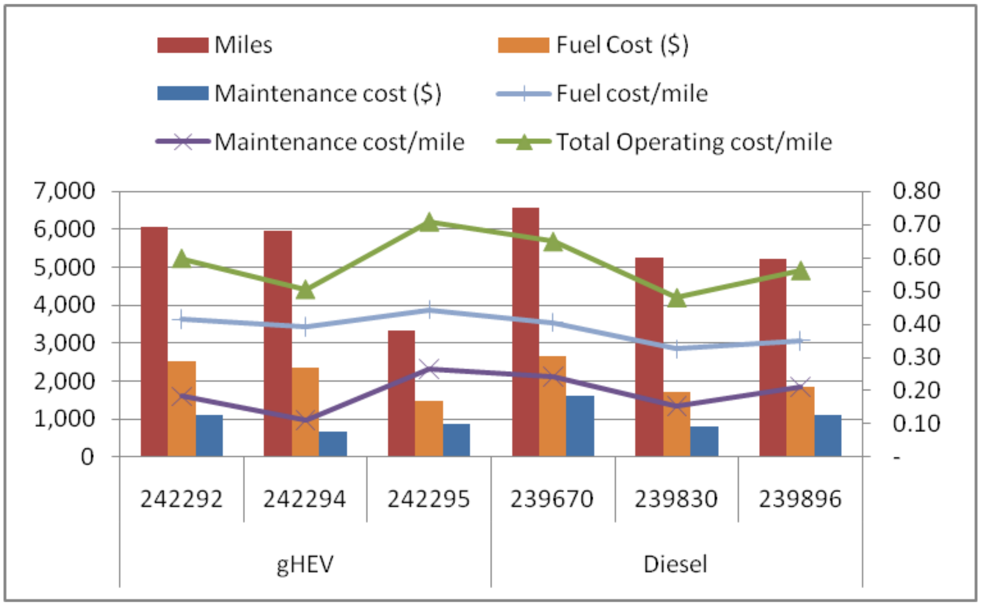

**Figure 10. Total operating costs**

## 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 for the study period is presented in Table 13 and Figure 11. The uptime goal of 98% is shown as a red dashed line in Figure 11.

Table 13. Vehicle Uptime

| Vehicle Type | Asset Number | Unplanned Days Out of Service | Total Days in Period | Days in Service | Uptime % |
|---|---|---|---|---|---|
| gHEV | 242292 | 4 | 183 | 179 | 97.8 |
| | 242294 | 19 | 183 | 164 | 89.6 |
| | 242295 | 2 | 183 | 181 | 98.9 |
| | **Total** | **25** | **549** | **524** | **95.4** |
| Diesel | 239670 | 1 | 183 | 182 | 99.5 |
| | 239830 | 2 | 183 | 181 | 98.9 |
| | 239896 | 6 | 183 | 177 | 96.7 |
| | **Total** | **9** | **549** | **540** | **98.4** |

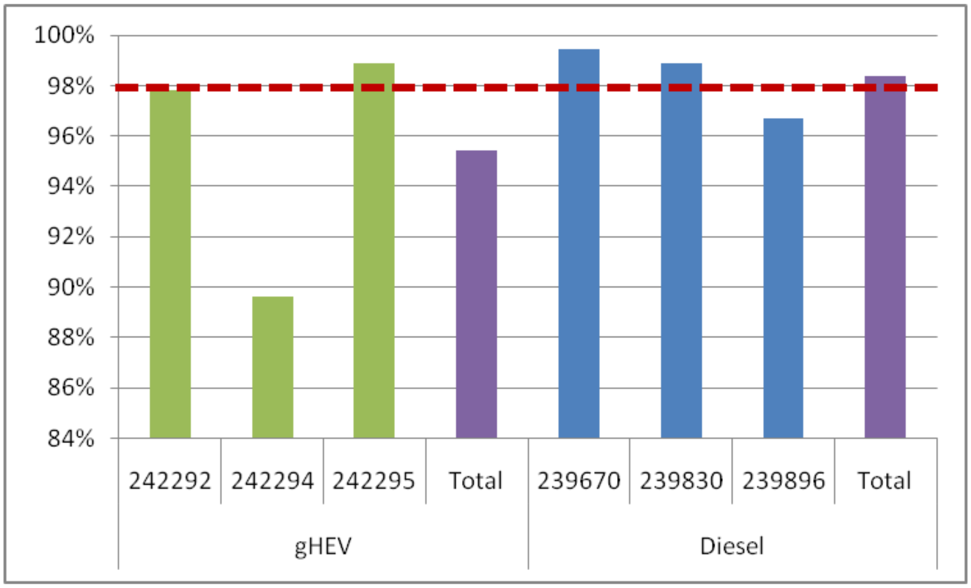

Figure 11. Vehicle uptime

It is important to note that none of the gHEVs experienced hybrid system related maintenance issues that resulted in downtime. Thus, vehicle uptime was 100% as related to hybrid system performance. Vehicle 242294 exhibited the most significant departure from uptime goals, driven by 15 days out of service to repair the keyless entry system.

