



California Energy Commission Clean Transportation Program FINAL PROJECT REPORT

Hydraulic Hybrid Vehicle Demonstration

Prepared for: California Energy Commission Prepared by: Parker Hannifin Corporation

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PREFACE

Assembly Bill 118 (Núñez, Chapter 750, Statutes of 2007) created the Clean Transportation Program, formerly known as the Alternative and Renewable Fuel and Vehicle Technology Program. The statute authorizes the California Energy Commission (CEC) to develop and deploy alternative and renewable fuels and advanced transportation technologies to help attain the state's climate change policies. Assembly Bill 8 (Perea, Chapter 401, Statutes of 2013) reauthorizes the Clean Transportation Program through January 1, 2024, and specifies that the CEC allocate up to \$20 million per year (or up to 20 percent of each fiscal year's funds) in funding for hydrogen station development until at least 100 stations are operational.

The Clean Transportation Program has an annual budget of about \$100 million and provides financial support for projects that:

- Reduce California's use and dependence on petroleum transportation fuels and increase the use of alternative and renewable fuels and advanced vehicle technologies.
- Produce sustainable alternative and renewable low-carbon fuels in California.
- Expand alternative fueling infrastructure and fueling stations.
- Improve the efficiency, performance and market viability of alternative light-, medium-, and heavy-duty vehicle technologies.
- Retrofit medium- and heavy-duty on-road and nonroad vehicle fleets to alternative technologies or fuel use.
- Expand the alternative fueling infrastructure available to existing fleets, public transit, and transportation corridors.
- Establish workforce-training programs and conduct public outreach on the benefits of alternative transportation fuels and vehicle technologies.

To be eligible for funding under the Clean Transportation Program, a project must be consistent with the CEC's annual Clean Transportation Program Investment Plan Update. The CEC issued solicitation PON-09-004 to provide funding opportunities under the Clean Transportation Program for Hybrid Hydraulic Vehicle Demonstration. In response to PON-09-004, the recipient submitted an application, which was proposed for funding in the CEC's Notice of Proposed Awards November 14, 2012. The agreement was executed as ARV-09-011 on December 14, 2012 in the amount of \$597,000. Parker Hannifin provided \$1.25 million in private matching funds.

ABSTRACT

This report examines the benefits of Parker Hannifin's hydraulic hybrid brake energy recovery system, which is intended for use in commercial refuse trucks. The hydraulic brake energy recovery system was field-tested in high start and stop applications to determine the magnitude of fuel and emissions reductions. Additional study topics included productivity, driver acceptance, and maintenance. During low speed, high start and stop driving tests, the refuse vehicles had 49 percent better fuel economy performance over the baseline diesel, plus a 30 percent reduction in carbon dioxide emissions per mile. This represents a substantial improvement over baseline technologies as approximately 80 percent of a refuse vehicle's time is spent in low speed operation. Field-testing data showed similar improvements in performance, with an average fuel economy of 2.8 miles per gallon, which represents a substantial improvement compared to the low speed dynamometer test result of 0.88 miles per gallon. Continued review of data in the areas of reliability, driver acceptance, and reduced maintenance would allow for expanded research for these platforms. Investigation of this solution for other vehicle platforms, such as shuttle and transport buses, combined with natural gas fuels, could yield interesting growth opportunities and new commercial applications.

Keywords: Hydraulic Hybrids, Energy Recovery, Advanced Series Hybrids, Refuse Vehicles, Parcel Delivery Vehicles, Start & Stop Operation, Vocational Vehicles, Reduced Emissions, Productivity, Maintenance

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EXECUTIVE SUMMARY

Introduction

Improving fuel economy and reducing emissions are critical improvement areas for over the road vocational vehicles that consume large amounts of petroleum fuel. Current refuse vehicles get less than one (1) mile per gallon with a conventional drivetrain. This report reviews the current and potential future hydraulic hybrid driveline configurations that can provide substantial fuel economy improvements for refuse and parcel delivery applications. The refuse truck data collected for this report was done in the field, while stationary dynamometer testing was performed at no expense to the CEC. Additional data from studies by the U.S. Department of Energy, CALSTART, and the National Renewable Energy Laboratory show how hydraulic hybrids can provide significant fuel savings when used in high start and stop duty cycles. Additional data from the U.S. Environmental Protection Agency's laboratories is also included. Independent research by the University of Michigan's Automotive Research Center documents that hydraulic hybrids have the potential to perform three times more efficiently than electric hybrids. This hydraulic hybrid technology should be evaluated carefully so that it is applied to the right applications to insure optimal commercial performance. This is best done through a study of the route and number of starts and stops.

The goal of this Agreement is to demonstrate the significant technical and financial benefits of hybrid hydraulics for use in heavy vehicles in terms of reduced fuel and emissions benefits.

Parker Hannifin's Hydraulic Hybrid Braking System

Parker Hannifin's advanced series technology allows the vehicle to reduce fuel consumption in three ways. The first is through regenerative braking, the second is through an advanced series gearbox that allows the engine to operate independently of vehicle speed or transmission output speed, and the third is the ability to shut the engine off and operate with the stored energy in the accumulator. Figure ES-1 is a schematic of the hydraulic hybrid braking system. Figure ES-2 describes the systems' operation in more detail.

During regenerative braking, kinetic energy from the truck's motion is stored in low and highpressure fluid-filled reservoirs known as "accumulators." This stored energy is used during initial take-off during start and stop operations. When the accumulator reservoir is depleted, the truck's engine is engaged. This cycle repeats continuously during start and stop operations. At speeds over 45 miles per hour, the hydraulic system disengages and the mechanical drivetrain propels the vehicle.

Figure ES-1: Parker Hannifin's Advanced Series Hydraulic Hybrid System Parker Refuse Advanced Series Hybrid



Advanced Series Hybrid with Brake Energy Recovery
Low speed hydrostatic 0-25 MPH
High speed Hydrostatic 26-45 MPH
Mechanical drive 46-65 MPH (Hydraulics Disengaged)

Source: Parker Hannifin

Figure ES-2: How the Hydraulic Hybrid System Works



Source: National Renewable Energy Laboratory

Methods and Results

The process for obtaining the data in this study is a combination of Lab Dynamometer Testing in controlled conditions for baseline and hybrid vehicle styles and field testing of vehicles both within and outside the test area of the State of California. The U.S. Department of Energy, CALSTART, National Renewable Energy Laboratory, and U.S. Environmental Protection Agency collected data on similar hydraulic hybrid applications for parcel delivery vehicles. This parallel data is relevant in demonstrating how this technology can be applied to other vehicle categories.

The refuse trucks fitted with the hydraulic hybrid braking system achieved positive results during low speed testing with high start and stop operations. These trucks had 49 percent better fuel economy over the baseline diesel, plus a 30 percent reduction in carbon dioxide emissions per mile. This represents a substantial improvement over baseline technologies as approximately 80 percent of a refuse vehicle's time is spent in low speed operation. Field test data showed similar performance improvements. Fuel economy improved to an average of 2.8 miles per gallon, up substantially when compared to the baseline level of 0.88 miles per gallon. The highest performing test vehicle obtained 4.5 miles per gallon. The corresponding reduction in criteria emissions is also substantial. The parallel data obtained from the agencies and outside parties listed above documents that similar hydraulic hybrid technology in parcel

delivery duty cycles improves fuel economy up to 50 percent while reducing carbon dioxide emissions almost 20 percent.

Parker Hannifin's data for 75 in-service vehicles shows a 97 percent uptime rate and fuel savings that are 43 percent above the baseline vehicles. Driver acceptance is critical for commercial deployment of this technology. Effective training is essential because it allows the operators ask questions, drive the vehicle, and get a feel for the operation. The operators have commented on smooth acceleration and braking of the vehicle resulting in less fatigue.

The stored energy from the hydraulic hybrid system's accumulators enables full acceleration from the time the truck is started. This can increase productivity due to quicker launches, smoother shifting and braking. One key difference in operations and productivity between the refuse and package delivery trucks is that refuse operators stay close to the refuse truck during operations, while the parcel delivery operators must stop their vehicles, walk to pick-up and deliver packages, and then return to the vehicles. This means the two sets of test results cannot be compared on an equivalent basis.

In terms of vehicle maintenance, trucks fitted with the hydraulic hybrid systems showed significant reduction in brake wear and did not require brake servicing during the test period. Parker Hannifin anticipates that these trucks will require only one brake job during the life of the vehicles.

This reduction in brake wear is a direct result of the regenerative braking and the use of the hydraulic hybrid energy recovery circuit to accelerate the vehicle. CALSTART reviewed the wear of the tires on both the front and rear of the vehicle, but the data was inconclusive. Further investigation and measurement will be needed.

