Demonstration of Medium-Duty Gasoline Hybrids

Final Report for South Coast Air Quality Management District – Rev 1
Contract No. 08334

December 2010
(Rev 1 2012)
Jasna Tomic
CALSTART

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Executive Summary

The purpose of this project was to demonstrate and evaluate a medium-duty gasoline hybrid-electric vehicle (GHEV) in a parcel delivery truck application and compare it to baseline diesel vehicles in fuel use and emissions. Another objective includes PHEV modeling and evaluation of business case and technology pathway from hybrid-electric to PHEV vehicles. CALSTART worked with partners FedEx Express, Azure Dynamics, and the National Renewable Energy Laboratory (NREL) to evaluate the gasoline hybrid-electric vehicle in use in the FedEx Express fleet. Engine, Fuel & Emissions Engineering lab (EFEE) conducted the on-road emissions testing.

The GHEVs are built upon a Ford E-450 stripped chassis and powered by a Ford 5.4L gasoline engine and Azure Dynamics Balance™ Hybrid System. Modeling and lifecycle cost analysis of a potential plug-in hybrid are evaluated as well.

The vehicles were evaluated in the laboratory using a chassis dynamometer. Both diesel and GHEV were compared on three duty cycles: 1) NYCC, 2) OC Bus, and 3) HTUF4. All the criteria emissions decreased considerably for the GHEV compared to diesel, as shown in table below.

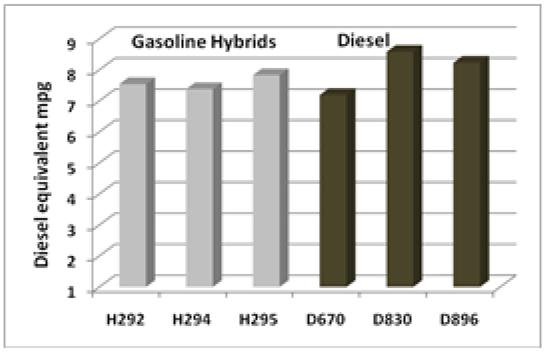
GHEV criteria emissions reductions by drive cycle in laboratory testing.

Duty 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

The GHEV showed a 20% improvement in fuel economy (measured in diesel equivalent mpg) in the NYCC cycle and no significant improvement in the other cycles (OC Bus and HTUF4).

The emission and fuel economy results from on-road measurements were similar to the laboratory testing. The GHEV exhaust had virtually no PM, very low HC (0.1 vs. 0.5 g/km for diesel) and lower NOx (1-2 vs. 3-4 g/km for diesel). The fuel economy measured during the on-road testing was 8 mpg for the GHEV and 9 mpg for the diesel vehicles.

The fuel economy was tracked during the 12-month evaluation. Compared on a diesel equivalent miles per gallon basis, the GHEV showed similar values to the diesel units.



Diesel equivalent miles per gallon for GHEV and diesel vehicles

The average fuel economy for the GHEV trucks was 7.5mpg and for the diesel trucks 7.9mpg. These results are positive given that diesel engines generally have higher fuel economy than gasoline. On a total operating cost per mile basis the two vehicle systems are very close. The GHEV total operating cost is $0.63/mi and the diesel is $0.59/mi.

Potential benefits of a plug-in design using fuel consumption and vehicle cost trade-offs were evaluated. Increased battery, component mass, and battery wear on fuel consumption were accounted for in the model and lifecycle costs analysis (15 years lifecycle). Under a current economic scenario – fuel cost $3/gallon and energy storage cost $700/kWh – the additional lifecycle cost ranges from $22,000 to $25,000 for a PHEV with 22kWh energy storage. However the simulation pointed out the need for a battery design specifically targeted for a PHEV. results The modeling underscores the importance of targeted design, especially that of the battery, and strategic deployment of electric-drive vehicles to maximize savings in fuel consumption and operating costs.

We evaluated the business case of using a PHEV for grid support (vehicle-to-grid or V2G power) when parked after regular work hours. This analysis showed that using the last three year market values of grid regulation services in California (CAISO), there was at least one year when this was quite positive economically. The net lifecycle benefit over 15 years from V2G was up to $25,000, which can totally offset the incremental lifecycle costs of a PHEV. The additional use of plug-in vehicles for V2G may significantly improve their business case.

The users rated the vehicles and compared them to the performance of the standard diesel vehicles. Overall, the users were satisfied with the performance of the trucks and rated them overall slightly above the diesels.

The GHEV trucks provide equal fuel economy results to diesel trucks but with considerably reduced emissions. The performance and operating costs per mile are very similar. The reduced emissions are clearly an important advantage of the GHEV trucks.

Acknowledgments

This work was a result of a team effort. The laboratory testing was conducted at NREL's ReFuel laboratory and was the work of Dan Pederson. The field evaluation was the contribution of Robb Barnitt and Kevin Walkowicz from NREL's Fleet Test and Evaluation team. Robb Barnitt and Aaron Brooker from NREL also focused on the modeling of PHEV. Chris Weaver, Engine, Fuel, and Emissions Engineering, Inc. conducted the in-use emissions testing. Jim Mancuso from Azure Dynamics provided valuable input and information regarding the hybrid system. We are especially grateful to Sam Snyder and other colleagues from FedEx who shared their time and provided access to the trucks and performance data during the course of this work. This work would not have been possible without their collaboration. Finally we are grateful to Jeff Cox, project officer from SCAQMD for his advice and engagement in discussions on technical aspects of the project.

We appreciate the funding from South Coast Air Quality Management District and US DOE Vehicle Technologies Program.

