NATIONAL HYBRID TRUCK MANUFACTURING PROGRAM

Hydraulic Hybrid Parcel Delivery Truck Deployment, Testing & Demonstration

Final Report

DOE Contract Number DE-FC26-06NT42791

Prepared by:

Jean-Baptiste Gallo
Project Engineer
CALSTART
(626) 744-5605 (work)
(626) 744-5610 (fax)
jgallo@calstart.org

3/7/2014

Disclaimer

Acknowledgements

CALSTART would like to express its appreciation to the U.S Department of Energy for providing funding for this project. This material is based upon work supported by the Department of Energy under Award Number DE-FC26-06NT42791.

The author would like to thank Freightliner Custom Chassis Corporation for providing technical support to the project and to FedEx Ground, Purolator and UPS who purchased the three first hydraulic hybrid pre-production parcel delivery vehicles and deployed the vehicles in commercial operation. In particular, the author expresses his appreciation to all fleet maintenance staff, drivers and mechanics who facilitated the in-use data collection and on-road testing activities.

Finally the author expresses his appreciation to Parker Hannifin and particularly to Tamar Williamson and Prasad Venkiteswaran who provided their technical expertise and advice throughout the entire project.

Abstract

Although hydraulic hybrid systems have shown promise over the last few years, commercial deployment of these systems has primarily been limited to Class 8 refuse trucks. In 2005, the Hybrid Truck Users Forum initiated the Parcel Delivery Working Group including the largest parcel delivery fleets in North America. The goal of the working group was to evaluate and accelerate commercialization of hydraulic hybrid technology for parcel delivery vehicles. FedEx Ground, Purolator and United Parcel Service (UPS) took delivery of the world's first commercially available hydraulic hybrid parcel delivery trucks in early 2012. The vehicle chassis includes a Parker Hannifin hydraulic hybrid drive system, integrated and assembled by Freightliner Custom Chassis Corp., with a body installed by Morgan Olson.

With funding from the U.S. Department of Energy, CALSTART and its project partners assessed the performance, reliability, maintainability and fleet acceptance of three pre-production Class 6 hydraulic hybrid parcel delivery vehicles using information and data from in-use data collection and on-road testing. This document reports on the deployment of these vehicles operated by FedEx Ground, Purolator and UPS. The results presented provide a comprehensive overview of the performance of commercial hydraulic hybrid vehicles in parcel delivery applications. This project also informs fleets and manufacturers on the overall performance of hydraulic hybrid vehicles, provides insights on how the technology can be both improved and more effectively used.

The key findings and recommendations of this project fall into four major categories:

- Performance,
- Fleet deployment,
- Maintenance,
- Business case.

Hydraulic hybrid technology is relatively new to the market, as commercial vehicles have been introduced only in the past few years in refuse and parcel delivery applications. Successful demonstration could pave the way for additional purchases of hydraulic hybrid vehicles throughout the trucking industry. By providing unbiased, third-party assessment of this "hybrid without batteries" technology, this report offers relevant, timely and valuable information to the industry.

Table of Contents

List of Figures

List of Tables

Executive Summary

Although hydraulic hybrid vehicle (HHV) systems have shown promise over the last few years, commercial deployment of these systems has been primarily limited to Class 8 refuse trucks. In 2005, the Hybrid Truck Users Forum initiated the Parcel Delivery Working Group including the largest parcel delivery fleets in North America. The goal of the working group was to evaluate and accelerate the commercialization of hydraulic hybrid technology for parcel delivery vehicles.

One of the biggest challenges for this deployment and testing program was in the long lead time that was required to place into service acceptable vehicles. The working group initially selected a promising supplier team that ultimately could not perform. As a result, selection of the right supplier team took several years and Parker Hannifin and Freightliner Custom Chassis Corp. were ultimately chosen in 2010 to build three hydraulic hybrid parcel delivery trucks. Once selected, vehicle development further delayed the project timeline and ultimately placed constraints on the project in terms of field time with the units and some flexibility of testing approaches (see Appendix A). These lessons from field experience stress the long lead times that are needed to manufacture an integrated system and highlight the still early state of hydraulic hybrid commercialization.

Despite these constraints, the report also documents the real-world benefits of a fully integrated series hydraulic hybrid system. FedEx Ground, Purolator and UPS took delivery of the world's first commercially available hydraulic hybrid parcel delivery trucks in early 2012. The vehicle chassis includes a Parker Hannifin hydraulic hybrid drive system, integrated and assembled by Freightliner Custom Chassis Corp., with a body installed by Morgan Olson (Figure ES-1).

Figure ES-1: The three FCCC / Parker Hannifin hydraulic hybrid vehicles (Photos courtesy Morgan Olson)

With funding from the U.S. Department of Energy, CALSTART and its project partners assessed the performance, reliability, maintainability and fleet acceptance of three pre-production Class 6 hydraulic hybrid parcel delivery vehicles using information and data from in-use data collection and on-road testing. This document reports on the deployment of these vehicles operated by FedEx Ground, Purolator and UPS. The results presented provide a comprehensive overview of the performance of commercial hydraulic hybrids in parcel delivery applications. This project also informs fleets and manufacturers on the overall performance of hydraulic hybrid vehicles, provides insights on how the technology can be both improved and more effectively used.

Hydraulic hybrid technology is relatively new to the market, as commercial vehicles have been introduced only in the past few years in refuse and parcel delivery applications. Successful demonstration could pave the way for additional purchases of hydraulic hybrid vehicles throughout the trucking industry. By providing unbiased, third-party assessment of this "hybrid without batteries" technology, this report offers relevant, timely and valuable information to the industry.

Performance Evaluation

The performance evaluation carried out for this project evaluated 3 HHVs (Unit A, B and C) operating on several parcel delivery routes from November 2012 to August 2013. The in-use data collection and on-road emissions testing provided a better understanding of HHV technology and evaluated performance in real-world parcel delivery application. We summarize below the main findings and recommendations derived from the performance evaluation.

- *HHVs show their best potential on operating areas characterized by low driving speeds and high number of stops.*

Please note that no data was collected on Unit A. Therefore, Unit A was not considered in the following parts of this report.

We used general parcel delivery baseline data and our knowledge of parcel delivery routes to estimate the fuel economy improvement of Unit B on Route 3.

A conventional diesel truck was equipped with a data acquisition system to collect vehicle and route information for baseline comparison with Unit C. The conventional diesel truck and Unit C operated on two parcel delivery routes (Route 1 and Route 2) at different times in the performance evaluation period. This allowed for close comparison of vehicle performance between the two vehicles on two parcel delivery routes. One driver is generally assigned to one specific route, which minimized the impact of driver behavior in the vehicle performance comparison.

Each route consisted of two distinct operating areas: Highway / Arterial, characterized by high driving speeds and low number of stops and Pick-up & Delivery, characterized by low driving speeds and high number of stops. Table ES-1 below summarizes the performance of HHVs on selected parcel delivery routes.

Table ES-1: Summary of HHV performance on selected parcel delivery routes

	Route 1	Route 2	Route 3
Total Daily Miles	53.1 miles	72.3 miles	73.6 miles
Average Speed (>0)	17.4 MPH	20.3 MPH	17.9 MPH
Stops per mile	3.73	3.29	5.10
Elevation Gain/Loss	7383 ft. / -7364 ft.	7595 ft. / -7558 ft.	3823 ft. / -3819 ft.
Fuel Economy Improvement	Best +22.8%	Best 23.3%	~30 – 40% (estimated)
Pick-up & Delivery	*Best +29.0%*	*Best +34.6%*	*~40 – 50%* (estimated)
Hwy/Arterial	*Best +7.0%*	*Best +4.7%*	*~5 – 10%* (estimated)
Miles Engine Off	15.5%	16.2%	13.4%
Avg. Daily Engine Off Driving Time	41 min.	52 min.	50 min.
Avg. Daily Engine Off @ Zero Speed Time	80 min.	115 min.	35 min.

At best, Unit C showed an average fuel economy improvement of 22.8% over the baseline on Route 1 and 23.3% on Route 2. We estimated that Unit B showed a fuel economy improvement of 30 to 40% over a comparable baseline on Route 3.

The highest fuel economy improvements over the baseline were observed on the Pick-up & Delivery operating areas: up to 34.6% for Unit C on Route 2 and an estimated 40 to 50% for Unit B on Route 3. These results confirmed the advantage of hydraulic hybrid technology on operating areas characterized by low average speeds and high number of stops.

Depending on operating conditions such as terrain, driver behavior and driving / traffic conditions, some fuel savings were achieved on operating areas characterized by high driving speeds and low number of stops, but savings remained small.

- *Driver behavior that is better adapted to the operation of HHVs would lead to better performance.*

Table ES-2 below looks at the time spent with the engine off while the vehicle is not moving.

Table ES-2: Comparison of engine off at zero speed times for Unit B and Unit C

	Cumulative Engine Off @ Zero Speed Time	Avg. Daily Engine Off @ Zero Speed Time
Unit B	18.2 hours	33 minutes
Unit C	191.7 hours	104 minutes

We can see that Unit B spent an average of 33 minutes each day with the engine off while the vehicle was not moving and Unit C, 104 minutes.

We noticed that some drivers took advantage of the advanced engine off feature to leave their vehicle “key on” while delivering packages. Leaving the hydraulic system energized allows stored energy to be depleted without doing useful work and ultimately increases fuel consumption. We showed on a particular day that fuel economy could have been over 6% better if the driver had not left his vehicle “key on” while delivering packages.

On the other hand, keeping the vehicle in the key on position with the engine off while delivering packages was seen as an advantage by some drivers who could save time by not having to switch on and off the vehicle for each stop.

- *The advanced engine off feature provides significant benefits to HHVs.*

Both HHVs took advantage of the engine off feature to operate on hydraulic power only. Unit B drove 1,605 miles and Unit C 1,838 miles with the engine off. Figure ES-2 below compares engine off driving miles for Unit B and Unit C.

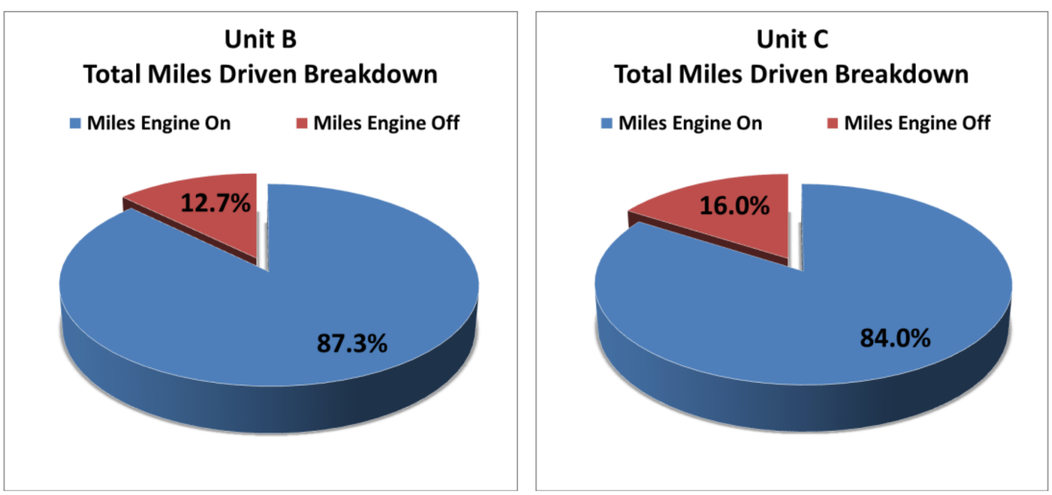


Figure ES-2: Comparison of engine off driving miles for Unit B and Unit C

Unit B drove an average of 12.7% of total miles on hydraulic power only and Unit C, 16.0%. Table ES-3 below compares the engine off driving times for Unit B and Unit C.

Table ES-3: Comparison of engine off driving times for Unit B and Unit C

	Cumulative Engine Off Driving Time	Avg. Daily Engine Off Driving Time
Unit B	26.5 hours	48 minutes
Unit C	88.9 hours	48 minutes

Both Unit B and Unit C spent an average of 48 minutes per day driving with the engine off.

- *HHVs are more efficient and cleaner to operate than conventional diesel vehicles.*

One FCCC / Parker Hannifin HHV was tested by Engine, Fuel, and Emissions Engineering, Inc. to compare in-service pollutant emissions to a conventional diesel package delivery truck. Measurements were conducted while the test vehicle followed and "shadowed" a package delivery truck in normal operation. Table ES-4 below summarizes the results of the on-road emissions testing.

Table ES-4: On-road emissions testing summary results

Operating Area	2008 FCCC MT-55 Diesel			2012 FCCC MT-55 HHV		
	Fuel Economy	CO_2 Emissions	NO_x Emissions	Fuel Economy	CO_2 Emissions	NO_x Emissions
Hwy/Arterial 1	11.64 MPG	1189.03 g/mi	1.83 g/mi	10.96 MPG	1107.66 g/mi	3.21 g/mi
Pick-up & Delivery	7.97 MPG	1390.45 g/mi	5.46 g/mi	11.20 MPG	1095.65 g/mi	4.13 g/mi
Hwy/Arterial 2	9.16 MPG	-	-	9.74 MPG	1261.55 g/mi	1.20 g/mi
Total	8.44 MPG	1364.28 g/mi	5.07 g/mi	10.92 MPG	1127.10 g/mi	3.53 g/mi

We find that the HHV is more efficient and cleaner to operate than a similar conventional diesel vehicle. With an average fuel economy of 10.92 MPG, the HHV showed a fuel economy improvement of 29.4% over the baseline. It produced 17.4% less CO_2 per mile and 30.4% less NO_x per mile than the conventional diesel.

The HHV showed its best potential in operating areas characterized by low driving speeds and high number of stops. With an average fuel economy of 11.20 MPG, the HHV achieved a fuel economy improvement of 40.5% over the baseline on the Pick-up & Delivery operating area. It produced 21.2% less CO_2 per mile and 24.4% less NO_x per mile than the conventional diesel.

The HHV produced 13.9% more CO_2 per mile in the Highway / Arterial 2 operating area than in the Highway / Arterial 1. This was expected as the HHV is heavier due to the HHV system and Highway / Arterial 1 is for a large part going downhill, while Highway / Arterial 2 goes uphill. However, the HHV produced 62.6% less NO_x per mile in the Highway / Arterial 2 operating area than in the Highway / Arterial 1. Looking at the exhaust temperature, we showed that these higher emissions were most likely due to poor NO_x conversion efficiency of the SCR system at cold start and are most likely not attributable to the HHV system.

User Acceptance

The user acceptance surveys and interviews showed a good acceptance of the FCCC / Parker Hannifin HHV by drivers and mechanics. Drivers recognized the superior braking behavior and acceleration capabilities of the HHV and acknowledged the quality of the vehicle manufacturing. Drivers complained about issues with initial launch from stand still caused by lags at take-off, especially when taking off up-hill. Lastly some drivers complained about elevated vehicle noise.

The user acceptance surveys and interviews also revealed a gap in driver training. We believe driver training is essential to ensure better acceptance of hydraulic hybrid trucks and successful hybrid vehicle deployments overall. Drivers are more likely to adopt and accept a vehicle if they are better trained on its operation.

Service and Maintenance

The service and maintenance evaluation carried out for this project collected general maintenance information and estimates of maintenance costs and benefits. The evaluation of the FCCC / Parker Hannifin HHV reported limited vehicle availability issues that were expected with pre-production vehicles and identified several opportunities for maintenance savings compared to conventional vehicles. Lastly, the evaluation also found some service and maintenance improvement opportunities.

- *Pre-production vehicle issues*

One unit encountered some issues that made the vehicle slightly less available than a conventional diesel truck. For instance, the vehicle experienced a HHV system failure early after the vehicle was put in commercial service. In addition, all three pre-production vehicles encountered issues with the vehicle odometer not recording mileage when the engine was off. Lastly, one unit faced issues with the air compressor governor, which prevented the engine from shutting off and resulted in higher fuel consumption.

- *Opportunities for savings*

The Parker Hannifin HHV system dramatically reduced 12V DC starter use (99% less starter use per day) compared to a conventional diesel truck. In addition, front brake pad wear was dramatically improved: preliminary estimates showed front brake life could be increased by 6 times over a conventional diesel truck. Lastly, the advanced engine off strategy allowed one unit to drive up to 16.2 miles with the engine off for each 100 miles driven on one particular parcel delivery route, eliminating an average of 75 minutes of engine run time per day despite air compressor governor issues and driver behavior not fully adapted to the operation of hydraulic hybrid vehicles.

A more complete analysis is needed to further investigate and understand the potential maintenance savings of HHVs.

- *Potential for improvement*

For pre- and early production vehicles, vehicle warranty should be extended to meet the useful life of the vehicles to encourage fleets and independent contractors to purchase hydraulic hybrid vehicles without fearing that vehicles will not be profitable once they come out of warranty. In addition, the vehicles have special parts that may complicate in-house servicing. At this early stage of vehicle deployment, fleets are forced to take vehicles to their dealership for repairs, which increases vehicle down-time and ultimately maintenance costs. Returning vehicles quickly when maintenance issues arise is important.

Lastly, a preliminary analysis identified that one HHV experienced accelerated wear on the rear tires while operating on two distinct parcel delivery routes. The cost to replace a set of 4 rear tires can represent a significant expense over the life of the vehicle and cancel other benefits such as fuel saved or other maintenance savings. A more complete and in-depth analysis into this last issue is needed to further investigate and validate the findings of this report.

Business Case

The business case for high-efficiency vehicles is important to understand in the early stages of market introduction. High-efficiency vehicles such as HHVs have higher upfront costs than similar diesel or gasoline trucks but will have lower operation and maintenance costs. With increased fuel economy and lower maintenance costs, HHVs can be cost effective. Three conditions need to be met to achieve a return on investment:

- High fuel economy increase,
- High maintenance savings,
- Low incremental cost.

The in-service performance evaluation showed pre-production HHVs achieving fuel economy improvements of up to 30% on selected parcel delivery routes. With an optimized HHV system, compatible driver behavior and vehicles operating in optimal driving cycles, we expect HHVs to achieve greater fuel economy improvements. The service and maintenance evaluation identified several opportunities for maintenance savings such as 12V DC starter use, front brake pad wear, increased engine and engine components life.

At this early stage in the HHV market, incentives for purchase can reduce incremental costs allowing attractive returns on investment and increasing fleet purchases. With more sales, HHV system cost savings can be achieved, improving the business case for HHVs.

Findings & Recommendations

To inform fleets and hydraulic hybrid vehicle manufacturers on the overall performance of HHVs and to provide insights on how the technology can be improved and better used, we developed the following list of findings and recommendations:

- Operating conditions impact HHV performance.
- HHVs are more efficient and cleaner to operate.
- Operating routes need to be carefully selected.
- Driver behavior should be managed to achieve best performance.
- Accelerated rear tire wear can negatively impact the business case for HHVs.
- HHVs show opportunities for lower maintenance costs.
- HHVs can achieve ROI with high fuel and maintenance savings and low incremental cost.
- Incentives for purchase play an important role for the early HHV market.

Chapter 1: Introduction

CALSTART proposed to accelerate the growth of the domestic hybrid truck industry via the National Hybrid Truck Manufacturing Program (NHTMP) in partnership with the U.S. Department of Energy (DOE). The NHMTP built on the success of the multi-year High-efficiency Truck Users Forum (HTUF) program, which has already established the base partnerships with industry and major national fleets.

The goals of the NHTMP were to help move medium- and heavy-duty hybrid technology closer to commercial viability, and to provide important assessments of the technical, performance and manufacturing gaps still remaining for broad hybrid system utilization. In particular, the program focused on:

- Providing valuable hybrid technology testing data for the DOE and stakeholders.
- Providing technology manufacturing assessment and validation for truck and system makers.
- Validating performance and business case assumptions for fleets.

1.1 Purpose of the Report

This report presents the deployment, testing and demonstration results of three pre-production hydraulic hybrid vehicles (HHVs) in parcel delivery application. The goal of this report is to inform fleets and hybrid truck manufacturers on the overall performance of HHVs and provide insights on how the technology can be improved on the one hand and better used on the other hand. Although hydraulic hybrid systems (HHV systems) have shown promise over the last few years, commercial deployment of these systems has been primarily limited to Class 8 refuse trucks. By providing unbiased, third-party assessment of this technology for the parcel delivery vocation, this report offers relevant, timely and valuable information to the industry.

This project evaluated the performance of one hydraulic hybrid vehicle model that is presented in Chapter 1 along with an overview of hydraulic hybrid technology and current hydraulic hybrid activities in North America. The deployment of the three pre-production HHV is reviewed in Chapter 2 and a comprehensive performance evaluation is covered in Chapter 3 which includes a review of in-use data collection and on-road testing activities. User acceptance is detailed in Chapter 4 followed by a preliminary service and maintenance evaluation of HHVs in Chapter 5. Finally, findings and recommendations are presented in Chapter 6. For more information about the project, please see a complete project timeline in Appendix A.

1.2 Hydraulic Hybrid System Technology

1.2.1 Overview

A hydraulic hybrid vehicle (HHV) uses a regular internal combustion engine and a hydraulic motor to power the wheels. Figure 1 shows a layout of a hydraulic hybrid system (HHV system):

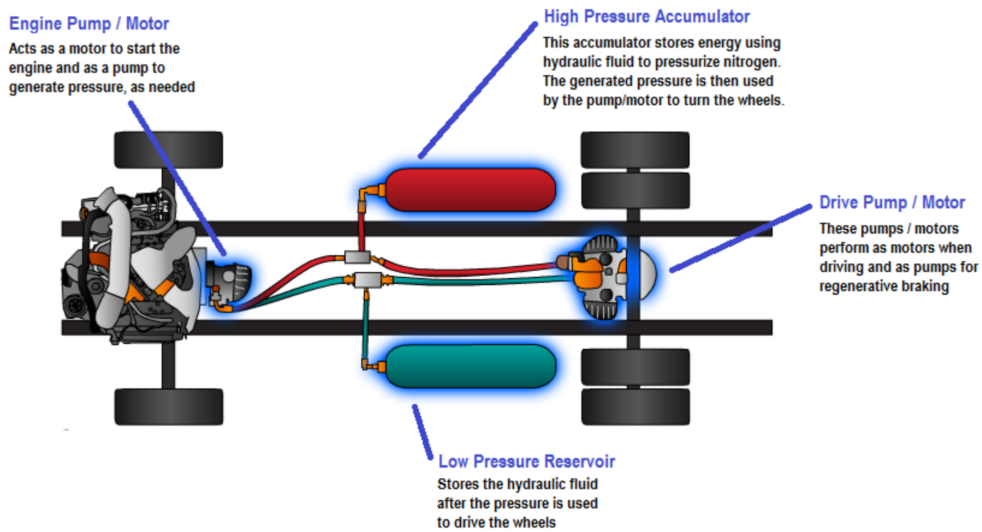


Figure 1: Hydraulic hybrid system layout [1]

HHV systems use four main components to power a vehicle: a low pressure reservoir, a high pressure accumulator, a hydraulic pump, and a hydraulic motor. The high pressure accumulator stores energy by using hydraulic fluid to pressurize a gas. Acting as a motor, the hydraulic drive uses the generated pressure to rotate the wheels. Acting as a pump, the hydraulic drive is used to re-pressurize the gas by using the momentum of the vehicle (regenerative braking). In the layout presented in Figure 1, the diesel engine is used to periodically recharge pressure in the hydraulic propulsion system [2].

There are two types of HHVs: parallel and series. In a parallel HHV, the engine still provides power to the wheels through a standard transmission. The hydraulic components are attached to the driveshaft and assist in stopping and accelerating the vehicle. In a series HHV, the conventional transmission and driveline are replaced by the hydraulic hybrid powertrain. Energy is transferred from the engine to the drive wheels through hydraulic power. Series HHV technology is suited to a broader number of applications than parallel hydraulic hybrids, although benefits will be highest in vehicles that operate in stop-and-go duty cycles [2].

To learn more, visit the Hydraulic Hybrid Research webpage of the EPA Office of Transportation and Air Quality at: http://www.epa.gov/otaq/technology/research/research-hhvs.htm.

1.2.2 Benefits of Hydraulic Hybrid Vehicles

Hydraulic hybrid technology presents several benefits that make it well suited for application in commercial vehicles [2]:

- **Simple** - The technology relies on a mature off-highway vehicle market from lawn and garden equipment to large earth-moving machines. As a result, it does not require breakthroughs to be manufactured, and can be produced with already available skills and manufacturing base.
- **Efficient** - Series HHVs can dramatically increase fuel efficiency.
- **Clean** – By reducing fuel use, HHVs can also reduce the emission of greenhouse gases and criteria pollutants.
- **Cost-effective** - The low cost to manufacture combined with reduced brake maintenance and increased fuel efficiency can result in thousands of dollars saved over the lifetime of the vehicle.

Series HHVs show the best potential for increased fuel efficiency. Three key design features help series HHVs achieve maximum fuel efficiency [3]:

- **Brake Energy Recovery** – HHVs are capable of capturing and returning over 70% of the energy normally wasted during braking. By comparison, hybrid electric vehicles (HEV) are generally credited with capturing and returning less than 25% of braking energy (Figure 2).

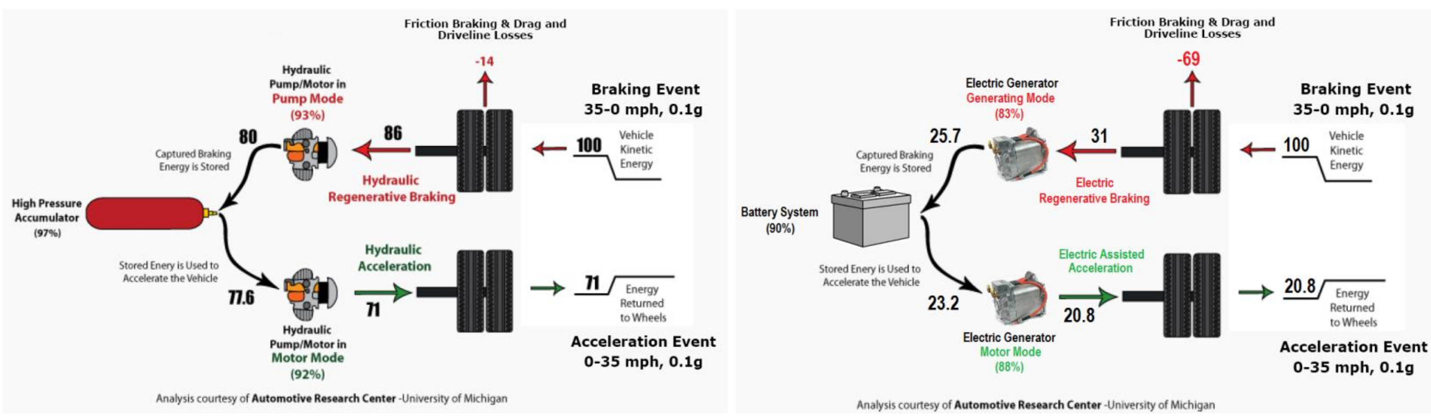


Figure 2: Comparison of brake energy recovery between hydraulic hybrid and hybrid electric [4]

- **Shutting Engine Off When Not Needed** – With power steering provided by the HHV system and air brakes not depending on the engine running all the time, HHVs can be operated on stored hydraulic power only, eliminating engine idling and launching or running the vehicle when possible.
- **Optimized Engine Control** – Since the engine is decoupled from the drive wheels, it is allowed to operate at a "sweet spot" of best fuel consumption and lower emissions for a given power level.

Similar to a HEV, the performance of a HHV will depend greatly on the drive / duty cycles on which the vehicle is operated. An HHV highly efficient regenerative braking system and ability to operate in engine off modes of operation make it ideal for vehicles that operate in more urban drive / duty cycles characterized by lower speeds and higher number of stops.

1.2.3 Comparison with Hybrid Electric Vehicles

Compared to HEVs, HHVs have higher power density and lower energy density (Figure 3).

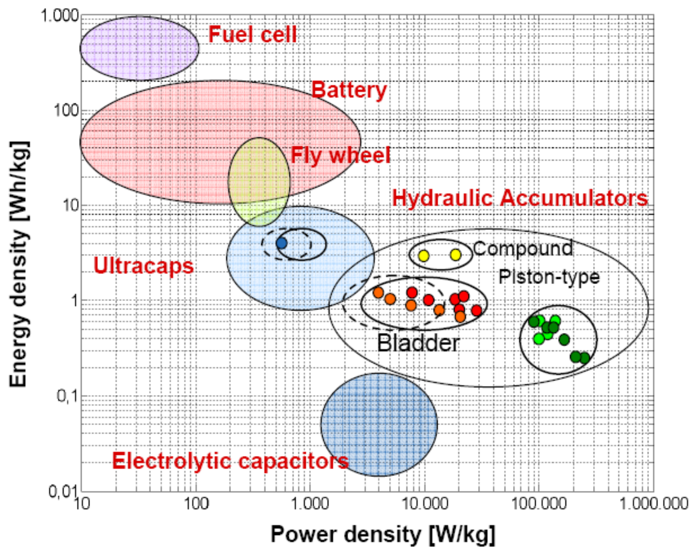


Figure 3: Power density versus energy density for several energy storage devices [5]

This characteristic translates into several advantages and disadvantages over HEVs [5]:

HHVs Have Higher Power Density

- Hydraulic accumulators are better suited than batteries for capturing and utilizing short duration brake energy.
- They take less time to collect and store braking energy than batteries, and are roughly comparable to ultracapacitors, while batteries need a relatively long charging time, making it more difficult to fully recapture the braking energy.
- Accumulated energy can be called upon as needed and be released in short periods of time.
- HHV systems provide higher torque than hybrid electric systems.
- HHVs leverage proven technologies and with no batteries have the potential for lower lifecycle cost than HEVs.

HEVs Have Higher Energy Density

- Hybrid electric systems can absorb a great deal of energy while hydraulic accumulators have limited energy storage capacity.
- HEVs can run for extended run times and easily provide auxiliary electric power source and extended peak load reduction.

1.3 Hydraulic Hybrid Vehicle Market

Although hydraulic hybrid systems have shown promise over the last few years, commercial deployment of these systems has been mostly limited to Class 8 refuse trucks because those vehicles presented a highly promising duty cycle for the technology. Building on successes in the refuse market, several companies moved on to the parcel delivery vocation as another application for hydraulic hybrid technology.

1.3.1 Hydraulic Hybrid Refuse Trucks

In the last few years, the hybrid vehicle market has seen an increasing growth of hydraulic hybrid refuse truck purchases across the U.S. and Canada. We estimate that over 240 hydraulic hybrid refuse trucks have been purchased in North America. The value proposition for hydraulic hybrid refuse trucks relies on the following benefits [6]:

- Reduced fuel consumption and emissions,
- Increased productivity,
- Better drivability and reduced noise,
- Lower operating costs.

Figure 4 shows three hydraulic hybrid refuse truck models currently deployed by various fleets across North America: the Eaton Hydraulic Launch Assist (HLA) on a Peterbilt platform, the Bosch-Rexroth parallel Hydrostatic Regenerative Braking system (HRB) on a Mack Truck chassis, and the Parker Hannifin RunWise Advanced Series Hybrid Drive on an Autocar platform.

Figure 4: (from left to right) a Peterbilt 320 with the Eaton HLA, the Mack LEU613 with the Bosch Rexroth HRB and the Autocar Xpeditor E3 with the Parker RunWise

In September 2013, Eaton Corporation discontinued its Hydraulic Launch Assist leaving the refuse hybrid market to Parker Hannifin and its RunWise Advanced Series Hybrid Drive (Bosch Rexroth has not fully commercialized its Hydrostatic Regenerative Braking system) [7]. With the benefit of lower fuel costs per gallon and abundant supply, some customers are electing to purchase refuse trucks powered by Compressed Natural Gas (CNG).

Parker Hannifin is currently working with Autocar to develop a commercially available RunWise hybrid fueled with CNG. The RunWise system fueled with CNG is said to reduce actual fuel consumed, significantly improve productivity from can to can, and reduce emissions over a baseline CNG vehicle. In October 2013, Parker Hannifin displayed an Autocar CNG E3 proof of concept vehicle featuring Parker Hannifin's RunWise Advanced Series Hydraulic Hybrid at the latest HTUF national meeting in Chicago, IL [8].