# 5 Summary

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.

A robust drive cycle data collection and analysis effort framed the selection of study vehicles and routes as well as 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 tested drive cycles than emissions from the diesel baseline vehicle. Fuel economy was similar between the gHEV and diesel vehicle, except for the highest kinetic intensity drive cycle where the hybrid exhibited ~20% higher fuel economy.

This interim report captures only the first six months of study. As noted previously, routes were exchanged between gHEV and diesel trucks after six months. Due to differences in routes, the 12-month average fuel economy will be a more accurate comparison between the two vehicle groups.

## Acknowledgments

The author wishes to thank Lee Slezak, U.S. DOE Vehicle Technologies Program, for his financial support in conducting this project. In addition, the author wishes to recognize the valued and significant contributions of the following individuals:

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

# Appendix. ReFUEL Test Report

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

# PROJECT SUMMARY REPORT

## Dynamometer Testing of FedEx Fleet Hybrid Electric Vehicle

October 2, 2009

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

Test Participants:

| Name | Organization |
|---|---|
| John Ireland | ReFUEL Lab, NREL |
| Dan Pedersen | ReFUEL Lab, NREL |
| Aaron Williams | ReFUEL Lab, NREL |
| Robb Barnitt | ReFUEL Lab, NREL |
| Kevin Walkowicz | ReFUEL Lab, NREL |
| | |
| Jasna Tomic | CALSTART |
| Sam Snyder | FedEx |

## Objectives

This work comprises chassis dynamometer testing of two medium-duty FedEx 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.

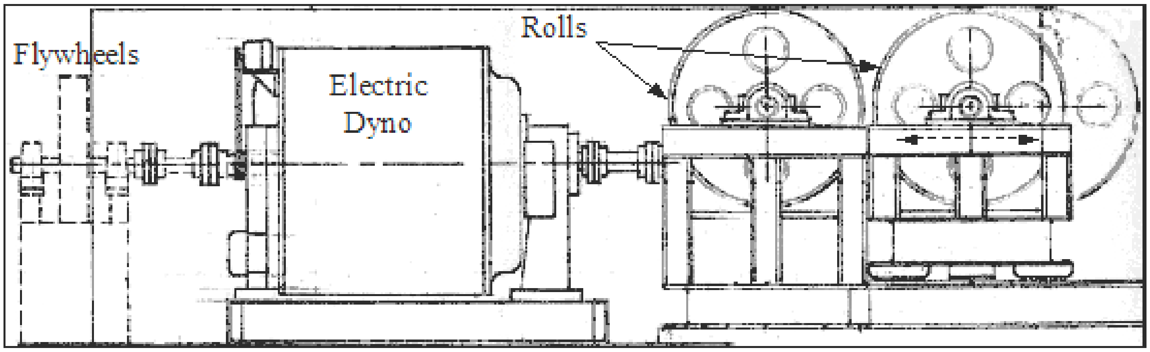


**Figure A-1. Chassis dynamometer schematic**

### *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.

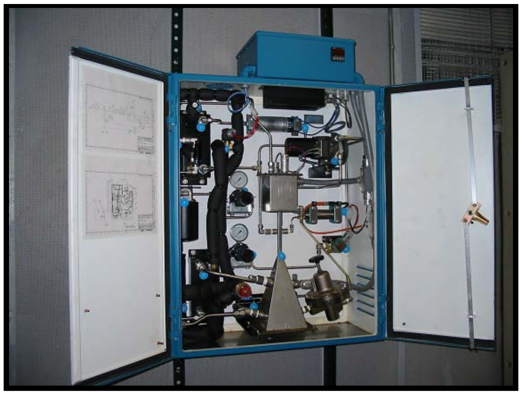


**Figure A-2. Pierburg fuel metering system**

### 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.

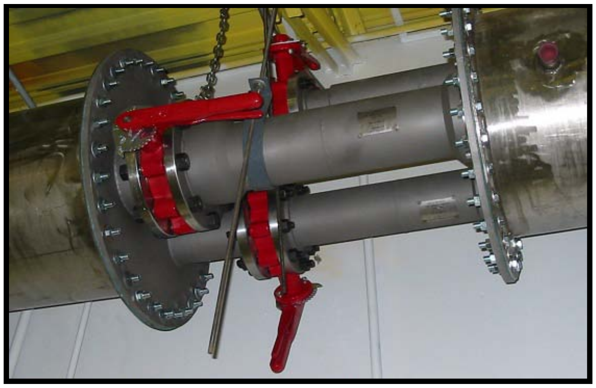


**Figure A-3. Venturi nozzles**

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 100kW 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 | 255 HP @ 4,500 RPM | 200 HP @ 2,300 RPM |
| Max. Torque | 350 lb-ft @ 2,500 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 (GVWR) | 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 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 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.