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I. Project Overview

This project intended to demonstrate the commercial and technical viability of using a gasoline engine in a Class 4 hybrid-electric, parcel delivery truck. Such a vehicle would provide clean air benefits while performing the work of a Class 4 work truck. Benefits to be derived from the use of a gasoline rather than diesel engine in this application were projected to be:

- Lower levels of criteria emissions based upon a cleaner fuel and more mature emission control technology
- Improved fuel economy due to the smaller engine and greater use of the electric motor and energy storage system
- Quieter operation and reduced fuel/exhaust odor

California has the opportunity to be the deployment focus of this project and jump-start the emissions benefits of using a new class of cleaner engines and hybrid systems in work vehicles. The gasoline hybrid vehicles were placed in the Los Angeles area within the FedEx Express fleet of parcel delivery vehicles. These vehicles, placed with diesel vehicles performing the same work, will be substantially cleaner and would possibly equal or exceed the fuel economy of the diesel system.

The purpose of this project was to demonstrate and evaluate medium-duty gasoline hybrid-electric vehicle (GHEV) in a parcel delivery truck application and compare it to baseline diesel vehicles in fuel use and emissions. Another objective includes modeling of plug-in hybrid-electric design and evaluation of business case and technology pathway from hybrid-electric to plug-in hybrid-electric vehicles. CALSTART worked with partners, FedEx, Azure Dynamics, and the National Renewable Energy Laboratory (NREL) to evaluate the gasoline hybrid-electric vehicle for use in the FedEx fleet and worked with Engine, Fuel & Emissions Engineering lab (EFEE) for on-road emissions testing.

The project consisted of the following parts:

1) Selecting a location and routes for the three GHEV and three baseline diesel vehicle
2) Laboratory testing for fuel economy and emissions of the GHEV and baseline diesel vehicles
3) On-road emissions data collection to measure the actual on-road emission improvements of GHEV compared to the diesel vehicles
4) Performance evaluation based on 12-month data collection from the GHEV and their conventional diesel counterparts. This included fuel use and maintenance data
5) Modeling of potential plug-in hybrid-electric (PHEV) vehicles in this application including lifecycle cost and business case of PHEV with a vehicle-to-grid (V2G) application

This report contains the summary and important results obtained during the demonstration and evaluation project. During the course of the project, individual reports were produced; this summary report pulls directly from the individual reports. For more details on the different components of the project, such as detailed process descriptions, data, and analysis steps, the reader is directed to the individual reports listed by title below:

- *Dynamometer Testing of FedEx Fleet Hybrid Electric Vehicle, NREL, October 2009*
- *FedEx Gasoline Hybrid Electric Delivery Truck Evaluation: 6-Month Interim Report, R. Barnitt, NREL, May 2010*
- *FedEx Express Gasoline Hybrid Electric Delivery Truck Evaluation: 12-Month Report, R. Barnitt, NREL, December 2010*
- *In-Service Emissions from Gasoline Hybrid and Conventional Diesel Package Delivery Trucks. Final report, C. Weaver, EFEE, May 2010*
- *PHEV Parcel Delivery Truck Simulation and Analysis, R. Barnitt, NREL, December 2010*
- *PHEV Modeling –Evaluating the Use of Plug-in Truck for Vehicle-to-Grid Power, J. Tomic, CALSTART, December 2010*

II. Vehicles

The vehicles used in the evaluation were gasoline hybrid-electric Class 4 vehicles built upon a Ford E-450 strip chassis and powered by a Ford 5.4 L gasoline engine and Azure Dynamic Balance Hybrid System. The specifications of the gasoline-hybrid system are listed in Table 1.

Table 1: Azure Dynamics 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

Three gasoline hybrid-electric vehicles were used during this evaluation and compared to three diesel baseline vehicles that normally operate as parcel delivery vehicles in the FedEx Express fleet. Description of the gasoline-hybrid and diesel baselines is provided in Table 2.

Table 2: Vehicle Description

	Gasoline hybrid-electric	Diesel Baseline
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 @ 4500 RPM 350 lb-ft @ 2500 RPM	 200 HP @ 2300 RPM 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 lbs.	9,700 lbs.
Gross Vehicle Weight (GVWR)	14,050 lbs.	16,000 lbs.

Figure 1: Gasoline hybrid-electric parcel delivery vehicle (Photo courtesy of Sam Snyder, FedEx)

III. Selection of Routes and Drive Cycles

The vehicles were placed in operation in the FedEx fleet in the South Coast Air Basin. The vehicles were specifically placed in several depots all located in the Los Angeles area.

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. 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.[1]

The 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 the 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.

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

Table 3: Parcel Delivery Study Routes Statistics

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})	$5.9 * 10^{-4}$	$5.5*10^{-4}$	$7.4*10^{-4}$	$6.3*10^{-4}$	16%	$3.7*10^{-4}$	$3.0*10^{-4}$	$3.9*10^{-4}$	$3.5*10^{-4}$	14%

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.