1.3.2 U.S. EPA / Eaton Corporation Hydraulic Hybrid Parcel Delivery Truck

In 2001, Eaton Corporation signed a Cooperative Research and Development Agreement with the U.S. Environmental Protection Agency (EPA) to develop hydraulic hybrid components and systems. The EPA, Eaton Corporation, International Truck and Engine Corporation, UPS, and the U.S. Army partnered to build the world's first hydraulic hybrid parcel delivery truck. This vehicle, a Class 6 International 1652 SC chassis with a VT-365 engine, was first shown publicly in June 2006 (Figure 5) [9].

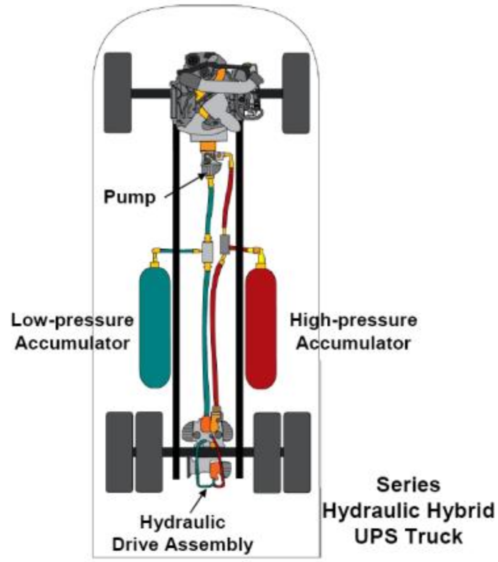


Figure 5: The U.S. EPA / Eaton hydraulic hybrid parcel delivery truck (left) and the description of the Eaton series hydraulic hybrid system [9]

The Eaton HHV system demonstrated 50 - 70% better fuel economy than a standard UPS truck over the EPA City Cycle with no degradation in performance. In addition, a UPS truck equipped with the series hybrid hydraulic drivetrain was put into service in the Detroit area in 2006 and 2007 and achieved 45 - 50% better fuel economy in "real world" use [9].

In 2010, Eaton Corporation discontinued its hydraulic hybrid parcel delivery vehicles activities.

1.3.3 FCCC / Parker Hannifin Hydraulic Hybrid Walk-in Chassis

With more than 20 years of experience with hydraulic hybrid technology and a successful commercial deployment of the RunWise Advanced Series Hybrid Drive in the refuse vocation, Parker Hannifin developed a hydraulic hybrid system for Class 4 – 6 medium duty trucks (Figure 6).

Figure 6: The FCCC / Parker Hannifin hydraulic hybrid walk-in van [10]

Like the RunWise system, the new Parker Hannifin HHV system is an advanced series hybrid drive (Figure 7). The heart of the system is a power-split transmission or Infinitely Variable Transmission that combines the features of both series hybrid and parallel hybrid in a highly efficient dual path (mechanical and hydraulic) operating system [3]. Appendix B shows how the Parker Hannifin hydraulic hybrid power split transmission functions in different operating conditions.

Figure 7: The Parker Hannifin HHV system [10]

The Parker Hannifin HHV system excels in stop-and-go applications where the system can recover the maximum braking energy and maximize the advanced engine off feature that shuts off the internal combustion engine when not needed. The system also excels in extended cruising or highway operations where the HHV system enables engine management and the majority of power is conveyed from the engine by way of mechanical path. The HHV system functionality of the series hybrid system also facilitates the operation of the engine at a "sweet spot" of best fuel consumption and lower emissions [3].

Freightliner Custom Chassis Corporation (FCCC), working with Parker Hannifin, has developed a hydraulic hybrid walk-in van chassis integrating the Parker Hannifin HHV system on the MT-55 chassis (Figure 8), the predominant chassis for walk-in vans in North America. Appendix C shows a layout of the FCCC MT-55 walk-in van chassis equipped with the Parker Hannifin HHV system.

Figure 8: The FCCC / Parker Hannifin hydraulic hybrid walk-in chassis [11]

The FCCC / Parker Hannifin MT-55 walk-in van chassis is equipped with a Cummins ISB10 engine, certified for EPA 2010 emission standards and is available in different Gross Vehicle Weight Ratings (GVWR) from 20,500 to 27,000 lbs. Table 1 below details the technical characteristics of the vehicle as tested in this project.

Table 1: FCCC / Parker Hannifin hydraulic hybrid vehicle characteristics

General	
Model Year	2012
Chassis Manufacturer	FCCC (MT-55 Model)
Body Manufacturer	Morgan Olson
GVWR	23,000 lbs.
Curb Weight	13,800 lbs.
Engine	
Model	Cummins ISB10 6.7L
Peak Power	280 HP (209 kW) @ 2,300 RPM
Peak Torque	660 ft-lbs. (895 Nm) @ 1,600 RPM
Fuel System	ULSD / 30-gallon fuel tank
Exhaust System	SCR and DPF 10-gallon DEF tank (2-3% injection rate)
Dimensions	
Tires	245/70 R19.5
Wheelbase	178 in.
Overall Length	303 in.
Overall Width	88.62 in.
Overall Height	30 in.
Hydraulic Hybrid System	
Make	Parker Powersplit Hybrid Series System
Type	Infinite Variable Advanced Series Transmission
Oil Capacity	Gearbox – 9 liters / System - 29 gallons
Components Weight	~ 1,700 lbs.

Due to the addition of the Parker Hannifin HHV system, the vehicle curb weight is about 1,700 lbs. more than for a conventional diesel MT-55 vehicle. In comparison, the Eaton hybrid electric system integrated on a MT-55 chassis weighs about 1,200 lbs. more than a conventional diesel MT-55 vehicle [12].

FCCC, Parker Hannifin and Morgan Olson built three pre-production HHVs for this project. In April 2012, FedEx Ground announced it would purchase 5 more units to be deployed in California and Michigan and in October 2012, UPS announced it would purchase 40 more units to be deployed in Maryland and Georgia. There are currently 48 pre-production FCCC / Parker Hannifin hydraulic hybrid walk-in vans in trial service across North America (Figure 9).

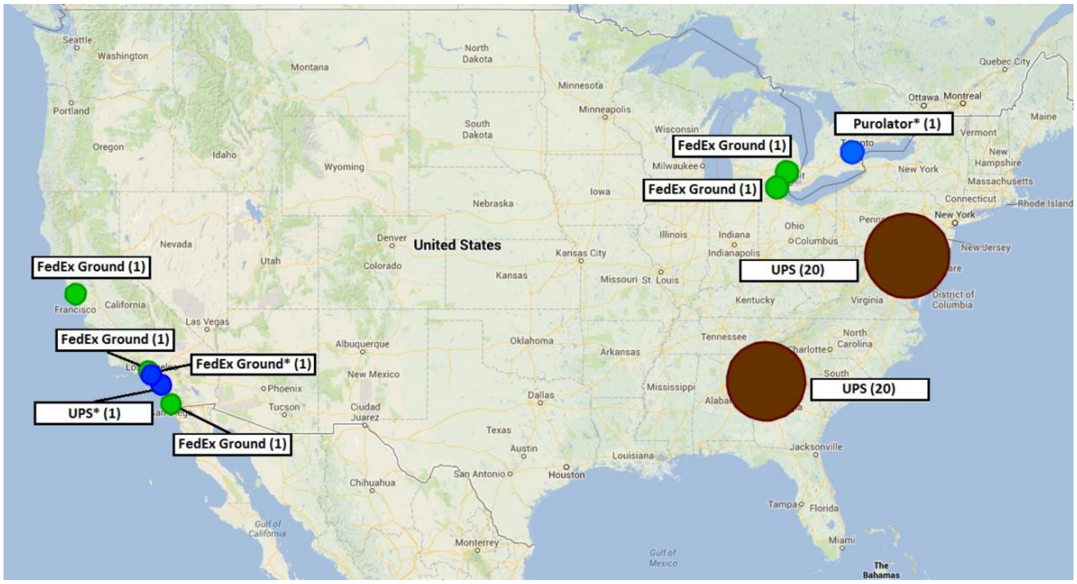


Figure 9: Map of current FCCC / Parker Hannifin hydraulic hybrid parcel delivery trucks deployment (in blue the three units purchased for this project)

1.4 Project Team

The project team was composed of the following partners:

The **U.S. Department of Energy** (DOE) provided funding for this project, including a grant to reduce the incremental cost of the three first hydraulic hybrid pre-production parcel delivery vehicles.

CALSTART administered, managed and coordinated the project for the DOE. In addition, CALSTART collected and analyzed in-use data from the three hydraulic hybrid pre-production parcel delivery vehicles and oversaw the on-road testing of one hydraulic hybrid pre-production parcel delivery vehicle.

Parker Hannifin Corporation (Parker) engineered and manufactured the three first hydraulic hybrid pre-production parcel delivery vehicles. In addition, Parker provided technical support and expertise to the project as well as additional in-use data to supplement CALSTART's data collection effort.

Freightliner Custom Chassis Corporation (FCCC) integrated and assembled the three first hydraulic hybrid pre-production parcel delivery vehicles. In addition, FCCC provided technical support to the project.

Morgan Olson provided bodies for the three first hydraulic hybrid pre-production parcel delivery vehicles.

FedEx Ground purchased one of the three first hydraulic hybrid pre-production parcel delivery vehicles and deployed the vehicle in commercial operation.

Purolator purchased one of the three first hydraulic hybrid pre-production parcel delivery vehicles and deployed the vehicle in commercial operation.

United Parcel Service (UPS) purchased one of the three first hydraulic hybrid pre-production parcel delivery vehicles and deployed the vehicle in commercial operation.

Chapter 2: Vehicle Deployment

Three pre-production hydraulic hybrid vehicles were built by FCCC, Parker Hannifin and Morgan Olson. The vehicles were delivered to the three partner fleets for their acceptance, validation and deployment, setting the stage for the performance evaluation phase. Each fleet purchased one vehicle from FCCC at a discounted price. The incremental cost of each pre-production vehicle was reduced by almost two thirds using allocated project funds as the offset.

2.1 Static and Pass-By Noise

Hydraulic drive systems generate characteristic noise and vibration when installed in vehicles [13]. The early pre-production vehicles experienced some difficulty to pass Federal Motor Vehicle Safety Standards static and pass-by noise tests which delayed the vehicle deployment phase. Two noise mitigation components were added on the three pre-production vehicles to pass the tests. A long term solution will be implemented on production trucks to pass the static and pass-by noise tests without the noise mitigation measures.

2.2 Fleet Deployment

One of the biggest challenges for this deployment and testing program was in the long lead time that was required to place into service acceptable vehicles. The working group initially selected a promising supplier team that ultimately could not perform. As a result, selection of the right supplier team took several years and Parker Hannifin and Freightliner Custom Chassis Corp. were ultimately chosen in 2010 to build three hydraulic hybrid parcel delivery trucks. Once selected, vehicle development further delayed the project timeline and ultimately placed constraints on the project in terms of field time with the units and some flexibility of testing approaches (see Appendix A). These lessons from field experience stress the long lead times that are needed to manufacture an integrated system and highlight the still early state of hydraulic hybrid commercialization.

FedEx Ground, Purolator and UPS took delivery of the world's first commercially available hydraulic hybrid parcel delivery trucks in early 2012. Two vehicles were put in commercial service with no issues while the Purolator vehicle experienced some delay in deployment.

2.2.1 FedEx Ground

The FedEx Ground hydraulic hybrid parcel delivery vehicle (Figure 10) was delivered in June 2012 and put in commercial service in November 2012 in Sun Valley, CA. FedEx Ground runs its package delivery service on an independent contractor model [14]. The HHV was purchased by FedEx Ground and provided for free to an independent contractor for an evaluation period of 1 year. At the end of the first 1-year evaluation period, the vehicle went to another independent contractor. No deployment issues were reported.

Figure 10: The FedEx Ground hydraulic hybrid parcel delivery vehicle (Photos courtesy Morgan Olson)

2.2.2 Purolator

The Purolator hydraulic hybrid parcel delivery vehicle (Figure 11) was delivered in June 2012. However, several issues delayed vehicle deployment:

- The vehicle comes with air-brakes which initially created licensing issues and required that drivers be trained to drive air-brake vehicles.
- In addition, the vehicle parking brake air pressure cut-off comes at 70 psi while Ontario law states 60 psi.
- Lastly, minor reliability issues further delayed vehicle deployment.

The Purolator hydraulic hybrid parcel delivery vehicle was finally put in commercial service in May 2013 in Mississauga, Ontario, Canada.

Figure 11: The Purolator hydraulic hybrid parcel delivery vehicle (Photos courtesy Morgan Olson)

2.2.3 UPS

The UPS hydraulic hybrid parcel delivery vehicle (Figure 12) was delivered in April 2012 and put in commercial service in July 2012 in Laguna Hills, CA. No deployment issues were reported.

Figure 12: The UPS hydraulic hybrid parcel delivery vehicle (Photos courtesy Morgan Olson)

Chapter 3: Performance Evaluation

This chapter discusses the performance of pre-production hydraulic hybrid vehicles based on in-use data collection and on-road emissions testing. The three HHVs were monitored for a period of about 10 months to collect summary performance data. In addition, vehicle and powertrain data was continuously recorded for selected periods of time, allowing the closer look into the performance of HHVs. Lastly one unit underwent on-road emissions testing for a period of one day. The results provide a comprehensive overview of the performance of HHVs in parcel delivery applications.

Since the goal of the project was to assess the performance of HHVs in parcel delivery application, we decided to identify each unit by a generic name: Unit A, Unit B and Unit C, instead of using the name of the fleet operating the vehicle.

3.1 General Monthly Summary

3.1.1 Methodology

All three vehicles were equipped with data loggers provided and installed by Parker. Data was collected by Parker who regularly provided monthly summary performance reports, reviewing performance achieved and lessons learned during the assessment.

3.1.2 Results & Discussions

Table 2 below presents the summary of the data that was collected for a period of about 10 months from November 2012 to August 2013.

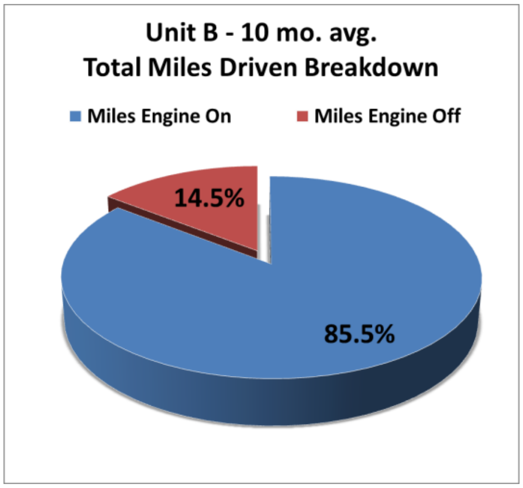
Table 2: Summary of cumulative HHV performance data

	Miles of Operation	Miles Engine Off	Hours Key ON	Hours Engine ON	Fuel Consumed (Gallons)	Fuel Economy (MPG)
Unit A	No data available					
Unit B	11,074	1,605	1,537	556	1,022	10.8
Unit C	11,914	1,838	1,838	633	1,407	8.5

Please note that due to project constraints, including the long delay leading to vehicle deployment and specific problems related to Unit A, no data was collected on Unit A. Therefore, Unit A was not considered in the following parts of this report.

Apart from a few days, Unit C was in operation for the most part during the 10-month period while Unit B was not operated for a period of 2 months because of warranty issues. From November 2012 to August 2013, Unit B drove 11,074 miles and consumed 1,022 gallons of diesel for an average fuel economy of 10.8 MPG. On the other hand, Unit C drove 11,914 miles and consumed 1,407 gallons of diesel for an average fuel economy of 8.5 MPG.

Both vehicles took advantage of the engine off feature to operate on hydraulic power only, eliminating engine idling and launching or running the vehicle when possible. Unit B drove a total of 1,605 miles and Unit C, 1,838 miles with the engine off. Figure 13 below compares engine off driving miles for Unit B and Unit C.



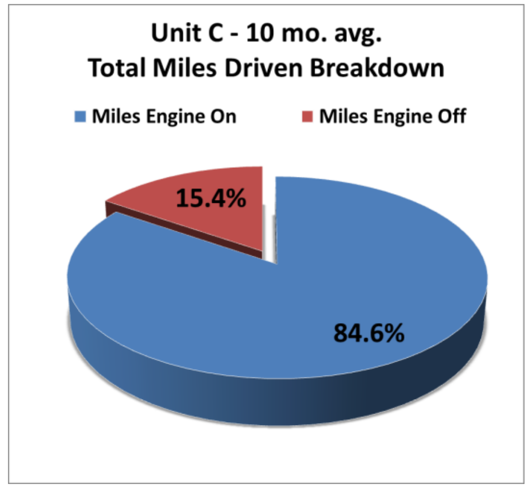


Figure 13: Comparison of engine off driving miles for Unit B and Unit C

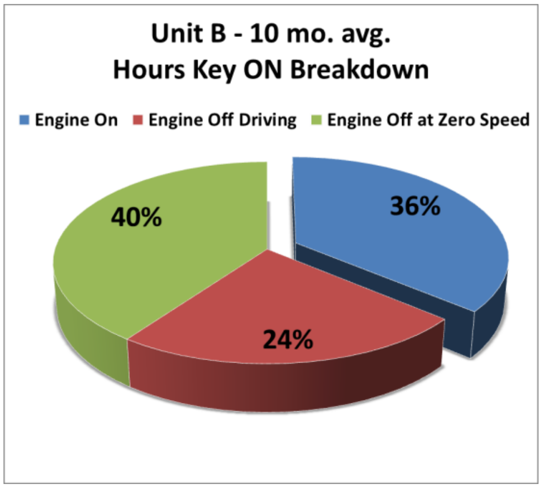
Unit B drove an average of 14.5% of total miles on hydraulic power only. This means that for each 100 miles that Unit B drove, 14.5 miles were done with the engine off. Unit C drove an average of 15.4% of total miles on hydraulic power only. A closer look at the monthly summaries revealed that Unit B spent more time than Unit C driving with the engine off. Table 3 below compares the engine off driving times for Unit B and Unit C.

Table 3: Comparison of engine off driving times for Unit B and Unit C

	Cumulative Engine Off Driving Time	Avg. Daily Engine Off Driving Time
Unit B	366.3 hours	138 minutes
Unit C	153.5 hours	44 minutes

Unit B spent an average of 138 minutes per day driving with the engine off and Unit C only 44 minutes. The data provided in the monthly summaries did not allow further analysis to understand the cause for this difference. We take a closer look at the discrepancy in section 3.2.2.

The monthly summaries also revealed that both Unit B and Unit C spent a large amount of time at idle: meaning, the ignition key is in the on position ("key on") and vehicle speed is equal to zero. Figure 14 below compares engine time for Unit B and Unit C.



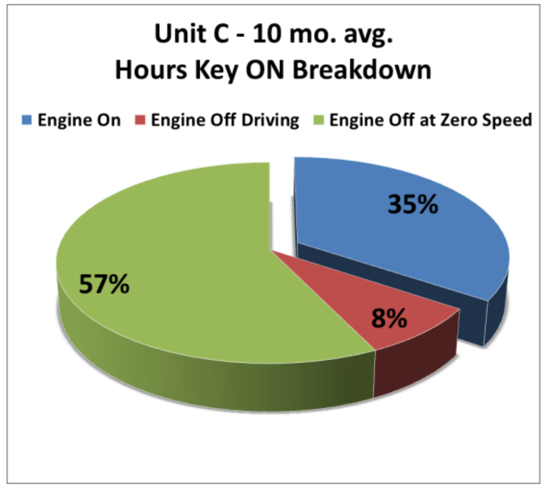


Figure 14: Comparison of engine time for Unit B and Unit C

Unit B spent 40% of the time at zero speed while the engine was on and Unit C, 57%. This means that for each 100 hours that Unit B (Unit C) spent "key on", 40 hours (57 hours) were with the engine off and the vehicle not moving. Table 4 below looks at the time spent with the engine off while the vehicle is not moving in more details.

Table 4: Comparison of engine off at zero speed times for Unit B and Unit C

	Cumulative Engine Off @ Zero Speed Time	Avg. Daily Engine Off @ Zero Speed Time
Unit B	613.1 hours	231 minutes
Unit C	1052.9 hours	299 minutes

Unit B spent an average of 231 minutes each day with the engine off while the vehicle was not moving and Unit C almost 300 minutes.

The confirmation and explanation of this unique operation mode required discussions with drivers and fleet maintenance personnel who acknowledged that drivers take advantage of the advanced engine off feature to leave the vehicle "key on" while delivering packages. While drivers are required to shut off their engines on conventional diesel vehicles to comply with anti-idle regulation and save fuel, the engine off feature of the HHV is seen as an advantage by drivers who can leave their vehicle "ready to go" while delivering packages and thus save precious time by not having to switch on and off the vehicle for each stop.

While it presents an advantage for productivity, keeping the vehicle "key on" while delivering packages presents certain disadvantages. The HHV system is kept energized like a diesel engine would be kept idling. The high pressure accumulator shut-off valve remains open and hydraulic fluid naturally leaks from the high pressure accumulator to the low pressure reservoir, allowing stored energy to be depleted without doing useful work.

3.2 High Resolution Data

3.2.1 Methodology

All three vehicles were equipped with data loggers provided and installed by Parker to continuously record vehicle and powertrain data during vehicle operation. In addition to the general monthly summary reports (see section 3.1), Parker provided upon request high resolution data for the following selected periods of time for both Unit B and Unit C:

- June & July 2013 for Unit B,
- January & June through August 2013 for Unit C.

Although the high resolution data covered a shorter period of time than the general monthly summary reporting period, it allowed to explore deeper into the performance of HHVs by looking into daily vehicles usage and identify driver behavior that impact overall fuel economy.

3.2.2 Results & Discussions

Table 5 below presents the summary of the high resolution data for Unit B and Unit C.

Table 5: Summary of high resolution HHV performance data

	Days in Operation	Miles of Operation	Miles Engine Off	Hours Key ON	Hours Engine ON	Fuel Consumed (Gallons)	Fuel Economy (MPG)
Unit B	33	2,462.6	313.2	173.2	128.6	236.4	10.4
Unit C	111	7,172.6	1147.5	617.8	337.2	782.4	9.2

During the data collection phase, Unit B was in operation on a single route (Route 3) during its 33 recorded days while Unit C was in operation on two separate routes: on Route 1 during 36 recorded days and on Route 2 during 75 recorded days. We take a closer look at these three parcel delivery routes in section 3.3.

In June and July 2013, Unit B drove 2,463 miles and consumed 236 gallons of diesel for an average fuel economy of 10.4 MPG, which is close to the cumulative fuel economy calculated in section 3.1.2. Unit C drove 7,173 miles and consumed 782 gallons of diesel for an average fuel economy of 9.2 MPG, which is better than the cumulative fuel economy calculated in section 3.1.2. This difference can be explained by the fact that from May 13 to August 31, 2013, Unit C operated on Route 2, where route characteristics led to better fuel economy (8.1 MPG on Route 1 versus 9.6 MPG on Route 2).

Both vehicles took advantage of the engine off feature to operate on hydraulic power only. Unit B drove 313 miles with the engine off, while Unit C drove 1,147 miles. Figure 15 below compares engine off driving miles for Unit B and Unit C.

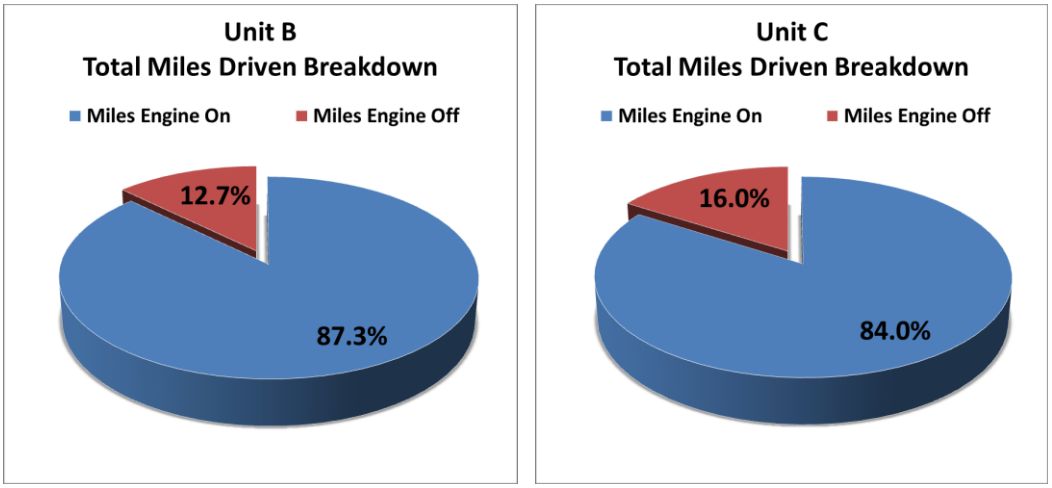


Figure 15: Comparison of engine off driving miles for Unit B and Unit C

Unit B drove an average of 12.7% of total miles on hydraulic power only and Unit C, 16%. This is slightly different from the results in section 3.1.2, where Unit B drove an average of 14.5% of miles on hydraulic power only and Unit C, 15.4%. Table 6 below compares the engine off driving times for Unit B and Unit C.

Table 6: Comparison of engine off driving times for Unit B and Unit C

	Cumulative Engine Off Driving Time	Avg. Daily Engine Off Driving Time
Unit B	26.5 hours	48 minutes
Unit C	88.9 hours	48 minutes

We can see that Unit C spent an average of 48 minutes per day driving with the engine off, which is comparable with the time calculated in section 3.1.2. However, Unit B spent an average of 48 minutes per day driving with the engine off which is 90 minutes less than the time calculated in section 3.1.2.

The difference comes from data acquisition issues on the data logger installed on Unit B. As Figure 16 shows, the vehicle speed (blue curve) recorded by the data logger "freezes" at a positive value when the vehicle comes to a stop. Thus, mileage and time is recorded when the vehicle is stopped and the engine is off.

To resolve the issue, we corrected the vehicle speed before analyzing the data. The red curve in Figure 16 shows the corrected vehicle speed matching the raw vehicle speed when the vehicle is in movement but being at zero when the vehicle is stopped.

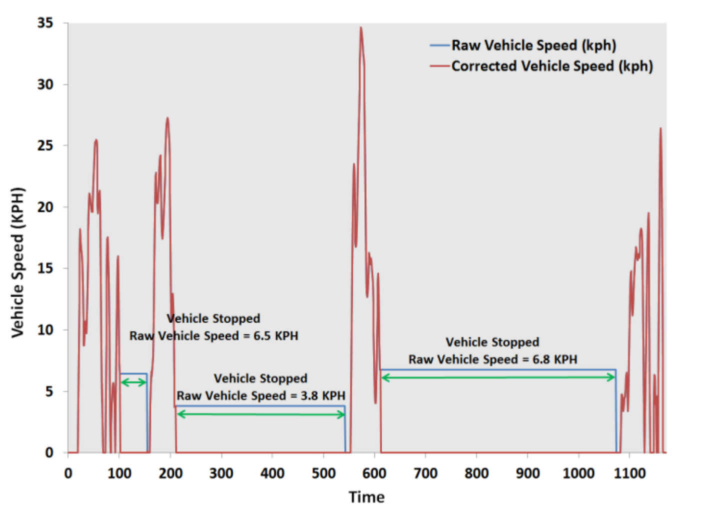


Figure 16: Plot of Unit B raw and corrected vehicle speed

Looking at the high resolution data, we noticed that the time spent with the engine off at zero speed seemed different than what was reported in section 3.1.2. We decided to recalculate the time spent with the engine off at zero speed using the following conditions:

- Vehicle speed = 0,
- Engine speed = 0,
- Accelerator and brake pedal position = 0%,
- Accumulator pressure is constant for 3 consecutive seconds.

In addition, we checked the results for consistency and accuracy and made modifications when necessary. Figure 17 below compares engine time for Unit B and Unit C.

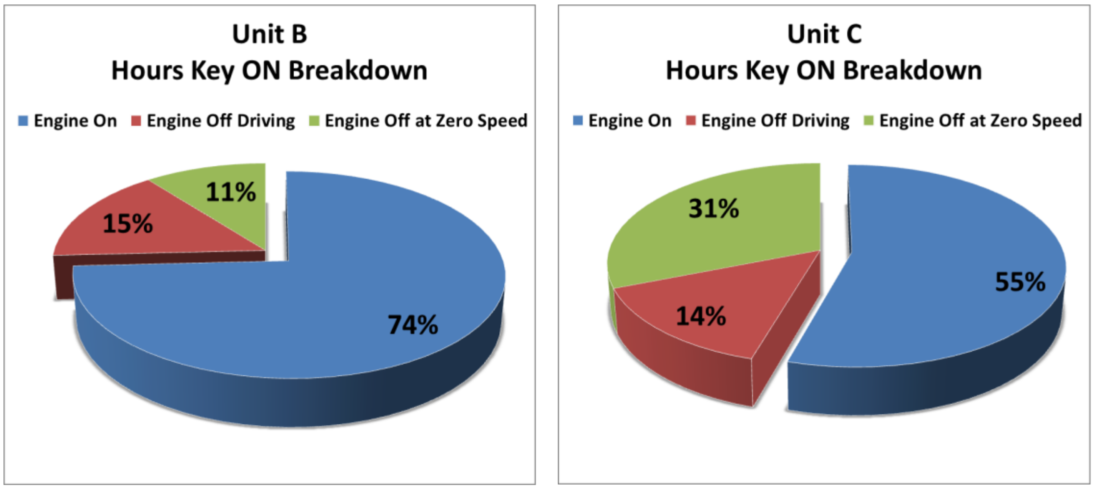


Figure 17: Comparison of engine times for Unit B and Unit C

Unit B spent 11% of the time at zero speed while the engine was off and Unit C, 31%. This means that for each 100 hours that Unit B (Unit C) spent "key on", 11 hours (31 hours) were with the engine off and the vehicle not moving. These numbers are different from those calculated in section 3.1.2 but they do correspond more closely with typical parcel delivery operations. Table 7 below looks at the time spent with the engine off while the vehicle is not moving in more details.

Table 7: Comparison of engine off at zero speed times for Unit B and Unit C

	Cumulative Engine Off @ Zero Speed Time	Avg. Daily Engine Off @ Zero Speed Time
Unit B	18.2 hours	33 minutes
Unit C	191.7 hours	104 minutes

We can see that Unit B spent an average of 33 minutes each day with the engine off while the vehicle was not moving, which is significantly lower than the 231 minutes that were calculated in section 3.1.2. Similarly, Unit C spent an average of 104 minutes each day with the engine off while the vehicle was not moving, significantly lower than the 299 minutes that were calculated in section 3.1.2.

The analysis above shows that drivers do take advantage of the advanced engine off feature to leave the vehicle "key on" while delivering packages but the time spent "key on" at zero speed is not as great as reported in section 3.1.2.

The example below identifies driver behavior that impact overall vehicle fuel economy by detailing a stop at a residential delivery site and its effect on the accumulator pressure.[1]

Phase 1: The HHV is driving to a delivery stop.
Phase 2: The HHV stops for 2 minutes and 12 seconds at a residential delivery stop in "key on" position, the engine is off and the transmission in Neutral. Accumulator pressure slowly decreases, losing about 21% of the system pressure.
Phase 3: The HHV restarts and leaves the delivery stop.

To quantify the energy lost while the HHV is kept in "key on" position while the driver is delivering packages, we analyzed a complete day when Unit C was in operation on Route 2. On August 29, 2013, we identified 163 events when the HHV was stopped and kept in "key on" position, with the transmission in Neutral and the parking brake on. This represented a total of 13,140 kJ of energy lost in

[1] *AccelPedPos1 = accelerator pedal position (%), BrkPedPct = brake pedal position (%), AccGasPress = accumulator gas pressure (psi), EngineSpeed = engine speed (RPM), WheelBasedVehSpd = wheel based vehicle speed (kph)*

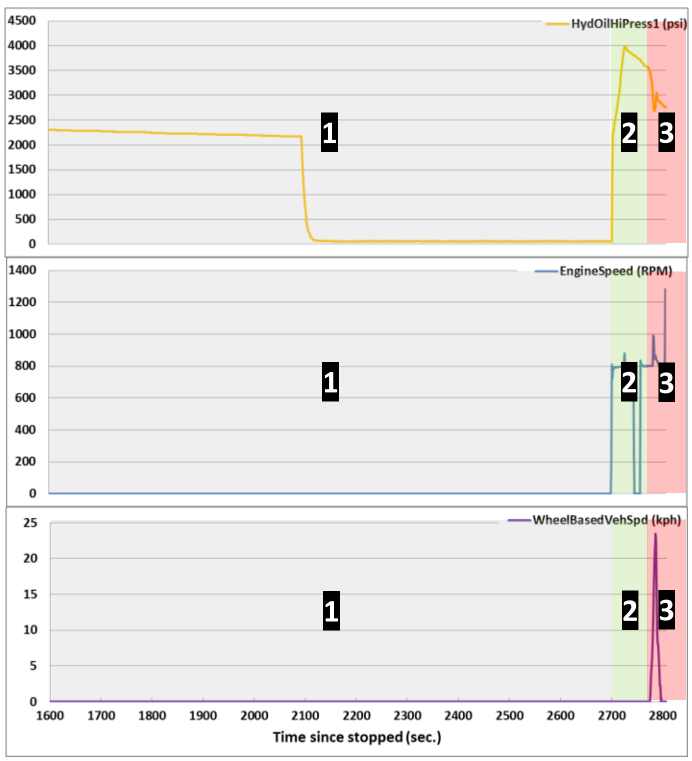
the high pressure accumulator. We estimated that the internal combustion engine would need to burn about 0.4 gallons of diesel to recover this amount of energy in the accumulator. Table 8 below details the results of the analysis.