# ReFUEL Test Report Appendix A. Test Cell Instrumentation

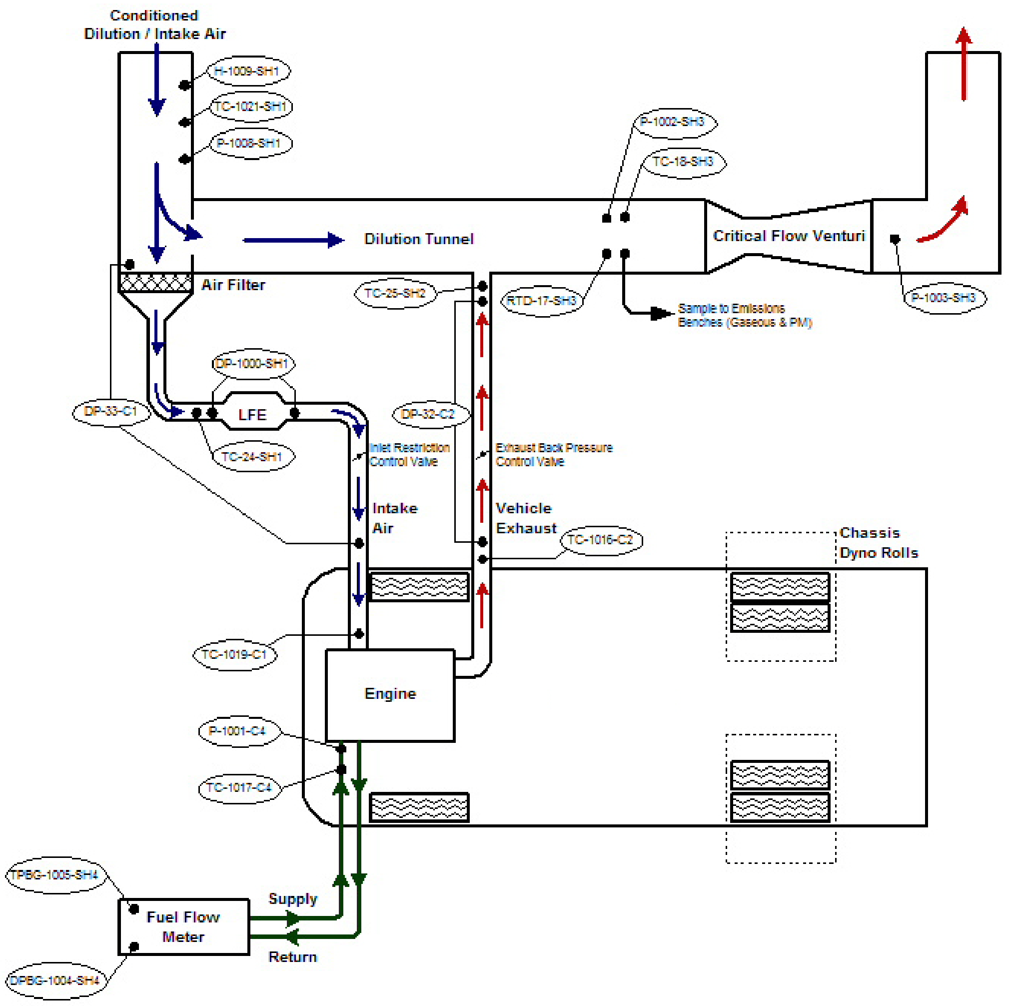
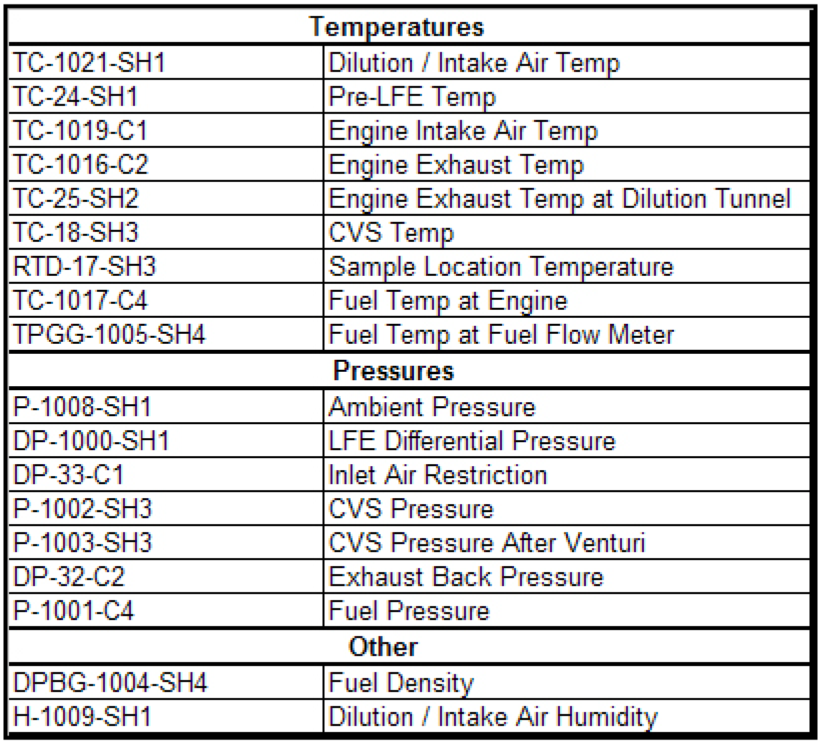


