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Twelve-Month Evaluation of UPS Diesel Hybrid Electric Delivery Vans

M. Lammert

Technical Report
NREL/TP-540-44134
December 2009

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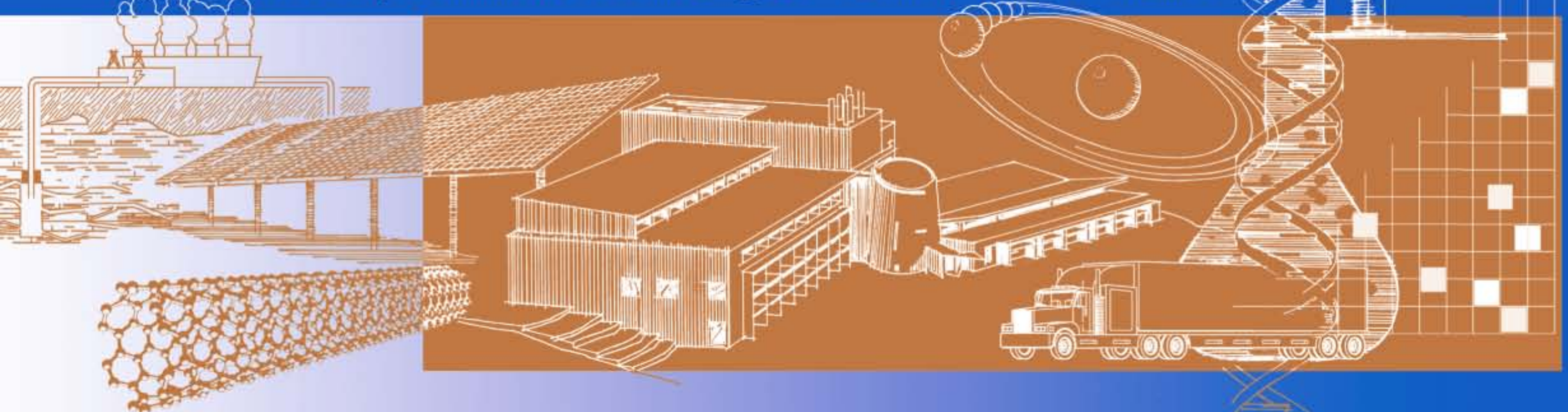

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Prepared under Task No. FC08.3000

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Robert K. Hall
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List of Acronyms and Abbreviations

AVTA	Advanced Vehicle Testing Activity
bhp	brake horsepower
CO	carbon monoxide
CO_2	carbon dioxide
DOE	U.S. Department of Energy
EGR	exhaust gas recirculation
FT&E	Fleet Test and Evaluation (NREL team)
g/bhp-hr	grams per brake horsepower hour
GPS	global positioning system
GVWR	gross vehicle weight rating
HC	hydrocarbon
HVAC	heating, ventilation, and air conditioning
mpg	miles per gallon
mph	miles per hour
MY	model year
NO_x	oxides of nitrogen
NREL	National Renewable Energy Laboratory
PM	particulate matter
ppm	parts per million
ReFUEL	Renewable Fuels and Lubricants (Laboratory)
rpm	revolutions per minute
THC	total hydrocarbons
ULSD	ultra-low-sulfur diesel
UPS	United Parcel Service
VDC	voltage direct current

Executive Summary

This 12-month evaluation is part of a series of evaluations from the U.S. Department of Energy (DOE). Using an established and documented evaluation protocol, DOE—through the National Renewable Energy Laboratory (NREL)—has been tracking and evaluating new propulsion systems in transit buses and trucks for more than 10 years. The DOE/NREL vehicle evaluations are a part of the Advanced Vehicle Testing Activity (AVTA), which supports DOE's Vehicle Technologies Program.

The role of AVTA is to bridge the gap between research and development and the commercial availability of advanced vehicle technologies that reduce petroleum use in the United States and improve air quality. The main objective of AVTA projects is to provide comprehensive, unbiased evaluations of advanced vehicle technologies in commercial use. Data are collected and analyzed for operation, maintenance, performance, costs, and emissions characteristics of both advanced-technology fleets and comparable conventional-technology fleets that are operating at the same site. AVTA evaluations enable fleet owners and operators to make informed vehicle-purchasing decisions.

This report focuses on a parallel hybrid-electric diesel delivery van propulsion system currently being operated by United Parcel Service (UPS). The propulsion system is an alternative to the standard diesel system and could enable reductions in emissions, primarily particulate matter and oxides of nitrogen (NO_x), as well as reductions in petroleum use. Hybrid propulsion allows for increased fuel economy, which ultimately reduces petroleum use.

Evaluation Design

This 12-month evaluation used six P70H hybrids and six P70D standard diesels that are located in two UPS facilities in the Phoenix, Arizona, area. Dispatch and maintenance practices are the same at both facilities. GPS logging, fueling, and maintenance records are used to evaluate the performance of these hybrid step delivery vans.

In addition, a P100H hybrid and a P100D standard diesel were tested at NREL's Renewable Fuels and Lubricants (ReFUEL) Research Laboratory. Testing was performed over multiple standard drive cycles—the Combined International Local and Commuter Cycle, the West Virginia University City cycle, and the Central Business District cycle—to evaluate the fuel economy and emissions benefits gained through hybridization. The P100 chassis and engine combination is different from the one used in the P70 and has a higher gross vehicle weight (GVW), but it uses the same hybrid system as the P70's.

Evaluation Results

The results and related discussions included here focus only on the selected facilities, the two P70 study groups, and the two P100 vehicles tested at the ReFUEL lab.

Delivery Van Use and Duty Cycle

The hybrids had an average monthly mileage rate that was 20% less than that of the diesel vans. The hybrids consistently were driven a fewer number of miles throughout the

evaluation period, but they also experienced extended downtime late in the year as a result of an accident and calibration issues. The hybrids spent more time idling and operating at slower speeds than the diesels did, and the diesels spent slightly more time operating at greater speeds; this accounted for much of the hybrids' fewer monthly miles.

Fuel Economy

The 12-month average fuel economy for the hybrid vans is 13.1 mpg, 28.9% greater than the diesel van group's 10.2 mpg. Figure ES-1 shows the average monthly miles per gallon for each van group and the cumulative average miles per gallon, as well.

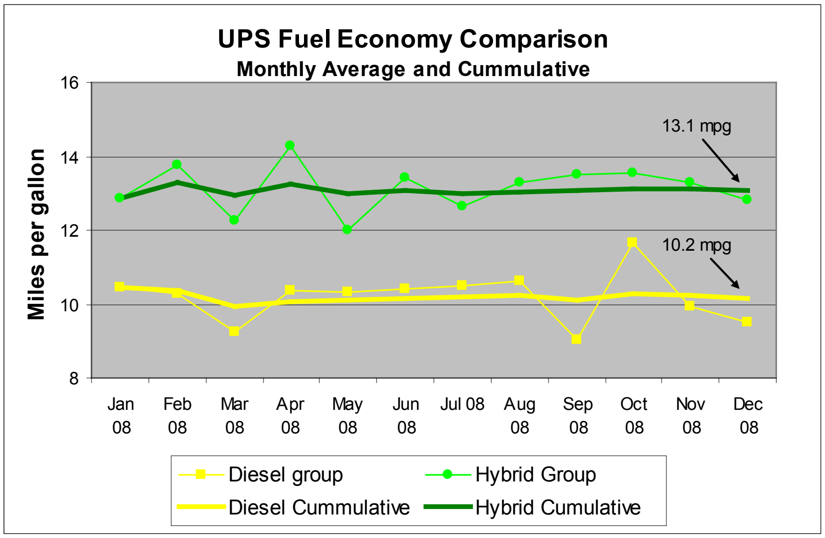

Figure ES-1. Average monthly and cumulative fuel economy

Maintenance Costs

The total maintenance cost per mile of $0.140 for the hybrid vans was 8% less than the $0.152 for the diesel vans. The propulsion-related maintenance cost per mile of $0.034 for the hybrid vans was 5% less than the $0.036 for the diesel vans. Using a t-test, researchers found neither difference to be statistically significant.

Reliability

The hybrid group had a cumulative average of 95.5% uptime over the 12-month study period, less than the diesel group's cumulative average of 99.3% uptime. The hybrids experienced troubleshooting and recalibration issues related to prototype components that are primarily responsible for the lower uptime figures.

Laboratory Fuel Economy and Emissions Testing

The P100 hybrid vans consistently showed a 31%-37% fuel economy improvement over the conventional P100 vans on the three tested duty cycles. The hybrid vans showed improvement in some emissions, but the results varied significantly depending on the cycle being run. The hybrid vans showed an increase in NO_x for all cycles.

Table of Contents

Overview

Advanced Vehicle Testing Activity

The role of the Advanced Vehicle Testing Activity (AVTA) is to help bridge the gap between research and development (R&D) and commercial availability for advanced vehicle technologies that reduce petroleum use and meet air-quality standards. AVTA supports the U.S. Department of Energy's (DOE) Vehicle Technologies Program by examining market factors and customer requirements and evaluating the performance and durability of alternative-fuel and advanced-technology vehicles in fleet applications. The National Renewable Energy Laboratory's (NREL) Fleet Test and Evaluation (FT&E) team conducts evaluations primarily with support from AVTA, but also with support from other DOE programs focused on non-petroleum-based and advanced petroleum-based fuels.

The main objective of FT&E projects is to conduct comprehensive, unbiased evaluations of advanced-technology vehicles. Data collected and analyzed include the operations, maintenance, performance, cost, and emissions characteristics of advanced-technology vehicles and comparable conventional technology in fleets operating at the same site. The FT&E evaluations help fleet owners and operators make informed vehicle-purchasing decisions. The evaluations also provide valuable data to DOE about the maturity of the technology being assessed.

The FT&E team has been conducting several evaluations of advanced-propulsion heavy-duty vehicles (see Table 1). Information on these and other evaluations involving advanced technologies or alternative fuels, such as biodiesel and Fischer-Tropsch diesel, is available at www.nrel.gov/vehiclesandfuels/fleettest.

Table 1. FT&E Heavy-Duty Vehicle Evaluations

Fleet	Location	Vehicle	Technology	Evaluation Status
Long Beach Transit	Long Beach, CA	New Flyer 40-ft low floor transit bus	Gasoline-electric series hybrid	Completed in June 2008
Metro	St. Louis, MO	GILLIG 40-ft transit bus	Biodiesel blend (B20)	Completed in July 2008
New York City Transit	Manhattan, NY; Bronx, NY	Orion VII 40-ft transit bus	Series hybrid, BAE Systems HybriDrive® propulsion system (diesel), order of 200 (Gen II); order of 125 (Gen I)	Completed in January 2008
New York City Transit	Manhattan, NY; Bronx, NY	Orion VII 40-ft transit bus	Series hybrid, BAE Systems HybriDrive® propulsion system (diesel), order of 125; DDC S50G CNG engines	Completed in November 2006
Denver RTD	Boulder, CO	GILLIG 40-ft transit bus	Biodiesel blend (B20)	Completed in October 2006
King County Metro	Seattle, WA	New Flyer 60-ft articulated transit bus	Parallel hybrid, GM–Allison E^P50 System (diesel)	Completed in December 2006
IndyGo	Indianapolis, IN	Ebus 22-ft bus	Series hybrid, Capstone MicroTurbine (diesel)	Completed in 2005
Knoxville Area Transit	Knoxville, TN	Ebus 22-ft bus	Series hybrid, Capstone MicroTurbine (propane)	Completed in 2005
Norcal	San Francisco, CA	Peterbilt/378, Class 8 truck	Cummins Westport ISXG high-pressure, direct- injection, lique-fied natural gas (LNG) and diesel	Completed in 2004

Project Design and Data Collection

This report discusses a 12-month evaluation of six model year (MY) 2007 Freightliner P70H hybrids that were placed in service in Phoenix, Arizona, during the second half of 2007. These hybrid vehicles are evaluated against six MY 2006 Freightliner P70D diesels that were placed in service in Estrella, Arizona, during the first months of 2007. The diesel vans were chosen by using UPS's database and comparing the average miles per day of the six hybrids to that of diesel vans that had the same size and cargo capability and that were located at the two facilities. All fueling and maintenance data are collected by UPS from its databases and were shared with NREL for this evaluation.

