Coca-Cola Refreshments Class 8 Diesel Electric Hybrid Tractor Evaluation: 13-Month Final Report

K. Walkowicz, M. Lammert, and P. Curran

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Technical Report
NREL/TP-5400-53502
August 2012

Contract No. DE-AC36-08GO28308

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Prepared under Task No. FC08.3000

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Steven Saltzgiver
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List of Acronyms and Abbreviations

ABS	anti-lock brake system
AVTA	Advanced Vehicle Testing Activity
B20	a blend of biodiesel fuel with petroleum-based diesel where 20% of the volume is biodiesel
bhp	brake horsepower
CARB	California Air Resources Board
CCR	Coca-Cola Refreshments
cfm	cubic feet per minute
CILCC	Composite International Truck Local Cycle and Commuter
CO	carbon monoxide
CO_2	carbon dioxide
DOE	U.S. Department of Energy
DPF	diesel particulate filter
Eaton	Eaton Corporation
ECM	engine control module
EPA	U.S. Environmental Protection Agency
FT&E	Fuel Test and Evaluation
GPS	global positioning system
HEV	hybrid electric vehicle
HHDDT	Heavy Heavy-Duty Diesel Truck
KI	kinetic intensity
lbs	pounds
mi	miles
mph	miles per hour
NO_x	nitrogen oxides
NREL	National Renewable Energy Laboratory
PM	particulate matter
ReFUEL	Renewable Fuels and Lubricants
regen	regeneration
sec	second
THC	total hydrocarbons
WVU City	West Virginia University City

Executive Summary

This 13-month evaluation is part of a series of evaluations by 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 tractor trailer propulsion system currently being operated by Coca-Cola Refreshments (CCR). The hybrid propulsion system is an alternative to the standard diesel system and allows for increased fuel economy, which ultimately reduces petroleum use.

This study highlights the importance of route selection and vehicle placement to optimize hybrid advantage. Hybrid advantage is optimized in routes which include high start-stop density.

Evaluation Design

This 13-month evaluation used five Kenworth T370 hybrid tractors and five Freightliner M2106 standard diesel tractors that are located at a CCR facility in the Miami, Florida, area. A random dispatch system ensures the vehicles are used in a similar manner. Global positioning system logging, fueling, and maintenance records and laboratory dynamometer testing are used to evaluate the performance of these hybrid tractors. The primary objective of this study is to evaluate the fuel economy, emissions, and operational field performance of hybrid electric vehicles (HEVs) when compared to similar use conventional diesel vehicles within the CCR fleet. CCR manages a North American workforce of roughly 59,000 employees and maintains a fleet of 17,500 vehicles, including 630 heavy-duty HEVs, the largest such fleet in North America. Additionally this analysis will provide CCR with route indicators that can be used to better match HEVs and routes to maximize return on investment.

Evaluation Results

The results and related discussions included here focus only on the selected facility and the two study groups.

Tractor Use and Duty Cycle

Route and drive cycle analysis showed that both study groups drive similar duty cycles with similar kinetic intensity (KI) (0.95 vs. 0.69), average speed (20.6 vs. 24.3 mph), and stops per mile (1.9 vs. 1.5). Figure ES-1 compares the KI and average speed of conventional and hybrid tractors to the selected laboratory drive cycles. Because of this similar usage of vehicles, the groups were judged to be a good comparison. The hybrid group accumulated 27% fewer miles than the diesel group during the study. However, the hybrids were driving a comparable number of miles per operational day. The discrepancy primarily stems from non-hybrid-related downtime experienced by two hybrid trucks during the first six months of the study.

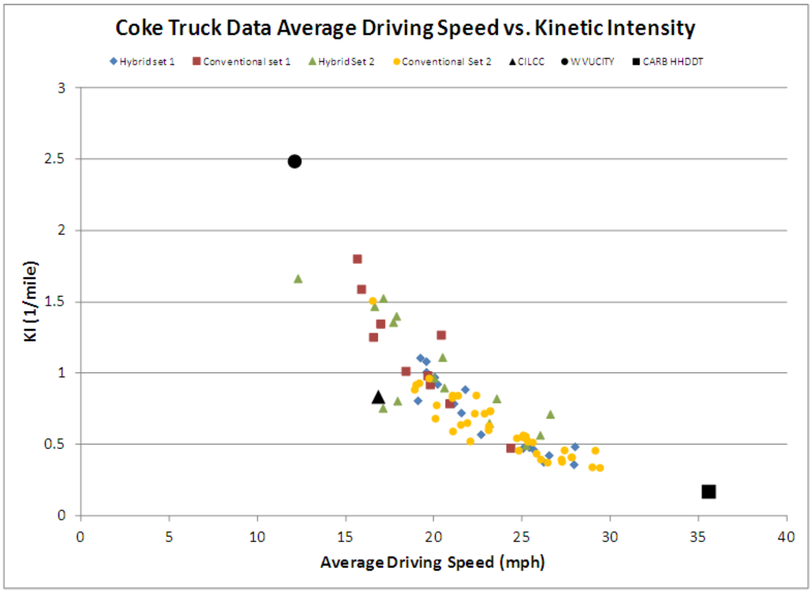

Figure ES-1. Average driving speed and kinetic intensity

Laboratory Fuel Economy

Laboratory dynamometer testing demonstrated 0%–30% hybrid fuel economy improvement, depending on duty cycle and up to a 32.1% improvement in ton-mi/gal.

In-Use Fuel Economy

The 13-month field study demonstrated the hybrid group had a 13.7% fuel economy improvement over the diesel group.

Laboratory fuel economy and field fuel economy studies showed similar trends along the range of KI, average speed and stops per mile. This means the vehicles could achieve higher in-field fuel economy results if they were used in a more urban location with drive cycle statistics closer to the WVU City cycle. Figure ES-2 shows a comparison of daily fuel economy results from hybrid and conventional tractors (with idle fueling removed) to laboratory fuel economy testing results.

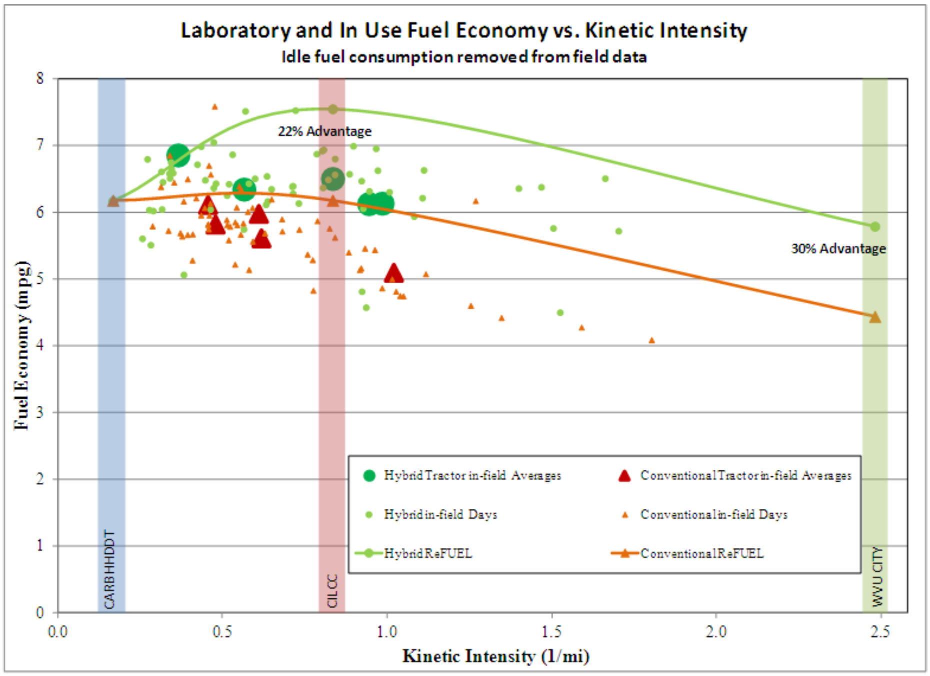

Figure ES-2. Laboratory and in-use fuel economy comparison

Fuel Costs

Hybrid fuel costs per mile were 12% less than for the diesels.

Operating Costs

Hybrid vehicle total cost of operation per mile was 24% less than the cost of operation for the diesel group ($0.74 vs. $0.97 per mile), which means the customer is realizing real savings with the hybrid.

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Overview

Advanced Vehicle Testing Activity

The role of the U.S. Department of Energy's (DOE's) Advanced Vehicle Testing Activity (AVTA) is to help bridge the gap between research and development and commercial availability for advanced vehicle technologies that reduce petroleum use and meet air-quality standards. AVTA supports the DOE's 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's) Fleet Test and Evaluation (FT&E) team conducts evaluations with support from AVTA.

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
FedEx	Los Angeles, CA	Ford E-450 strip chassis	Gasoline hybrid electric parcel delivery trucks, Azure Dynamics	Completed in January 2011
UPS	Phoenix, AZ	P70 Delivery Van	Parallel hybrid, Eaton system	Completed in December 2009
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 compressed natural gas 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 EP 50 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

Project Design and Data Collection

Introduction

This project represents a collaborative opportunity for NREL and Coca-Cola Refreshments (CCR) to evaluate the field performance, fuel economy, and emissions performance of two Class 8 propulsion technologies. The first technology is a conventional diesel engine with a manual 7-speed transmission. The second utilizes a smaller diesel engine and an Eaton UltraShift automated manual transmission integrated with the Eaton Parallel Hybrid Electric System (**Figure 1)**. Both of these Class 8 technologies are currently being utilized by CCR in a similar manner in commercial service. Chosen for its pairing of hybrid and conventional tractors in one location and unbiased, random delivery route assignments, the Miami, Florida, CCR fleet was the source of vehicles and data for this evaluation. The study vehicles consisted of five Kenworth T370 single-axle tractors equipped with a PACCAR PX-6 6.7-liter diesel engine, Eaton Fuller UltraShift transmission and the Eaton Parallel Hybrid Electric System (shown in **Figure 2**) with 5.38:1 rear axle gearing, and five Freightliner M2 106 single-axle tractors equipped with a Cummins ISC 8.3-liter diesel engine, an Eaton Fuller 7-speed manual transmission and 3.58:1 rear axle gearing. Both the Kenworths and the Freightliners were certified to the 2007 U.S. Environmental Protection Agency (EPA) certification levels; however the Kenworth was certified at a higher NOx level. Additional tractor details are given in Table 2. While the two tractors serve the same role within the CCR fleet and are used interchangeably in Miami, some of the specification choices could lead to impacts in performance beyond the direct hybrid system effect that is the focus of this evaluation. The engine downsizing observed is a vehicle design available due to the addition of the electrical motor to supplement torque. In Miami, CCR specified the tractors with the smaller engine, but for other locations they ordered the same engine as part of their fleet-wide hybrid experimentation process. The hybrids in Miami also received 5.38:1 axle gearing as part of that experimentation process. The lower axle gearing could help with around-town responsiveness, but could also adversely affect the fuel economy of the hybrids. Finally, while the hybrid system uses an automated manual transmission, the conventional vehicles use a manual transmission that then introduces driver shifting habit variation into the performance results. All of these factors are choices all fleets make when specifying their vehicle purchases to suit their operational needs. This evaluation does not try to assign weighted effects to these specification choices, but rather evaluates the vehicles as specified by CCR and used in a similar manner by CCR at the Miami location. It is beyond the scope of this evaluation to compare all the tractor configurations in use by CCR.

Figure 1. CCR hybrid tractor and trailer

Table 2. Coca Cola Refreshments Delivery Truck Details

Vehicle Information	HEV Tractor	Conventional Tractor
Asset Numbers (mileage at start of test)	643879 (4,943 mi) 643880 (6,233 mi) 643881 (7,333 mi) 643882 (5,034 mi) 643883 (11,487 mi)	644024 (19,325 mi) 644025 (22,931 mi) 644079 (20,481 mi) 644081 (24,400 mi) 644082 (17,056 mi)
Chassis Manufacturer/Model	Kenworth T370	Freightliner M2106
Chassis Model Year	2010	2009
Engine Manufacturer/Model	PACCAR PX-6 280	Cummins ISC-285
Engine Displacement (L)	6.7	8.3
EPA Emissions Certification (2007)		
NO_x (Family Emissions Limit)	1.95 g/bhp-hr	1.25 g/bhp-hr
CO (Family Emissions Limit)	19.4 g/bhp-hr	19.4 g/bhp-hr
CARB Emissions Certification	2008 (Clean Idle)	2008 (Clean Idle)
Engine Ratings		
Max. Horsepower	280 HP @ 2,300 RPM	285 HP @ 2,000 RPM
Max. Torque	660 lb-ft @ 1,600 RPM	800 lb-ft @ 1,300 RPM
Fuel Capacity	56 gallons	80 gallons
Transmission Manufacturer/Model	Eaton Fuller UltraShift Automated Manual	Eaton Fuller T-14607 Manual 7-speed
Rear Axle Gear Ratio	5.38:1	3.58:1

Figure 2 provides a schematic of the system and Table 3 presents additional details on Eaton Corporation's (Eaton's) parallel hybrid system.

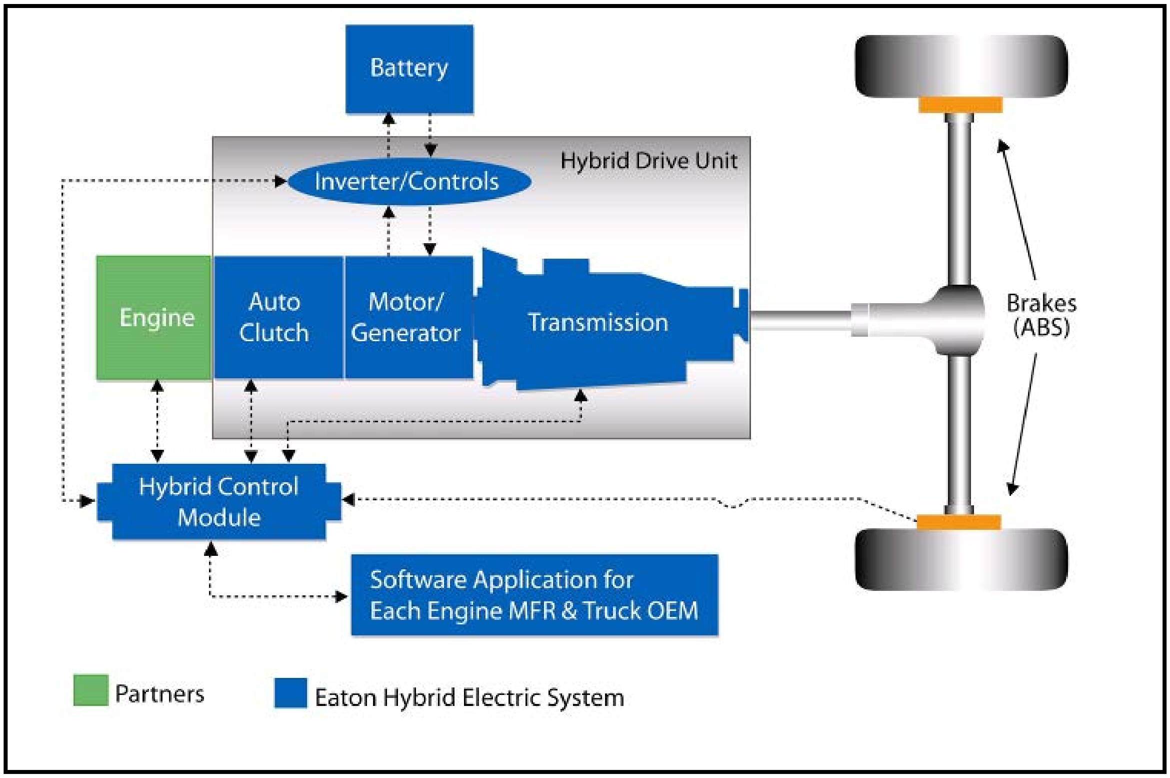


Figure 2. Eaton hybrid system schematic

Table 3. Hybrid Propulsion-Related Systems

Category	**Hybrid System 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 3 shows the primary hybrid components in the Eaton system.