Table 8: Impact of driver behavior on fuel economy for Unit C on August 29, 2013

August 29, 2013	Normal Driving	Optimal Driving
Distance driven	79.6 miles	
Fuel consumed	7.6 gallons	7.2 gallons
Fuel economy	10.41 MPG	11.06 MPG

We can see that with optimal driving for best fuel economy, Unit C would have achieved a fuel economy of 11.06 MPG on August 29, 2013, which is 6.2% better than the actual fuel economy achieved on that day (10.41 MPG).

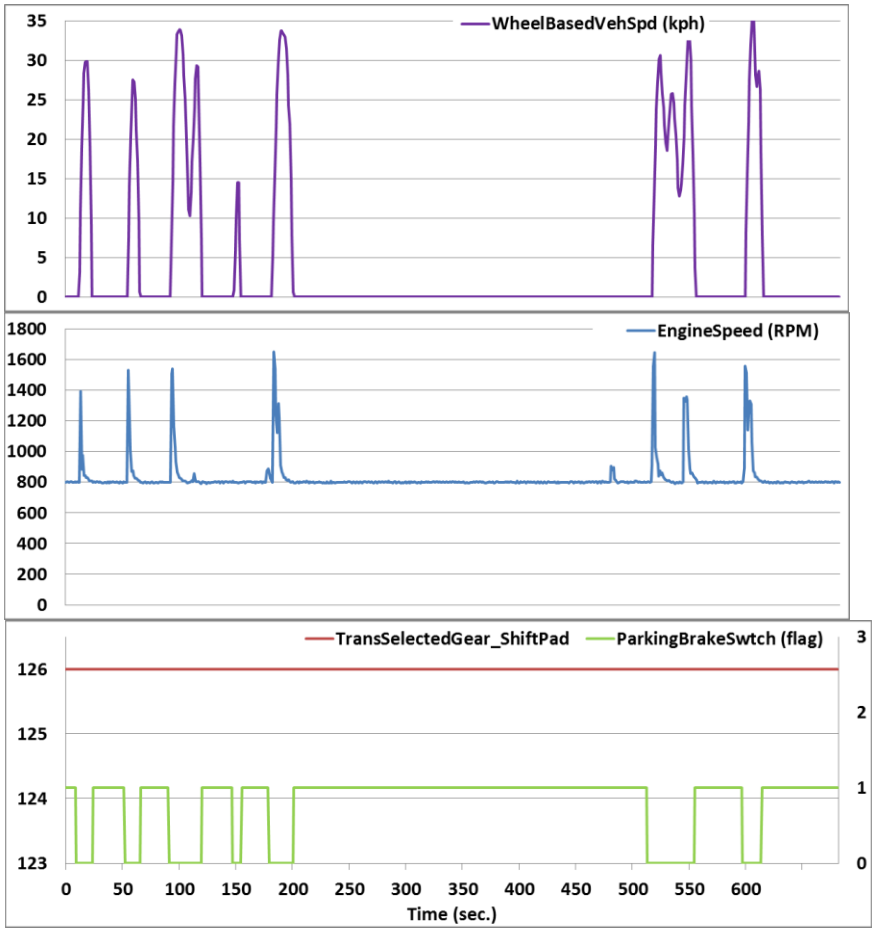
On several occasions, longer periods of engine off at zero speed were observed. The example below details a 45-minute stop and its effect on the accumulator pressure and fuel consumption.[2]



Phase 1: The HHV is stopped in key on position with the parking brake on and transmission in Neutral. Engine is off and the accumulator pressure drains until the accumulator is a zero state of charge.
Phase 2: The accumulator pressure reaches a low threshold. The engine is restarted to increase the accumulator pressure and maintain the system energized and ready to go.
Phase 3: After a stop of more than 45 minutes, the driver leaves and moves the HHV to another delivery stop.

[2] *HydOilHiPress1 = accumulator gas pressure (psi), EngineSpeed = engine speed (RPM), WheelBasedVehSpd = wheel based vehicle speed (kph)*

Lastly, the example below shows 6 consecutives events when the HHV is key-on, stopped, with the parking brake on but the transmission remains in drive which prevents the engine from shutting off.[3]



These extreme examples show how driver behavior can greatly influence hydraulic hybrid vehicle performance and reinforce the idea that drivers of HHVs should turn the ignition key off as if they were driving a conventional diesel vehicle. This would prevent hydraulic pressure leakage while the HHV system is energized and ultimately save fuel.

[3] *WheelBasedVehSpd = wheel based vehicle speed (kph), EngineSpeed = engine speed (RPM), TransSelectedGear_ShiftPad = selected gear, ParkingBrakeSwitch = parking brake state*

3.3 Performance on Selected Parcel Delivery Routes

3.3.1 Methodology

All three HHVs were equipped with data loggers provided and installed by Parker to continuously record vehicle and powertrain data during vehicle operation. Data was collected by Parker which provided data files upon request. One conventional diesel truck was equipped with a data acquisition system provided and installed by CALSTART staff to collect vehicle and route information for baseline comparison with Unit C. Table 9 below details the technical characteristics of the conventional diesel vehicle.

Table 9: FCCC conventional diesel vehicle characteristics

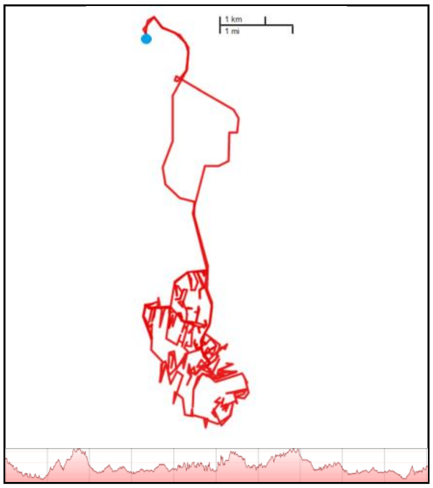
General	
Model Year	2008
Chassis Manufacturer	FCCC (Model MT-55)
Body Manufacturer	Utilimaster Corporation
GVWR	23,000 lbs.
Curb Weight	12,100 lbs.
Engine	
Model	Cummins ISB 6.7L
Peak Power	200 HP (149 kW) @ 2,400 RPM
Peak Torque	520 ft-lbs. (705 Nm) @ 1,600 RPM
Fuel System	ULSD / 40-gallon fuel tank
Exhaust System	Oxidizing Catalyst and Periodic Trap Oxidizer
Dimensions	
Tires	245/70 R19.5
Wheelbase	178 in.
Overall Length	-
Overall Width	-
Overall Height	-
Transmission	
Make	Allison
Type	2200 HS Automatic
Rear Axle Ratio	4.10

The conventional diesel truck and Unit C operated on two parcel delivery routes (Route 1 and Route 2) at different times in the performance evaluation period. This allowed for close comparison of vehicle performance between the two vehicles on two parcel delivery routes. One driver is generally assigned to one specific route, which minimized the impact of driver behavior in the vehicle performance comparison.

Unit B operated on one single parcel delivery route (Route 3). The project schedule did not allow the collection of baseline data from a similar conventional diesel vehicle. Instead, we used general parcel delivery baseline data and our knowledge of parcel delivery routes to estimate the fuel economy improvement of Unit B.

3.3.2 Results & Discussions

- **Route 1**



Route 1 mostly serves residential customers and also some businesses. The vehicle drives an average of 56 miles per day, through heavy morning traffic and over 2 large hills and many smaller hills throughout the rest of the route. Route 1 is characterized by 2 different operating areas:

- Highway / Arterial 1 & 2 where the vehicle gets to and from the delivery area. Characterized by high driving speeds and low number of stops.
- Pick-up & Delivery (P&D) where the vehicle gets from customer to customer. Characterized by low driving speeds and high number of stops.

With about 200 stops per day, Route 1 is a good target for hybrid technology.

Table 10 below details the different operating areas of Route 1.

Table 10: Route 1 characteristics

Route 1	Hwy & Arterial 1	P & D	Hwy & Arterial 2
Distance	5.8 miles	41.3 miles	6.0 miles
Maximum Speed	69.0 MPH	55.6 MPH	59.3 MPH
Average Speed (>0)	27.3 MPH	15.8 MPH	30.8 MPH
Stops per mile	1.91	4.35	1.51
Kinetic Intensity	1.25 (1/mile)	4.55 (1/mile)	0.97 (1/mile)
12VDC Starter Use	3	177	1
Idle Time	10%	7%	26%
Engine Hours	0h14	2h45	0h16
Elevation Gain/Loss	1028 ft. / -1265 ft.	6454 ft. / -6519 ft.	1311 ft. / -1006 ft.

The Highway / Arterial 1 operating area covers about 6 miles at an average driving speed of 27 MPH. Driving is for a large part downhill throughout the 6 miles. On the other hand, the Highway / Arterial 2 operating area covers about 6 miles at an average driving speed of 31 MPH. Driving is for a large part uphill throughout the 6 miles.

The Pick-up & Delivery operating area covers about 41 miles at an average driving speed of 16 MPH. With a higher number of stops and lower average driving speed, the Pick-up & Delivery operating area should be better suited for hydraulic hybrid technology.

To assess the performance of Unit C on Route 1, we ran both the HHV and a similar conventional diesel vehicle (Table 9), the baseline, on Route 1 for several weeks. Table 11 below compares the performance of both vehicles on Route 1.

Table 11: Performance comparison on Route 1

	FCCC MT-55 Diesel	FCCC MT-55 HHV
Number of Days in Operation	70 days	36 days
Avg. Daily Key On Time	200 min.	327 min.
Avg. Daily Engine On Time	200 min.	206 min.
Avg. Daily Idle Time	20 min.	138 min.
Miles Driven	3693.6 miles	2023.7 miles
Miles Engine Off	N/A	312.7 miles
Fuel Consumed	478.1 gallons	248.5 gallons
Average Fuel Economy	**7.73 MPG**	**8.14 MPG (6.69 Worst - 9.49 Best)**

With an average fuel economy of 8.14 MPG, the HHV showed a fuel economy improvement of 5.3% over the baseline. The HHV showed a large daily fluctuation in fuel economy: from a worst of 6.69 MPG to a best of 9.49 MPG, which represent a fuel economy improvement over the baseline of -13.5% and +22.8% respectively. These daily fluctuations in fuel economy can be primarily explained by:

- Air compressor governor issue (explained in detail in section 5.1.3), which prevents the engine from shutting off and results in higher fuel consumption. With an updated control strategy able to get more consistent engine off operation, Unit C was able to show an average fuel economy improvement of about 30% over the baseline on Route 1.
- Specific driver behavior (explained in detail in sections 3.1.2 & 3.2.2), which allows energy stored during regenerative braking to be depleted without doing useful work.

The HHV spent an average of 127 minutes more per day than the diesel in "key on" position and 118 minutes more at idle (vehicle not moving in "key on" position). This contributed to an average daily engine on time that is 6 minutes more than for the diesel. Figure 18 below presents the summary of engine off data for Unit C on Route 1.

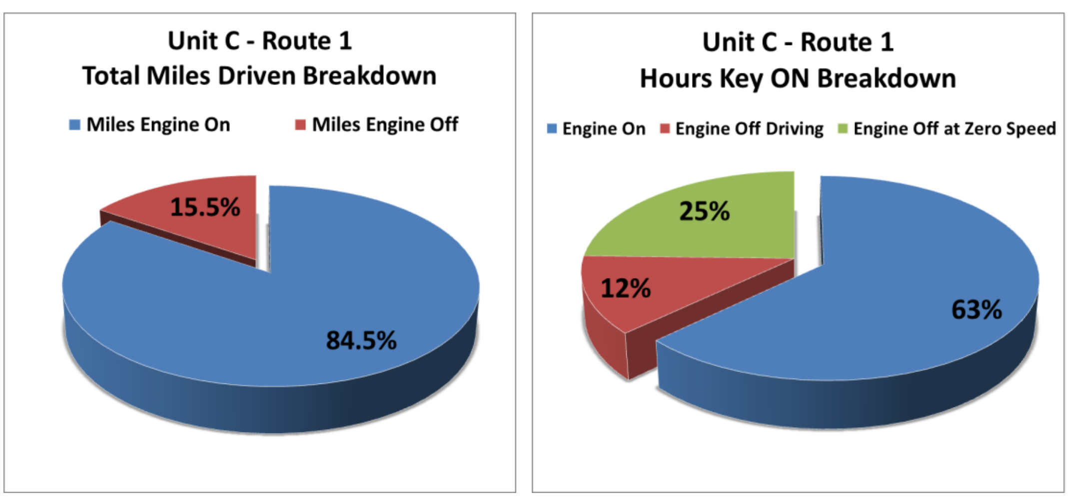


Figure 18: Engine On/Off miles and times for Unit C on Route 1

Unit C took advantage of the engine off feature to operate on hydraulic power only, driving an average of 15.5% of miles with the engine off. It also spent 25% of the time at zero speed while the engine was off. Table 12 below shows the engine off driving time for Unit C on Route 1.

Table 12: Engine off driving times for Unit C on Route 1

	Cumulative Engine Off Driving Time	Avg. Daily Engine Off Driving Time
Unit C – Route 1	24.5 hours	41 minutes

Unit C spent an average of 41 minutes per day driving with the engine off. Table 13 below shows the engine off at zero speed for Unit C on Route 1.

Table 13: Engine off at zero speed times for Unit C on Route 1

	Cumulative Engine Off @ Zero Speed Time	Avg. Daily Engine Off @ Zero Speed Time
Unit C – Route 1	48.2 hours	80 minutes

Unit C spent an average of 80 minutes per day with the engine off while the vehicle was not moving.

In order to further analyze the performance of Unit C on Route 1, we decided to compare the day where the HHV achieved the best fuel economy to a day close to the average performance of the baseline. This allowed us to assess the performance of the HHV when the air compressor governor issue was not dramatically affecting vehicle performance. Table 14 below compares an average day for the baseline to the day where the HHV achieved the best fuel economy on Route 1.

Table 14: Performance comparison of average diesel and best HHV day on Route 1

Route 1	Miles	Fuel Used (gallons)	Fuel Economy (MPG)	Time Key ON (s)	Time @ Zero Speed (s)	Fuel @ Zero Speed (gallons)	Avg. MPH (>0)	Max. MPH
Diesel	52.77	6.83	7.73	11991	1189	0.21	17.34	70.01
HHV	63.10	6.65	9.49	21349	6941	0.40	15.77	66.56
Difference	+19.6%	**-2.6%**	**+22.8%**	+78.0%	+483.8%	+90.5%	-9.1%	-4.9%

Although the vehicles operated on the same route, the HHV drove more miles and at a lower average driving speed on the day where it achieved the best fuel economy. With an average fuel economy of 9.49 MPG, the HHV showed a fuel economy improvement of 22.8% over the baseline. As expected, the HHV spent more time in "key on" position and at zero speed, which led to a higher fuel consumption at zero speed and ultimately to a lower fuel economy.

We then compared the vehicle performance of the baseline and HHV on each operating area of Route 1 (Table 15).

Table 15: Performance comparison of average diesel and best HHV day on Route 1 per operating area

Route 1 Hwy/Arterial 1	Miles	Fuel Used (gallons)	Fuel Economy (MPG)	Time Key ON (s)	Time @ Zero Speed (s)	Fuel @ Zero Speed (gallons)	Avg. MPH (>0)	Max. MPH
Diesel	5.96	0.72	8.30	1000	187	0.04	27.39	68.94
HHV	5.97	0.67	8.88	1005	259	0.04	28.81	66.56
Difference	+0.2%	**-6.9%**	**+7.0%**	+0.5%	+38.5%	-	+5.2%	-3.5%

Route 1 P&D	Miles	Fuel Used (gallons)	Fuel Economy (MPG)	Time Key ON (s)	Time @ Zero Speed (s)	Fuel @ Zero Speed (gallons)	Avg. MPH (>0)	Max. MPH
Diesel	46.03	5.99	7.69	10751	735	0.12	16.23	55.66
HHV	50.78	5.12	9.92	18494	5655	0.19	22.91	58.51
Difference	+10.3%	**-14.5%**	**+29.0%**	+72.0%	+669.4%	+58.3%	+41.2%	+5.1%

Route 1 Hwy/Arterial 2	Miles	Fuel Used (gallons)	Fuel Economy (MPG)	Time Key ON (s)	Time @ Zero Speed (s)	Fuel @ Zero Speed (gallons)	Avg. MPH (>0)	Max. MPH
Diesel	6.03	0.63	9.61	792	97	0.02	31.46	58.09
HHV	6.28	0.67	9.38	1058	343	0.02	31.64	61.75
Difference	+4.1%	**+6.3%**	**-2.4%**	+33.6%	+253.6%	-	+0.6%	+6.3%

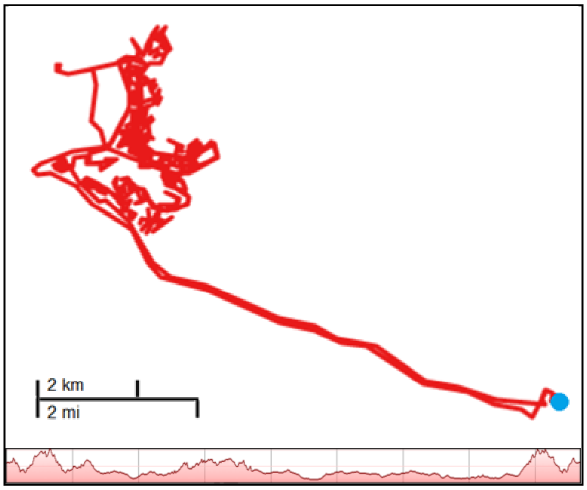
With an average fuel economy of 8.88 MPG, the HHV showed a fuel economy improvement of 7% over the baseline on the Highway / Arterial 1 operating area of Route 1 (driving downhill). Time in "key on" position was similar between HHV and baseline but the HHV spent 38.5% more time at zero speed.

With an average fuel economy of 9.92 MPG, the HHV showed a fuel economy improvement of 29.0% over the baseline on the Pick-up & Delivery operating area of Route 1. This shows the advantage of hydraulic hybrid technology on operating areas characterized by low average speeds and high number of stops. The HHV spent 129 minutes more in "key on" position and 82 minutes more at zero speed than the baseline. Coupled with air compressor governor issues, this led to higher fuel consumption at zero speed than the baseline.

With an average fuel economy of 9.38 MPG, the HHV showed a fuel economy decrease of 2.4% over the baseline on the Highway / Arterial 2 operating area of Route 1 (driving uphill).

This analysis shows that most of the fuel savings on Route 1 are achieved on the Pick-up & Delivery operating area and highlights clearly where the advantages of hydraulic hybrids are greatest. Depending on operating conditions such as terrain, driver behavior and driving / traffic conditions, some fuel savings can be achieved on the Highway / Arterial 1 & 2 operating areas but savings will remain small.

- **Route 2**



Route 2 mostly serves residential customers with some institutional customers such as churches and schools. The vehicle drives an average of 71 miles per day, through a relatively hilly terrain. Like Route 1, Route 2 is characterized by 2 different operating areas:

- Highway / Arterial 1 & 2,
- Pick-up & Delivery (P&D).

With about 230 stops per day, Route 2 is a good target for hybrid technology.

Table 16 below details the different operating areas of Route 2:

Table 16: Route 2 characteristics

Route 2	Hwy & Arterial 1	P & D	Hwy & Arterial 2
Distance	7.7 miles	53.4 miles	11.0 miles
Maximum Speed	71.1 MPH	60.5 MPH	70.4 MPH
Average Speed (>0)	39.5 MPH	17.4 MPH	47.1 MPH
Stops per mile	0.65	4.10	0.64
Kinetic Intensity	0.29 (1/mile)	3.08 (1/mile)	0.32 (1/mile)
12VDC Starter Use	1	188	1
Idle Time	2%	13%	14%
Engine Hours	0h12	3h29	0h16
Elevation Gain/Loss	2692 ft. / -3002 ft.	4989 ft. / -5195 ft.	3058 ft. / -2550 ft.

The Highway / Arterial 1 operating area covers about 8 miles at an average driving speed of 40 MPH. Driving is for a large part downhill throughout the 8 miles. On the other hand, the Highway / Arterial 2 operating area covers about 11 miles at an average driving speed of 47 MPH. Driving is for a large part uphill throughout the 11 miles.

The Pick-up & Delivery operating area covers about 53 miles at an average driving speed of 17 MPH. With a higher number of stops and lower average driving speed, the Pick-up & Delivery operating area should be better suited for hydraulic hybrid technology.

To assess the performance of Unit C on Route 2, we ran both the HHV and the baseline on Route 2 for several weeks. Table 17 below compares the performance of both vehicles on Route 2.

Table 17: Performance comparison on Route 2

	FCCC MT-55 Diesel	FCCC MT-55 HHV
Number of Days in Operation	142 days	75 days
Avg. Daily Key On Time	246 min.	337 min.
Avg. Daily Engine On Time	246 min.	171 min.
Avg. Daily Idle Time	38 min.	137 min.
Miles Driven	10,141.3 miles	5,148.9 miles
Miles Engine Off	N/A	834.8 miles
Fuel Consumed	1,201.4 gallons	533.9 gallons
Fuel Economy	**8.44 MPG**	**9.64 MPG (6.49 Worst - 10.41 Best)**

With an average fuel economy of 9.64 MPG, the HHV showed a fuel economy improvement of 14.2% over the baseline. Unit C showed a large daily fluctuation in fuel economy: from a worst of 6.49 MPG to a best of 10.41 MPG, which represent a fuel economy improvement over the baseline vehicle of -23.1% and +23.3% respectively. These daily fluctuations in fuel economy can be primarily explained by:

- Air compressor governor issue which prevents the engine from shutting off and results in higher fuel consumption.
- Specific driver behavior which allows energy stored during regenerative braking to be depleted without doing useful work.

As discussed earlier, these two previous issues negatively impact HHV operation and ultimately fuel economy: the HHV spent an average of 91 minutes more per day than the diesel in "key on" position and 99 minutes more at idle (vehicle not moving in "key on" position). Despite this, the HHV ran its engine an average of 75 minutes less per day than the baseline.

Figure 19 below presents the summary of engine off data for Unit C on Route 2.

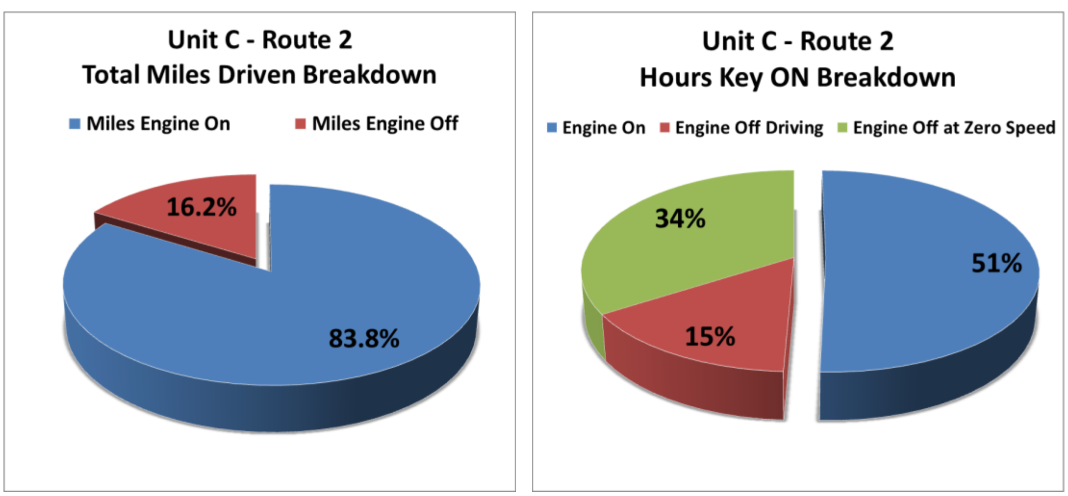


Figure 19: Engine On/Off miles and times for Unit C on Route 2

Unit C took advantage of the engine off feature to operate on hydraulic power only, driving an average of 16.2% of miles with the engine off. It also spent 34% of the time at zero speed while the engine was off. Table 18 below shows the engine off driving time for Unit C on Route 2.

Table 18: Engine off driving times for Unit C on Route 2

	Cumulative Engine Off Driving Time	Avg. Daily Engine Off Driving Time
Unit C – Route 2	64.5 hours	52 minutes

Unit C spent an average of 52 minutes per day driving with the engine off. Table 19 below shows the engine off at zero speed for Unit C on Route 2.

Table 19: Engine off at zero speed times for Unit C on Route 2

	Cumulative Engine Off @ Zero Speed Time	Avg. Daily Engine Off @ Zero Speed Time
Unit C – Route 2	143.5 hours	115 minutes

Unit C spent an average of 115 minutes per day with the engine off while the vehicle was not moving.

In order to further analyze the performance of Unit C on Route 2, we decided to compare the day where the HHV achieved the best fuel economy to a day close to the average performance of the baseline. This allowed us to assess the performance of the HHV when the air compressor governor issue was not dramatically affecting vehicle performance. Table 20 below compares an average day for the baseline to the day where the HHV achieved the best fuel economy on Route 2.

Table 20: Performance comparison of average diesel and best HHV day on Route 2

Route 2	Miles	Fuel Used (gallons)	Fuel Economy (MPG)	Time Key ON (s)	Time @ Zero Speed (s)	Fuel @ Zero Speed (gallons)	Avg. MPH (>0)	Max. MPH
Diesel	79.48	9.53	8.34	18476	3935	0.52	19.51	70.79
HHV	79.52	7.64	10.41	28933	15856	0.21	21.89	71.23
Difference	-	**-19.8%**	**+24.8%**	+56.6%	+302.9%	-59.6%	+12.2%	+0.6%

Although the vehicles operated on the same route, the HHV drove at a higher average driving speed on the day where it achieved the best fuel economy. With an average fuel economy of 10.41 MPG, the HHV showed a fuel economy improvement of 24.8% over the baseline. As expected, the HHV spent more time in "key on" position and at zero speed.

We then compared the vehicle performance of the baseline and HHV on each operating area of Route 2 (Table 21).

Table 21: Performance comparison of average diesel and best HHV day on Route 2 per operating area

Route 2 Hwy/Arterial 1	Miles	Fuel Used (gallons)	Fuel Economy (MPG)	Time Key ON (s)	Time @ Zero Speed (s)	Fuel @ Zero Speed (gallons)	Avg. MPH (>0)	Max. MPH
Diesel	7.68	0.80	9.60	797	73	0.02	38.27	70.79
HHV	7.98	0.79	10.05	910	171	0.02	38.85	71.23
Difference	+3.9%	**-1.3%**	**+4.7%**	+61.1%	+134.2%	-	+1.5%	+0.6%

Route 2 P&D	Miles	Fuel Used (gallons)	Fuel Economy (MPG)	Time Key ON (s)	Time @ Zero Speed (s)	Fuel @ Zero Speed (gallons)	Avg. MPH (>0)	Max. MPH
Diesel	61.25	7.71	7.95	16617	3714	0.47	16.67	58.90
HHV	60.62	5.66	10.70	26472	15099	0.17	19.19	54.80
Difference	-1.0%	**-26.6%**	**+34.6%**	+59.3%	+306.5%	-63.8%	+15.1%	-7.0%

Route 2 Hwy/Arterial 2	Miles	Fuel Used (gallons)	Fuel Economy (MPG)	Time Key ON (s)	Time @ Zero Speed (s)	Fuel @ Zero Speed (gallons)	Avg. MPH (>0)	Max. MPH
Diesel	10.55	1.03	10.28	1062	148	0.03	41.05	69.98
HHV	10.92	1.18	9.24	1551	586	0.02	40.75	69.62
Difference	+3.5%	**+14.6%**	**-10.1%**	+46.0%	+295.9%	-33.3%	-0.7%	-0.5%

With an average fuel economy of 10.05 MPG, the HHV showed a fuel economy improvement of 4.7% over the baseline on the Highway / Arterial 1 operating area of Route 2 (driving downhill).

With an average fuel economy of 10.70 MPG, the HHV showed a fuel economy improvement of 34.6% over the baseline on the Pick-up & Delivery operating area of Route 2. This shows the advantage of hydraulic hybrid technology on operating areas characterized by low average speeds and high number of stops. The HHV spent 164 minutes more in "key on" position and 190 minutes more time at zero speed than the baseline. Coupled with air compressor governor issues, this led to significant fuel consumption at zero speed.

With an average fuel economy of 9.24 MPG, the HHV showed a fuel economy decrease of 10.1% over the baseline on the Highway / Arterial 2 operating area of Route 2 (driving uphill).

This analysis shows that most of the fuel savings on Route 2 are achieved on the Pick-up & Delivery operating area. Depending on operating conditions such as terrain, driver behavior and driving / traffic conditions, some fuel savings can be achieved on the Highway / Arterial 1 & 2 operating areas but savings will remain small.

- **Route 3**

Route 3 serves a mix of business and residential customers. The vehicle drives an average of 74 miles per day, through a somewhat flat terrain. Like Route 1 and 2, Route 3 is characterized by 2 different operating areas:

- Highway / Arterial 1 & 2,
- Pick-up & Delivery (P&D).

With about 370 stops per day, Route 3 is a good target for hybrid technology.

Table 22 below details the different operating areas of Route 3:

Table 22: Route 3 characteristics

Route 1	Hwy & Arterial 1	P & D	Hwy & Arterial 2
Distance	11.0 miles	51.1 miles	13.4 miles
Maximum Speed	59.1 MPH	56.3 MPH	62.0 MPH
Average Speed (>0)	30.7 MPH	14.7 MPH	27.1 MPH
Stops per mile	0.54	6.85	1.12
Kinetic Intensity	0.83 (1/mile)	3.57 (1/mile)	0.86 (1/mile)
12VDC Starter Use	-	-	-
Idle Time	16%	27%	11%
Engine Hours	-	-	-
Elevation Gain/Loss	635 ft. / -1067 ft.	2246 ft. / -2298 ft.	942 ft. / -454 ft.

The Highway / Arterial 1 operating area covers about 11 miles at an average driving speed of 31 MPH. Driving is for a large part downhill throughout the 11 miles. On the other hand, the Highway / Arterial 2 operating area covers about 13 miles at an average driving speed of 27 MPH. Driving is for a large part uphill throughout the 13 miles.

The Pick-up & Delivery operating area covers about 51 miles at an average driving speed of 15 MPH. With a higher number of stops and lower average driving speed, the Pick-up & Delivery operating area should be better suited for hydraulic hybrid technology.

To assess the performance of Unit B on Route 3, we ran the HHV on Route 3 for several weeks. Table 23 below shows the performance of the HHV on Route 3.

Table 23: HHV performance on Route 3

	FCCC MT-55 HHV
Number of Days in Operation	31 days
Avg. Daily Key On Time	324 min.
Avg. Daily Engine On Time	240 min.
Avg. Daily Idle Time	77 min.
Miles Driven	2,283.0 miles
Miles Engine Off	305.5 miles
Fuel Consumed	221.7 gallons
Fuel Economy	**10.30 MPG**

With an average fuel economy of 10.30 MPG, we estimate that the HHV showed a fuel economy improvement of 30 to 40% over a comparable baseline. Unit B showed some daily fluctuation in fuel economy: from a worst of 9.20 MPG to a best of 11.08 MPG. These daily fluctuations in fuel economy can be primarily explained by:

- Specific driver behavior which allows energy stored during regenerative braking to be depleted without doing useful work.