Figure 1. UPS hybrid van

Table 2 presents additional details on Eaton Corporation's parallel hybrid system, and Figure 2 provides a schematic of the system.

Table 2. Hybrid Propulsion-Related Systems

Category	Hybrid Van Description
Manufacturer/integrator	Eaton Corporation
Transmission	Fuller medium-duty automated manual 6-speed Prototype
Motor	Synchronous brushless, permanent magnet Continuous power, 26 kW Peak power, 44 kW
Energy storage	Lithium ion batteries 340 VDC 1.8 kWh total storage

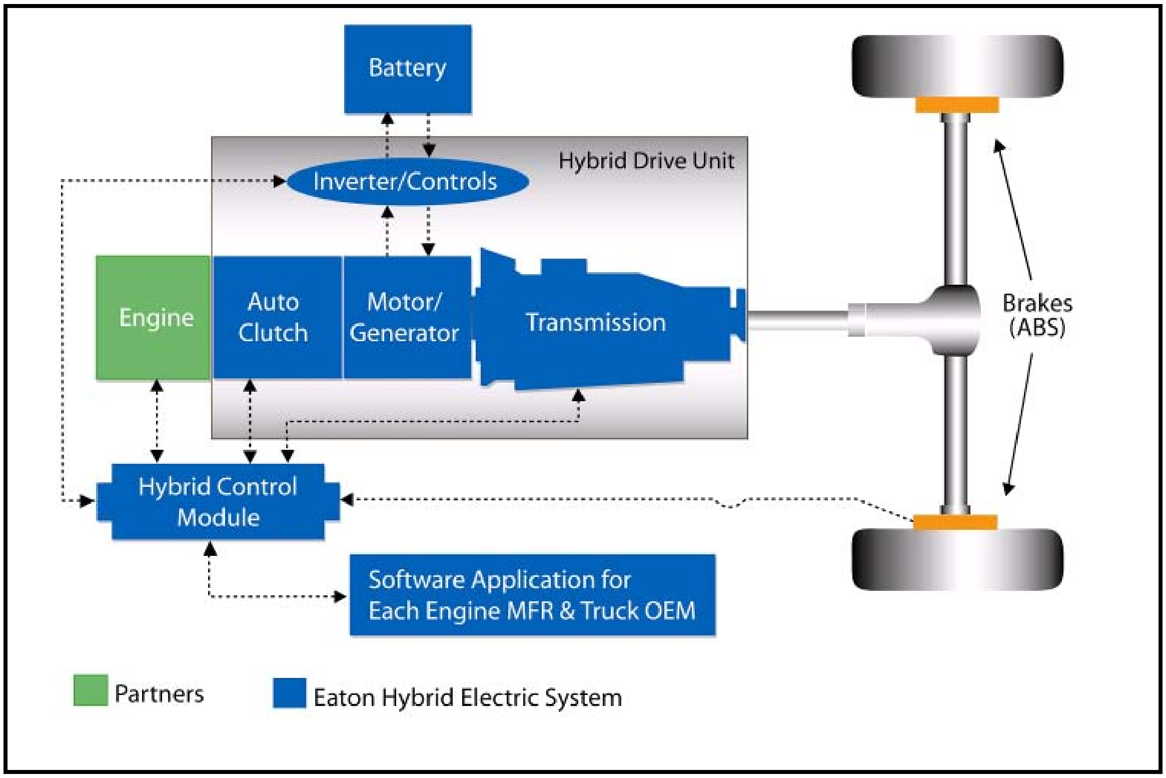

Figure 2. Eaton hybrid system schematic

Figure 3 shows the primary hybrid components in the Eaton system.

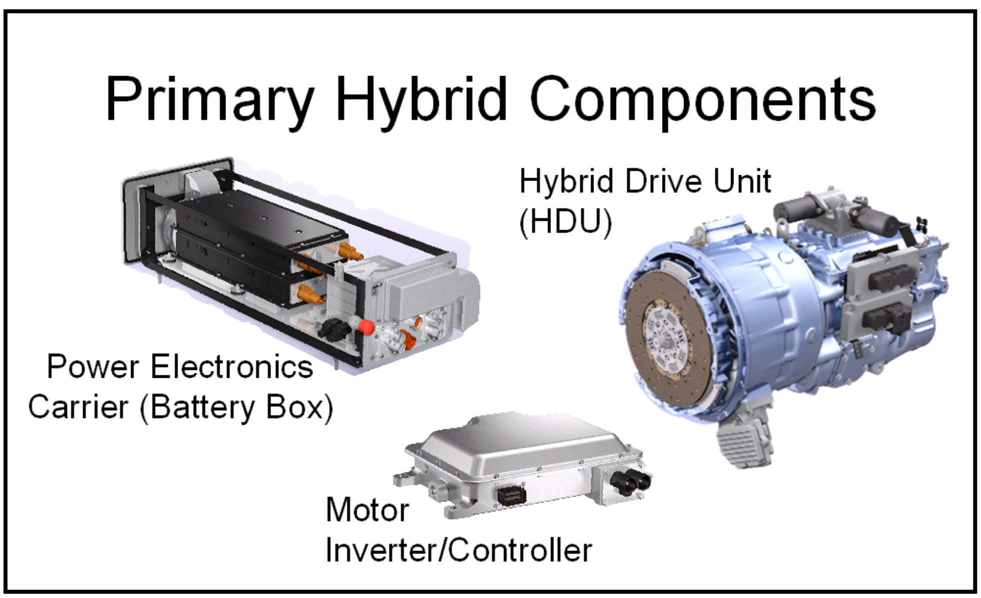

Figure 3. Eaton hybrid system components

Figure 4 shows the primary hybrid components arranged in the undercarriage of a UPS delivery van.

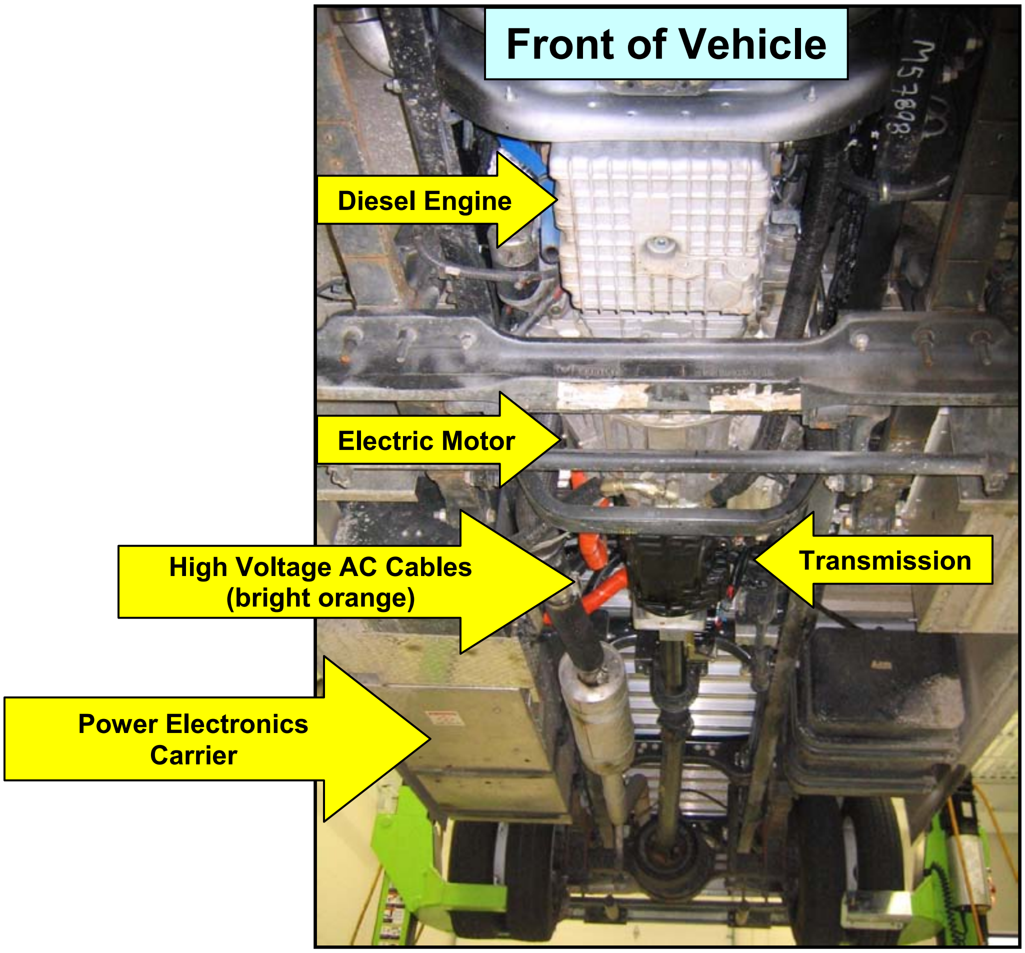

Figure 4. Eaton hybrid system components on UPS undercarriage

UPS has custom delivery vans built to the company's specifications. The P70 vehicles in this study are manufactured by Freightliner for UPS. Table 3 provides brief descriptions of the vehicle systems.

Table 3. Vehicle System Descriptions

Van Specification	Hybrid Electric Vans	Diesel Vans
Van manufacturer	Freightliner Corp.	Freightliner Corp.
Van model	P70H step van	P70D step van
Van model year	2007	2006
Engine manufacturer and model	Mercedes-Benz MBE 904 4 cyl. MY 2006	Mercedes-Benz MBE 904 4 cyl. MY 2006
Emissions equipment	No DPF[a]	No DPF
Retarder/regenerative braking	Regenerative braking	None
Air conditioning type	None	None
GVW	15,200 lb	14,360 lb

[a] DPF = diesel particle filter

Host Site Profile—UPS, Phoenix, Arizona

The host site consisted of the two UPS Arizona facilities—Phoenix and Estrella. Estrella is an expansion facility located about five miles west of the main Phoenix facility, and it became necessary as the Phoenix facility outgrew its footprint. Figure 5 is a site map showing the locations of the two facilities in the greater Phoenix area. The vehicles used for this evaluation are six hybrids from the Phoenix facility and six standard diesels from the Estrella facility. It was not necessary to modify the Phoenix facility in any way to implement the hybrid vehicles into the fleet. Drivers were given training on the operation of the hybrids, but no restrictions or special accommodations were made for their use; however, UPS did assign them to urban routes rather than rural routes to make the best use of the hybrid drive train. Dispatch and maintenance practices are the same at both facilities. The Phoenix facility has on-site fueling, and the vehicles are fueled by drivers as needed, using an internal fuel card system. The Estrella facility does not have on-site fueling; drivers fuel the vehicles at public stations using a corporate fuel card. In both cases the drivers need to log their fueling events on their electronic tablets, and the records are uploaded to a central database.

Figure 5. UPS Phoenix site map

Evaluation Results

Van Use

Figure 6 shows the average monthly miles driven per van for each van group with ±95% confidence interval lines. An accident involving one hybrid van that affected mileage accumulation during August and September was not included in the figure. The width of the 95% confidence interval gives some idea about how uncertain we are about the average. Van average usage did not change significantly during the first nine months of the evaluation period; the hybrids consistently were driven fewer miles throughout this period because of their shorter, more urban routes. In October and November, the hybrid group showed a dip in average usage and an increase in the 95% confidence interval due to calibration issues for three vans; the result was that these vehicles were not available for service for extended periods of time. Starting in October, the diesel group experienced an increase in miles per van resulting from UPS's consolidation of routes.