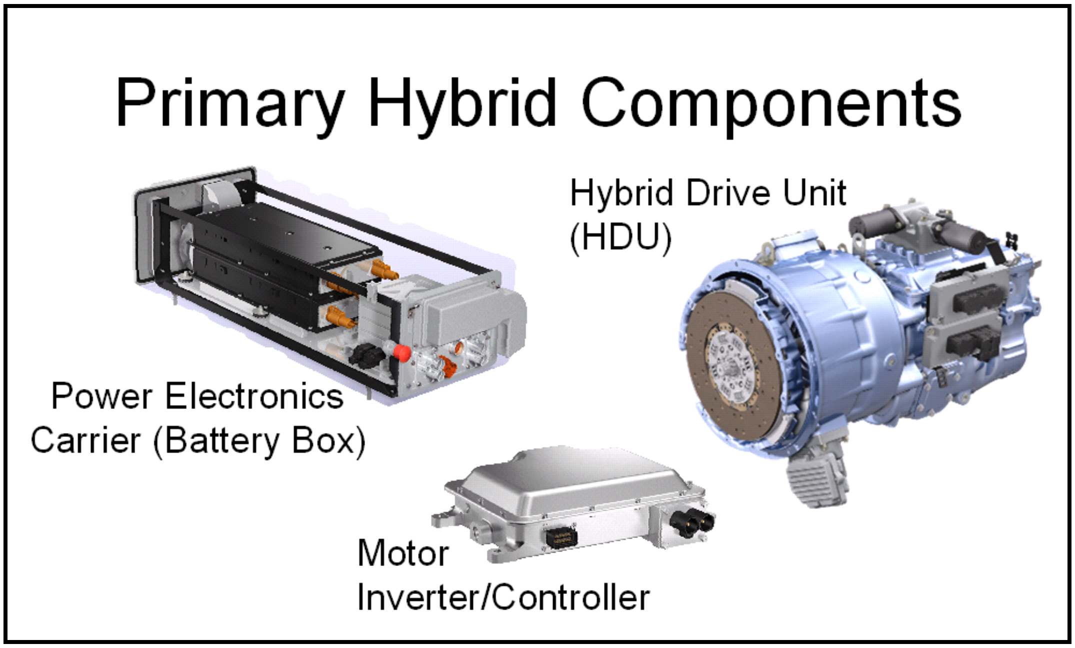


Figure 3. Eaton hybrid system components

Data Collection and Testing Overview

For an initial assessment of typical usage of the vehicles in the CCR fleet, NREL installed data loggers on all ten study vehicles for a period of two weeks to collect time, position, and speed data. The data were then used to characterize daily drive cycles and compare the two study groups (five hybrid tractors versus five conventional tractors) and ensure the two types of vehicles were being used in a consistent manner. The daily drive cycle characteristics of each group were then compared to a library of heavy-duty chassis dynamometer duty cycles to determine three test duty cycles that best represent this fleet.

Using one hybrid tractor and one conventional tractor that were equipped the same as the in-use test vehicles in Miami, NREL recorded the fuel economy and regulated emissions while driving the representative duty cycles on a heavy-duty chassis dynamometer at NREL's Renewable Fuels and Lubricants (ReFUEL) Research Laboratory in Denver, Colorado. This testing provided laboratory results for a side-by-side comparison of the two propulsion technologies under the same laboratory conditions.

In addition to the initial data logging and chassis dynamometer testing, NREL performed a 13-month in-use evaluation of the two study groups at the fleet location to determine long-term fuel usage and operational cost data. This evaluation relied on data provided to NREL by the fleet operators at CCR's Miami fleet. The data collected included daily mileage provided by CCR driver logs and maintenance/service records provided by CCR's operations manager. In addition to these data, CCR also regularly downloaded engine control module (ECM) data from each tractor. The ECM data provided NREL with information such as engine run time, idle time, fuel used, miles driven and the number of aftertreatment regeneration events.

Initial Data Logging and Duty Cycle Selection

NREL implemented two data logging periods for this study, one summer and one winter. Two weeks of on-vehicle data logging began on May 13, 2010, using NREL-supplied data loggers.

Global positioning system (GPS) data were collected on the ten study vehicles in CCR's Miami fleet. All ten loggers recorded speed, time, and position data, and three, more advanced loggers recorded additional vehicle information such as fuel rate, engine speed, and accelerator pedal position. Two additional weeks of data logging began on February 24, 2011, using ten of the more advanced data loggers recording both GPS and vehicle parameters. The GPS data were used only to visualize typical routes. **Figure 4** illustrates the individual routes of two hybrid tractors and two conventional tractors on one day during the initial two-week study. The same route data was also broken down and used to define events and features of each specific route recorded.

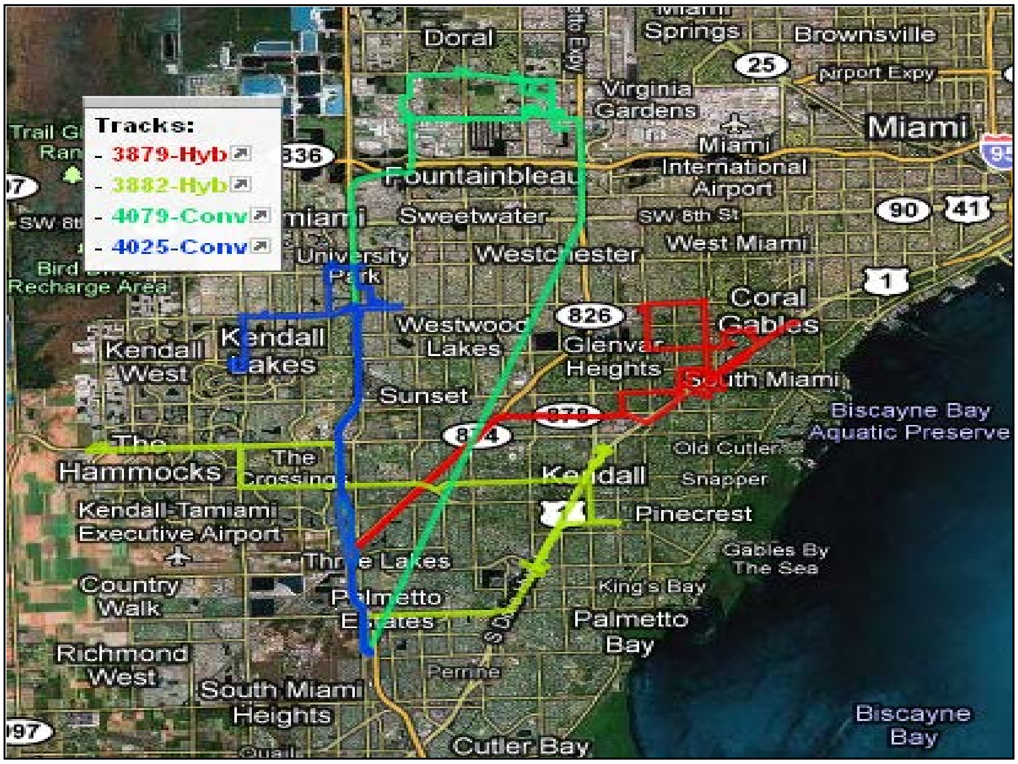


Figure 4. CCR route image

Using a MATLAB-based tool developed at NREL called the Drive-cycle Rapid Investigation and Visualization and Evaluation tool (DRIVE), the data collected in Miami were processed to provide over 150 statistical metrics of the Miami routes. Several of these metrics are listed in **Table 4** as the two-week average for each vehicle. Both study groups exhibit a similar range of vehicle averages which makes the selected vehicles good for an in-use comparison. While the group averages may be different the ranges do not show statistically significant differences. Once the data were processed using DRIVE, a route selection methodology used a number of these route characteristics to compare those routes to standard dynamometer duty cycles for selection. Using the cycle selection process, these characteristics helped select three representative duty cycles for testing on the chassis dynamometer: the Heavy Heavy-Duty Diesel Truck (HHDDT) cycle, the Composite International Truck Local Cycle and Commuter (CILCC) cycle, and the West Virginia University City (WVU City) cycle.

Table 4. Route Characteristics

Vehicle Number	Distance Traveled (miles)	Average Driving Speed (mph)	Maximum Speed (mph)	Number of Stops	Average Stop Duration (sec)	Number of Stops per mile	Number of Stops > 60 seconds	Kinetic Intensity (1/mi)*
643879 Avg	30.65	18.33	55.87	78.33	179.90	2.66	22.83	0.99
643880 Avg	58.64	25.68	67.19	49.40	130.63	0.83	17.60	0.53
643881 Avg	42.63	19.71	64.31	59.40	144.86	1.40	19.80	1.00
643882 Avg	31.46	18.61	59.37	84.00	201.90	2.72	31.67	1.29
643883 Avg	N/A	N/A	N/A	N/A	N/A	N/A	N/A	N/A
Hybrid Avg	**40.84**	**20.58**	**61.68**	**67.78**	**164.33**	**1.91**	**22.98**	**0.95**
644024 Avg	37.05	24.63	64.60	61.50	521.71	1.71	23.00	0.57
644025 Avg	56.10	24.56	66.78	80.00	209.76	1.56	28.09	0.57
644079 Avg	42.52	27.30	71.89	64.14	213.39	1.49	22.00	0.53
644081 Avg	53.61	26.68	69.41	73.43	201.50	1.38	22.14	0.48
644082 Avg	36.67	18.18	59.77	51.60	211.37	1.46	21.70	1.29
Conventional Avg	**45.19**	**24.27**	**66.49**	**66.13**	**271.55**	**1.52**	**23.39**	**0.69**

* "Duty Cycle Characterization and Evaluation Towards Heavy Hybrid Vehicle Applications," SAE 2007-01-0302; Michael P. O'Keefe, Andrew Simpson, Kenneth J. Kelly - National Renewable Energy Laboratory; Daniel S. Pedersen - Oshkosh Truck Corporation

Figures 5 and 6 illustrate how the HHDDT, CILCC and WVU City cycles compare to the observed daily in-use fleet data. The selected cycles bracket the range of collected fleet data well on these and other metrics and bracket the in-field data on both the X and Y axis. Although the curve created by these three cycles does not perfectly match the field data in both figures, it is the best fit available using standard duty cycles and considering all of the prioritized metrics, only some of which are shown here. The WVU City cycle is more aggressive than most of the observed data from Miami in regard to low average speed, high stops per mile, and high KI, but this cycle represents a better hybrid scenario that may be available in other CCR fleet locations. Most of the observed data points fall around the CILCC cycle or between it and the HHDDT cycle.

Also, it is important to note that the hybrid and conventional vehicle data overlap significantly in the cloud of observed fleet data. The two selected groups were determined to be well matched for a fleet comparison because the comparison shows that they are being used in the same manner. This is due in part to the random dispatch system used by CCR.