Conclusions

The Hydraulic Hybrid solution for refuse trucks and the parallel data from the parcel delivery trucks indicate a substantial improvement in fuel economy and substantial reductions in emissions. Low speed testing with high start and stop operations demonstrated a 49 percent improvement in fuel economy and a 30 percent reduction in carbon dioxide per mile. This represents a substantial improvement over baseline technologies as approximately 80 percent of a refuse truck's time is spent in this area of low speed operation. Field test data showed similar improvements in performance; average fuel economy increased to 2.8 miles per gallon, which is a substantial improvement over the baseline dynamometer results of 0.88 miles per gallon. Similar results were observed in the parcel delivery vehicles as well. Parcel delivery vehicles outfitted with the hydraulic hybrid systems reduced fuel consumption by 19 to 52 percent. Parker Hannifin's data for parcel delivery vehicles parallels these results; fuel consumption decreased by 35 to 50 percent, carbon dioxide emissions per mile decreased 17.4 percent and oxides of nitrogen emissions decreased 30.4 percent.

CHAPTER 1: Introduction and Objectives

Project Purpose

The goal of this agreement is to demonstrate the significant technical, financial, fuel economy and emissions reduction benefits of hybrid hydraulic systems installed in heavy-duty vehicles.

The objectives of this agreement are to demonstrate, test and measure the tangible results of field trials for the parameters of fuel economy and emissions reduction over baseline vehicles.

The principal barriers to entry into the marketplace of hydraulic hybrid technology today are 1): The lack of market knowledge and acceptance of hydraulic technology when compared to increasing awareness of electric drive and other competing technologies; and 2) Higher initial costs due to lower volumes of production. From the fleet owner and end-users perspective, the technical and financial benefits are not clear when comparing one technology over another.

Fleet owners and end users want to be shown first-hand the benefits of the technologies via the use of individual trial operation of the technology in their locations and fleets. There is a higher upfront cost of the technology compared to that of a current vehicle configuration, which results in resistance to acceptance and purchase of technology for fleets in high numbers. As the technical results, financial benefits, and number of vehicles using the hydraulic hybrid braking system become more widely known, this technology has the opportunity to become more widely adopted and accepted in fleets.

Introduction

The use of hydraulic hybrids for certain vocational applications has shown to have significant benefits in the right duty cycle and route profiles. Identifying the appropriate duty cycles is critical to optimizing the payback periods. This has to be done carefully so as to not offset the fleet vehicle distribution or cause limitations in service. Parker Hannifin has experience with similar technology since the early 1990's on refuse truck and bus applications. This demonstration was performed with advanced series technology that has leapfrogged the performance observed in earlier years. Additionally, research performed by the Automotive Research Center at the University of Michigan highlights the significant benefits and efficiencies from braking and accelerating; hydraulic hybrids showed a three times greater benefit versus electric hybrids (Kargul, 2007, p13).1

¹ Kargul, J (2007). Hydraulic Hybrids. (http://www.epa.gov/region9/wcc/files/meetings/2007-12-11/HHV.pdf)

Figures 1 and 2 show the relative efficiencies between electric regenerative braking systems and the hydraulic hybrid braking systems.

Figure 1: Efficiency Benefits from Electric Drive Braking and Accelerating Systems.



Source: Gallo, 2014²

² Gallo, J. (2014). Hydraulic Hybrid Parcel Delivery Truck Deployment, Testing & Demonstration. Paper presented as a final report to DOE Contract Number DE-FC26-06NT42791.

Figure 2: Efficiency Benefits from Hydraulic Hybrid Braking and Acceleration Systems



Source: Parker Hannifin from Gray, 20063

These results represent significant improvements over competing technologies, which creates commercialization potential for vocational platforms that would allow for broader acceptance in the marketplace. The U.S. Environmental Protection Agency (U.S. EPA) also performed detailed lab benchmarking comparing the Parker Hydraulic Parcel Delivery advanced series hybrid technology with gearbox, engine off, and engine management to hybrid electric vehicle drivetrains and the U.S. EPA series hydraulic hybrid vehicle (HHV). As a result of this testing, the U.S. EPA validated that "... benchmarking confirms that production viable HHVs can

³ Gray, C (2006). Hydraulic Hybrids. (http://kerstech.com/PDFs/EPA%20Hybrid%20Truck%20Initiative.pdf)

achieve high miles per gallon (MPG) in city driving conditions" (Kargul, 2013).4 Figure 3 shows these test results.





Source: U.S. EPA

Additionally, results identified in studies of the Parker Parcel Delivery solution by other third parties validated the fuel savings potential. Test results showed fuel use reduction of 19 to 52

⁴ Kargul, J (2013). Advanced Hydraulic Hybrids Delivering Real-world Savings. Presented at 2013 Green Truck Summit March 6, 2013.

percent over the baseline in terms of MPG (Lammert, 2014, p11).⁵ Parker Hannifin field data show similar benefits: 35 to 50 percent increase in fuel efficiency with emissions reductions of 17.4 percent in carbon dioxide (CO2) per mile and 30.4 percent lower oxides of nitrogen (NOx) emissions per mile (Gallo, 2014, p15). Field tests also indicated maintenance improvement in the areas of brake and starter replacement.

For refuse trucks, the capacity to improve vehicle efficiency is accomplished through brake energy recovery and decoupling the engine from the wheels, which allows for improved engine operation (Parker 2013).6 The following image shows how energy is saved versus wasted as brake heat when using the refuse brake energy recovery system.

Figure 4: Energy Recapture on Refuse Trucks Using Hydraulic Hybrid System

Fuel Savings

RunWise saves fuel two ways. First, by decoupling the engine from the wheels at speeds under 45 mph, this allows the engine to operate at its peak efficiency. Second, by recovering brake energy to reducing the total fuel consumption of the vehicle. Combined, these features reduce fuel consumption by to 35-50%. On average, a refuse truck burns 8,600 gallons of diesel per year. You can imagine the savings RunWise can make on your bottom dollar!



Source: Parker, 2013

5 Lammert, M (2014). Hydraulic Hybrid and Conventional Package Delivery Vehicles Measured Laboratory Fuel Economy on Targeted Drive Cycles. Paper presented at SAE COMVEC show in September 2014, document number 2014-01-2375. (http://www.nrel.gov/docs/fy15osti/62408.pdf)

6 Parker (2013). The Clean Side of Garbage.

(http://www.parker.com/literature/Hybrid%20Drive%20Systems%20Division/Parker%20RunWise_%20E missions%20White%20Paper2013.pdf)

Independent testing at the Ohio State Center for Automotive research using baseline diesel, diesel Hydraulic Hybrid, Baseline CNG, and CNG Hydraulic Hybrid showed the following performance results (Figure 5). These tests again document the significant benefits of the Parker Hydraulic Hybrid in low and high speed cycles.

Figure 5: Test Results from the Ohio State Center for Automotive Research

Low Speed Cycle		High Sp	eed Cycle
	mpg		mpg
	Fuel		Fuel
	Economy		Economy
Diesel	0.88	Diesel	3.78
Diesel Hybrid	1.31	Diesel Hybrid	4.32
CNG	0.61	CNG	3.8
CNG Hybrid	0.94	CNG Hybrid	4.06

Source: Parker, 2013

The Parker Hydraulic Hybrid system can save up to 4,300 gallons of fuel in a one-year period when used on appropriate duty cycles and routes. Figure 7 shows these fuel savings in terms of 860 5-gallon cans.

Figure 6: One-Year Fuel Savings from the Parker Hydraulic Hybrid System



Source: Parker, 2013

There are varying technologies and efficiency gains for hydraulic hybrids, as shown in the following figure and table.

Figure 7: Technology Comparison – Conventional Drivetrain and Hybrid Hydraulic Drivetrain



Source: Parker Hannifin

Table 1: Summary of Hydraulic Hybrid Configurations Summary of Hydraulic Hybrids

	Parallel	Series	Adv Series
Brake Recovery	✓	✓	✓
Engine Management		>	✓
High Speed Efficiency			 Image: A set of the set of the
Fuel Usage Reduction *	0-15%	25-35%	35-50%
Brake Life Extension *	1.5X	3X	15X
Productivity *	Good	Better	Best

* Depending on route profile and duty cycle

-Parker

Source: Parker Hannifin

What is a Hydraulic Hybrid?

Parker's development of the hydraulic hybrid drivetrain started in the late 1980's. Prior to the adoption of this early technology, vehicles utilized a conventional mechanical drivetrain as shown below.

Figure 8: Conventional Mechanical Driveline.