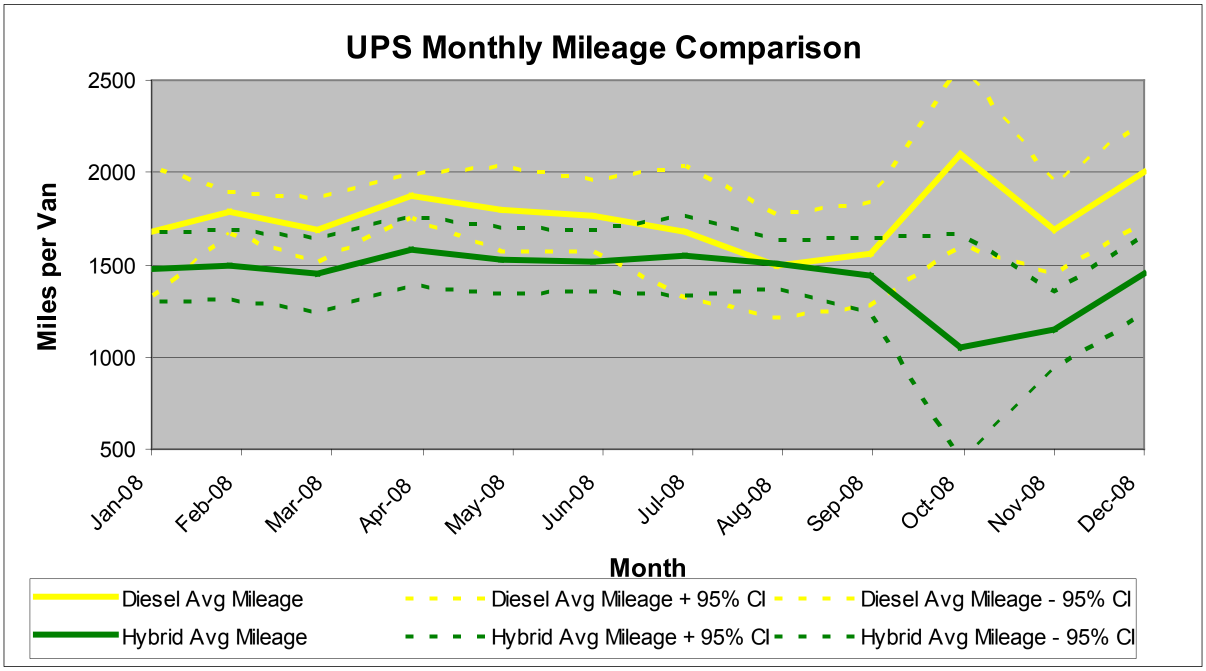

Figure 6. Hybrid and diesel monthly mileage per van

Table 4 presents the average monthly mileage per van during the evaluation period for the two groups of vans. The hybrids had a monthly mileage accumulation rate that is 20% less than that of the diesel vans (1,403 miles versus 1,758 miles). The average monthly rate was affected by downtime because four hybrid vehicles had a combined 7 months of operation impacted by extended downtime, as described above. With those 7 months of operation removed, the hybrids averaged 93 miles per month more, which was 15% less than that of the diesel group. This lower rate could also indicate a more urban duty cycle with lower speeds and more stops per mile. Half of this difference is explained by the 7.5% fewer average miles per day driven by the hybrids, as discussed in the Van Duty Cycle section of this report.

Table 4. Average Van Miles Driven per Month by Study Group

Van Number	Start Mileage	End Mileage	Evaluated Miles	Miles per Delivery Day	Miles per Month
663982	59,305	77,899	18594	73.5	1,550
665020	42,559	65,834	23275	93.1	1,940
665044	30,682	51,526	20844	82.7	1,737
665086	32,085	55,248	23163	91.9	1,930
665087	43,875	65,412	21537	86.5	1,795
665150	32,335	51,470	19135	75.9	1,595
Diesel Average	**40,140**	**61,232**	**21,091**	**84**	**1,758**
Diesel Stdev	**10,976**	**10,409**	**1,969**	**8**	**164**
666131	11,813	24,210	12397	53.7	1,033
666132	15,711	34,997	19286	82.1	1,607
666133	15,598	34,834	19236	76.0	1,603
666139	15,899	32,902	17003	76.2	1,417
666142	14,212	30,224	16012	69.6	1,334
666145	13,732	30,823	17091	68.6	1,424
HybridAverage	**14,494**	**31,332**	**16,838**	**71**	**1,403**
Hybrid Stdev	**1,583**	**4,009**	**2,539**	**10**	**212**
Difference	**25,646**	**29,900**	**4,254**	**13**	**354**
% Difference	**64%**	**49%**	**20%**	**15%**	**20%**

Van Duty Cycle

GPS data loggers were installed in two vans from each study group to obtain detailed information on the routes they were assigned to. Data were collected for one week of operation, providing 10 days of "typical" operation for each vehicle group. The data are not representative of the entire UPS fleet but only of the P70 vehicles operating out of these two depots. Figure 7 shows a GPS visualization of the routes of the four logged vans. The red and orange traces each show one day of the diesel van's operations out of the Estrella depot. The blue and purple traces each show one day of the hybrid van's operations out of the Phoenix depot. The exact routes vary daily, but the depictions shown are typical of a day of operation for that van, as captured by the GPS loggers.

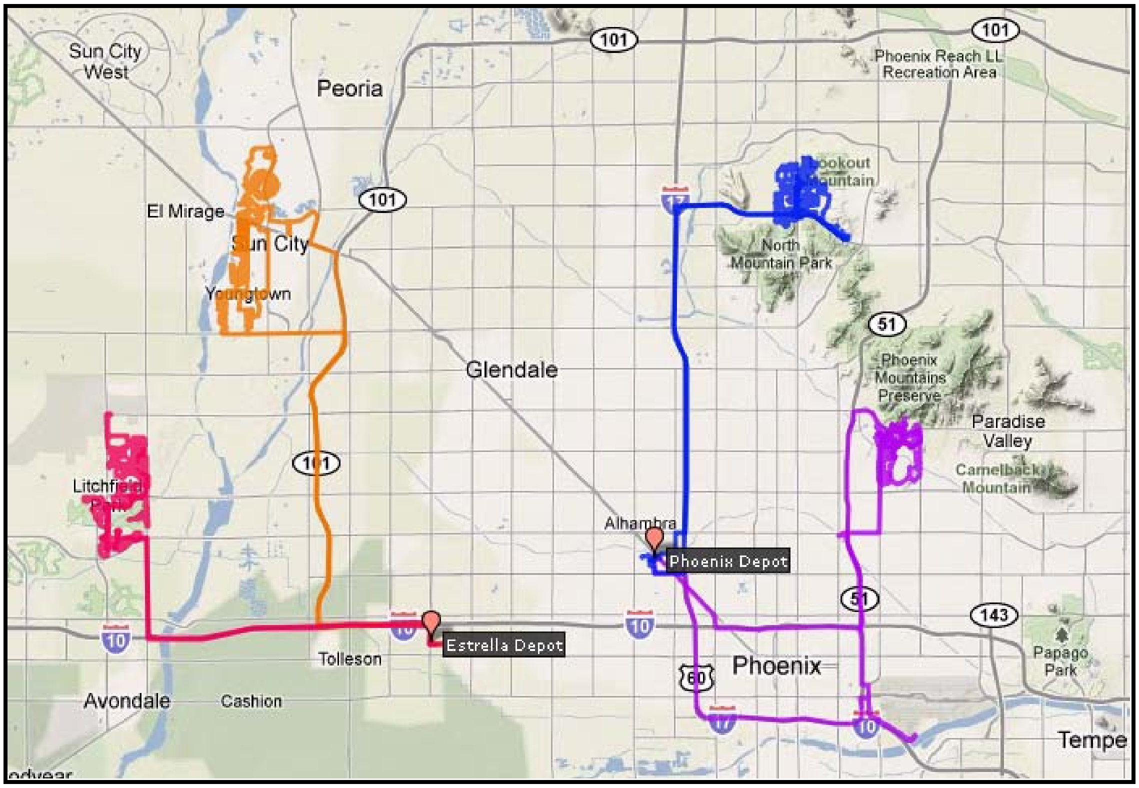

Figure 7. Hybrid and diesel route visualization

Figure 8 shows the average time (as a percentage) that vans with GPS loggers spent at different vehicle speeds. The hybrids spent more time idling and operating at slower speeds than the diesels did, and the diesels spent slightly more time operating at higher speeds.

- The hybrid vans spent 13% of their time at zero speed, about twice the idle time spent by the diesels (6.1%).
- The hybrid vans spent 20% of their time in the 0 to 10 mph range, 31% more than the diesels did (15%).
- The hybrid vans spent 18% of their time in the 20-35 mph range, 32% less time than the diesels spent there (26%).
- The hybrids spent 7.6% of their time in the 50-65 mph range, twice as much as the diesels did (3.7%).
- The diesels spent significantly more time above 65 mph (5% vs. 1% for the hybrids). This was because the hybrids are speed-limited while the diesel vans are not.

The greater time spent by the hybrids at slower speeds indicates a more urban duty cycle; had the diesel group driven the same exact duty cycle, they likely would have had lower fuel economy as a result. Both groups spent about 70% of their non-idle driving time at speeds less than 35 mph, indicating that both groups were on city/residential delivery routes. The higher average highway speed could also negatively impact the fuel economy of the diesel group as a result of higher aerodynamic drag. Both groups spent about 8.5% of their driving time at speeds above 50 mph, indicating they had similar distances to travel from depot to delivery zone.

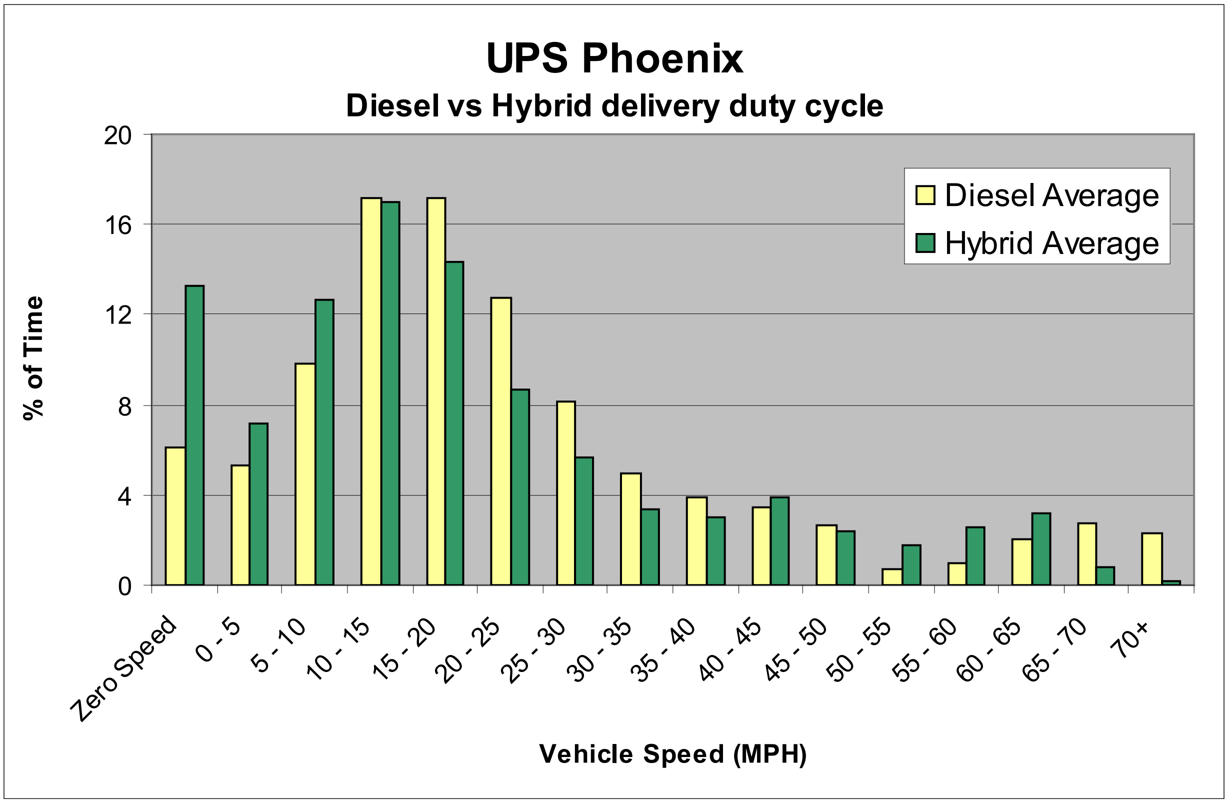

Figure 8. Hybrid and diesel duty cycle breakdown

Table 5 presents other duty-cycle statistics gathered from the GPS data logging.

- The hybrids' average driving speed of 22.3 mph was 7% lower than the diesels' 24.1 mph.
- The hybrids averaged 94 stops per day, 90% more than the diesels' 49 stops.
- The hybrids averaged 1.4 stops per mile, twice as many stops per mile as the diesels' 0.7.
- The hybrids had 16.9 acceleration events per mile, 22% more than the diesels' 13.8.
- The hybrids had 15.8 deceleration events per mile, 19% more than the diesels' 13.3.