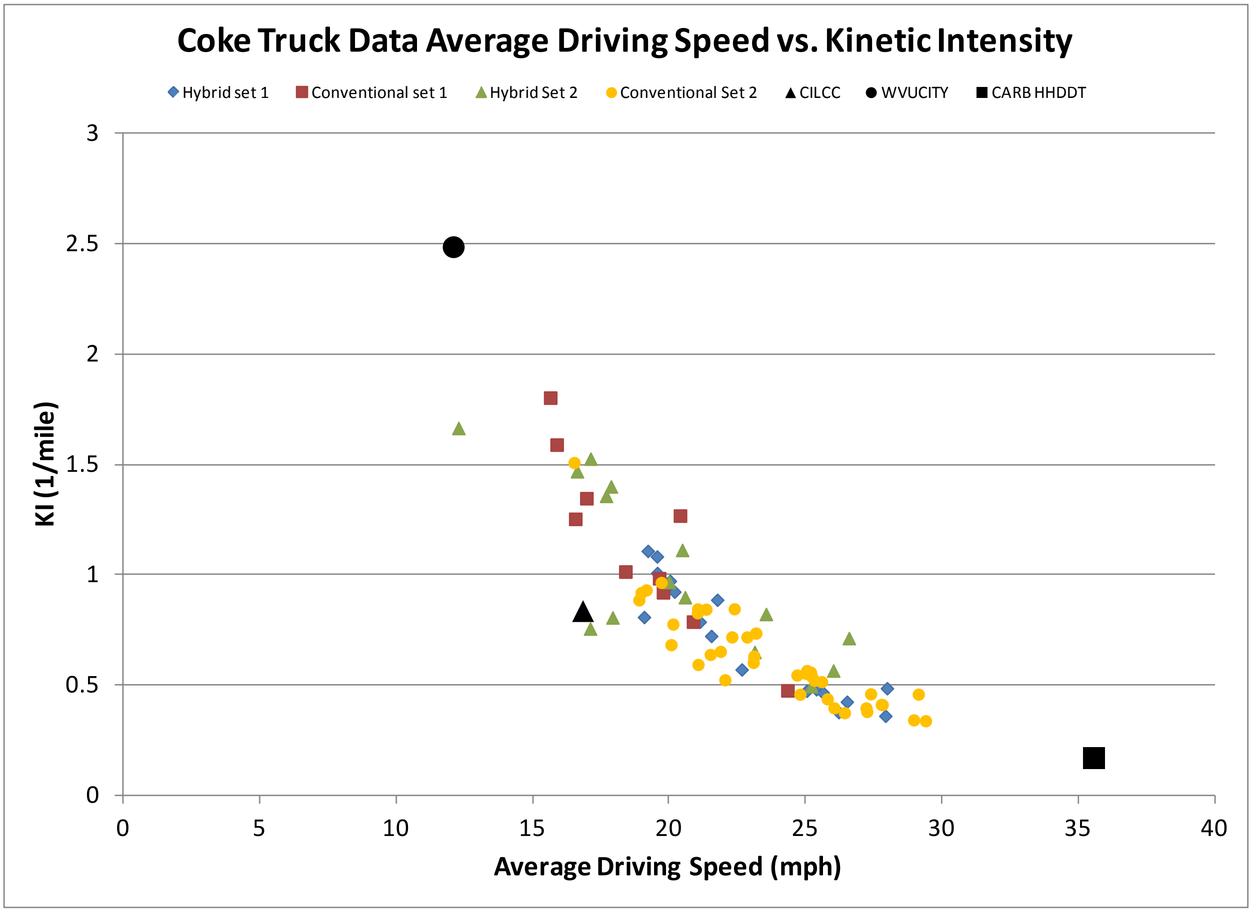


Figure 5. Average driving speed and kinetic intensity comparison

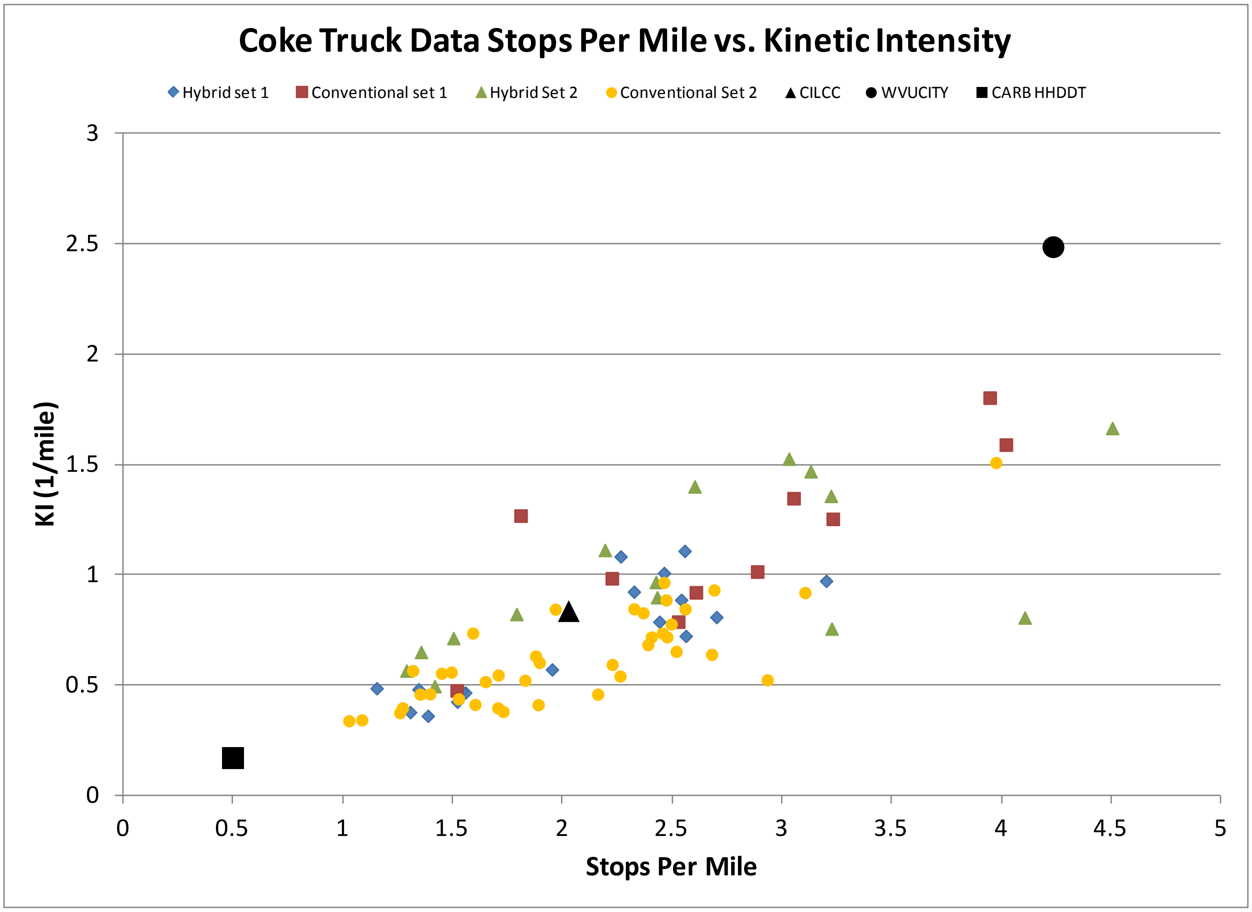


Figure 6. Stops per mile and kinetic intensity comparison

Selected Duty Cycle Description

The WVU City duty cycle (**Figure 7**) represents "city" or urban driving commonly performed by medium- and heavy-duty commercial trucks. The WVU City is 1,400 seconds in length with an average driving speed of approximately 12.1 mph and travels a distance of 3.3 miles with a kinetic intensity (KI) of 2.5. This cycle was determined to represent a more "urban" route than was observed during the drive cycle assessment of the CCR fleet, but which would be possible in other cities; the most "urban" driving of the data collected shows most of the data below a KI of 1.6 and above 15 mph average speed so this cycle brackets the urban end of the spectrum.

The CILCC duty cycle (**Figure 8**) is a composite duty cycle developed to represent typical delivery truck driving characteristics. It consists of one segment lasting approximately 745 seconds and an average driving speed of approximately 15 mph repeated a total of four times with a highway segment lasting 200 seconds and averaging approximately 44 mph in the middle of the four. The total cycle lasts 3,192 seconds, reaches a top speed of 55 mph, has an average speed of approximately 17 mph with a KI of 0.83 and travels a distance of 12.3 miles. This cycle was selected to represent the most "average" CCR operation; much of the data collected is between 15 and 25 mph average speed with a KI of 0.5 to 1.0.

The California Air Resources Board (CARB) HHDDT duty cycle (**Figure 9**) is a composite duty cycle developed to represent medium- and heavy-duty commercial vehicles. It consists of four segments: an initial idle segment (600 sec, average driving speed 0 mph), a creep segment (250 sec, average driving speed approximately 3 mph), a transient segment (650 sec, average driving speed approximately 18 mph), and finally, a highway segment (2,100 sec, average driving speed approximately 43 mph). The total cycle, which lasts 3,600 seconds, reaches a top speed of 59.3 mph and travels a distance of 26 miles with an average speed of 35.6mph and a KI of 0.17. This cycle was selected to represent the most "rural" or "highway" type operation observed in the CCR fleet; the most rural type of driving of the data collected shows most of the data are above a KI of 0.4 and below 30 mph average speed. These statistics along with others are presented in **Table 5** for all three selected duty cycles.

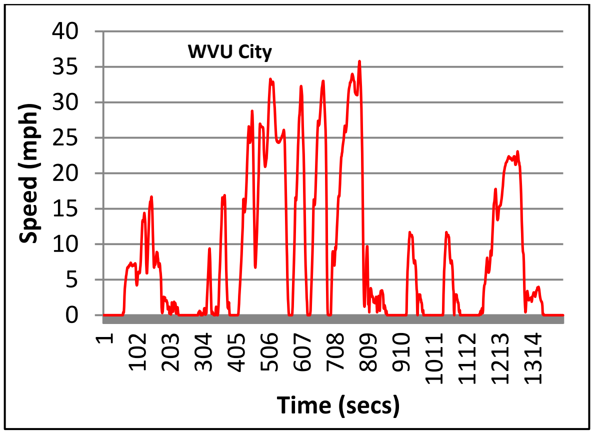


Figure 7. WVU City

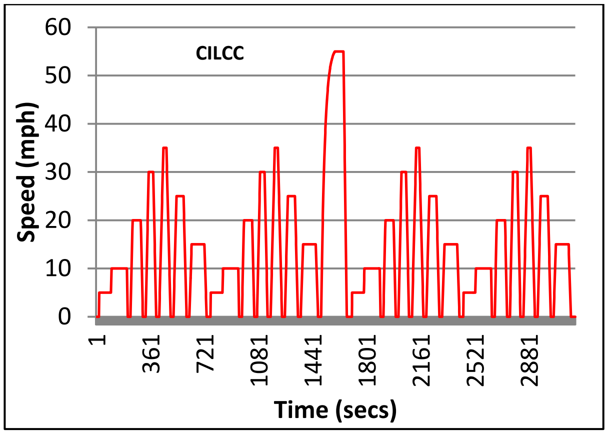


Figure 8. CILCC

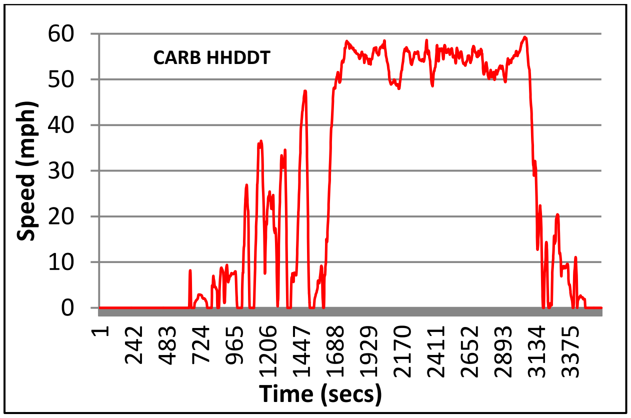


Figure 9. CARB HHDDT

Table 5. Duty Cycle Details and In-field Tractor Average Comparison

Vehicle Number	Distance Traveled (miles)	Average Driving Speed (mph)	Maximum Speed (mph)	Average Stop Duration (sec)	Number of Stops per mile	Kinetic Intensity (1/mi)
WVU City	3.3	12.1	35.8	30.4	4.24	2.5
CILCC	12.3	16.9	55	22.4	2.03	0.83
CARB HHDDT	26.0	35.6	59.3	74.54	0.50	0.17
Hybrid Tractor in-field Data Range		18.3 – 25.7			0.8 – 2.7	0.5 – 1.3
Conventional Tractor in-field Data Range		18.2 – 27.3			1.6 – 1.7	0.5 – 1.3

Vehicles Tested in the Laboratory

One vehicle similar to each of the vehicle types in the study groups was tested according to these duty cycles at the ReFUEL Laboratory. Rather than transport both vehicles from Miami, CCR searched its fleet inventory for similar configuration vehicles closer to Denver. A Kenworth hybrid tractor was located in the Denver CCR fleet, and the conventional diesel was located in Omaha, Nebraska. These vehicles were exact matches to the tractors being used in the study fleet.

To test these vehicles on the ReFUEL Laboratory's chassis dynamometer rolls (rear wheels spinning and the front wheels stationary), it is necessary for performance reasons that the ECM ignore the antilock brake system (ABS) fault that results in a speed difference between the front and rear wheels. For the conventional diesel tractor, this was simply accomplished by removing the ABS fuse on the vehicle. However, on the hybrid, when the ABS fuse is removed, an ABS fault is observed, which results in deactivation of the hybrid system. The only solution to enable the testing of this vehicle was for Eaton to provide a Hybrid Control Module programmed to ignore the ABS fault and continue to operate as usual. This controller was identical to the standard controller with the only modification being that it ignored the ABS fault and allowed the vehicle to be tested on a chassis dynamometer.

Testing at ReFUEL Laboratory

Along with the single-axle tractors, CCR's Miami fleet utilizes 35-foot trailers for delivery of the Coca-Cola products. Because the trailer starts full and returns empty, the chassis dynamometer testing used one half the initial product mass plus the mass of the tractor and empty trailer as the test mass. The test weight for the hybrid Kenworth was 34,300 lbs while test weight for the conventional Freightliner was 33,840 lbs. The difference is test weight is due to the difference in tractors and the added weight of the hybrid system.

Testing began on August 13, 2010, with the Kenworth hybrid tested first on the dynamometer. The first cycle to be tested was the WVU City cycle, followed by the CILCC cycle, and then the CARB HHDDT cycle. Each day started by warming up the dynamometer and the tractor, followed by an initial conditioning run, which provided a consistent starting point, and then at least three "hot" cycles. The average, standard deviation, and 95% confidence intervals were calculated from these "hot" cycles. This pattern was followed again for the conventional diesel tractor. Testing was completed on both tractors for all three cycles on August 24, 2010. A complete report on the chassis dynamometer testing is included in the appendix.

Fuel Economy Results

The hybrid electric vehicle (HEV) demonstrated improved fuel economy on the two duty cycles with higher KI and lower average driving speed, achieving a 30.3% increase in fuel economy between the two tractors on the WVU City cycle, as seen in **Table 6** and 22% increase in fuel economy on the CILCC cycle. However, on the CARB HHDDT duty cycle, which has a higher average driving speed and a lower KI, the two tractors are statistically indistinguishable, as shown graphically in **Figure 10**. **Table 6** also shows the relationship between KI and hybrid advantage. As such, the hybrid advantage, indicated here as percent increase in fuel economy, increased with an increase in the KI of the duty cycle.

Table 6. CCR Fuel Economy Results

Drive Cycle	HEV Fuel Economy (mpg)	Conventional Diesel Fuel Economy (mpg)	HEV Percent Increase (%)	P Value
WVU City	5.79	4.44	30.3%	0.0003
CILCC	7.55	6.18	22.2%	0.0001
CARB HHDDT	6.17	6.18	~~-0.13%*~~	0.69

* Indicates at the 95% confidence interval there is no statistical difference between the two data sets.

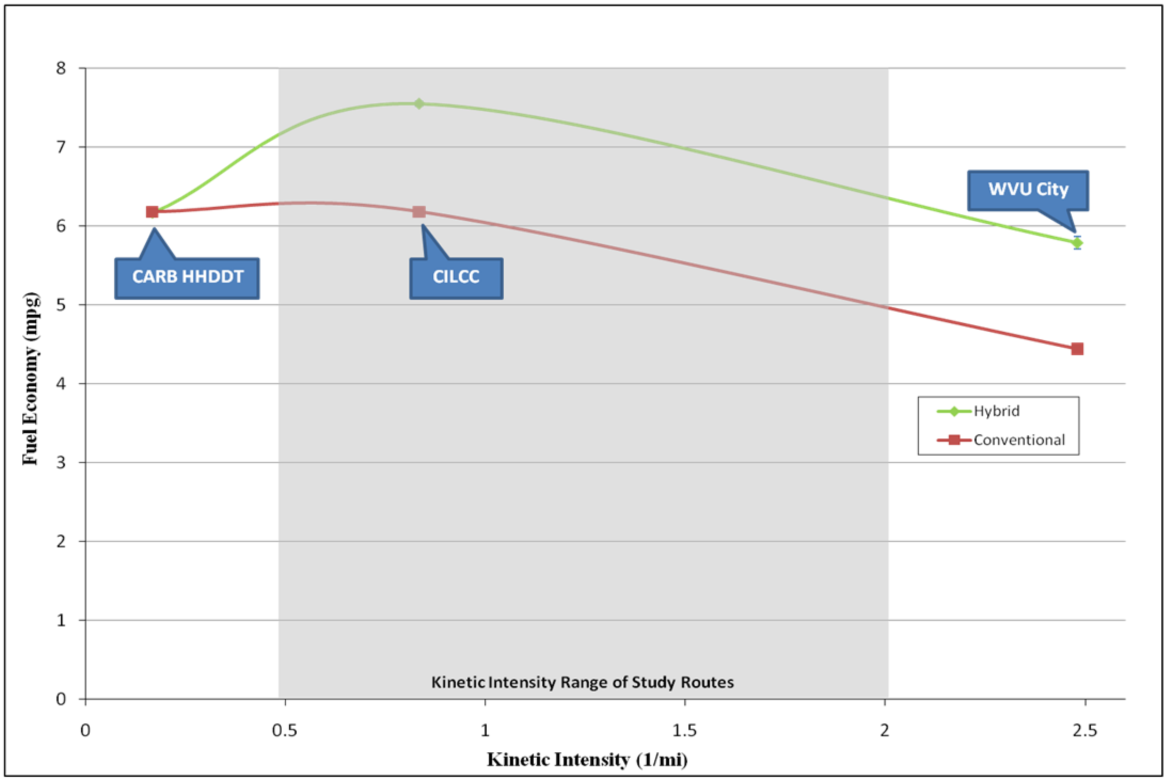


Figure 10. Fuel economy and fleet kinetic intensity

The hybrid tractor demonstrated improved ton-mi/gal fuel economy (combined vehicle test weight, not solely cargo) on the two duty cycles with higher KI and lower average driving speed, achieving a 32.1% increase in ton fuel economy between the two tractors on the WVU City cycle, as shown in **Table 7**. However, on the CARB HHDDT duty cycle, which has a higher average driving speed and a lower KI, the two tractors are statistically indistinguishable.

Table 7. CCR ton-mi/gal Fuel Economy Results

Drive Cycle	HEV Fuel Economy (ton-mi/gal)	Conventional Diesel Fuel Economy (ton-mi/gal)	HEV Percent Increase (%)	P Value
WVU City	99.24	75.13	32.1%	0.0003
CILCC	129.54	104.54	23.9%	0.0001
CARB HHDDT	105.78	104.49	~~1.23%~~	0.31

* Indicates at the 95% **confidence interval there is no** statistical difference between the two data sets

Emissions Results

The emissions results were as expected for carbon monoxide (CO), total hydrocarbons (THC) and carbon dioxide (CO_2). The HEV produced fewer of these emissions on each of the three selected duty cycles, as detailed in **Tables 8 and 9**. However, nitrogen oxides (NO_x) increased for the HEV over the conventional tractor for each of the tested duty cycles. For the HHDDT cycle, the HEV produced more than double the NO_x emissions when compared to the conventional tractor. This is shown in **Table 9** as a percent improvement in emissions for the hybrid over the conventional tractor (a negative number indicates a decrease in emissions and vice versa). While both engines tested met the 2007 EPA emissions-certification requirements, they were certified to different NO_x emissions levels, something which is commonly done with heavy-duty engines. The conventional tractor with the 8.3L Cummins ISC engine was certified at the 1.25 g/bhp-hr certification level, and the HEV with the 6.7L PACCAR PX-6 engine was certified at the 1.95 g/bhp-hr level, as noted in **Table 1** and illustrated in **Figure 11**. The higher NO_x emissions certification is thought to be a major contributor to the increased NO_x observed on all three duty cycles tested.