Conventional Mechanical Driveline





Source: Parker Hannifin

The early systems from Parker were parallel hybrid systems. The hybrid system was installed in addition to the conventional drivetrain. There are some limited benefits allowing for some brake energy recovery, however this is only allows for a small percentage of energy capture as the conventional drivetrain remains in place as shown below.

Figure 9: Parallel Launch Hydraulic Hybrid Parallel Launch - Hydraulic Hybrid



Source: Parker Hannifin

Following this technology development was the series hydraulic hybrid systems that featured advancements on hydrostatic drivetrains that had a pump and motor configured to operate in series utilizing brake energy recovery. Parker entered into a Cooperative Research and Development Agreement (CRADA) with the U.S. EPA in 2003 through 2008 to develop an improved hydrostatic series hydraulic transmission. This series concept is depicted below in Figure 11.

High Pressure Accumulator University of the second second

Figure 10: Parker Hannifin Series Hydraulic Hybrid Drivetrain

This series system investigated by Parker involved the use of a primary pump motor, a single gear gearbox, and two pump motors driving the rear axle.

Continued development and research was performed outside of the CRADA to develop the advanced series technology that is in use today. This advanced series technology allows the vehicle to reduce fuel consumption in three ways. The first is through regenerative braking, the second is through an advanced series gearbox that allows the engine to operate independently of vehicle speed or transmission output speed, and the third is the ability to shut the engine off and operate with the stored energy in the accumulator.

The following images depict the Parker advanced series hybrid solutions used on refuse applications.

Source: Kargul, 2013

Figure 11: Refuse Truck - Advanced Series Hybrid Parker Refuse Advanced Series Hybrid



Advanced Series Hybrid with Brake Energy Recovery

- Low speed hydrostatic 0-25 MPH
- High speed Hydrostatic 26-45 MPH
- Mechanical drive 46-65 MPH (Hydraulics Disengaged)

Source: Parker Hannifin

Figure 12: Engine Performance of Baseline Test Vehicle Engine Operating Points - Baseline Truck (simulated drive cycle with representative engine map)



Engine Speed (RPM)

Parker

Source: Parker Hannifin

Figure 13: Engine Performance of Series Hybrid Truck Engine Operating Points – Series Hybrid Truck

(simulated drive cycle with representative engine map)



-Parker

Source: Parker Hannifin

In terms of engine management, the advanced series gearbox allows the engine to be operated in the most efficient area on the engine map. Figures 13 and 14 show the engine map performance of the baseline vehicle and the advanced series hybrid engine map after the optimal engine control algorithms developed by Parker were installed.

This methodology allows Parker to take advantage of the enabling technologies discussed earlier, including: highly efficient bent axis pump/motor units, advanced series gearbox, and the utilization of modern control method to control the hydraulic and engine interfaces. Figure 15 shows these operations schematically.

Figure 14: Schematic of the Hydraulic Hybrid System



Note: "RunWise" is Parker Hannifin's proprietary name for the advanced series hydraulic hybrid system

Source: National Renewable Energy Laboratory

Hydraulic hybrids use standard materials, which allow for more stable technology costs. In contrast, the rare earth metals and coppers used for lithium ion batteries have shown significant materials increases over time (Tomazic, 2013).7 Technology integration will allow for ongoing cost decreases and reductions in design complexity. In terms of energy storage, accumulators have higher power density (W/kg) levels than batteries. Figure 16 compares power density levels of multiple propulsion technologies.

⁷ Tomazic, D (2013). Reducing Energy and Expenses Utilizing Hydraulic Hybrid Waste Trucks Transit Buses and Delivery Vehicles. (http://www.nfpa.com/events/pdf/2013-fpsc/002-2013-11-20_hydraulic-hybridvehicles_chicago_rev3.pdf)



Figure 15: Power Density Levels of Multiple Propulsion Technologies.

Venkat Srinivasan and John Newman; Environmental Energy Technologies Division; Lawrence Berkeley National Laboratory; Berkeley, CA

Source: Lawrence Berkeley National Laboratory

Figure 16: Comparison of Electric Drive and Hydraulic Hybrid Technologies

Electric vs. Hydraulic Hybrids

Characteristic	Hydraulic	Ele	ctric
Power Density Motors	Hydraulic Motors 7000 W/kg	Electric 600	: Motors W/kg
Power Density Storage	Accumulators 3000 W/kg	Battery 650 W/kg	Ultra- Capacitors 2500+ W/kg
Relative Cost	Low to Medium	Med	High
Relative Weight	Low to Medium	High	Med
Useful Life	10+ yrs	> 5yrs	?
Risk	Low to Medium	Med	High
Data source: • SwRI study of Hybrid Technology			Darker

Source: Lawrence Berkeley National Laboratory

Lawrence Berkley National Laboratory

From a start and stop potential, field-testing shows the amount of energy used and available for savings during a daily duty cycle (Figure 18).

If this energy is not saved, it converts to heat energy in the brakes, which is wasted energy.



Figure 17: Wasted Heat Energy during Braking

Source: Parker Hannifin

Figure 19 show a high-level representation of the energy used and saved during braking. Because actual duty cycles and routes vary tremendously, specific routes need to be evaluated to determine their suitability for hybrid technology application. Hybrid hydraulic drivetrains cannot be used on all routes. For example, the technology is on par or slightly less efficient than standard drivetrains when used on highway transit routes with low start and stop cycles (Lammert, 2014).8 As shown in Figure 20, there is significant variation in routes in terms of speeds and number of stops. This variation yields significantly different results in a start/stop hybrid technology (Kargul, 2013).9

⁸ Lammert, M (2014). Hydraulic Hybrid and Conventional Package Delivery Vehicles Measured Laboratory Fuel Economy on Targeted Drive Cycles. Paper presented at SAE COMVEC show in September 2014, document number 2014-01-2375. (http://www.nrel.gov/docs/fy15osti/62408.pdf)

⁹ Kargul, J (2013). Advanced Hydraulic Hybrids Delivering Real-world Savings. Presented at 2013 Green Truck Summit March 6, 2013.



Figure 18: Energy Use and Potential Energy Savings

Source: Parker Hannifin

Figure 19: US EPA Test Cycles

Driving Conditions Matter!

1. EPA Highway Test Cycle

high speed highway avg speed = 48.3 mph, 0 stops

2. EPA City Cycle – Bag 1

Connector urban traffic, high speed highway link avg speed = 25.6 mph, 5 stops

3. EPA City Cycle – Bag 2

Business district/residential urban traffic avg speed = 15.3 mph, 13 stops

4. Manhattan Bus Cycle

Congested urban bus route avg speed = 6.8 mph, 24 stops



Source: US EPA

The following chart from WestStart-CALSTART compares hydraulic and electric hybrid technology applications across multiple duty cycles. (Maxwell, 2008).

Figure 20: Comparing Hydraulic and Electric Hybrid Technologies across Duty Cycles



Hybrid Solutions for Stop-Start Truck Applications

Source: WestStart – CALSTART

Figure 21: Original Equipment Manufacturer Strategy for Uses of Hydraulic and Electric Hybrids



Source: Conrad, 200810

¹⁰ Conrad, M (2008). Hydraulic Hybrid Vehicle Technologies.

⁽http://www.airquality.org/mobile/ctf/Events/20080909NearTerm-BoschRexroth-ConradM.pdf)

Sample Field Data

The following chart (Figure 23) illustrates data collected during the field trials. This data was collected via remote data acquisition systems for each vehicle. This allowed Parker Hannifin to monitor and evaluate field data and to provide driver training opportunities. Braking events were tracked to identify maximum performance and efficiency.

Parker Hannifin currently has over 75 trucks in service with various municipalities and fleets in the U.S. Fuel savings for this fleet was 43 percent better than baseline vehicles. This data relates directly to the actual fuel consumption data captured by the telematics systems. Field-testing also revealed significant reductions in brake wear, at times eliminating the need for brake servicing. Generally though, use of the hydraulic hybrid braking system will result in just one brake job over the service life of the vehicles.

