Parker Hannifin

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# Hybrid Hydraulic Drivetrain Demonstration

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James Howland
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Parker Hannifin Corporation

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## Abstract

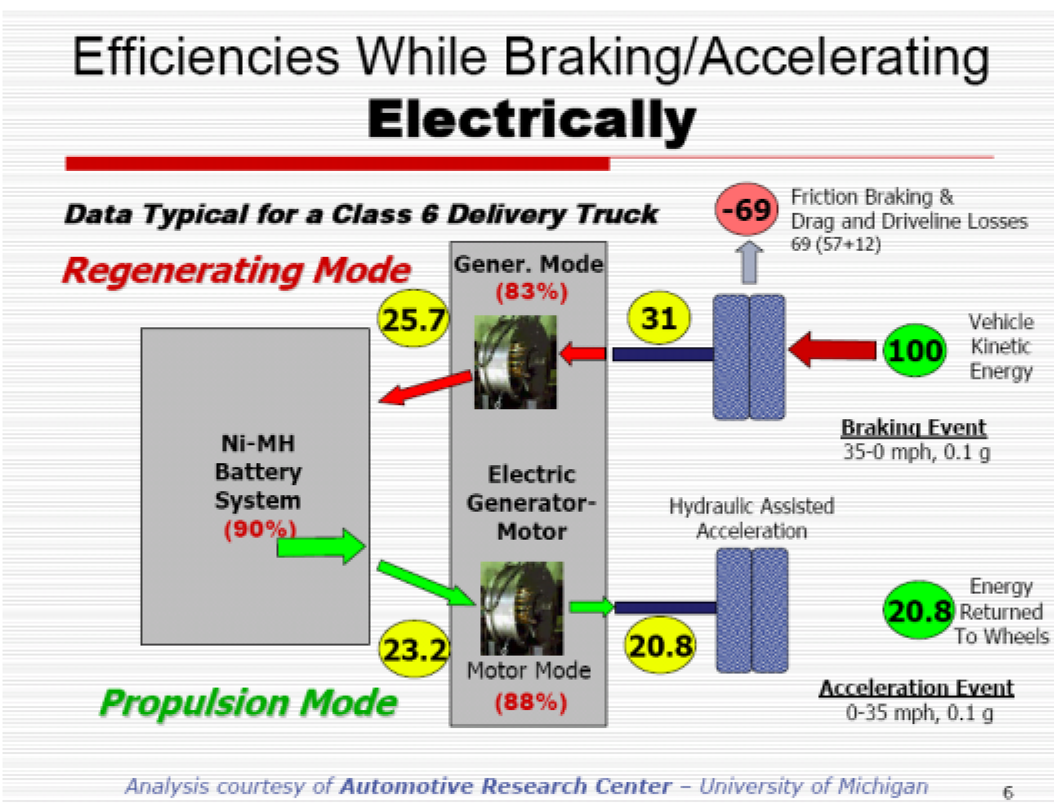
This report examines the benefits of Parker Hannifin hydraulic hybrid brake energy recovery systems used in commercial applications for vocational purposes. A detailed background on the problem statement being addressed as well as the solution set specific for parcel delivery will be provided. Objectives of the demonstration performed in high start & stop applications included opportunities in fuel usage reduction, emissions reduction, vehicle productivity, and vehicle maintenance. Completed findings during the demonstration period and parallel investigations with NREL, CALSTART, along with a literature review will be provided herein on this research area. Lastly, results identified in the study by third parties validated the savings potential in fuel reduction of on average of 19% to 52% over the baseline in terms of mpg (Lammert, 2014, p11), Parker data for parcel delivery vehicles in the field parallels this at a range of 35% - 50%, emissions reduction of 17.4% lower $CO_2$ per mile and 30.4% lower $NO_x$ per mile (Gallo, 2014, p15), with maintenance improvement in the areas of brake and starter replacement, while leaving room for further study in the area of productivity in terms of specific metrics that can be applied and studied.

## Acknowledgement

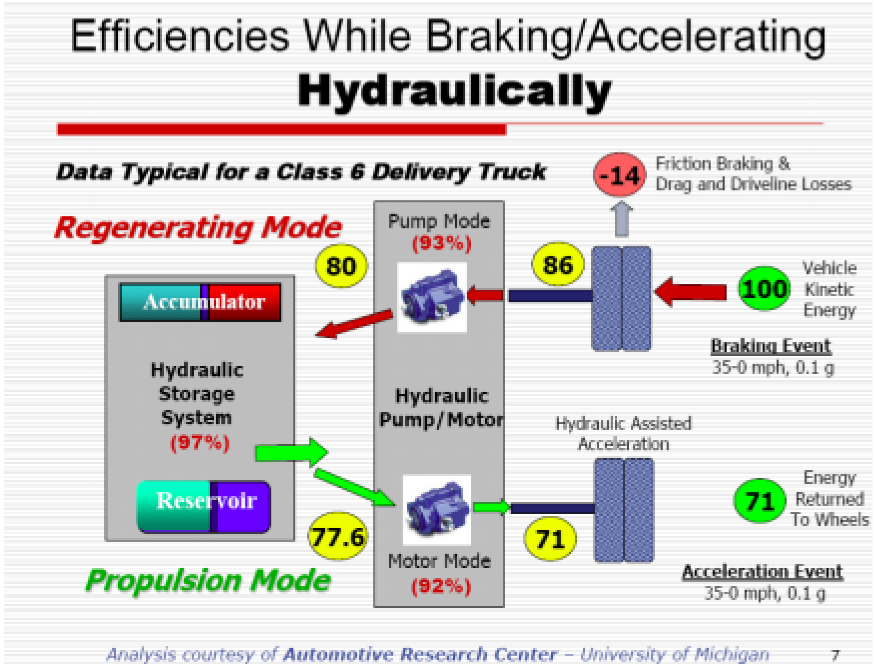
Parker would like to express thanks to the U.S. Department of Energy for supporting this project with funding for demonstration support of the hydraulic hybrid vehicles (HHV) in the field. Additional thanks to the USEPA NVFEL team in Ann Arbor Michigan, specifically the work and support from Charles Gray, and John Kargul. Key team members that were instrumental in this demonstration include the teams at Freightliner Custom Chassis Corporation (OEM Chassis Manufacturer), Morgan Olson (Body Manufacturer), and the end user customers that deployed vehicles in the field at UPS, FedEx Ground, and Purolator. Additionally, during this period key research and efforts were performed in parallel on these vehicles by US EPA & NREL & CALSTART that will be referred to herein that allowed for a more rich content report to be provided for the readers of this report. Lastly, special thanks to Parker’s Hybrid Drive Systems Division team members, based in Columbus, OH, and more specifically Prasad Venkiteswaran and James Howland for the unending support and field efforts to work with all teams involved. Their participation throughout this demonstration in the areas of technical expertise, training, and advice in many areas along with co-authoring support of this program made this a success.

## Executive Summary

The use of hydraulic hybrids for vocational applications has significant benefits in the right duty cycle and route profiles. Parker has had deployment experience with this technology since the early 1990's on refuse and bus applications. Additionally, research performed by the Automotive Research Center at the University of Michigan highlights the significant benefits and efficiencies while braking and accelerating leveraging hydraulic hybrids shows a 3+ TIMES GREATER benefit versus electric hybrids (Kargul, 2007, p13).

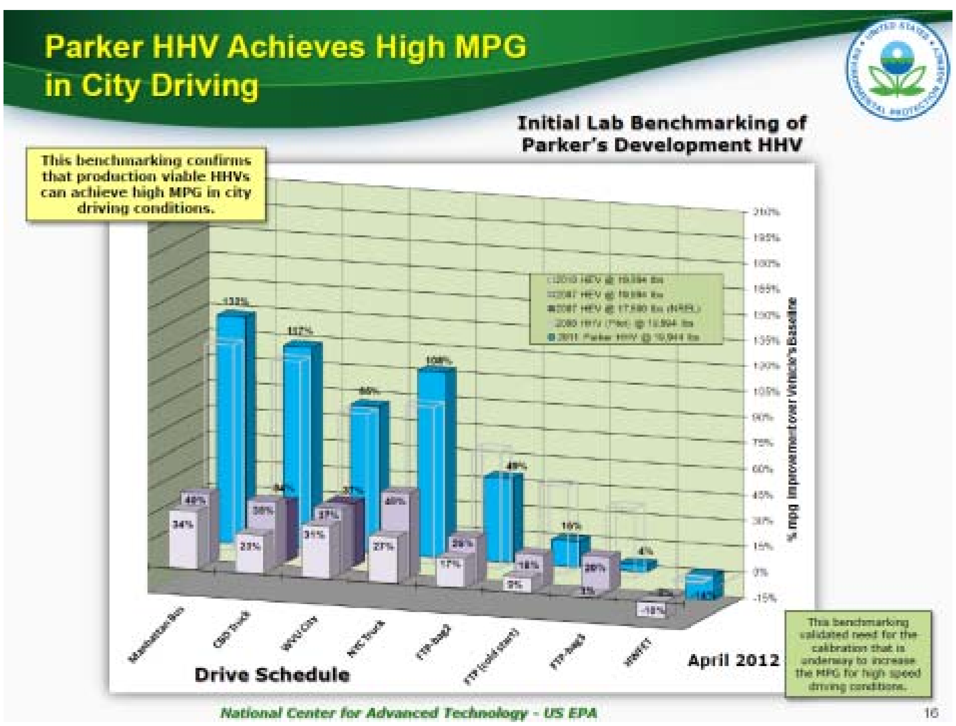



Gallo, 2014, p21



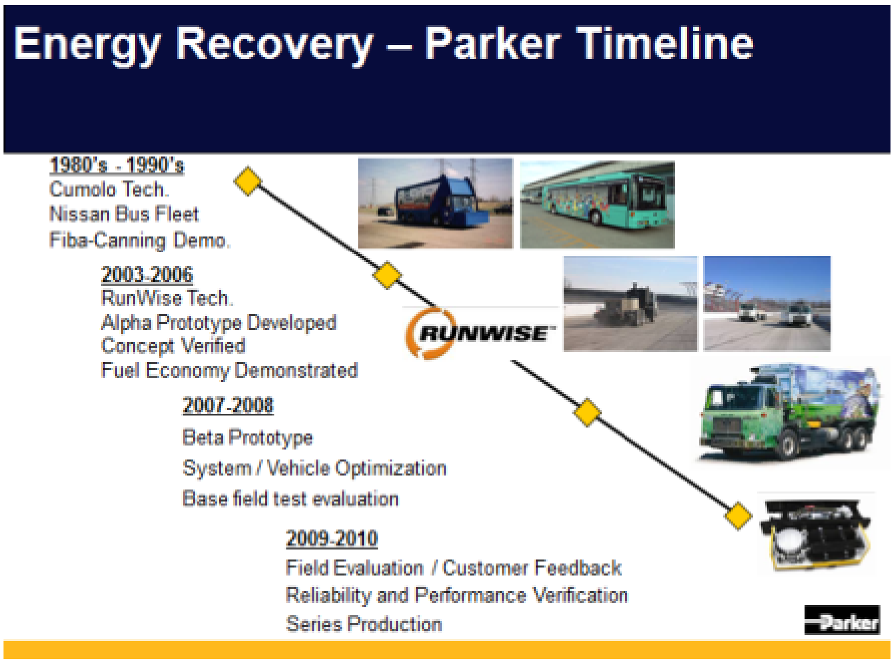

Gray, 2006, p14

These are substantial benefits that as commercialized on vocational platforms could allow for broader opportunities to pursue and deliver to the marketplace. Detailed lab benchmarking was also performed by third party, the US EPA comparing the Parker Hydraulic advanced series hybrid technology with gearbox, engine off, and engine management to hybrid electric vehicle drivetrains and the US EPA series HHV. As a result of this testing, the US EPA validated that "… benchmarking confirms that production viable HHVs can achieve high MPG in city driving conditions" (Kargul, 2013, p16). Again, when comparing test data and cycles, proper route selection is critical to the process to ensure parity and proper selection of the technology for the routes in question. Additionally, results identified in the study by other third parties validated the savings potential in fuel reduction of on average of 19% to 52% over the baseline in terms of mpg (Lammert, 2014, p11), Parker data in the field parallels this at a range of 35% - 50%, emissions reduction of 17.4% lower CO2 per mile and 30.4% lower NOx per mile (Gallo, 2014, p15), with maintenance improvement in the areas of brake and starter replacement, while leaving room for further study in the area of productivity in terms of specific metrics that can be applied and studied.



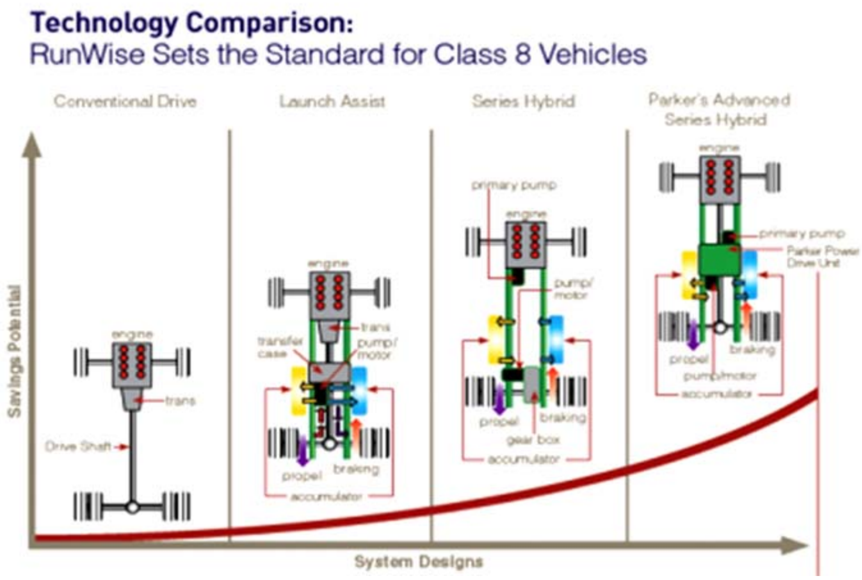

Kargul, 2013, p16

In terms of technology development Parker's early systems were parallel hydraulic hybrid applications that leveraged the existing transmission and drivetrain systems. The following is a timeline of advancements in Parker's technologies from the late 1980's to date.




With continued development improvements on specific enabling technologies and simulation capabilities enabled Parker teams to develop advancements in these hybrid platforms.


Parker's engineering team's developed and launched advanced series hydraulic hybrid drivetrain systems that yielded better brake energy recovery capabilities versus the initial parallel, and series systems. As you can see in the summary table, performance is always based on routes; however technology can be viewed as good, better, best in terms of the advancements made.




## Summary of Hydraulic Hybrids

| | Parallel | Series | Adv Series |
|---|---|---|---|
| **Brake Recovery** | ✓ | ✓ | ✓ |
| **Engine Management** | | ✓ | ✓ |
| **High Speed Efficiency** | | | ✓ |
| **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

These advanced series systems were installed on FCCC chassis' with Morgan Olson bodies deployed into service revenue generating routes by UPS, FedEx Ground, and Purolator in this study:


As documented in Parker’s Statement of Project Objectives (SOPO) for this demonstration, the activities of this report and project with funding from the US Department of Energy were to support the demonstration of in-use benefits of hydraulic hybrid drive technology as applied to the commercial vehicles with high start and stop duty cycles.  More specifically:

1) Fuel Usage Reduction – demonstrated fuel economy improvement

2) Emissions Reduction – corresponding reduction in emissions associated with reduced fuel consumption

3) Vehicle Productivity – greater improvement in acceleration & performance

4) Vehicle Maintenance – greatly reduced brake wear & improved electric starter life

In addition Parker’s team supporting these vehicles in the field with success, third party evaluation of these specific vehicles were performed by CALSTART and NREL further supporting the content of this report with unbiased testing in field and on dynamometer.