Table 8. CCR Emissions Summary

Drive Cycle	Vehicle	NO_x (g/mile)	CO (g/mile)	THC (g/mile)	CO_2 (kg/mile)
WVU City	HEV	9.94	1.64	-0.09	1.77
	Conventional	7.70	1.70	0.07	2.31
CILCC	HEV	7.53	0.35	-0.03	1.36
	Conventional	7.16	0.93	0.06	1.66
CARB HHDDT	HEV	5.75	0.49	-0.01	1.66
	Conventional	2.86	0.71	0.03	1.66

Table 9. CCR Hybrid Emissions

HEV % Reduction								
Drive Cycle	**NO_x**	**P Value**	**CO**	**P Value**	**THC**	**P Value**	**CO_2**	**P Value**
WVU City	29.1%	1.7E-5	-3.6%*	0.75	-222.7%*	0.28	-23.3%	8.5E-6
CILCC	5.1%	8.8E-3	-62.3%	1.1E-6	-147.5%	1.4E-3	-18.1%	1.9E-9
CARB HHDDT	101.3%	8.5E-9	-31.3%*	7.7E-2	-141.9%	2.1E-4	0.2%*	0.85

* Indicates that at the 95% confidence interval there is no statistical difference between the two data sets

The percent emissions reduction for CO and THC on the WVU City cycle and CO and CO_2 on the CARB HHDDT cycle have been marked as not statistically significant at the 95% confidence interval. The data sets associated with these results are similar enough that they are not statistically distinguishable; therefore, the differences are not considered noteworthy.

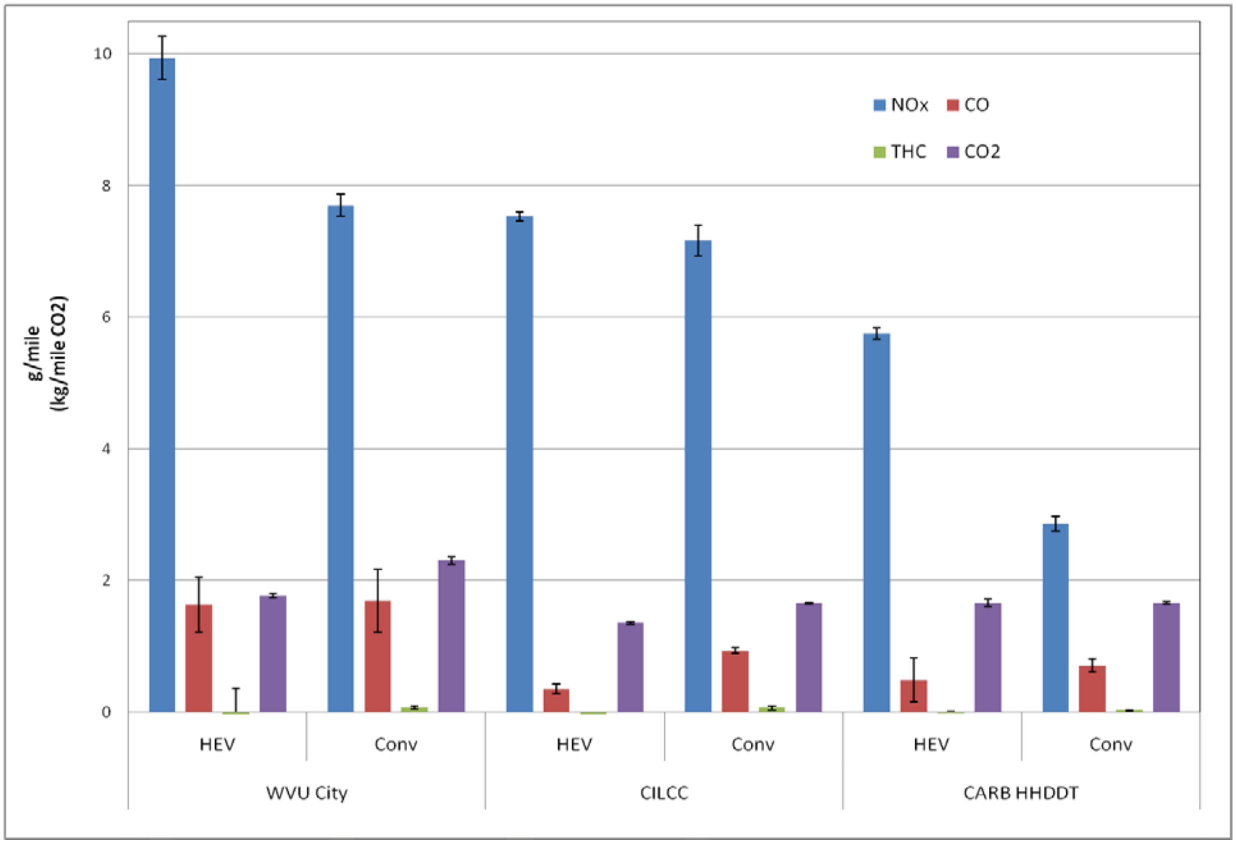


Figure 11. Regulated emissions arranged by duty cycle (Error bars represent 95% confidence interval)

Acceleration Test Results

In addition to the three duty cycles chosen to compare these two tractors, a series of 0 to 60 mph maximum acceleration tests was also performed on both vehicles equipped and loaded as noted for the dynamometer testing. **Figure 12** shows that the conventional diesel tractor average time over three runs was 77 seconds, while the hybrid tractor average was 104 seconds. This 35%

increase in time to achieve 60 mph is attributed to optimizing the hybrid for lower speed driving and the hybrid being equipped with a smaller (lower maximum torque) engine.

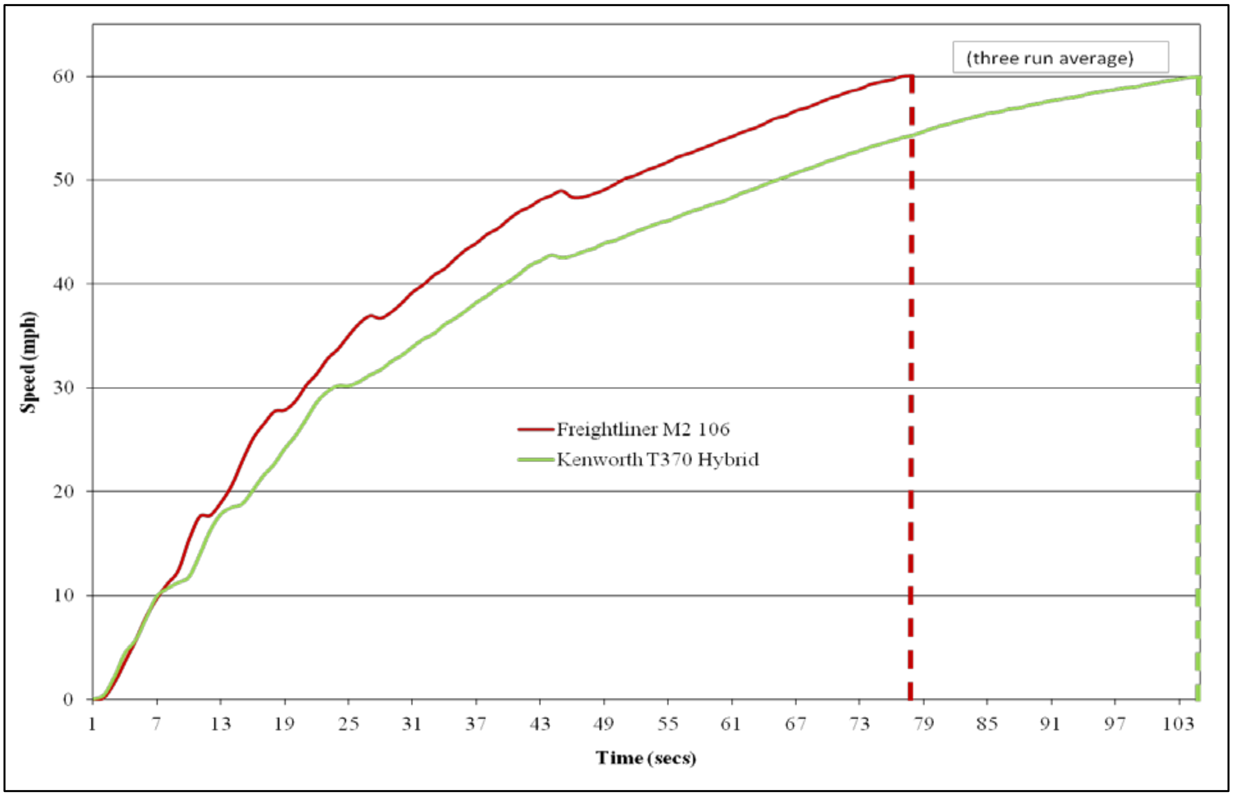


Figure 12. Acceleration test, 0 to 60 mph

Fleet Study

During the 13-month fleet study, several data sources were utilized to gather information such as fueling record, mileage data, and maintenance/service reports. Due to an accident and an engine warranty repair, two vehicles, Hybrid 1 and Hybrid 2, had significant out-of-service time during the initial six months of the study, and as a result were not included in the fleet study data during that time.

ECM-recorded fuel consumption and mileage are used in this report to compare the in-use fuel consumption. This has the advantage of being able to assign fuel consumption to different activities [e.g., driving, idle, diesel particulate filter (DPF) regeneration]. These results are discussed later in the report.

Mileage Accumulation

The hybrid group accumulated 27% fewer miles than the diesel group during the study. However, the hybrids were driving a comparable number of miles per day. The discrepancy primarily stems from down-time experienced by two hybrid trucks during the first six months of the study. **Figure 13** shows group average daily miles, average days per month, and cumulative group miles. Note that while the cumulative miles were on different trajectories during the first six months due to downtime of two of the HEVs, they are parallel during the second half of the study when all vehicles were in operation.

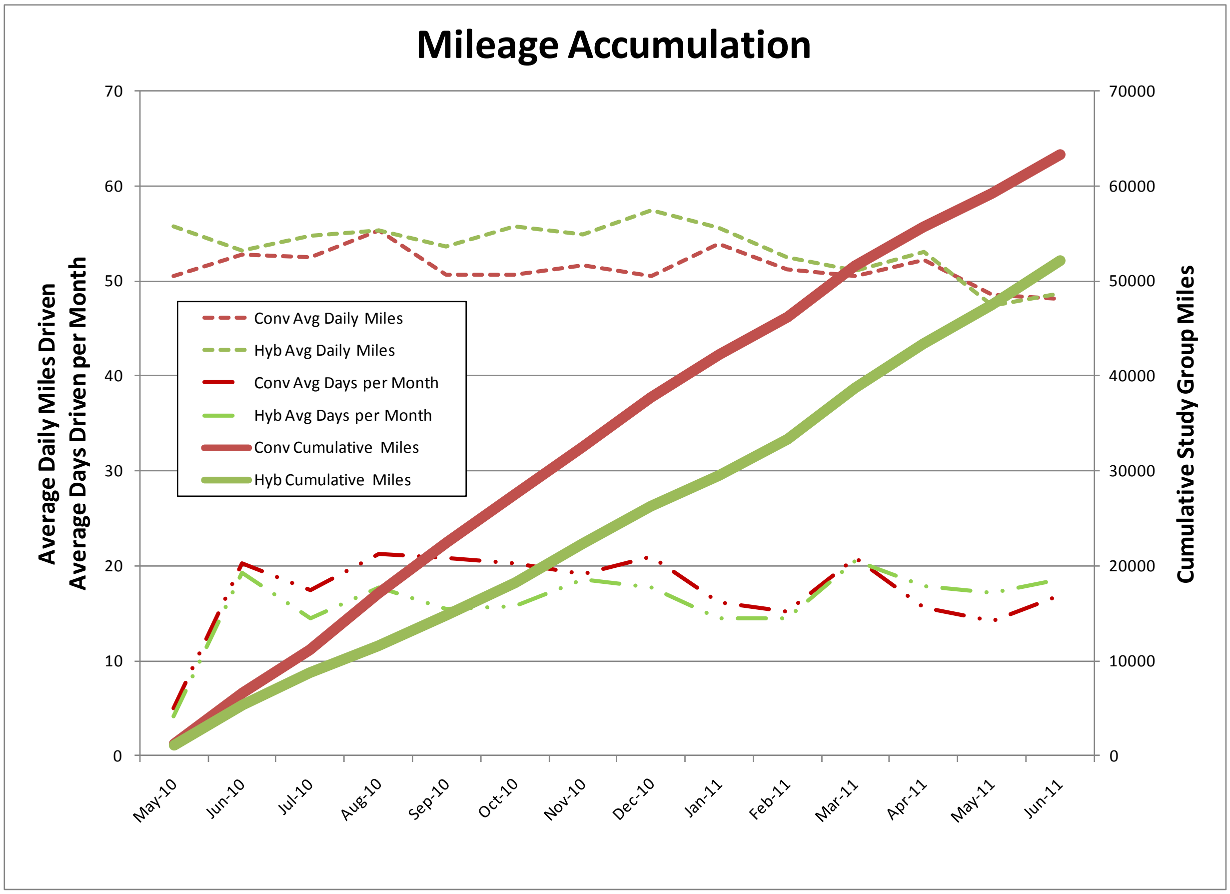


Figure 13. Group mileage accumulation, days per month, and miles per day

Maintenance Cost Analysis

This evaluation focuses on tractor operations spanning 13 of the first 28 months of operation for the hybrid tractors. This snapshot does not yield enough operating cost data to provide a complete understanding of the full life-cycle cost of the hybrid tractors. Understanding full life-cycle costs requires an examination of the purchase cost of the tractors plus warranty, longer term maintenance activities such as engine rebuilds or replacements and battery replacements, which NREL either did not have access to or cannot predict, in addition to the operational costs considered here. Finally, it is critical that areas in which cost savings can be achieved (e.g., brake repair) be examined. The intent of this evaluation, however, is to capture accurate, known operations costs associated with the hybrid and diesel vehicles for the selected period. This analysis is not predictive of maintenance costs assumed by CCR beyond the warranty period. The exact components and warranty periods—as negotiated by CCR, Eaton, and Kenworth or Freightliner —are contractual and confidential.

The hybrid and diesel tractors all are still 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 CCR during the period selected.

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

Maintenance and Overall Operational 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 tractor 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; other analysts can change this rate to one more similar to their own situation. This rate does not directly reflect CCR's current hourly mechanic rate.

Figure 14 shows monthly and cumulative maintenance cost per mile for both study groups. The hybrid group's $0.14/mile maintenance costs were 51% less than the diesel group's $0.29/mile. However, there were fewer maintenance events for these study groups and less granularity during this period than NREL has seen with other fleet studies. This could be due to much of the maintenance taking place at dealerships, under warranty or CCR mechanics not recording all small events. Because of this a breakdown by vehicle system was not possible and as such NREL and Coca-Cola do not see these results as being widely representative of the experience with these two vehicle groups. The data are reported here for completeness.