These statistics indicate that the hybrids were operating in a more dense urban delivery zone than the diesels were. The lower speeds and more stops per mile are in line both with the hybrids' greater percent of time spent at speeds lower than 10 mph and the fewer miles driven per month. The 7.5% fewer average miles per day explains part of the 15% fewer miles per month mentioned in the Van Use section.

Table 5. Drive Cycle Statistics from Vans with GPS Loggers from Each Study Group

Cycle Statistics	Diesel Average	Hybrid Average	Difference (Diesel - Hybrid)	% Difference
Distance traveled (miles)	73.7	68.2	5.5	-7.5%
Average speed over cycle (mph)	22.6	19.4	3.2	-14.3%
Average driving speed (mph)	24.1	22.3	1.8	-7.3%
Maximum speed (mph)	74.0	69.2	4.8	-6.5%
Time at idle (s)	732	1725	-993	136%
Maximum acceleration (ft/s^2)	12.8	10.0	2.8	-21.8%
Maximum deceleration (ft/s^2)	-10.0	-10.9	0.9	9.1%
Acceleration (% of total cycle)	44.1	40.0	4.0	-9.2%
Deceleration (% of total cycle)	40.8	35.7	5.1	-12.4%
Average acceleration (ft/s^2)	1.9	2.0	-0.1	3.8%
Average deceleration (ft/s^2)	-2.0	-2.2	0.2	7.5%
Number of acceleration events	1018.3	1150.2	-131.9	13.0%
Number of acceleration events per mile	13.8	16.9	-3.1	22.3%
Number of deceleration events	983.1	1077.9	-94.8	9.6%
Number of deceleration events per mile	13.3	15.8	-2.5	18.6%
Number of stops	49.2	93.9	-44.7	90.9%
Average duration of stop (s)	14.5	18.4	-3.9	27.3%
Number of stops per mile	0.7	1.4	-0.7	105.9%

Fuel Economy

UPS fuels its hybrids and diesels with standard ultra-low-sulfur diesel (ULSD), which has a sulfur content of less than 30 parts per million (ppm). From June through September, three diesel vans experienced spikes in their monthly fuel economy:

- One van had 1 month of high fuel economy results
- One van had 2 months of high fuel economy results
- One van had 3 months of very high fuel economy results.

UPS confirmed that drivers failed to log fueling events during this period of time. In one case, an impossible number of miles were accumulated without a recorded fueling event. The six suspect diesel-group vehicle months of fuel economy data have been removed from the total of 72 diesel-group vehicle months of results presented in this report. As such, miles used are different for the calculation of diesel-group fuel economy than those reported in other sections of the report.

Table 6 shows the fuel consumption and economy data for each van in each study group. The hybrid vans consumed 7,714 gallons of fuel over 101,025 miles for the 12-month period, resulting in an average fuel economy for the hybrid vans of 13.1 mpg, which was 28.9% greater than that of the diesel van group's 10.2 mpg (P value = 0.0002).

Table 6. Hybrid and Diesel Van Fuel Use and Economy

Hybrid Vehicles			
Van	Miles	Gallons Consumed	Miles per Gallon
666131	12,397	989	12.5
666132	19,286	1,395	13.8
666133	19,236	1,455	13.2
666139	17,003	1,357	12.5
666142	16,012	1,281	12.5
666145	17,091	1,237	13.8
Hybrid Total	101,025	7,714	13.1
Diesel Vehicles			
Van	Fuel Economy Miles	Fuel Economy Gallons	Miles per Gallon
663982	15,590	1,463	10.7
665020	23,275	2,203	10.6
665044	19,052	1,819	10.5
665086	20,204	2,322	8.7
665087	21,537	2,181	9.9
665150	19,135	1,706	11.2
Diesel Total	118,793	11,694	10.2

Figure 9 shows the monthly miles per gallon for each van group and cumulative miles per gallon for each van group. In this figure, the group is considered as a whole, and monthly miles per gallon are calculated by considering the sum of the miles and sum of the gallons for the group each month. This figure weights all vehicle miles equally and relates directly to the fleet's actual fuel consumption.

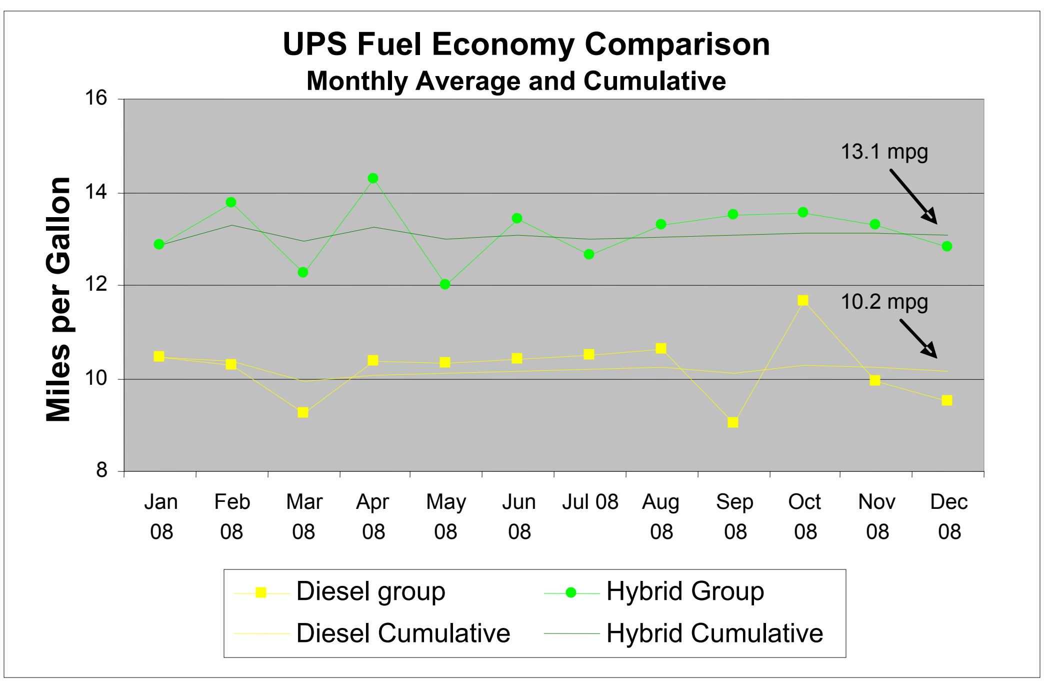

Figure 9. Average monthly and cumulative fuel economy

Figure 10 shows the average monthly miles per gallon for each group of vans with ±95% confidence interval lines. This figure considers each group as six individual vehicles and averages their monthly miles per gallon results. This figure weights each vehicle equally and better takes into account the effect of different duty cycles and miles per day on fuel economy. With a small sample size, one outlier can offset the average significantly. The width of the 95% confidence interval gives some idea about how uncertain we are about the average. By considering each vehicle as an individual and calculating a 95% confidence interval, it is possible to understand the consistency of the population's fuel economy and gain a better understanding of how a larger population of vehicles would behave. The average miles per gallon results can be different from those obtained when considering the group as a whole, as in Figure 9, and in this study, both groups have 1%-2% higher monthly miles per gallon results with this calculation, with few exceptions.

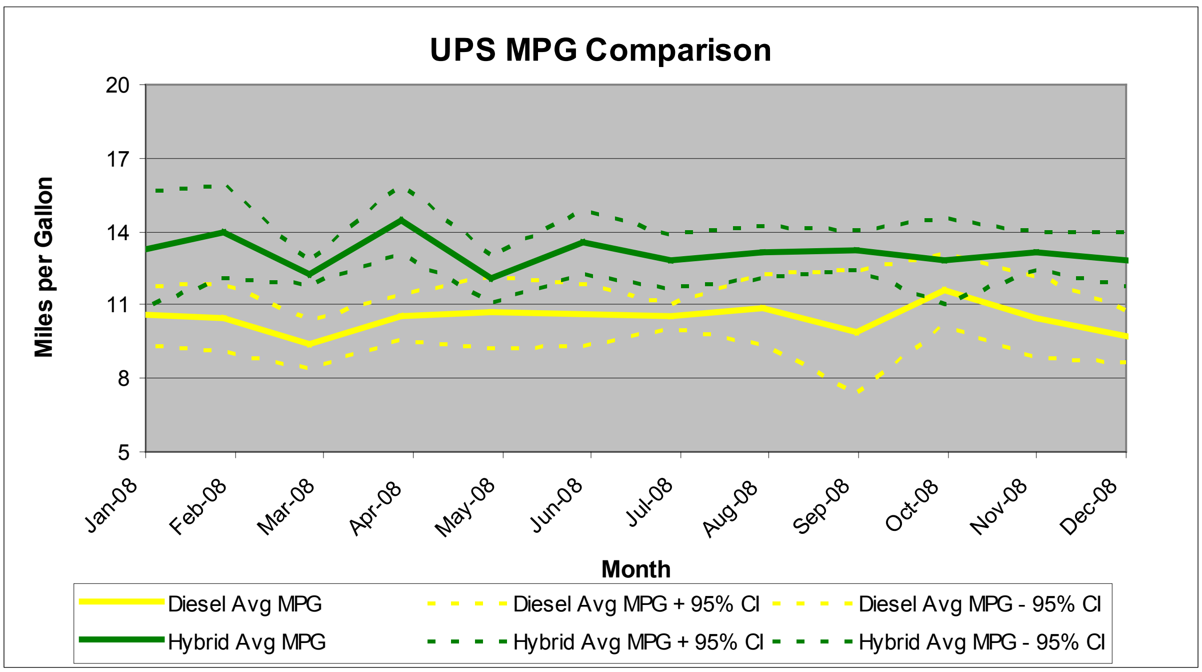

Figure 10. Average monthly fuel economy

Maintenance Cost Analysis

This evaluation focuses on van operations spanning 12 of the first 18 months of operation for the hybrid vans. This snapshot does not yield enough capital and operating cost data to provide a complete understanding of the full life-cycle cost of the hybrid vans, however. Understanding costs requires an examination of the purchase cost of the vans plus warranty and operation costs. Longer term maintenance activities, such as engine rebuilds or replacements and battery replacements, also must be considered. Finally, it is critical that areas in which cost savings can be achieved (e.g., in brake repair) be examined. The intent of this evaluation, however, is to capture accurate actual capital and known operations costs associated with the hybrid and diesel vehicles for the selected period. This analysis is not predictive of maintenance costs assumed by UPS beyond the warranty period. The exact components and warranty periods—as negotiated by UPS, Eaton, and Freightliner—are contractual and confidential.

The hybrid and diesel vans all are new enough that much of the maintenance is completed under warranty. All maintenance for the Eaton hybrid drive was done by Eaton mechanics. These maintenance costs are not included in the maintenance-cost analysis in this section. Not accounting for warranty repairs in the evaluation of total maintenance cost does offer an incomplete picture of total maintenance cost. Even without warranty costs, however, this analysis reflects the actual cost to UPS during the period selected.

Maintenance costs were collected in the same manner for each study group. All work orders and parts information available were collected for the study vans, and the maintenance practices are the same for both diesel and hybrid study groups. The maintenance analysis discussions include only the maintenance data that were gathered during the evaluation period on the study group vans.

Maintenance Costs

This cost category includes the costs for parts and for labor, at $50 per hour; it does not include warranty costs. All costs related to an accident on a hybrid vehicle have been removed from this section as they do not represent the vehicle and powertrain comparison of interest. Cost per mile is calculated as follows.

Cost per mile = ((labor hours * 50) + parts cost)/mileage.

The labor rate has been set artificially at a constant rate of $50 per hour so other analysts can change this rate to one more similar to their own situations. This rate does not directly reflect UPS's current hourly mechanic rate.

Table 7 shows total and propulsion-related maintenance costs for the two study groups. The propulsion-related vehicle systems include the engine; transmission; electric propulsion; exhaust; fuel; and nonlighting electrical, which includes general electrical, charging, cranking, and ignition. The propulsion-related maintenance cost per mile of $0.034 for the hybrid vans was 5% less than the $0.036 for the diesel vans. The total maintenance cost per mile of $0.140 for the hybrid vans was 8% less than the $0.152 for the diesel vans.