## Data Acquisition

During the testing period, the vehicles were all equip with data acquisition systems to capture key performance indicators off the J1939 bus. These data acquisition systems and data were collected at no cost to this program. This included 48 fielded vehicles that were supported as part of this demonstration, UPS (40), FedEx Ground (5), CALSTART (3 – UPS(1), FedEx Ground (1), and Purolator (1)). During the demonstration period that the vehicles were on road, July 01, 2011 thru March 31, 2014, the vehicles logged a total of 678,543 miles. A table of the vehicle data is shown below highlighting the Vehicle Identification Number (VIN), date that the vehicle was placed into service (this was after the vehicle build, body build onto the chassis, vehicle shakedown, customer inspection, plating, and final preparation for field service), Vehicle location that it was placed into service, current status, vehicle owner, and total miles during the period. It should be noted that results identified in the study by other third parties validated the savings potential in fuel reduction of on average of 19% to 52% over the baseline in terms of mpg (Lammert, 2014, p11), Parker data in the field parallels this at a range of 35% - 50%. This means that when you review the Fuel economy average data in the table below, you need to recognize that comparative review by

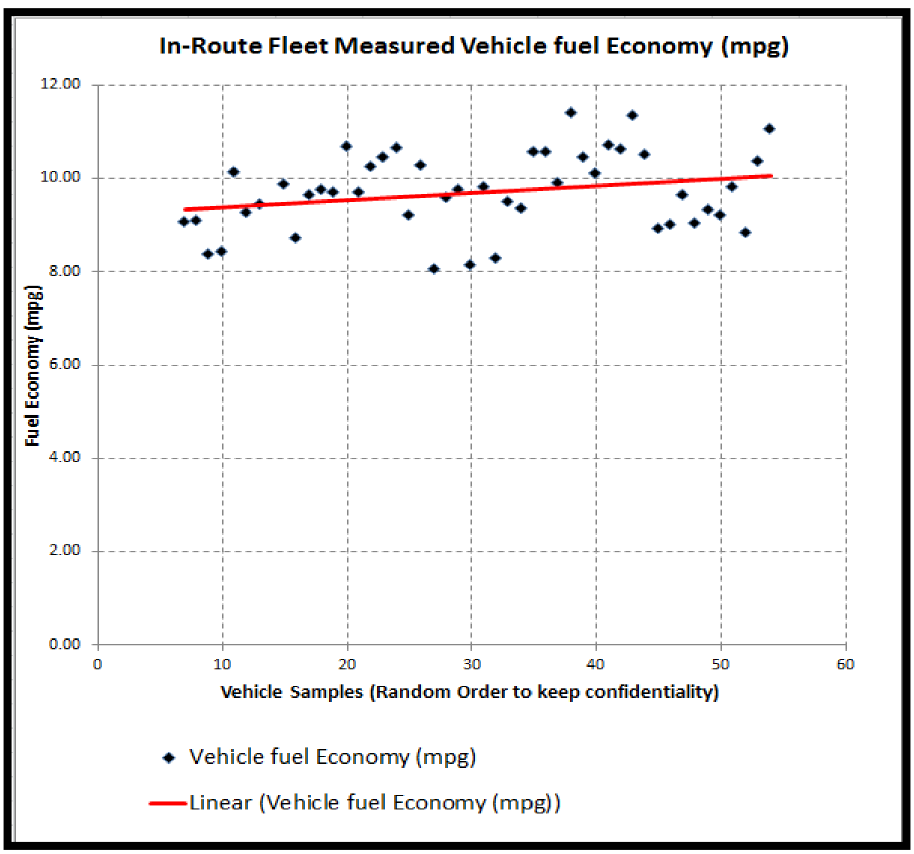
Parker teams of field data documented that these routes were improved approximately 35% - 50% in terms of fuel economy as a result of deploying these systems:

| US Department of Energy Tracking Chart | | | | | | |
|---|---|---|---|---|---|---|
| Period | July 01, 2011 thru March 31, 2014 | | | | | |
| Completed by: | James Howland and Prasad Venkiteswaran | | | | | |
| # | Vehicle ID / last 4 of vin | First Date of Service | Vehicle Location | Vehicle Status | Vehicle Customer | Total Miles during period |
| 1 | PDV01 | 7/1/2011 | Columbus, OH | Lifecycle test complete | Freightliner | 9412.84 |
| 2 | PDV02 | 7/11/2011 | Columbus, OH | Controls Development | Freightliner | 5673.24 |
| 3 | PDV03 | 7/5/2011 | Gaffney, SC | FCCC DVP Testing Needs | Parker | 26275.29 |
| 4 | PDV04 | 7/1/2011 | Columbus, OH | Durability | Parker | 52429.42 |
| 5 | PDV05 | 11/2/2011 | Columbus, OH | Control Software Testing | Parker | 33026.56 |
| 6 | PDV06 | 2/10/2012 | Columbus, OH | EMB Testing | Parker | 799.17 |
| 7 | 2321 | 11/15/2011 | Livonia, MI | On Route | FedEx | 15229.07 |
| 8 | 2322 | 11/15/2011 | Saline, MI | On Route | FedEx | 19695.99 |
| 9 | 2323 | 10/7/2011 | Vernon, CA | On Route | FedEx | 11170.53 |
| 10 | 2324 | 10/5/2011 | San Francisco, CA | On Route | FedEx | 9924.23 |
| 11 | 2325 | 11/15/2011 | San Diego, CA | On Route | FedEx | 26959.94 |
| 12 | 2326 | 11/15/2011 | Whittier, CA | On Route | FedEx (CalStart) | 13966.46 |
| 13 | 1072 | 11/15/2011 | Toronto, Canada | On Route | Purolator (CalStart) | 4267.76 |
| 14 | 1073 | 11/15/2011 | Laguna Hills, CA | On Route | UPS (CalStart) | 21424.86 |
| 15 | 1079 | 9/14/2012 | Laurl, MD | On Route | UPS | 18718.48 |
| 16 | 1080 | 6/18/2012 | Laurl, MD | On Route | UPS | 17009.63 |
| 17 | 1081 | 9/25/2012 | Helethoroe, MD | On Route | UPS | 12854.17 |
| 18 | 1082 | 6/19/2012 | Laurl, MD | On Route | UPS | 19234.71 |
| 19 | 1083 | 9/24/2012 | Laurl, MD | On Route | UPS | 14845.75 |
| 20 | 1084 | 6/20/2012 | Laurl, MD | On Route | UPS | 17488.83 |
| 21 | 1085 | 6/25/2012 | Laurl, MD | On Route | UPS | 13507.85 |
| 22 | 1086 | 9/21/2012 | Laurl, MD | On Route | UPS | 13208.84 |
| 23 | 1087 | 9/21/2012 | Helethoroe, MD | On Route | UPS | 12800.18 |
| 24 | 1088 | 6/21/2012 | Helethoroe, MD | On Route | UPS | 19797.47 |
| 25 | 1089 | 6/21/2012 | Laurl, MD | On Route | UPS | 17134.20 |
| 26 | 1090 | 9/24/2012 | Helethoroe, MD | On Route | UPS | 15428.90 |
| 27 | 1091 | 9/27/2012 | Helethoroe, MD | On Route | UPS | 7097.13 |
| 28 | 1092 | 9/24/2012 | Helethoroe, MD | On Route | UPS | 21694.33 |
| 29 | 1093 | 9/21/2012 | Helethoroe, MD | On Route | UPS | 16651.63 |
| 30 | 1094 | 9/24/2012 | Helethoroe, MD | On Route | UPS | 16954.56 |
| 31 | 1095 | 9/27/2012 | Helethoroe, MD | On Route | UPS | 12295.82 |
| 32 | 1096 | 10/2/2012 | Laurl, MD | On Route | UPS | 18132.09 |
| 33 | 1097 | 9/24/2012 | Laurl, MD | On Route | UPS | 14721.59 |
| 34 | 1098 | 9/24/2012 | Laurl, MD | On Route | UPS | 17491.23 |
| 35 | 1099 | 2/12/2013 | Atlanta, GA | On Route | UPS | 14089.51 |
| 36 | 1100 | 2/12/2013 | Atlanta, GA | On Route | UPS | 12835.22 |
| 37 | 1101 | 2/12/2013 | Atlanta, GA | On Route | UPS | 11961.08 |
| 38 | 1102 | 2/12/2013 | Atlanta, GA | On Route | UPS | 18553.82 |
| 39 | 1103 | 2/22/2013 | Atlanta, GA | On Route | UPS | 11214.87 |
| 40 | 1104 | 2/26/2013 | Atlanta, GA | On Route | UPS | 12938.30 |
| 41 | 1105 | 2/25/2013 | Atlanta, GA | On Route | UPS | 12539.61 |
| 42 | 1106 | 3/5/2013 | Atlanta, GA | On Route | UPS | 9757.59 |
| 43 | 1107 | 3/18/2013 | Atlanta, GA | On Route | UPS | 12270.12 |
| 44 | 1108 | 3/21/2013 | Atlanta, GA | On Route | UPS | 19965.24 |
| 45 | 1109 | 3/12/2013 | Atlanta, GA | On Route | UPS | 12190.35 |
| 46 | 1110 | 3/22/2013 | Atlanta, GA | On Route | UPS | 6685.26 |
| 47 | 1111 | 2/4/2013 | Atlanta, GA | On Route | UPS | 10044.63 |
| 48 | 1112 | 3/26/2013 | Atlanta, GA | On Route | UPS | 11972.32 |
| 49 | 1113 | 4/1/2013 | Atlanta, GA | On Route | UPS | 8536.23 |
| 50 | 1114 | 3/27/2013 | Atlanta, GA | On Route | UPS | 10513.00 |
| 51 | 1115 | 5/1/2013 | Atlanta, GA | On Route | UPS | 7771.18 |
| 52 | 1116 | 2/8/2013 | Atlanta, GA | On Route | UPS | 8844.58 |
| 53 | 1117 | 4/25/2013 | Atlanta, GA | On Route | UPS | 9479.08 |
| 54 | 1118 | 1/30/2013 | Atlanta, GA | On Route | UPS | 16674.85 |

The vehicle demonstration data represents the following distribution representing a nice sample size of 48 vehicles over 10K miles:

| Distribution of Vehicle Mileage | | | | |
|---|---|---|---|---|
| Mileage | 20K+ | 15K - 20K | 10K - 15K | 4K - 10K |
| Number of Vehicles | 3 | 16 | 20 | 9 |

The following is a distribution of the fuel economy for the above vehicles listed, as you can see the average for the 48 vehicle sample size with the advanced series hybrid raised the average fuel economy to 8 to 12 mpg.



Fuel Usage Reduction

The Parker advanced series hydraulic Hybrid drivetrain allows the vehicle to reduce fuel consumption in three ways, the first is through the regenerative braking, the second through an advanced series gearbox that allows for the engine to be decoupled from the driveshaft to allow for the engine to operate in the most efficient area on the engine map, and lastly through its ability to shut the engine off and operate with the stored energy in the accumulator. Fuel consumption testing was performed by Parker, CALSTART, and NREL. Parker testing was performed in March & April of 2014 utilizing a baseline vehicle with a 2010 ISB engine and Allison 2200 transmission along with the hybrid vehicle #1104 that was placed into service in Atlanta 0n 2/26/2013 that at the end of the demonstration period had a total miles of 12,938 miles. In route testing was performed for this testing on comparable routes in terms of stop density and distances. The overall savings represented during the testing reflected an improvement in fuel economy of 35% to 66%.

CALSTART testing (Gallo, 2014, p14) found similar results over the three vehicles tested in the field over a baseline vehicle with an improvement in fuel economy of 22% to 50% (Gallo, 2014, p14). NREL dynamometer testing found similar results over a baseline gas and diesel vehicles with an improvement in fuel economy of 19% to 52% over conventional diesel vehicle on non-highway cycles, and an improvement in fuel economy of 30% to 56% over conventional gasoline vehicle on non-highway (Lammert, 2014, p11). The dynamometer testing for the non-highway cycles or high start and stop cycles included standard cycles at NREL for the NY Comp, CSHVC, and a custom cycle developed with Parker to represent real data from the UPS Baltimore field vehicles so as to allow for a comparison of standard cycles with actual field cycle (Lammert, 2014, p11).

Emissions Reduction

Based on the operating principles discussed above, there are inherent opportunities to reduce emissions as a direct result of reduced fuel consumption in terms of engine management, brake energy recovery, and engine off. Field testing was performed by CALSTART in route by a third party, Engine, Fuel, and Emissions Engineering Inc. (Gallo, 2014, p15) at no cost to this program. This data is directly applicable to this summary as all of these vehicles are using 2010 diesel engines, and the same Parker hybrid hydraulic drivetrain. As a result of this testing, the Parker hydraulic hybrid was found to be "….more efficient and cleaner to operate than a similar conventional diesel vehicle.….It produced 17.4% less $CO_2$ per mile and 30.4% less $NO_x$

per mile than the conventional diesel" (Gallo, 2014, p15).

Vehicle Productivity

By having stored energy on the vehicle in the accumulators, the vehicles have the opportunity to have full acceleration capability from the time the key is turned on, in-field feedback discussions from the vehicle drivers in route is that the start time acceleration from key on is faster than a baseline vehicle and reported as a positive. Although key on performance and acceleration was reported as a plus during the demonstration period, we were unable to establish key metrics in this area to allow for successful measurement thereof. It should be noted that research on the hydraulic hybrid refuse solution from Parker known as RunWise identified the opportunity to increase productivity based on a combination of quicker launch, smoother shifting, and braking showing a time based improvement of 5% - 15% improvement based on test results shown below which only highlights field data on acceleration.

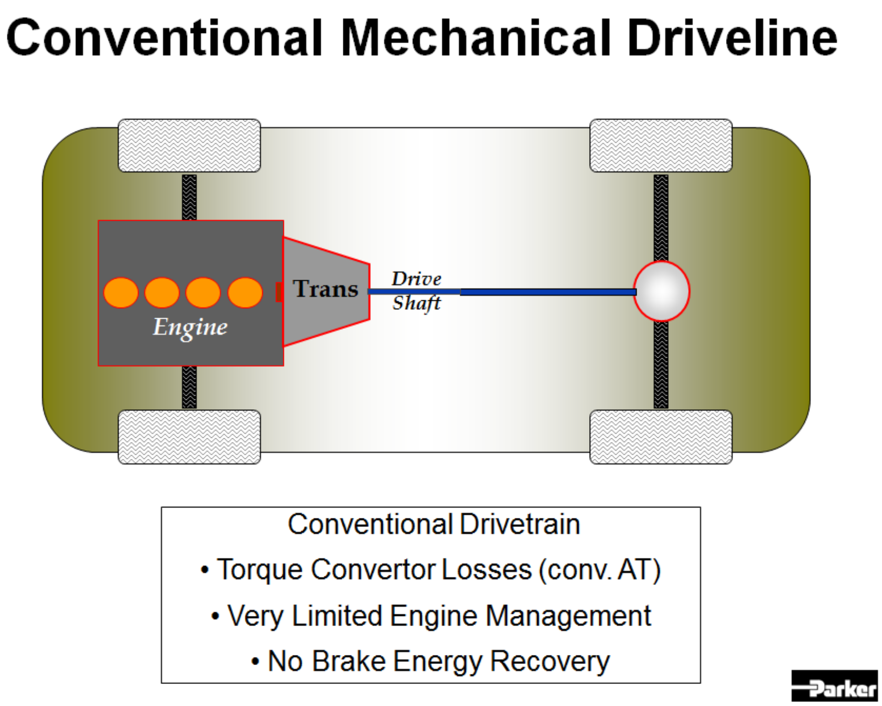
Actual reductions in daily route performance would then vary based on the route and need to be individually calculated and tested. During the refuse application, it should be noted that the operators are in close proximity to the vehicle vs the parcel delivery application where operators stop the vehicles, walk to pick-up and deliver packages, and then return to the vehicles. As a result of this, productivity measurements will be require different evaluation techniques, suggesting that the above data is pertinent, however lends itself to further investigation in the future.