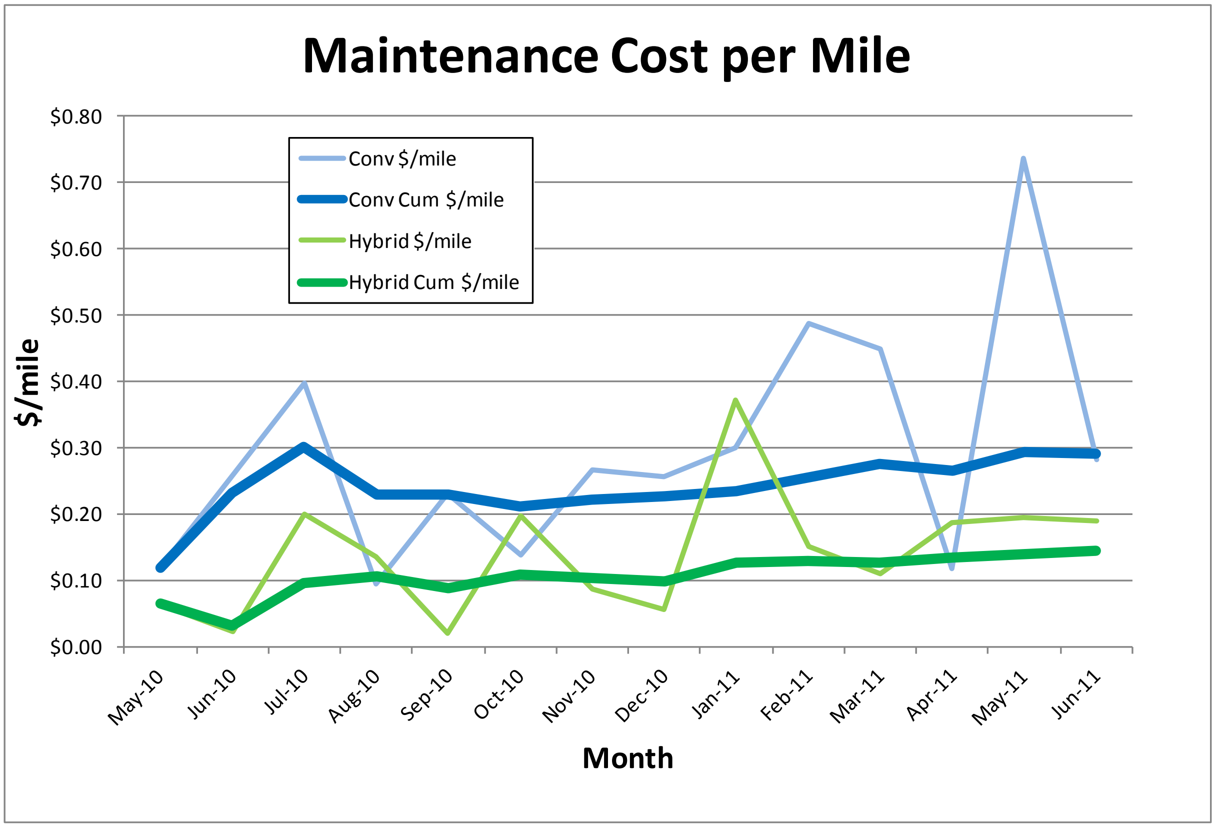


Figure 14. Maintenance cost per mile

Table 10 shows the cumulative operational costs for both groups. The hybrid group drove 18% fewer miles over the study period, but two hybrids missed a combined 9 months of operation due to an accident and an engine repair. Hybrid maintenance costs per mile are 51% less than maintenance costs for the diesels. Based on the in-use fuel economy observed Hybrid fuel costs per mile were 12% less than for the diesels. As such, hybrid total cost of operation per mile was 24% less than the diesels.

Table 10. Vehicle Operating Costs per Mile

	Group Miles	Maint. Materials Cost	Labor Hours	Total Maint. Costs[a]	Maint. $/mile	Fuel Gallons	Fuel $/Mile[b]	Total $/mile
Conventional	63,305	$6,926.03	231.1	$18,479.12	$0.29	13,123.1	$0.68	$0.97
Hybrid	52,100	$1,558.76	118.5	$7,483.54	$0.14	8,430.4	$0.60	$0.74
Hybrid % difference	-18%	-77%	-49%	-60%	-51%	-36%	-12%	-24%

a. Labor rate artificially set to $50/hr .
b. Fuel $/mile based on ECM gallons and ECM miles and diesel cost average of $3.37/gal over study period.

Fuel Economy

Table 11 shows mileage and fuel used according to ECM trip records for the 13-month period from May 22, 2010, through June 30, 2011, and the resulting fuel economy for each vehicle. Overall, for the 13-month study period, the hybrid group fuel economy was 5.63 mpg, 13.7 %

better than the diesel group's 4.95 mpg, which is directly between the CILCC and HHDDT cycle laboratory results.

Table 11. Vehicle Fuel Economy

Fuel Economy Comparison (May 2010 - June 2011)					
Tractor	**Powertrain**	**Mileage Total**	**Fuel Used**	**$/mile**	**MPG**
644024	Diesel	14496.3	2604.1	$0.61	5.57
644025	Diesel	15842.9	3165.1	$0.67	5.01
644079	Diesel	12551.1	2373.8	$0.64	5.29
644081	Diesel	13101.9	2682.5	$0.69	4.88
644082	Diesel	8965.9	2297.6	$0.86	3.90
Conventional	**Fleet Total**	**64,958**	**13,123**	**$0.68**	**4.95**
Conventional	**Average**	**12,992**	**2,625**	**$0.69**	**4.93**
643879	Hybrid Diesel	4339.6	698.8	$0.54	6.21
643880*	Hybrid Diesel	3315.4	552.9	$0.56	6.00
643881	Hybrid Diesel	10889.6	1822.2	$0.56	5.98
643882	Hybrid Diesel	10685.6	2012.8	$0.63	5.31
643883	Hybrid Diesel	18214.1	3343.7	$0.62	5.45
Hybrid	**Fleet Total**	**47,444**	**8,430**	**$0.60**	**5.63**
Hybrid	**Average**	**9,489**	**1,686**	**$0.58**	**5.79**
Hybrid Advantage				**12.0%**	**13.7%**

*643880 ECM records from May 2010 to January 2011 only due to a missed ECM download.

Figure 15 compares the in-field daily fuel economy results collected from the two data logging events mentioned previously and in-field vehicle averages with the measured chassis dynamometer (ReFUEL) fuel economy results. The X axis is the spread of the KI of the represented cycles/days. The in-field results had idle times ranging from 23% to 78%. This wide range of idle time influences the major variation in the fuel economy and lowers the averages well below the laboratory results. Of note is how the field KI vehicle averages were predominantly between the HHDDT and CILCC KI numbers or just barely higher than the CILCC number. This helps to explain why the field fuel economy results were less than seen on the CILCC or the more intense WVU City laboratory tests. The in-use hybrid advantage of 13.7% falls between the laboratory results for HHDDT and CILCC. If routes are identified at other locations that are composed primarily of the high KI (> 1.5) days seen as the upper end of the in-use experience in Miami (the handful of in-field day points in the figure below around and above 1.5 KI), hybrid advantage in the 25% range could be expected.

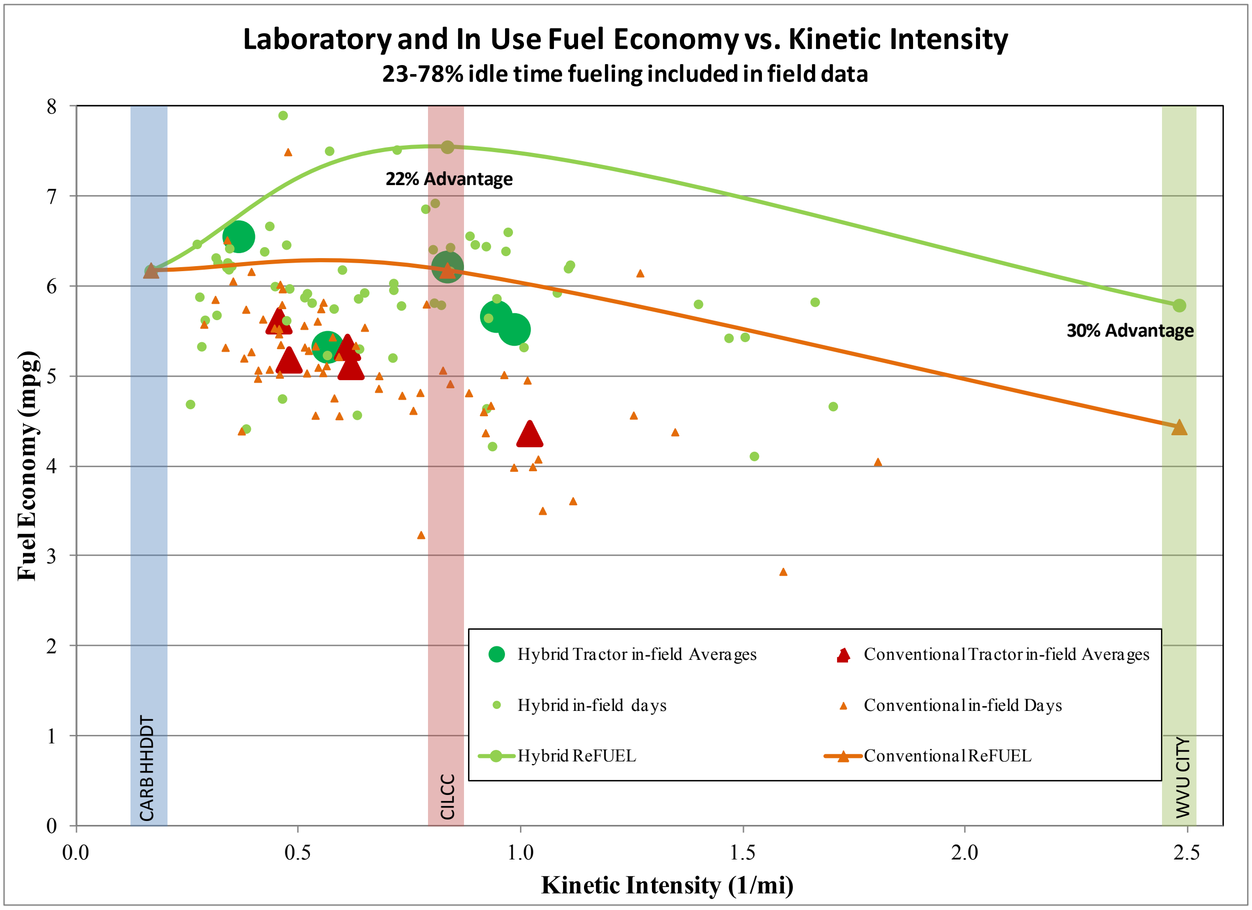


Figure 15. Fuel economy vs. kinetic intensity

Figure 16 is the same as Figure 15 but with the fuel consumption associated with periods of engine at idle removed from the in-field daily and tractor average data points. The laboratory test cycles do not include this amount of idle time. With no idle time included in the calculated fuel economy, the in-use data variation decreases and aligns better with the laboratory data. Also note the consolidation of the data point "clouds." Idle time is the cause of much of the fuel economy variation and is responsible for 0.5 mpg to 1 mpg (5%–15%) reduction of in-field vehicle average fuel economy. The CCR fleet would benefit from "engine off at idle" technology. The remaining daily variation is likely due to driver habits and traffic patterns.

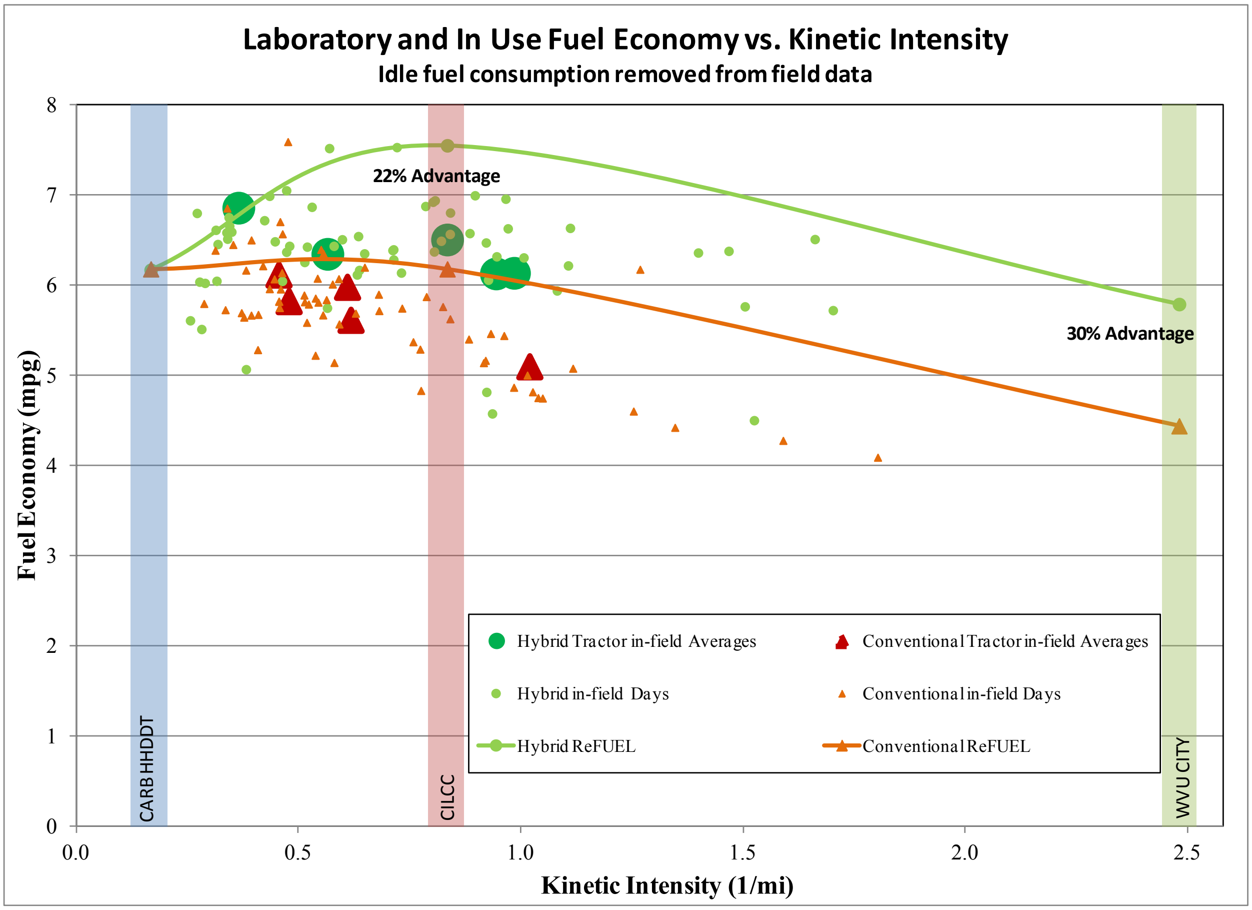


Figure 16. Fuel economy vs. kinetic intensity, idle fueling removed

Looking at the relationship of average driving speed versus fuel economy, Figure 17 compares the in-field daily fuel economy results and in-field vehicle averages with the ReFUEL laboratory fuel economy results with the fuel consumption associated with periods of engine at idle removed from the in-field daily and tractor average data points. The x axis is the spread of average driving speeds of the represented cycles/days. Using this metric, it is very clear that the laboratory results accurately predict the in-use fuel economy seen in Miami. The majority of the observed in-use data falls between the CILCC and HHDDT cycles just as the in-use hybrid fuel economy advantage falls directly between laboratory hybrid fuel economy advantage results.