Figure 20 below presents the summary of engine off data for Unit B on Route 3.

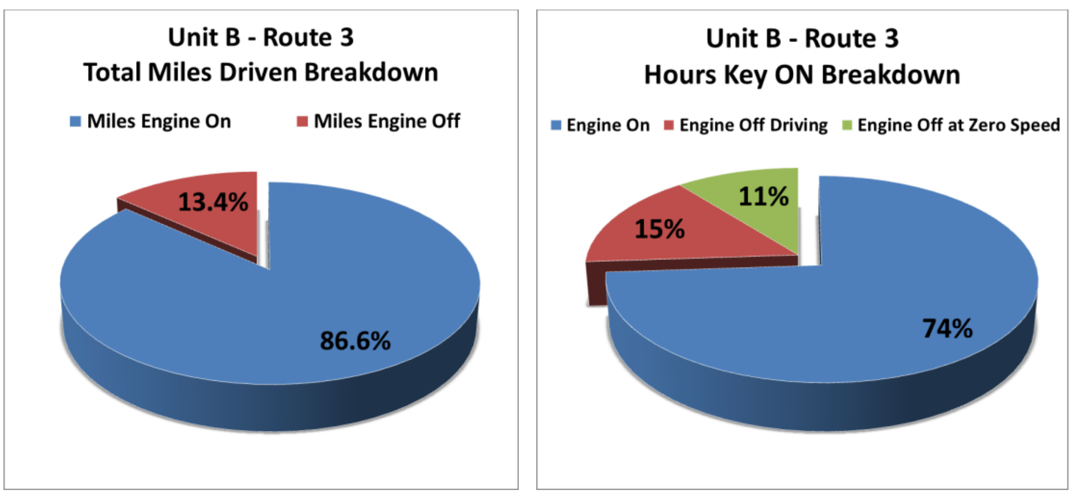


Figure 20: Engine On/Off miles and times for Unit B on Route 3

Unit B took advantage of the engine off feature to operate on hydraulic power only, driving an average of 13.4% of miles with the engine off. It also spent 11% of the time at zero speed while the engine was off. Table 24 below shows the engine off driving time for Unit B on Route 3.

Table 24: Engine off driving times for Unit B on Route 3

	Cumulative Engine Off Driving Time	Avg. Daily Engine Off Driving Time
Unit B – Route 3	25.8 hours	50 minutes

Unit B spent an average of 50 minutes per day driving with the engine off. Table 25 below shows the engine off at zero speed for Unit B on Route 3.

Table 25: Engine off at zero speed times for Unit B on Route 3

	Cumulative Engine Off @ Zero Speed Time	Avg. Daily Engine Off @ Zero Speed Time
Unit B – Route 3	17.9 hours	35 minutes

Unit B spent an average of 35 minutes per day with the engine off while the vehicle was not moving.

In order to further analyze the performance of Unit B on Route 3, we looked at the day where the HHV achieved the best fuel economy. This allowed us to assess the performance of the HHV when the air compressor governor issue was not dramatically affecting vehicle performance. Table 26 below shows the vehicle performance of the HHV on each operating area of Route 3.

Table 26: HHV performance comparison of best HHV day on Route 3

Route 3 HHV	Miles	Fuel Used (gallons)	Fuel Economy (MPG)	Time Key ON (s)	Time @ Zero Speed (s)	Fuel @ Zero Speed (gallons)	Avg. MPH (>0)	Max. MPH
Hwy/Arterial 1	11.02	0.76	14.48	1534	242	0.06	30.71	59.12
P&D	51.09	4.98	10.26	17219	4664	0.41	14.65	56.28
Hwy/Arterial 2	13.41	1.08	12.47	1993	215	0.01	27.14	61.96
Best Day	**75.52**	**6.82**	**11.08**	**20744**	**5119**	**0.48**	**17.40**	**61.96**

With an average fuel economy of 14.48 MPG on the Highway / Arterial 1 operating area (driving downhill) and 12.47 MPG on the Highway / Arterial 2 operating area (driving uphill), we estimate that the HHV showed a fuel economy improvement of 5 to 10% over a comparable baseline.

With an average fuel economy of 10.26 MPG on the Pickup & Delivery operating area, we estimate that the HHV showed a fuel economy improvement of 40 to 50% over a comparable baseline. This shows the advantage of hydraulic hybrid technology on operating areas characterized by low average speeds and high number of stops.

This analysis shows that most of the fuel savings on Route 3 are achieved on the Pick-up & Delivery operating area. Depending on operating conditions such as terrain, driver behavior and driving / traffic conditions, some fuel savings can be achieved on the Highway / Arterial 1 & 2 operating areas but savings will remain small.

3.4 On-road Emissions Testing

3.4.1 Purpose

CALSTART contracted with Engine, Fuel, and Emissions Engineering, Inc. (EF&EE) to measure in-service pollutant emissions from one model year 2012 hydraulic hybrid and one model year 2008 conventional diesel package delivery truck. Measurements were conducted while the test vehicle followed and "shadowed" a package delivery truck in normal operation. The measurements were performed using EF&EE's Ride-Along Vehicle Emission Measurement (RAVEM) system (Figure 21). The test trucks were also fitted by CALSTART staff with data loggers, which recorded a wide variety of vehicle and powertrain parameters.

Figure 21: RAVEM system installed in the hydraulic hybrid truck

Mass emissions of carbon dioxide (CO_2), carbon monoxide (CO), oxides of nitrogen (NO_x), particulate matter (PM), and total hydrocarbons (THC) from the hydraulic hybrid and the conventional diesel test vehicle were each measured over the course of a typical day delivering packages. The vehicles were operated on Route 2 described in section 3.3.2 and tested according to the schedule in Table 27.

Table 27: On-road emissions testing schedule

	Test Vehicle	Test Driver	Lead Vehicle	Lead Driver
Diesel	On 9/16/13	A	On 9/18/13	B
HHV	On 9/18/13	A	On 9/16/13	B

Actual fuel economy and criteria pollutant emissions will vary widely with driving conditions such as drive cycle and driver behavior. The numbers presented in this report are representative of specific driving conditions and were derived from testing done in a unique testing environment. They should not be used to predict fuel economy and criteria pollutant emissions in different driving conditions.

3.4.2 Results

We present below the main results and findings of the on-road emissions testing. For further information, please see Appendix D. Please note that the two vehicles were somewhat different from each other as the conventional diesel vehicle was equipped with a 200 hp. Cummins ISB engine, while the HHV was equipped with a 280 hp. Cummins ISB engine. In addition, both engines were not EPA certified to the same emissions level: the conventional diesel vehicle was 2007 EPA certified and the hydraulic hybrid vehicle was 2010 EPA certified.

Table 28 below compares the results of the on-road emissions testing from the data collected by the data loggers installed by CALSTART staff.

Table 28: On-road emissions testing results from data loggers

CALSTART Data Loggers	Date	Miles	Fuel Used (gal.)	Fuel Economy (MPG)	Time Key ON (s)	Time @ Zero Speed (s)	Fuel @ Zero Speed (gal.)	Avg. MPH (>0)	Max. MPH
Diesel	9/16	70.51	8.36	8.44	14882	1215	0.24	18.13	70.21
HHV	9/18	75.44	6.91	10.92	24233	10765	0.08	20.13	69.40
Difference	-	+7.0%	**-17.3%**	**+29.4%**	+62.8%	+786.0%	-66.7%	+11.0%	-1.2%

Although both vehicles operated on the same route, the HHV drove more miles and at a higher average driving speed. Parcel delivery routes are subject to variation, as the number and location of deliveries vary from day to day. With an average fuel economy of 10.92 MPG, the HHV showed a fuel economy improvement of 29.4% over the baseline. The HHV spent more time in "key on" position and at zero speed.

Table 29 below compares the results of the on-road emissions testing from the data collected by EF&EE's RAVEM system.

Table 29: On-road emissions testing results from RAVEM

RAVEM	Date	Miles	CO_2 (g/mi)	NO_x (g/mi)	PM (g/mi)
Diesel	9/16	53.0	1364.28	5.07	0.01
HHV	9/18	70.2	1127.10	3.53	0.02
Difference	-	+32.4%	**-17.4%**	**-30.4%**	**+100.0%**

The RAVEM system recorded 17.2 less miles on the conventional diesel than on the HHV. On September 16, a technical issue occurred which prevented the RAVEM system from recording data on the conventional diesel for the last part of the day. As a result, between 10 and 12 miles of operation were not recorded. In addition, Table 28 showed that the HHV drove almost 5 miles more than the conventional diesel which was most likely due to variation in the number and location of deliveries. Lastly, due to the testing configurations, the RAVEM system was not able to record all the vehicle operation for both diesel and HHV.

The HHV produced 17.4% less CO_2 per mile and 30.4% less NO_x per mile than the conventional diesel. PM emissions from the HHV were higher than from the conventional diesel vehicle, but were extremely low for both vehicles. The uncertainty in the measured values of PM emissions is of the same order as the value itself.

As described in section 3.3.2, Route 2 is characterized by 2 different operating areas:

- Highway / Arterial 1 & 2 where the vehicle gets to and from the delivery area. Characterized by high driving speeds and low number of stops.
- Pick-up & Delivery (P&D) where the vehicle gets from customer to customer. Characterized by low driving speeds and high number of stops.

We now compare the results of the on-road emissions testing on each operating area. Table 30 below compares the results on the Highway / Arterial 1 operating area, from the data collected by the data loggers installed by CALSTART staff.

Table 30: On-road emissions testing results from data loggers on Hwy/Arterial 1

CALSTART Data Loggers	Date	Miles	Fuel Used (gal.)	Fuel Economy (MPG)	Time Key ON (s)	Time @ Zero Speed (s)	Fuel @ Zero Speed (gal.)	Avg. MPH (>0)	Max. MPH
Diesel	9/16	7.78	0.67	11.64	854	106	0.02	37.40	67.88
HHV	9/18	7.68	0.70	10.96	710	56	0.01	42.27	68.21
Difference	-	-1.3%	**+4.5%**	**-5.8%**	-16.9%	-45.3%	-50.0%	+13.0%	+0.5%

With an average fuel economy of 10.96 MPG, the HHV showed a fuel economy decrease of 5.8% over the baseline on the Highway / Arterial 1.

Table 30 below compares the results on the Highway / Arterial 1 operating area, from the data collected by the RAVEM system.

Table 31: On-road emissions testing results from RAVEM on Hwy/Arterial 1

RAVEM	Date	Miles	CO_2 (g/mi)	NO_x (g/mi)
Diesel	9/16	7.65	1189.03	1.83
HHV	9/18	7.68	1107.66	3.21
Difference	-	+0.4%	**-6.8%**	**+75.4%**

The HHV produced 6.8% less CO_2 per mile and 75.4% more NO_x per mile than the conventional diesel. PM emissions for the Highway / Arterial operating areas were not available.

Table 32 below compares the results on the Pick-up & Delivery operating area, from the data collected by the data loggers installed by CALSTART staff.

Table 32: On-road emissions testing results from data loggers on Pickup & Delivery

CALSTART Data Loggers	Date	Miles	Fuel Used (gal.)	Fuel Economy (MPG)	Time Key ON (s)	Time @ Zero Speed (s)	Fuel @ Zero Speed (gal.)	Avg. MPH (>0)	Max. MPH
Diesel	9/16	51.57	6.47	7.97	12937	991	0.18	15.30	60.59
HHV	9/18	55.89	4.99	11.20	22226	10437	0.07	17.07	57.74
Difference	-	+8.4%	**-22.9%**	**+40.5%**	+71.8%	+953.2%	-61.1%	+11.6%	-4.7%

With an average fuel economy of 11.20 MPG, the HHV showed a fuel economy improvement of 40.5% over the baseline on the Pick-up & Delivery operating area. The HHV spent more time in "key on" position and at zero speed. Sections 3.1.2 & 3.2.2 explain in detail the specific driver behavior that causes this greater "key on" time.

Table 33 below compares the results on the Pick-up & Delivery operating area, from the data collected by the RAVEM system.

Table 33: On-road emissions testing results from RAVEM on Pickup & Delivery

RAVEM	Date	Miles	CO_2 (g/mi)	NO_x (g/mi)
Diesel	9/16	44.46	1390.45	5.46
HHV	9/18	49.23	1095.65	4.13
Difference	-	+10.7%	**-21.2%**	**-24.4%**

The HHV produced 21.2% less CO_2 per mile and 24.4% less NO_x per mile than the conventional diesel. PM emissions for the Pick-up & Delivery operating area were not available.

Table 34 below compares the results on the Highway / Arterial 2 operating area, from the data collected by the data loggers installed by CALSTART staff.

Table 34: On-road emissions testing results from data loggers on Hwy/Arterial 2

CALSTART Data Loggers	Date	Miles	Fuel Used (gal.)	Fuel Economy (MPG)	Time Key ON (s)	Time @ Zero Speed (s)	Fuel @ Zero Speed (gal.)	Avg. MPH (>0)	Max. MPH
Diesel	9/16	11.15	1.22	9.16	1091	118	0.04	41.22	70.21
HHV	9/18	11.86	1.22	9.74	1297	272	0.00	41.67	69.40
Difference	-	+6.4%	**+0.0%**	**+6.3%**	+18.9%	+130.5%	-100.0%	+1.1%	-1.2%

With an average fuel economy of 9.74 MPG, the HHV showed a fuel economy improvement of 6.3% over the baseline on the Highway / Arterial 2 operating area.

Table 35 below compares the results on the Highway / Arterial 2 operating area, from the data collected by the RAVEM system.

Table 35: On-road emissions testing results from RAVEM on Hwy/Arterial 2

RAVEM	Date	Miles	CO_2 (g/mi)	NO_x (g/mi)
Diesel	9/16	N/A	N/A	N/A
HHV	9/18	11.86	1261.55	1.20

Unfortunately, a technical issue occurred which prevented the RAVEM system from recording data on the conventional diesel for the last part of the day. As a result, no emissions data was recorded for the Highway / Arterial 2 operating area.

We can see that the HHV produced 13.9% more CO_2 per mile in the Highway / Arterial 2 operating area than in the Highway / Arterial 1. This was expected as the HHV is heavier due to the hydraulic hybrid system and Highway / Arterial 1 is for a large part going downhill, while Highway / Arterial 2 goes uphill. However, the HHV produced 62.6% less NO_x per mile in the Highway / Arterial 2 operating area than in the Highway / Arterial 1. Highway / Arterial 1 is at the beginning of the shift when the ambient temperature is lower and the Selective Catalytic Reduction (SCR) system is cold, while Highway / Arterial 2 is at the end of the shift when the ambient temperature is higher and the SCR system is warmed up.

Table 36 below compares the ambient and exhaust temperatures for Highway / Arterial 1 and Highway / Arterial 2.

Table 36: Ambient and exhaust temperature analysis for Hwy/Arterial 1 & 2

	Avg. Ambient Temp.	Min. Exhaust Temp.	Avg. Exhaust Temp.	Max. Exhaust Temp.	Time with Temp. > 200°C
Hwy/Arterial #1	12.4°C	18.9°C	139.6°C	305.9°C	34% of total time
Hwy/Arterial #2	21.5°C	53.5°C	211.0°C	376.8°C	52% of total time

We can see that the exhaust temperature is significantly higher for Highway / Arterial 2. Since current SCR systems have a poor NO_x conversion efficiency when exhaust temperature is low [15], the higher NO_x emissions per mile for Highway / Arterial 1 are most likely not attributable to the HHV system.

3.4.3 Conclusions

On-road emissions testing cannot provide the same controlled environment as a chassis dynamometer test. Operating conditions such as road traffic, variation in the number and location of deliveries or driver behavior cannot be controlled and may impact the testing results. In addition, as we mentioned in section 3.4.2, the test vehicles were equipped with different engines and were not EPA certified at the same emissions level, which can impact fuel economy and emissions. Lastly, the driver operating the test vehicle was a replacement driver who had limited experience driving the HHV and limited knowledge of the parcel delivery route. While we recognize the limitations of on-road emissions testing, the results of the present test provide real-world evaluation of the FCCC / Parker Hannifin HHV on an actual parcel delivery route and offer valuable information for prospective fleets looking at replacing existing diesel parcel delivery vehicles by HHVs. Table 37 below summarizes the test results.

Table 37: On-road emissions testing summary results

Operating Area	2008 FCCC MT-55 Diesel			2012 FCCC MT-55 HHV		
	Fuel Economy	CO_2 Emissions	NO_x Emissions	Fuel Economy	CO_2 Emissions	NO_x Emissions
Hwy/Arterial 1	11.64 MPG	1189.03 g/mi	1.83 g/mi	10.96 MPG	1107.66 g/mi	3.21 g/mi
Pick-up & Delivery	7.97 MPG	1390.45 g/mi	5.46 g/mi	11.20 MPG	1095.65 g/mi	4.13 g/mi
Hwy/Arterial 2	9.16 MPG	-	-	9.74 MPG	1261.55 g/mi	1.20 g/mi
Total	8.44 MPG	1364.28 g/mi	5.07 g/mi	10.92 MPG	1127.10 g/mi	3.53 g/mi

We find that the HHV is more efficient and cleaner to operate than a similar conventional diesel vehicle. It shows its best potential in operating areas characterized by low driving speeds and high number of stops. Depending on operating conditions such as terrain, driver behavior and driving / traffic conditions, some fuel savings can be achieved on operating areas characterized by high driving speeds and low number of stops, but savings will remain small.

We also find that the 2010 EPA certified HHV emits more NO_x per mile than a 2008 EPA certified conventional diesel vehicle at cold start. Looking at the exhaust temperature, we showed that these higher emissions at cold start were most likely due to poor NO_x conversion efficiency of the SCR system and are most likely not directly attributable to the HHV system.

3.5 Hydraulic Hybrid Vehicle Performance Conclusions

The performance evaluation carried out for this project evaluated 2 HHVs operating on several parcel delivery routes. The in-use data collection and on-road emissions testing provided a better understanding of HHV technology and evaluated performance in real-world parcel delivery application. We summarize below the main findings and recommendations derived from the performance evaluation.

- *HHVs show their best potential on operating areas characterized by low driving speeds and high number of stops.*

A maximum fuel economy improvement of 40.5% compared to a similar diesel vehicle was observed on a Pick-up & Delivery operating area. Depending on operating conditions such as terrain, driver behavior and driving / traffic conditions, some fuel savings can be achieved on operating areas characterized by high driving speeds and low number of stops, but savings will remain small.

- *Driver behavior that is better adapted to the operation of HHVs would lead to better performance.*

Some drivers took advantage of the advanced engine off feature to leave their vehicle "key on" while delivering packages. Drivers can save time by not having to switch on and off the vehicle for each stop, but leaving the HHV system energized allows stored energy to be depleted without doing useful work and ultimately increases fuel consumption. Preliminary analysis of driver behavior showed that with optimal driving for best fuel economy, up to 6% better fuel economy could be achieved.

- *The advanced engine off feature provides significant benefits to HHVs.*

Analysis of the data showed that the HHVs drove up to 16.2 miles with the engine off for each 100 miles driven. In addition, data also showed that the HHVs consumed significantly less fuel while the vehicle was stopped, for instance at a traffic light. Lastly, the engine off feature eliminated up to 75 minutes of engine run per day compared to a similar diesel vehicle.

Although this leads to hydraulic fluid leakage and ultimately higher fuel consumption, keeping the vehicle in the key on position with the engine off while delivering packages was seen as an advantage by some drivers who could save time by not having to switch on and off the vehicle for each stop.

- *HHVs are more efficient and cleaner to operate than conventional diesel vehicles.*

A maximum fuel economy increase of 29.4% compared to a similar diesel vehicle was observed on a complete parcel delivery route. In addition, the on-road emissions testing showed that the HHV produced 17.4% less CO_2 per mile and 30.4% less NO_x than a similar diesel vehicle (albeit with different emission certification levels).

Chapter 4: User Acceptance

In order to assess the user acceptance of the FCCC / Parker Hannifin HHV, we conducted surveys and interviewed fleet staff. Comparisons were made between hydraulic hybrid and conventional trucks to determine the advantages and disadvantages during normal everyday use.

Drivers were asked to complete a survey rating the HHVs in key vehicle performance areas compared to typical diesel trucks. Due to the subjective nature of driver impressions, performance was rated on a scale from “Much worse” to “Much better” than a similar conventional truck. The driver survey covered the following areas:

- Maneuverability at low speeds,
- Acceleration / Deceleration,
- In-cab controls,
- Braking,
- Interior / Exterior noise level,
- Overall vehicle rating,
- Additional driver comments.

In order to evaluate the serviceability and maintainability of the HHVs, mechanics were asked to provide subjective feedback on various service and maintenance aspects of hydraulic hybrid and conventional vehicles.

Lastly, fleets managers were asked about their overall experience and impressions with HHVs from a parcel delivery fleet management perspective compared to conventional vehicles.

4.1 Summary of User Acceptance Surveys

Three drivers were surveyed regarding their experience with the FCCC / Parker Hannifin HHV. While this is a small sample size, the information captured by the surveys provides valuable input from actual HHV users to evaluate the performance of the FCCC / Parker Hannifin HHV and identify areas of improvement. The tables below provide the summary of the survey results that were obtained from the three drivers. All surveys were also accompanied by extended interviews.

Table 38: Summary results of performance surveys

Property of the HHV compared to a similar conventional delivery vehicle	Much worse	Somewhat worse	Same	Better	Much better
Initial launch from stand still	☐	☒	☐	☐	☐
Maneuverability at slow speeds	☐	☐	☒	☐	☐
Acceleration	☐	☐	☐	☒	☐
Coasting / Deceleration	☐	☐	☒	☐	☐
Overall braking behavior	☐	☐	☐	☐	☒
Productivity (able to cover routes quicker)	☐	☐	☐	☒	☐

Table 39: Summary results of operation surveys

Property of the HHV compared to a similar conventional delivery vehicle	Much worse	Somewhat worse	Same	Better	Much better
Cold Start	☐	☐	☒	☐	☐
Reliability	☐	☐	☒	☐	☐
Inside noise level	☐	☒	☐	☐	☐
Outside noise level	☐	☒	☐	☐	☐
In-cab ergonomics (driver interface / if applicable)	☐	☐	☐	☒	☐

- **Please provide an overall rating of the FCCC / Parker Hannifin HHV.**

Very poor	Poor	Good	Very good	Excellent
☐	☐	☐	☒	☐

The above summary results indicate that the overall ratings of the FCCC / Parker Hannifin HHV were found to be very good. In terms of performance, all but one rating were better than a similar conventional truck or equally good. Inside and outside noise levels were judged "somewhat worse" than for a conventional truck. Drivers rated in-cab ergonomics as "better" than for a conventional diesel powered truck, while they rated reliability as "same".

4.2 Summary of Interviews

Drivers and mechanics were interviewed in informal discussions to gather feedback on some of the FCCC / Parker Hannifin HHV features, investigate low ratings identified in the surveys and discuss ways the vehicle could be improved. In this section, we discuss findings derived from these interviews.

- **Noise level**

As explained in section 2.1, hydraulic drive systems generate characteristic noise and vibration when installed in vehicles [13]. The drivers and mechanics interviewed all noticed that the HHV produced different outside and inside noises than conventional diesel vehicles. Two drivers acknowledged elevated outside and inside noise levels, which was their number one complaint about the HHV.

- **Driver training**

While FCCC and Parker Hannifin planned to provide specific HHV driver and maintenance training for all three fleets, we learned that not all drivers had undergone specific HHV training. We learned that one fleet did not provide specific HHV training to their replacement drivers (when the main route driver goes on vacation for instance) and that they usually did not provide training when drivers switch to another route or change vehicles.

- **Acceleration lag**

The initial launch from stand still was judged "somewhat worse" by the drivers. After further discussion, it was determined that drivers operating Unit C noticed in certain cases a "significant" time between pressing the accelerator pedal and the vehicle moving up to speed. The lag was particularly noticeable when the vehicle was taking off up-hill.

- **Engine shut-down at high speeds**

While the FCCC / Parker Hannifin HHV is capable of driving up to 72 MPH, one fleet specification required maximum vehicle speed to be limited at 65 MPH. This led to some issues on Unit C: if the vehicle travels at a speed above 65 MPH for an extended period of time, the engine control unit shuts off the internal combustion engine and forces the vehicle to come to a complete stop before the driver can turn the system on again. The issue was identified as a software glitch.

- **Air brakes**

The FCCC / Parker Hannifin HHV comes with air-brakes. This caused vehicle deployment issues for Purolator which generally uses vehicles equipped with hydraulic brakes.

- **Additional comments**

Below is a non-exhaustive list of additional driver and mechanic comments collected during the interview process:

- HHV acceleration is sometimes slow especially up-hill.
- Starting the HHV up-hill is difficult.
- HHV is unable to reverse up-hill.
- Available power cannot accommodate reversing up hill, but software fix changed programming to allow for reversing up hills.
- HHV is too loud.
- Drivability and maneuverability is consistent, smooth and steady.
- Engine off is a nice feature and reduces vehicle noise.
- Quality and size of the HHV is good.

- Steering is controlled, responsive and consistent.
- Brakes feel very safe. HHV can be parked on steep hills and hold steady.
- Steering radius does not allow making same turns and it breaks natural habit.
- HHV has a lot of torque and "burns out" on wet pavement.

4.3 Conclusions

The user acceptance surveys and interviews show a good acceptance of the FCCC / Parker Hannifin HHV by drivers and mechanics. Drivers recognized the superior braking behavior and acceleration capabilities of the HHV and acknowledged the quality of the vehicle manufacturing. Drivers complained about issues with initial launch from stand still caused by lags at take-off, especially when taking off up-hill. Lastly some drivers complained about elevated vehicle noise.

The user acceptance surveys and interviews also revealed a gap in driver training. We believe driver training is essential to ensure better acceptance of HHVs and successful hybrid vehicle deployments overall. Drivers are more likely to adopt and accept a vehicle if they are better trained on its operation.

Chapter 5: Service & Maintenance

Hydraulic hybrid vehicles are expected to have lower maintenance costs than conventional vehicles for the following reasons:

- Brake energy recovery can capture and return over 70% of brake energy for vehicle operation, which can reduce brake wear.
- Stored hydraulic power can operate the vehicle when possible allowing the engine to be shut off completely, which can extend engine life.
- The power-split transmission is capable of restarting the engine without using the traditional 12V DC starter system, which can reduce starter and switch replacements.

In order to estimate the service and maintenance benefits of HHVs compared to conventional vehicles, we regularly interviewed fleet mechanics in charge of vehicle maintenance at the site from which Unit C was operating. While we only collected general HHV maintenance information and estimates of conventional vehicles maintenance costs, we were able to develop a first look at the service and maintenance benefits of HHVs in parcel delivery applications. We believe a more complete and in-depth analysis is needed to further investigate and validate our findings.

5.1 Pre-production Vehicle Availability & Reliability

5.1.1 Vehicle Availability

Vehicle availability is defined as the percentage of time that a vehicle is potentially available for use, regardless of whether the vehicle is actually used on the particular day. Due to project constraints, vehicle availability was not tracked accurately during the performance testing period but fleet maintenance personnel and Parker Hannifin staff regularly provided updates on major maintenance issues that occurred during the performance testing period.

Parker Hannifin engineers responded promptly to any reported issues in order to bring the HHVs back to service as soon as possible. They also provided several software upgrades to the HHVs that improved their performance or solved issues identified during the deployment.

The HHVs encountered some issues that made them slightly less available than conventional diesel trucks. Since they were pre-production vehicles and had limited in-service experience, maintenance issues were anticipated during the project performance period. Fleet mechanics had limited experience with hydraulic hybrid system maintenance procedures and thus all major repairs were handled by the supplier team, adding some delays when solving any maintenance issue. At this early stage of vehicle development, true vehicle availability comparison between HHVs and conventional diesel vehicles would be difficult.

5.1.2 Vehicle Odometer

All three pre-production vehicles encountered issues with the vehicle odometer not recording mileage when the engine is off. The issue was caused by the engine software not being configured to handle engine off operation. While the issue was specific to the engine supplier and not the HHV supplier, it proved especially important for FedEx Ground, who uses vehicle mileage to pay its contractors.

The supplier team implemented a temporary short term solution relying on field engineers manually reading mileage from installed hubometers. In addition, all three HHVs were equipped with data loggers that provided accurate mileage data even if the vehicle odometers were not recording miles in engine off operation. Lastly, the supplier team also developed a long term solution that was successfully implemented on one of the three pre-production vehicles and will be used on future production vehicles.

5.1.3 Air Compressor Governor

Engine off operation issues on Unit C were identified during the performance evaluation period. Table 40 and Table 41 below show the worst, average and best days in terms of performance on the two routes Unit C drove.

Table 40: Unit C worst, average and best performance on Route 1

Route 1	Daily Engine Off Driving Time	Daily Engine Off Driving Miles	Fuel Economy
Worst	20 minutes	4.8 miles	6.69 MPG
Average	41 minutes	8.7 miles	8.14 MPG
Best	88 minutes	11.7 miles	9.49 MPG

Table 41: Unit C worst, average and best performance on Route 2

Route 2	Daily Engine Off Driving Time	Daily Engine Off Driving Miles	Fuel Economy
Worst	0.5 minutes	0.1 miles	6.49 MPG
Average	52 minutes	11.1 miles	9.64 MPG
Best	71 minutes	17.3 miles	10.41 MPG

For both Route 1 and 2, there is a large variation in fuel economy: from a worst of 6.69 MPG to a best of 9.49 MPG on Route 1 and from a worst of 6.49 MPG to a best of 10.41 MPG on Route 2. The worst fuel economy days happen when the HHV shows the lowest time and miles spent with the engine off, while the best fuel economy days happen when the HHV shows the highest time and miles spent with the engine off.

Parker Hannifin identified that Unit C faced issues with the air compressor governor, which prevents the engine from shutting off and results in higher fuel consumption. Figure 22 below shows 5 consecutives events when the engine on Unit C fails to shut off while the vehicle is key-on, stopped, with the parking brake on and the transmission in neutral.

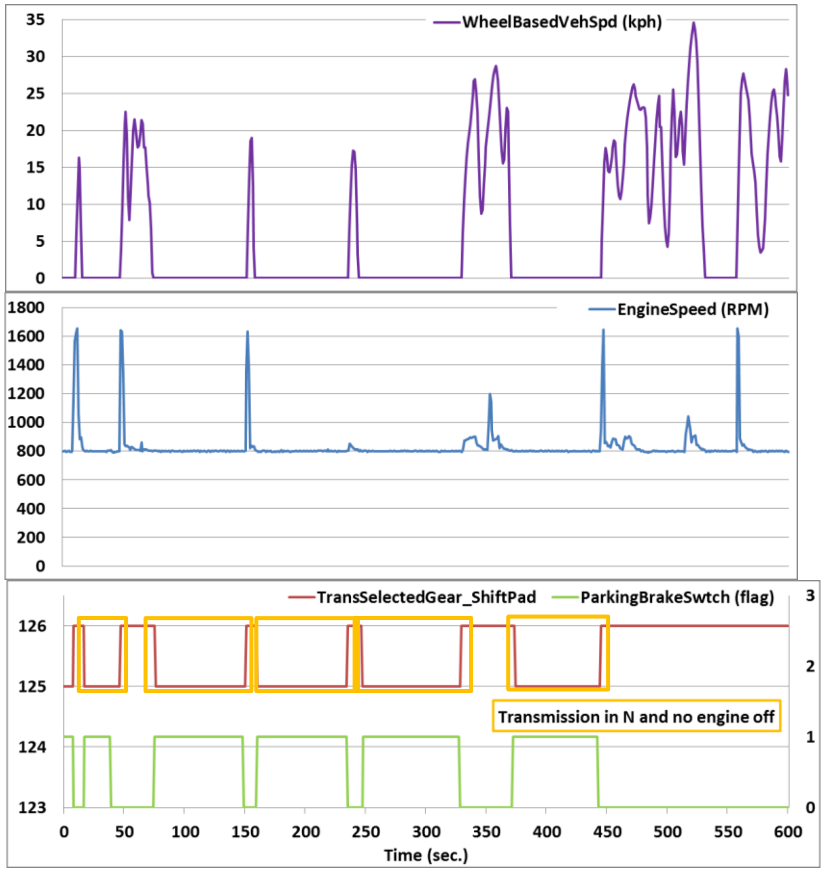


Figure 22: Zoom on 5 consecutive events where engine fails to shut off

Higher fuel economy could be reached more easily with better air compressor governing strategy. Parker Hannifin has developed a different control strategy to get more consistent engine off operation and installed it on Unit C in September 2013. Preliminary results indicate that Unit C achieved a fuel economy of about 10.0 MPG on Route 1 with the update. This represents a fuel economy improvement over the baseline of about 30%, while Unit C showed an average fuel economy improvement of only 5.3% and a best of 22.8% over the baseline during the performance evaluation period (section 3.3.2).