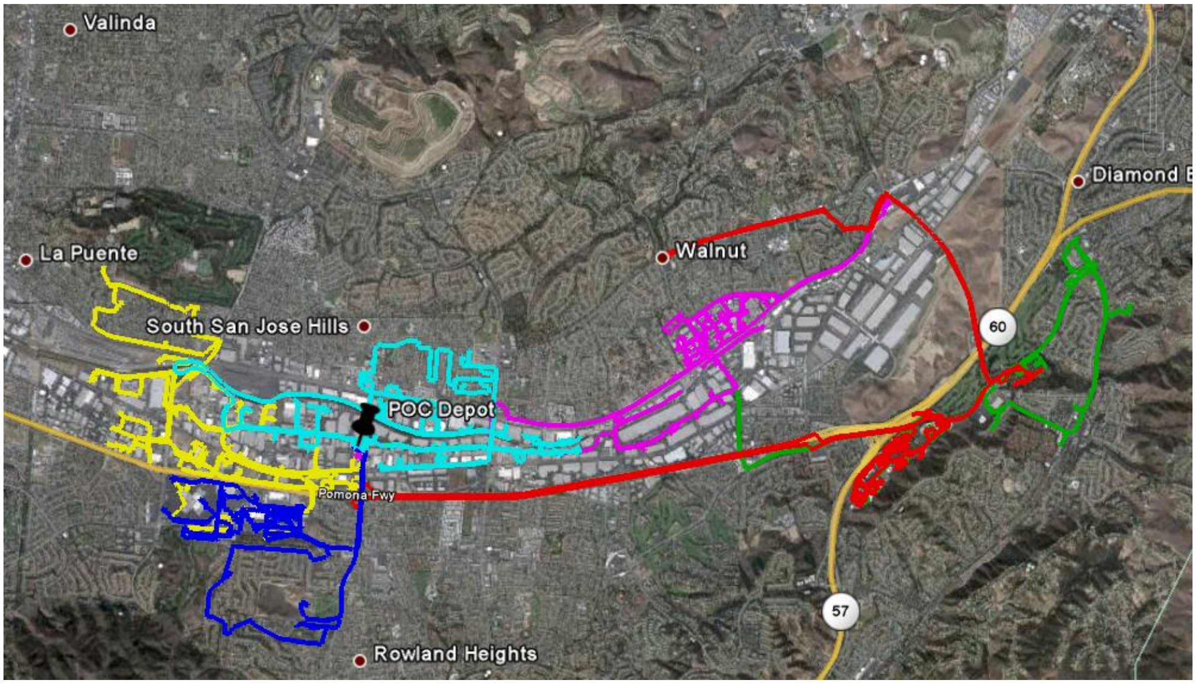

Figure 2: Study routes

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.

A total of four vehicles were involved in this project overall. Three vehicles were part of the year-long data collection and evaluation and one vehicle was dedicated specifically to laboratory (chassis dynamometer) testing and in-use emissions testing.

IV. Laboratory Testing – Fuel Economy and Emissions

The purpose of the testing was to compare the gasoline hybrid-electric vehicle to the baseline diesel vehicle in terms of fuel economy and emissions under a controlled testing environment. The vehicles were tested at the ReFUEL laboratory operated by NREL in Denver Colorado on a heavy-duty vehicle (chassis) test cell and engine dynamometer test cell with emission measurements capability.

The selection of the appropriate chassis dynamometer test cycles, calculated kinetic intensity[2] was used to compare real, collected drive cycle data to other 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.

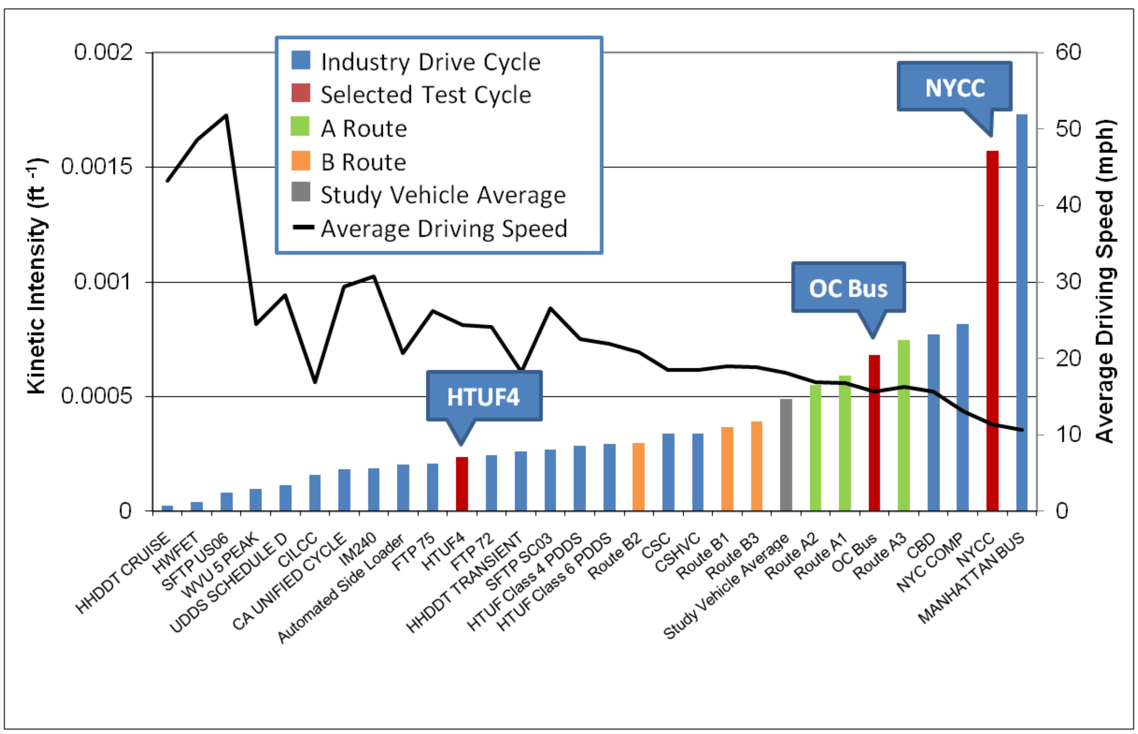

Figure 3: Comparison of drive cycle kinetic intensities

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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.