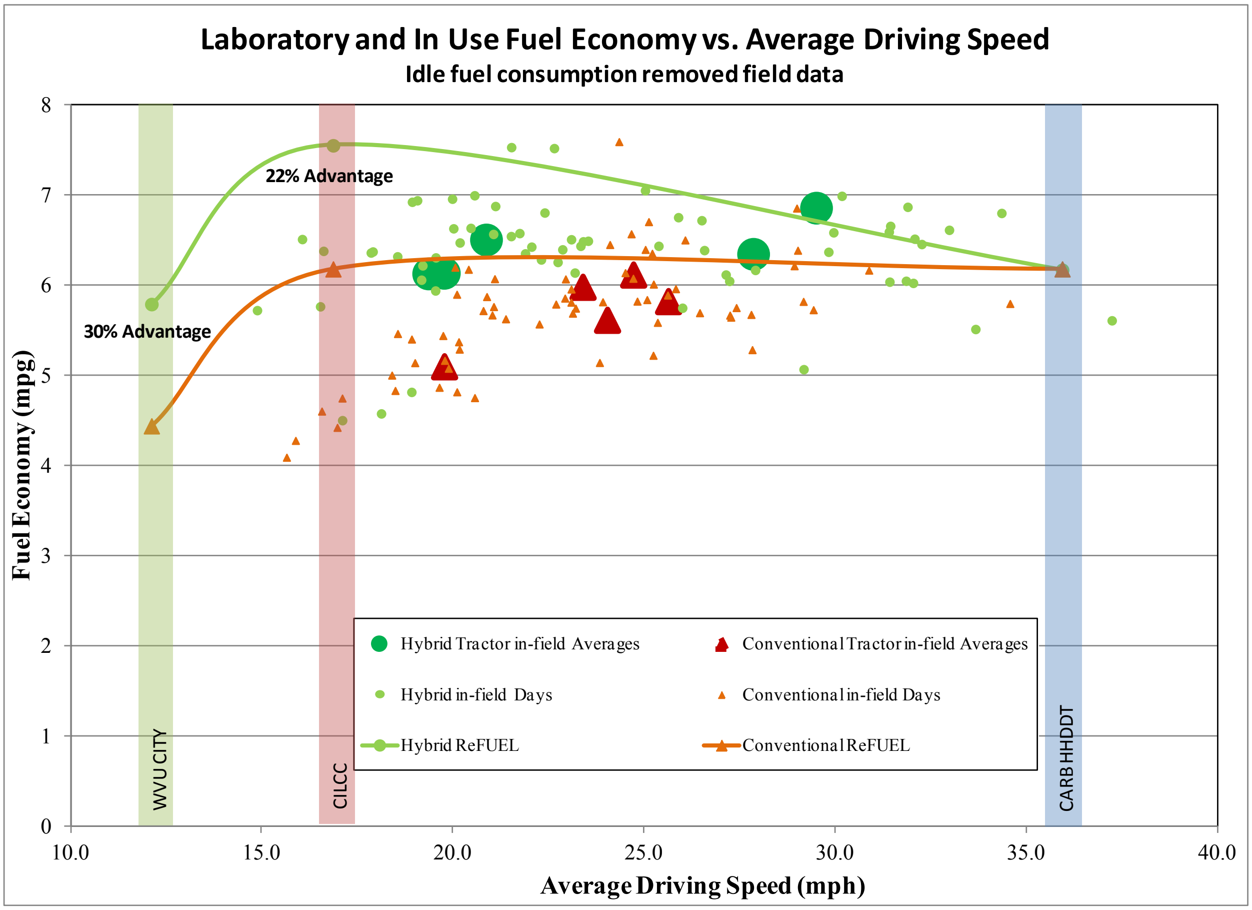


Figure 17. Fuel economy vs. average driving speed, idle fueling removed

To ensure accuracy of the ECM data, CCR also provided NREL with operator-provided daily mileage data. Each driver recorded the beginning of the day odometer reading and the end of the day odometer reading and the unit number of the tractor driven that day. The data were sent to NREL on a monthly basis and correlated well with the ECM mileage data. A comparison between the two mileage accumulation records is shown in **Table 12**. Hybrid 2 missed its last ECM download, so the comparison only goes to January 14, 2011. Most vehicle mileage errors are in the low single digits, which can be accounted for by driver rounding in logs and some movement of trucks by maintenance and loading personnel other than the drivers. Driver log mileage data were used with maintenance cost analysis because they were daily reports that could be tabulated monthly. ECM mileage data were only used for fuel economy analysis because downloads occurred at irregular intervals due to scheduling inconsistencies.

Table 12. Delivery Miles Measurement Comparison

Vehicle	Driver Logs	ECM Data	Percent Difference
643879 Avg	4,169	4,339.6	4%
643880 Avg*	2,906	3,315.4	12%
643881 Avg	10,818	10,889.6	1%
643882 Avg	10,225	10,685.6	4%
643883 Avg	17,866	18,214.1	2%
Hybrid Avg	**9,197**	**9,489**	**3%**
644024 Avg	14,053	14,496.3	3%
644025 Avg	15,601	15,842.9	2%
644079 Avg	12,045	12,551.1	4%
644081 Avg	12,743	13,101.9	3%
644082 Avg	8,863	8,965.9	1%
Conventional Avg	**12,661**	**12,992**	**3%**

*643880 ECM records from May 2010 to January 2011 only due to a missed ECM download.

Considering that a typical life cycle for these tractors in a CCR fleet is 15 years, the vehicles in both study groups are relatively new. The hybrid vehicles were manufactured in the spring of 2009 and had been driven on average 7,000 miles as of the first ECM image download on May 22, 2010. The conventional vehicles were manufactured in the spring of 2008 and had been driven on average 20,840 miles as of May 22, 2010.

Diesel Particulate Filter Performance

Table 13 shows details about DPF regeneration obtained through periodic ECM image downloads during the study. The hybrid group averaged only 11.5 DPF regenerations per tractor during this time, 73% less than the diesel group's 42 regenerations. The conventional tractors averaged a regeneration about every 300 miles while the hybrid tractors averaged over 900 miles between regenerations. This difference saved less than 9 gallons of fuel per tractor during the study, but may add to the life expectancy of the DPF unit. This is because DPF failures usually occur by cracking during a runaway regeneration; fewer regenerations mean fewer opportunities to crack the DPF.

Table 13. DPF Regeneration Data

DPF Regeneration Comparison (May 2010 - June 2011)					
Tractor	**Powertrain**	**Mileage Total**	**Regen Fuel**	**Number of Regenerations**	**Mile / regen**
644024	Diesel	14496.3	4.1	19	763
644025	Diesel	15842.9	16.1	52	305
644079	Diesel	12551.1	10.3	36	349
644081	Diesel	13101.9	8.6	22	596
644082	Diesel	8965.9	22.1	82	109
Conventional	**Fleet Total**	**64,958**	**61.2**	**211**	**308**
Conventional	**Average**	**12,992**	**12.2**	**42.2**	**424**
643879	Hybrid Diesel	4339.6	1.1	5	868
643880*	Hybrid Diesel				
643881	Hybrid Diesel	10889.6	2.8	9	1210
643882	Hybrid Diesel	10685.6	5.06	13	822
643883	Hybrid Diesel	18214.1	5.8	19	959
Hybrid	**Fleet Total**	**44,129**	**14.8**	**46**	**959**
Hybrid	**Average**	**11,032**	**3.7**	**11.5**	**965**
Hybrid Advantage			**70%**	**73%**	**127%**

*643880 ECM records omitted data on DPF regeneration

Idle Time Evaluation

Table 14 shows details of the study groups' idle time behavior obtained through periodic ECM image downloads during the study. The hybrid group had nearly half as much idle time as the diesel group. The hybrids still consumed 9% of their fuel while idling, and the diesel group consumed 16% of their fuel idling. Substantial fuel savings are still available to both fleets through further idle reduction techniques. CCR started addressing the idle time issue by beginning to train its 11,000 drivers with a new "smartdriver" training course in December 2010. This course covered not only idle reduction, but managing momentum driving techniques to save fuel as well. The effectiveness of this training was not evaluated in this study as the study location did not receive this training until May 2011.

Table 14. Idle Time Data

Idle Time and Fuel Comparison (May 2010 - June 2011)					
Tractor	**Powertrain**	**Idle Time (hours)**	**Percent Idle Time**	**Idle Fuel (gallons)**	**Percent Idle Fuel**
644024	Diesel	623	58%	389	15%
644025	Diesel	782	60%	506	16%
644079	Diesel	384	49%	220	9%
644081	Diesel	636	61%	422	16%
644082	Diesel	861	72%	599	26%
Conventional Fleet		**3,286**	**61%**	**2,136**	**16%**
643879	Hybrid Diesel	219	60%	92	13%
643880*	Hybrid Diesel	134	52%	59	11%
643881	Hybrid Diesel	528	61%	227	12%
643882	Hybrid Diesel	379	29%	169	8%
643883	Hybrid Diesel	422	23%	194	6%
Hybrid Fleet		**1,682**	**35%**	**741**	**9%**
Hybrid Advantage		**49%**	**42%**	**65%**	**-47%**

*643880 ECM records from May 2010 to January 2011 only due to a missed ECM download.

Batteries

The Eaton system uses lithium-ion batteries supplied by Hitachi for energy storage. These batteries 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 located on the driver's side of the chassis just behind the cab. No battery failure or a cell failure was reported by Eaton or CCR during the study. The service life of the battery is estimated by Eaton at more than 7 years.

Status of CCR Hybrid Fleet

CCR has made a public commitment to reduce its carbon footprint 15% by 2020. As part of that commitment, CCR operates 730 class 7–8 hybrid tractors and straight trucks in its fleet, almost 6% of the total fleet. CCR is actively evaluating and experimenting with the fleet-wide hybrid performance and all the specification options that affect that performance including engine size and rear axle gear ratios. CCR plans to purchase another 80 hybrids in 2012.

Conclusions

- Route and drive cycle analysis showed that both study groups drive similar duty cycles with similar KI (0.95 vs. 0.69), average speed (20.6 vs. 24.3 mph), and stops per mile (1.9 vs. 1.5). Because of this similar usage of vehicles, the groups were judged to be a good comparison.
- The hybrid group accumulated 27% fewer miles than the diesel group during the study. However, the hybrids were driven a comparable number of miles per operational day. The discrepancy primarily stems from non-hybrid-related down-time experienced by two hybrid trucks during the first six months of the study.
- Laboratory dynamometer testing demonstrated 0%–30% hybrid fuel economy improvement, depending on duty cycle, and up to a 32.1% improvement in ton-mi/gal.
- The 13-month field study demonstrated the hybrid group had a 13.7% fuel economy improvement over the diesel group.
- Laboratory fuel economy and field fuel economy study showed similar trends along the range of KI, average speed and stops per mile. This means the vehicles could achieve higher in-field fuel economy results if they were used in a more urban location with drive cycle statistics closer to the WVU City cycle.
- Hybrid fuel costs per mile were 12% less than for the diesels.
- Hybrid vehicle total cost of operation per mile was 24% less than the cost of operation for the diesel group ($0.74 vs. $0.97 / mile), which means the customer is realizing real savings with the hybrids.
- CCR is actively evaluating the fleet-wide hybrid and conventional performance and all the specification options that affect that performance including engine size, transmission type and rear axle gear ratios.

Appendix: ReFUEL Test Report

Prepared by Petr Sindler

Test Summary Report

Project Title: Coca-Cola Refreshments Class 8 Delivery Truck
Report Date: September 2010

Testing Period:

	Baseline Vehicle	August 20, 2010 – August 24, 2010
	Hybrid Vehicle	August 12, 2010 – August 19, 2010

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

Test Participants:

Matthew Thornton	ReFUEL Lab, NREL
Petr Sindler	ReFUEL Lab, NREL
Jonathan Burton	ReFUEL Lab, NREL
Scott Walters	ReFUEL Lab, NREL
Patrick Curran	Fleet Test & Evaluation, NREL

Abstract

The National Renewable Energy Laboratory’s Renewable Fuels and Lubricants (ReFUEL) group conducted chassis dynamometer testing of two single-axle tractors, one conventional and one hybrid. The 2009 conventional tractor was equipped with a Cummins engine, and the 2010 hybrid tractor was equipped with a PACCAR engine. Both test vehicles utilized diesel particle filters (DPFs), and the hybrid vehicle incorporated an Eaton electric drive train. The fuel economy and emissions benefits of the hybrid vehicle were evaluated over three drive cycles: Combined International Local and Commuter Cycle (CILCC), West Virginia University City (WVU City) cycle, and the Heavy Heavy-Duty Diesel Truck (HHDDT) cycle.

Objectives

The goal of this study was to evaluate the benefits of a hybrid-electric drive train incorporated in the Coca-Cola Refreshments (CCR) product delivery fleet of trucks operated in the Miami, Florida, area. The areas of interest of this study were fuel economy, criteria emissions, and performance.

General Laboratory Description and Methods

The vehicles were tested at the ReFUEL Laboratory, which is operated by NREL and located in Denver, Colorado. The laboratory is equipped with a heavy-duty vehicle chassis dynamometer with emissions measurement capability.

Chassis Dynamometer

The chassis dynamometer is capable of simulating transient loads on heavy-duty vehicles of up to 80,000 lbs gross vehicle weight at speeds up to 60 mph. The dynamometer is an in-ground installation with 40-in. diameter rolls protruding above the surface to interface with the vehicle wheels. The base inertia of the dynamometer rotating components is 31,000 lbs. A direct current motor (380 hp absorption/360 hp motoring capacity) is supplemented to simulate the vehicle inertia in the range of 8,000 to 80,000 lbs, as well as to simulate aerodynamic drag, rolling resistance, and grade loading. Figure 1 indicates the layout of the major components of the chassis dynamometer.

To assure the accuracy and consistency of road load simulation, the dynamometer is subjected to various procedures and checks. With the vehicle lifted off the rolls, an automated dynamometer warm-up procedure is performed prior to testing until the parasitic losses in the dynamometer are stabilized. An unloaded coast-down procedure is also conducted to confirm that inertia and road load are being simulated by the dynamometer control system accurately. Additionally, after each test run, a loaded coast-down procedure is performed to further ensure stability of vehicle and dynamometer parasitic losses and accurate road load simulation during testing.

When tested, the vehicle is secured to the dynamometer with the drive axle(s) over the rolls. The vehicle is exercised by a driver following a prescribed speed trace on the test aid monitor. A large fan is used to force cooling air onto the vehicle radiator to roughly simulate the ram cooling effect of a vehicle in motion. The engine exhaust stream is collected by the emissions measurement system for analysis, and various vehicle parameters are monitored and logged by the data acquisition system.

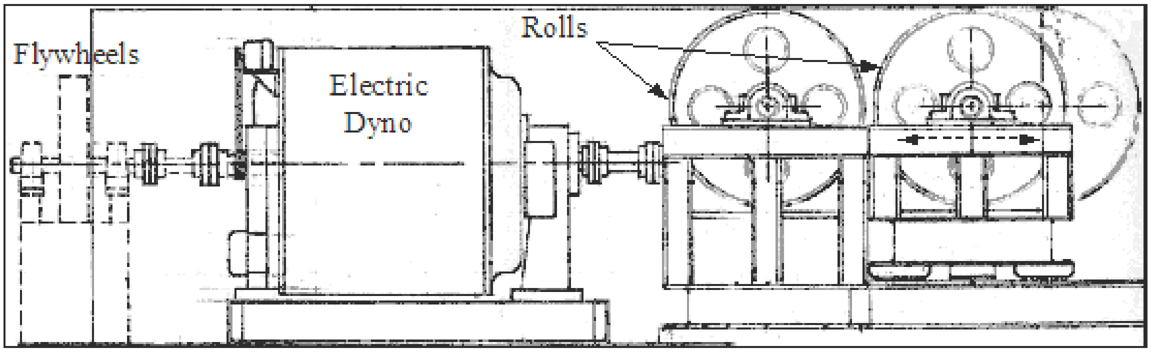


Figure 1. Chassis dynamometer schematic

Fuel Metering and Conditioning

The fuel metering and conditioning system, Pierburg Model PII 514 (shown in Figure 2), supplies temperature conditions and measures the fuel consumed by the vehicle during testing. The fuel mass rate is measured by means of instantaneous measurements of volumetric rate and fuel density.