Figure 22: Sample Data from Hydraulic Hybrid Field Trials

Fleet Summary					
Date Range Start	2/1/2015 12:01:00 AM				
Date Range End	3/1/2015 12:00:00 AM				
Vehicle Operations					
Vehicle	Driving Distance	Collection Distance	Fuel Consumption	Fuel Economy	Fuel Economy (gph)
P SC Austin TX 212189 Cust #12657	mi 025.22	% 0.00	gai	mpg	gpn
R WE Manteca CA 21/712	1083 34	28.50	369.90	2 93	2.70
R WE Sacramento CA 215/90	8/3 //	35 55	281.90	2.55	2.70
R WE Marin Sanitation CA 215203	542.82	0.00	201.30	2.55	2.20
R WE Recology CA 217930	226.21	0.00	95.00	2.38	2.20
R WE Redding CA 218555	170.54	0.00	68.40	2.49	2.80
R WE Santa Cruz CA 215043	471.34	26.35	168.80	2.79	2.40
R WE Santa Cruz CA 217968	628.95	25.87	230.60	2.73	2.20
R WE Santa Cruz CA 217969	871.95	20.13	290.00	3.01	2.50
R WE Santa Cruz CA 217970	428.40	23.59	140.40	3.05	2.60
R WE Santa Cruz CA 217971	633.42	28.17	236.80	2.68	2.70
R WE Santa Cruz CA 217972	723.24	24.86	275.30	2.63	2.50
NOTE on data provided	Actual Miles Dirven during period	This represents low vehicle speed below 10 mph. Also if there is a zero (0), there was an arm operation count either not installed or not functioning	Fuel consumed during period	Reporting an average of 35% - 50% lower fuel consumption	Fuel Economy during period
Vehicle	Engine Run Time	Average Speed	Total Engine Time	Total Distance	Arm Operations
hr		mph	hr	mi	count
R SC Austin TX 213188 Cust #12G57	99.10	9.34	4968.85	48716.15	0.00
R WE Manteca CA 214712	138.05	7.85	3259.45	26819.07	22397.00
R WE Sacramento CA 215490	125.85	6.70	2878.70	20632.23	5450.00
R WE Marin Sanitation CA 215203	102.45	5.30	3264.05	19419.91	0.00
R WE Recology CA 217930	42.55	5.32	204.40	3165.78	0.00
R WE Redding CA 218555	24.25	7.03	228.05	3159.10	0.00
R WE Santa Cruz CA 215043	71.25	6.62	2357.15	18491.64	14028.00
R WE Santa Cruz CA 217968	105.55	5.96	690.40	6704.94	7955.00
R WE Santa Cruz CA 217969	116.25	7.50	620.90	7217.88	8373.00
R WE Santa Cruz CA 217970	54.65	7.84	498.85	6199.83	3688.00
R WE Santa Cruz CA 217971	87.85	7.21	494.70	6135.95	6586.00
R WE Santa Cruz CA 21/9/2	109.35	6.61	363.00	5642.95	//82.00
NOTE on data provided	Run time during period	Average speed during period	Total engine hours during period	Total distance during period	Total number of arm cycling during period. Also if there is a zero (0), there was an arm operation count either not installed or not
					installed or not functioning

Source: Parker Hannifin

The following table depicts vehicle build / deployment details:

- Vehicle Location
- City
- Production Build Date
- Ship Built Vehicle

- Body on Vehicle Date
- Receipt of Vehicle to Dealer
- Final Customer Inspection and Commissioning of Vehicle
- Vehicles placed in Service

Table 2: Build Schedule for Eight Hydraulic Hybrid Trucks

Vehicle Location Name	City	Production Vehicle Build Date	Ship Build Vehicle	Body Date	Receipt of Vehicle	Final Inspection & Commissioning of Vehicle	Vehicles in Service
City of Santa Cruz	Santa Cruz	5/23/2014	June 2014	July 2014	October 2014	November 2014	December 2014
City of Santa Cruz	Santa Cruz	5/28/2014	June 2014	July 2014	October 2014	November 2014	December 2014
City of Santa Cruz	Santa Cruz	5/29/2014	June 2014	July 2014	October 2014	November 2014	December 2014
City of Santa Cruz	Santa Cruz	5/30/2014	June 2014	July 2014	October 2014	November 2014	December 2014
City of Santa Cruz	Santa Cruz	5/30/2014	June 2014	July 2014	October 2014	November 2014	December 2014
Marin Sanitation	San Rafael	5/27/2014	June 2014	August 2014	November 2014	December 2014	December 2014
Recology	San Francisco	5/12/2014	June 2014	August 2014	November 2014	December 2014	December 2014
Redding	Redding	8/23/2014	September 2014	November 2014	November 2014	December 2014	January 2015

Source: Parker Hannifin

CHAPTER 2: Laboratory and Field Testing Methods and Data

Laboratory Testing at the Ohio State University Center for Automotive Research

This section describes methods and results for Parker Hannifin's testing of refuse and delivery trucks. These tests were performed at no expense to the CEC.

Parker Hannifin performed baseline and comparative testing of four technologies at the Ohio State Center for Automotive Research:

- Baseline Diesel
- Diesel Hydraulic Hybrid
- Baseline CNG
- CNG Hydraulic Hybrid

The Center for Automotive Research (CAR) is an interdisciplinary research center at The Ohio State University College of Engineering. Established in 1991, the Center focuses on research, technology and education with an emphasis on energy, safety, and the environment. This research encompasses energy systems, electromechanical systems, modeling and simulation, sensing actuation and control. The center specializes in fields such as combustion engineering, the fluid and thermal sciences, electro-mechanics, control systems, and software engineering.

The Center for Automotive Research conducted the following test cycles:

Drive Cycles by Vehicle:

- CNG Baseline:
 - 3x Parker High Speed
 - 4x Parker Low Speed
 - 3x New York City
- Diesel Baseline:
 - o 3x Parker High Speed
 - 4x Parker Low Speed
 - 3x New York City

- RunWise® Diesel Hybrid:
 - o 3x Parker High Speed
 - 4x Parker Low Speed
- RunWise® CNG Hybrid:
 - 3x Parker Low Speed
 - 3x New York City

The tests were conducted at the CAR-TESS facilities using a heavy-duty chassis dynamometer. Each truck was positioned on the chassis dynamometer and repeatedly subjected to a highspeed refuse drive cycle (NY RT) and a low speed drive cycle (Red Cycle) under the load conditions described below.



Figure 23: Refuse Truck Dynamometer Tests at Ohio State University

Source: Ohio State University Center for Automotive Research

The following table gives a description of each vehicle. All refuse trucks tested were automated side loaders.

	2010 Peterbilt	2011 Peterbilt 2013 Autocar		2010 Autocar
Engine Family	ISL G	ISL 320HP	ISL G 320	ISL
Fuel	CNG	Diesel CNG		Diesel
After-treatment	-	DOC, SCR, DPF	TWC	DOC, SCR, DPF
Transmission	Allison HD4560	Allison HD4560	RunWise® MY14	RunWise® MY14
Rear-end	Dana/Spicer D46- 170 with 6.14 gear ratio	Dana/Spicer D46- 170 with 4.88 gear ratio	4.33 gear ratio	4.33 gear ratio
Initial Mileage	10,345	14,513	654	43,769

Table 3: Test Vehicle Parameters and Statistics

Source: Ohio State University Center for Automotive Research

Test Equipment

The testing facilities at CAR-TESS are equipped with a MAE Mustang heavy-duty dynamometer, which can simulate on-road driving conditions for any medium-duty or heavy-duty vehicle using its 48-inch precision rollers. The dynamometer uses dual, direct-connected,

300 hp (223 kW) motors attached to each roll set, resulting in 900 hp or 671 kW combined peak. The dynamometer can apply the same loading that a vehicle would experience from roadway friction and wind resistance as it would experience under typical driving conditions. Additional large inertia weights can be incorporated into the dynamometer to increase the base mechanical inertia and enable the dynamometer to provide precise on-road simulation for an even wider range of vehicle weights. Specifications of the dynamometer are shown in the following figure and table.



Figure 24: Mustang AC-48-300HD Tandem Axle Chassis Dynamometer

Source: Ohio State University Center for Automotive Research

Item	Value	
Dynamometer rated power	1000	hp
Dynamometer base speed	1150	rpm
Dynamometer max speed	1720	rpm
Dynamometer max torque at base speed	4566.96	lb-ft
Dynamometer max torque at max speed	3053.49	lb-ft
Roll diameter	48	in
Roll inertia	$63,\!276.05$	lb-ft ²

Table 4: Mustang AC-48-300HD Tandem Axle Chassis Dynamometer Specifications

Source: Ohio State University Center for Automotive Research

The data acquisition system is composed of the following components:

- National Instrument data acquisition device NI USB-6009 used for the measurement of speed and torque.
- National Instrument data acquisition device NI ENET-9206 used for the atmospheric pressure measurement.
- SEMTECH-DS Gaseous Portable Emissions Measurement System for the measurement of CO, CO2, O2, CH4, NO, and NO2 in the exhaust gases.
- SEMTECH-FID THC Analyzer used for the measurement of total hydrocarbons of tailpipe exhaust flow.
- Exhaust Flow Tube of appropriate diameter to match the vehicle exhaust system.
- Weather Probe, for the measurement of ambient conditions.