Each vehicle was driven through three test cycles:

1) New York City Cycle
2) Orange County Bus Cycle
3) HTUF Class 4 Parcel Delivery Cycle

The details of the lab description and testing procedure can be found in the report "*Dynamometer Testing of FedEx Express Fleet Hybrid Electric Vehicle*." Table 4 is a summary of the measurements of fuel economy and emissions using the three test cycles.

Table 4: Summary of Laboratory Emissions Results

Drive Cycle	Vehicle	Fuel economy (mpg)	Diesel Equivalent Fuel Economy (mpg)	NOx (g/mile)	CO (g/mile)	THC (g/mile)	PM (g/mile)
NYCC	GHEV	6.75	7.34	3.24	0.84	ND	0.0016
	Diesel	6.08	6.08	12.70	7.60	0.80	0.7930
OC Bus	GHEV	8.61	9.36	1.05	0.29	ND	0.0004
	Diesel	9.52	9.52	7.60	2.90	0.60	0.3000
HTUF4	GHEV	10.45	11.36	0.57	1.03	0.04	0.0006
	Diesel	11.66	11.66	5.20	2.50	0.40	0.2820

The fuel economy in Table 4 is presented as direct measure mpg for each vehicle and drive cycle and as diesel equivalent value taking into account the different energy content of gasoline and diesel. The fuel economy of the GHEV and the diesel are similar indicating that the adding the hybrid has compensated for the lower fuel economy of a gasoline system compared to diesel. In terms of measured emissions the GHEV is much cleaner. We should note that the GHEV was equipped with a three-way catalyst and that the diesel vehicle was not equipped with a diesel particulate filter. The reduction in criteria emissions for each of the test cycles is shown in Table 4.

Table 5: 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

The GHEV showed large improvements in emissions over the diesel vehicle. The differences varied with the drive cycle used but the range was between 75 – 89% decreases in NOx and over 99% in PM. There is somewhat greater variability in the CO measurements and THC caused by the precision and calibration of the system optimized for measuring NOx and PM.

V. On-Road Emissions Testing

Emissions measurements were also done on-road during normal operations of the vehicles. Engine, Fuel, and Emissions Engineering, Inc. (EF&EE) was contracted to quantify the pollutant emissions from a sample of hybrid-electric and conventional diesel trucks using EF&EE's Ride-Along Vehicle Emission Measurement (RAVEM) system. Mass emissions of carbon dioxide (CO2), carbon monoxide (CO), oxides of nitrogen (NOx), particulate matter (PM), and total hydrocarbons (THC) were measured. A total of five trucks were used for this testing:

- Two Ford-Azure GHEV with 2008 gasoline engine
- Two Freightliner diesel with 2006 diesel engine
- One Freightliner diesel with 2007 diesel engine with diesel particulate filter (DPF)

The main reason for including an additional diesel vehicle was to compare the emissions with a newer engine and a DPF filter to the GHEV emissions. Details on the test equipment and procedure are available in the report "*In-Service Emissions from Gasoline Hybrid and Conventional Diesel Package Delivery Trucks*."

All of the emission testing was conducted during normal package pickup and delivery route driving. A specific route was chosen for the emission measurements based on recommendation from NREL and GPS route information obtained earlier in the testing program. The route was selected as the one that has less day to day variability compared to other routes. Summary of the measured results is provided in Table 6.

Table 6: Summary of emissions and fuel use in grams per kilometer

	Emissions (g/km)					Fuel g/km		Calc
Vehicle	**CO_2**	**CO**	**NOx**	**PM**	**HC**	**Calc**	**Meas**	**MPG**
H295 - Hybrid	739	1.1	1.98	(0.00)	0.1	233	234	7.6
H293 - Hybrid	629	1.0	1.06	0.00	0.1	199	224	8.9
D137 - Diesel w DPF	788	0.1	3.21	0.00	0.0	248	235	8.1
D830 - Diesel	675	1.3	4.63	0.12	0.4	213	208	9.4
D896 - Diesel	687	1.2	4.47	0.14	0.6	217	229	9.2

The mass fuel consumption during each test was also calculated by carbon balance from the emissions data, using corresponding weight percentages of 86.6 and 86.7% carbon, respectively, in the gasoline and diesel fuel. The calculated fuel economy (in mpg) confirms the earlier laboratory testing results that the GHEV have similar fuel economy to the diesel vehicles. From the current in-use testing we observe that the DPF-equipped diesel vehicle has a lower fuel economy that the diesels with no DPF, which was also an expected result.

The two GHEV trucks and the DPF-equipped diesel showed zero emissions of particulate matter. NOx emissions from the hybrid trucks were lower than those of any the diesels. Even in comparison to the DPF-equipped diesel, the GHEV has up to 70% lower emissions of NOx. Occurrence of short, sharp NOx "spikes" was observed from the GHEV most likely related to isolated transient load instances (*i.e.* hard acceleration starts).

Hydrocarbon emissions from the two GHEV trucks were comparable to those from the DPF-equipped diesel, and significantly lower than those of the two older diesels. CO emissions from the DPF-equipped diesel were extremely low. This and the low HC emissions from that vehicle were presumably due to the effect of the oxidation catalyst in the DPF. Carbon dioxide emissions from the hybrid vehicles were comparable to but more variable than those of the two older diesels. The 2007 model DPF-equipped diesel exhibited somewhat higher CO_2 emissions per kilometer than the other trucks. These results were consistent with the volumetric fuel consumption reported by the vehicles' engine control computers.