Figure A-7. Process and instrumentation diagram

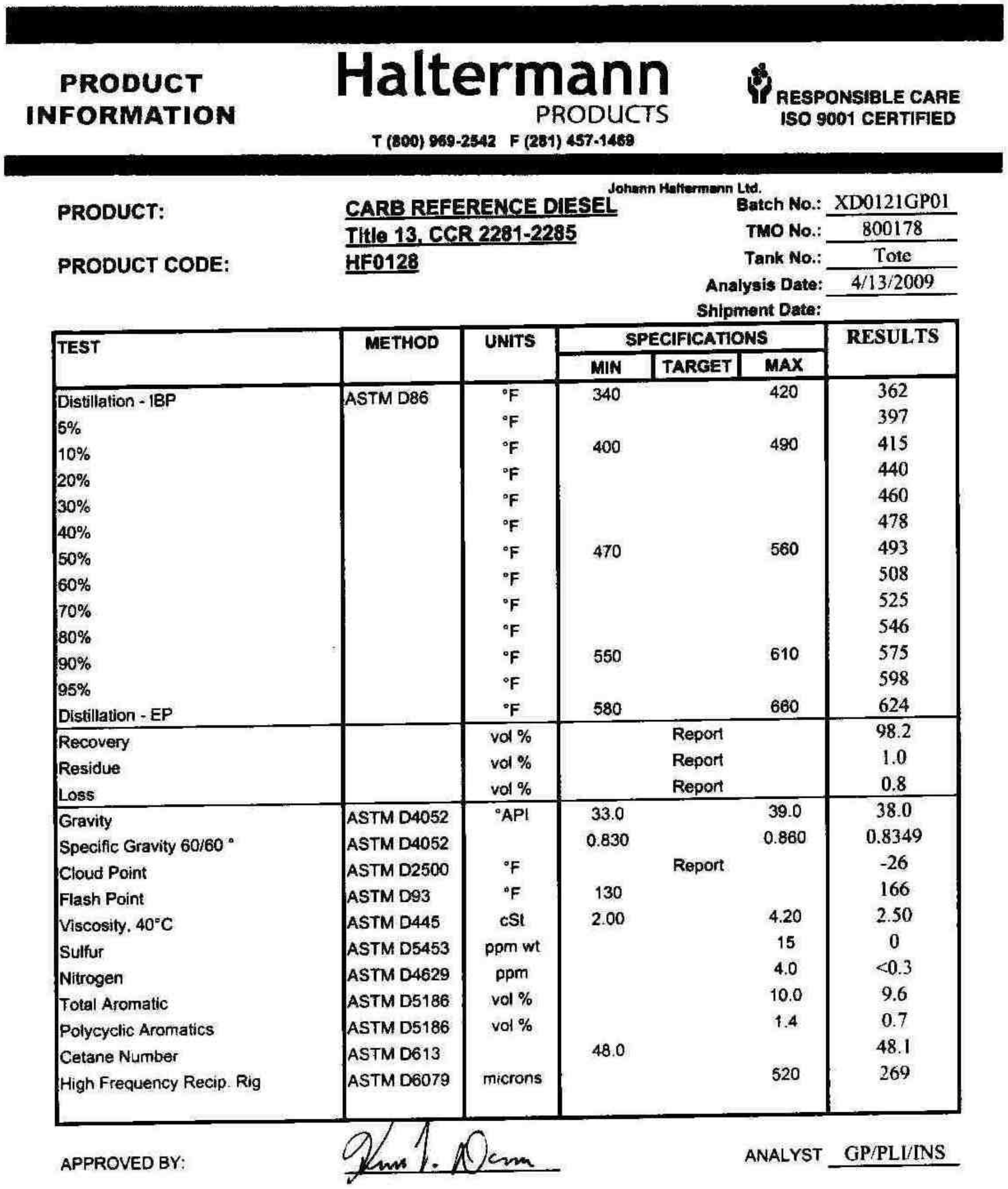
### Table A-2. Instrumentation List



| **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 |

# ReFUEL Test Report Appendix B. Fuel Analysis

**Table A-3. CARB Diesel Fuel Analysis**



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| | | | |
|---|---|---|---|
| **PRODUCT:** | **CARB REFERENCE DIESEL**<br>**Title 13, CCR 2281-2285** | **Batch No.:** | XD0121GP01 |
| | | **TMO No.:** | 800178 |
| **PRODUCT CODE:** | **HF0128** | **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 |