5.1.4 Hydraulic Hybrid Vehicle System

Unit C suffered a hydraulic fluid leak caused by a hydraulic pump/motor port failure on October 2012 after about 230 hours in operation (3,400 miles). FedEx Ground and UPS reported similar issues with the HHV system on other FCCC / Parker Hannifin HHVs not part of this project.

The supplier team responded promptly to the issue, replacing the HHV system and limiting vehicle down-time to only a few days. Parker Hannifin quickly completed a comprehensive analysis of the issue and implemented a design change to mitigate the hydraulic fluid leak in case of HHV system failure. Unit C has been running without any issues since.

Beyond the mitigation measure implemented on all three units, Parker Hannifin worked to find a long term solution and implement a design change.

5.1.5 Tire Wear

Accelerated tire wear was noticed on Unit C while operating on Route 1. Local fleet maintenance personnel indicated that tires were replaced every 3,000 miles or every 3 months on the HHV running on Route 1. To investigate the issue further, we compared tire wear on 3 vehicles and 2 different routes:

- 1 gasoline-powered Workhorse W62 operating on Route 1,
- 1 conventional diesel-powered FCCC MT-55 operating on Route 1 and Route 2,
- 1 hydraulic hybrid diesel-powered FCCC MT-55 operating on Route 1 and Route 2.

Table 42 below details each vehicle characteristics.

Table 42: Comparison of vehicle characteristics for tire wear analysis

	Workhorse W62	FCCC MT-55 Diesel	FCCC MT-55 HHV
Model Year	2011	2008	2012
Chassis Manufacturer	Workhorse (W62 Model)	FCCC	FCCC
Body Manufacturer	Morgan Olson	Utilimaster Corporation	Morgan Olson
GVWR	23,000 lbs.	23,000 lbs.	23,000 lbs.
Curb Weight	-	12,100 lbs.	13,800 lbs.
Engine			
Model	GM Vortec 6.0L V8 Gasoline	Cummins ISB 6.7L	Cummins ISB10 6.7L
Peak Power	299 HP (223 kW) @ 4,400 RPM	200 HP (149 kW) @ 2,400 RPM	280 HP (209 kW) @ 2,300 RPM
Peak Torque	357 ft-lbs. (484 Nm) @ 4,400 RPM	520 ft-lbs. (705 Nm) @ 1,600 RPM	660 ft-lbs. (895 Nm) @ 1,600 RPM
Fuel System	Gasoline / 40-gallon fuel tank	ULSD / 40-gallon fuel tank	ULSD / 30-gallon fuel tank
Exhaust System	Three-way Catalyst	Oxidizing Catalyst and Periodic Trap Oxidizer	SCR and DPF 10-gallon DEF tank (2-3% injection rate)
Dimensions			
Tires	245/70 R19.5	245/70 R19.5	245/70 R19.5
Wheelbase	178 in.	178 in.	178 in.
Transmission / Hydraulic Hybrid System			
Make	Allison	Allison	Parker Powersplit Hybrid Series System
Type	2000 HS Automatic	2200 HS Automatic	Infinite Variable Advanced Series Transmission
Rear Axle Ratio	5.13:1	4.10	N/A
Oil Capacity	N/A	N/A	Gearbox – 9 liters System - 29 gallons
Components Weight	N/A	N/A	~ 1,700 lbs.

➢ **Route 1 Analysis**

From November 2011 to July 2012, the gasoline-powered Workhorse W62 operated on Route 1 prior to the HHV being deployed on that route. The vehicle operated on Route 1 for about 8.5 months and drove about 12,000 miles. Both front tires were replaced at about 9,500 miles and the rear tires at about 12,000 miles.

On May 13, 2013, the conventional diesel-powered FCCC MT-55 was moved to operate on Route 1. All tires were changed on the vehicle on May 2, 2013 and the truck drove 398 miles on Route 2 before switching to Route 1. On September 9, 2013, after driving 4,092 miles (398 miles on Route 2 and 3,694 on Route 1) a tread depth measurement was done using a depth gauge. Table 43 below summarizes the results of the tread depth measurement and provides measurements on brand new tires and tire replacement limits for comparison. Please note that both inside and outside rear right tires were not accessible at the time of measurement.

Table 43: Conventional FCCC MT-55 tread depth measurement (9/9/2013)

Tread Depth Measurement	9/9/2013	New Tires	Replacement Limit
Front Right	6/32"	17/32"	4/32"
Front Left	5/32"	17/32"	4/32"
Inside Left Rear	8/32"	17/32"	2/32"
Outside Left Rear	8/32"	17/32"	2/32"
Inside Rear Right	N/A	17/32"	2/32"
Outside Rear Right	N/A	17/32"	2/32"

Figure 23 and Figure 24 below shows the rear and front tires at the time of measurement (on the left) and for comparison, new tires (on the right).

Figure 23: Conventional FCCC MT-55 rear right tires (left) and new rear right tires (right)

Figure 24: Conventional FCCC MT-55 left front tire (left) and new left front tires (right)

Knowing the mileage of the tires and the tread depth at the time of the tread depth measurement, we can estimate the tire replacement interval for the conventional FCCC MT-55 operating on Route 1[4]:

- About 6,800 miles for the rear tires,
- About 4,800 miles for the front left tire,
- About 4,400 miles for the front right tire.

[4] We assume that the steer tires are replaced when tread depth reaches 4/32" and the drive tires when tread depth reaches 2/32".

The hybrid FCCC MT-55 was in operation on Route 1 from July 2012 to May 13, 2013. From the maintenance records, we estimated the tire replacement interval on Route 1:

- Between 2,300 – 5,100 miles for the rear tires (average 4,000),
- 7,100 miles for front left tire,
- 8,900 miles for front right tire.

➢ Route 2 Analysis

The conventional FCCC MT-55 has been in operation on Route 2 for several years. From the last 3 years of maintenance records, we estimated the tire replacement interval on Route 2:

- Between 12,500 – 13,500 miles for the rear tires (average 12,800),
- Between 4,200 – 16,000 miles for the front left tire (average 11,000),
- Between 7,500 – 14,500 miles for the front right tire (average 11,000).

On May 13, 2013, the hybrid FCCC MT-55 was moved to operate on Route 2. On September 9, 2013, after driving about 5,500 miles on Route 2, a tread depth measurement was done using a depth gauge. Table 44 below summarizes the results of the tread depth measurement and provides measurements on brand new tires and tire replacement limits for comparison.

Table 44 : Hybrid FCCC MT-55 tread depth measurement (9/9/2013)

Tread Depth Measurement	9/9/2013	New Tires	Replacement Limit
Front Right	5/32"	17/32"	4/32"
Front Left	5/32"	17/32"	4/32"
Inside Left Rear	4/32"	17/32"	2/32"
Outside Left Rear	3/32"	17/32"	2/32"
Inside Rear Right	2/32"	17/32"	2/32"
Outside Rear Right	2/32"	17/32"	2/32"

Figure 25 and Figure 26 below shows the rear and front tires at the time of measurement (on the left) and for comparison, new tires (on the right).

Figure 25: Hybrid FCCC MT-55 rear right tires (left) and new rear right tires (right)


Figure 26: Hybrid FCCC MT-55 left front tire (left) and new left front tires (right)

The front tires were changed last in February 2013 (for the left front tire) and March 2013 (for the right front tire) and thus operated several months on Route 1 before the vehicle was switched to operate on Route 2. Given the tire replacement interval on Route 1 and knowing the mileage of the tires and the tread depth at the time of the tread depth measurement, we can estimate the tire replacement interval for the hybrid FCCC MT-55 operating on Route 2[5]:

- About 8,900 miles for the front left tire,
- About 6,200 miles for the front right tire.

The rear tires were changed while the vehicle was operating on Route 2 (in July 2013) and we can thus estimate the tire replacement interval on Route 2:

- About 5,600 miles for the inside left rear tire,
- About 5,200 miles for the outside left rear tire,
- About 4,900 miles for the inside and outside right rear tire.

➢ **Summary**

Table 45 and Table 46 summarize the tire replacement interval estimates for the 3 study vehicles on Route 1 and for the conventional and hybrid FCCC MT-55 on Route 2. It is important to note that the mileage figures below are estimates based on maintenance records and tread depth measurement.

Table 45 : Estimates of tire replacement interval on Route 1

	Route 1		
Vehicle	**Workhorse W62**	**FCCC MT-55 Diesel**	**FCCC MT-55 HHV**
Front (Left / Right)	~9,500 miles	~4,800 / 4,400 miles	~7,100 / 8,900 miles
Rear	~12,000 miles	~6,800 miles	~4,000 miles

Front tire wear on the HHV appears to be consistent with the estimates on the Workhorse W62 and better than the conventional FCCC MT-55 on Route 1. However, the rear tires of the HHV seem to be experiencing accelerated wear on Route 1.

[5] We assume that the steer tires are replaced when tread depth reaches 4/32" and the drive tires when tread depth reaches 2/32".

Table 46 : Estimates of tire replacement interval on Route 2

	Route 2	
Vehicle	FCCC MT-55 Diesel	FCCC MT-55 HHV
Front (Left / Right)	?	~8,900 / 6,200 miles
Rear	~12,800 miles	~4,900 / 5,600 miles

Front tire wear on the conventional FCCC MT-55 varied largely from 4,200 to 16,000 miles. Therefore, it is difficult to assess if front tire wear was better or worse on the HHV operating on Route 2. However, the rear tires of the HHV seem to be experiencing accelerated wear on Route 2.

The cost to replace a set of 4 rear tires is about $350 (labor not included), which can represent a significant expense over the life of the vehicle and cancel other benefits such as fuel saved or other maintenance savings. Several reasons can explain the accelerated tire wear on the rear tires of the HHV:

- Use of retread tires which will wear out faster than new tires.
- Heavier curb weight (about 1,700 lbs. more than for a conventional diesel MT-55 vehicle).
- Different weight distribution (Appendix C shows where the high pressure accumulator, low pressure reservoir and the HHV system are placed on the vehicle chassis).
- Excessive torque from the pump/motor while accelerating or braking.
- Driver behavior.

As accelerated rear tire wear has only been reported on Unit C, we believe a more complete and in-depth analysis is needed to further investigate and validate our findings.

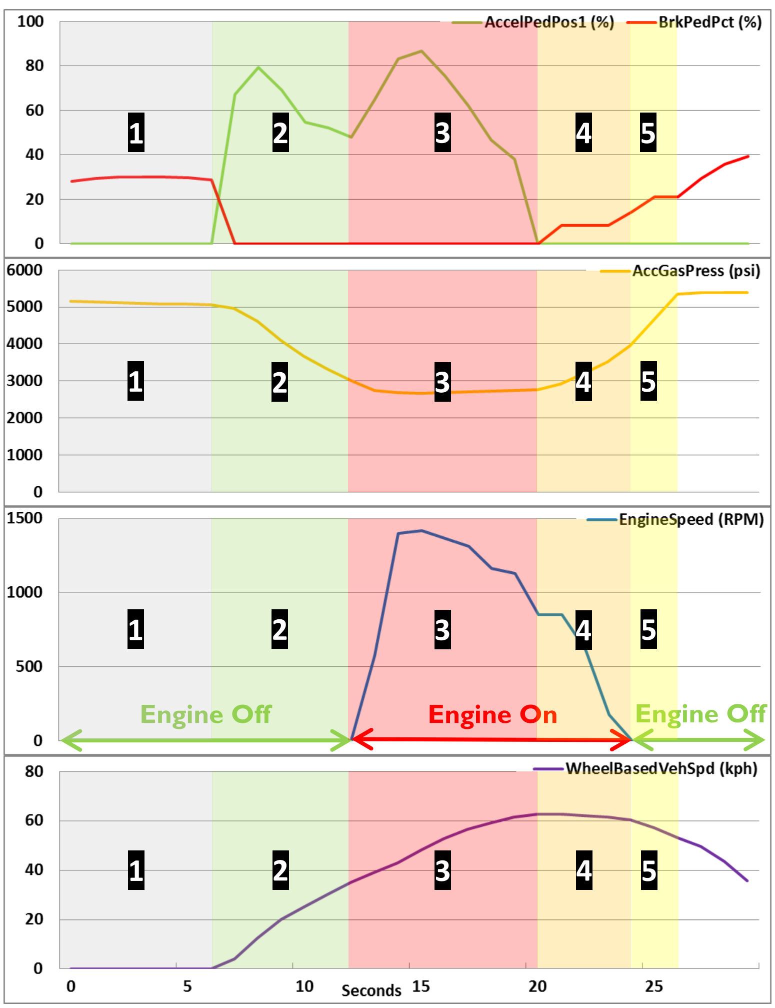
5.2 Preliminary Maintenance Cost Analysis

We collected general maintenance costs and maintenance interval data for the three vehicles presented in section 5.1.5. In order to analyze potential maintenance savings from hydraulic hybrid technology, we looked at recurring maintenance procedures where hydraulic hybrid technology can provide significant savings.

Please note that maintenance costs and intervals reported in this section will vary widely with driving conditions such as miles driven and number of stops per day. The numbers presented in this section are representative of a specific facility and specific driving conditions. They should not be used to predict HHV maintenance savings under different driving conditions.

5.2.1 12V DC Starter

The Parker Hannifin HHV system is capable of launching the vehicle while the internal combustion engine is off. If the internal combustion engine is needed, the HHV system can start the engine without using the traditional 12V DC starter. The example below details a typical starting sequence with the Parker Hannifin HHV system.



Phase 1: The driver maintains the HHV stopped by pressing on the brakes. Engine is off.

Phase 2: The driver releases the brakes and accelerates the HHV. Engine is off and the HHV system provides all the torque needed to meet driver demand (reflected by the accumulator gas pressure dropping).

Phase 3: The driver keeps accelerating the HHV. The accumulator reaches a low pressure and the engine is started (without using the 12V DC starter) to supply torque and meet driver demand.

Phase 4: The driver is braking and the HHV system regenerates energy while braking (reflected by the accumulator gas pressure rising). Engine RPM decreases and ultimately shuts off.

Phase 5: The driver keeps braking and the HHV system regenerates energy while braking. Engine is off.

AccelPedPos1 = accelerator pedal position (%)
BrkPedPct = brake pedal position (%)
AccGasPress = accumulator gas pressure (psi)
EngineSpeed = engine speed (RPM)
WheelBasedVehSpd = wheel based vehicle speed (kph)

We analyzed the data from both Unit B and Unit C to assess how many times the traditional 12V DC starter was used to start the internal combustion engine. Table 47 below shows the number of starter uses for Unit B and Unit C operating on two different routes.

Table 47: 12V DC starter use analysis for Unit C on Route 1 & 2 and for Unit B on Route 3

	Unit C (Route 1)	Unit C (Route 2)	Unit B (Route 3)
Days in operation	30	77	34
12V DC starter use	45	208	111
Starter use per day	**1.5**	**2.7**	**3.3**

Results show that on average, 12V DC starter use is between 1.5 and 3.3 times per day in operation. The difference between the three values can be explained by different operating conditions such as miles driven and number of stops.

Figure 27 below compares 12V DC starter use on Route 1 and Route 2 between Unit C and the conventional diesel vehicle.

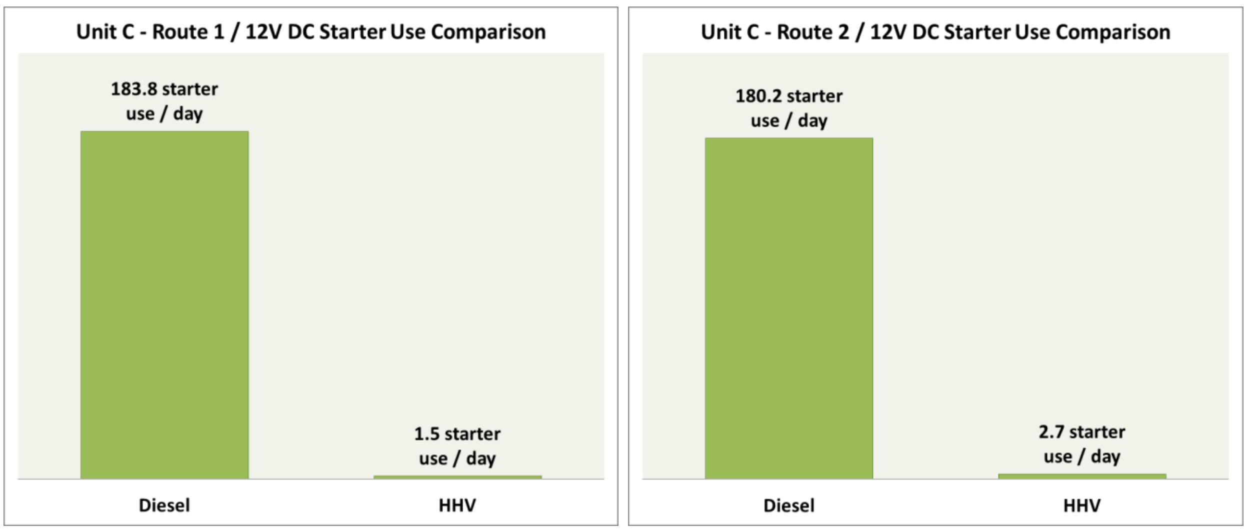


Figure 27: Conventional diesel and HHV 12V DC starter use comparison on Route 1 & 2

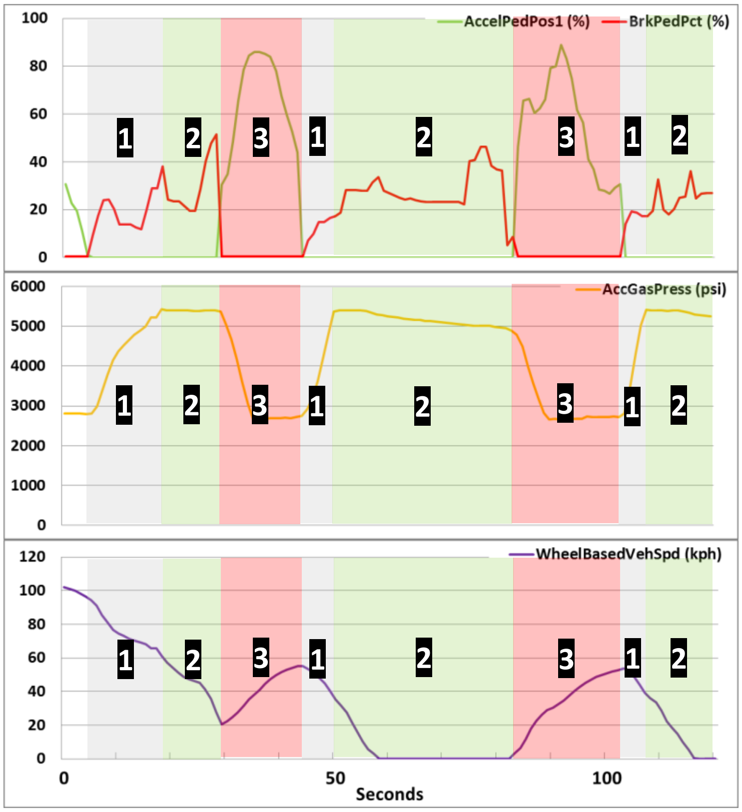
Starter use is dramatically reduced on the HHV unit on both routes: the HHV system saves about 180 12V DC starter uses for each day the vehicle is in operation. For a vehicle that is used about 250 days per year and kept in service for 10 years, a HHV will use its 12V DC starter system about 5,000 times in its lifetime versus 450,000 times for a conventional diesel vehicle.

12V DC starters can be replaced every year on parcel delivery routes with a high number of stops. The cost to replace a 12V DC starter is about $120 (labor not included), which can represent a significant expense over the life of the vehicle.

Some fleets replace 12V DC starters at fixed intervals based on vehicle mileage. To take advantage of the reduced wear and tear on the 12V DC starter system, fleets will need to use different replacement intervals specific to the operating conditions of HHVs.

5.2.2 Brake Wear

With brake energy recovery capable of capturing and returning over 70% of brake energy for vehicle operation, HHVs are expected to reduce brake wear and increase brake life over a conventional diesel truck. The example below shows the Parker Hannifin HHV system capturing and returning brake energy during vehicle operation.



Phase 1: The driver presses the brake pedal to slow down. The rising accumulator pressure indicates that the HHV is slowed down using the HHV system which recovers brake energy.

Phase 2: The driver keeps braking. The pressure in the accumulator has reached its maximum and no additional brake energy can be recovered. The HHV is slowed down using the conventional air-brakes.

Phase 3: The driver presses the accelerator pedal to increase vehicle speed. The decreasing accumulator pressure indicates that brake energy is returned by the HHV system to accelerate the vehicle.

AccelPedPos1 = accelerator pedal position (%)
BrkPedPct = brake pedal position (%)
AccGasPress = accumulator gas pressure (psi)
WheelBasedVehSpd = wheel based vehicle speed (kph)

To assess potential brake savings, we compared brake pad thickness on Unit C and the conventional FCCC MT-55 presented in section 5.1.5. The conventional FCCC MT-55 has been in operation on Route 2 for several years. From the last 3 years of maintenance records, we estimated the brake pad replacement interval on Route 2 at between 22,000 – 26,000 miles for the front and rear brake pads.

On September 18, 2013, after driving 15,051 miles (about 2/3 on Route 1 and 1/3 on Route 2), a brake pad thickness measurement was done using a depth gauge. Table 48 below summarizes the results of the brake pad thickness measurement and provides measurements on brand new brake pads and replacement limits for comparison.

Table 48: Hybrid FCCC MT-55 brake pad thickness measurement (9/18/2013)

Brake Pad Thickness Measurement	9/18/2013	New Brake Pads	Replacement Limit
Front Right	22/32"	23/32"	12/32"
Front Left	22/32"	23/32"	12/32"
Rear Left	16/32"	23/32"	12/32"
Rear Right	16/32"	23/32"	12/32"

Knowing the brake pad thickness and the HHV mileage at the time of the brake pad thickness measurement, we can estimate the brake pad replacement interval for the HHV:

- About 165,600 miles for the front brake pads,
- About 23,700 miles for the rear brake pads.

Table 49 summarizes the brake pad replacement interval estimates for Unit C and the conventional FCCC MT-55. It is important to note that the mileages below are estimates based on maintenance records and brake pad thickness measurement. In addition, Unit C operated on both Route 1 and 2 during the evaluation period, while the estimates for the conventional FCCC MT-55 are for Route 2 only.

Table 49: Estimates of brake pad replacement interval

Vehicle	FCCC MT-55 Diesel (Route 2)	FCCC MT-55 HHV (Route 1 & 2)
Front	22,000 – 26,000 miles	~165,600 miles
Rear	22,000 – 26,000 miles	~23,700 miles

Front brake pad wear is dramatically improved on the HHV, while the rear brake pad wear appears to be consistent with the estimates on the conventional FCCC MT-55. This first rough look at brake savings indicates that the HHV system has the potential to provide significant savings on the front brake pads.

Several reasons can explain the different brake pad wear between front and rear:

- Heavier curb weight (about 1,700 lbs. more than for a conventional diesel MT-55 vehicle).
- Different weight distribution (Appendix C shows where the high pressure accumulator, low pressure reservoir and the IVT are placed on the vehicle chassis).
- Driver behavior.

The cost to replace a complete vehicle set of brake pads is between $60 and $80 (labor not included), which can represent a significant expense over the life of the vehicle. We believe a more complete and in-depth analysis is needed to further investigate and validate our findings.

5.2.3 Optimized Engine Control

The Parker Hannifin HHV system enables optimized engine control, which presents several advantages in terms of operation and maintenance savings [3]:

- *Stored hydraulic energy is able to power the vehicle without using the engine.*

We saw in sections 3.1, 3.2 and 3.3 that both Unit B and C took advantage of the engine off feature to operate on hydraulic power only. While operating on Route 2, Unit C drove 16.2 miles with the engine off for each 100 miles, eliminating an average of 75 minutes of engine run time per day despite air compressor governor issues and driver behavior not fully adapted to the operation of HHVs.

Engine off operation can extend engine life and increase replacement intervals of the following engine related components: oil change / oil filter, fuel filter, air filter and engine coolant. Some fleets replace the previous components at fixed intervals based on vehicle mileage. To take advantage of the reduced wear and tear on the engine and its components, fleets will need to use different replacement intervals specific to the operating conditions of HHVs.

- *Series HHV decouples the engine from the drive wheels allowing the operation of the engine at a "sweet spot" of best fuel consumption and lower emissions for a given power level.*

Figure 28 below shows the engine speed and torque distribution for the conventional FCCC MT-55 during an entire day in operation on Route 1 and Figure 29, the same for Unit C.

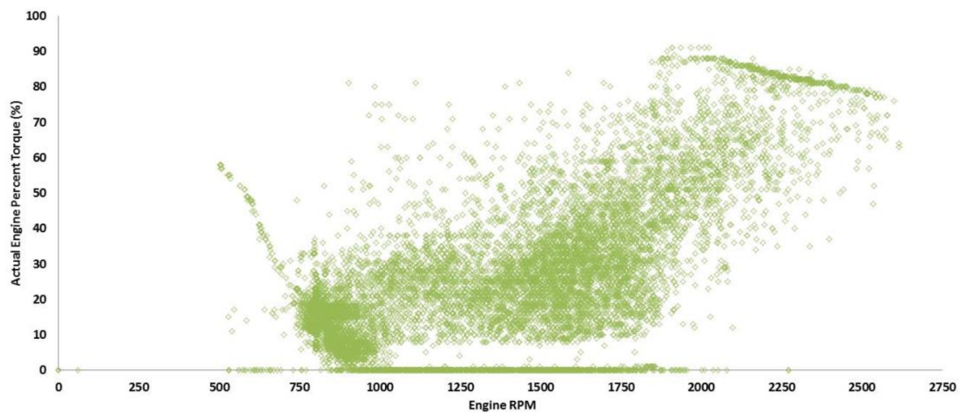


Figure 28: Conventional diesel engine speed and torque distribution

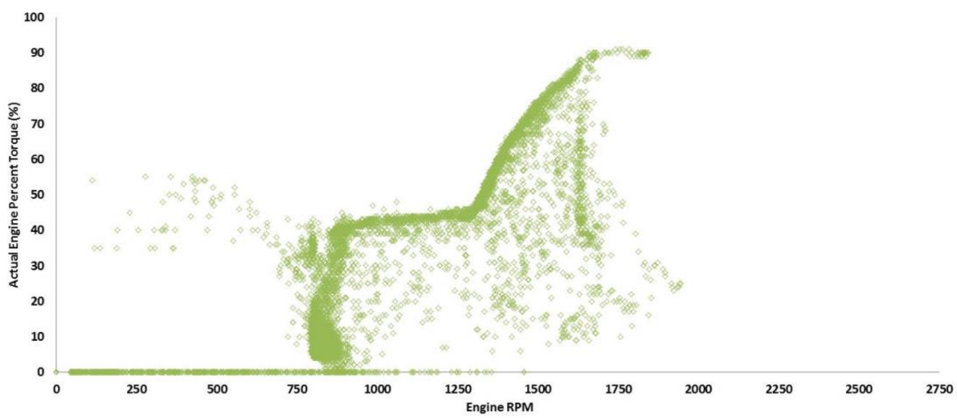
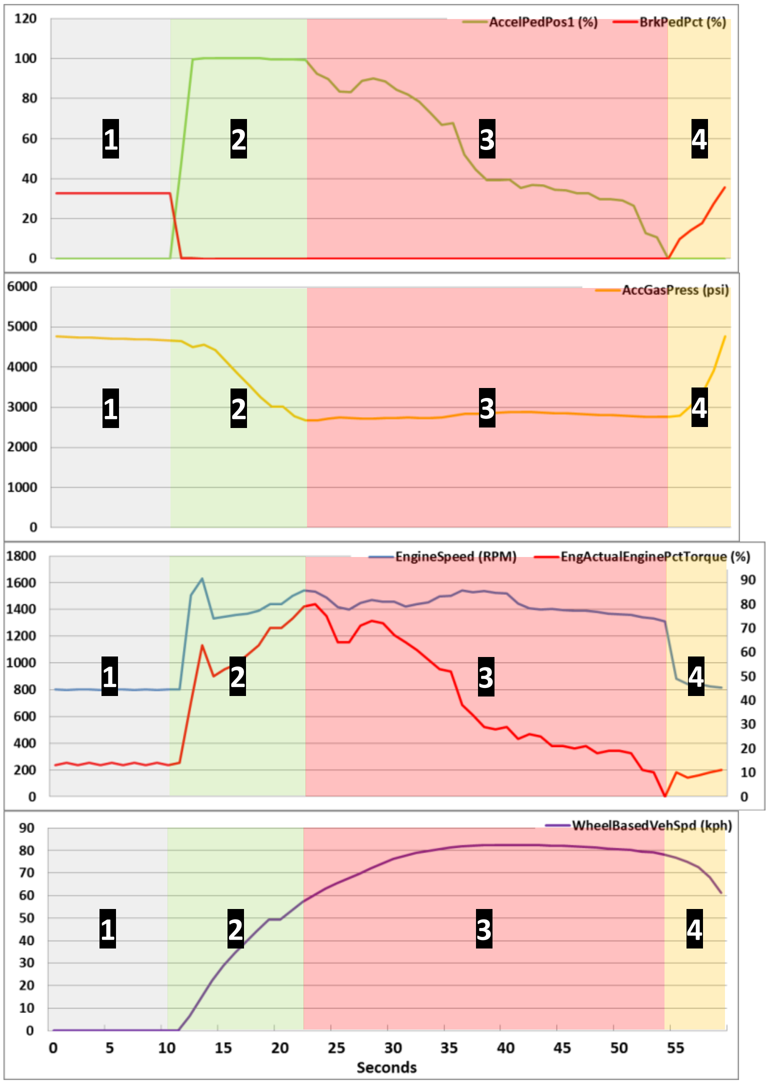


Figure 29: Hydraulic hybrid engine speed and torque distribution

We can see that the engine on the HHV is operated differently than on the conventional vehicle. The engine operating points are more concentrated, indicating that the HHV system is able to provide the required power level while operating the engine at higher efficiencies.

The example below shows how the Parker Hannifin HHV system is able to blend power from the high pressure accumulator and the engine to meet driver torque demand, while operating the engine at a "sweet spot" of best fuel consumption and lower emissions for a given power level.



Phase 1: The driver maintains the HHV stopped by pressing on the brakes. Engine is on.

Phase 2: The driver releases the brakes and accelerates the HHV. Mechanical and hydraulic powers are blended through the highly efficient dual-mode operating system to provide the torque needed to meet driver demand.

Phase 3: The driver keeps accelerating the HHV. As the accumulator reaches a low pressure, mechanical power from the engine provides all the torque needed to meet driver demand. Power level then drops as the vehicle speed governor acts to limit vehicle speed.

Phase 4: The driver is braking and the HHV system regenerates energy while braking (reflected by the accumulator gas pressure rising). Engine RPM decrease.

AccelPedPos1 = accelerator pedal position (%)
BrkPedPct = brake pedal position (%)
AccGasPress = accumulator gas pressure (psi)
EngineSpeed = engine speed (RPM)
EngActualEnginePctTorque = actual engine torque (%)
WheelBasedVehSpd = wheel based vehicle speed (kph)

5.3 Conclusions

The service and maintenance evaluation carried out for this project collected general maintenance information and estimates of maintenance costs and benefits from Unit C. The evaluation of the FCCC / Parker Hannifin HHV reported limited vehicle availability issues that were expected with pre-production vehicles and identified several opportunities for maintenance savings compared to conventional vehicles. Lastly, the evaluation also found some service and maintenance improvement opportunities.

- *Pre-production vehicle issues*

Unit C encountered some issues that made the vehicle slightly less available than a conventional diesel truck. For instance, Unit C experienced a HHV system failure early after the vehicle was put in commercial service. In addition, all three pre-production vehicles encountered issues with the vehicle odometer recording mileage when the engine was off. Lastly, Unit C faced issues with the air compressor governor, which prevented the engine from shutting off and resulted in higher fuel consumption.