Table 7. Hybrid and Diesel Van Total and Propulsion Maintenance Costs

Study Group	Miles	Parts Cost	Labor Hours	Maintenance Cost	Cost per Mile ($/mile)
Hybrid total	101,025	$3,985	203.3	$14,148	$0.140
Hybrid propulsion-related	101,025	$38	69.0	$3,485	$0.034
Diesel total	126,548	$7,122	242.8	$19,260	$0.152
Diesel propulsion-related	126,548	$1,545	61.0	$4,594	$0.036

Included in the "total" maintenance cost data are tire replacements, which are a large part of the vehicle operating costs and are responsible for spikes in monthly total maintenance costs. Cumulative tire expenses are on the same level as cumulative propulsion-related costs for either drive train ($0.032/mile to $0.037/mile). Figure 11 shows total monthly and cumulative maintenance costs for the two study groups. Tire costs are responsible for most of the spike in March ($0.08/mile) for the hybrid group. A group of tire changes during the month of September ($0.16/mile) is responsible for the spike during that month. While both study groups have similar tire replacement costs over the course of the year ($3,688 for hybrids vs. $4,041 for diesels), the hybrids seem to experience them in large groups that create spikes, while for the diesel group, the replacements are spread evenly over the course of the year. This is likely because the hybrids were all put in service during the same month in 2007, while the diesels were put in service over about 9 months in that same year. This resulted in a much higher standard deviation in evaluation start mileages and, as such, a wider range of tire wear-out events. The hybrids had a lower average evaluation start mileage; the range of start mileages was one-seventh that of the diesel group, as discussed in the Van Use section.

Table 8 shows a breakdown by individual van of the total cost per mile. Total maintenance cost per mile between the diesel and hybrid groups had no statistical significance (P value = 0.82). Propulsion maintenance cost per mile showed no statistically significant difference between the diesel and hybrid groups (P value = 0.95). Fuel cost per mile dominated the total cost per mile for both groups, and the fuel cost per mile was 22% less for the hybrid group (P value = 0.0008). As such, total cost per mile was 18% less for the hybrid group (P value = 0.0134). The 2008 average price for diesel was $3.80/gallon, and this figure was used to calculate fuel cost per mile.

Table 8. Hybrid and Diesel Van Total Cost per Mile

Total Cost per Mile Comparison						
Car	**PWRTRN**	**Mileage Total**	**Non-Prop Mnt ($/mile)**	**Prop Maint ($/mile)**	**Fuel Cost ($/mile)**	**Total Cost ($/mile)**
663982	Diesel	18,594	$0.142	$ 0.077	$ 0.357	$ 0.576
665020	Diesel	23,275	$0.077	$ 0.032	$ 0.360	$ 0.468
665044	Diesel	20,844	$0.119	$ 0.038	$ 0.363	$ 0.519
665086	Diesel	23,163	$0.141	$ 0.023	$ 0.437	$ 0.601
665087	Diesel	21,537	$0.140	$ 0.017	$ 0.385	$ 0.542
665150	Diesel	19,135	$0.077	$ 0.038	$ 0.339	$ 0.454
Total	**Diesel**	**126,548**	**$0.116**	**$ 0.036**	**$ 0.374**	**$ 0.526**
666131	Hybrid Diesel	12,397	$0.112	$ 0.061	$ 0.303	$ 0.476
666132	Hybrid Diesel	19,286	$0.064	$ 0.020	$ 0.275	$ 0.358
666133	Hybrid Diesel	19,236	$0.087	$ 0.020	$ 0.287	$ 0.394
666139	Hybrid Diesel	17,003	$0.089	$ 0.024	$ 0.303	$ 0.416
666142	Hybrid Diesel	16,012	$0.145	$ 0.067	$ 0.304	$ 0.515
666145	Hybrid Diesel	17,091	$0.149	$ 0.029	$ 0.275	$ 0.453
Total	**Hybrid Diesel**	**101,025**	**$0.106**	**$ 0.034**	**$ 0.290**	**$ 0.430**

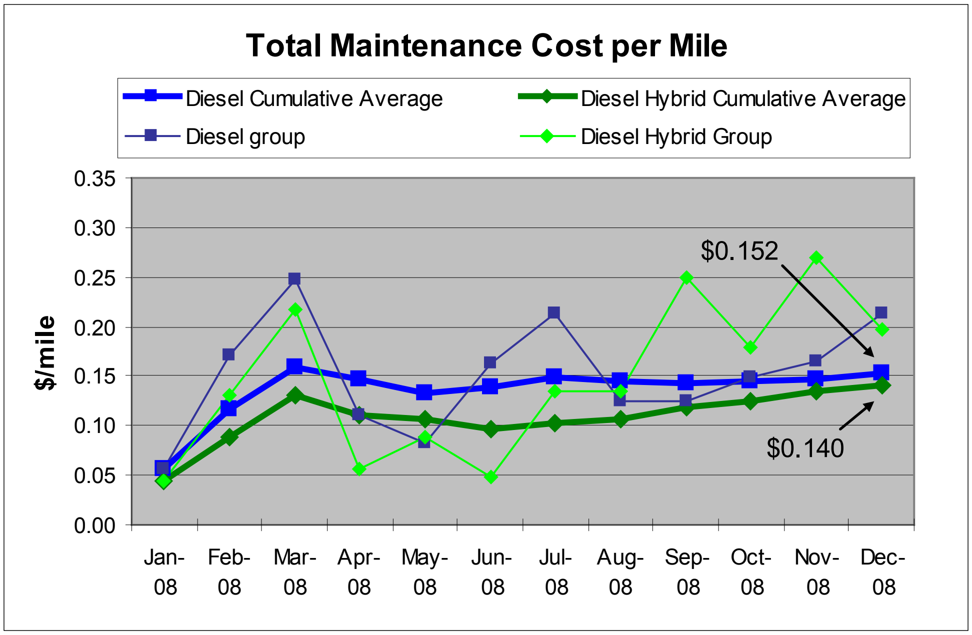

Figure 11. Total maintenance cost per mile

Figure 12 shows monthly and cumulative propulsion-related maintenance costs for the two study groups. The hybrid spike during October and November is due to Eaton recalibration activities and is responsible for raising the hybrid cumulative propulsion-related maintenance cost per mile to parity with that of the diesel group. Three of the hybrid units were experiencing faults related to the calibration of a prototype parking pawl in use on these vans. While Eaton covered the costs for materials, UPS technicians spent time troubleshooting and working with Eaton, and these hours generated the spike in propulsion maintenance cost per mile.

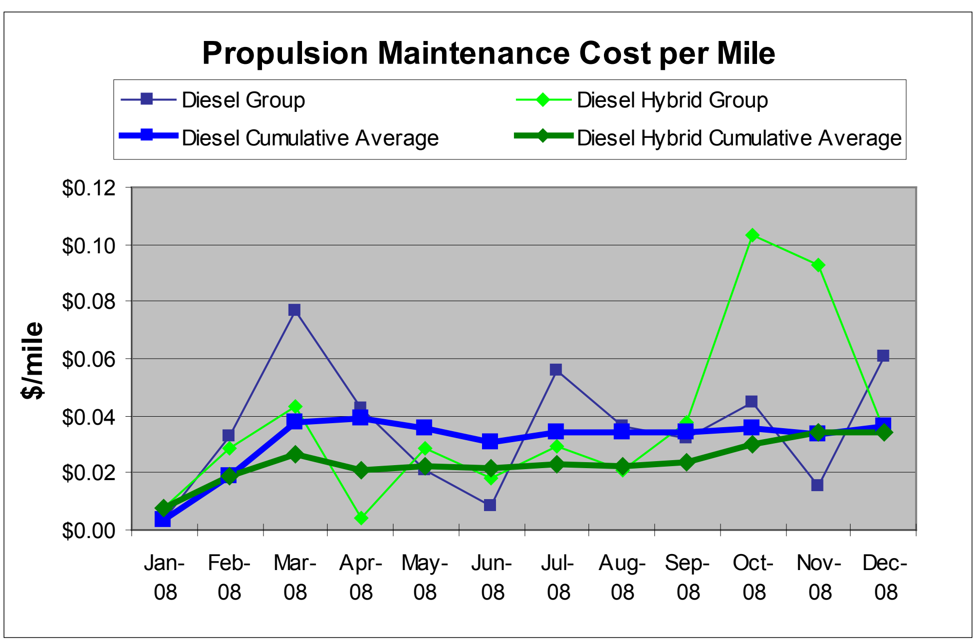

Figure 12. Propulsion maintenance cost per mile

Figures 13 and 14 show a breakdown of total and propulsion-related maintenance costs per mile for the diesel and hybrid study groups, respectively. Note the similar percentage breakdowns for each category, which indicates that the hybrid drivetrain is not driving maintenance costs any more than the standard conventional drivetrain. Also note that for both study groups, the complete propulsion system costs an amount similar to the tire-related costs for the group. Propulsion system and tire-related costs were 19% and 17%, respectively, for the diesel group and 20% and 21%, respectively, for the hybrid group.

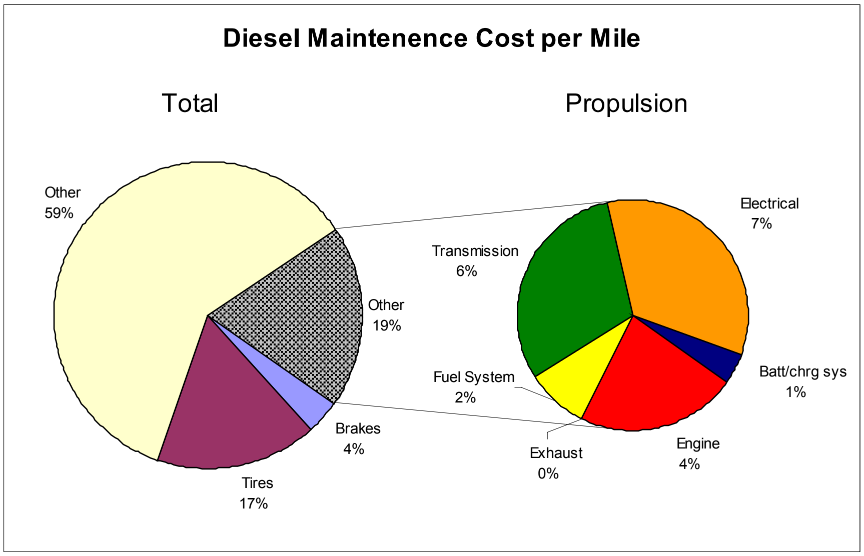

Figure 13. Propulsion maintenance cost per mile (diesels)

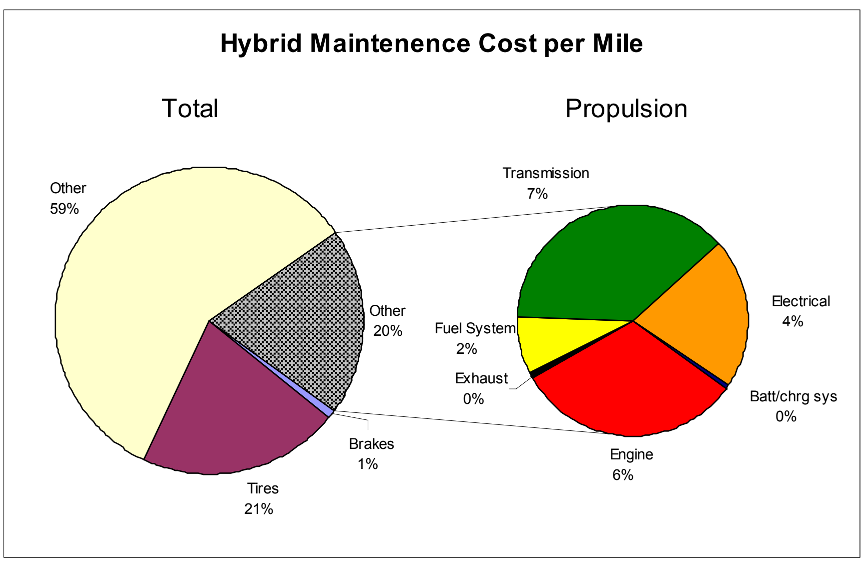

Figure 14. Propulsion maintenance cost per mile (hybrids)

Reliability

UPS records instances in which a vehicle is not available to load in the morning, as scheduled. Scheduled maintenance events of any kind do not get recorded in this way. During this 12-month evaluation, there were 253 operational days available for deliveries. That is a total of 1,518 days for each study group of six vans. Both groups had a comparable number of missed operational days during the first 6 months of the evaluation. In August one of the hybrid vehicles was involved in an accident, which caused it to miss 29 operational days during August and September. A combined 55 operational days were missed during October and November while Eaton was troubleshooting faults related to a prototype parking pawl on three of the hybrid units. The diesel study group missed a total of 10 operational days during the 12-month study period, while the hybrid group missed 68 operational days for the reasons mentioned above (excluding the accident). Table 9 breaks down the monthly and cumulative uptime percent for each group. Figure 15 shows the monthly and cumulative uptime for each group as a percentage of the total available delivery days. The 29 days missed because of an accident are not included in Table 9 or Figure 15 because that event was outside normal van and powertrain operations.