The research team calibrated the SEMTECH-DS unit and Exhaust Flow Meter to verify that they met the linearity requirements of CFR 40 Part 1065 Subpart D. In addition, the SEMTECH-DS unit underwent standard preventive maintenance procedures including leak checks and filter changes. Table 5 contains a list of gas concentrations used to calibrate the measuring instruments.

Table 5: Gases Used to Calibrate Test InstrumentsCalibration Gases Used in Tests

Bottle	Listed Concentrations
CO ₂ , CO, NO, Propane	13.3% CO_2, $1278~\mathrm{ppm}$ CO, $1736~\mathrm{ppm}$ NO,
	253 ppm Propane
Methane	9500 ppm Methane
NO_2	252 ppm NO_2

Source: Ohio State University Center for Automotive Research

The SEMTECH-DS was calibrated using NIST traceable gases standards each day before and after the test routes were performed. Zero calibrations were performed using ambient air as allowed under EPA heavy-duty in-use (HDIU) testing rules.

The emissions results were converted into gallons per mile using the conversion procedures and calculations detailed by Horiba. Fuel economy can then be derived with the carbon balance technique using the procedures outlined by the EPA in section 600.113-93. This data was calculated and provided to us for analysis by Sensors.11

The following is a detailed summary and comparison of the test data prepared by Parker from the CAR testing results¹²:

Ohio State University Emissions Testing

To explore the potential for reducing the fuel consumption and emissions of heavy-duty trucks using hydraulic hybrid technology, The Ohio State University College of Engineering's Center for Automotive Research conducted emissions testing on CNG, conventional diesel, diesel hybrid and CNG hybrid refuse trucks equipped with the RunWise technology.

The evaluations were designed to compare fuel economy and emissions, and were conducted in three separate cycles:

- Low speed based on a rear-loading refuse truck serving a densely populated neighborhood (below 20 mph).
- High speed based on a rear-loading truck traveling from a route to a transfer station (above 20 mph).
- Standard speed from a West Virginia University study (a special route cycle developed to compare performance).

¹¹ Jones et al, 2013, p8-11.

¹² Parker, 2013, p3.

The testing was carried out between December 2012 and September 2013 to determine the fuel economy, CO2 emissions, hydrocarbon emissions, carbon monoxide (CO) and oxides of nitrogen (NOx) emissions. The low speed comparison for fuel economy and CO2 emissions clearly demonstrated the benefits of the trucks using the RunWise drivetrain. The diesel hybrid achieved a low speed fuel economy of 1.3 MPG, more than double that of the CNG truck and 49 percent higher than the standard diesel. The diesel hybrid truck also produced just 7,800 grams of CO2 per mile, a reduction of over 30 percent compared to the diesel configuration. Additionally, the CNG hybrid demonstrated significant reductions over the CNG baseline, 37 percent reduction of CO2 emitted per mile.

The hybrid trucks, while typically regarded for operational benefits at low speeds, also fared well in the high speed tests. The diesel hybrid truck achieved 4.32 MPG in the high speed fuel economy test, marginally higher than the 3.78 MPG for diesel. High speed CO2 emissions were lowest with the CNG hybrid truck, followed closely by the CNG baseline at 2,035 grams per mile.13

The following data tables review this data in more detail in terms of the high and low speed cycles and the comparison of the fuel economy in terms of MPG, and the emissions in terms of g/mi:

Low opeed Oyole								
	mpg	g/mi						
	Fuel							
	Economy	CO2	CO	kNOx	THC			
Diesel	0.88	11,007	14.01	3.80	0			
Diesel	1.31	7,800	7.25	2.29	0.13			
CNG	0.61	12,733	61.23*	3.25*	30.06*			
CNG Hybrid	0.94	8,025	18.6	1.00	3.7			

Table 6: Low Speed Cycle Test Results

*Baseline CNG vehicle does not have aftertreatment catalyst.

Source: Parker, 2013, p3

13 Parker, 2013.

nigh Speed Cycle							
	mpg	g/mi					
	Fuel Economy	CO₂	со	kNOx	тнс		
Diesel	3.78	2,689	1.16	2.13	0.06		
Diesel Hybrid	4.32	2,352	1.6	2.29	0.01		
CNG	3.8	2,035	27.75*	0.29*	4.27*		
CNG Hybrid	4.06	1,928	8.33	0.82	0.11		

Table 7: High Speed Cycle Test Results High Speed Cycle

*Baseline CNG vehicle does not have aftertreatment catalyst.

Source: Parker, Center for Automotive Research

Parker Hannifin Parcel Delivery Vehicles

Working with the team at NREL, Parker & NREL performed baseline and comparative testing on similar Parcel Delivery vehicles achieving similar results worth noting herein (this testing was performed outside of the report at no expenses to the CEC) on dynamometer systems, the following is a background detailing the setup (Lammert 2014):

DUTY-CYCLE ANALYSIS and TEST CYCLE SELECTION

GPS and J1939 Vehicle Data Logging

Isaac Instruments DRU900/908 data logging devices with 5 Hz Global Positioning System (GPS) antennas and J1939 CAN bus connections were deployed to the UPS Baltimore fleet in addition to a month of raw telematics data provided by Parker Hannifin from systems on their hybrid vehicles. In total, 484 vehicle days of hybrid operation on 20 vans were documented. The GPS and J1939 channels were recording at a 1-Hz rate. J1939 CAN bus channels included wheel-based vehicle speed, engine speed, and engine fuel rate among others (see Appendix Table A1 for a complete list). These same devices and channel settings (minus GPS) were used during laboratory dynamometer testing to capture vehicle systems activity during the test runs.

DRIVE[™] Analysis

Filtration and analysis of the in-use field data collected as part of the study were performed using NREL's Drive-Cycle Rapid Investigation, Visualization, and Evaluation (DRIVE[™]) analysis tool [5,6]. Employing NREL's DRIVE analysis tool, researchers were able to ensure data quality by analyzing daily vehicle operation via a list of approximately 150 unique drive cycle metrics. The 150 drive cycle metrics calculated as part of the analysis ranged from high level route descriptors such as average driving speed (mph) and stops per mile, down to vehicle energy level metrics such as kinetic power density consumed (W/kg) and kinetic intensity, all of which were calculated using different variations of the fundamental road load equation [7]. When performing the road load calculations, it was assumed, due to a lack of reliable elevation data, that the vehicle differential elevation component was negligible as were the effects of road grade.

Laboratory Standard Test Cycle Selection

When selecting standard test cycles for lab testing purposes, a multivariate least squares method was employed in an effort to select standard cycles most reflective of the aggregate group in-use data. By performing a comparison of drive cycle metrics such as average driving speed, stops per mile, and others, a highly representative set of test cycles was chosen representing driving conditions displaying the least, average, and greatest hybrid advantage. The corresponding cycles chosen in order of least to greatest advantage were the California Air Resources Board Heavy Heavy-Duty Diesel Truck (HHDDT), CSHVC, and New York City (NY) Comp.

DRIVE[™] Custom Test Cycle Generation

DRIVE employs a deterministic multivariate hierarchical clustering method to generate representative drive cycles from source data. Starting with source drive cycles, the tool begins the process of generating representative cycles of specified duration by first analyzing the composite of each input drive cycle concatenated into a single "super" cycle. In generating a composite this way, time-based weighting is achieved whereby the duration of each source cycle adjusts the underlying metrics of the super cycle based on the cycle duration, as opposed to the common approach of non-weighted averages computed from of a set of cycle metrics representing each source cycle which can disproportionally weigh the metrics associated with short duration cycles. Once the "super" cycle has been characterized over more than 170 drive cycle metrics, the tool then decomposes the cycle into its component microtrips which are individually analyzed over the same set of operational metrics. This set of statistics include well known metrics such as average driving speed, stops per mile, and zero speed time as a percentage of cycle operation, as well as specialized metrics such as kinetic intensity, aerodynamic speed, and characteristic acceleration which are used to characterize energy consumption [8]. Having been characterized, the individual microtrips undergo an iterative multivariate kmeans clustering process in which the microtrips are grouped into clusters and ranked based on a set of performance metrics. Upon ranking, the ideal microtrip from each cluster is selected and concatenated to form a representative cycle. This clustering process is iterated over the number of clusters chosen for the data as well as the performance metrics chosen for ranking, based on a maximum number of clusters which is the calculated as the product of the desired representative cycle duration, the number of stops per mile for the "super" cycle, and the average speed over the "super" cycle. As a final step in the generation of a representative drive cycle, zero speed time is either added or removed from the final drive cycle output to match the percentage found in the original data "super" cycle.