Overall, the in-use emission results are in agreement with the laboratory fuel and emission results. The GHEV vehicles achieve a fuel economy comparable to that of the baseline diesel vehicles with much lower emissions of PM and NOx.

VI. **Performance Evaluation**

The 12-month evaluation was conducted by NREL and its Fleet Test and Evaluation Team. Details of the approach and collected data are available in the report titled "*FedEx Express Gasoline Hybrid Electric Delivery Truck Evaluation: 12-Month Report*."

Fuel Economy and Fuel Costs

The performance evaluation included measurement of fuel economy and maintenance records. Three in-use fuel economy evaluation methods were used for corroboration:

- Fuel logs located in each truck to be filled out by drivers
- Retail fuel purchases via monthly electronic statements
- Control Area Network (CAN) bus-derived fuel measurements for spot check

Most consistent data was acquired via the electronic retail fuel purchases with the other two methods used for back-up and occasional cross-check.

Maintenance included scheduled and unscheduled maintenance performed at the local FedEx depot. The scope of the maintenance was identical for the GHEV and diesel trucks with preventative maintenance following California requirements of 90-day interval. The trucks were under warranty during the evaluation period and the warranty costs were not included in the operating costs.

Table 7 lists the data on fuel economy and costs of fuel per mile of operation.

Table 7: Fuel Economy and Costs from Retail Fueling Records

Vehicle	Start Date	End Date	Miles	Fuel Volume (gallons)	Fuel Economy (mpg)	Diesel Equivalent FE (mpg)	Fuel Cost ($)[a]	Fuel Cost per Mile ($/mile)
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
D610	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