Table 9. Hybrid and Diesel Van Cumulative Missed Operating Days

	Jan	Feb	Mar	Apr	May	Jun	Jul	Aug	Sep	Oct	Nov	Dec
Diesel Monthly % uptime	100%	99.2%	97.6%	100%	100%	100%	96.2%	100%	100%	99.3%	100%	100%
Hybrid Monthly % uptime	100%	100%	97.6%	100%	100%	100%	100%	98.4%	100%	65.9%	85.2%	100%
Diesel Cumulative % uptime	100%	99.6%	99.0%	99.2%	99.4%	99.5%	99.0%	99.1%	99.2%	99.2%	99.3%	99.3%
Hybrid Cumulative % uptime	100%	100%	99.2%	99.4%	99.5%	99.6%	99.7%	99.5%	99.6%	96.0%	95.1%	95.5%

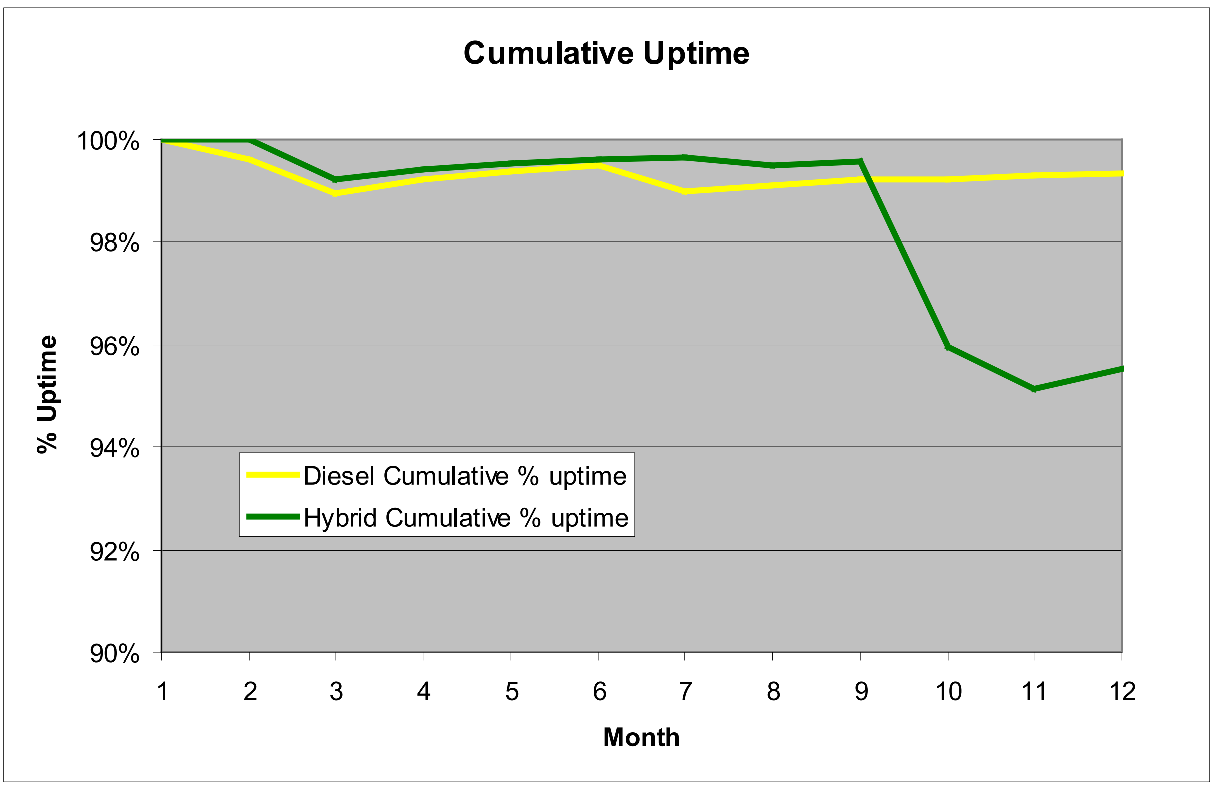

Figure 15. Cumulative uptime

Batteries

The Eaton system uses lithium ion batteries supplied by Hitachi for energy storage. They have a capacity of 1.8 kWh and operate at a nominal voltage of 340 VDC. These batteries were not available to NREL during the evaluation period for detailed evaluation. The batteries are included in the power electronics carrier (PEC). Eaton's records indicate one PEC was replaced because of water intrusion during an atypical monsoon flood event. UPS records indicate preventive efforts to seal the PEC air filter on the hybrids, and these costs are captured as part of the maintenance cost analysis under the "electrical" heading. No record of a battery failure or a cell failure exists. The service life of the battery is estimated by Eaton at 7 years.

Laboratory Fuel Economy and Emissions Testing

This work comprises chassis dynamometer testing of two UPS delivery vehicles. The remainder of this document includes the test plan and results from vehicle testing performed at NREL's ReFUEL Research Laboratory. The ReFUEL laboratory description, experimental setup, and test procedures can be found in the appendix.

Test Plan

Tests were performed on one 2007 hybrid electric Workhorse P100 delivery van and one conventional 2007 Workhorse P100 delivery van during May and June 2007 to determine emissions and fuel economy benefits of the hybrid electric powertrain being evaluated at UPS. The tests were conducted over three driving cycles: the Combined International Local and Commuter Cycle (CILCC), the West Virginia University City (WVU City) cycle, and the Central Business District (CBD) cycle. Vehicle exhaust emissions and fuel consumption were measured for repeated test conditions. The speed/time traces of each cycle are shown in Figures 16, 17, and 18.