Laboratory Chassis Dynamometer Testing Procedures

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

To assure the accuracy and consistency of road load simulation, the dynamometer is subjected to various procedures and checks. From a practical perspective, the daily testing routine

consists of the following steps. In the morning, the vehicle is lifted off the rollers and the dynamometer is subjected to its warm-up procedure until the parasitic losses stabilize. Then the unloaded coastdown procedure is used to verify that the parasitic losses did not change from the previous testing due to component failure and that the load cell calibration has not drifted. Following this verification, the vehicle is dropped on the rollers and driven for roughly 20 minutes to warm up. After the warm-up, a conditioning test run is performed to stabilize the vehicle's temperature for a given test cycle. At this point, the system is ready to either set or verify the correct road load simulation through a loaded coastdown procedure. The following test runs are considered usable in terms of data validity provided the road load simulation proves consistent. This is verified after each test to ensure that changing conditions (test facility temperature) are not affecting vehicle loading. To maximize consistency, the soak period between one test end and the following test start is kept at 20 minutes.

Emissions Measurement

The emissions measurement system is based on the recommendations in Code of Federal Regulations Section 40, Part 86, Subpart N. The system consists of a full flow dilution tunnel with a constant volume sampling system for mass flow measurement. The tunnel flow rate is measured and controlled using critical flow venturis. The dilution and engine combustion air is supplied by an air handling unit that maintains the desired air temperature and humidity.

The diluted engine exhaust was sampled for gravimetric particulate matter analysis and by a Horiba MEXA 7100 series system for gaseous analysis, including total hydrocarbons, oxides of nitrogen, carbon monoxide (CO), and CO2. The gas analytical system was verified prior to beginning the testing period, including linearization checks and oxides of nitrogen efficiency test. On a daily basis, the analyzers were zero and span calibrated, and each test was bracketed by zero and span response readings used for corrections. The emissions measurement data were then reduced to distance specific mass results using the Code of Federal Regulations-recommended calculations, including humidity, dry to wet, zero, span, and background corrections.

Fuel Consumption Measurement

The fuel consumption measurement in this project relied primarily on a gravimetric approach. The engine fuel supply and return lines were connected to a fuel container placed on a scale. The scale mass measurements were recorded in a real time along with all the test data. The difference between the beginning and the end test mass measurement indicated the mass of fuel consumed during the test. Prior to testing, the scale calibration was verified with a known calibration weight. A Sartorius Midrics MAPP1U-60ED-L was used for this test. The fuel consumption measurement was also backed up using the carbon balance method back-calculating the mass of fuel consumed from measurement of exhaust emission constituents.

State-of-Charge Considerations

SAE Recommended Practice J2711 is a recommended protocol for measuring fuel economy and emissions of hybrid-electric and conventional heavy-duty vehicles and was used for this project. The recommended practice describes a state-of-charge correction for chargesustaining hybrid electric vehicles. This methodology was used while measuring the pressure change in the high pressure hydraulic accumulator along with a pressure to energy conversion provided by Parker Hannifin. All the tests in this program involving the hydraulic hybrid vehicle resulted in negligible net energy changes and thus did not require correction as per SAE J2711.

For the Parcel Delivery vehicles, Table 8 shows the baseline and advanced series hybrid test vehicles tested by NREL14 for both diesel and gasoline.

Van Specification	Conventional	Conventional	Hydraulic
	Diesel Van	Gasoline Van	Hybrid Van
Chassis Manufacturer	Freightliner	Workhorse	Freightliner
		W62	
Van manufacturer	<u>Utilimaster</u>	Morgan Olson	Morgan Olson
Van model	NA	P100	P10HH
Van model year	2011	2012	2010
Engine manufacturer	Cummins	GM	Cummins
Engine model	ISB	LQ4	ISB
Engine Power Rating	200 HP	299 HP	280HP
Engine Displacement	6.7L	6.0L	6.7L
Engine model year	2012	2012	2012
Emissions equipment	DPF, SCR	3 way catalyst	DPF, SCR
Transmission	Allison	Automatic	Parker
	Automatic		Hannifin IVT
Retarder/regenerative	None	None	Regenerative
braking			Braking
Air conditioning type	None	None	None
Gross vehicle weight	23,000 lbs	19,500 lbs	23,000 <u>lbs</u>

Table 8: NREL Test Results for Parcel Delivery Vehicles

Source: NREL - Lammert

Table 9 shows the specifications for the Parker Hybrid as tested by NREL.15

14 Lammert, 2014.

15 *Ibid*.

Category	Hybrid System Description
Manufacturer/integrator	Parker Hannifin Corporation
Transmission	Parker IVT
Drive mode max power	200 <u>hp</u>
Brake mode max power	200 <u>hp</u>
	22 gallon accumulator
Energy storage	3500-4000 psi nominal
	5400 psi max pressure

Table 9: NREL Test Results for the Parker Hannifin Hybrid Drivetrain

Source: NREL - Lammert

Figure 25: Hybrid Duty Cycle Breakdown by Percentage of Miles Traveled DELIVERY VAN IN USE DUTY CYCLE RESULTS

The hybrids averaged 56 miles per day with an average driving speed of 18 mph. Figure 1 shows the average distance (as a percentage) that vans drove at different vehicle speeds.

- The hybrid vans drove 20% of their miles below 15 mph, where the engine is transmitting more than 50% of its
 power hydraulically
- The hybrid vans drove 35% of their miles between 15 mph and 30 mph, where the engine is transmitting less than 50% of its power hydraulically
- The hybrid vans drove 45% of their miles above 30 mph, where the engine is transmitting over 90% of its power mechanically, and there is less opportunity for savings from a hybrid system



Figure 1. Hybrid Duty Cycle Breakdown by Percent Miles Traveled

Table 3 below shows some drive cycle statistics from the Baltimore Vans. These statistics and those above indicate that the Baltimore HHVs were not operating on ideal routes for the hybrid advantage to be maximized. A denser urban assignment would provide more opportunities for the hydraulic hybrids to capture braking energy, save fuel, and potentially reduce emissions.

Cycle Statistics	Baltimore HHV Average	
Distance traveled (miles)	56.0	
Average speed over cycle (mph)	12.1	
Average driving speed (mph)	18.2	
Maximum speed (mph)	64.0	
Average acceleration (ft/s ²)	1.5	
Average deceleration (ft/s ²)	-1.8	
Number of acceleration events	661.4	
Number of acceleration events per mile	12.1	
Number of deceleration events	661.4	
Number of deceleration events per mile	12.1	
Number of stops	203	
Number of stops per mile	3.9	
Kinetic Intensity (1/mile)	1.5	

Table 3, Drive Cycle Statistics from Baltimore Vans

Source: NREL

Based on the specifications described in Tables 8 and 9, NREL leveraged standard practice for GPS and J1939 vehicle data logging, DRIVE Analysis, standard and custom test cycle selection, dynamometer testing, emissions and fuel measurements. In addition to the standard tests utilized for evaluation, (a Baltimore Custom cycle was developed based on real world data), Figure 26 highlights the daily vehicle performance in Baltimore and the distribution of speed vs miles travelled in the evaluation to develop the custom cycle.

Table 10 shows test results for the various vehicle routes that were identified and tested.

Gravimetric Fuel Economy		CSHVC	CARB	Baltimore
	Comp		HHDDT	Custom
Conventional Gasoline MPGe (diesel equiv gal)	6.94	9.43	11.03	7.86
Diesel Conventional MPG	7.15	9.45	11.44	8.52
Diesel HHV MPG	10.84	12.82	11.36	10.18
Conv Diesel MPG Advantage over Conv Gas	3%	0%	4%	8%
HHV MPG Advantage over Conv Diesel	52%	36%	-1%	19%
HHV MPG Advantage over Conv Gas	56%	36%	3%	30%

Table 10: Results from NREL Test Routes

Source: Lammert - NREL

Based on NREL's test results from Table 10, and in the Summary conclusion notes below (Figure 26), the Parker Hydraulic Hybrid Advanced Series unit does display significant advantages for high start and stop operations. Also, in those over the road, high highway miles, the improvement is lower, showing only a three percent improvement.

Figure 26: Summary Conclusions from NREL Testing SUMMARY/CONCLUSIONS

The Parker Hannifin hydraulic hybrids consistently are demonstrating a fuel economy advantage. Laboratory testing demonstrated:

- Hydraulic Hybrid demonstrated 19-52% better fuel economy than conventional diesel on cycles other than the highway oriented HHDDT on which it achieved parity.
- Hydraulic Hybrid demonstrated 30-56% better fuel economy than conventional gasoline on cycles other than the highway oriented HHDDT on which it was 3% better.
- NREL's custom Baltimore cycle, statistically created from pieces of collected field data using DRIVE, most accurately matched observed in-field fuel economy
 - Both conventional vans also saw lower fuel economy on the custom cycle
 - CSHVC over predicted the fuel economy for the HHV

Additionally field usage data indicate:

 Hydraulic Hybrid could show higher percent improvement if deployed on more kinetically intense routes more similar to the NY Comp.