Additionally, the fuel consumed by the vehicle is measured by a gravimetric method, carbon balance of the gaseous engine exhaust emissions, and by monitoring the engine electronic control module (ECM) broadcast of fuel rate information.

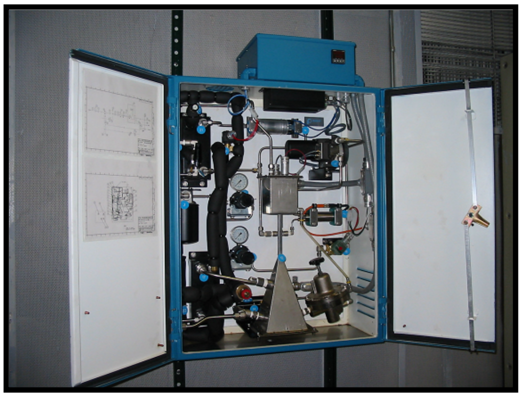


Figure 2. Pierburg fuel metering system

Air Handling and Conditioning

The exhaust dilution air and the combustion air consumed by the test vehicle were conditioned in accordance with the Code of Federal Regulations specification. The air is conditioned for humidity and temperature as well as HEPA filtered to eliminate background particulate matter (PM) as a source of uncertainty in particulate measurements. The air handling system is also capable of regulating the air pressure to simulate testing at different elevations.

Emissions Measurement

The ReFUEL laboratory's emissions measurement system is based on the full flow exhaust dilution tunnel with a Constant Volume Sampling system for mass flow measurement. The exhaust stream from the vehicle is transferred through an insulated piping into the 18–in. diameter stainless steel dilution tunnel where it is introduced to the dilution air. The diluted exhaust is then sampled far enough downstream to ensure thorough mixing. The samples are typically used for gaseous analyses and for gravimetric PM measurement.

The flow rate in the dilution tunnel is measured and controlled using critical flow venturis. A system with three venturi nozzles is employed to maximize the flexibility of the emissions measurement system. Featuring 500-cfm, 1,000-cfm, and 1,500-cfm venturi nozzles and gas-tight valves, the system flow can be varied from 500-cfm to 3,000-cfm flow rates in 500-cfm increments. This arrangement, illustrated in Figure 3, allows the dilution level to be tailored to the engine size being tested, maximizing the accuracy of the emissions measurement equipment.

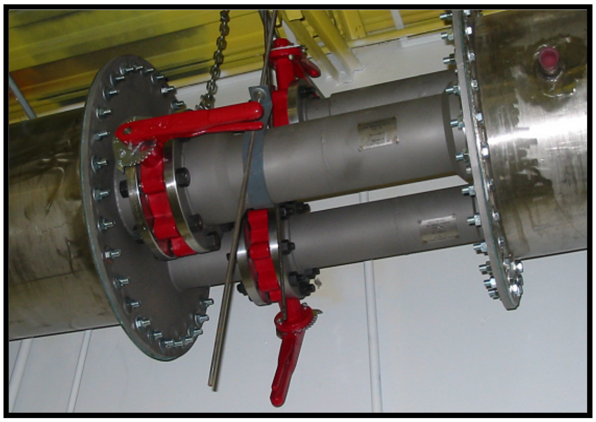


Figure 3. Venturi nozzles

The gaseous analytical system is a Horiba MEXA 7100. It features continuous analyzers for total hydrocarbons (THC), nitrogen oxides (NO_x), carbon monoxide (CO), and carbon dioxide (CO_2).

The analyzers in this bench are typical grade instruments used in engine research and certification laboratories as recommended by the Code of Federal Regulations. The NO_x analyzer is a chemiluminescence analyzer, The THC is a flame ionization detector, and the CO and CO_2 analyzers are non-dispersive infrared analyzers. The system is highly automated in terms of performing self-checking and calibrating functions. It communicates with the data acquisition system via ethernet interface.

Project Specific Setup and Methods

Test Vehicles

The conventional test vehicle was a 2009 Freightliner M2 106 single-axle tractor, powered by a Cummins ISC diesel engine, equipped by an Eaton Fuller manual 7-speed transmission. The hybrid test vehicle was a 2010 Kenworth T370 single-axle tractor, powered by a PACCAR PX-6 (Cummins ISB), equipped with an Eaton Fuller autoshifted manual transmission and an Eaton hybrid electric system. The hybrid system's battery pack has a nominal voltage of 340 V. Appendix Table 9 lists the vehicles' technical specifications in more detail.

Vehicle Instrumentation

Intake air was conditioned and supplied to the test vehicle by the ReFUEL air-handling system with continuously recorded measurements of absolute pressure, inlet restriction, humidity, and temperature.

Approximately 40 ft of 6-in. diameter, insulated, stainless steel tubing connected the test vehicle exhaust pipe to the dilution tunnel. The vehicle engine exhaust temperature was continuously measured post-DPF and logged along with the exhaust backpressure.

All tests were performed with certification diesel fuel. The results of the fuel analysis are included in Appendix Table 8. Fuel supply and return lines from the engine were separated from the vehicle's fuel storage tank and connected to the laboratory fuel metering and conditioning system. Continuous measurements of fuel temperature, density, and consumption rate were logged with the laboratory data acquisition system.

The engine ECM broadcast over the J1939 link was monitored and recorded using Cummins Insite software via Cummins Inline 5 hardware interface.

Additional vehicle parameters measured and recorded during testing were the radiator inlet air temperature, cab air temperature and, in the case of the hybrid vehicle, the hybrid battery pack current.

Vehicle Simulation

The test weights for the test vehicle were calculated to be 33,840 lbs for the conventional vehicle and 34,300 lbs for the hybrid vehicle. The dynamometer road load simulation coefficients for the hybrid vehicle were derived from track coast-down data provided by the manufacturer. No track coast data were provided for the conventional vehicle, thus the dynamometer road load simulation coefficients had to be derived using the hybrid vehicle track data with some corrections and assumptions. The aerodynamic and tire rolling resistance between the two vehicles were assumed similar as the design and components of the vehicles were similar. After the dynamometer coefficients were derived for the hybrid, the vehicles were swapped, and the conventional vehicle was coasted using the hybrid dynamometer coefficients. As anticipated, the conventional vehicle exhibited less drive train losses and consequently coasted longer. The dynamometer coast test data indicated only a difference of roughly 30 lbs in the constant term of the second-order road load equation. This offset was then used to modify the hybrid vehicle track data for the use with the conventional vehicle. The conventional vehicle dynamometer simulation road load coefficients were then derived using the "new, developed" track coefficients.

To assess testing errors potentially induced by these assumptions and corrective calculations to the road load coefficients, a road load sensitivity study was undertaken. The conventional vehicle was tested on a portion of the CILCC cycle using the derived road load coefficients and also with the constant coefficient (A) increased and decreased by 30 lbs. Test results indicated that a variation of 30 lbs on the A coefficient did not significantly influence fuel economy of the tested vehicle. The variation due to coefficient change was within the typical variation associated with chassis testing. Figure 4 demonstrates the lack of a firm link between small coefficient changes and fuel economy. In this figure, the first column shows the fuel consumed using a baseline "A" coefficient, and the following two columns indicate the amount consumed when the coefficient was lowered and increased, respectively. Note that the error bar spread (indicating the highest and the lowest measured value within the group of three tests) exceeds the differences between the averages of the groups. Additionally, the average fuel consumption with the increased coefficient was lower than the baseline consumption.

Due to the different operating temperatures of both the vehicle and the dynamometer experienced during testing with different test cycles, each test cycle required deriving its own set of dynamometer load coefficients to assure the best possible accuracy of road load simulation.

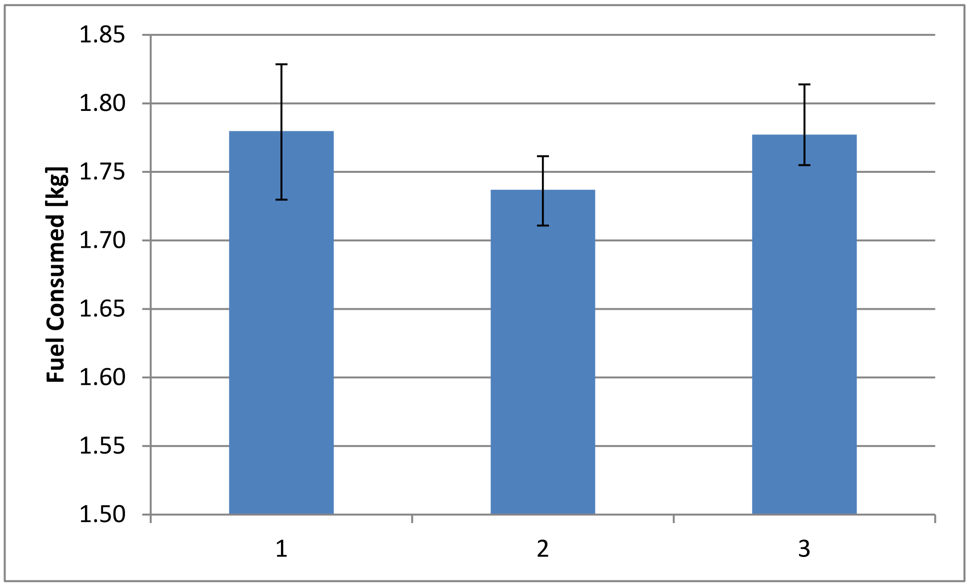


Figure 4. Effect of an "A" dynamometer coefficient on test fuel consumption (1-A=319 lbs, 2-A=292lbs, 3-A=351lbs)

The track road load coefficients used for derivations of dynamometer load coefficients are shown in Table 1.

Table 1. Road Load Coefficients

Coefficient	Conventional Truck	Hybrid Truck
A	283.2 lbs	323.5 lbs
B	0 lb/mph	0 lb/mph
C	0.209 lbs/mph^2	0.209 lbs/mph^2

Instrumentation Calibration

Prior to beginning this project, all critical instrumentation was calibrated and verified.

The gaseous analyzers were checked for linearization, and the NO_x converter efficiency check was performed. All the pressure transducers were calibrated, and the thermocouple channels were verified. The fuel meter flow rate measurement was calibrated upon starting the program due to concerns of accuracy. All test data collected prior to the calibration were post processed to reflect the new calibration.

State-of-Charge Considerations

SAE Recommended Practice J2711 is a recommended protocol for measuring fuel economy and emissions of hybrid-electric and conventional heavy-duty vehicles and was used for this project. The recommended practice provides a description of state-of-charge correction for charge-sustaining hybrid electric vehicles (HEVs).

The basic premise of the procedure is to ensure that fuel economy and emissions data for a HEV are not unduly increased or decreased due to significant changes in energy storage levels over a single drive cycle. The procedure determines the percent change in the state of charge of the hybrid energy storage system over each individual test cycle run. The basis for this is the net energy change (change in stored energy) divided by the total energy used during the test cycle run, calculated from the consumed fuel energy content. If the change is less than 1%, no correction is needed for any test results. If the change is greater than 5%, the results are deemed invalid. However, if the storage energy change falls between 1% and 5%, a correction factor must be applied to the test results to obtain accurate values for fuel economy and emissions.

In the case of a battery storage system, the net energy change is calculated by multiplying the nominal voltage of the battery pack (340V) by the integrated value of the continuously measured battery current (measured using a current clamp). Note that the net energy change on all tests in this study was less than 1%, thus there was no need to correct the data.

Drive Cycles

The test cycles for this project were selected based on a study of actual CCR delivery routes in the Miami, Florida, area. Actual delivery trucks were instrumented to record various parameters during their operation. The route data obtained were then analyzed for characteristic features, such as, speed, number of stops, and acceleration rates. Using these data, appropriate chassis dynamometer test cycles were selected to simulate the typical vehicle operation in the laboratory. The test cycles used in this project were the WVU City, CILCC, and the HHDDT cycle. The plots of these tests are included in Figures 5, 6, and 7, respectively. Each vehicle was tested on each cycle several times to get three repeatable hot-start test data sets. A hot-start test is a test that is conducted following a previous test of the same cycle separated by a 20-minute soak time. Occasionally, more than three hot-start tests were conducted due to unsatisfactory results or inconsistencies inherent to chassis testing. The expected inconsistencies of chassis testing are caused partly by changing conditions during testing (ambient temperature), but largely also by the driver of the tested vehicle, who is not able to perform the test exactly the same every time.