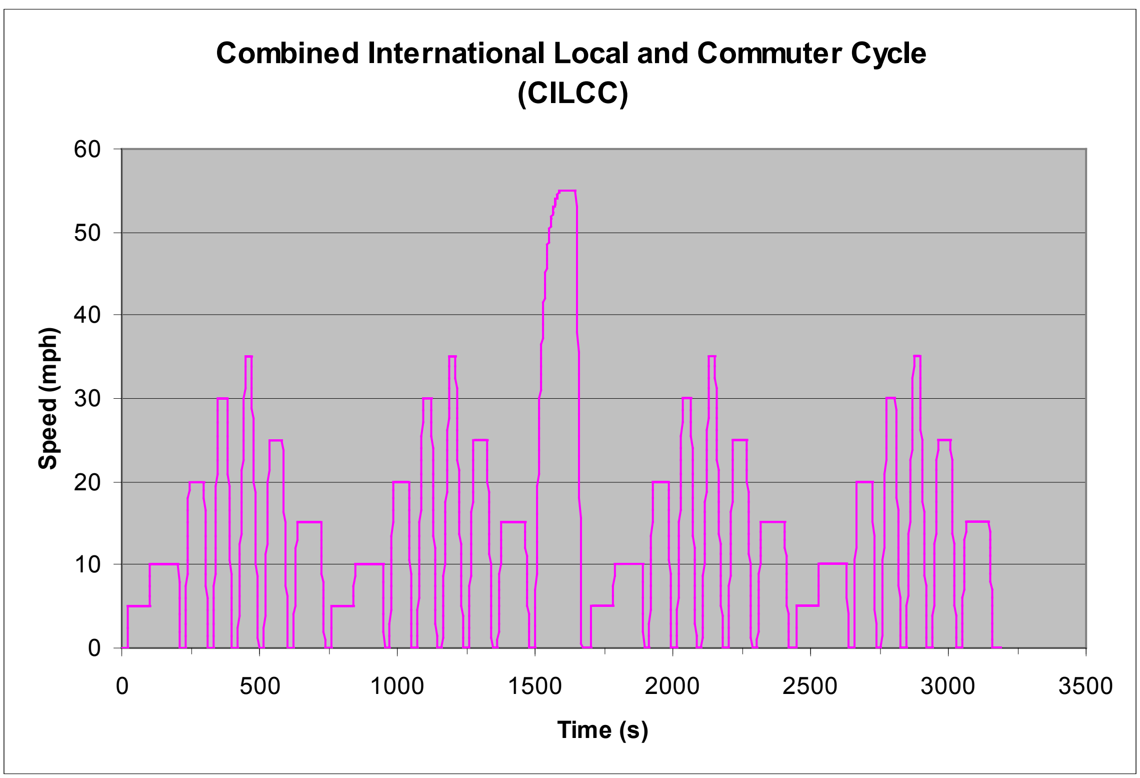

Figure 16. CILCC trace

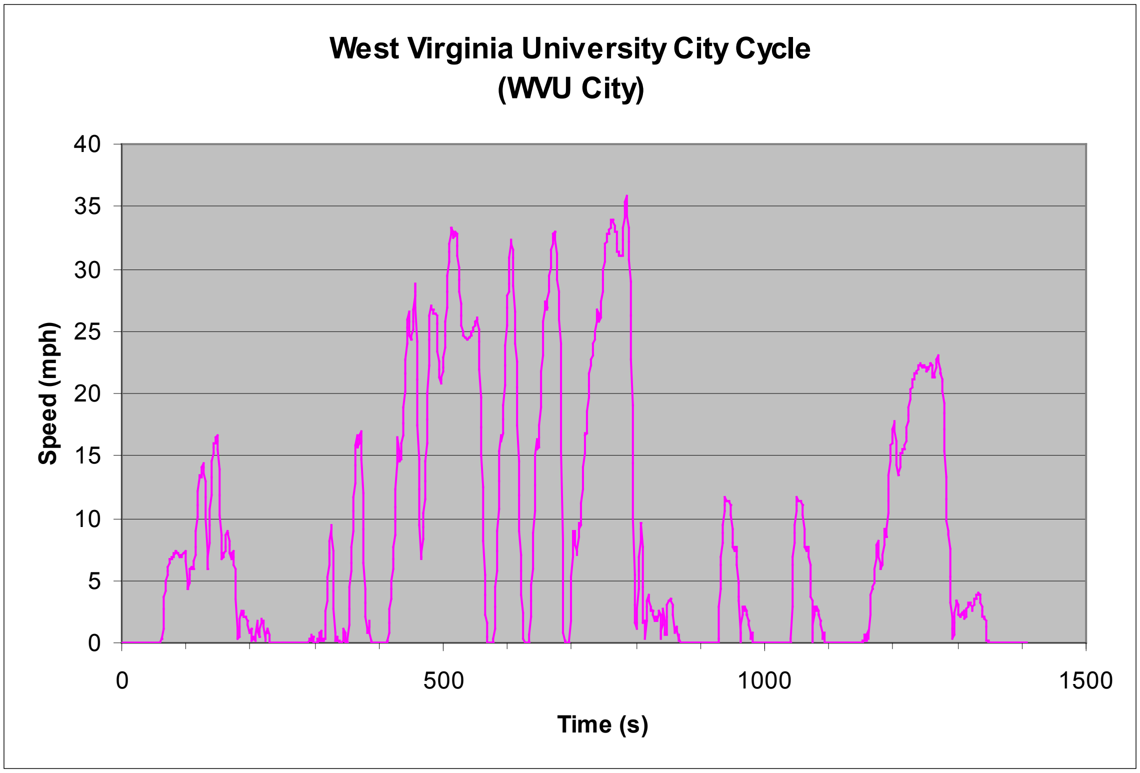

Figure 17. WVU City trace

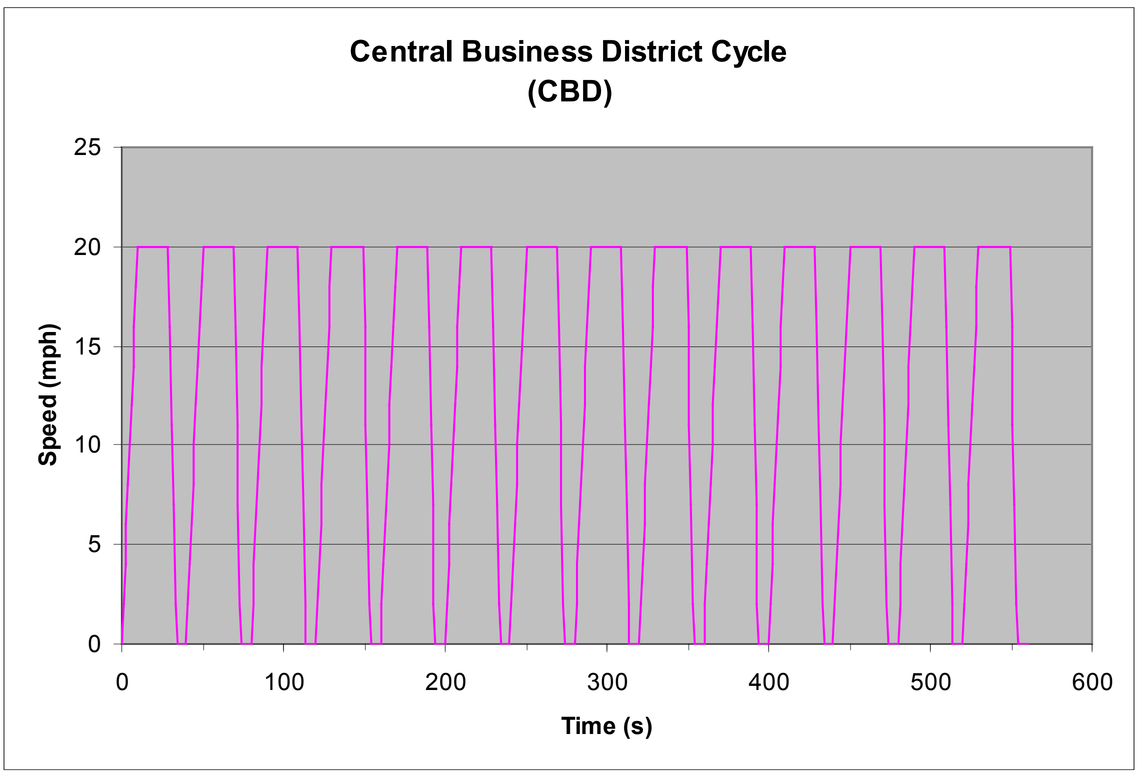

Figure 18. CBD trace

The test vehicles were installed on the chassis dynamometer shown in Figure 19. All sensors were monitored and recorded continuously by the ReFUEL data acquisition system throughout each test cycle run, unless otherwise noted.

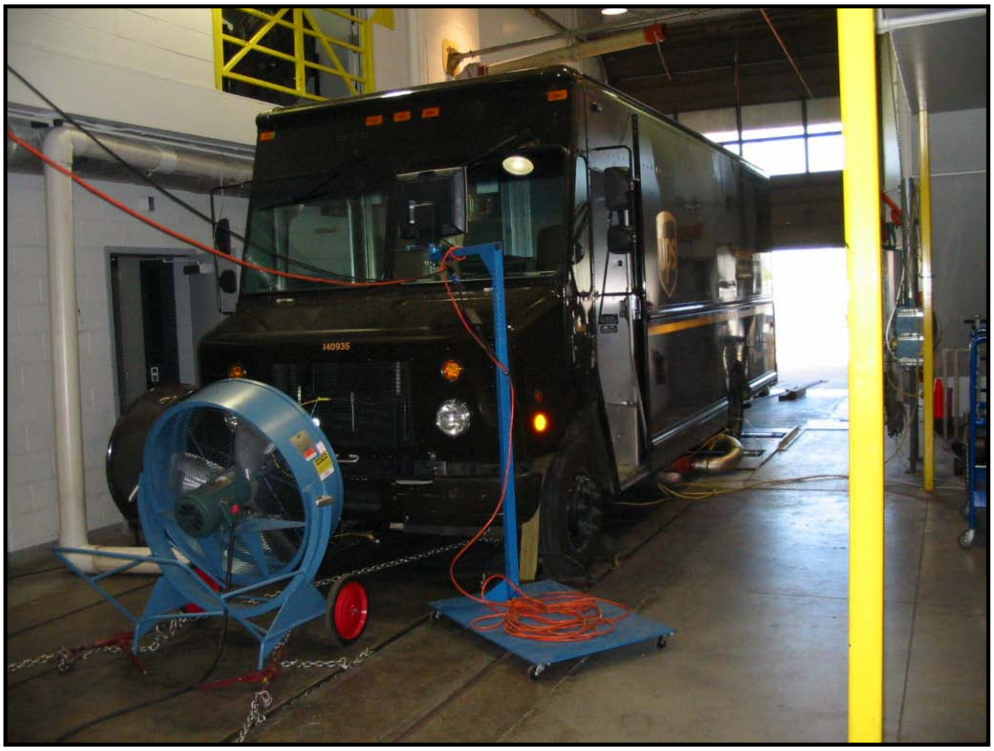

Figure 19. UPS P100 van on NREL's ReFUEL dynamometer

Vehicle Specifications

Table 10 shows test vehicle information. Due to timing and test vehicle availability, the tests were conducted on Workhorse P100 chassis with VT275 engine—not the same chassis or engine evaluated in this report at the Phoenix location but still the same hybrid system. While the chassis and engine are different, the Eaton hybrid system is the same as the one used on the P70H chassis. P100 vans are not necessarily assigned to the same type of routes as the P70 vans discussed in the rest of the report.

Table 10. Test Vehicle Information

	Engine	Transmission	GVWR	Test Weight	After-Treatment	Fuel	Chassis
Conventional P100	International VT275	Allison Automatic	23,500 lb	17,500 lb	N/A	Diesel	Workhorse P100
Hybrid P100	International VT275	Eaton Parallel Hybrid Autoshift	23,500 lb	17,500 lb	N/A	Diesel	Workhorse P100

Laboratory Test Results

All fuel economy and emissions results are averaged from three test runs of each cycle. Fuel economy results for the vans are shown in Table 11. The hybrid vans showed a 31%-37% improvement in fuel economy over the conventional vans on the tested duty cycles.

Table 11. Fuel Economy of Hybrid and Diesel Van on Various Cycles on Chassis Dynamometer

	CILCC	WVU City	CBD
Conventional P100 (mpg)	9.1	6.87	6.83
Hybrid P100 (mpg)	11.99	9.38	9.16
Fuel Economy (mpg) % increase w/hybrid	31%	37%	34%
P Value	0.0010	0.0014	0.0024

Emissions results for carbon dioxide (CO_2), oxides of nitrogen (NO_x), total hydrocarbons (THC), carbon monoxide (CO), and particulate matter (PM) are shown in Table 12. Results that are not statistically significant at the 95% confidence level appear in the gray areas. The hybrid vans showed some improvement in emissions, but the results varied significantly depending on the cycle being run. This variation is not unexpected, because the engines operate at different load points with and without the hybrid system. The engine in the hybrid vehicle has not been calibrated for hybrid operation. More consistent improvement in emissions may be possible with hybrid-specific engine calibrations. Heavy-duty engines are certified with an engine certification test but are not certified in chassis.

Table 12. Average Values for Emission Results of Hybrid and Diesel Vans on Specified Cycles

	CILCC				WVU City				CBD			
	Diesel	Hybrid	**Hybrid % diff**	**P Value**	Diesel	Hybrid	**Hybrid % diff**	**P Value**	Diesel	Hybrid	**Hybrid % diff**	**P Value**
CO_2 (gram/mile)	1026	773	**-25%**	0.0005	1333	933	**-30%**	0.0001	1396	1017	**-27%**	0.0021
NO_x (gram/mile)	7.52	9.69	**29%**	0.0014	9.22	10.42	**13%**	0.0137	*10.56*	*10.56*	*NS*	***0.98***
THC (gram/mile)	1.47	1.27	**-14%**	0.0413	*3.85*	*3.27*	*NS*	***0.48***	*1.34*	*1.17*	*NS*	***0.61***
CO (gram/mile)	7.59	5.38	**-29%**	0.0025	14.31	12.07	**-16%**	0.0097	*8.31*	*8.80*	*NS*	***0.13***
PM (gram/mile)	0.142	0.064	**-55%**	0.0148	*0.120*	*0.214*	*NS*	***0.15***	*0.116*	*0.114*	*NS*	***0.37***

*NS - % difference is not reported because the P Value indicates the difference is not statistically significant at the 95% confidence level.

Figure 20 shows emissions and fuel consumption results on the CILCC duty cycle. The hybrid unit produced 25% less CO_2, 14% fewer THC, 29% less CO, and 55% fewer PM emissions than the diesel unit did. The hybrid also showed a 29% increase in NO_x, as well as a 31% improvement in fuel economy over the cycle.

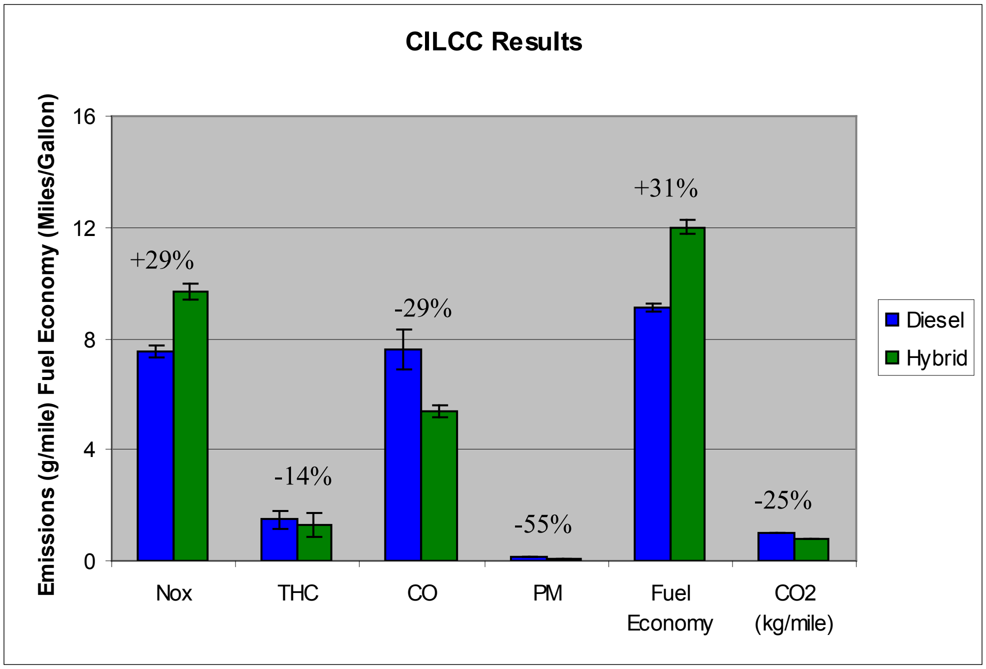

Figure 20. UPS P100 CILCC results

Figure 21 shows emissions and fuel consumption results on the WVU City cycle. The hybrid unit produced 30% less CO_2, 16% less CO, and 13% more NO_x. The hybrid had a 37% improvement in fuel economy over this cycle. There was no statistically significant difference in THC or PM emissions.