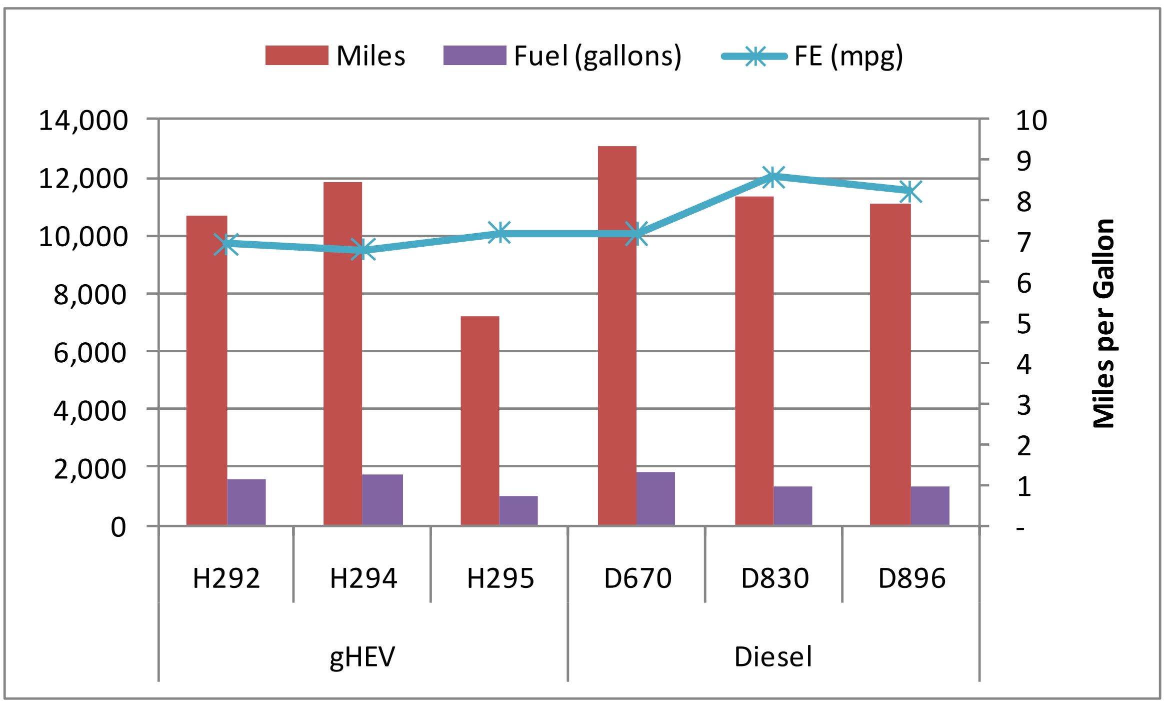

Figure 4: Fuel economy results

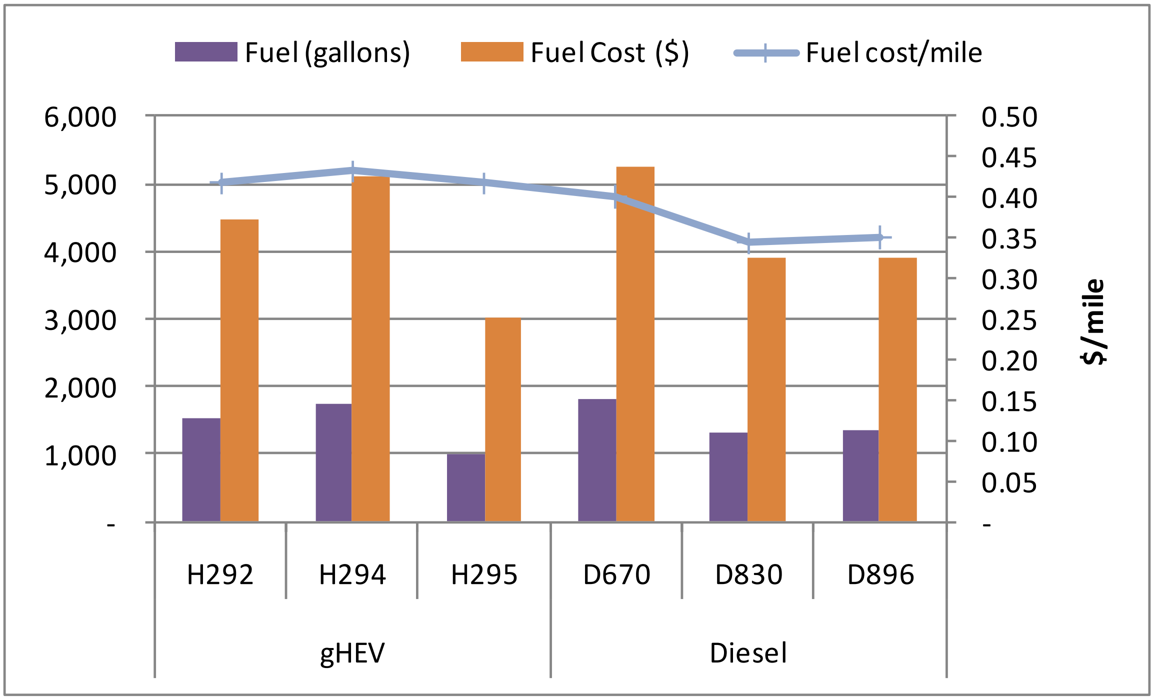

Figure 5: Fuel and fuel cost per mile results

The trucks drove around 11,000 miles during the evaluation period with two trucks falling out of this average with a low of 7,000 miles and high of 13,000 miles. Comparing the fuel economy diesel equivalent values of the GHEV (6.94 mpg) and the diesel trucks (7.91 mpg) we note very similar numbers confirming the earlier finding that the GHEV fuel economy is similar to that of a diesel truck. When the fuel costs per miles were compared, the GHEV was $0.42 mi and diesel was $0.37/mi. This difference is a result of slightly higher cost of gasoline over diesel fuel

Maintenance Costs

Maintenance costs were collected and analyzed for the two vehicles. When all the maintenance costs were included and normalized per miles of driving, the values were $0.206/mi for the GHEV and $0.223/mi for the diesel vehicles. An interesting finding is that the maintenance costs are dominated by preventative maintenance activities and tire replacement – these two costs make up close to 50% of all maintenance costs.

Total Operating Costs

Finally, total operating costs were compared, combining the fuel cost and maintenance costs. Table 7 shows the operating costs of the GHEV and the diesel vehicles.

Table 8: Total Operating Cost

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

The average operating costs for the three GHEVs are $0.63/mile and for the diesel vehicles $0.59/mile which is very similar.

VII. Modeling of Plug-in Hybrid Benefits – Lifecycle and Business Case with V2G Application

This task addressed modeling of a plug-in hybrid vehicle in this size and application and assessing the business case of using the plug-in for V2G application. The objective was to model a plug-in design with various battery capacity sizes and assuming different fuel costs and battery costs and to evaluate the lifecycle costs of the plug-in version.

Table 9: Parcel Delivery Simulation Matrix

Variable	**Level**	**Scenarios**
Drive cycles	3	NYCC, HTUF4, OC Bus
Control Strategies	2	All-Electric Range (AER), charge-depleting (CD)-battery dominant
Daily VMT	4	25, 50, 75, 100 miles
Battery capacity	5	2, 22, 42, 62, 82 kWh
ESS cost	2	Current ($700/kWh) and Future ($300/kWh)
Fuel cost	2	Current ($3/gallon) and Future ($5/gallon)
Electricity cost	1	$0.12/kWh

Analytic outputs for each scenario will consist of:

- Liquid fuel consumption or economy
- ESS mass, ESS manufacturing cost, and ESS retail cost (1.75x manufacturing cost)
- Total vehicle cost including ESS and electric motor
- Lifetime (15-year) vehicle cost, including vehicle purchase price, operating costs (liquid fuel, electricity, plus incremental retail ESS cost) for current and future economic scenarios, including ESS replacement if necessary
- Well to wheel greenhouse gas emissions based upon Greenhouse Gas, Regulated Emissions, and Energy Use in Transportation (GREET) Fleet Footprint Calculator

Vehicle Model Development, Battery Life and Simulation

The model was developed by NREL using high-level modeling tool developed in-house and it includes vehicles components such as battery, motor, engine and runs through speed vs. time drive cycles calculating the power to overcome drag, acceleration, ascent, rolling resistance, and inertia similar to some more complex tools. Tables 10 and 11 show the costs and assumptions used in the simulation scenarios.

Table 10: Simulation and Analysis Matrix - Cost Scenarios

Scenario	ESS cost	Fuel cost	Electricity cost
Current	$700/kWh	$0.79/liter	0.12 $/kWh
Midterm	$300/kWh	$1.32/liter	0.12 $/kWh

Table 11: Additional Simulation Assumptions

Vehicle life (years)	15
Battery cost	$22/kW + scenario $/kWh + $680
Motor and controller cost	$21.7/kW + $425
Markup factor	1.75
Discount rate	8%
Charger efficiency	0.9

Summary of Simulation Results

The following is a summary of the modeling results on fuel consumption, energy storage system mass and cost as well as lifetime incremental cost under different scenarios.

The simulation indicated that it is important to know the drive cycle and its intensity and the daily distance traveled when designing and selecting and deploying the most appropriate technology for the given route.