Vehicle Maintenance

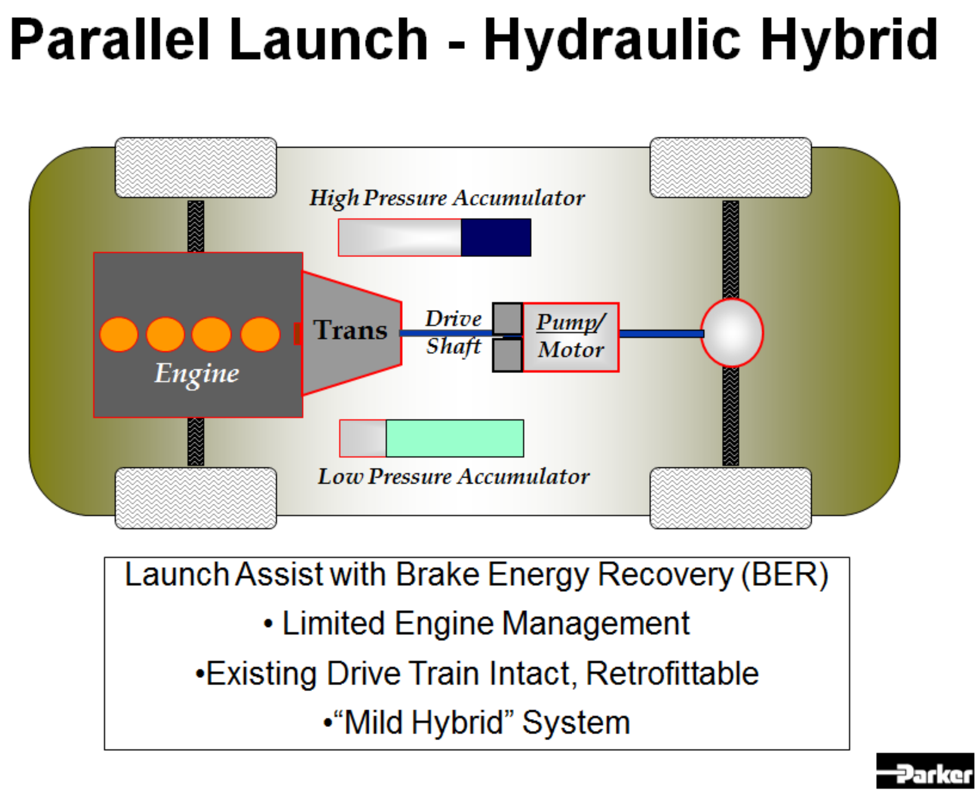
The demonstration vehicles built as part of this were early production vehicles that did have some upgrades performed as reported in the quarterly reports in the area of the gearbox, cooler, low pressure reservoir, air tanks, ECU mounting brackets, minor paint touch up, and the latest control software, this occurred prior to and also after fielding the vehicles. Once upgraded, the vehicles performed successful in route. Routine and scheduled maintenance was performed per the Parker schedule, there were some hose and fitting failures that were replaced and the vehicles placed back in service. In terms of brake and starter performance, there were significant gains in this area, during the demonstration period, not starters or brake changes had to be performed. Based on discussions with end-user customers in the field, typical brake service and replacement occurs on a 9 - 12 month cycle, while the starter replacement cycle occurs on a 3 -4 month cycle. These benefits are a direct result of the use of regenerative braking and the use of the hydraulic circuit to start the engine versus the use of the starter. The CALSTART report (Gallo, 2014, p82-88) reviewed the wear of the tires on both the front and rear of the vehicle and did not come up with conclusive evidence in the positive or negative leaving room for further investigation and measurement (Gallo, 2014, p82-88).

## Introduction

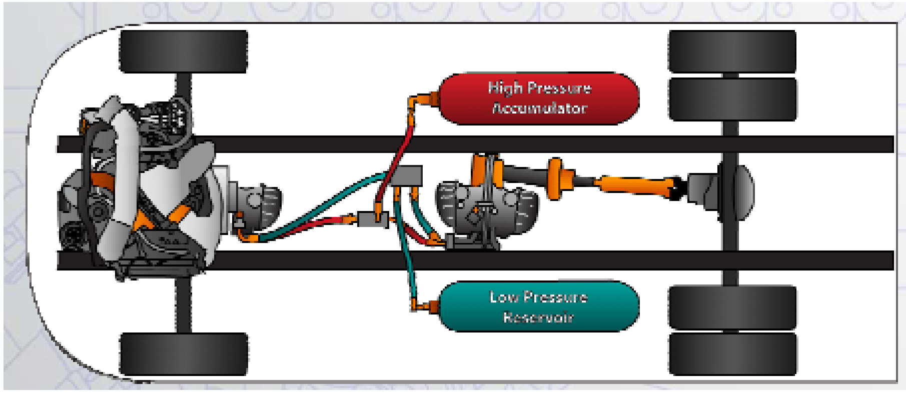
Parker's development of the hydraulic hybrid drivetrain started in the late 1980's, the focus was and continues to be to optimize the use of and decrease the use of fuel, early adopters of the technology were bus and refuse applications. Prior to the adoption of this early technology, vehicles utilized a conventional mechanical drivetrain as shown below.




These early systems from Parker were parallel hybrid systems, that is to say that the hybrid system was installed in addition to the conventional drivetrain. There are some benefits seen with this system to allow for some brake energy recovery, however the limit of this system is only a small percentage of energy capture as the conventional drivetrain remains in place as shown below.




Following this technology development was the series hydraulic hybrid systems that were 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 USEPA in 2003 through 2008 to develop an improved hydrostatic series hydraulic transmission, this series concept is depicted below:

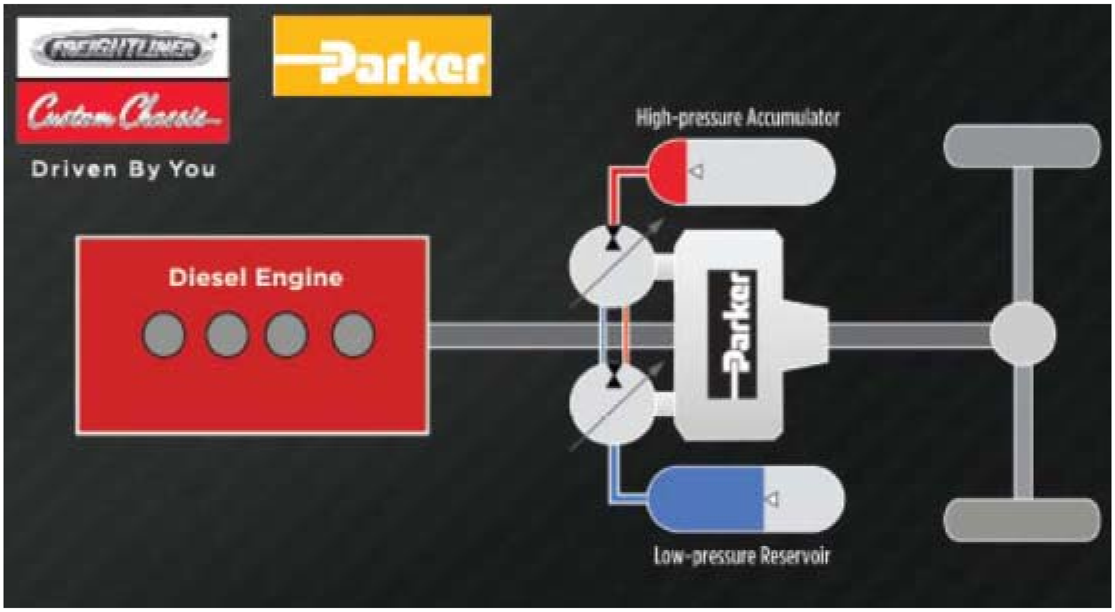



Kargul, 2013, p10

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.

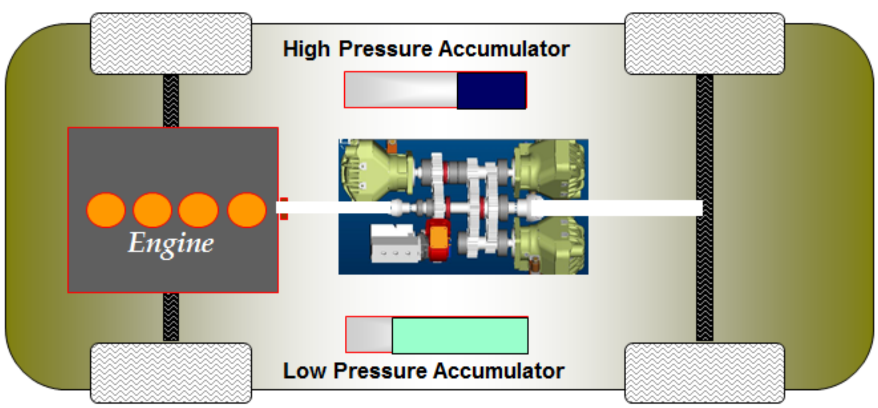
Continued development and research was performed outside of the CRADA evaluating the system to develop the advanced series technology that is in use today. This advanced series technology allows the vehicle to reduce fuel consumption in three ways, the first is through the regenerative braking, the second through an advanced series gearbox that allows for the engine to operate independent of vehicle speed or transmission output speed in the most efficient area on the engine map, and lastly through its 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 delivery & refuse applications.




Delivery System Advanced Series Hybrid

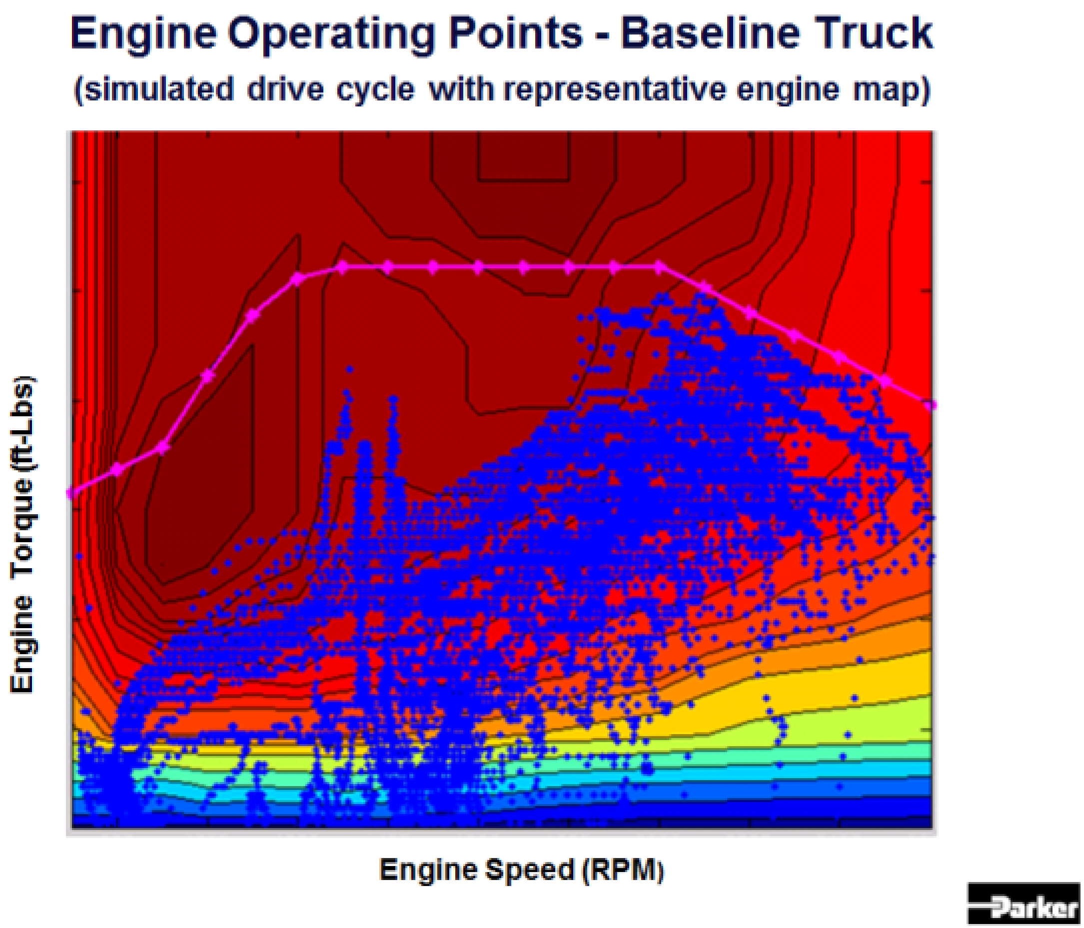
## Parker Refuse Advanced Series Hybrid

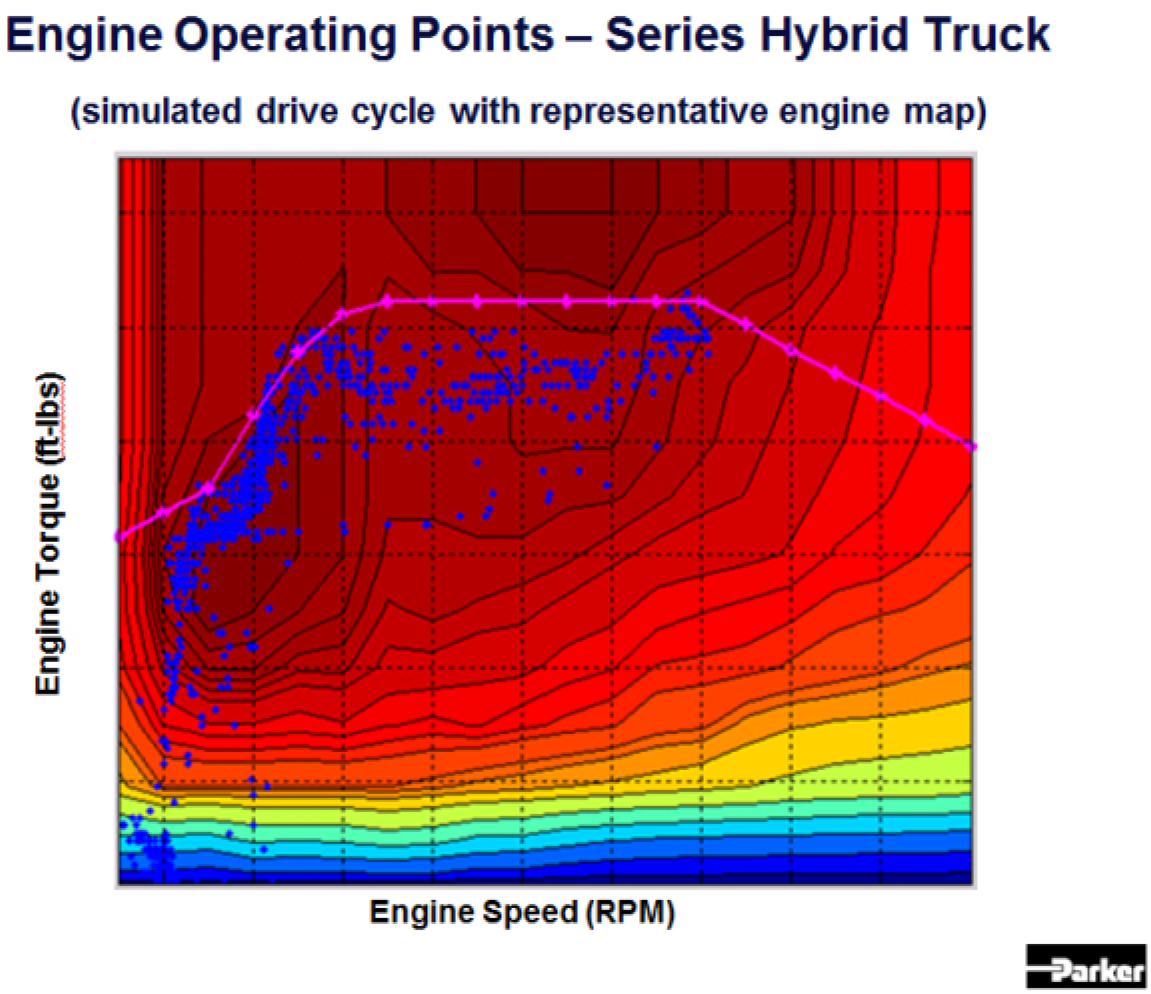



- Advanced Series Hybrid with Brake Energy Recovery
  - Low speed hydrostatic 0-25 MPH
  - High speed Hydrostatic 26-45 MPH
  - Mechanical drive 46-65 MPH (Hydraulics Disengaged)

Refuse System Advanced Series Hybrid

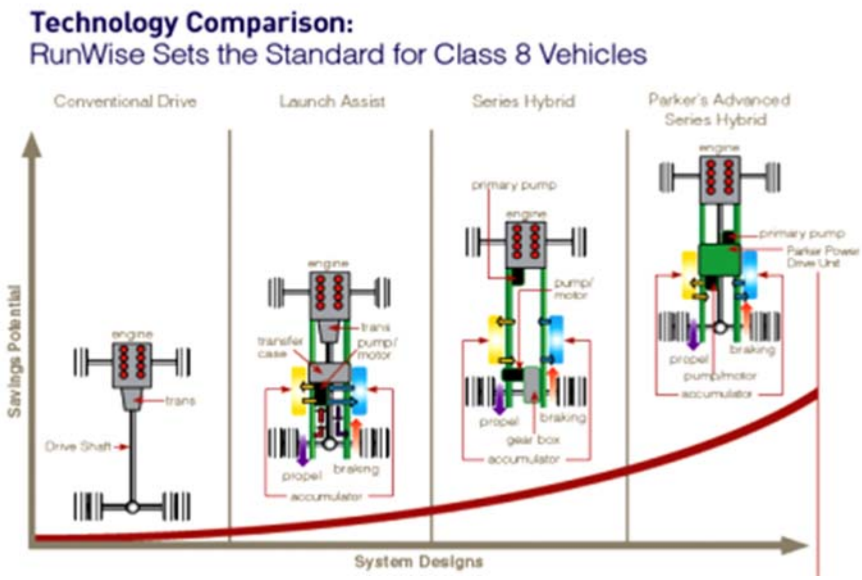
In terms of the engine management, the advanced series gearbox allows for the engine to be operated in the most efficient area on the engine map. The following images show the engine map performance of the baseline vehicle before and the advanced series hybrid engine map after the optimal engine control algorithms developed by Parker were implemented with this system.