- *Opportunities for savings*

The Parker Hannifin HHV system dramatically reduced 12V DC starter use (99% less starter use per day) compared to a conventional diesel truck. In addition, front brake pad wear was dramatically improved: preliminary estimates showed front brake life could be increased by 6 times over a conventional diesel truck. Lastly, the advanced engine off strategy allowed Unit C to drive up to 16.2 miles with the engine off for each 100 miles driven on one particular parcel delivery route, eliminating an average of 75 minutes of engine run time per day despite air compressor governor issues and driver behavior not fully adapted to the operation of hydraulic hybrid vehicles.

A more complete analysis is needed to further investigate and understand the potential maintenance savings of HHVs.

- *Potential for improvement*

For pre- and early production vehicles, vehicle warranty should be extended to meet the useful life of the vehicles to encourage fleets and independent contractors to purchase HHVs without fearing that vehicles will not be profitable once they come out of warranty. In addition, HHVs have special parts that may complicate in-house servicing. At this early stage of vehicle deployment, fleets are forced to take vehicles to their dealership for repairs, which increases vehicle down-time and ultimately maintenance costs. Returning vehicle quickly when maintenance issues arise is important. Lastly, a preliminary analysis identified that Unit C experienced accelerated wear on the rear tires while operating on two distinct parcel delivery routes. The cost to replace a set of 4 rear tires can represent a significant expense over the life of the vehicle and cancel other benefits such as fuel saved or other maintenance savings. A more complete and in-depth analysis into this last issue is needed to further investigate and validate the findings of this report.

Chapter 6: Findings & Recommendations

This chapter summarizes the findings and recommendations developed in this report to inform fleets and hydraulic hybrid vehicle manufacturers on the overall performance of HHVs, to provide insights on how the technology can be improved and better used.

6.1 HHV Performance

Chapter 3 presented a comprehensive performance evaluation of hydraulic hybrid vehicles, including results from in-use data collection and on-road emissions testing. The HHV performance key findings are:

- *Operating conditions impact HHV performance.*
- *HHVs are more efficient and cleaner to operate.*

The in-service performance evaluation and the on-road emissions testing showed that HHVs achieved higher fuel economy savings in operating areas characterized by low driving speeds and high number of stops. In addition, the in-service performance evaluation showed how driver behavior can impact HHV performance.

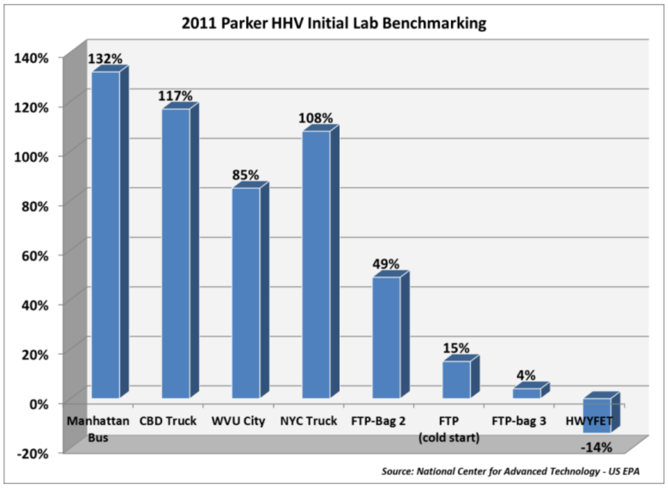
In general, both in-service performance evaluation and the on-road emissions testing showed that HHVs are more efficient than conventional diesel vehicles and operate with fewer emissions.

6.2 HHV Fleet Deployment

Chapter 3 presented a comprehensive performance evaluation of hydraulic hybrid vehicles, including results from in-use data collection and on-road emissions testing. Chapter 4 detailed HHV user acceptance. The HHV fleet deployment key findings are:

- *Operating routes need to be carefully selected.*
- *Driver behavior should be managed to achieve best performance.*

Actual vehicle fuel economy varies widely with driving conditions such as drive cycle and driver behavior. Figure 30 below shows the results of extensive fuel economy testing done in 2012 on a prototype version of the FCCC / Parker Hannifin HHV at the U.S. EPA National Vehicle and Fuel Emissions Laboratory [15].



Drive Cycle	Average Speed (>0)	Stops per Mile
HWYFET	48.6	0.10
FTP Bag 3	31.8	1.39
FTP Cold Start	26.2	1.99
FTP Bag 2	19.7	3.11
NYC Truck	15.7	9.37
WVU City	12.1	4.24
CBD Truck	11.4	6.41
Manhattan Bus	10.7	9.68

Figure 30: Results of 2011 Parker HHV Initial Lab Benchmarking [16].

Results clearly show how drive cycle influences vehicle fuel economy and confirms that HHVs are better suited for routes with a higher number of stops and lower average speeds. When deploying a HHV, fleet managers should identify the route close to the target parameters identified in Table 50 below.

Table 50: Target route parameters for optimal HHV performance

Route Parameter	Target
Brake Wear	High
Daily Miles	50-70 miles per day
Stops / Mile	>3-4
Number of Pickup & Deliveries	>100 per day
Highway / Arterial Miles	Minimize
Pickup & Delivery Miles	Maximize
Idle Time	High

Sections 3.1 and 3.2 show how driver behavior can significantly impact vehicle performance and ultimately fuel economy. Hybrid vehicles can present a challenge to drivers as they require modifying driving techniques to take advantage of regenerative braking for instance. We recommend that drivers operating HHVs be trained and coached to learn to drive their new truck more efficiently throughout their parcel delivery route. Driver training is essential to ensure better acceptance of HHVs and successful HHV deployments overall.

6.3 HHV Maintenance

Chapter 5 presented a preliminary service and maintenance evaluation of HHVs. The HHV maintenance key findings are:

- *Accelerated rear tire wear can negatively impact the business case for HHVs.*
- *HHVs show opportunities for lower maintenance costs.*

A preliminary analysis identified that Unit C experienced accelerated wear on the rear tires while operating on two distinct parcel delivery routes. The cost to replace a set of 4 rear tires can represent a significant expense over the life of the vehicle and cancel other benefits such as fuel saved or other maintenance savings.

Section 5.2 shows potential to have lower maintenance costs than conventional vehicles. Our first look identified 12V DC starter, front brake wear and reduced engine run time as areas for saving opportunities. Some fleets employ maintenance procedures at fixed intervals based on vehicle mileage. To take advantage of these potential maintenance savings, fleets will need to use different replacement intervals specific to the operating conditions of HHVs.

We expect HHVs maintenance savings to vary widely with driving conditions such as miles driven and number of stops per day. A more complete and in-depth analysis into this issue is needed to further investigate and validate the findings of this report.

6.4 HHV Business Case

The business case for high-efficiency vehicles is important to understand in the early stages of market introduction. High-efficiency vehicles such as hydraulic hybrid vehicles have upfront costs much higher than similar diesel or gasoline trucks but will have lower operation and maintenance costs. With increased fuel economy and lower maintenance costs, HHVs can be cost effective. Three conditions need to be met to achieve a return on investment (ROI):

- High fuel economy increase,
- High maintenance savings,
- Low incremental cost.

The in-service performance evaluation showed pre-production HHVs achieving fuel economy increases of up to 30% on selected parcel delivery routes. With an optimized HHV system, compatible driver behavior and vehicles operating in optimal driving cycles, we expect HHVs to achieve greater fuel economy increases. We also identified in section 5.2 several opportunities for maintenance savings such as 12V DC starter use, front brake pad wear, increased engine and engine components life.

Table 51 below analyzes the business case and environmental benefits given three fuel economy performance levels and assuming a level of maintenance savings.[6]

Table 51: HHV business case analysis

	30% MPG Increase	40% MPG Increase	50% MPG Increase
Maximum Incremental Cost for 7-yr. Payback	$21,100	$24,380	$27,210
Net Present Value (10 yrs.)	$5,310	$6,320	$7,200
Yearly Fuel Savings	468 gallons	579 gallons	676 gallons
Yearly WTW CO_2 Savings	6.0 metric tons	7.4 metric tons	8.7 metric tons
Yearly Petroleum Savings	12.0 barrels	14.9 barrels	17.4 barrels

If a HHV achieved a 30% fuel economy increase compared to a similar diesel vehicle, the maximum incremental cost would have to be $21,100 to achieve a 7-year payback period. If the HHV achieved a 40% fuel economy increase, the maximum incremental cost would have to be $24,380 to achieve a 7-year payback period. Lastly, if the HHV achieved a 50% fuel economy increase, the maximum incremental cost would have to be $27,210.

The HHV business case key findings are:

- *HHVs can achieve ROI with high fuel and maintenance savings and low incremental cost.*
- *Incentives for purchase play an important role for the early HHV market.*

The present report shows that HHVs have the potential to achieve high fuel and maintenance savings with an optimized HHV system, compatible driver behavior and vehicles operating in optimal driving cycles. At this early stage in the HHV market, incentives for purchase can reduce incremental costs allowing attractive returns on investment and increasing fleet purchases. With more sales, HHV system cost savings can be achieved, improving the business case for HHVs.

[6] We assume the following: vehicle life = 10 years, days in operation = 250 days / year, total daily range = 60 miles, conventional diesel fuel economy = 7.4 MPG, conventional diesel cost = $70,000, maintenance savings = $0.07 / mile, diesel fuel price = $4.20 / gallon, fuel escalation rate = 3%, discount rate = 7%.

Chapter 7: Bibliography

[1] U.S. Environmental Protection Agency. *Hydraulic Hybrid Vehicle Layouts.* http://www.epa.gov/otaq/technology/research/prototype-vehicles.htm. Accessed on 2013-12-10.

[2] U.S. Environmental Protection Agency. *Hydraulic Hybrid Research.* http://www.epa.gov/otaq/technology/research/research-hhvs.htm. Accessed on 2013-10-21.

[3] Stark, Mike. *Shaping Future Transportation. CleanDrive Technologies. A Daimler Initiative.* Presented at the HTUF 2011 annual conference. Baltimore, MD. September 2012.

[4] Treharn, John. *Hydraulics: Rebirth of a Mature Technology.* Presented at the Fluid Power Conference & Expo. Cleveland, OH. December 2011. http://insidepenton.com/machinedesign/JohnTreharn.pdf. Accessed on 2013-12-10.

[5] Conrad, Michael. *Hydraulic Hybrid Vehicle Technologies.* Presented at the Clean Technologies Forum. Sacramento, CA. September 2008. http://www.airquality.org/mobile/ctf/Events/20080909NearTerm-BoschRexroth-ConradM.pdf. Accessed on 2013-12-10.

[6] Marotta, R. J. *Parker's Hydraulic Hybrid Technologies.* Presented at the 2013 Green Truck Summit. Indianapolis, IN. July, 2012. http://www.wwcleancities.org/documents/HydraulicHybrid_Parker_Marotta.pdf. Accessed on 2013-12-10.

[7] TruckingInfo.com. *Eaton Drops Hydraulic Hybrid System.* http://www.truckinginfo.com/channel/aftermarket/news/story/2013/09/eaton-drops-hydraulic-hybrid-system.aspx. Accessed on 2013-12-10.

[8] Fleets & Fuel. *CNG Addition To Hydraulic Hybrid Line.* http://www.fleetsandfuels.com/fuels/cng/2013/10/cng-fueled-hydraulic-hybrid/. Accessed on 2013-10-21.

[9] Bohlmann, Brad. *Hybrid Hydraulic System Development for Commercial Vehicles.* Presented at the SCAQMD Hydraulic Hybrid Forum. Diamond Bar, CA. November 2007. http://www.aqmd.gov/tao/conferencesworkshops/HydraulicHybridForum/BohlmannSlides.pdf. Accessed on 2013-12-10.

[10] Fleets & Fuel. *Parker Launches Its IVT Hybrid.* http://www.fleetsandfuels.com/fuels/hybrids/2013/03/parker-launches-its-ivt/. Accessed on 2013-12-10.

[11] Freightliner Custom Chassis Corporation. *Hydraulic Hybrid Power Walk-in Van Chassis.* http://freightlinerchassis.com/Walk-In-Van-Chassis/hhv-chassis/menu-id-115.html. Accessed on 2013-12-10.

[12] U.S. Department of Energy, Energy Efficiency & Renewable Energy. *Project Overview: United Parcel Service's Second-Generation Hybrid-Electric Delivery Vans.* www.nrel.gov/docs/fy12osti/51308.pdf. Accessed on 2013-11-05.

[13] Hu, Haoran, Rudy Smaling and Simon J. Baseley. *Advanced Hybrid Powertrains for Commercial Vehicles.* ISBN 978-0-7680-3359-5. Warrendale, PA: SAE International, 2012

[14] Braun Consulting News. *FedEx Ground vs. UPS: Two Worldviews. Two opposing models in the delivery business raise questions.* http://www.braunconsulting.com/bcg/newsletters/winter2004/winter20041.html. Accessed on 2013-12-10.

[15] Lowell, Dana and Fanta Kamakaté. *Urban off-cycle NO_x emissions from Euro IV/V trucks and buses.* The International Council on Clean Transportation, 2012. http://www.theicct.org/sites/default/files/publications/ICCT_WP18_urban_Nox_emissions.pdf. Accessed on 2013-12-10.

[16] Kargul, John. *Advanced Hydraulic Hybrids – Delivering Real-World Savings.* Presented at the 2013 Green Truck Summit. Indianapolis, IN. March 2013.

Appendix A: Project Timeline

2005

- The Parcel Delivery Working Group (WG) including FedEx Express, FedEx Ground, Purolator, United Parcel Service (UPS) and United States Postal Service (USPS) is initiated.
- The WG members express desire to demonstrate Class 4 and Class 6 hydraulic hybrid parcel delivery vehicles since FedEx Express is already experimenting with hybrid electric vehicles.
- The WG identifies a lack of sufficient parcel delivery vehicle drive cycle information to share.

2006

- August: A draft Request For Proposals (RFP) for Class 4 and Class 6 hydraulic hybrid vehicle is developed.
- October: CALSTART receives funding from the U.S. Department of Energy (DOE) to support the WG and demonstrate prototype hydraulic hybrid vehicles.
- October: CALSTART conducts several ride-along activities to better define Class 4 and Class 6 parcel delivery drive cycles.
- November: A WG meeting is held at the HTUF National Meeting in San Diego, CA.

2007

- February: The HTUF Class 4 Parcel Delivery Drive Cycle is developed by CALSTART and accepted by the WG.
- April: The HTUF Class 6 Parcel Delivery Drive Cycle is developed by CALSTART and accepted by the WG.
- April: The WG decides to focus the RFP on Class 6 vehicles.
- April: Key industry suppliers indicate that functional vehicles are 2-3 years away but new, smaller suppliers indicate better near-term availability.
- May: A revised draft RFP for a Class 6 Hydraulic Hybrid Parcel Delivery Vehicle is issued for 3 to 6 technology validation vehicles which would be leased to participating fleets for a period of 18 months.
- June: The final RFP including comments to the draft RFP is issued.
- September: The WG receives 3 proposals from Parker Hannifin Corp., Hybra-Drive Systems LLC and SuperDrive. Eaton Corp., already working on a hydraulic hybrid parcel delivery vehicle with UPS did not answer positively to the RFP.
- October: The 3 participating fleets (FedEx Ground, Purolator, UPS) provide a preliminary evaluation of the submitted proposals.
- November: Parker-Hannifin and Hybra-Drive Systems present their proposals to the WG in Detroit, MI.

2008

- April: Hybra-Drive Systems is selected as winning proposer for the Class 6 Hydraulic Hybrid Parcel Delivery demonstration. Parker-Hannifin is the runner-up.
- May: A WG teleconference to establish the final configuration of the test vehicles is held.
- October: A WG meeting is held at the HTUF National Meeting in South Bend, IN. The WG agrees to delay test vehicles availability to accommodate further Hybra-Drive Systems development.

2009

- January / March: Hybra-Drive Systems is successful in acquiring funding from the State of Michigan and from venture capital investors to secure development activities for the hydraulic hybrid transmission. Test vehicles availability is further delayed.
- March: Freightliner Custom Chassis Corp. (FCCC) and Parker Hannifin roll out hydraulic hybrid walk-in van at the National Truck Equipment Association Work Truck Show.
- April / June: Hybra-Drive Systems continues development of concept with periodic review from the WG.
- July / September: Hybra-Drive Systems becomes Limo-Reid Technologies and continues development of hydraulic drivetrain and tests a production-ready transmission in a Humvee. Test vehicles availability is further delayed.
- September: FCCC developmental unit with Parker Hannifin system is tested for 3 weeks on a commercial FedEx Ground route in Pontiac, MI.
- October / December: Limo-Reid Technologies further delays test vehicles availability.
- November: FCCC developmental unit with Parker Hannifin system is tested for 4 weeks on a commercial UPS route in Cleveland, OH.

2010

- January / March: The WG contacts Eaton and Parker Hannifin to determine their ability to supply hydraulic hybrid test vehicles.
- April / June: Eaton discontinues its hydraulic hybrid parcel delivery vehicles activities.
- August: A WG teleconference meeting is held where the WG unanimously agree to keep pursuing hydraulic hybrid technology for parcel delivery vehicles.
- September: FCCC and Parker Hannifin are selected to replace Limo-Reid Technologies who was unable to deliver functional vehicles as originally proposed.
- September: A WG meeting is held at the HTUF National Meeting in Dearborn, IL. FCCC / Parker Hannifin present vehicle specifications and a delivery timeline for federally certified vehicles to be purchased by the WG fleets. The WG agrees that CALSTART through DOE funding would reduce the incremental cost of the 3 first hydraulic hybrid vehicles.
- December: A WG teleconference is held to discuss pricing and delivery schedule. Vehicles availability is delayed to May 2011.

2011

- January / March: Vehicles availability is delayed to July 2011.
- April / June: Vehicles availability is delayed to August 2011.
- June: A WG teleconference is held to review final vehicle specifications.
- July / September: Vehicles availability is delayed to December 2011.
- October: Purolator and CALSTART representatives attend vehicle review at the Michigan Proving Grounds in Romeo, MI.
- November: A WG teleconference meeting is held. FCCC / Parker Hannifin finalize its hydraulic hybrid vehicle development and testing.
- December: Vehicles availability is delayed to January 2012.

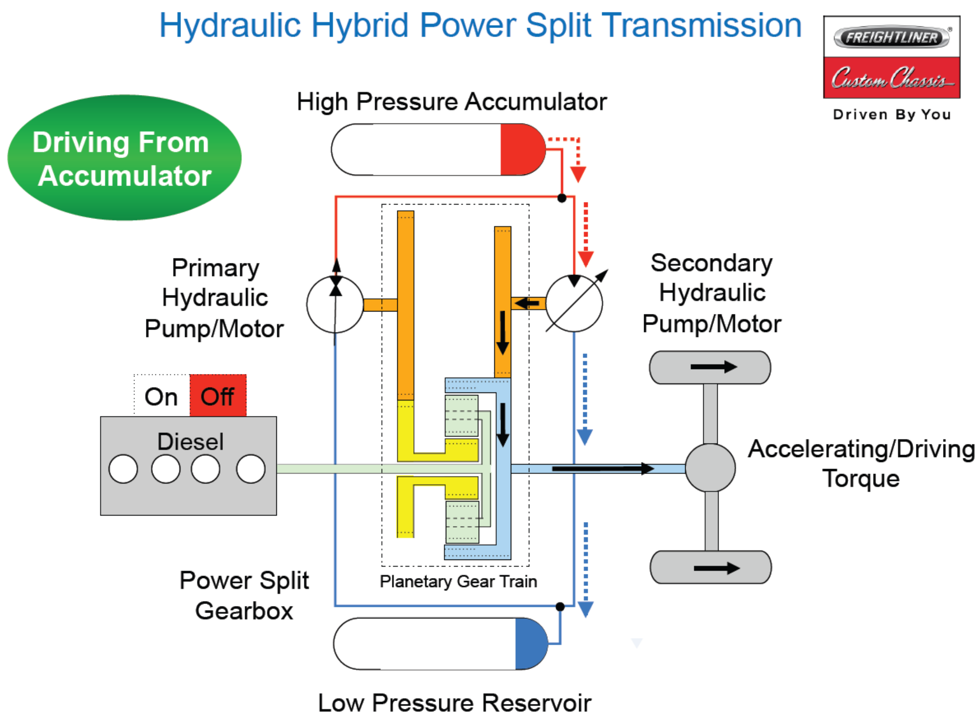
2012

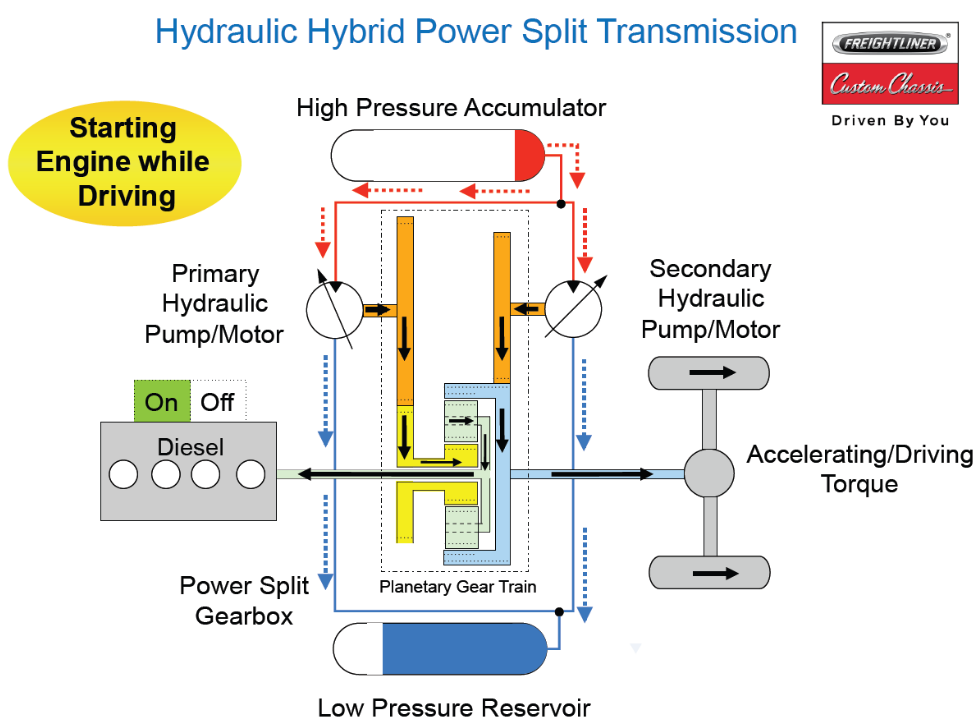
- January / March: FCCC / Parker Hannifin establish the expected delivery date of the 3 vehicles to be April 2012.
- February: FCCC / Parker Hannifin validate vehicle durability testing and test 1 prototype vehicle for fuel economy.
- February: A WG teleconference meeting is held.
- March: CALSTART instruments a conventional diesel Class 6 parcel delivery vehicle from Purolator in Mississauga, ON for baseline comparison. CALSTART staff rides along a Purolator Class 6 truck to better understand the typical route configuration.
- April: UPS takes delivery of the world's first commercially available hydraulic hybrid parcel delivery truck.
- April: The UPS vehicle is displayed at Fortune Brainstorm Green in Laguna Niguel, CA.
- April: One FCCC / Parker Hannifin hydraulic hybrid vehicle undergoes extensive emissions and fuel economy testing at the U.S. EPA National Vehicle and Fuel Emissions Laboratory.
- April: FedEx Ground announces it will deploy 5 additional hydraulic hybrid vehicles in California and Michigan.
- May: CALSTART instruments a conventional diesel Class 6 parcel delivery vehicle from UPS in Laguna Hills, CA for baseline comparison.
- June: FedEx Ground and Purolator take delivery of their hydraulic hybrid parcel delivery trucks.
- July: UPS puts its hydraulic hybrid vehicle in commercial operation in Laguna Hills, CA.
- September: CALSTART instruments a conventional diesel Class 6 parcel delivery vehicle from FedEx Ground in Vernon, CA for baseline comparison.
- October: CALSTART instruments an additional conventional diesel Class 6 parcel delivery vehicle from UPS in Laguna Hills, CA for baseline comparison.
- October: UPS announces it will deploy 40 additional hydraulic hybrid vehicles in Atlanta, GA and Baltimore, MD.
- November: FedEx Ground puts its hydraulic hybrid vehicle in commercial operation in Sun Valley, CA.

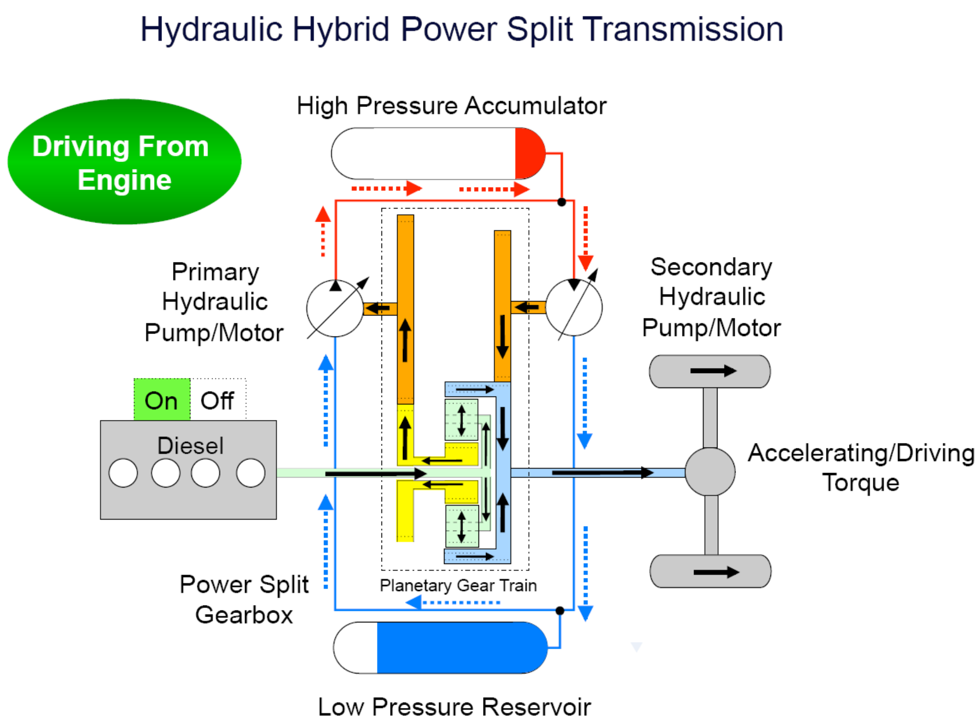
2013

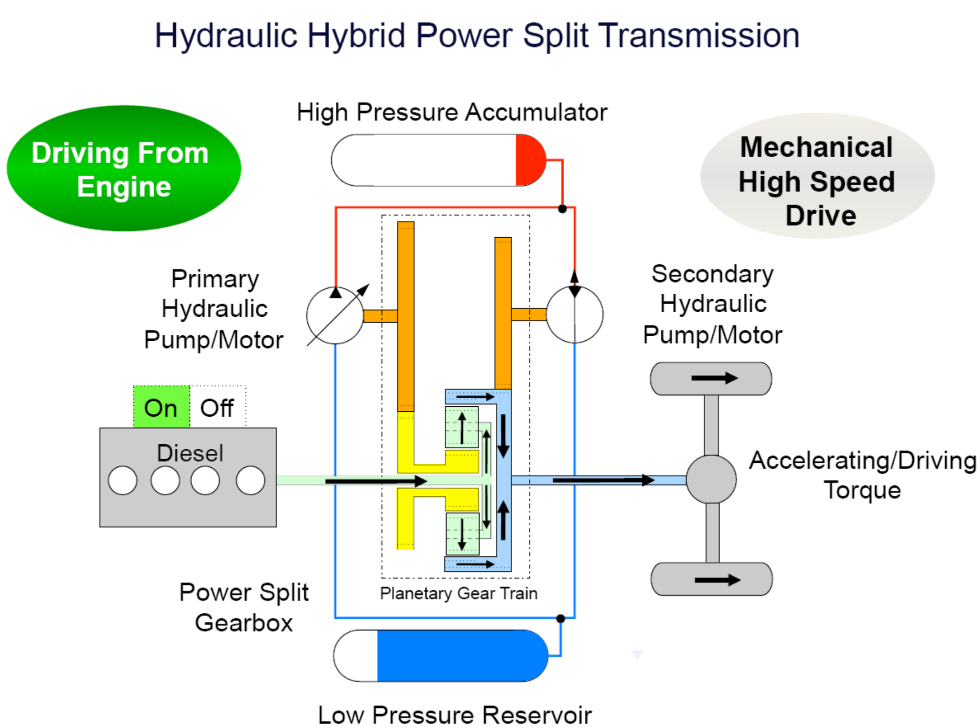
- January: A WG teleconference meeting is held.
- March: Parker Hannifin officially launches its Parker IVT system at the Green Truck Summit in Indianapolis, IN.
- May: Purolator puts its hydraulic hybrid vehicle in commercial operation in Mississauga, ON.
- July: A WG teleconference fleet meeting is held.
- September: CALSTART contracts Engine, Fuel, and Emissions Engineering Inc. (EF&EE) to carry on in-service validation testing of one hydraulic hybrid vehicle to measure emissions and fuel economy.