Lifetime operating costs are an important in assessing the value of purchasing and operating a plug-in vehicle. For parcel delivery vehicles a lifecycle expectation of 15 years was included and operating costs for liquid fuel, electricity, additional battery capacity and electric motor size. Capital costs of the vehicle were not included as it is subject to many more variables than included here. Lifetime incremental costs for fuel, energy storage and electricity were compared for a baseline GHEV designed to last the expected 15 years (BSfL) and for PHEV models with additional energy storage (20, 40, 60, and 80 kWh). The results shown in Figure 6 show the lifetime incremental costs for the baseline case and are clustered in groups of three representing the three drive cycles, HTUF4, OC Bus, and NYCC. The lifetime incremental fuel costs are between $20,000 – $30,000 depending on the drive cycle for the base case and similar for the PHEV with no additional battery added. For the other designs with additional battery added, the lifetime incremental costs are much higher.

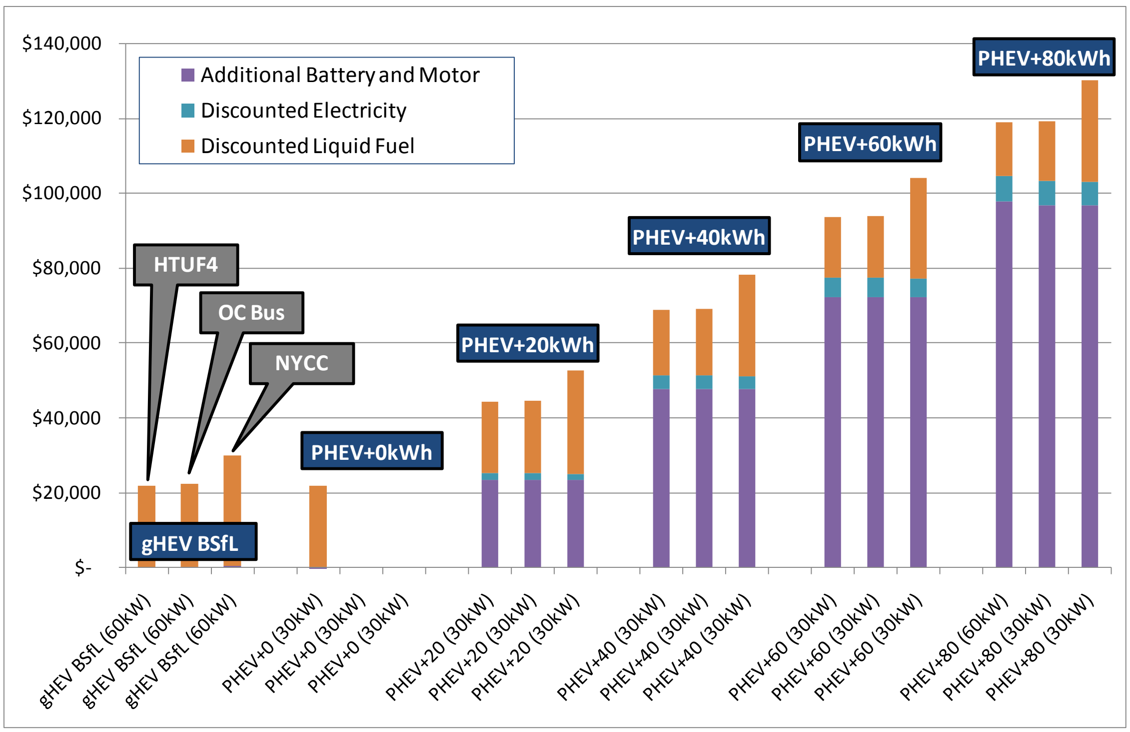

Figure 6: Lifetime incremental fuel costs, 40 km/day, current economic scenario

However, this analysis was done with a variation of SOC of the battery that was equivalent to that of the hybrid system or close to it. Thus the minimum SOC of the battery was 70%. It is presumed that a battery for a PHEV design would have a larger SOC window it would operate in and that this would affect the results. The modeling would have to include a different battery design and appropriate lifecycle costs.

Given this caveat and under the current simulations, the most cost-effective configuration is the PHEV+20 kWh under the current economic scenario with incremental lifetime cost around $20,000. The costs again vary significantly with drive cycle and daily distance traveled. Under the future scenario the incremental delta lifetime costs for the same configuration is between roughly $6,000 and $18,000. More specific delta incremental cost numbers for this configuration and varying with drive cycle and distance traveled are shown in Table 12.

Table 12: PHEV+20kWh Incremental Lifetime Costs, future economic scenario

Vehicle	Drive Cycle	40 km/day	80 km/day	120 km/day	160 km/day
PHEV+20 (30kW)	HTUF4	$6,568	$7,525	$9,018	$10,473
PHEV+20 (60kW)	HTUF4	$7,944	$9,247	$11,150	$13,029
PHEV+20 (30kW)	OC Bus	$6,154	$7,600	$9,200	$10,854
PHEV+20 (60kW)	OC Bus	$7,661	$9,719	$11,880	$14,149
PHEV+20 (30kW)	NYCC	$7,620	$9,678	$11,838	$14,049
PHEV+20 (60kW)	NYCC	$9,311	$12,040	$14,924	$17,927

Under a current economic scenario – fuel cost $3/gallon and energy storage cost $700/kWh – the additional lifecycle cost ranges from $22,000 to $25,000 for a PHEV with 22kWh energy storage. Battery costs have a dominant impact on the additional lifecycle costs and duty cycle and daily miles have a much smaller impact. Under a future economic scenario – fuel cost $5/gallon and energy storage $300/kWh – the additional lifecycle cost ranges from $6,500 to $18,000 depending on the duty cycle and daily miles. The dependence on duty cycle indicates the importance of strategic deployment in targeted routes.