This system methodology allows Parker to take advantage of the enabling technologies that have allowed for the advanced series solution including: highly efficient bent axis pump/motor units, advanced series gearbox, and the utilization of modern control methods controlling the hydraulic and engine interfaces.


Parker's engineering team's developed and launched advanced series hydraulic hybrid drivetrain systems that yielded better brake energy recovery capabilities versus the initial parallel, and series systems. As you can see in the summary table, performance is always based on routes; however technology can be viewed as good, better, best in terms of the advancements made



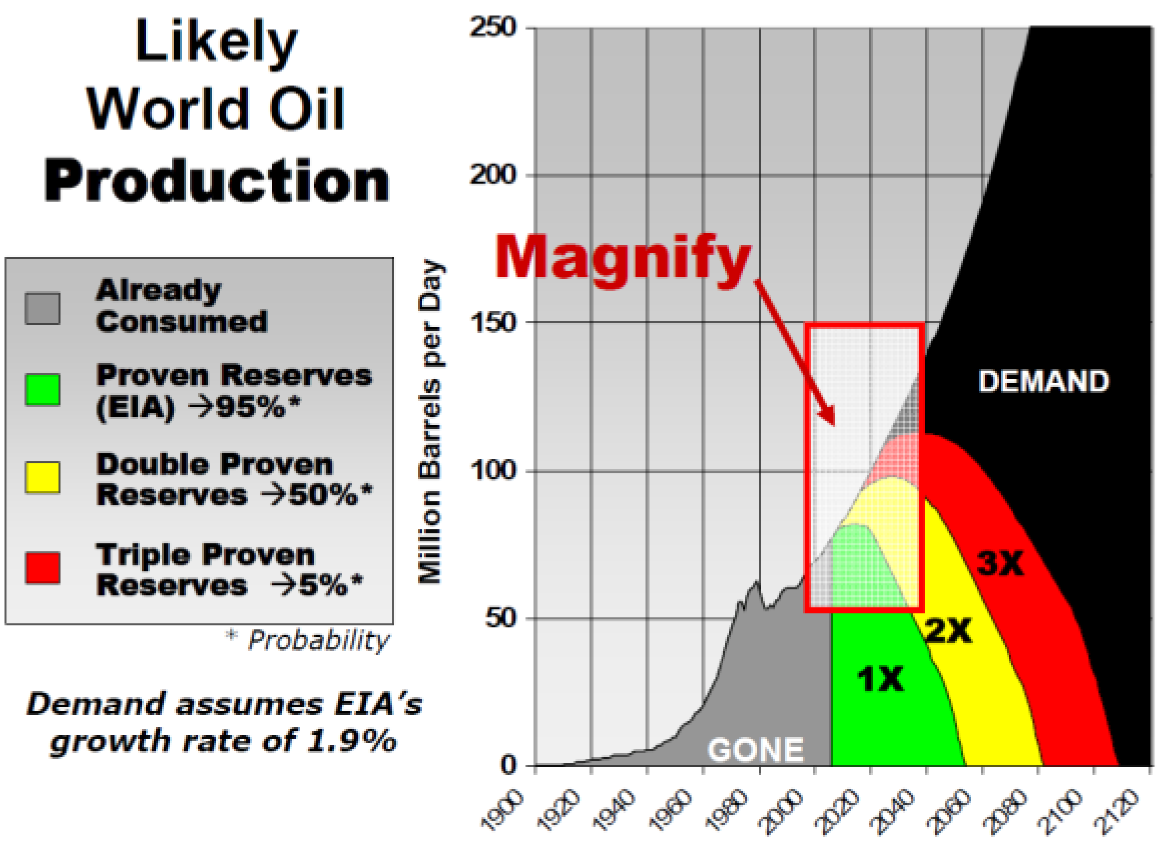

## Summary of Hydraulic Hybrids

| | Parallel | Series | Adv Series |
|---|---|---|---|
| **Brake Recovery** | ✓ | ✓ | ✓ |
| **Engine Management** | | ✓ | ✓ |
| **High Speed Efficiency** | | | ✓ |
| **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

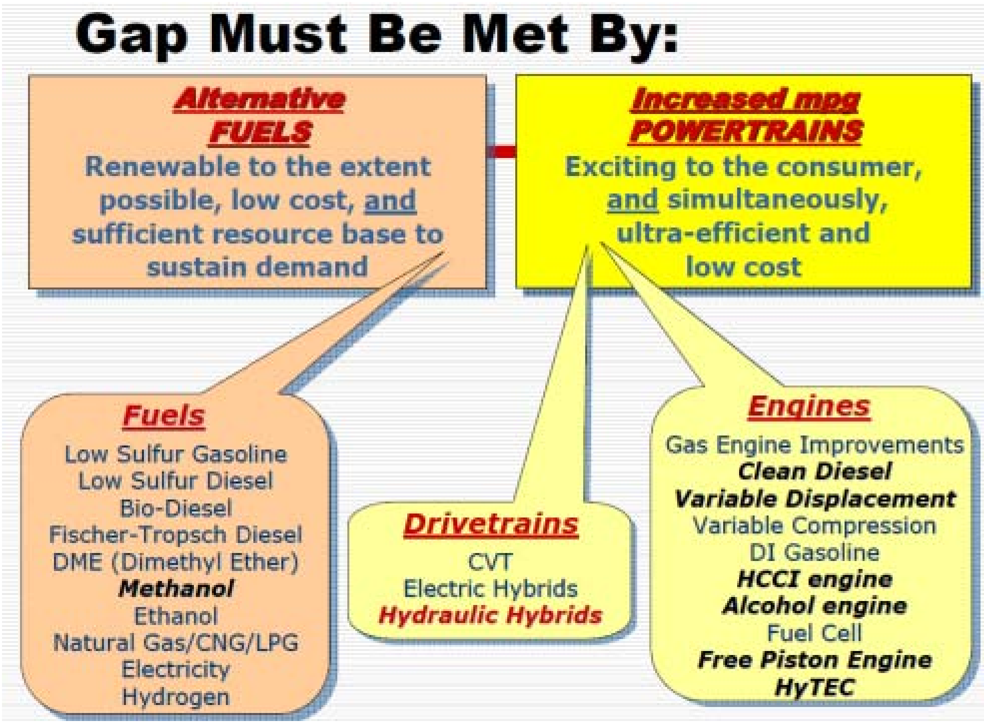
This demonstration supported by the US DOE allows customers, government agencies, and third parties to see the types of savings that Parker's advanced series drivetrain can provide to the marketplace.

Drivers of technology in the area of fuel economy historically have been price, available reserves, and more recently by the desire to be less dependent on foreign oil sources. Evaluating current consumption, available reserves, and demand for World Oil production as shown below indicates that there is a clear concern to improve the use of the current oil sources as soon as possible.




Gray, 2006, p2

Responding to the above concern, the US EPA investigated and reported potential methods to address the gap of supply to demand for fuel as shown below (Gray, 2006, p6). The purpose of this document is to address the increase in mpg for powertrains, further investigation of alternative fuels would provide for a suitable evaluation in the future.




(Gray, 2006, p6)

In addition to the US EPA & world oil supply and demand concerns mentioned above, this report would not be global in thinking if not evaluating and understanding the global megatrends. Megatrend forces have large-scale impacts as they represent shifts across the globe not only on the business side, but also on the society side that can represent major shifts in large cities and regions of the world (Efrat, n.d., p2). Key Mega Trend themes that can drive opportunities for high start and stop applications include Urbanization, Infrastructure Development, Energy & Environment, and Social (Efrat, n.d., p2). As these represent 4 of the 6 Mega Trends developed by Frost & Sullivan, this represents the need to maintain awareness and impacts of these trends as it applies to high start & stop vehicles (Efrat, n.d., p2).


(Efrat, n.d., p2)

Mega Trends can have impacts on legislation and policy resulting in technology shifts (Tomazic, 2013, p3). As seen in the table below, there are some potential expected impacts on auto, on & off road legislation across the globe (Tomazic, 2013, p3).

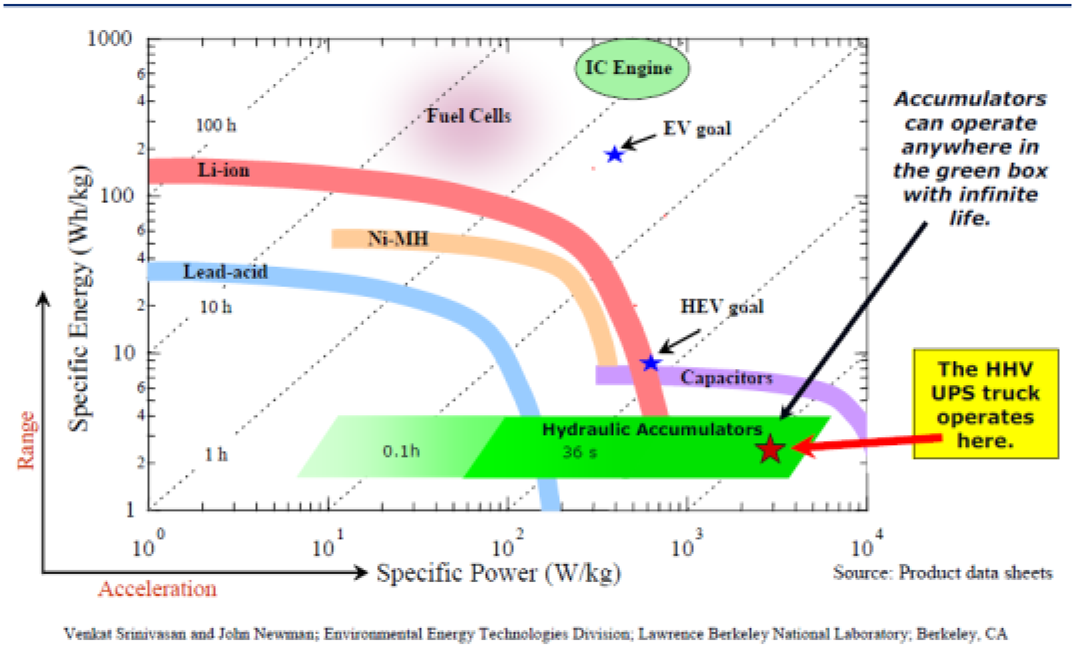
**Global mega trends impact total cost of ownership, legislation and other government policies which in turn impact future vehicle technology**

| | EU | United States | Japan | China | India | Brazil |
|---|---|---|---|---|---|---|
| **Passenger Cars** | • Expected **75g** $CO_2$/km fleet average target | • **54.5**mpg target for 2025 (c. 107g $CO_2$/km) | • Proposed target of c. **105g** $CO_2$/km in 2020, further tightening likely for 2025 | • Proposed target of c. **117g** $CO_2$/km in 2020, further tightening likely for 2025 | • FE legislation under review, CO2 target of **100-115g** $CO_2$/km likely by 2025 | • Currently no FE regulation, potentially lagged follower of U.S. Standards |
| **On-Road Commercial Vehicles** | • $CO_2$ regulation expected to phase-in from 2017 and by 2020 result in 30% improve-ment vs. 2012<br>• Further tightening thereafter | • EPA & NHTSA Emission Standards (g $CO_2$/ton-mile) and FE standards (gal/1,000 ton – mile) – 9-23% improvement by 2017 – further 2-3% p.a. expected | • FE regulation in km/l effective from 2015<br>• Moderate improvement of 12% over 2002<br>• After 2015, further steps expected, 1.5-2% p.a. improve. | • China Stage II fuel consumption limits to be introduced from 7/2014 → 10.5-14% lower consumption than industry standard of Stage I<br>• Further steps until 2025 | • Adoption of EU legislation with 5-8 year time lag expected | • Adoption of US legislation with 3-6 year time lag expected |
| **Non-Road Mobile Machinery** | • First $CO_2$ regulation for large NRMM expected for 2020 | • Phase-in potentially from 2016; likely similar reduction steps as on-road | • FE legislation for large NRMM expected for 2020 | • FE legislation may be phased in towards end of relevant timeframe | • No significant FE legislation expected during relevant timeframe | • No significant FE legislation expected during relevant timeframe |

Tomazic, 2013, p3

Technologies that are provided to the marketplace must have suitable economics and optimal total cost of ownership. The basics of the technology showcased in the demonstration improve fuel economy on average of 35% - 50% in route versus diesel/gas conventional drivetrains as discussed in the executive summary. Additionally, brake and starter savings show opportunities for savings as well as neither have had any need of replacement to date in the demonstration.

In terms of technology comparison costs, hydraulic hybrids use standard materials for construction versus rare earth metals and coppers that have shown more significant materials increases over time (Tomazic, 2013, p17-18) thus allowing for more stable technology costs. Technology integration will allow for continued decreases of costs to reduce component and complexities of design. In terms of storage devices, the use of accumulators versus batteries allow for higher power density (W/kg) as shown in the table below. Based on the above material references, the potential for lower costs of storage media using accumulator's vs other methods is applicable and relative.




Kargul, 2012, p24

## Electric vs. Hydraulic Hybrids

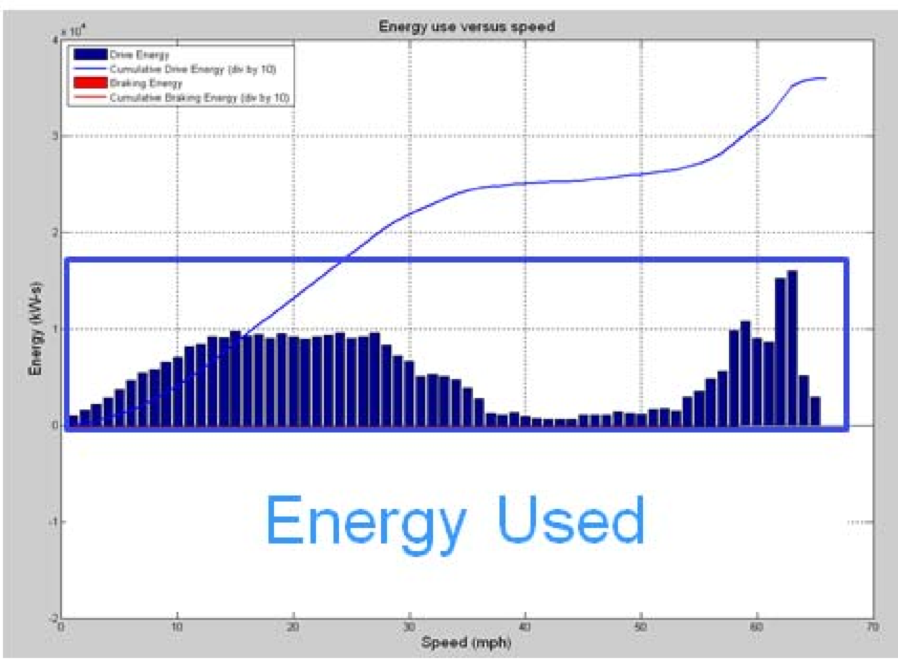
| Characteristic | Hydraulic | Electric | |
|---|---|---|---|
| Power Density Motors | Hydraulic Motors 7000 W/kg | Electric Motors 600 W/kg | |
| Power Density Storage | Accumulators 3000 W/kg | Battery 650 W/kg | Ultra-Capacitors 2500+ W/kg |
| Relative Cost | Low to Medium | Med | High |
| Relative Weight | Low to Medium | High | Med |
| Useful Life | 10+ yrs | > 5yrs | ? |
| Risk | Low to Medium | Med | High |