Source: Lammert - NREL

Field Testing

Parker Hannifin Refuse Vehicles

Data Acquisition

During the testing period, the vehicles were all equipped with third party data acquisition systems to capture key performance indicators off the J1939 bus. These data acquisition systems and data were collected at no cost to the CEC. This included eight fielded vehicles under this report in the following areas/customers: Santa Cruz (5 vehicles), Marin Sanitation (1 vehicle), Recology (1 vehicle), and City of Redding (1 vehicle). Additionally, data from similar vehicles and regions was shared during the waiting period for commissioning in the following areas: Austin, TX (1 vehicle), Manteca, CA (1 vehicle), Sacramento, CA (1 vehicle), Miami Dade, FL (1 vehicle).

During the test period, the following data was collected and documented:

- Driving Distance (miles) Actual Miles Driven during period
- Collection Distance Percentage This represents low vehicle speed below 10 mph, or approximate amount of time in collection mode. Also if there is a zero (0), there was an arm operation count either not installed or not functioning
- Fuel Consumption (Gallons) Fuel consumed during period
- Fuel Economy (miles per gallon) Reporting an average of 35 50 percent lower fuel consumption vs comparative baseline vehicles previously in field
- Fuel Economy (gallons per hour) Fuel Economy during period
- Engine Run Time (hours) Run time during period
- Average Speed (miles per hour) Average speed during period
- Total Engine Time (hours) Total engine hours during period
- Total Distance (miles total on vehicle) Total distance on vehicle
- Arm Count Operations (count) Total number of arm cycling during period. Also if there is a zero (0), there was an arm operation count either not installed or not functioning

Based on the above, following is a summary of the collected data:

- Driving Distance (miles)
 - Total 60,852 miles
 - Average 845 miles
- Collection Distance Percentage
 - Average 28 percent of the time in collection mode
- Fuel Consumption (Gallons)
 - Total 21,198 gallons
 - Average 294 gallons

- High 1.1 gallons (this would represent a month where the vehicles were not running or being commissioned or tested)
- Low 954 gallons
- Fuel Economy (miles per gallon)
 - Average 2.79 MPG
 - High 4.48 MPG
 - Low 0.33 MPG (this would represent a month where the vehicles were not running or being commissioned or tested)
- Fuel Economy (gallons per hour)
 - Average 2.77 gph
 - High 5.4 gph (86% of the sample size were below 3 gph, this represents an outlier)
 - Low 1.6 gph
- Engine Run Time (hours) per vehicle
 - Total 8,028 hours
 - Average 111 hours
 - High 463.4 hours
 - Low 0.55 hours (this would represent a month where the vehicles were not running or being commissioned or tested)
- Average Speed (miles per hour)
 - Average 7.68 mph
 - High 24.36 mph (93 percent of the sample size was below 10 mph. This represents an outlier)
 - Low 0.53 mph

The graph in Figure 28 represents the data acquired during the test period. It shows a cluster of data in the 2.0 - 3.0 gph for the Average Vehicle Fuel Economy Range. This is below the baseline range of 4.25 gph recorded in the test area and across the country, representing an average reduction of 42 percent. There are a few outliers in the data set, which is to be expected when there are vehicles in service and others just being started up and commissioned. However, 86 percent of the data is below 3 gph, indicating a good sample set and strong results.



Figure 27: Fuel Economy Results Based on Vehicle Speed Vehicle Average Fuel Economy Based on Average Vehicle Speed

Source: NREL

Figure 29 is a graph of the average fuel economy per month in miles per gallon. These results are based on an average speed of 7.6 mph, with 93 percent of the data set below 10 mph. When compared with the results of the CAR dynamometer testing, this shows that the average vehicle fuel economy ranges from 2.75 MPG to 3.00 MPG, whereas the low speed CAR data for the baseline vehicle was in the range of 0.88 MPG. This indicates a strong increase in performance.



Figure 28: Monthly Vehicle Fuel Economy Vehicle Fuel Economy by Month

Source: NREL

Figure 30 displays a graph of the average fuel economy based on an vehicle speed of 7.6 mph. Ninety three percent (93) of the data represent results for speeds below 10 mph. This data is commensurate with the monthly average data; it has a clustered range for speeds between 5 mph and 10 mph with a fuel economy range of 2.25 MPG to 3.5 MPG. Total average is 2.8 MPG. Compared with the CAR low speed dynamometer test results of 0.88 MPG, this demonstrates a strong increase in performance.



Figure 29: Fuel Economy Results Based On Average Vehicle Speeds. Vehicle Average Fuel Economy Based on Average Vehicle Speed

Source: NREL

Parker Hannifin Parcel Delivery Vehicles

Working with the CALSTART team (at no expense to the CEC), improvements in fuel economy were identified in similar smaller Class 6 Delivery vehicles from UPS, FedEx and Purolator.

Figure 30: Photos of Class 6 Package Delivery Vehicles Used for CALSTART Testing



Source: CALSTART

With funding from the U.S. Department of Energy, CALSTART and its project partners assessed the performance, reliability, maintainability and fleet acceptance of three preproduction Class 6 hydraulic hybrid parcel delivery vehicles using information and data from inuse data collection and on-road testing. The test vehicles were provided by FedEx Ground, Purolator and UPS. The results 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 and provides insights on how the technology can be improved.¹⁶

The testing conducted with these vehicles showed strong field performance and up to 50 percent improvement in fuel economy.

	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.

Figure 31: Hydraulic Hybrid Vehicle Field Test Results for Fuel Economy Table ES-4: Summary of HHV performance on selected parcel delivery routes

Source: J Gallo, 2014

Testing was also conducted for on-road emissions and fuel economy with similar improvements during high start & stop operations. (Note that Figures 32 and 33 were taken from the original source report and inserted into this CEC Report as pdf charts).

¹⁶ Gallo, J. *Hydraulic Hybrid Parcel Delivery Truck Deployment, Testing & Demonstration*. Paper presented as a final report out to DOE Contract Number DE-FC26-06NT42791. 2014.

Figure 32: Hydraulic Hybrid Vehicle Field Test Results for Criteria Emissions

On-road Emissions Testing

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-5 below summarizes the results of the on-road emissions testing.

	200	8 FCCC MT-55 Di	sel 2012 FCCC MT-55 HHV			HV
Operating Area	Fuel Economy	CO ₂ Emissions	NO. Emissions	Fuel Economy	CO ₂ Emissions	NO. 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

Table ES-5: On-road emissions testing summary results

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 CO₂ per mile and 30.4% less NO₂ 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 CO₂ per mile and 24.4% less NQ₄ 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 NO₄ 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 NO₄ conversion efficiency of the SCR system at cold start and are most likely not attributable to the HHV system.

Source: J Gallo, 2014

CHAPTER 3: Advancements and Assessment

Goals of the Agreement

The goal of this agreement was to demonstrate the significant technical, financial, fuel economy and emissions reduction benefits of hybrid hydraulics when used in heavy-duty vehicles.

Fuel economy increased 49 percent over the diesel baseline and CO2 emissions decreased by 30 percent on a per mile basis. This represents a substantial improvement over baseline technologies as approximately 80 percent of a refuse vehicle's time is spent in low speed operation. Field-testing data showed similar improvements in performance with an average fuel economy of 2.8 MPG, which represents a substantial fuel efficiency benefit when compared to the low speed baseline of 0.88 MPG. This result should be considered a positive success in highlighting the improvements in fuel economy, and reduction in emissions. This represents a positive improvement for vocational vehicles deployed in California.

Objectives of the Agreement

The objectives of this Agreement are to demonstrate and document potential improvements in fuel economy, emissions reduction, improved reliability, driver acceptance and reduced maintenance.

As discussed in preceding chapters, the dynamometer and field test data represent substantial results in fuel economy improvement and reduced emissions. Parker Hannifin's data to date for 75 vehicles placed in service shows a 97 percent uptime rate and average fuel savings of 43 percent. Driver acceptance is positive. Parker Hannifin found that driver training is key to successful vehicle deployment because it allows operators time to ask questions, test drive the vehicles, and get a feel for the operation. The operators commented positively on the smooth acceleration and braking, which reduces driver fatigue.