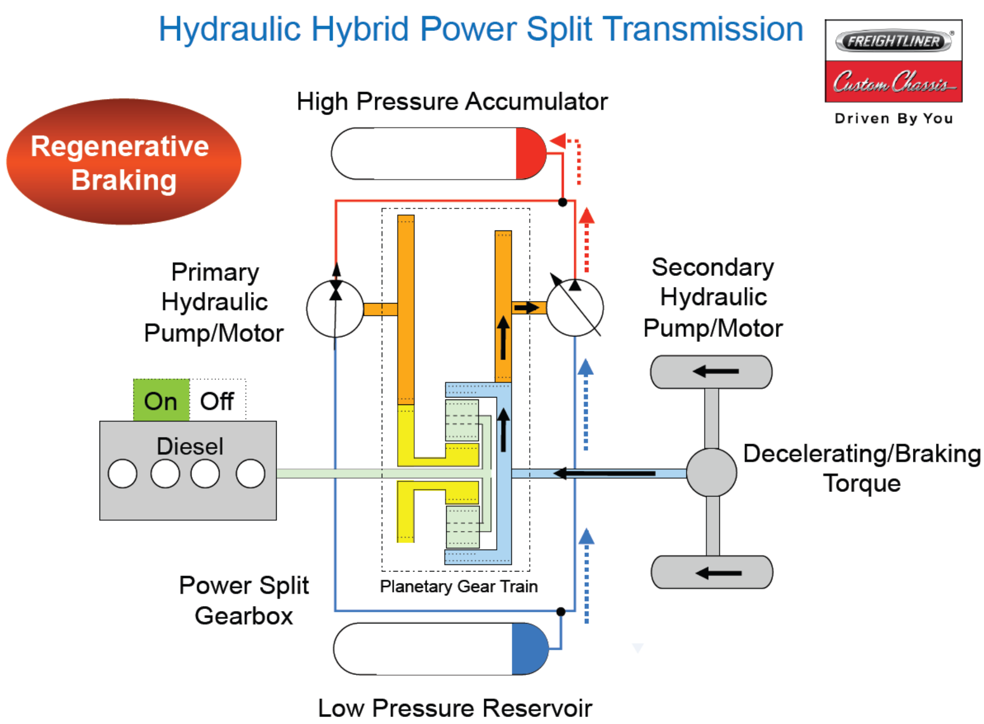
Appendix B: Parker Hannifin Hydraulic Hybrid Power Split Transmission





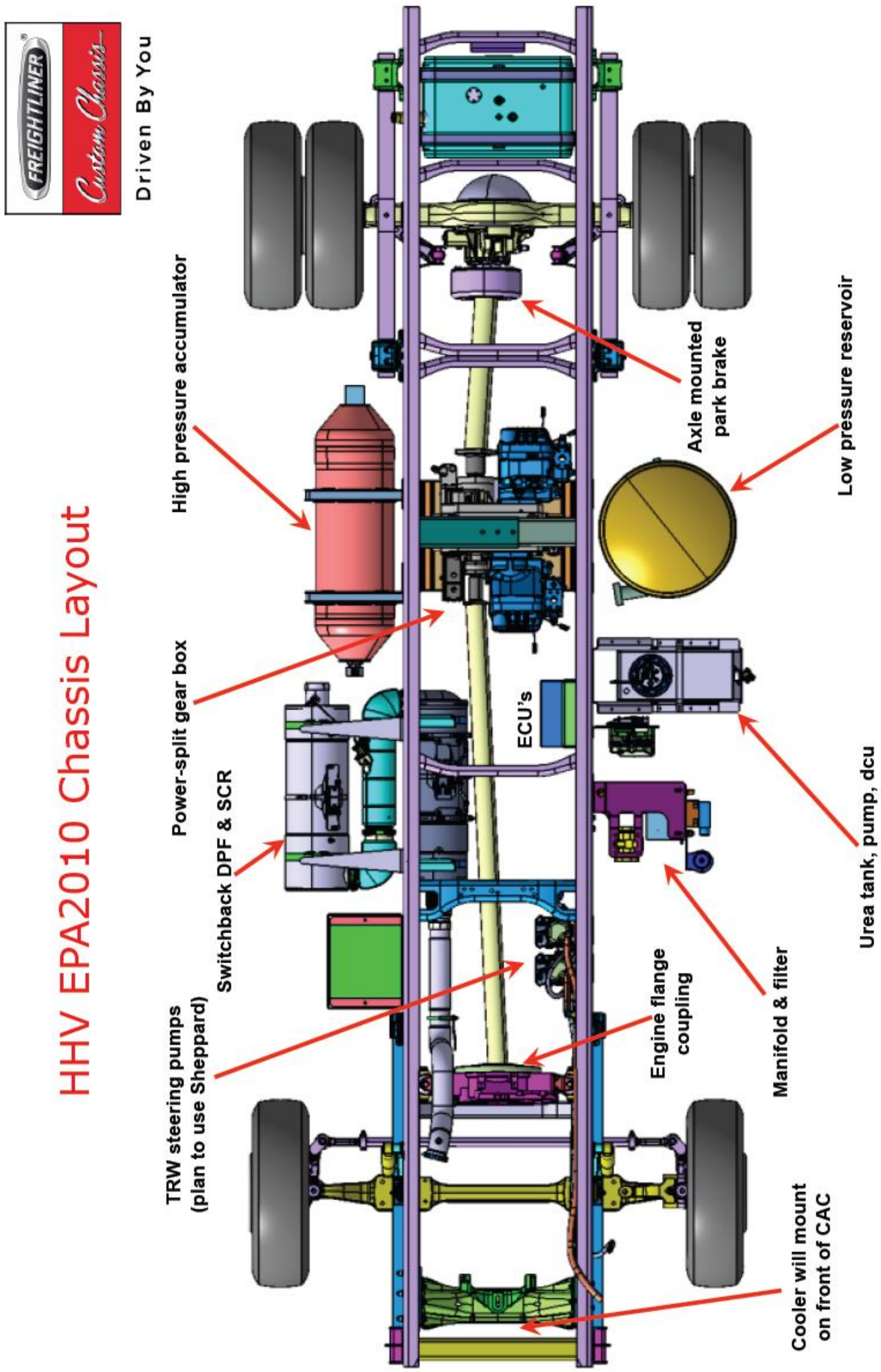

Hydraulic Hybrid Power Split Transmission
Driving From Engine
High Pressure Accumulator
Primary Hydraulic Pump/Motor
Secondary Hydraulic Pump/Motor
On
Off
Diesel
Accelerating/Driving Torque
Power Split Gearbox
Planetary Gear Train
Low Pressure Reservoir


Hydraulic Hybrid Power Split Transmission
Driving From Engine
High Pressure Accumulator
Mechanical High Speed Drive
Primary Hydraulic Pump/Motor
Secondary Hydraulic Pump/Motor
On
Off
Diesel
Accelerating/Driving Torque
Power Split Gearbox
Planetary Gear Train
Low Pressure Reservoir



Hydraulic Hybrid Power Split Transmission
FREIGHTLINER
Custom Chassis
Driven By You
Regenerative Braking
High Pressure Accumulator
Primary Hydraulic Pump/Motor
Secondary Hydraulic Pump/Motor
On
Off
Diesel
Decelerating/Braking Torque
Power Split Gearbox
Planetary Gear Train
Low Pressure Reservoir

Appendix C: FCCC MT55 HHV EPA2010 Chassis Layout



Appendix D: HHV In-Service Validation Testing / Final Report

IN-SERVICE EMISSIONS FROM MODEL YEAR 2012 HYDRAULIC HYBRID AND MODEL YEAR 2008 CONVENTIONAL DIESEL PACKAGE DELIVERY TRUCKS

FINAL REPORT

December 5, 2013

Submitted to:

CALSTART
48 South Chester Ave.
Pasadena, CA 91106

EF & EE
ENGINE, FUEL, AND EMISSIONS ENGINEERING, INCORPORATED

IN-SERVICE EMISSIONS FROM MODEL YEAR 2012 HYDRAULIC HYBRID AND MODEL YEAR 2008 CONVENTIONAL DIESEL PACKAGE DELIVERY TRUCKS

Final Report

December 5, 2013

Submitted to
CALSTART
48 South Chester Ave.
Pasadena, CA 91106

Submitted by
Christopher Weaver, P.E.
Engine, Fuel, and Emissions Engineering, Inc.
8614 Unsworth Ave. Suite 100
Sacramento, CA 95828
(916) 368-4770

EXECUTIVE SUMMARY

Hybrid vehicles – combining internal-combustion engines with on-board energy storage and kinetic energy recovery during braking – hold significant promise for reducing emissions and fuel consumption by package delivery fleets. One innovative hybrid drive approach uses a hydraulic system for power transmission and energy storage. To assess the benefits and operational impacts of the hydraulic hybrid technology, United Parcel Service (UPS) is hosting a pilot program to compare package delivery trucks using this technology with their present diesel delivery trucks. Funding for this program has been provided by the U.S Department of Energy, and the program is being managed by CALSTART.

CALSTART contracted with Engine, Fuel, and Emissions Engineering, Inc. (EF&EE) to measure in-service pollutant emissions from one model year 2012 hydraulic hybrid and one model year 2008 conventional diesel package delivery truck. Measurements were conducted while the test vehicle followed and "shadowed" a UPS package delivery truck in normal operation. The measurements were performed using EF&EE's Ride-Along Vehicle Emission Measurement (RAVEM) system. Mass emissions of carbon dioxide (CO_2), carbon monoxide (CO), oxides of nitrogen (NOx), particulate matter (PM), and total hydrocarbons (THC) from the hydraulic hybrid and the conventional diesel test vehicle were each measured over the course of a typical day of package deliveries.

The two vehicles were somewhat different from each other as the conventional diesel vehicle was equipped with a 200 hp Cummins engine, while the hydraulic hybrid vehicle was equipped with a 280 hp Cummins engine. In addition, both engines were not EPA certified at the same emissions level: 2007 EPA certified for the conventional diesel vehicle and 2010 EPA certified for the hydraulic hybrid vehicle.

Table E-1 summarizes the results of the test program. The measured emissions of CO and PM were near zero for both the conventional and the hybrid truck. THC emissions from both vehicles were negative – the exhaust THC concentration was less than the ambient background level. Compared to the conventional vehicle, the hybrid showed 17% lower CO_2 emissions and 30% lower NO_x emissions over the testing period.

Table E-1: Summary results

Daily Total	Distance (mi.)	Minutes Total	Minutes Stopped	Avg. MPH	Emissions (g/mile) CO2	Emissions (g/mile) NOx	Emissions (g/mile) PM
Conventional	53.0	350	174	18.03	1364.28	5.07	0.01
HHV	70.2	390	177	19.74	1127.10	3.53	0.02
Percent Difference	32%	12%	2%	10%	-17%	-30%	87%

Table E-2 summarizes the results of the test program per operating areas: highway/arterial outbound, pick-up & delivery and highway/arterial inbound. In the low-speed / stop-and-go pickup and delivery operating area, the hybrid showed 21% lower CO_2 emissions, while it showed 7% higher CO_2 emissions in the high-speed highway/arterial outbound operating area.

Table E-2: Summary results by operating area

Vehicle	Driving Type	Distance (mi.)	Minutes Total	Minutes Stopped	Avg. MPH	Emissions (g/mile) CO2	NOx	PM
Conventional	Hwy/Art. Outbound	7.65	12	1	41.55	1189.03	1.83	-
	Pick-up & Delivery	44.46	335	170	16.17	1390.45	5.46	-
HHV	Hwy/Art. Outbound	7.68	12	1	42.27	1107.66	3.21	-
	Pick-up & Delivery	49.23	351	182	17.48	1095.65	4.13	-
	Hwy/Art. Outbound	11.86	21	4	41.67	1261.55	1.20	-
Percent Difference	Hwy/Art. Outbound	0%	-1%	-2%	2%	-7%	75%	N/A
	Pick-up & Delivery	11%	5%	7%	8%	-21%	-24%	N/A
	Hwy/Art. Outbound	N/A	N/A	N/A	N/A	N/A	N/A	N/A

The hybrid was equipped with a SCR system for NO_x control, while the conventional vehicle was not. This would be expected to result in much lower NO_x emissions. Measured NO_x emissions from the hybrid were 24% less than the conventional vehicle in the pickup and delivery operating area. NO_x emissions from the hybrid were higher than the conventional vehicle in the highway/arterial outbound operating area, which began with a cold start. NO_x emissions in both highway/arterial operating areas (outbound and inbound) from the hybrid were 63% lower on the return than on the outbound trip. This difference is probably attributable to the low SCR catalyst temperature at the beginning of the trip.

Actual emission rates will vary widely with driving conditions such as drive cycle and driver behavior. The numbers presented in this report are representative of specific drive cycles and driving conditions and were derived from testing done in a semi-controlled environment. They should not be used to predict emission rates in different driving conditions.

CONTENTS

LIST OF TABLES

LIST OF FIGURES

1. INTRODUCTION

Hybrid vehicles – combining internal-combustion engines with on-board energy storage and kinetic energy recovery during braking – hold significant promise for reducing emissions and fuel consumption by package delivery fleets. One innovative hybrid drive approach uses a hydraulic system for power transmission and energy storage.[1]

To assess the benefits and operational impacts of the hydraulic hybrid technology, United Parcel Service (UPS) is hosting a pilot program to compare package delivery trucks using this technology with their present diesel delivery trucks. Funding for this program has been provided by the U.S Department of Energy, and the program is being managed by CALSTART.

CALSTART contracted with Engine, Fuel, and Emissions Engineering, Inc. (EF&EE) to measure in-service pollutant emissions from one hydraulic hybrid and one conventional diesel package delivery truck. Measurements were conducted while the test vehicle followed and "shadowed" a UPS package delivery truck in normal operation. The measurements were performed using EF&EE's Ride-Along Vehicle Emission Measurement (RAVEM) system. Mass emissions of carbon dioxide (CO_2), carbon monoxide (CO), oxides of nitrogen (NOx), particulate matter (PM), and total hydrocarbons (THC) from the hydraulic hybrid and the conventional diesel test vehicle were each measured over the course of a typical day of package deliveries.

[1] "Hydraulic Hybrid Power Walk-In Van Chassis", Freightliner Corp., undated.

2. THE TEST PROGRAM

2.1 Test Vehicles

EF&EE carried out on-board emission measurements on the two UPS package delivery trucks listed below in Table 1. These trucks were located at and operated from the UPS facility at 22 Brookline Ave, Aliso Viejo, CA.

Table 1: Test vehicles characteristics

	FCCC MT-55 Diesel	FCCC MT-55 HHV
Model Year	2008	2012
Chassis Manufacturer	FCCC	FCCC
Body Manufacturer	Utilimaster Corporation	Morgan Olson
GVWR	23,000 lbs.	23,000 lbs.
Curb Weight	12,100 lbs.	13,800 lbs.
Model	Cummins ISB 6.7L	Cummins ISB10 6.7L
Peak Power	200 HP (149 kW) @ 2,400 RPM	280 HP (209 kW) @ 2,300 RPM
Peak Torque	520 ft-lbs. (705 Nm) @ 1,600 RPM	660 ft-lbs. (895 Nm) @ 1,600 RPM
Fuel System	ULSD / 40-gallon fuel tank	ULSD / 30-gallon fuel tank
Exhaust System	Oxidizing Catalyst and Periodic Trap Oxidizer	SCR and DPF 10-gallon DEF tank (2-3% injection rate)
Tires	245/70 R19.5	245/70 R19.5
Wheelbase	178 in.	178 in.
Make	Allison	Parker Powersplit Hybrid Series System
Type	2200 HS Automatic	Infinite Variable Advanced Series Transmission
Rear Axle Ratio	4.10	N/A
Oil Capacity	N/A	Gearbox – 9 liters System - 29 gallons
Components Weight	N/A	~ 2,500 lbs.

The two vehicles were somewhat different from each other as the conventional diesel vehicle was equipped with a 200 hp Cummins engine, while the hydraulic hybrid vehicle was equipped with a 280 hp Cummins engine. Please note that engines with different horsepower ratings may have different engine calibrations and deliver different performance, fuel consumption and emissions levels.

In addition, both engines were not EPA certified at the same emissions level: 2007 EPA certified for the conventional diesel vehicle and 2010 EPA certified for the hydraulic hybrid vehicle. Both vehicles were equipped with diesel engines fitted with diesel particulate filters. The hydraulic hybrid vehicle was also equipped with a selective catalytic reduction (SCR) system. Please note that SCR systems may impact engine efficiency and ultimately increase fuel consumption compared to a similar engine not equipped with a SCR system.

2.2 Driving Route

All of the emission testing was conducted during normal package delivery route driving. UPS organizes its daily delivery activities into "routes", where each route comprises a geographic area and a path through that area calculated to minimize time and fuel consumption. This path is subject to variation, as the locations of package deliveries vary from day to day.

The route chosen for the emission measurements in this program was that normally followed by the diesel vehicle. This route comprises primarily suburban, single-family residences, and is moderately hilly. The few institutional deliveries are to churches and schools.

For emission testing purposes, the normal route driver, Driver A, followed his normal package delivery practices in one of the two trucks, while being followed as closely as possible by the truck under test driven by Driver B. Thus, Driver A drove the hybrid truck while the conventional truck was under test driven by Driver B, and vice versa. This arrangement was adopted to simulate the actual delivery process as closely as possible without interfering with it. The actual route followed, and the length of stops during each day, were recorded by the GPS receiver included in the RAVEM system. The test truck was also fitted by CALSTART with a data-logger, which recorded fuel consumption rate and vehicle speed (measured by the rotation rate of the wheels).

During each day, the emission measurements were divided into a series of emission "tests", where each test comprises a single set of particulate filters, and a single bag sample of background pollutant concentrations. The target length for these tests was about 40 minutes, but the actual length varied depending on operating conditions. The time between the end of one test and the start of the next was about seven minutes. This was the time required to change the PM filters, calibrate analyzers, and read the bag samples. When possible, the operation was done when the vehicle was stopped for a delivery or a break. Sometimes, the operation had to be done while the test vehicle was driving to follow the lead vehicle. As a result, not all the vehicle operation was recorded by the RAVEM system as detailed in Table 2.

Table 2: Comparison of data logger and RAVEM recording times

	Diesel	HHV
Data Logger Recording Time	396 min.	437 min.
RAVEM Recording Time	339 min.	384 min.
Missing Key On Time	57 min. (14.4%)	53 min. (12.1%)

Figure 1 shows the plots of vehicle speed vs. time for the nine emission tests completed on the conventional truck. The first test includes the freeway travel from the UPS facility to the beginning of the delivery route. The final test includes relatively high-speed operation on main streets while completing the last few deliveries, but does not include the return to the UPS facility. This is due to the loss of the RAVEM's isokinetic sampling capability when a pressure tube melted in contact with the hot exhaust pipe.

Figure 1: Vehicle speed vs. time for emission testing on the conventional diesel truck

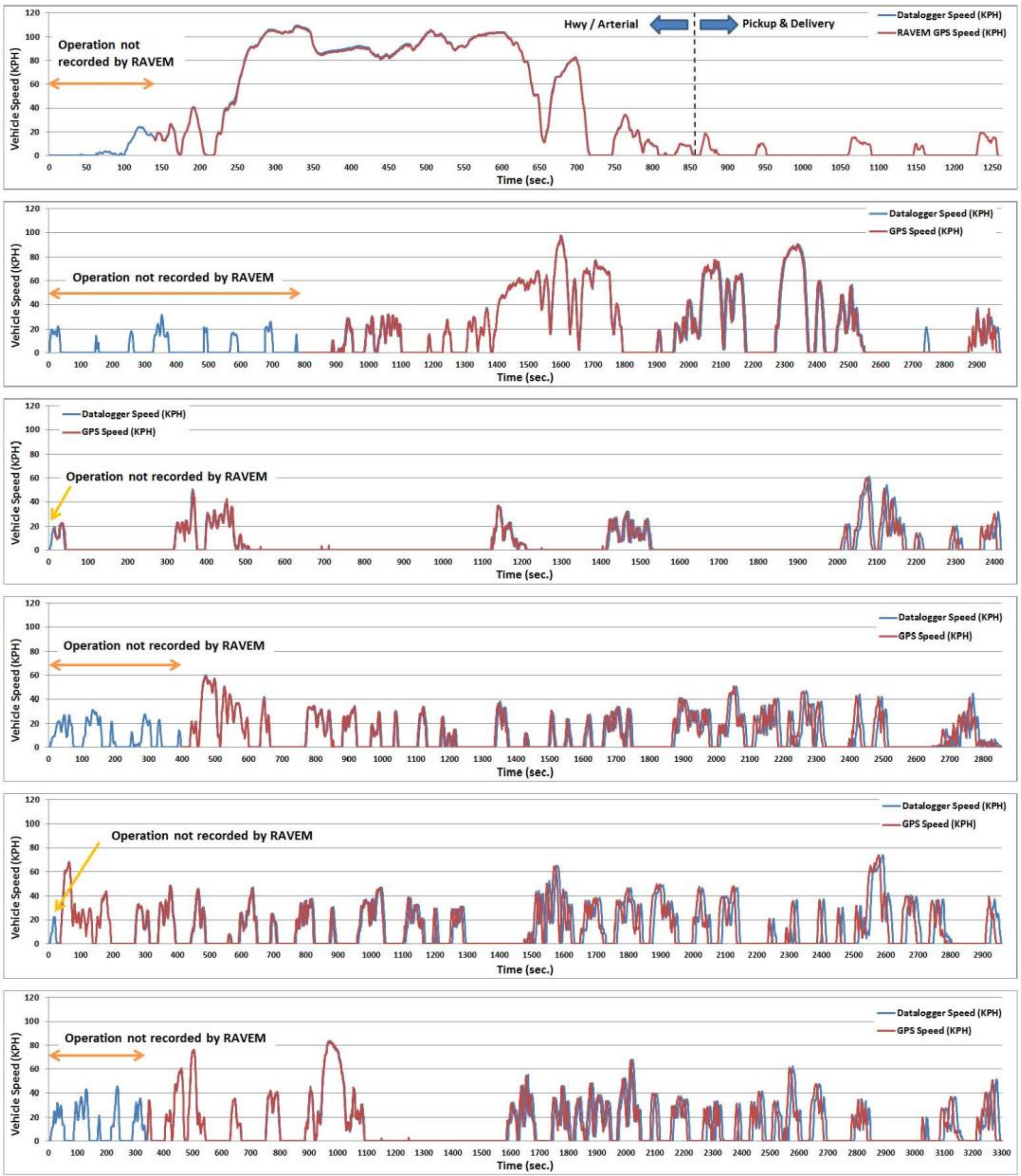


Figure 1 (continued)

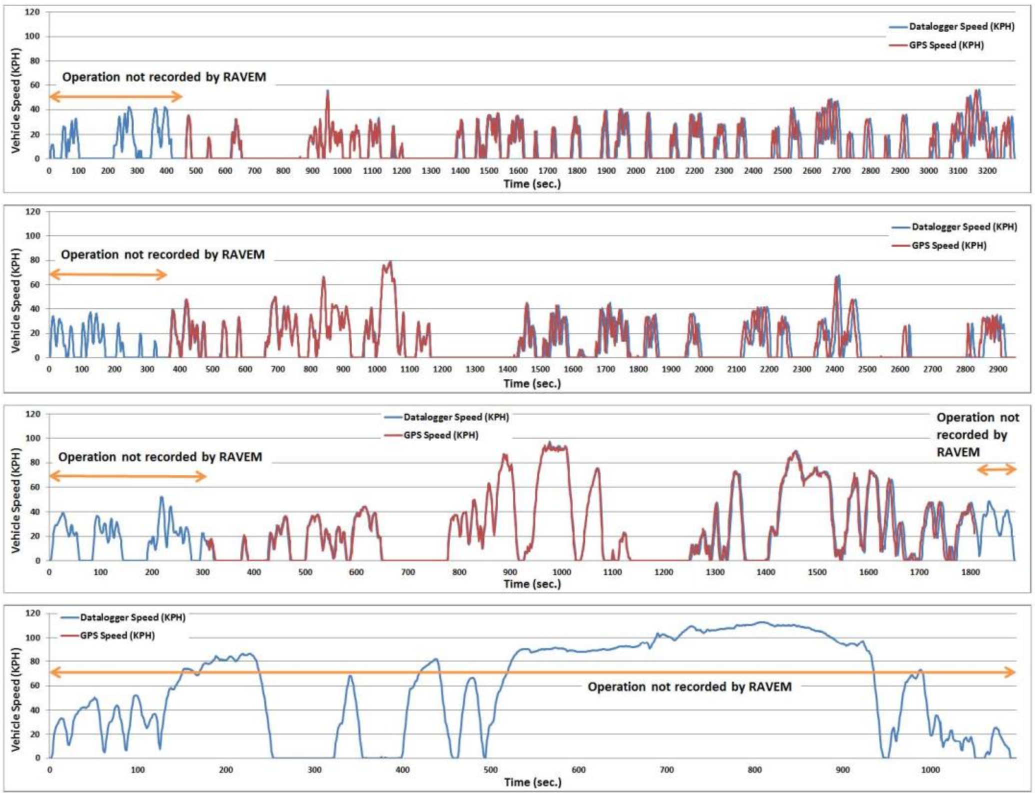


Figure 2 plots the vehicle speed vs. time for the emission testing on the hybrid truck. The first test includes the freeway travel from the UPS facility to the delivery area, as well as the first few institutional deliveries. The final test in this series includes relatively high-speed travel on surface streets for the last few deliveries, as well as the return to the freeway and surface segments of the return to the UPS facility.

Figure 2: Vehicle speed vs. time for emission testing on the hybrid truck

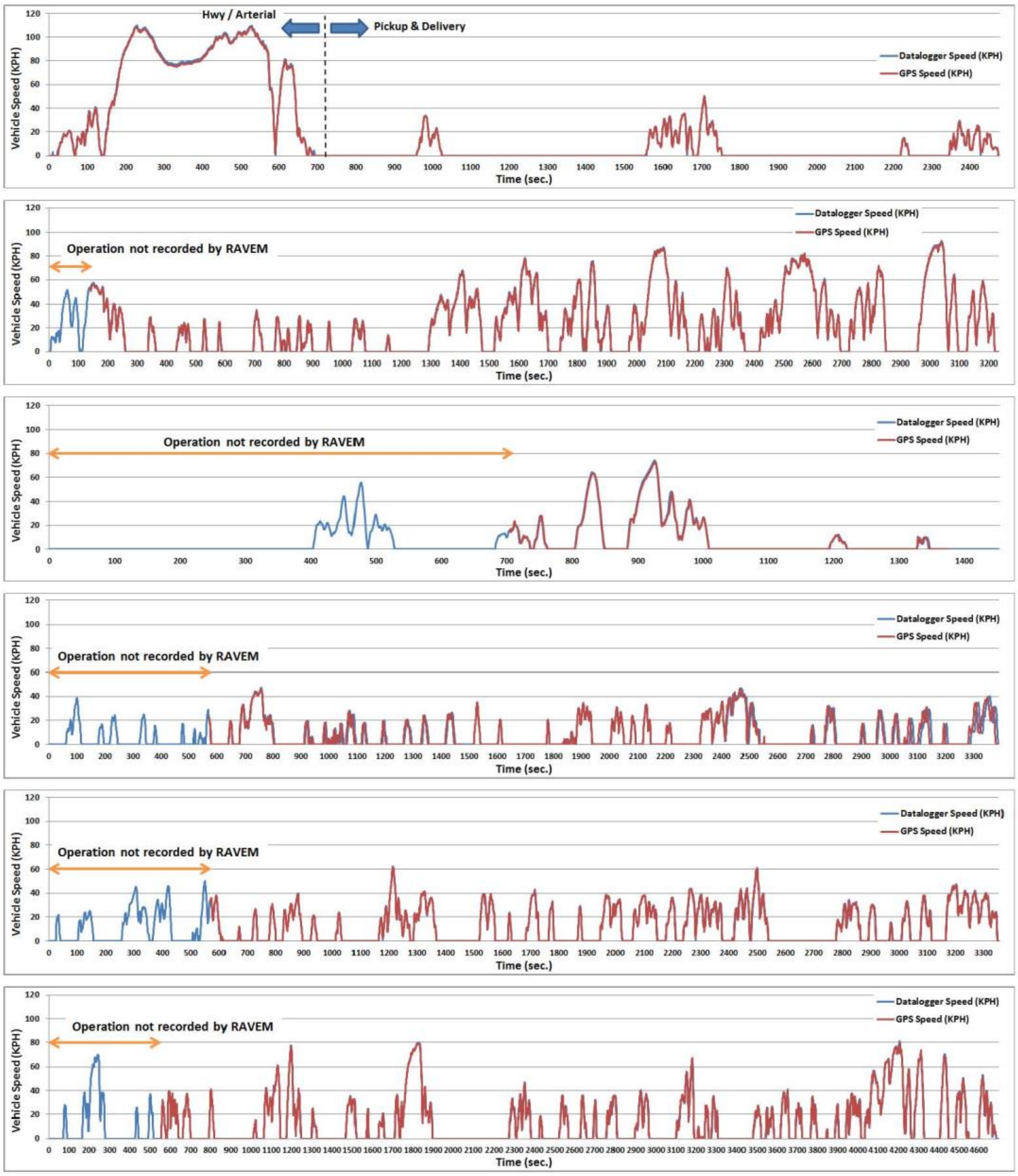
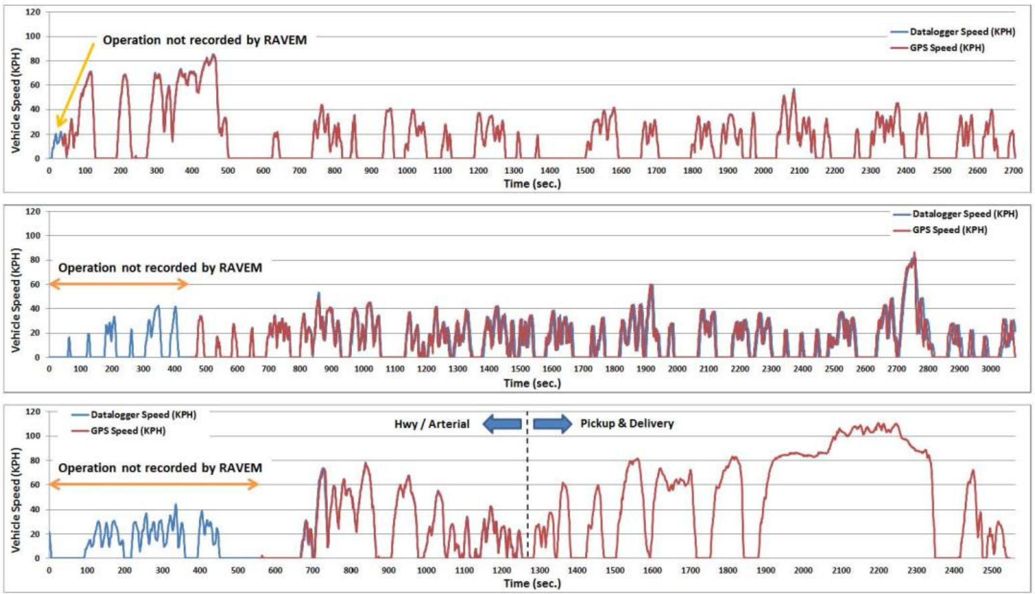


Figure 2 (continued)



2.3 EMISSION MEASUREMENTS

Emission testing was performed using EF&EE's RAVEM portable emission measurement system. The exhaust gas was sampled from the exhaust pipe, which was located under the cargo space. The RAVEM system uses constant-volume sampling (CVS) with a proportional partial-flow sampling system to achieve emission measurement capabilities similar to those of a conventional full-flow CVS laboratory in a package small enough to be mounted on a vehicle.

Figure 3 shows the RAVEM system installed on the hybrid truck. The analyzers for CO_2, CO, NOx, and total HC are contained in the yellow shock-mounted cases at left. The CVS dilution tunnel is in the rectangular aluminum box in the center. The black-insulated sample line runs from the dilution tunnel into open access panel in the floor, and from there to the isokinetic probe in the exhaust outlet. Technical details of the RAVEM system are given in Appendix A.

Electric power to operate the system was supplied by a small gasoline generator. The generator exhaust was located as far as possible from the dilution air intake to minimize cross-contamination. A bag sample integrating the pollutant concentrations in the dilution air was collected during each test, and analyzed immediately afterward. These background values were automatically subtracted from the measured pollutant concentrations.

Normally, a UPS package delivery truck would begin the day with 1,000 to 2,000 pounds of packages aboard. This load would gradually diminish to near zero as the packages are delivered. The test vehicle did not carry any packages, but did carry the mass of the RAVEM system, system operator, and calibration gas cylinders. These totaled 578 kg, or 1,274 lb.

The installation of the isokinetic probe in the exhaust outlet is shown in Figure 4. The isokinetic sampling system adjusts the sample flow rate to equalize the velocity of the exhaust entering the probe with that of the exhaust surrounding the probe's exterior. To ensure that the exhaust velocity at the probe tip is representative, EF&EE normally seeks to have at least 10 diameters of straight pipe upstream of the probe tip. For this 4" diameter exhaust system, 10 diameters is equal to 40 inches. In this case, the exhaust system configuration and the bulk of the hybrid system limited the available straight length to about 24 inches, or six diameters.

Figure 3: RAVEM system installed in the hybrid truck

Figure 4: Isokinetic probe and sample line installed in the exhaust outlet of the hybrid vehicle

As discussed earlier, the emission measurements during each day were divided into nine separate emission tests, with each test typically lasting about 40 to 60 minutes. During each emission test, NOx, THC, CO, and CO_2 emissions were recorded second-by-second in real time. At the end of each test, the NOx, CO, and CO_2 concentrations were also measured in integrated bag samples of dilute exhaust collected over the test run. Background concentrations of CO_2, CO, and NOx were determined from a separate integrated bag sample of the CVS dilution air collected over the test run. This sample was analyzed immediately after the integrated sample bag.

PM emissions during each emission test were determined from integrated samples collected on pre-weighed filters over each test run. A blank PM filter exposed to the same volume of dilution air was also collected during each test run. Any change in weight of the blank filter was subtracted from the change in weight of the sample filter in calculating the PM emissions.

Background HC concentrations could not be determined from the background bag sample, as experience has shown that semi-volatile HC deposited in the sampling system can affect the results. Instead, background HC levels during each test run were estimated from the HC readings observed with the engine off during stops.

Vehicle speed and position during each test run were measured by GPS, and recorded second-by-second. The exhaust temperature -- measured at the isokinetic probe – was also recorded second-by-second. The ambient temperature, humidity, and barometric pressure at the start of each test were also recorded automatically by the RAVEM system. For testing on the conventional vehicle, the ambient temperature (measured at the dilution air inlet) ranged from 29 to 40°C, and the humidity from 45% in the morning to 26% at the end of the afternoon. For the hybrid vehicle tests, ambient temperature ranged from 28 to 34°C, and the humidity from 43 to 32%.

Where possible, the PM filter changes, gas analyzer calibration, and reading of gas sample bags at the end of each test run were accomplished during stops, when the engine would be turned off. In many cases, however, these activities could not be completed by the time the driver restarted the engine to move on to the next delivery. Thus, data on the portion of the emissions produced between the end of one test and the beginning of the next were not recorded. The periods of operation not recorded by the RAVEM system are identified in Figure 1 and Figure 2.