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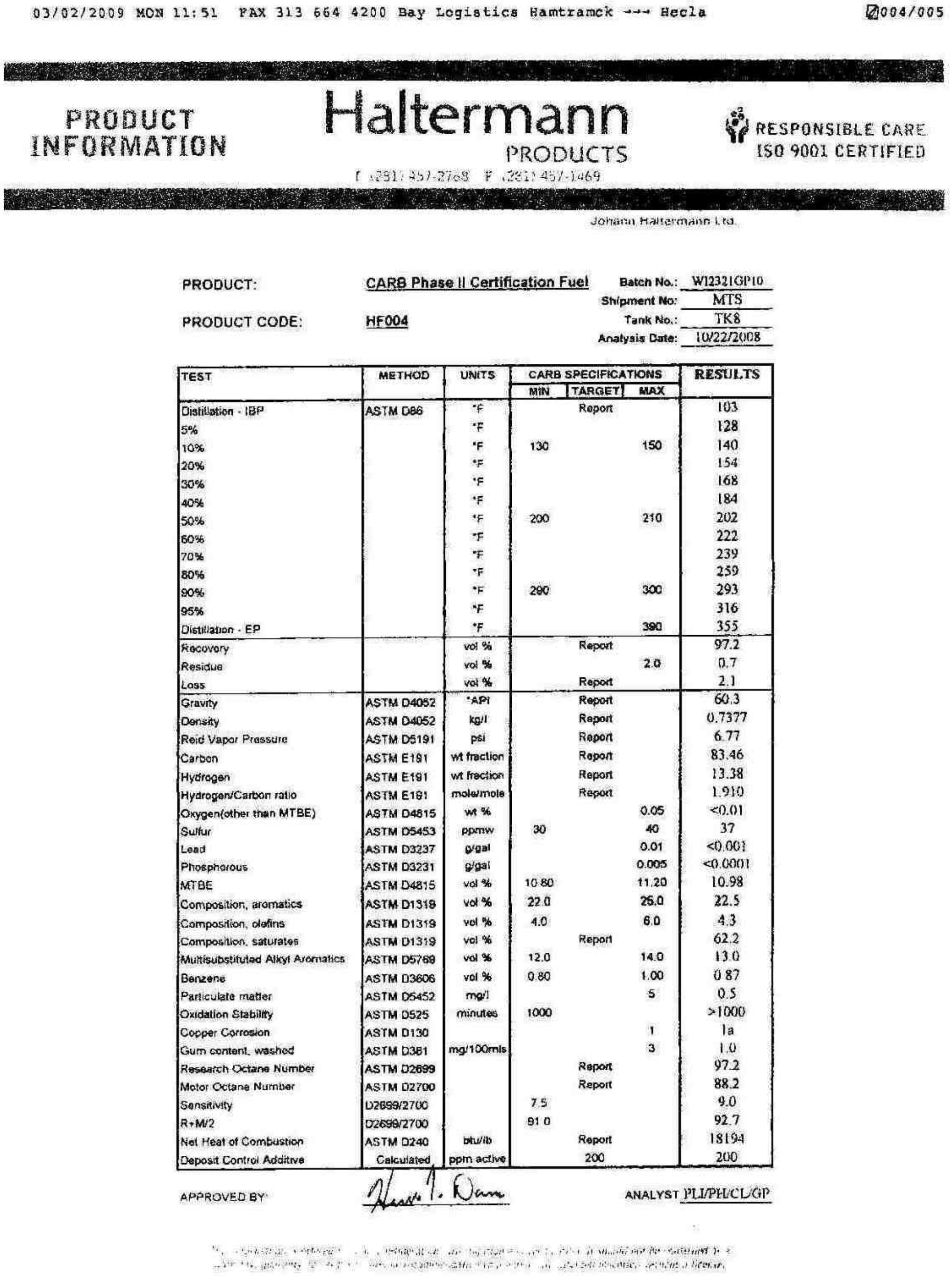
## Table A-4. CARB Phase II Gasoline



03/02/2009 MON 11:51 FAX 313 664 4200 Bay Logistics Hamtramck →→→ Hecla 004/005

PRODUCT INFORMATION

**Haltermann**
PRODUCTS
T (281) 457-2768 F (281) 457-1469

RESPONSIBLE CARE
ISO 9001 CERTIFIED

Johann Haltermann Ltd.

| | | | |
|---|---|---|---|
| PRODUCT: | CARB Phase II Certification Fuel | Batch No.: | W12321GP10 |
| | | Shipment No: | MTS |
| PRODUCT CODE: | HF004 | 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 | | 25.0 | 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 |