Data source:
- SwRI study of Hybrid Technology
- Lawrence Berkley National Laboratory

Parker

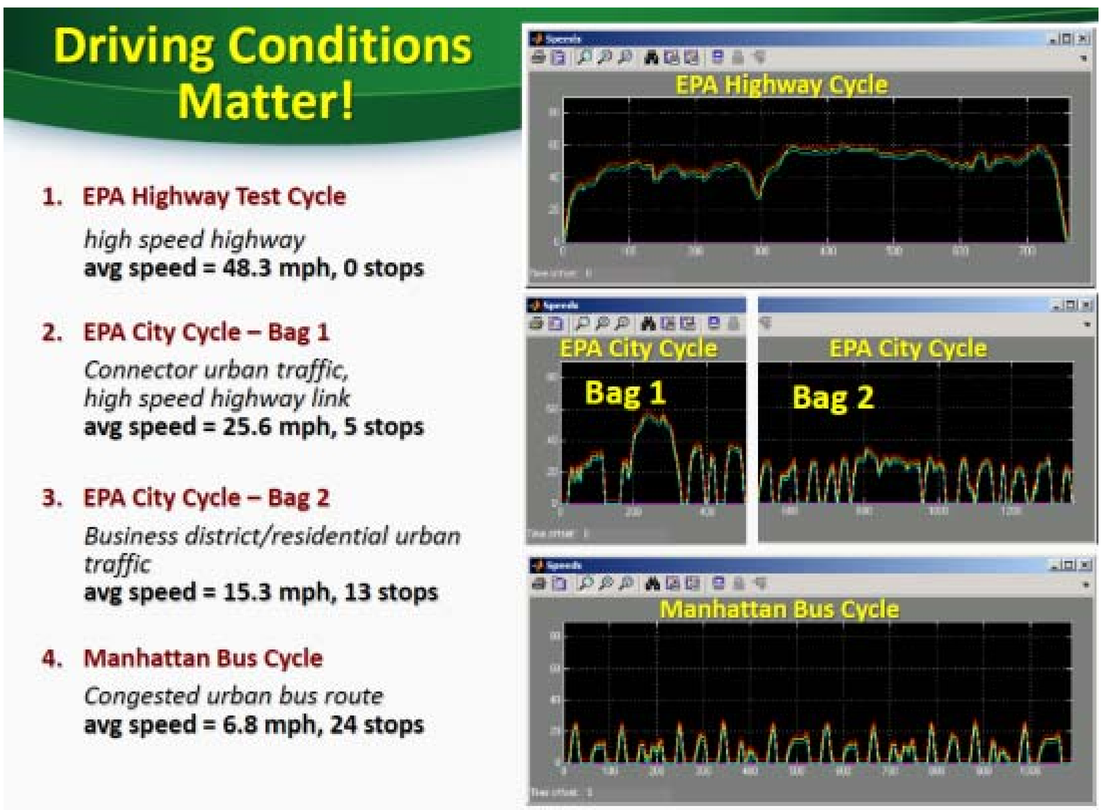
Maxell, 2008, p27

From a start and stop potential, field testing shows that during a daily duty cycle there is a specific amount of energy used and available for savings as shown below:



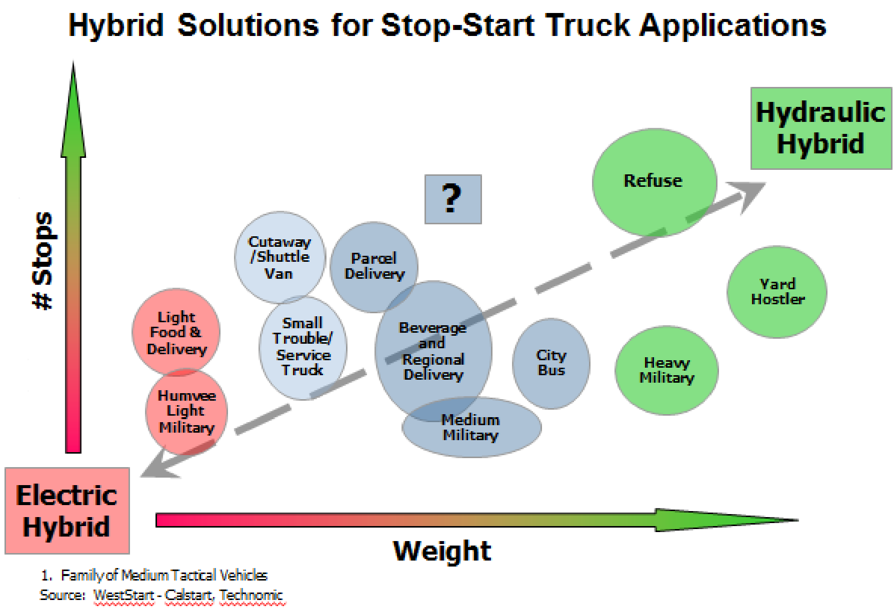

If this energy is not saved, it is rejected as heat energy in the brakes, this results in wasted energy.

The above energy used and available savings is a high level of the representation of the opportunity to solve using hybrid hydraulic technology. However it needs to be noted that all routes are not the same and a profile of routes need to be evaluated at a customer site to be able to recommend the utilization of hybrid technology. As our research has shown, hybrid hydraulic drivetrains cannot address all routes, in fact, the technology has shown to be on par or slightly less when compare to high highway transit routes with low start/stop cycles (Lammert, 2014, p8).As you can see in the attached standard US EPA cycles there is significant variation in routes in terms of high speeds and number of stops that will yield significantly different results in a start/stop hybrid technology (Kargul, 2013, p13).

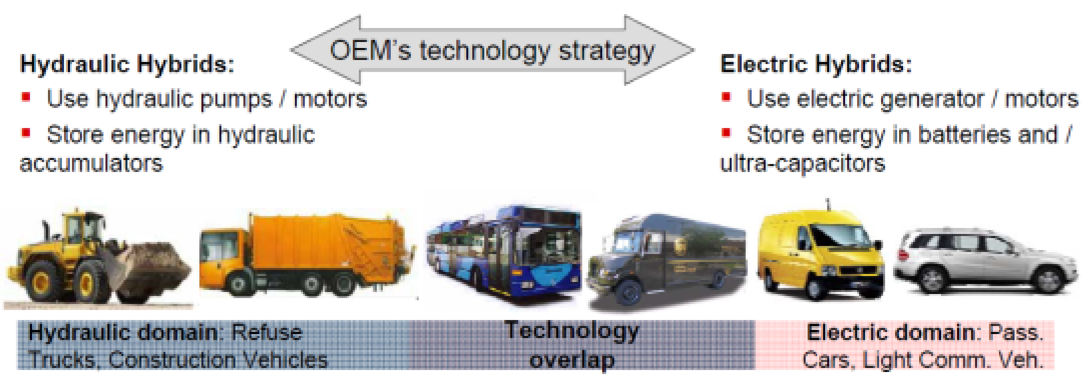



(Kargul, 2013, p13)

Evaluating the right technology for the right application has been a point of discussion at many of the hybrid discussion forums through the years, the attached table from Westart-CALSTART shows some comparisons of technology selection that might be considered in the process for hydraulic versus electric and those platforms in the middle that are to be determined for the right technologies (Maxwell, 2008, p26).

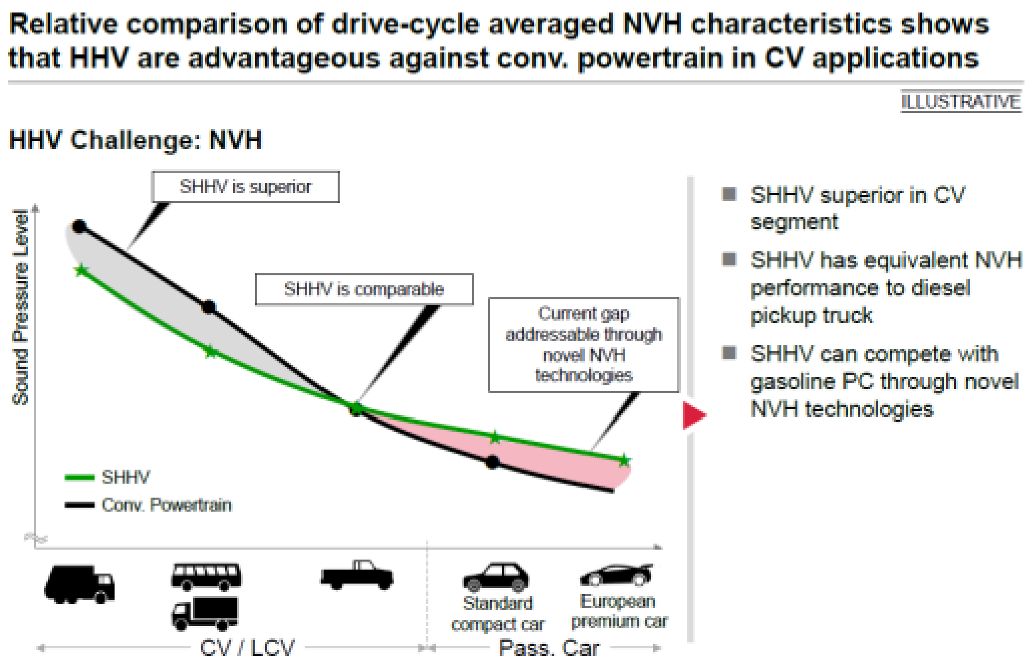



(Maxwell, 2008, p26)



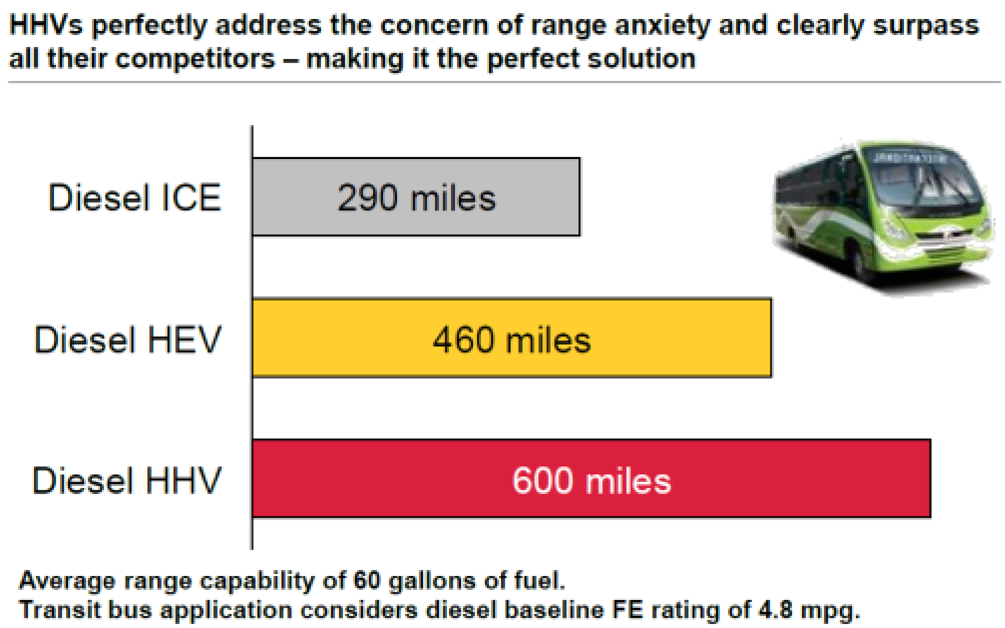

Conrad, 2008, p11

Hydraulics in the area of delivery vehicles is new to the delivery marketplace. Additional training for field resources within the customers was provided; existing support capabilities from the Freightliner dealer network and Parker distribution were made available to support these vehicles in the field to supplement the needs of the customer maintenance teams. From a new technology standpoint, this system presented some new components and complexities that the teams were able to understand and grasp with training. The current technology represented individual components including gear boxes, pump motors, coolers, reservoirs, accumulators, and other devices. Future configurations represent opportunities to more closely couple some of these technologies for improvements in such areas as packaging, connectivity, and noise optimization based on packaging. Independent research has shown that noise in heavy vehicle on-road applications appears to be better, with areas for improvement for lower weight automotive applications (Tomazic, 2013,p20).




(Tomazic, 2013,p20

Lastly, based on the fuel economy gains provided and summarized above in the executive summary, this represents potential for adoption in the future, as with all technologies the investment and payback periods need to be satisfactory to all in the value chain of the procurement process. On another front, independent research for hydraulic hybrids for buses as depicted in the below table appear to be in seen in a positive light further reinforcing the use of and potential adoption of hydraulic hybrid technology (Tomazic, 2013,p16).




Tomazic, 2013,p16

## Methodology

To review the methodology, we must start with the key team members that were instrumental in this demonstration including the teams at Freightliner Custom Chassis Corporation (OEM Chassis Manufacturer), Morgan Olson (Body Manufacturer), and the end user customers that deployed vehicles in the field at UPS, FedEx Ground, and Purolator. Additionally, it should also be noted that during this period key research and efforts were performed in parallel on these vehicles by NREL & CALSTART that will be referred to herein that allowed for a more rich content report to be provided for the readers of this report. This report and the deliverables in the SOPO could not have been completed or documented with these team members above and the support of the Parker’s Hybrid Drive Systems Division team members, based in Columbus, OH, and more specifically Prasad Venkiteswaran and James Howland for the unending support and field efforts to work with all teams involved.

The scope and scale of this project was governed by the Statement of Project Objectives submitted, funded, and approved by the US Department of Energy. The following are the details of the SOPO:

STATEMENT OF PROJECT OBJECTIVES

## A. PROJECT OBJECTIVES

To demonstrate the potential in-use benefits of hydraulic hybrid drive technology as applied to the commercial vehicles with high start and stop duty cycles. More specifically:

1) Fuel Usage Reduction – demonstrated fuel economy improvement

2) Emissions Reduction – corresponding reduction in emissions associated with reduced fuel consumption

3) Vehicle Productivity – greater improvement in acceleration & performance

4) Vehicle Maintenance – greatly reduced brake wear & improved electric starter life

The demonstration results for the above benefits are as follows:

Fuel Usage Reduction

The Parker advanced series hydraulic Hybrid drivetrain allows the vehicle to reduce fuel consumption in three ways, the first is through the regenerative braking, the second through an advanced series gearbox that allows for the engine to be decoupled from the driveshaft to allow for the engine to operate in the most efficient area on the engine map, and lastly through its ability to shut the engine off and operate with the stored energy in the accumulator. Fuel consumption testing was performed by Parker, CALSTART, and NREL.

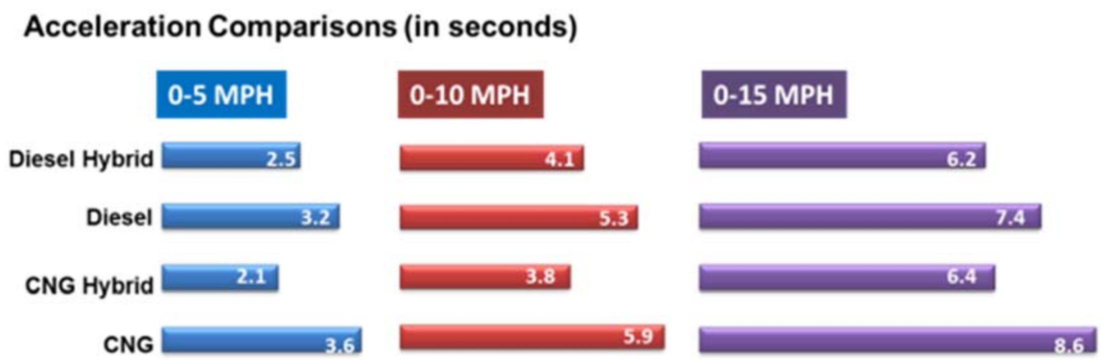
Parker testing was performed in March & April of 2014 utilizing a baseline vehicle with a 2010 ISB engine and Allison 2200 transmission along with the hybrid vehicle #1104 that was placed into service in Atlanta 0n 2/26/2013 that at the end of the demonstration period had a total miles of 12,938 miles. In route testing was performed for this testing on comparable routes in terms of stop density and distances. The overall savings represented during the testing reflected an improvement in fuel economy of 35% to 66%. CALSTART testing (Gallo, 2014, p14) found similar results over the three vehicles tested in the field over a baseline vehicle with an improvement in fuel economy of 22% to 50%. NREL dynamometer testing found similar results over a baseline gas and diesel vehicles with an improvement in fuel economy of 19% to 52% over conventional diesel vehicle on non-highway cycles, and an improvement in fuel economy of 30% to 56% over conventional gasoline vehicle on non-highway (Lammert, 2014, p8). The dynamometer testing for the non-highway cycles or high start and stop cycles included standard cycles at NREL for the NY Comp, CSHVC, and a custom cycle developed with Parker to represent real data from the UPS Baltimore field vehicles so as to allow for a comparison of standard cycles with actual field cycle (Lammert, 2014, p5-6).