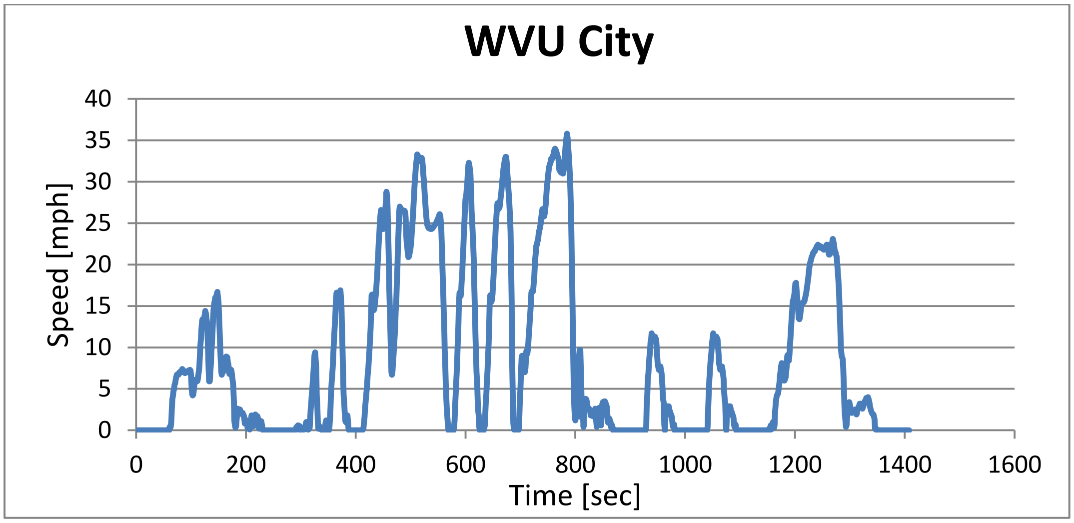


Figure 5. Speed trace of WVU City cycle

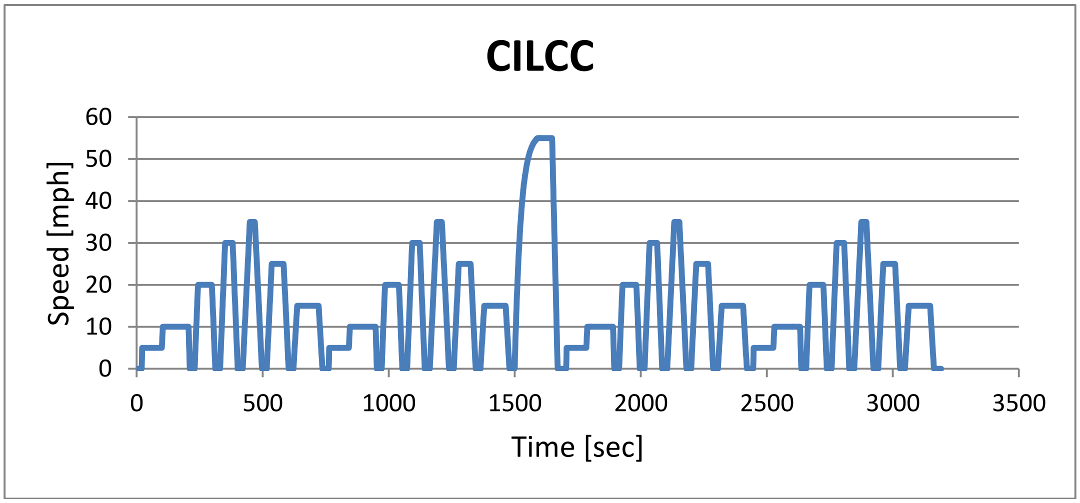


Figure 6. Speed trace of CILCC cycle

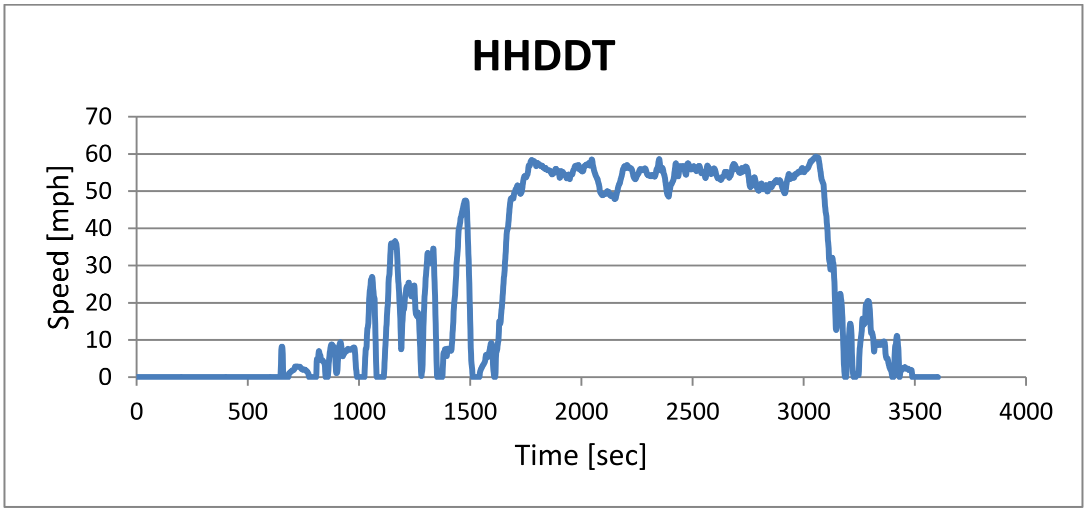


Figure 7. Speed trace of HHDDT cycle

To compare their performance, the two test vehicles were also subjected to an acceleration test. This test consisted of the vehicle being accelerated at the maximum possible rate from a complete stop to 60 miles per hour. Each vehicle was accelerated four times consecutively to eliminate possible driver-related shortcomings in the case of the manually shifted conventional vehicle and to identify and eliminate the influence of varying state of charge of the batteries in the hybrid vehicle.

Results

Emissions Tests

Tables 2 through 7 show the results of distance-specific engine NO_x, THC, CO, and CO_2 exhaust emissions. Tables 2 and 3 show the results of CILCC cycle test with the conventional and hybrid vehicles respectively. Note that the hybrid vehicle tests were repeated number of times due to some inconsistencies during testing. Due to longer than expected warm-up time requirement, the dynamometer load coefficients were derived repeatedly until stable coast-down results were achieved. The grey-shaded cells in Table 3 show data from tests done prior the derivation of final accepted dynamometer load coefficients. Tables 4 and 5 indicate results of HHDDT tests, and Tables 6 and 7 show the WVU City test results.

Of the three fuel consumption measurement results presented in the tables, the Pierburg fuel meter (denoted as FM in the tables) measurement should, by design, provide the most accurate data. However, during this project, the unit did not work correctly and the results proved to be somewhat variable from test to test. The gravimetric method, although not expected to be as accurate due to the low resolution (0.1 lb) of the scale used, showed reasonable consistency of measurements. The carbon balance method (denoted as CB in the tables) is the fuel measurement method used in this report.

Acceleration Tests

The conventional vehicle accelerated from 0 to 60 mph in average 77 seconds after discarding the first run, which took (due to a driver error) 99 seconds. The hybrid vehicle took on average 104 seconds to reach 60 mph from a complete stop. Again, the first acceleration ramp was discarded due to not being consistent with the remaining three. The first run took 115 seconds, likely due to an insufficiently charged battery pack. Between the acceleration ramps, the vehicle was allowed to coast and recharge the battery pack through regeneration.

Table 2. Results of CILCC Tests with Conventional Vehicle

Run #	Cold/Hot /Regen	Date_Run	NO_x (g/mile)	THC (g/mile)	CO (g/mile)	CO_2 (g/mile)	Fuel FM (g/mile)	Fuel CB (g/mile)	Fuel Scale (g/mile)
1	cold	8/23/10_01	**7.463**	0.137	0.410	2,048	675	644	676
2	hot	8/23/10_02	**7.021**	0.078	0.959	1,650	520	519	545
3	hot	8/23/10_03	**7.081**	0.077	0.951	1,654	508	520	
4	hot	8/23/10_04	**7.353**	0.033	0.893	1,670	503	525	537
5	hot	8/23/10_05	**7.204**	0.062	0.932	1,655	497	520	544

Table 3. Results of CILCC Tests with Hybrid Vehicle

Run #	Cold/Hot /Regen	Date_Run	NO_x (g/mile)	THC (g/mile)	CO (g/mile)	CO_2 (g/mile)	Fuel FM (g/mile)	Fuel CB (g/mile)	Fuel Scale (g/mile)
1	cold	8/17/10_01	**7.270**	0.001	0.245	1,334	415	419	383
2	warmup	8/17/10_02	**7.179**	-0.055	0.380	1,317	432	414	386
3	warmup	8/17/10_03	**7.344**	-0.006	0.395	1,309	416	411	382
4	hot	8/17/10_04	**7.533**	-0.045	0.340	1,339	404	421	387
5	hot	8/17/10_05	**7.501**	-0.036	0.387	1,345	394	423	
6	cold	8/18/10_01	**7.461**	-0.025	0.228	1,371	439	431	431
7	hot	8/18/10_02	**7.527**	-0.030	0.274	1,371	416	431	436
8	hot	8/18/10_03	**7.482**	-0.020	0.332	1,360	383	427	439
9	hot	8/18/10_04	**7.615**	-0.017	0.425	1,368	368	430	435

Table 4. Results of HHDDT Tests with Conventional Vehicle

Run #	Cold/Hot /Regen	Date_Run	NO_x (g/mile)	THC (g/mile)	CO (g/mile)	CO_2 (g/mile)	Fuel FM (g/mile)	Fuel CB (g/mile)	Fuel Scale (g/mile)
1	cold	8/24/10_01	**2.953**	0.016	0.433	1,744	546	548	554
2	hot	8/24/10_02	**2.768**	0.028	0.659	1,648	540	518	540
3	hot	8/24/10_03	**2.849**	0.019	0.731	1,648	541	518	540
4	hot	8/24/10_04	**2.928**	0.031	0.653	1,669	539	525	542
5	hot	8/24/10_05	**2.888**	0.025	0.784	1,669	544	525	

Table 5. Results of HHDDT Tests with Hybrid Vehicle

Run #	Cold/Hot /Regen	Date_Run	NO_x (g/mile)	THC (g/mile)	CO (g/mile)	CO_2 (g/mile)	Fuel FM (g/mile)	Fuel CB (g/mile)	Fuel Scale (g/mile)
1	warmup	8/18/10_05	**5.729**	-0.005	0.367	1,624	472	510	509
2	hot	8/18/10_06	**5.724**	-0.007	0.639	1,638	484	515	511
3	cold	8/19/10_01	**5.854**	0.005	0.368	1,709	529	537	511
4	hot	8/19/10_02	**5.790**	-0.010	0.421	1,679	512	528	521
5	hot	8/19/10_03	**5.749**	-0.016	0.396	1,666	499	524	511

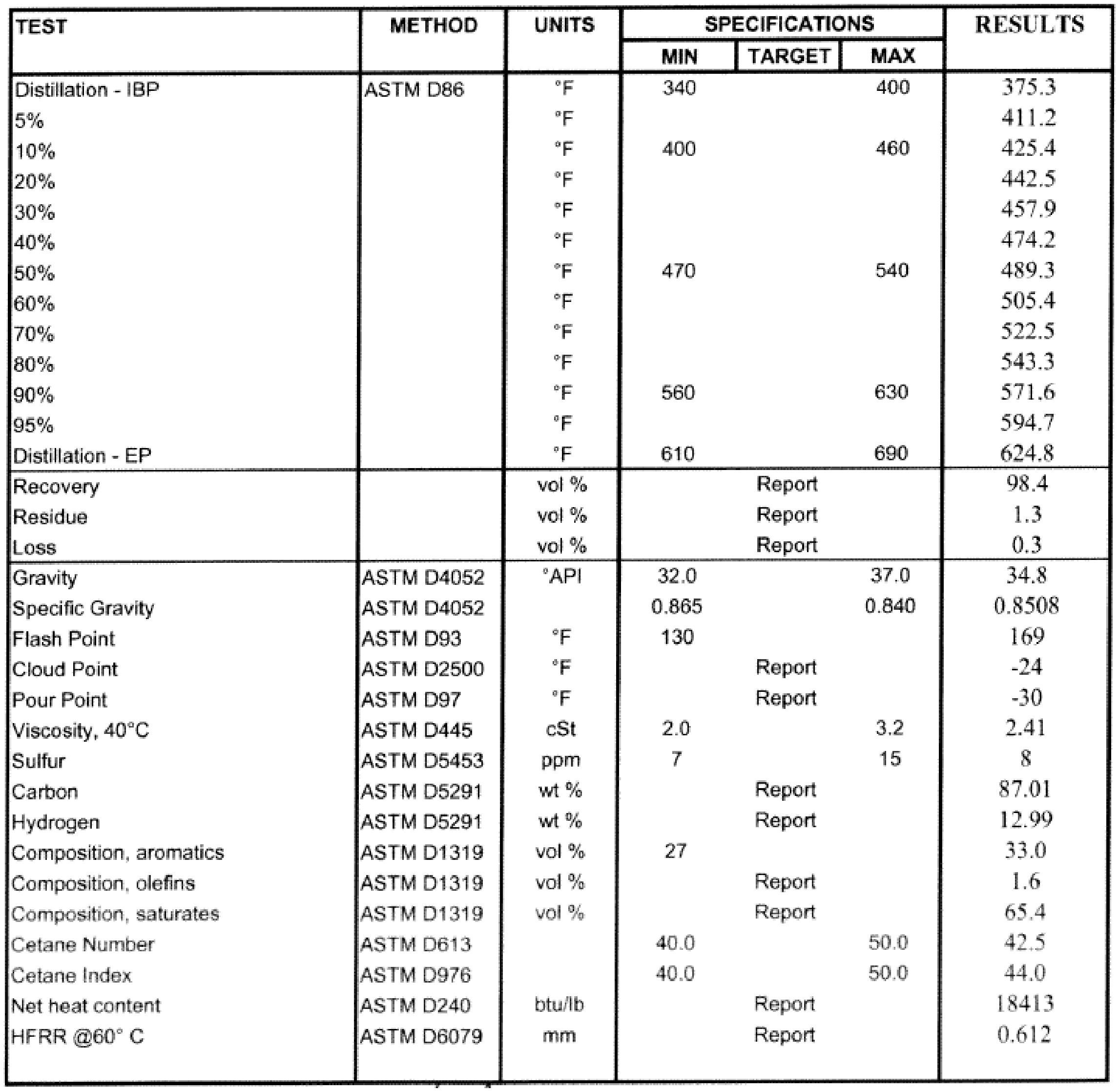
Table 6. Results of WVU City Tests with Conventional Vehicle

Run #	Cold/Hot /Regen	Date_Run	NO_x (g/mile)	THC (g/mile)	CO (g/mile)	CO_2 (g/mile)	Fuel FM (g/mile)	Fuel CB (g/mile)	Fuel Scale (g/mile)
1	hot	8/20/10_01	**7.632**	0.090	1.667	2,290	725	720	712
2	hot	8/20/10_02	**7.627**	0.057	1.472	2,299	741	723	726
3	hot	8/20/10_03	**7.848**	0.071	2.130	2,355	737	741	744
4	hot	8/20/10_04	**7.700**	0.064	1.515	2,279	661	717	728

Table 7. Results of WVU City Tests with Hybrid Vehicle

Run #	Cold/Hot /Regen	Date_Run	NO_x (g/mile)	THC (g/mile)	CO (g/mile)	CO_2 (g/mile)	Fuel FM (g/mile)	Fuel CB (g/mile)	Fuel Scale (g/mile)
1	warmup	8/13/10_02	**9.854**	0.048	2.287	1,772	592	558	582
2	hot	8/13/10_03	**10.066**	-0.297	1.817	1,769	567	556	566
3	hot	8/13/10_04	**9.948**	0.027	1.604	1,756	519	553	566
4	hot	8/13/10_05	**9.804**	0.012	1.484	1,782	517	561	566

Table 8. Fuel Analysis Results



TEST	METHOD	UNITS	SPECIFICATIONS			RESULTS
			MIN	TARGET	MAX	
Distillation - IBP	ASTM D86	°F	340		400	375.3
5%		°F				411.2
10%		°F	400		460	425.4
20%		°F				442.5
30%		°F				457.9
40%		°F				474.2
50%		°F	470		540	489.3
60%		°F				505.4
70%		°F				522.5
80%		°F				543.3
90%		°F	560		630	571.6
95%		°F				594.7
Distillation - EP		°F	610		690	624.8
Recovery		vol %		Report		98.4
Residue		vol %		Report		1.3
Loss		vol %		Report		0.3
Gravity	ASTM D4052	°API	32.0		37.0	34.8
Specific Gravity	ASTM D4052		0.865		0.840	0.8508
Flash Point	ASTM D93	°F	130			169
Cloud Point	ASTM D2500	°F		Report		-24
Pour Point	ASTM D97	°F		Report		-30
Viscosity, 40°C	ASTM D445	cSt	2.0		3.2	2.41
Sulfur	ASTM D5453	ppm	7		15	8
Carbon	ASTM D5291	wt %		Report		87.01
Hydrogen	ASTM D5291	wt %		Report		12.99
Composition, aromatics	ASTM D1319	vol %	27			33.0
Composition, olefins	ASTM D1319	vol %		Report		1.6
Composition, saturates	ASTM D1319	vol %		Report		65.4
Cetane Number	ASTM D613		40.0		50.0	42.5
Cetane Index	ASTM D976		40.0		50.0	44.0
Net heat content	ASTM D240	btu/lb		Report		18413
HFRR @60° C	ASTM D6079	mm		Report		0.612

Table 9. Test Vehicle information

Vehicle Information	HEV Tractor	Diesel Tractor
Chassis Manufacturer/Model	Kenworth T370	Freightliner M2106
Chassis Model Year	2010	2009
Engine Manufacturer/Model	PACCAR PX-6 260	Cummins ISC-285
EPA Emissions Certification	2007	2007
CARB Emissions Certification	2008 (Clean Idle)	2008 (Clean Idle)
Engine Ratings		
Max. Horsepower	280 HP @ 2,300 RPM	285 HP @ 2,000 RPM
Max. Torque	660 lb-ft @ 1,600 RPM	800 lb-ft @ 1,300 RPM
Fuel Capacity	56 gallons	80 gallons

Vehicle Information	**HEV Tractor**	**Diesel Tractor**
Transmission Manufacturer/Model	Eaton Fuller UltraShift Automatic	Eaton Fuller T-14607 Manual 7 speed
Front Axle load lbs	12,000	12,000
Rear Axle load lbs	22,700	22,700
GVMR lbs	34,700	34,700
GVCM lbs	55,000	58,000
Odometer	6,531	58,683
Tire Size	275/80R22.5	275/80R22.5
Tire Make	Michelin	Michelin
Tire Tread Depth	Front-1/2, Rear-7/8	Front-3/8, Rear-3/8
Tire Pressure	100 psi	110 psi
Axle Ratio	5.38	3.58