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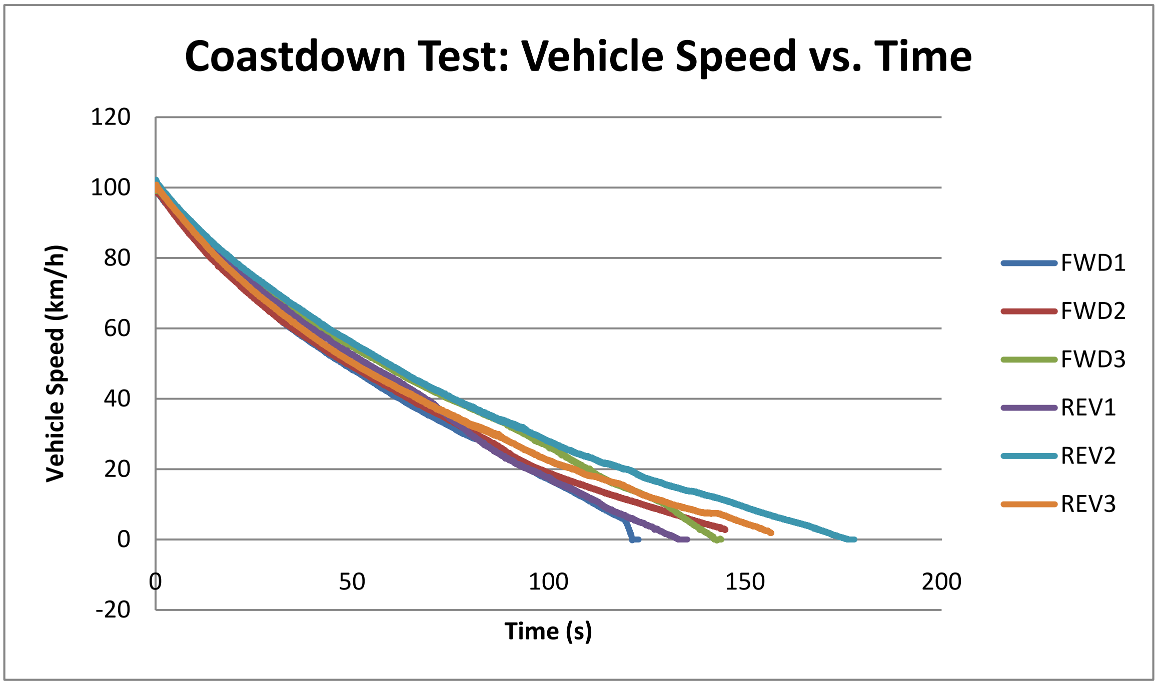