Emissions Reduction

Based on the operating principles discussed above, there are inherent opportunities to reduce emissions as a direct result of reduced fuel consumption. Field testing was performed by CALSTART in route by a third party, Engine, Fuel, and Emissions Engineering Inc. (Gallo, 2014, p15) at no cost to this program. This data is directly applicable to this summary as all of these vehicles are using 2010 diesel engines, and the same Parker hybrid hydraulic drivetrain. As a result of this testing, the Parker hydraulic hybrid was found to be "….more efficient and cleaner to operate than a similar conventional diesel vehicle.….It produced 17.4% less $CO_2$ per mile and 30.4% less $NO_x$ per mile than the conventional diesel" (Gallo, 2014, p15).

Vehicle Productivity

By having stored energy on the vehicle in the accumulators, the vehicles have the opportunity to have full acceleration capability from the time the key is turned on, in-field feedback discussions from the vehicle drivers in route is that the start time acceleration from key on is faster than a baseline vehicle and reported as a positive. Although key on performance and acceleration was reported as a plus during the demonstration period, we were unable to establish key metrics in this area to allow for successful measurement thereof. It should be noted that research on the hydraulic hybrid refuse solution from Parker known as RunWise identified the opportunity to increase productivity based on a combination of quicker launch, smoother shifting, and braking showing a time based improvement of 5% - 15% improvement based on test results, acceleration data shown below. Actual reductions in daily route performance would then vary based on the route and need to be individually calculated and tested. During the refuse application, it should be noted that the operators are in close proximity to the vehicle vs the parcel delivery application where operators stop the vehicles, walk to pick-up and deliver packages, and then return to the vehicles. As a result of this, productivity measurements will be require different evaluation techniques, suggesting that the above data is pertinent, however lends itself to further investigation in the future.



Vehicle Maintenance

The demonstration vehicles built as part of this were early production vehicles that did have some upgrades performed as reported in the quarterly reports in the area of the gearbox, cooler, low pressure reservoir, air tanks, ECU mounting brackets, minor paint touch up, and the latest control software, this occurred prior to and also after fielding the vehicles. Once upgraded, the vehicles performed successfully in route. Routine and scheduled maintenance was performed per the Parker schedule, there were some hose and fitting failures that were replaced and the vehicles placed back in service. In terms of brake and starter performance, there were significant gains in this area, during the demonstration period, not starters or brake changes had to be performed. Based on discussions with end-user customers in the field, typical brake service and replacement occurs on a 9 - 12 month cycle, while the starter replacement cycle occurs on a 3 -4 month cycle. These benefits are a direct result of the use of regenerative braking and the use of the hydraulic circuit to start the engine versus the use of the starter. The CALSTART report (Gallo, 2014, p82-88) reviewed the wear of the tires on both the front and rear of the vehicle and did not come up with conclusive evidence in the positive or negative leaving room for further investigation and measurement (Gallo, 2014, p82-88).

Details of the vehicle deployment in the field and the data acquired during the testing are as follows:

During the testing period, the vehicles were all equip with data acquisition systems to capture key performance indicators off the J1939 bus. These data acquisition systems and data were collected at no cost to this program. This included 48 fielded vehicles that were supported as part of this demonstration, UPS (40), FedEx Ground (5), CALSTART (3 – UPS(1), FedEx Ground (1), and Purolator (1)). During the demonstration period that the vehicles were on road, July 01, 2011 thru March 31, 2014, the vehicles logged a total of 678,543 miles.

A table of the vehicle data is shown below highlighting the Vehicle Identification Number (VIN), date that the vehicle was placed into service (this was after the vehicle build, body build onto the chassis, vehicle shakedown, customer inspection, plating, and final preparation for field service), Vehicle location that it was placed into service, current status, vehicle owner, and total miles during the period. Additionally, the last column on the chart highlights the Fuel economy average in the field during the demonstration period. It should be noted that results identified in the study by other third parties validated the savings potential in fuel reduction of on average of 19% to 50% over the baseline in terms of mpg (Lammert, 2014, p8), Parker data in the field parallels this at a range of 35% - 50%. This means that when you review the Fuel economy average data in the table below, you need to recognize that comparative review by Parker teams of field data documented that these routes were improved 35% - 50% in terms of fuel economy as a result of deploying these systems. This means that when you review the Fuel economy average data in the table below, you need to recognize that comparative review by Parker teams of field data documented that these routes were improved approximately 35% - 50% in terms of fuel economy as a result of deploying these systems:

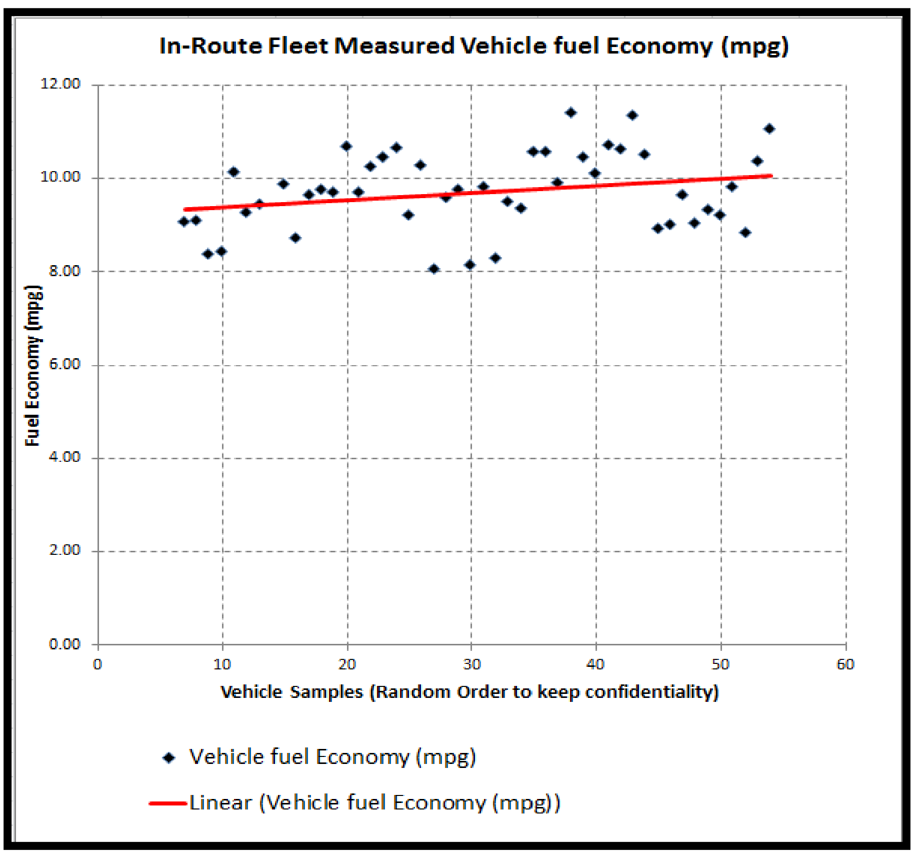
# US Department of Energy Tracking Chart

| Period | July 01, 2011 thru March 31, 2014 | | | | | |
|---|---|---|---|---|---|---|
| Completed by: | James Howland and Prasad Venkiteswaran | | | | | |
| # | Vehicle ID / last 4 of vin | First Date of Service | Vehicle Location | Vehicle Status | Vehicle Customer | Total Miles during period |
| 1 | PDV01 | 7/1/2011 | Columbus, OH | Lifecycle test complete | Freightliner | 9412.84 |
| 2 | PDV02 | 7/11/2011 | Columbus, OH | Controls Development | Freightliner | 5673.24 |
| 3 | PDV03 | 7/5/2011 | Gaffney, SC | FCCC DVP Testing Needs | Parker | 26275.29 |
| 4 | PDV04 | 7/1/2011 | Columbus, OH | Durability | Parker | 52429.42 |
| 5 | PDV05 | 11/2/2011 | Columbus, OH | Control Software Testing | Parker | 33026.56 |
| 6 | PDV06 | 2/10/2012 | Columbus, OH | EMB Testing | Parker | 799.17 |
| 7 | 2321 | 11/15/2011 | Livonia, MI | On Route | FedEx | 15229.07 |
| 8 | 2322 | 11/15/2011 | Saline, MI | On Route | FedEx | 19695.99 |
| 9 | 2323 | 10/7/2011 | Vernon, CA | On Route | FedEx | 11170.53 |
| 10 | 2324 | 10/5/2011 | San Francisco, CA | On Route | FedEx | 9924.23 |
| 11 | 2325 | 11/15/2011 | San Diego, CA | On Route | FedEx | 26959.94 |
| 12 | 2326 | 11/15/2011 | Whittier, CA | On Route | FedEx (CalStart) | 13966.46 |
| 13 | 1072 | 11/15/2011 | Toronto, Canada | On Route | Purolator (CalStart) | 4267.76 |
| 14 | 1073 | 11/15/2011 | Laguna Hills, CA | On Route | UPS (CalStart) | 21424.86 |
| 15 | 1079 | 9/14/2012 | Laurl, MD | On Route | UPS | 18718.48 |
| 16 | 1080 | 6/18/2012 | Laurl, MD | On Route | UPS | 17009.63 |
| 17 | 1081 | 9/25/2012 | Helethoroe, MD | On Route | UPS | 12854.17 |
| 18 | 1082 | 6/19/2012 | Laurl, MD | On Route | UPS | 19234.71 |
| 19 | 1083 | 9/24/2012 | Laurl, MD | On Route | UPS | 14845.75 |
| 20 | 1084 | 6/20/2012 | Laurl, MD | On Route | UPS | 17488.83 |
| 21 | 1085 | 6/25/2012 | Laurl, MD | On Route | UPS | 13507.85 |
| 22 | 1086 | 9/21/2012 | Laurl, MD | On Route | UPS | 13208.84 |
| 23 | 1087 | 9/21/2012 | Helethoroe, MD | On Route | UPS | 12800.18 |
| 24 | 1088 | 6/21/2012 | Helethoroe, MD | On Route | UPS | 19797.47 |
| 25 | 1089 | 6/21/2012 | Laurl, MD | On Route | UPS | 17134.20 |
| 26 | 1090 | 9/24/2012 | Helethoroe, MD | On Route | UPS | 15428.90 |
| 27 | 1091 | 9/27/2012 | Helethoroe, MD | On Route | UPS | 7097.13 |
| 28 | 1092 | 9/24/2012 | Helethoroe, MD | On Route | UPS | 21694.33 |
| 29 | 1093 | 9/21/2012 | Helethoroe, MD | On Route | UPS | 16651.63 |
| 30 | 1094 | 9/24/2012 | Helethoroe, MD | On Route | UPS | 16954.56 |
| 31 | 1095 | 9/27/2012 | Helethoroe, MD | On Route | UPS | 12295.82 |
| 32 | 1096 | 10/2/2012 | Laurl, MD | On Route | UPS | 18132.09 |
| 33 | 1097 | 9/24/2012 | Laurl, MD | On Route | UPS | 14721.59 |
| 34 | 1098 | 9/24/2012 | Laurl, MD | On Route | UPS | 17491.23 |
| 35 | 1099 | 2/12/2013 | Atlanta, GA | On Route | UPS | 14089.51 |
| 36 | 1100 | 2/12/2013 | Atlanta, GA | On Route | UPS | 12835.22 |
| 37 | 1101 | 2/12/2013 | Atlanta, GA | On Route | UPS | 11961.08 |
| 38 | 1102 | 2/12/2013 | Atlanta, GA | On Route | UPS | 18553.82 |
| 39 | 1103 | 2/22/2013 | Atlanta, GA | On Route | UPS | 11214.87 |
| 40 | 1104 | 2/26/2013 | Atlanta, GA | On Route | UPS | 12938.30 |
| 41 | 1105 | 2/25/2013 | Atlanta, GA | On Route | UPS | 12539.61 |
| 42 | 1106 | 3/5/2013 | Atlanta, GA | On Route | UPS | 9757.59 |
| 43 | 1107 | 3/18/2013 | Atlanta, GA | On Route | UPS | 12270.12 |
| 44 | 1108 | 3/21/2013 | Atlanta, GA | On Route | UPS | 19965.24 |
| 45 | 1109 | 3/12/2013 | Atlanta, GA | On Route | UPS | 12190.35 |
| 46 | 1110 | 3/22/2013 | Atlanta, GA | On Route | UPS | 6685.26 |
| 47 | 1111 | 2/4/2013 | Atlanta, GA | On Route | UPS | 10044.63 |
| 48 | 1112 | 3/26/2013 | Atlanta, GA | On Route | UPS | 11972.32 |
| 49 | 1113 | 4/1/2013 | Atlanta, GA | On Route | UPS | 8536.23 |
| 50 | 1114 | 3/27/2013 | Atlanta, GA | On Route | UPS | 10513.00 |
| 51 | 1115 | 5/1/2013 | Atlanta, GA | On Route | UPS | 7771.18 |
| 52 | 1116 | 2/8/2013 | Atlanta, GA | On Route | UPS | 8844.58 |
| 53 | 1117 | 4/25/2013 | Atlanta, GA | On Route | UPS | 9479.08 |
| 54 | 1118 | 1/30/2013 | Atlanta, GA | On Route | UPS | 16674.85 |

The vehicle demonstration data represents the following distribution representing a nice sample size of 48 vehicles over 10K miles:

| Distribution of Vehicle Mileage | | | | |
|---|---|---|---|---|
| Mileage | 20K+ | 15K - 20K | 10K - 15K | 4K - 10K |
| Number of Vehicles | 3 | 16 | 20 | 9 |

The following is a distribution of the fuel economy for the above vehicles listed, as you can see the average for the 48 vehicle sample size with the advanced series hybrid raised the average fuel economy to 8 to 12 mpg.



## B. PROJECT SCOPE

The scope of the project is to demonstrate the hydraulic hybrid technology which has been developed for the purpose of significantly improving fuel economy in commercial vehicles that have high start and stop cycles such as delivery vehicles. This type of technology is becoming more viable as fuel costs continue to rise. The system works by capturing the braking energy of the vehicle and reusing this captured energy for the subsequent acceleration of the vehicle.

This project is in support of the Department of Energy’s goal to improve combustion engine efficiency for highway vehicles and reduce dependency on foreign oil. The scope of this project is to test and support complete hybrid hydraulic systems on dynamometers and in-use vehicles. The team will collect technical data that represents the simulated route profiles on a test track with third party drivers’ involvement and synthesize this data and report it to DOE on an agreed upon basis. Additionally, the team will collect technical data on vehicles that will also be tested by the end user in their fleets to demonstrate real world applications. This collected data will be analyzed and reported to the DOE on a monthly basis. It is intent of this project to hire systems engineers to learn the systems, collect data, support the uptime and maintenance of systems that will be used for durability testing, oversee & support the proper installation onto test stands and vehicles that will solely be used for durability testing at the track, regulatory testing, and customer in-field testing, along with the instrumentation and testing of baseline vehicle(s) for comparison purposes without said systems. Acquisition of and installation of systems is not considered part of the project cost. This is being done outside of this project, only the support and collection of data from vehicles will be considered a project cost. The project will also include utilizing the systems engineers to serve as a support team for the testing the vehicles when in the field and analyzing and reporting the associated test data. In terms of facilities and testing, the use of internal or external personnel would be utilized and modified as needed to support the needs of the program and availability of skilled resources to support, in terms of equipment and facilities, this may also be done with internal or external resources based on the availability of qualified locations and facilities that are available to support the needs of the program and are most effective to support in terms of locations, costs, support resources. Options will be reviewed with the DOE for input on a routine basis throughout the program.