3. EMISSION RESULTS

The results of the emission tests are summarized in Table 3. Each table shows the starting time and the length of each test, in minutes and miles, the amount of time spent with the vehicle stationary, and the average vehicle speed during the periods when it was not stationary. Total emissions of CO_2, CO, NOx, and particulate matter (PM) measured during each test are also shown. Total hydrocarbon emissions are not shown in the table, and are discussed separately.

Table 3: Emission measurements by test

Conventional Diesel Vehicle									
Test File	Start Date / Time	Distance (mi.)	Minutes Total	Minutes Stopped	Avg. MPH	Emissions (g/test) CO2	CO	NOx	PM
R3T2551	9/16/2013 8:59	7.77	19	8	40.53	9524.51	-2.26	15.72	-0.07
R3T2552	9/16/2013 9:58	8.47	36	11	19.79	9918.89	10.60	35.57	0.14
R3T2553	9/16/2013 10:41	2.04	40	29	11.43	2024.63	-25.49	13.56	0.01
R3T2554	9/16/2013 11:28	4.78	41	19	13.27	7582.07	-23.42	30.51	0.13
R3T2555	9/16/2013 12:36	6.78	49	24	16.25	8785.93	-13.50	32.57	0.10
R3T2556	9/16/2013 13:32	6.62	49	26	17.09	8872.28	-15.62	31.64	-0.12
R3T2557	9/16/2013 14:29	4.39	47	27	13.19	5273.25	-4.38	25.62	0.14
R3T2558	9/16/2013 15:23	5.36	43	22	15.14	7922.14	26.98	28.17	0.18
R3T2559	9/16/2013 16:12	6.74	25	8	23.46	12346.21	10.76	55.27	0.00
Daily Total		**53.0**	**350**	**174**	**18.03**	**72249.91**	**-36.32**	**268.62**	**0.52**

Hydraulic Hybrid Vehicle									
Test File	Start Date / Time	Distance (mi.)	Minutes Total	Minutes Stopped	Avg. MPH	Emissions (g/test) CO2	CO	NOx	PM
R3T2560	9/18/2013 8:52	8.75	41	24	29.69	9867.69	2.83	29.89	0.14
R3T2561	9/18/2013 9:43	12.30	51	18	22.12	14042.36	15.88	35.82	0.49
R3T2562	9/18/2013 10:46	1.22	13	7	12.25	1828.13	1.50	1.43	-0.12
R3T2563	9/18/2013 11:08	3.87	48	27	11.09	4179.44	-22.84	31.02	0.08
R3T2564	9/18/2013 12:05	5.95	46	22	14.69	6440.99	6.51	33.58	0.14
R3T2565	9/18/2013 13:00	9.62	69	36	17.67	9391.62	-47.49	38.06	0.13
R3T2566	9/18/2013 15:12	7.35	45	20	17.99	8269.37	-11.19	19.01	0.18
R3T2567	9/18/2013 16:04	6.49	44	16	14.10	7488.57	52.36	37.25	0.11
R3T2568	9/18/2013 16:57	14.64	33	7	33.45	17579.31	13.93	21.66	0.14
Daily Total		**70.2**	**390**	**177**	**19.74**	**79087.48**	**11.48**	**247.72**	**1.29**

The measured CO and PM values are both extremely low, with some values less than zero. In both cases, the uncertainty in the measured values is of the same order as the value itself. The CO measurements are also affected by the cross-interference effects of CO_2 and water vapor on the CO measurement. In this case, the underlying values are so low that the interference – while well within the EPA guideline of 2% – is still large enough to affect the results.

3.1 Hydrocarbon emissions

Measured hydrocarbon concentrations in the dilute exhaust gas from both vehicles were extremely low, and were observed to vary inversely to the concentration of other pollutants. Figure 5 compares the HC and CO_2 concentrations for a typical test segment. As this figure shows, the background HC concentration with the engine off is about 2 ppm. With the engine running and producing power, the measured HC concentration in the dilute exhaust is less than the background level measured with the engine off. This shows that the HC concentration in the exhaust gas is lower than the background level found in the RAVEM's dilution air. Assuming that the HC concentration at the engine air intake is similar, the engine is producing negative THC emissions – ie. it is removing THC from the atmosphere. This was found to be the case for both the conventional and the hybrid vehicle.

The mass of THC so removed from the atmosphere depends mostly on the background THC concentration, which varies with time and the geographic location. There is little point, therefore, in attempting to quantify the magnitude of these negative emissions.

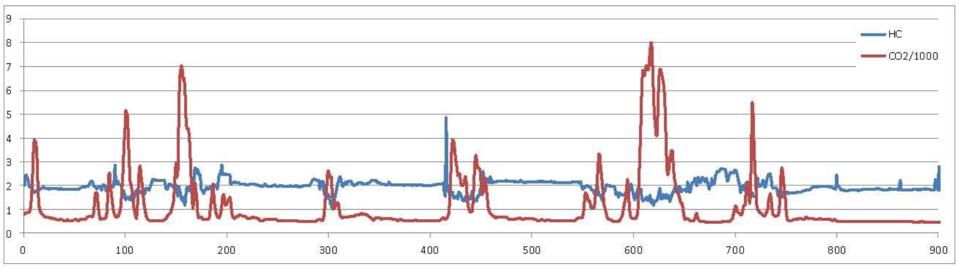


Figure 5: HC vs CO concentrations for a typical test segment

3.2 Driving cycle effects

Tests 2551 and 2560 – the first tests of each day – are dominated by relatively high-speed driving. This includes a freeway segment as well as driving on arterial streets. The same is true of test 2568, the last test on the hybrid vehicle. Each of these tests also included some pick-up and delivery activity as well. The remaining tests contained only pick-up and delivery activity, comprising large numbers of relatively short-distance movements, along with lower average speeds.

Table 4 shows the average emissions in grams per mile, over the entire day for the conventional and HHV vehicles.

Table 4: Summary results, in grams per mile

Daily Total	Distance (mi.)	Minutes Total	Minutes Stopped	Avg. MPH	Emissions (g/test) CO2	Emissions (g/test) NOx	Emissions (g/test) PM
Conventional	53.0	350	174	18.03	1364.28	5.07	0.01
HHV	70.2	390	177	19.74	1127.10	3.53	0.02
Percent Difference	32%	12%	2%	10%	-17%	-30%	87%

Compared to the conventional vehicle, the hybrid showed 17% lower CO_2 emissions and 30% lower NO_x emissions over the testing period. PM emissions from the hybrid vehicle were higher than from the conventional, but PM emissions from both vehicles were very low.

Table 5 shows the average emissions in grams per mile, for each type of driving (highway/arterial outbound, pick-up & delivery and highway/arterial inbound) for the conventional and HHV vehicles. The values shown for highway/arterial driving were calculated by integrating the second-by-second emissions data for only the highway/arterial portions of the tests that included highway/arterial activity. PM results for the highway/arterial portion are not available, as PM could only be measured as the integrated value for the entire test. The values for package delivery were obtained by summing the emissions and distance travelled over the remaining tests for each vehicle – those that did not include highway/arterial activity. The small amount of package delivery activity in the highway/arterial tests was also included.

For the hybrid vehicle, the results for the highway/arterial segments of the outbound and return trips were significantly different. This is explained by the change in altitude during the journey. From GPS data, the outbound freeway leg includes a net descent of 117 meters, while the return includes a net ascent of 130 meters.

Table 5: Emissions by type of driving, in grams per mile

Vehicle	Driving Type	Distance (mi.)	Minutes Total	Minutes Stopped	Avg. MPH	Emissions (g/mile) CO2	Emissions (g/mile) NOx	Emissions (g/mile) PM
Conventional	Hwy/Art. Outbound	7.65	12	1	41.55	1189.03	1.83	-
	Pick-up & Delivery	44.46	335	170	16.17	1390.45	5.46	-
HHV	Hwy/Art. Outbound	7.68	12	1	42.27	1107.66	3.21	-
	Pick-up & Delivery	49.23	351	182	17.48	1095.65	4.13	-
	Hwy/Art. Outbound	11.86	21	4	41.67	1261.55	1.20	-
Percent Difference	Hwy/Art. Outbound	0%	-1%	-2%	2%	-7%	75%	N/A
	Pick-up & Delivery	11%	5%	7%	8%	-21%	-24%	N/A
	Hwy/Art. Outbound	N/A	N/A	N/A	N/A	N/A	N/A	N/A

Highway/arterial data was not available for the conventional vehicle on the return trip, due to the melted pressure line. Comparing only the outbound trips, the hybrid emitted 7% less CO_2, but produced 75% more NO_x. The NO_x emissions from the hybrid were much lower on the return journey, so it is likely that the higher NO_x on the outbound trip is due to the time required to warm up the SCR catalyst.

In pick-up and delivery operation, the hybrid emitted 21% less CO_2, and produced 24% less NO_x. CO emissions from both vehicles were effectively zero. PM emissions from the hybrid vehicle were higher than from the conventional, but PM emissions from both vehicles were very low.

3.3 Discussion

Actual emission rates will vary widely with driving conditions such as drive cycle and driver behavior. The numbers presented in this report are representative of specific drive cycles and driving conditions and were derived from testing done in a semi-controlled environment. They should not be used to predict emission rates in different driving conditions.

One vehicle was tested per day and while route and operating conditions were similar, the location and number of package deliveries may vary from day to day. As a result, the hydraulic hybrid vehicle travelled more miles than the conventional diesel vehicle. In addition, different road traffic, driver behavior and weather may impact operating conditions.

The two vehicles were somewhat different from each other as the conventional diesel vehicle was equipped with a 200 hp Cummins engine, while the hydraulic hybrid vehicle was equipped with a 280 hp Cummins engine. Please note that engines with different horsepower ratings may have different engine calibrations and deliver different performance, fuel consumption and emissions levels.

In addition, both engines were not EPA certified at the same emissions level: 2007 EPA certified for the conventional diesel vehicle and 2010 EPA certified for the hydraulic hybrid vehicle. Both vehicles were equipped with diesel engines fitted with diesel particulate filters. The hydraulic hybrid vehicle was also equipped with a selective catalytic reduction (SCR) system. Please note that SCR systems may impact engine efficiency and ultimately increase fuel consumption compared to a similar engine not equipped with a SCR system.

While we recognize the limitations of on-road emissions testing, the results of the present test provide real-world evaluation of the FCCC / Parker Hannifin HHV on an actual parcel delivery route and offer valuable information for prospective fleets looking at replacing existing diesel parcel delivery vehicles by hydraulic hybrid vehicles.

4. CONCLUSIONS

On-board emissions measurements were conducted on two UPS package delivery trucks: one conventional diesel and one with a diesel-hydraulic hybrid powertrain. Both diesel engines were equipped with diesel particulate filters. The hybrid was also equipped with a selective catalytic reduction (SCR) system. The emission measurements were taken under conditions closely simulating normal package delivery operation, with the truck under test closely following a truck on an actual package delivery route.

The measured emissions of CO and PM were extremely low for both the conventional and the hybrid truck. THC emissions from both vehicles were negative – the exhaust THC concentration was less than the ambient background level. Compared to the conventional vehicle, the hybrid showed 21% lower fuel consumption in low-speed stop-and-go delivery service. In highway/arterial driving, the hybrid consumed 7% less fuel.

The hybrid was equipped with an SCR system for NOx control, while the conventional vehicle was not. This would be expected to result in much lower NOx emissions. Measured NOx emissions from the hybrid were 24% less than the conventional vehicle in low-speed package delivery service. NOx emissions from the hybrid were higher than the conventional vehicle in the outbound highway/arterial sequence, which began with a cold start. Highway/arterial NOx emissions from the hybrid were 63% lower on the return (with the SCR catalyst warmed up) than on the outbound trip.

ENGINE, FUEL, AND EMISSIONS ENGINEERING, INCORPORATED

8614 Unsworth Ave. Suite 100
Sacramento, CA 95828
ph. (916) 368-4770
fax (916) 362-2579
www.efee.com

APPENDIX A
RAVEM SYSTEM TECHNICAL DESCRIPTION

Christopher Weaver, P.E.
RAVEM Version 3.3 – March 2010

The Ride-Along Vehicle Emissions Measurement (RAVEM) was among the first portable emission measurement systems (PEMS) to be developed, and is presently the only commercially-available PEMS that can measure emissions of PM as well as NOx, CO, and CO_2. Optional capabilities also allow the measurement and quantification of total hydrocarbons (THC), sulfur dioxide (SO_2), ammonia (NH_3), and nitrous oxide (N_2O), as well as individual species of volatile organic compounds (VOC) and carbonyls such as formaldehyde, acetaldehyde, and acrolein.

During the last eight years, RAVEM systems have been applied to measure pollutant emissions from a wide variety of mobile sources, ranging from transit buses in Mexico City[1] and over-the-road trucks in Los Angeles, to ferryboats[2], locomotives, and construction machinery. RAVEM systems have been applied to the evaluation of emission control systems including selective catalytic reduction, diesel particulate filters, diesel oxidation catalysts, natural gas and LPG engines, and emulsion fuels; as well as for emissions certification of large spark-ignition (LSI) engines.

Principles of Operation

The RAVEM system is described in two published papers[3,4], so its operating principles are summarized only briefly here. As Reference 3 explains in more detail, the RAVEM system is based on proportional *partial-flow* constant volume sampling (CVS) from the vehicle exhaust pipe. The CVS principle is widely used for vehicle emission measurements because the air dilution and total flow arrangements are such that the pollutant *concentration* in the CVS dilution tunnel is proportional to the pollutant *mass flow rate* in the vehicle exhaust. Gaseous pollutant concentrations can be measured readily, as can integrated concentrations of particulate matter. On the other hand, exhaust mass flow rates are difficult and expensive to measure accurately – especially under transient conditions.

The total pollutant mass emissions over a given driving cycle, such as the US Federal Test Procedure, European Transient Cycle, or Mexico City Bus Cycle, are equal to the integral of the pollutant mass flow rate over that cycle. In a CVS system, this integrated value can readily be determined by integrating the concentration measurement alone. The CVS flow rate enters into the calculation as a constant multiplier. The integration of pollutant concentration can be accomplished either numerically or physically. The vehicle exhaust mass flow rate does not enter into the calculation, making it unnecessary to measure.

For gases, the RAVEM system uses both numerical and physical integration. Concentrations of NOx, CO_2, and CO in the dilute exhaust gas are recorded second-by-second during each test. In addition, integrated samples of the dilute exhaust mixture and dilution air are collected in Tedlar® bags during the test, and analyzed afterward for NOx, CO_2, CO and (optionally) other pollutants such as methane and non-methane hydrocarbons (NMHC).

In CVS sampling for particulate matter, sample integration is accomplished physically -- by passing dilute exhaust mixture through a pre-weighed filter at a constant, controlled flow rate. The weight gained by the filter is then divided by the volume of mixture passed through it to yield the average particulate concentration over the test cycle.

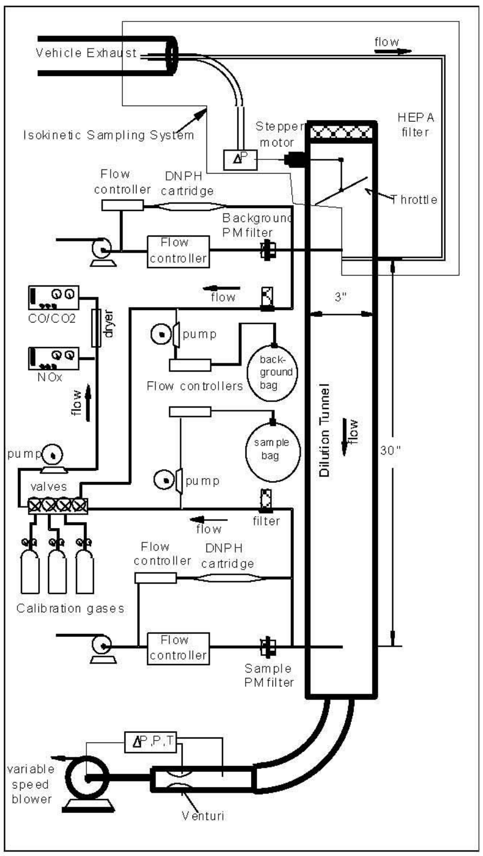


Figure 1: Schematic diagram of the RAVEM system

A schematic diagram of the RAVEM system is shown in Figure 1. Except for the isokinetic sampling system at the top of the figure, this diagram closely resembles a conventional single-dilution CVS emission measurement system.

Conventional emission laboratory methods defined by the U.S. EPA[5] and California ARB[6] utilize full-flow CVS, in which the entire exhaust flow is extracted and diluted with air. However, the large amounts of dilution air required make full-flow CVS impractical for portable systems.

Rather than the entire exhaust flow, the RAVEM sampling system extracts and dilutes only a small, constant fraction of the total exhaust. The dilution air requirements and dilution tunnel size can thus be reduced to levels compatible with portable operation. The patented isokinetic proportional sampling system[7] continuously adjusts the sample flow rate so that the flow velocity in the sample probe is equal to that of the surrounding exhaust. Since the velocities are equal ("isokinetic"), the ratio of the flow rates in the exhaust pipe and the sample probe is equal to the ratio of their cross-sectional areas.

The principle of proportional, partial-flow sampling used in the RAVEM system has now been accepted by both the U.S. EPA (40 CFR 1065) and the International Standards Organization (ISO 8178). Pollutant concentration measurements in the RAVEM system also follow the methods specified in 40 CFR 1065. Except for PM (where the RAVEM uses the more-reliable CFR method), these methods are also compatible with ISO 8178. The pollutants measured are:

- Oxides of Nitrogen (NOx) by chemilumenescent analysis of the dilute exhaust sample;
- Carbon monoxide (CO) and carbon dioxide (CO_2) by non-dispersive infrared analysis of the dehumidified dilute exhaust sample;
- Particulate matter (PM) by passing the dilute exhaust sample through pre-weighed 47 mm filters of Teflon film or Teflon-coated borosilicate glass fiber, followed by post-conditioning and reweighing (Teflon film is recommended where low PM concentrations are expected, Teflon-coated borosilicate glass is suggested where PM are expected to be typical of pre-control diesel engines);
- (Optional) total hydrocarbons by flame ionization detection (FID). This option is most useful for gasoline and alternative fuels, since THC emissions from diesel engines are usually very low and of little concern. When used, the separate sample probe, sample line, and FID analyzer are all heated to 190 ^{o}C;
- (Optional) speciated volatile organic compounds (VOC) can be measured by gas-chromatographic (GC) analysis of the integrated bag samples, using flame ionization detectors in a method patterned on California Air Resources Board methods 102 and 103. This approach is especially useful with natural gas vehicles, as it is possible to distinguish un-reactive methane and ethane from reactive VOC species;
- (Optional) aldehydes and other carbonyls by collection in silica-gel cartridges coated with di-nitro phenyl hydrazine (DNPH), followed by elution with acetonitrile and analysis of the eluate by high-pressure liquid chromatography, as specified in U.S. EPA method TO-11a;
- (Optional) sulfur dioxide (SO_2) by UV fluorescence or non-dispersive UV analysis;
- (Optional) ammonia (NH_3) and nitrous oxide (N_2O) emissions by Fourier transform infrared (FTIR) analyis, using a heated sample line, and sample cell.

RAVEM Subsystems and Operation

The RAVEM system comprises the following key subsystems.

- Miniature constant volume dilution system
- Isokinetic proportional sampling system
- Bag sampling system: a) exhaust sample; b) background air sample
- Gas analyzer system: a) CO/CO_2; b) NO_x
- Particulate sampling system
- Total hydrocarbon sampling and analysis system
- Cartridge sampling system (not used in this test program)
- Data processing and handling system
- Auxiliary inputs

Miniature Constant-Volume Dilution System

This constitutes the heart of the RAVEM system. As diagrammed in Figure 1, the variable speed blower draws dilute air/exhaust gas mixture out of the dilution tunnel at a constant rate (expressed in standard liters per minute). The flow rate is controlled by a closed-loop system that measures volumetric flow rate via a venturi meter, corrects this to standard conditions of one atmosphere pressure and 20^{o} C, and then adjusts the blower speed to maintain the flow setpoint. The venturi meter is calibrated against a high-accuracy hot-wire mass flow meter (not shown) in order to compensate for any drift. High accuracy is needed, as any error in the mass flow will result in a proportional error in the final results.

Raw exhaust gas enters the dilution tunnel near the upper end, where it mixes with filtered dilution air. The relative proportions of exhaust gas and dilution air are controlled by the isokinetic sampling system, by means of the throttle in the air inlet.

Isokinetic Proportional Sampling System

The isokinetic sampling system comprises: a) the sampling probe in the exhaust pipe; b) an insulated sample line connecting the sampling probe to the raw gas inlet on the dilution tunnel; and c) the system for controlling the sample flow to maintain isokinetic conditions. The control system uses static pressure taps on the inside and outside surfaces of the probe, connected to a sensitive differential pressure sensor. When this sensor reads zero, the inside and outside pressures are the same. This requires that the velocities inside and outside the sample probe also be equal – i.e. isokinetic. Thus, exhaust gas entering the sampling probe is equal in velocity to that in the main engine exhaust stream ($v_1 = v_2$).

The throttle at the upstream end of the dilution tunnel is connected to a "smart" motor/controller combination. The controller responds to the signal from the differential pressure sensor by changing the throttle position to maintain isokinetic conditions. When the exhaust flow rate increases, the controller closes the throttle somewhat, increasing the pressure drop between the probe and the dilution tunnel, and thus increasing the flow velocity through the probe. When the exhaust flow decreases, the throttle opens, decreasing the pressure drop and the flow velocity in the probe. A fan upstream of the throttle (not shown) extends the possible range of dilution tunnel pressures to include slightly positive as well as negative values (compared to ambient atmospheric pressure).

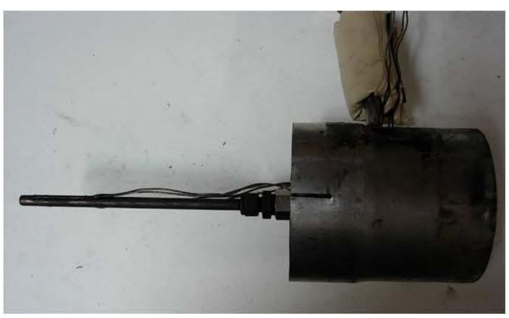


Figure 2: Exhaust probe, mount, and sample line

Since the control system depends on equalizing the static pressures measured inside and outside the probe, leaks or other problems in the pressure taps, pressure lines, or differential pressure sensor can affect the measured pressure difference, and thus the emission results. To aid in detecting this problem, the RAVEM incorporates a system for *in situ* leak checks on the differential pressure lines.

Bag Sampling System

The bag sampling system is designed to fill one pair of Tedlar bags for each test. One bag contains an integrated sample of the dilute exhaust from the dilution tunnel, and the other contains an integrated sample of the dilution air. Two choices are available with respect to the Tedlar bags: a pair of internal bags having a usable volume of about 10 liters, or a pair of 60 liter external bags fed through two quick-connect ports on the exterior of the system unit. The system is designed to allow the external bags to be exchanged quickly between tests, so that the bag samples for each test can analyzed off-board – e.g. by gas chromatograph. A pair of electronically-actuated three-way valves selects the internal or external bags.

For each bag, gas is drawn from a sample port in the dilution tunnel, through a filter to a small pump. It then passes through a mass flow controller to the bag selector valve, and thence to the bag. The flow rate to the bags typically ranges from 0.25 to 1.5 standard liters per minute, and is kept constant during each emission test. The flow rate is normally calculated and set automatically, to capture a specified volume of gas over the length of the emission test. It can also be set manually by the RAVEM operator. The volume flowing to the sample bag is added to the total CVS flow in calculating the emission results.

Any leaks in the sample bag will directly affect the bag emission results. A leak check is therefore performed in the process of emptying the sample bags before each test.

Gas Analyzer System

The gas analyzer system comprises a sample pump, valve manifold, and conventional laboratory-grade heated NOx and ambient-temperature CO/CO_2 analyzers installed in a shock-mounted 19 inch rack inside a protective case. The standard NOx analyzer is a California Analytical Instruments 600 HCLD equipped with an NO to NO_2 converter using activated carbon. The analyzer is maintained at 60°C, making it unnecessary to dry the sample to avoid condensation Dry, low-pressure compressed air for the ozone generator is supplied by an on-board pump by way of a filter and desiccant cartridge.

The standard analyzer for CO and CO_2 is a California Analytical Instruments model 602 non-dispersive infrared (NDIR) analyzer. Water vapor interferes with the NDIR measurement, especially for CO, and must be removed from the sample. This is accomplished by passing it through a Nafion™ semi-permeable membrane mass-exchanger. Dry gas for the other side of the mass exchanger is supplied by a small pump circulating air through a desiccant cartridge.

The gas analyzer system valve manifold allows the analyzer sample feed to be drawn from any one of the following sources: the dilute exhaust mixture in the dilution tunnel, the dilution air entering the tunnel (for background measurements), the integrated sample bag, the integrated background bag, zero gas, CO/CO_2 span gas, or NOx span gas. The latter three gases are used for calibration, and are supplied to quick-connect ports on the exterior of the RAVEM system unit.

During an emission test, gas concentrations in the dilute exhaust are monitored continuously, and recorded once per second. After the test ends, the analyzers are normally again calibrated prior to analyzing the concentrations in the sample and background bags.

Since the second-by-second pollutant readings can be affected by drift, vibration, and changes in background pollutant concentrations as the vehicle drives, the bag data are normally more accurate, and are generally the ones reported. The second-by-second data are useful for examining the variation in emissions over the driving cycle, and also provide a backup should the bag results be compromised – e.g. by bag failure during a test.

Particulate Sampling System

The particulate sampling system comprises a vacuum pump, two flow controllers, and two filter cassette holders: one for the PM sample, and one for the background dilution air. The system uses 47 mm filter cassettes, as recommended in 40 CFR 1065.

During an emission test, dilute exhaust gas and dilution air are drawn through their respective filter sets. The filtered gas then passes through the flow controllers to the vacuum pump, where it is exhausted. The flow controllers maintain a constant flow rate (typically 10 to 30 SLPM, depending on the anticipated PM loading) throughout the emission test. Integrated flow volume is recorded during the emission test in order to calculate the particulate mass concentration in the dilute air/exhaust sample and in the background dilution air.

Figure 3: PM filter cassette holder

The filter set exposed to the dilution air provides a "blank" sample for each test, correcting for the effects of changing humidity, atmospheric pressures, and any ambient PM (including condensable species) present in the filtered dilution air. Experience has shown that such corrections can amount to 0.01 to 0.02 grams of PM per BHP-hr, which is of the same order as the PM emissions from some low-emission vehicles.

Total Hydrocarbon Sampling System

The total hydrocarbon sampling system comprises the additional equipment needed to measure total hydrocarbons (THC) by flame ionization detector in real time, second-by-second, according to the methods specified by the U.S. EPA and ISO 8178 for diesel vehicles and engines. This method is also acceptable for gasoline, CNG, LPG, etc. When combined with GC analysis of the integrated sample bag to determine methane, this system can also be used to determine non-methane hydrocarbon emissions.

The THC sampling system includes a removable, heated probe to collect the HC sample from the dilution tunnel. The probe is configured to fit a sample port in the RAVEM dilution tunnel. An electrically heated sample line goes from the heated probe to a California Analytical Model 600

HFID heated flame ionization detector analyzer. This analyzer is equipped with a built-in heated filter and heated sample pump. The probe, line, filter, pump, and sample oven of the gas analyzer are all maintained at 190 °C.

The HFID analyzer is mounted in a shock and vibration-resistant military-type rack-mount case. This case also contains a small compressed gas cylinder with the compressed hydrogen-helium fuel mixture required by the HFID, as well as an air pump, filter, dryer, and activated carbon adsorbtion bed to supply clean, dry, hydrocarbon free combustion air required by the HFID.

Cartridge Sampling System

The DNPH cartridge sampling system is similar in design to the PM sampling system described above, comprising two shutoff valves, two holders for SKC 6 mm glass sampling tubes, two flow controllers, and two sample pumps. The DNPH sampling system differs from the PM sampling system in having much lower designed flow rates (i.e. 0 to 2 liters per minute, rather than 0 to 30), and in drawing from the filtered sample stream that also feeds the Tedlar bags, rather than directly from the dilution tunnel.

To measure the concentration of carbonyls such as formaldehyde, acetaldehyde, and acetone, the cartridge sampler is loaded with two 6 mm glass tubes containing DNPH-impregnated silica gel. Gas is drawn from the sample and dilution air ports, through filters, and then through the cartridges, where any carbonyls present react with the DNPH and are retained in the cartridge. The cartridges are then removed, placed in a cooler at approximately 4 °C, and transported to the laboratory, where they are kept in a freezer until analysis by high performance liquid chromatography (HPLC), as specified in EPA method TO-11a.

Data Processing and Handling System

The data processing and handling system comprises a laptop computer, connected to a National Instruments Fieldpoint system containing 24 analog-to-digital channels, 8 digital-to-analog channels, 36 digital outputs, 8 general-purpose digital inputs, and 4 counter inputs. These include a number of spare inputs and outputs beyond those required by the RAVEM system itself, making it easy to interface auxiliary sensors.

The RAVEM system measures and records numerous data on a second-by-second basis during each emission test, including the raw inputs and calculated concentrations of CO, CO_2, and NOx, the CVS flow rate, throttle position, and differential pressure sensor reading. Calibration data relating the raw inputs and calculated concentrations are also recorded, making it possible to recalculate the second-by-second results using the calibration at the end of the test. Exhaust temperature and up to two auxiliary temperatures are recorded second-by-second; in addition, the temperature, barometric pressure, and humidity are recorded at the beginning of each test. All of these are stored in separate data file for each test, in a compact binary format.

A data file reading utility is supplied with the RAVEM system. This utility can be used to review and correct the data collected for each test, and to add data developed later such as the post-test weights of the particulate filters. This utility can also copy the data to a Microsoft Excel worksheet file. The Excel file is formatted to be "human readable", and occupies much more space than the compact binary format.

Auxiliary Inputs

Auxiliary inputs to the RAVEM system include a global positioning system (GPS) receiver, as well as user-specified pulse, voltage, and 4-20 ma current inputs. The GPS system provides three-dimensional location and velocity data, based on signals from the global positioning network. These are supplied and recorded at a frequency of 1 Hz. The user- supplied inputs can be used for a variety of purposes, including dynamometer speed and load, current flow in hybrid-electric systems, etc. EF&EE can readily customize the RAVEM control software to calculate, display, and record a wide variety of additional inputs.

Quality Control Measures

RAVEM operating procedures include a number of quality assurance measures. Two key QA procedures are CO_2 recovery tests and fuel consumption checks. The CO_2 recovery check injects CO_2 gas from a cylinder into the dilution tunnel, and compares the CO_2 mass measured to the change in weight of the CO_2 cylinder. This confirms the accuracy of the CVS flow measurement, as well as the gas sampling system and the CO_2 analyzer.

Fuel consumption checks compare the mass of fuel consumed by the vehicle under test to the fuel consumption calculated from the CO_2 and CO emissions by carbon balance. Given good data on the carbon content of the fuel, the two measures should normally agree within 4 to 5 percent. In addition to the CVS and gas sampling system, this procedure also checks that the isokinetic sampling system is working properly.

References

[1] C.S. Weaver and Marco V. Balam Almanza, Measurement of Air Pollutant Emissions From Public Transport Buses, in the Insurgentes Corridor Of Mexico City, report to the Secretariate of the Environment, Government of Mexico City, December, 2005

[2] Weaver, C.S., L.M. Chan and L. Petty, Measurement of Air Pollutant Emissions From In-Service Passenger Ferries, report to the Water Transit Authority of San Francisco Bay, August, 2002.

[3] C.S. Weaver and L.E. Petty "Reproducibility and Accuracy of On-Board Emission Measurements Using the RAVEM™ System ", SAE Paper No. 2004-01-0965, March, 2004.

[4] Weaver, C.S. and M.V. Balam-Almanza, "Development of the 'RAVEM' Ride-Along Vehicle Emission Measurement System for Gaseous and Particulate Emissions", SAE Paper No. 2001-01-3644.

[5] 40 CFR 86, Subpart N "Emission Regulations for New Otto-Cycle and Diesel Heavy-Duty Engines; Gaseous and Particulate Exhaust Test Procedures"

[6] "California Exhaust Emission Standards and Test Procedures for 1985 and Subsequent Model Heavy-Duty Diesel Engines and Vehicles" as amended on February 26, 1999, California Air Resources Board

[7] U.S. Patent No. 6,062,092. "System for Extracting Samples from a Stream", May 16, 2000.