Anecdotally, fleet managers reported increases in productivity when the hydraulic hybrid vehicles are placed in service. The benefit of having stored energy on the vehicle in the accumulators is the capacity of the vehicle to have full acceleration capability from the time the vehicle is started. This represents the opportunity to increase productivity based on a combination of quicker launch, smoother shifting, and braking.

The fleet managers and test team observed significant reductions in brake wear and reported that the vehicles used in the field trials have not required brake servicing. It is expected that this will result in only one brake job in the life of the vehicles. This is direct result of the use of regenerative braking and the use of the hydraulic hybrid energy recovery circuit to accelerate the vehicle.

The CALSTART report also reviewed the wear of the tires on both the front and rear of the vehicle. The data was inconclusive and further investigation is needed.

CHAPTER 4: Observations, Conclusions and Further Investigation

Results

Test results for the Hydraulic Hybrid drivetrains for the refuse trucks and parcel delivery trucks represent a substantial improvement for vocational vehicles in the area of improved fuel economy and reduced emissions. Low speed testing, which is the high start and stop duty cycle, produced a 49 percent increase in fuel economy over the diesel baseline and a 30 percent decrease in CO2 emissions. This represents a substantial improvement over baseline technologies because approximately 80 percent of a refuse truck's time is spent in low speed operation. Field test data showed similar improvements in performance with an average fuel economy of 2.8 MPG, which is a substantial improvement over the baseline dynamometer result 0.88 MPG. The corresponding decrease in carbon and criteria emissions from reduced fuel consumption is substantial.

Similar results were observed in the parcel delivery vehicles. Third party test results showed reduced fuel consumption of 19 to 52 percent. Parker Hannifin's field test results showed reduced fuel consumption ranging from 35 to 50 percent from the diesel baseline, reduced CO2 emissions that were 17.4 percent lower per mile, and reduced NOx emissions that were 30.4 percent lower per mile.

Opportunities for Further Investigation

As discussed in Chapter 3, there were positive improvements in fuel economy and reduced emissions. Limited test time hindered full assessments of vehicle reliability, driver acceptance, and reduced maintenance. Continued review of data in these areas would allow for expanded research and verification of the preliminary results. Gains in fuel economy and emissions were observed with the hybrid hydraulic diesel over the baseline CNG and CNG hydraulic hybrid. Future investigations could yield interesting results for performance, emissions, and cost effectiveness. Future investigations of shuttle and transport buses with the hydraulic hybrid drivetrains could demonstrate positive benefits for inner city applications. However, careful study of cost and performance parameters would be needed to insure commercial viability.

GLOSSARY

CALSTART - A nonprofit organization working nationally and internationally with businesses and governments to develop clean, efficient transportation solutions. CALSTART is a network that connects companies and government agencies and helps them do their jobs better. CALSTART is located in Pasadena, California.17

CARBON DIOXIDE (CO2) - A colorless, odorless, non-poisonous gas that is a normal part of the air. Carbon dioxide is exhaled by humans and animals and is absorbed by green growing things and by the sea. CO2 is the greenhouse gas whose concentration is being most affected directly by human activities. CO2 also serves as the reference to compare all other greenhouse gases (see carbon dioxide equivalent). The major source of CO2 emissions is fossil fuel combustion. CO2 emissions are also a product of forest clearing, biomass burning, and non-energy production processes such as cement production. Atmospheric concentrations of CO2 have been increasing at a rate of about 0.5% per year and are now about 30% above preindustrial levels.

CARBON MONOXIDE (CO) - A colorless, odorless gas resulting from the incomplete combustion of hydrocarbon fuels. CO interferes with the blood's ability to carry oxygen to the body's tissues and results in numerous adverse health effects. Over 80 percent of the CO emitted in urban areas is contributed by motor vehicles. CO is a criteria air pollutant.

CENTER FOR AUTOMOTIVE RESEARCH (CAR) - The preeminent research center in sustainable and safe mobility in the United States and an interdisciplinary research center in The Ohio State University's College of Engineering. With a concentration on preparing the next generation of automotive leaders, CAR is recognized for interdisciplinary emphasis on systems engineering, advanced and unique experimental facilities, collaboration on advanced product development projects with industry, and a balance of government and privately sponsored research. CAR's research focuses on energy, safety and the environment and it offers state-ofthe-art facilities for students, faculty, research staff and industry partners.¹⁸

COMPRESSED NATURAL GAS (CNG) - Natural gas that has been compressed under high pressure, typically between 2,000 and 3,600 pounds per square inch, held in a container. The gas expands when released for use as a fuel.

HYDRAULIC HYBRID VEHICLE (HHV) - In a series hydraulic hybrid system, the conventional transmission and driveline are replaced by the hydraulic hybrid powertrain, and energy is transferred from the engine to the drive wheels through fluid power. The vehicle uses hydraulic pump/motors and hydraulic storage tanks to recover and store energy, similar to the way in which hybrid electric vehicles employ electric motors and batteries. The system is

¹⁷ CALSTART (https://calstart.org/)

¹⁸ Ohio State University Center for Automotive Research (https://car.osu.edu/about-us)

suited to vehicles that operate in stop-and-go duty cycles, including heavy-duty refuse hauling.¹⁹

KILOWATT (kW) -- One thousand (1,000) watts. A unit of measure of the amount of electricity needed to operate given equipment. On a hot summer afternoon a typical home, with central air conditioning and other equipment in use, might have a demand of four kW each hour.

MILES PER GALLON (MPG) - A measure of vehicle fuel efficiency. Miles per gallon or MPG represents "Fleet Miles per Gallon. For each subgroup or "table cell," MPG is computed as the ratio of the total number of miles traveled by all vehicles in the subgroup to the total number of gallons consumed. MPGs are assigned to each vehicle using the EPA certification files and adjusted for on-road driving.

NATIONAL RENEWABLE ENERGY LABORATORY (NREL) - The National Renewable Energy Laboratory (NREL), located in Golden, Colorado, is the United States' primary laboratory for renewable energy and energy efficiency research and development. NREL is the only Federal laboratory dedicated to the research, development, commercialization, and deployment of renewable energy and energy efficiency technologies.

OXIDES OF NITROGEN (NOx) - a chief component of air pollution that can be produced by the burning of fossil fuels. Also called nitrogen oxides.

UNITED STATES ENVIRONMENTAL PROTECTION AGENCY (U.S. EPA) - A federal agency created in 1970 to permit coordinated governmental action for protection of the environment by systematic abatement and control of pollution through integration or research, monitoring, standards setting and enforcement activities.

¹⁹ Clean Cities Guide to Alternative Fuel and Advanced Medium and Heavy-Duty Vehicles. National Renewable Energy Laboratory. DOE/GO-102013-3624. August 2013.

REFERENCES

- Gallo, J. (2014). Hydraulic Hybrid Parcel Delivery Truck Deployment, Testing & Demonstration. Paper presented as a final report out to DOE Contract Number DE-FC26-06NT42791.
- Kargul, J (2007). Hydraulic Hybrids. Retrieved March 01, 2015 from http://www.epa.gov/region9/wcc/files/meetings/2007-12-11/HHV.pdf
- Kargul, J (2012). Hydraulic Hybrids 101. Retrieved March 01, 2015 from http://www.wwcleancities.org/documents/HydraulicHybrids_EPA_Kargul.pdf
- Kargul, J (2013). Advanced Hydraulic Hybrids Delivering Real-world Savings. Presented at 2013 Green Truck Summit March 6, 2013
- Lammert, M (2014). Hydraulic Hybrid and Conventional Package Delivery Vehicles Measured Laboratory Fuel Economy on Targeted Drive Cycles. Paper presented at SAE COMVEC show in September 2014, document number 2014-01-2375. Retrieved March 01, 2015 from <u>http://www.nrel.gov/docs/fy15osti/62408.pdf</u>
- Maxwell C. (2008). Unlimited Opportunity in the World of Motion Control. Retrieved March 01, 2015 from <u>http://media.corporate-ir.net/media_files/irol/97/97464/Goldman_08.pdf</u>
- Parker (2013). The Clean Side of Garbage. Retrieved March 01, 2015 from <u>http://www.parker.com/literature/Hybrid%20Drive%20Systems%20Division/Parker%20</u> <u>RunWise_%20Emissions%20White%20Paper2013.pdf</u>
- Tomazic, D (2013). Reducing Energy and Expenses Utilizing Hydraulic Hybrid Waste Trucks Transit Buses and Delivery Vehicles. Retrieved March 01, 2015 from <u>http://www.nfpa.com/events/pdf/2013-fpsc/002-2013-11-20_hydraulic-hybrid-vehicles_chicago_rev3.pdf</u>