Figure A-8a. HEV track coast down curves

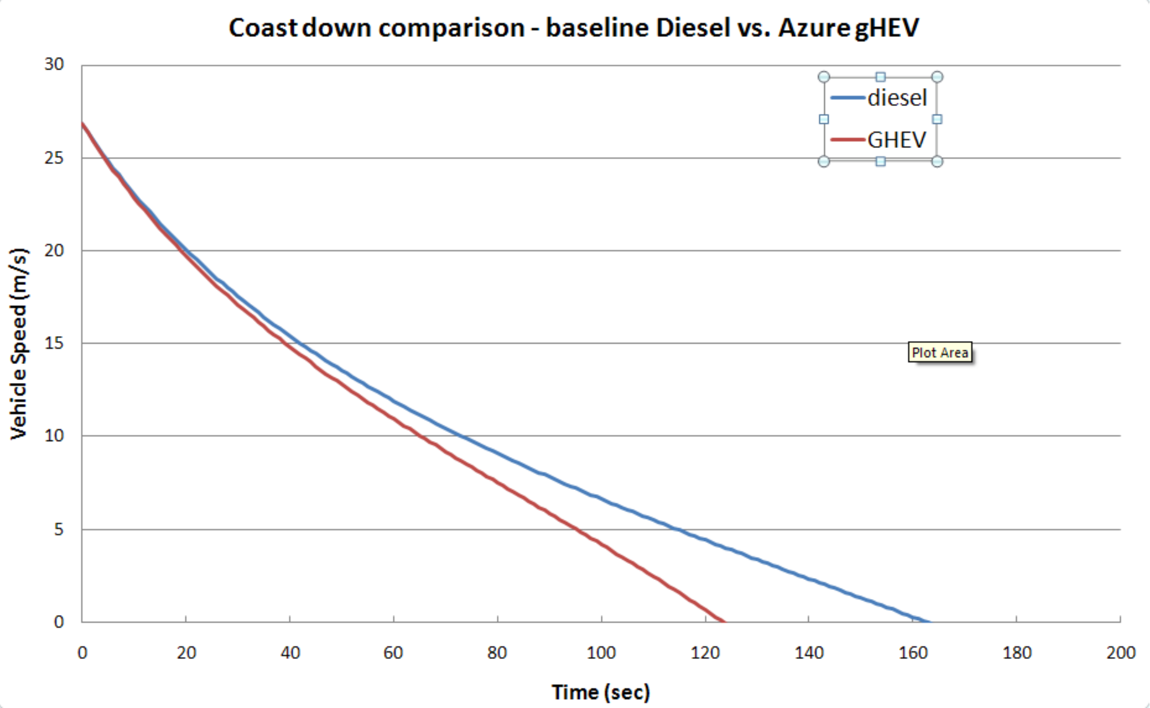

Figure A-8b. Coast down comparison – conducted at ReFUEL

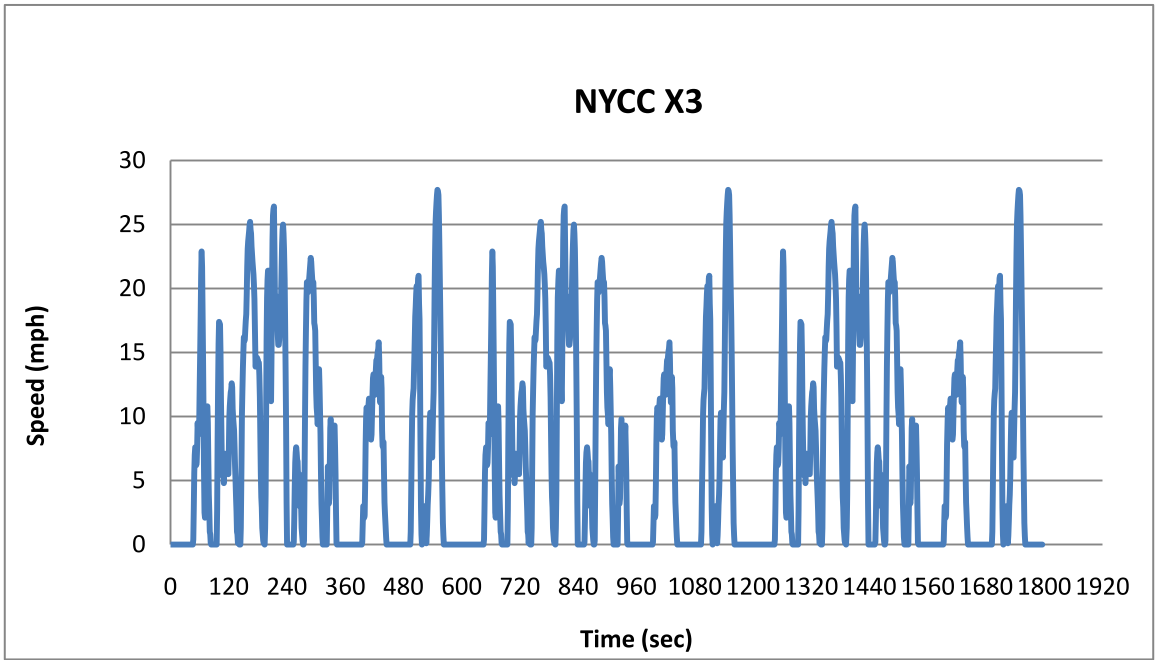

Figure A-9. NYCC drive cycle

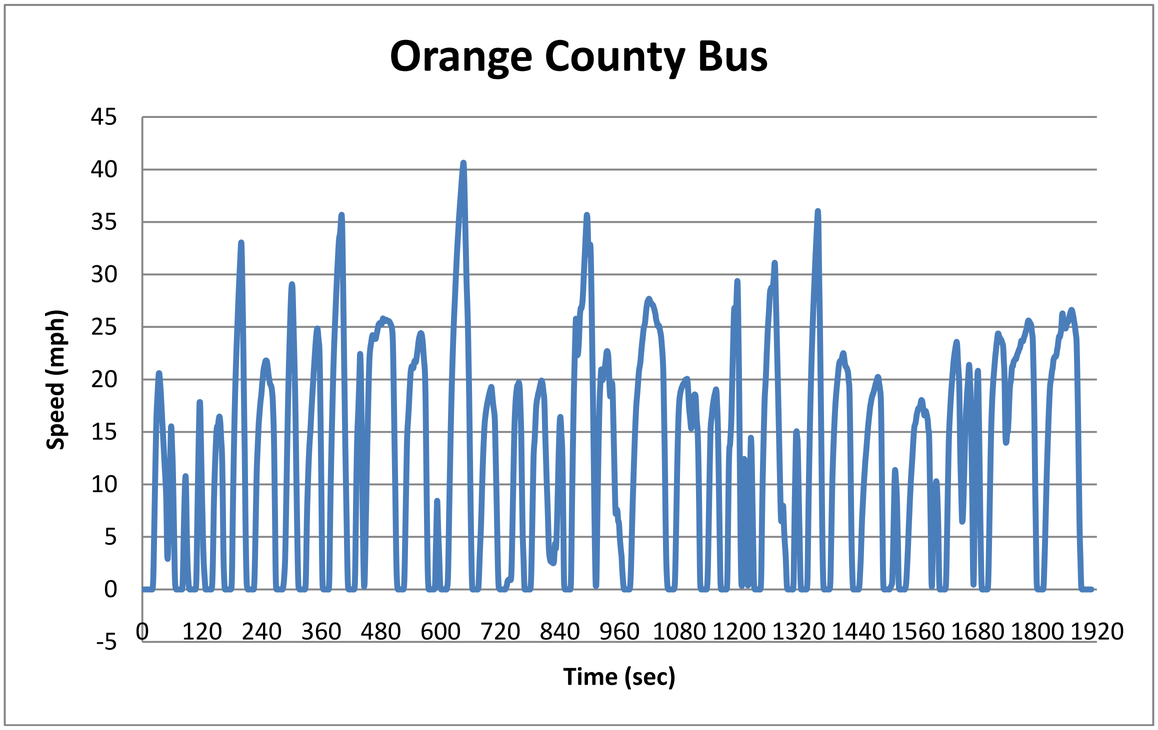

Figure A-10. Orange County Bus drive cycle

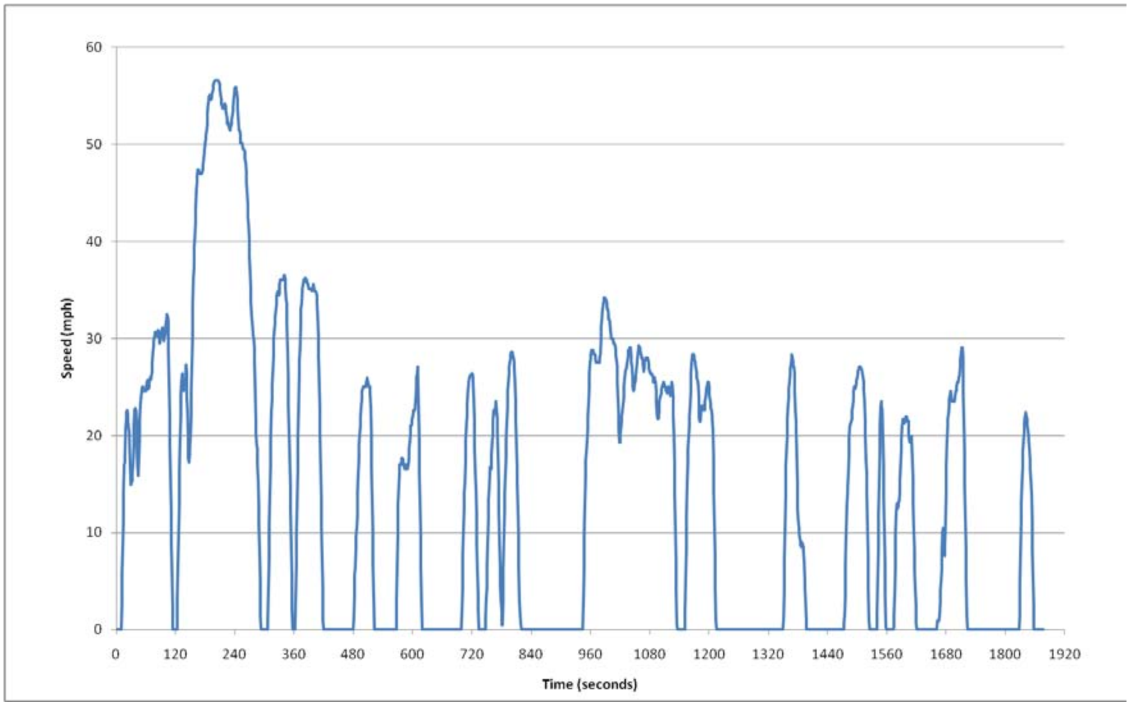

Figure A-11. HTUF4 drive cycle

### 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<br>g/mile | CO<br>g/mile | THC<br>g/mile | CO2<br>g/mile | PM<br>g/mile | Fuel Econ<br>mpg | Distance<br>miles | SOC<br>% |
|---|---|---|---|---|---|---|---|---|---|---|
| 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<br>g/mile | CO<br>g/mile | THC<br>g/mile | CO2<br>g/mile | PM<br>g/mile | Fuel Econ<br>mpg | Distance<br>miles | SOC<br>% |
|---|---|---|---|---|---|---|---|---|---|---|
| 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<br>g/mile | CO<br>g/mile | THC<br>g/mile | CO2<br>g/mile | PM<br>g/mile | Fuel Econ<br>mpg | Distance<br>miles | SOC<br>% |
|---|---|---|---|---|---|---|---|---|---|---|
| 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%* | |

# REPORT DOCUMENTATION PAGE

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May 2010

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Technical Report

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5c. **PROGRAM ELEMENT NUMBER**

6. **AUTHOR(S)**
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14. **ABSTRACT** *(Maximum 200 Words)*

This interim report presents partial (six months) results for a technology evaluation of gasoline hybrid electric parcel delivery trucks operated by FedEx in and around Los Angeles, CA. A 12 month in-use technology evaluation comparing in-use fuel economy and maintenance costs of GHEVs and comparative diesel parcel delivery trucks was started in April 2009. Comparison data was collected and analyzed for in-use fuel economy and fuel costs, maintenance costs, total operating costs, and vehicle uptime. In addition, this interim report presents results of parcel delivery drive cycle 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 the National Renewable Energy Laboratory's (NREL) ReFUEL laboratory. A final report will be issued when 12 months of in-use data have been collected and analyzed.

15. **SUBJECT TERMS**
FedEx; gasoline hybrid electric vehicle; gHEV; ReFUEL; diesel; fuel economy; emissions

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