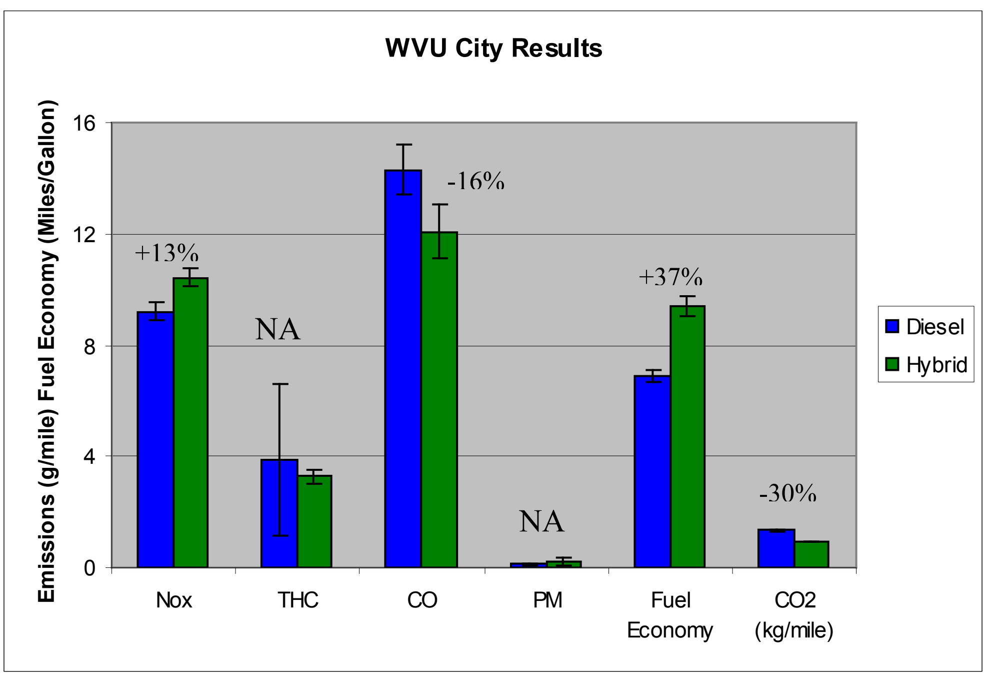

Figure 21. UPS P100 WVU City results

Figure 22 shows emissions and fuel consumption results on the CBD duty cycle. The hybrid unit produced 27% less CO_2 than the diesel did and showed a 34% improvement in fuel economy over this cycle. There was no statistically significant difference in THC, CO, PM or NO_x.

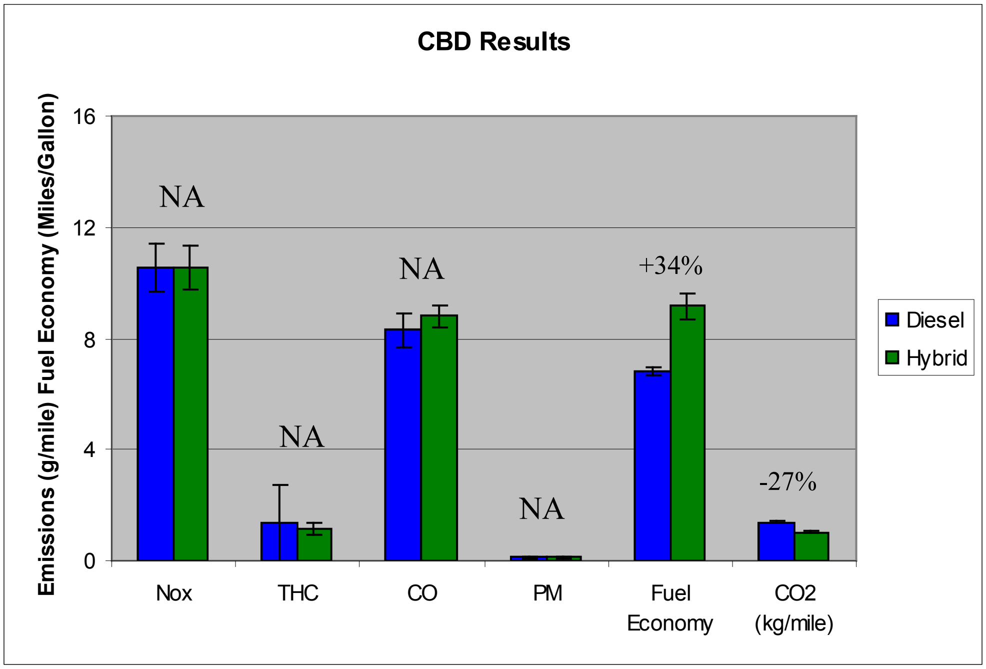

Figure 22. UPS P100 CBD results

Status of UPS Hybrid Fleet

UPS has been satisfied with the performance of the original 50 (prototype) hybrid electric vans over the first year of service. UPS has ordered an additional 200 hybrids to be deployed in 2009 with additional features and updates.

Conclusions

- Monthly (and cumulative) miles per van for the hybrids were 20% lower than they were for the diesels as a result of a more urban duty cycle and lower uptime related to troubleshooting and recalibrating prototype components.
- Miles per operational day were 15% lower for the hybrids than they were for the diesels. This indicates that the hybrids were assigned more urban routes with more stops per mile and more time spent at slow speeds.
- Fuel economy of the hybrid group was 28.9% greater than that of the diesel group. Had the diesel group been operating on the same duty cycle as the hybrids, the improvement might have been greater.
- There was no statistically significant difference between the diesel and hybrid groups for total maintenance cost per mile (P value = 0.82).
- There was no statistically significant difference between the diesel and hybrid groups for propulsion maintenance cost per mile (P value = 0.95).

- Total operating costs per mile for the hybrids were 15% less than those for the diesels (assuming $3.80/gal).
- Emissions testing generally showed a decrease in CO_2, THC, CO, and PM but an increase in NO_x.
- Laboratory fuel economy testing showed a 31% to 37% improvement for the hybrids over the diesels.

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Appendix: Laboratory Description and Test Methods

General Lab Description

The vehicles were tested at the ReFUEL Laboratory, which is 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. Regulated emissions measurements are performed using procedures consistent with SAE J2711. Instrumentation and sensors at the laboratory are maintained with National Institute of Standards and Technology (NIST)-traceable calibration. Test procedures, calibrations, and measurement accuracies are maintained to meet the requirements outlined in the current Code of Federal Regulations (CFR) title 40, section 86, subpart N. Data acquisition and combustion analysis equipment are used to measure vehicle performance and emissions. Other capabilities of the laboratory include 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, 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 installed, 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, illustrated in Figure A-1, 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 is used to measure the shaft torque from the rolls. The energy 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 test vehicle 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 may be used to cool 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. When the vehicle is jacked up off 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 are being simulated by the dynamometer control system accurately. Between test runs, a loaded coast-down procedure is performed to further ensure the stability of vehicle and dynamometer parasitic losses and accurate road load simulation during testing.

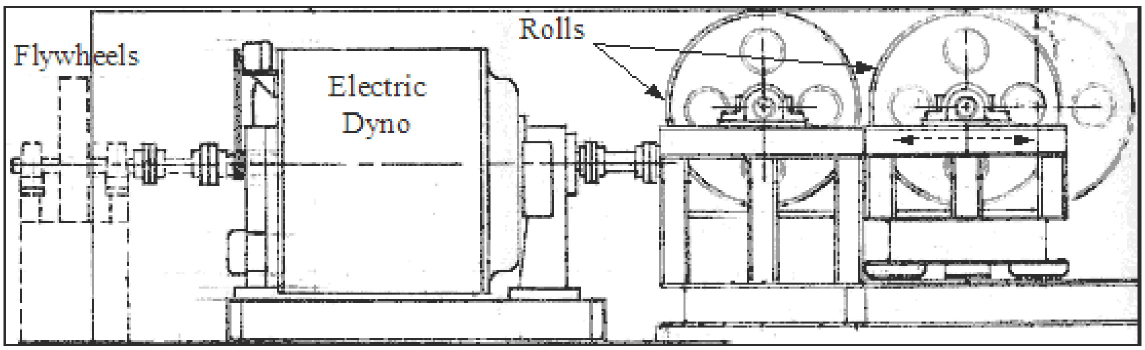

Figure A-1. Chassis dynamometer schematic

Fuel Storage and Blending

There are buildings designed specifically for safely storing and handling fuels at the ReFUEL facility. The fuel storage shed is 8 ft x 26 ft and holds up to 48 drums (55 gal. each). Features include heating/cooling, secondary containment to 25% of 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 has a nominal storage capacity of 24 drums. It has all of the features of the storage shed plus explosion-proof electrical outlets for powering accessories. The fuel blending can be performed on a gravimetric or volumetric basis, with capability for both large-scale (L/kg) and small-scale (cc/g) measurements.

A fuel line inside 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 and Conditioning

The fuel metering and conditioning system (Figure A-2) supports test work for both the engine and the chassis dynamometers. The meter measures volumetric flow to an accuracy of ±0.5% of the reading, with a manufacturer's stated reproducibility of 0.2%. An in-line sensor measures the density with an accuracy of ±0.001 g/cc, allowing an accurate mass measurement over the test cycle even if the density of the fuel blend is not known prior to testing.

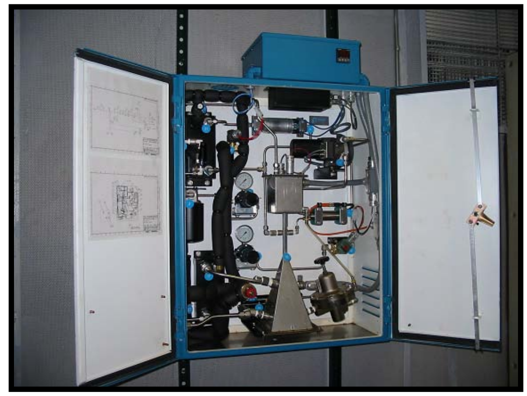

Figure A-2. Pierburg fuel metering system

Air Handling and Conditioning

Dilution air and the air supplied to the test 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. The system can also pressurize the incoming air to simulate sea level combustion. This gives the lab the ability to simulate any altitude between sea level and 5280 ft. This air is passed through a HEPA filter, in accordance with 2007 CFR specifications, to eliminate background particulate matter as a source of uncertainty in particulate measurements. The average inlet air temperature to the vehicle is maintained within a window of 75°F ± 4°F for all test runs, and average humidity is controlled to 75 grains/lb (absolute) ± 4 grains/lb.

Emissions Measurement

The ReFUEL Laboratory's emissions measurement system supports both the engine and chassis dynamometers. It is based on the full-scale exhaust dilution tunnel method with a constant volume sampling (CVS) system for mass flow measurement. The system is designed to comply with the requirements of 2007 CFR, 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 (Figure A-3) is employed to maximize the flexibility of the emissions measurement system. Featuring 500 cubic feet per minute (cfm), 1000 cfm, and 1500 cfm venturi nozzles and gas-tight valves, the system flow can be varied from 500 cfm to 3000 cfm flow rates in 500 cfm increments.

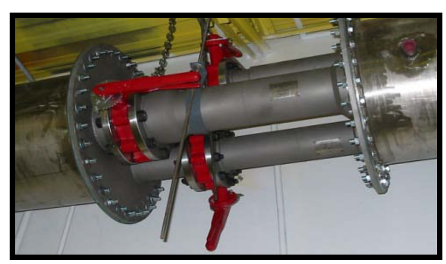

Figure A-3. Venturi nozzles

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.

The gaseous emissions bench is a Pierburg model AMA-2000 (Figure A-4, center). It features continuous analyzers for THC, NO_x, CO, CO_2, and O_2. The system also 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 heated sample trains for gaseous emissions measurement: one for HC and another for the other gaseous emissions. The NO_x and HC measurements are performed on a wet basis, while CO, CO_2, and O_2 are measured on a dry basis. Sample probes are located in the same plane in the dilution tunnel.

Figure A-4. Emissions bench

The particulate matter sample control bench, shown in Figure A-4, 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 (Figure A-5, center), 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 the desired temperature, flow, and concentration characteristics. A cyclone separator, as described in the CFR requirements, is employed to mitigate tunnel PM artifacts.

A dedicated clean room/environmental chamber (Figure A-5, left) is 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.

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

The microbalance (Figure A-5, right) for weighing PM filters has a readability of 0.1 µg (a CFR requirement) and features 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.

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This 12-month evaluation is part of a series of evaluations from the U.S. Department of Energy. Through the National Renewable Energy Laboratory (NREL), DOE has been tracking and evaluating new propulsion systems in transit buses and trucks. This report focuses on a parallel hybrid-electric diesel delivery van propulsion system operated by United Parcel Service. The propulsion system is an alternative to the standard diesel system and could enable reductions in emissions, primarily particulate matter and oxides of nitrogen, as well as reductions in petroleum use. Hybrid propulsion allows for increased fuel economy, which ultimately reduces petroleum use.

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