In summary, the results of the modeling underscore the importance of targeted design, especially that of the battery, and strategic deployment of electric-drive vehicles to maximize savings in fuel consumption and operating costs.

Evaluating Use of Plug-in Truck for Vehicle-to-Grid Power

We also investigated the potential annual revenues if the plug-in truck was used for vehicle-to-grid power (V2G) or specifically for ancillary services in the CA Independent System Operator (CA ISO) market. The costs and the benefits of using the plug-in truck when parked for V2G power for ancillary services were examined. The objective was to evaluate if using the PHEV for grid services can provide additional revenue that improves the business case of owning and operating a PHEV.

The analysis was performed based on the model described in several publications. [3][4] The details can be found in "PHEV Modeling – Evaluating the Use of a Plug-in Truck for Vehicle-to-Grid Power." The net value of PHEV providing regulation ancillary service in the CAISO market given the market prices in 2008, 2009, and 2010 was positive in one year. The annual net value of the additional

[3] W. Kempton, J. Tomic, Vehicle-to-grid Power Fundamentals: Calculating Capacity and Net Revenue, J Power Sources 144 (205) 285-279.

[4] J. Tomic, W. Kempton, Using Fleet of Electric-drive Vehicles for Gird Support, J Power Sources 168 (2007) 459-468.

revenue from V2G was $1,200 – 1,700 which over the lifetime of the vehicle (15 years) can lead to a total of $18,000 – 25,000. This can offset the incremental costs of the PHEV vs baseline hybrid vehicle. In the two other years, the market price for regulation was unusually low thus not giving a positive net value for V2G power.

There is potential to improve the business case of PHEV by using them to provide V2G power for grid regulation. The analysis showed that the lifetime incremental costs of a PHEV may be significantly or totally offset if the PHEV provides V2G power for grid regulation. The cost is highly dependent on the market clearing price of regulation as well as the battery costs.

VIII. Vehicle Acceptance

Vehicle acceptance evaluation was conducted to understand how the users adopt the new technology and to collect the users' input on performance of the vehicle technology. We assessed the vehicle acceptance through surveys that were filled out by the drivers. The surveys asked the drivers to evaluate the hybrids in comparison to their baseline trucks on a scale from 1-5, "1" being the lowest ("much worse than") and "5" the highest ("much better than").
Another set of surveys was given to the operations managers asking them to evaluate the reliability and availability of the trucks as well as generally ranking of the hybrids for service in their fleet.

A total of 8 drivers responded to the surveys. The results are summarized below in Table13 with the average score for the property of the truck evaluated.

Table 13: Summary of driver survey results

Property of truck	***Score***
Launch from stand still	2.4
Overall braking behavior	3.0
Slow speed maneuverability	1.9
Acceleration	1.9
Deceleration	4.0
Grade pulling ability	2.7
Shift quality of transmission	3.2
Noise level inside hybrid truck	4.7
Noise outside hybrid truck	4.7
In cab ergonomics	3.8
Overall rating	3.2

Very positive evaluation was found on the noise level and deceleration while slow speed maneuverability and acceleration were ranked lower than the standard truck.

The operations managers found that the vehicles were fairly similar to baseline vehicles. Most of the responses were around “3” showing that the vehicles were “same as standard truck.”

Table 14: Summary of driver survey results

Property of truck	***Ave. Score***
Reliability of hybrid truck	2.7
Availability for job assignments	2.5
Safety of hybrid truck	3.0
Score for general satisfaction	3.0
Overall ranking	3.5

Overall, the users were satisfied with the performance of the trucks and rated them overall slightly above the diesels. Future improvements in acceleration and slow speed maneuverability were noted.

IX. Summary and Conclusions

Gasoline hybrid electric vehicles were compared to the standard baseline diesel vehicles used in parcel delivery in Los Angeles. The vehicles were tested in a laboratory (chassis dynamometer) for fuel economy and emissions. The emission were also collected an evaluated from on-road use measurements. The vehicle evaluation took place over a 12-month period of in-use data collection for fuel economy, maintenance cost and total operating cost. Simulation and modeling of a plug-in truck was also conducted with different battery sizes and the additional value of providing grid balancing services from plug-in trucks was evaluated.

The overall conclusion is that the gasoline hybrid-electric trucks performed well. In terms of fuel economy they are similar to the diesel trucks; 7.5 mpg for GHEV and 7.9 mpg for the diesel vehicles. Considering that diesel engines have an advantage in efficiency this result is positive. A much bigger advantage was seen when comparing the emissions. The tailpipe emissions from the GHEVs were substantially lower; 89% lower for NOx and over 99% lower for PM in comparison to a 2004 diesel. When compared to the emissions of a later diesel model equipped with a DPF filter, the GHEV and like the DPF diesel measured no PM emissions and the GHEV has about 70% lower emissions of NOx. The GHEV vehicles achieve a fuel economy comparable to that of the baseline diesel vehicles with much lower emissions of PM and NOx.

The results of the modeling underscore the importance of targeted design, especially that of the battery, and strategic deployment of electric-drive vehicles to maximize savings in fuel consumption and operating costs. Simulation and modeling of PHEV parcel delivery truck showed that PHEV configuration with smaller battery capacities, 22 kWh represent the lowest lifetime incremental cost option of those evaluated here. The analysis of using PHEV for V2G power showed that the lifetime incremental costs of a PHEV may be significantly or totally offset if the PHEV provides V2G power for grid regulation.

X. Project Costs

The project was completed within budget. The total cost of the project was $595,000. The SCAQMD contributed $325,000 to this project. Co-funding from FedEx and NREL provided additional $270,000. Actual in-kind contributions exceeded the co-funding amount.