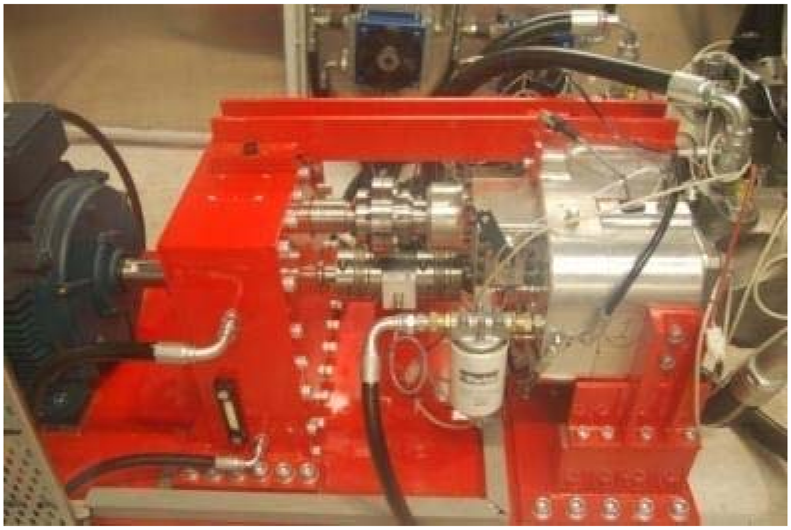
## C. TASKS TO BE PERFORMED

### Task 1 – Hybrid System Build for Durability Testing on Test Stand

Build three (3) hydraulic hybrid Power Transmission Assemblies for full lifecycle loading on a durability stand.

Task 1 Report-out – As reported in the Quarterly report for the US DOE Project period ending 03/31/2011 the following is the summary and report out for the Hybrid System Build for Durability Testing on Test Stand. Two Durability Units transmission units were built and tested during the period. Testing parameters were defined based on route profile data and life expectancy. Input parameters included torque, rpm, hydraulic system pressure, and pump displacement(s). Output of the calculations based on this was the necessary run time to test the gears and bearings to meet life expectancy. An image of the unit on test stand is provided below, unit #1 was tested to life expectancy during the period, units #2 & #3 were put on test and testing started during the period. All units passed the life expectancy during the test periods.

Additional summary notes are provided to summarize the testing and test set-ups: three transmissions were built from the initial designed assembly. These were tested on a bench dynamometer with a torque sensor for the output and a rudimentary hydraulic circuit with a fixed relief pressure to simulate hydraulic load. They were tested at steady state conditions, and the output torque was transferred back to the input shaft in supplemented with an electric motor to simulate the engine input, also known as a four square test setup. The purpose of this testing was to determine any major flaws in the design for this application. After a rigorous cycle of testing without failure, the units were taken off and disassembled to determine if there were any obvious signs of fatigue or overloading. These can be done with a dye penetrant to determine if there was any pitting or cracking in any gears or shafts inside the gearbox. Also, metal shavings found inside the case or lubrication system would be obvious signs of wear. Since none of those were found, the design was moved forward to the vehicle level. If they had been found, the design would be adjusted to compensate once the loading condition that caused it was discovered. This could have involved for example increasing the diameter of a shaft, changing a choice of bearing, changing lubrication channels, or changing a heat treatment on a component.



Parker Durability Unites on Test Stand

Task 2 – Hybrid System Build for Durability Testing in vehicle

Build (18) complete hydraulic hybrid Power Transmission Assemblies and complete hydraulic circuit with associated control hardware and sub-system components for installation into a vehicle. Please note that this vehicle count may be reduced as a part of this program, notice would be provided to DOE in a timely fashion.

Task 2 Report-out – This Hybrid System Build for Durability Testing in vehicle was performed and durability testing only performed throughout this report for 48 vehicles in the field. Note that the increased vehicle count added to the quality and content of data available in this report, exposure to multiple routes, route profiles, route geography and drivers. The systems were built and prepared for shipment to the OEM partner FCCC for final assembly onto the chassis for final chassis build on the assembly line.

Task 3 – Chassis build

Complete chassis build for (18) vehicles, which will be delivered to the body builder for body installation. Please note that this vehicle count may be reduced as a part of this program, notice would be provided to DOE in a timely fashion.

Task 3 Report-out – As discussed in task 2, 48 vehicle systems were built and demonstration data provided in this final report. As part of this report, work supporting vehicle chassis builds starting from the quarterly report period ending 03/31/11 through 12/31/12. All vehicle build data and internal reports are property of our OEM partner FCCC and are not available for disclosure in this report. Vehicles are not shipped unless they pass the internal rigorous standards as well as internal dynamometer testing and internal reporting.

Task 4 – Body Assembly onto Chassis.

Transport vehicle chassis’ with hybrid hydraulic drivetrain installed to the body builder. Install the vehicle bodies onto the chassis. Please note that this vehicle count may be reduced as a part of this program, notice would be provided to DOE in a timely fashion.

Task 4 Report-out – The body assembly process was relatively simple compared to the chassis integration, work supporting vehicle body assembly builds occurred starting from the quarterly report period ending 03/31/11 through 12/31/12. The body designer, Morgan Olson, was responsible for altering one of their designs while working with us to ensure it has the functionality we need. The main differences between the design for our vehicle and the standard vehicle were the required access panels to our hydraulic equipment for monitoring and servicing in the floor. Part of the design we incorporated a panel with a gauge for showing the current air pressure on the low pressure reservoir. This was incorporated with a push to test valve to prevent the gauge from being under pressure all the time. There is also a fill valve for the air side and for the hydraulic side for draining the reservoir when necessary. These need to have direct and easy access to maintenance personnel, but also need to be protected from the elements of the road so that they do not provide leak points for the system. The other difference was due to the change in components on the underside, mostly the accumulator and cooler, they had to provide tie down points to mount the body to the chassis. None of these modifications were incurred as part of this demonstration program.

Task 5 – Vehicle preparation for rolling dynamometer test

Vehicle startup and shakedown. Perform final check of vehicle and data acquisition prior to starting on rolling dynamometer for component and system testing and controls verification.

Task 5 Report-out – vehicle rolling dynamometer testing was actually performed prior to the body build, data acquisition system integration was performed as part of Vehicle preparation for field test with preferred partner(s). All dynamometer testing performed by the OEM partner was performed as part of the factory build, vehicles all passed internal dynamometer testing, and vehicles would not have been allowed to be shipped from FCCC unless they passed their detailed internal testing requirements. All of this data is considered confidential and not provided as part of this final report.

Task 6 – Vehicle preparation for durability, regulatory and simulated route profiles at test track

Final vehicle startup and shakedown at test track. Train drivers in operation of hybrid and baseline vehicles on simulated routes. Perform final check of vehicle and data acquisition.

Task 6 Report-out – vehicle build and preparation for durability, regulatory and simulated route profiles at test track was performed at the chassis and body builder, lessons learned were incorporated into build processes to streamline procedures. This task and subsequent future builds performed for all future vehicles became easier as time progressed, there were no major items to report in the build process

Task 7 – Vehicle testing for durability, regulatory and simulated route profiles at test track

Perform testing and operation of hybrid vehicle vehicles on simulated routes. This is to be completed at regulatory testing locations, and test track.  Monitor, collect data, maintain vehicle on established schedule.

Task 7 Report-out – Vehicle testing for durability, regulatory and simulated route profiles at test track were performed to accelerate mileage and durability prior to sending vehicles to the field. This durability testing identified opportunities for upgrades. The durability vehicles built as part of this were early production vehicles that did have some upgrades performed as reported in the quarterly reports in the area of the gearbox, cooler, low pressure reservoir, air tanks, ECU mounting brackets, minor paint touch up, and the latest control software. Once upgraded, the vehicles performed successfully in route. Additionally, demonstration data was recorded for all vehicles built with Parker advanced series hybrid systems, more specifically in terms of durability vehicles, 6 vehicles were built. Data was collected from all vehicles, and support provided for only for 3 of these units as 3 were used as development vehicles and supported by other resources outside of this program. The benefit of data collection from all vehicles is to document the mileage collected. Lastly, during this program, Parker utilized proving grounds for testing purposes; these included the Chrysler Proving Grounds in Chelsea, MI, the Ford Proving Grounds in Romeo MI, and lastly at the Transportation Research Center in East Liberty, OH. During the entire project period, 126, 616 test miles were collected.

Task 8 – Vehicle preparation for field test with preferred partner(s)

Final vehicle startup and shakedown at test track of the (14) vehicles for preferred partner(s) field testing. Please note that this vehicle count may be reduced as a part of this program, notice would be provided to DOE in a timely fashion. Train drivers in operation of hybrid and baseline vehicles on selected routes.  Perform final check of vehicle and data acquisition.

Task 8 Report-out – As earlier discussed, the support for the 48 vehicle systems that were built for this durability and demonstration starting from the quarterly report period ending

03/31/11 through 12/31/12. The shakedown, upgrades, and vehicle preparation for field test with preferred partner(s) was performed through this period to prepare the vehicles to go into the field.

Task 9 – Field test (at multiple locations locations)

Begin field testing on selected routes with hybrid units. Field training complete and support personnel and equipment in place. Begin data acquisition to support monthly reports.

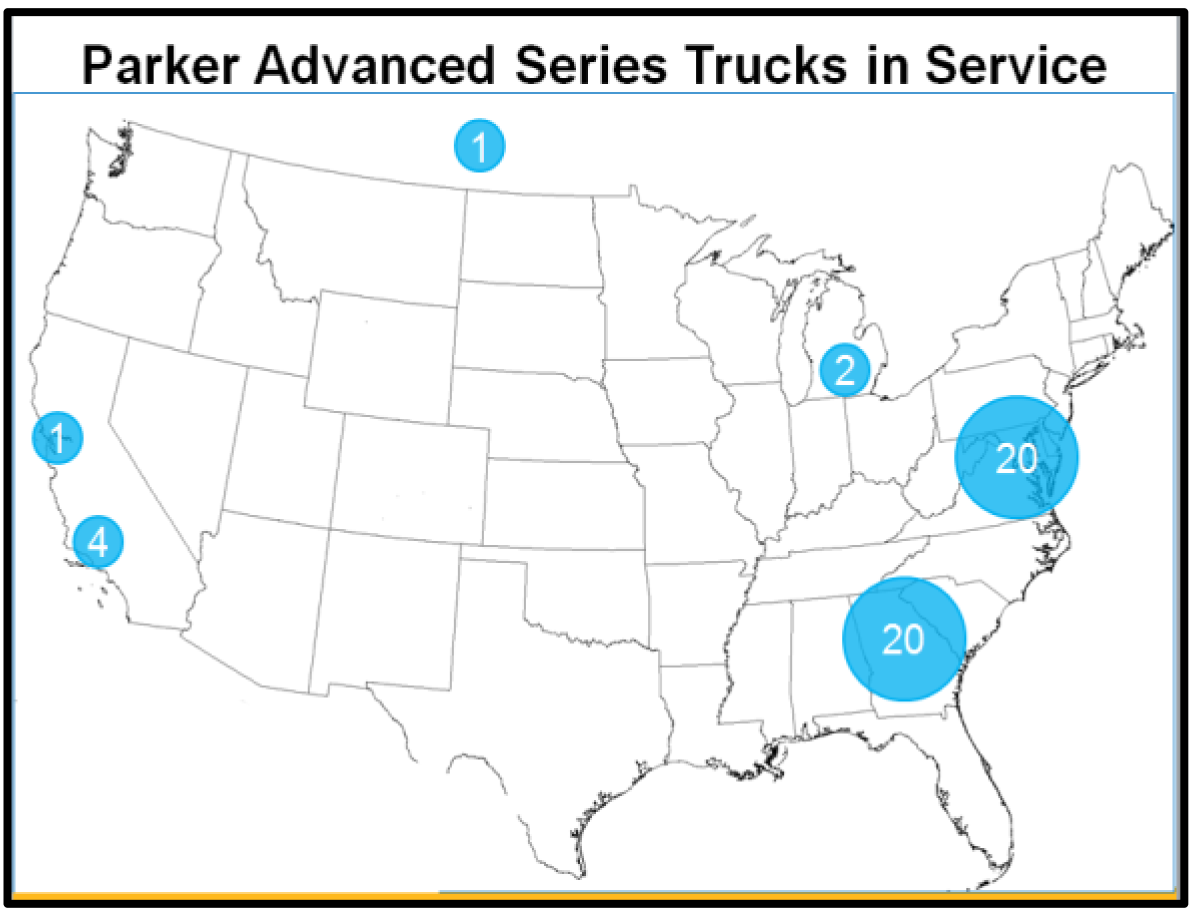
Subtask 9.1 – Field test (repeat based on locations)

Final vehicle startup and shakedown. Assist with driver training in operation and data collection methods for hybrid vehicles on selected routes. Perform final check of vehicle and instrumentation. Conduct field testing on selected routes with hybrid and active baseline units. Establish support personnel to maintain the hybrid drive units for the (14) vehicles and collect data for the entire hybrid fleet – (14) vehicles.

Task 9 Report-out – This section involved more interaction with the customer as their teams needed to inspect, plate and be trained on the vehicles prior to being placed into service. Once placed into service, additional training and support was provided as needed to support the drivers and field maintenance teams. It was at this point, that real world demonstration data was collected via telematics at no cost to the program on the following vehicle types:

- UPS vehicles – 41 vehicles
- FedEx Ground vehicles – 6 vehicles
- Purolator vehicle – 1 vehicle

Geographically, the vehicles were placed into service in the following areas and supported through this demonstration, in total 806,159 miles were accumulated:




The following is a detailed review of the vehicles, locations, and miles accumulated, as it can be seen the first vehicle placed into revenue service was done in 10/05/2011 and the last in 05/01/2013.

A table of the vehicle data is shown below highlighting the Vehicle Identification Number (VIN), date that the vehicle was placed into service (this was after the vehicle build, body build onto the chassis, vehicle shakedown, customer inspection, plating, and final preparation for field service), Vehicle location that it was placed into service, current status, vehicle owner, and total miles during the period. Additionally, the last column on the chart highlights the Fuel economy average in the field during the demonstration period. It should be noted that results identified in the study by other third parties validated the savings potential in fuel reduction of on average of 19% to 52% over the baseline in terms of mpg (Lammert, 2014, p8), Parker data in the field parallels this at a range of 35% - 50%. This means that when you review the Fuel economy average data in the table below, you need to recognize that comparative review by Parker teams of field data documented that these routes were improved 35% - 50% in terms of fuel economy as a result of deploying these systems. This means that when you review the Fuel economy average data in the table below, you need to recognize that comparative review by Parker teams of field data documented that these routes were improved approximately 35% - 50% in terms of fuel economy as a result of deploying these systems:

## US Department of Energy Tracking Chart

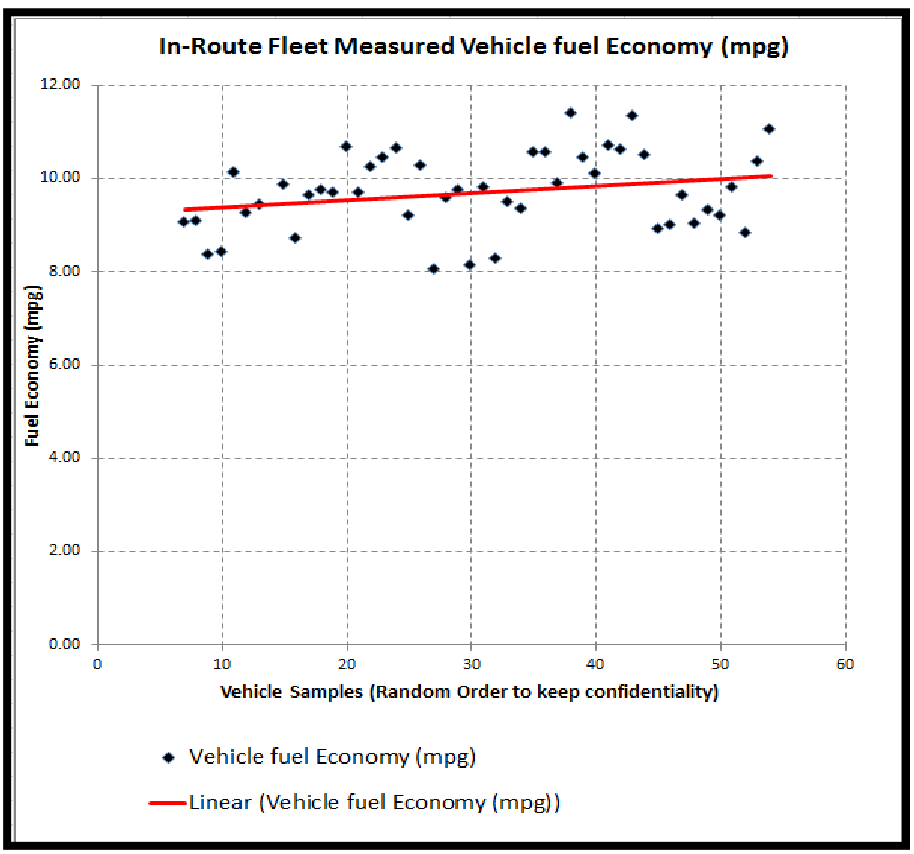
| Period | July 01, 2011 thru March 31, 2014 | | | | | |
|---|---|---|---|---|---|---|
| Completed by: | James Howland and Prasad Venkiteswaran | | | | | |

| # | Vehicle ID / last 4 of vin | First Date of Service | Vehicle Location | Vehicle Status | Vehicle Customer | Total Miles during period |
|---|---|---|---|---|---|---|
| 1 | PDV01 | 7/1/2011 | Columbus, OH | Lifecycle test complete | Freightliner | 9412.84 |
| 2 | PDV02 | 7/11/2011 | Columbus, OH | Controls Development | Freightliner | 5673.24 |
| 3 | PDV03 | 7/5/2011 | Gaffney, SC | FCCC DVP Testing Needs | Parker | 26275.29 |
| 4 | PDV04 | 7/1/2011 | Columbus, OH | Durability | Parker | 52429.42 |
| 5 | PDV05 | 11/2/2011 | Columbus, OH | Control Software Testing | Parker | 33026.56 |
| 6 | PDV06 | 2/10/2012 | Columbus, OH | EMB Testing | Parker | 799.17 |
| 7 | 2321 | 11/15/2011 | Livonia, MI | On Route | FedEx | 15229.07 |
| 8 | 2322 | 11/15/2011 | Saline, MI | On Route | FedEx | 19695.99 |
| 9 | 2323 | 10/7/2011 | Vernon, CA | On Route | FedEx | 11170.53 |
| 10 | 2324 | 10/5/2011 | San Francisco, CA | On Route | FedEx | 9924.23 |
| 11 | 2325 | 11/15/2011 | San Diego, CA | On Route | FedEx | 26959.94 |
| 12 | 2326 | 11/15/2011 | Whittier, CA | On Route | FedEx (CalStart) | 13966.46 |
| 13 | 1072 | 11/15/2011 | Toronto, Canada | On Route | Purolator (CalStart) | 4267.76 |
| 14 | 1073 | 11/15/2011 | Laguna Hills, CA | On Route | UPS (CalStart) | 21424.86 |
| 15 | 1079 | 9/14/2012 | Laurl, MD | On Route | UPS | 18718.48 |
| 16 | 1080 | 6/18/2012 | Laurl, MD | On Route | UPS | 17009.63 |
| 17 | 1081 | 9/25/2012 | Helethoroe, MD | On Route | UPS | 12854.17 |
| 18 | 1082 | 6/19/2012 | Laurl, MD | On Route | UPS | 19234.71 |
| 19 | 1083 | 9/24/2012 | Laurl, MD | On Route | UPS | 14845.75 |
| 20 | 1084 | 6/20/2012 | Laurl, MD | On Route | UPS | 17488.83 |
| 21 | 1085 | 6/25/2012 | Laurl, MD | On Route | UPS | 13507.85 |
| 22 | 1086 | 9/21/2012 | Laurl, MD | On Route | UPS | 13208.84 |
| 23 | 1087 | 9/21/2012 | Helethoroe, MD | On Route | UPS | 12800.18 |
| 24 | 1088 | 6/21/2012 | Helethoroe, MD | On Route | UPS | 19797.47 |
| 25 | 1089 | 6/21/2012 | Laurl, MD | On Route | UPS | 17134.20 |
| 26 | 1090 | 9/24/2012 | Helethoroe, MD | On Route | UPS | 15428.90 |
| 27 | 1091 | 9/27/2012 | Helethoroe, MD | On Route | UPS | 7097.13 |
| 28 | 1092 | 9/24/2012 | Helethoroe, MD | On Route | UPS | 21694.33 |
| 29 | 1093 | 9/21/2012 | Helethoroe, MD | On Route | UPS | 16651.63 |
| 30 | 1094 | 9/24/2012 | Helethoroe, MD | On Route | UPS | 16954.56 |
| 31 | 1095 | 9/27/2012 | Helethoroe, MD | On Route | UPS | 12295.82 |
| 32 | 1096 | 10/2/2012 | Laurl, MD | On Route | UPS | 18132.09 |
| 33 | 1097 | 9/24/2012 | Laurl, MD | On Route | UPS | 14721.59 |
| 34 | 1098 | 9/24/2012 | Laurl, MD | On Route | UPS | 17491.23 |
| 35 | 1099 | 2/12/2013 | Atlanta, GA | On Route | UPS | 14089.51 |
| 36 | 1100 | 2/12/2013 | Atlanta, GA | On Route | UPS | 12835.22 |
| 37 | 1101 | 2/12/2013 | Atlanta, GA | On Route | UPS | 11961.08 |
| 38 | 1102 | 2/12/2013 | Atlanta, GA | On Route | UPS | 18553.82 |
| 39 | 1103 | 2/22/2013 | Atlanta, GA | On Route | UPS | 11214.87 |
| 40 | 1104 | 2/26/2013 | Atlanta, GA | On Route | UPS | 12938.30 |
| 41 | 1105 | 2/25/2013 | Atlanta, GA | On Route | UPS | 12539.61 |
| 42 | 1106 | 3/5/2013 | Atlanta, GA | On Route | UPS | 9757.59 |
| 43 | 1107 | 3/18/2013 | Atlanta, GA | On Route | UPS | 12270.12 |
| 44 | 1108 | 3/21/2013 | Atlanta, GA | On Route | UPS | 19965.24 |
| 45 | 1109 | 3/12/2013 | Atlanta, GA | On Route | UPS | 12190.35 |
| 46 | 1110 | 3/22/2013 | Atlanta, GA | On Route | UPS | 6685.26 |
| 47 | 1111 | 2/4/2013 | Atlanta, GA | On Route | UPS | 10044.63 |
| 48 | 1112 | 3/26/2013 | Atlanta, GA | On Route | UPS | 11972.32 |
| 49 | 1113 | 4/1/2013 | Atlanta, GA | On Route | UPS | 8536.23 |
| 50 | 1114 | 3/27/2013 | Atlanta, GA | On Route | UPS | 10513.00 |
| 51 | 1115 | 5/1/2013 | Atlanta, GA | On Route | UPS | 7771.18 |
| 52 | 1116 | 2/8/2013 | Atlanta, GA | On Route | UPS | 8844.58 |
| 53 | 1117 | 4/25/2013 | Atlanta, GA | On Route | UPS | 9479.08 |
| 54 | 1118 | 1/30/2013 | Atlanta, GA | On Route | UPS | 16674.85 |

The vehicle demonstration data represents the following distribution representing a nice sample size of 48 vehicles over 10K miles:

| Distribution of Vehicle Mileage | | | | |
|---|---|---|---|---|
| Mileage | 20K+ | 15K - 20K | 10K - 15K | 4K - 10K |
| Number of Vehicles | 3 | 16 | 20 | 9 |

The following is a distribution of the fuel economy for the above vehicles listed, as you can see the average for the 48 vehicle sample size with the advanced series hybrid raised the average fuel economy to 8 to 12 mpg.



Task 10 – Hybrid System Testing on Durability Test Stand

Install on stand, and perform full lifecycle loading on a durability stand

Task 10 Report-out – The detailed dynamometer route testing was not performed as part of this demonstration, however work was performed by independent third parties on a sample of the vehicles that were monitored and supported in the field in this demonstration. This work was performed by two independent agencies, NREL & CALSTART. Based on this independent testing, the following data was collected validating the fuel economy performance and emissions reductions.

The following is a table of the baseline and advanced series hybrid test vehicles tested by NREL (Lammert, 2014, p2) for both diesel and gasoline.

| Van Specification | Conventional Diesel Van | Conventional Gasoline Van | Hydraulic Hybrid Van |
|---|---|---|---|
| Chassis Manufacturer | Freightliner | Workhorse W62 | Freightliner |
| Van manufacturer | Utilimaster | 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 | Automatic | Parker Hannifin IVT |
| Retarder/regenerative braking | None | None | Regenerative Braking |
| Air conditioning type | None | None | None |
| Gross vehicle weight | 23,000 lbs | 19,500 lbs | 23,000 lbs |

Lammert, 2014, p2

Specifications for the Parker Hybrid as tested by NREL are as follows (Lemmert, 2014, p3):

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

Lammert, 2014, p3

Based on the above, NREL used standard practice for GPS & J1939 vehicle data logging, DRIVE Analysis, standard and custom test cycle selection, dynamometer testing, emissions and fuel measurements (Lemmert, 2014, p3-10). In addition to the standard tests utilized for evaluation, a Baltimore Custom cycle was developed based on in route real world data, the following highlights the daily vehicle performance in Baltimore and the distribution of speed vs miles travelled in the evaluation to develop the custom cycle (Lammert, 2014, p6).

## 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

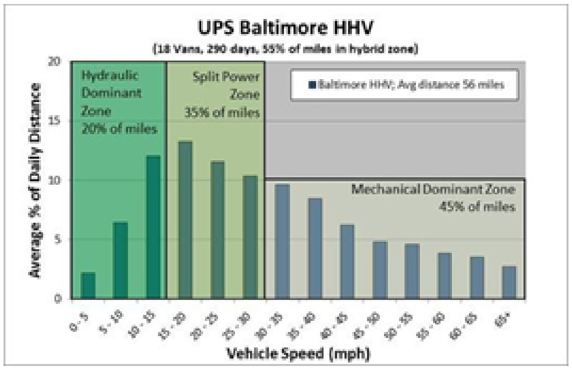



*Figure 1. Hybrid Duty Cycle Breakdown by Percent Miles Traveled*

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.

**Table 3. Drive Cycle Statistics from Baltimore Vans**

| 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 |

Lammert, 2014, p6

Based on the vehicle routes identified and then tested, the following is a table of the test results.

| Gravimetric Fuel Economy | NY Comp | CSHVC | CARB HHDDT | Baltimore 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% |

Lammert, 2014, p8

As can be seen from the numbers highlighted by NREL above, and in the Summary conclusion notes below, the Parker Hydraulic Hybrid Advanced Series unit does display significant advantages for high start & stop operations. Also, in those over the road, high highway miles, the improvement is lower, only showing a 3% improvement (Lammert, 2014, p8).

## 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.

Lammert, 2014, p11

In addition to the great work completed by NREL on the dynamometer and use of field data for custom dynamometer route profiles, CALSTART also completed independent research on the Parker Advanced Series hydraulic Hybrid and performed testing in the field for fuel economy and emissions (Gallo, 2014, p10-18). During their entire demonstration period, the CALSTART team data logged 22,988 (Parker telematics data) miles on 2 of the three vehicles, data acquisition was not connected to the third vehicle during the demonstration period (Gallo, 2014, p10). Parker data shows that the three vehicles deployed under the CALSTART program accumulated a total of 39,836 from

11/15/2011 through 03/31/2014. The CALSTART data report is interesting as it showcases and evaluates the engine run time, and the engine off time, both of which conditions contribute significantly to the reduction in fuel consumed (Gallo, 2014, p10-15). The following is a sample of this data for the vehicle operation results (Gallo, 2014, p10):

High resolution data was provided for selected periods of time for both Unit B and Unit C. Table 5 below presents the summary of the high resolution data for the following periods of time.

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

Gallo, 2014, p10

Based on this data, the engine was shut off between 12 % - 16% of the time during operation showcasing the capability of the vehicle to propel itself without the engine using stored power with normal route loading in the vehicle with the standard hydraulic hybrid configuration in the vehicle (Gallo, 2014, p10). In order to collect data from a conventional vehicle in route, the following is the information from the baseline vehicle tested (Gallo, 2014, p28).

| 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 |

Gallo, 2014, p28

This vehicle was driven on three (3) similar routes as one of the CALSTART vehicles so that a meaningful comparison could be made in terms of fuel and emissions performance (Gallo, 2014, p14-15). The following is the comparison data of the routes and the performance, as in the case of the NREL data, the CALSTART data reinforces the performance of the vehicles in high start applications 29% to 50% as well as smaller performance gains in the on highway low start stop cycles 4.7% to 10% for an average improvement of 22.8% to 40% improvement in fuel economy (Gallo, 2014, p14-15).

**Table ES-4: 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. |

Gallo, 2014, p14

Additional testing was performed by CALSTART in the area of on-route emissions testing using a third party testing lab Engine, Fuel, and Emissions Engineering, Inc. This testing was performed by testing the in service vehicle and also testing the baseline vehicle while following the in service vehicle (Gallo, 2014, p15). Based on this testing, the following is the data and conclusions drawn by CALSTART highlighting the improved fuel economy and emission of the Parker Hydraulic Advanced Series Unit (Gallo, 2014, p15).

**Table ES-5: 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.

Gallo, 2014, p15

Task 11 – Baseline Vehicle Lease

Lease baseline vehicles that can be utilized to operate at test track for testing on a simulated route to enable a comparison of emissions generation and fuel consumption as compared to a hydraulic hybrid delivery vehicle. This vehicle can also be shipped to the field for testing, associated expenses with transportation, licensing, and insurance will be captured

Task 11 Report-out – The detailed dynamometer route testing on a baseline vehicle was not performed as part of this demonstration, however work was performed by independent third parties on a sample of the vehicles that were monitored and supported in the field in this demonstration. This work was performed by two independent agencies, NREL & CALSTART as reported in task 10

Task 12 – Baseline Vehicle Testing for Fuel Economy and Emissions

Perform testing and operation of baseline on a simulated route to enable a comparison of emissions generation and fuel consumption as compared to a hydraulic hybrid delivery vehicle

Task 12 Report-out – The detailed dynamometer route testing on a baseline vehicle was not performed as part of this demonstration, however work was performed by independent third parties on a sample of the vehicles that were monitored and supported in the field in this demonstration. This work was performed by two independent agencies, NREL & CALSTART as reported in task 10

Task 13 - Project Management and Reporting

This project has an assigned team that is responsible for meeting all outlined deliverables.  Project reviews, planning, open issues meetings, scheduling, and cost collection and outside supplier reviews are held on a regular basis to ensure that the program is on track to meet outlined objectives. Test reports will be provided in accordance with the Federal Assistance Reporting Checklist following the instructions included therein.

Task 13 Report-out – Project Management and Reporting activities were logged throughout this program and then used in the documentation of the quarterly reports provided throughout the project. Additionally, Project Management and Reporting support documentation was used in the creation of this report.

## D. DELIVERABLES

The Recipient shall provide reports in accordance with the enclosed Federal Assistance Reporting Checklist and the instructions accompanying the Checklist. In addition to the reports identified on the Reporting Checklist, the Recipient shall provide the following to the Project Manager identified in Block 11 of the Notice of Financial Assistance Award (NFAA):

The Recipient shall prepare a Project Management Plan designed to achieve the project objectives, covering the entire Project Period, but focusing on the current Budget Period. The Project

Management Plan shall include a task structure and supporting narrative that concisely addresses the overall project as set forth in the agreement.  In addition, the Project Management Plan shall provide a concise summary of the technical objectives and technical approach for each Task and include a detailed plan for reporting on the key activities and/or tasks.  The Project Management Plan shall provide detailed schedules and planned expenditures for each Task, major milestones, and decision points, including the development of the criteria upon which GO/NO decisions are based.

The Recipient shall prepare a Risk Management and Mitigation Plan designed to identify key technical and schedule risk items and outline mitigation strategies to minimize project impacts. If a suitable Failure Management and Effects Analysis or Risk Management Plan has been developed for internal use by the Recipient, this is acceptable for use in this award.

In addition, the Recipient will provide the following deliverables to the Project Manager:

1) In person kickoff meeting to layout detailed milestones and objectives for each phase.

Report-out – this was done via phone with the DOE representative assigned to the program

2) Monthly informal progress updates that will highlight significant events including accomplishments and milestones achieved. These reports will serve as verification and documentation that specific milestones were completed.

Report-out – these were performed as required, informal calls occurred throughout the program as necessary

3) A brief summary report for inclusion in DOE annual program progress report (due by Sept 30th each year of program).

Report-out – all summaries were submitted quarterly as part of the quarterly updates

4) A written report to DOE leadership at the end of each program phase.

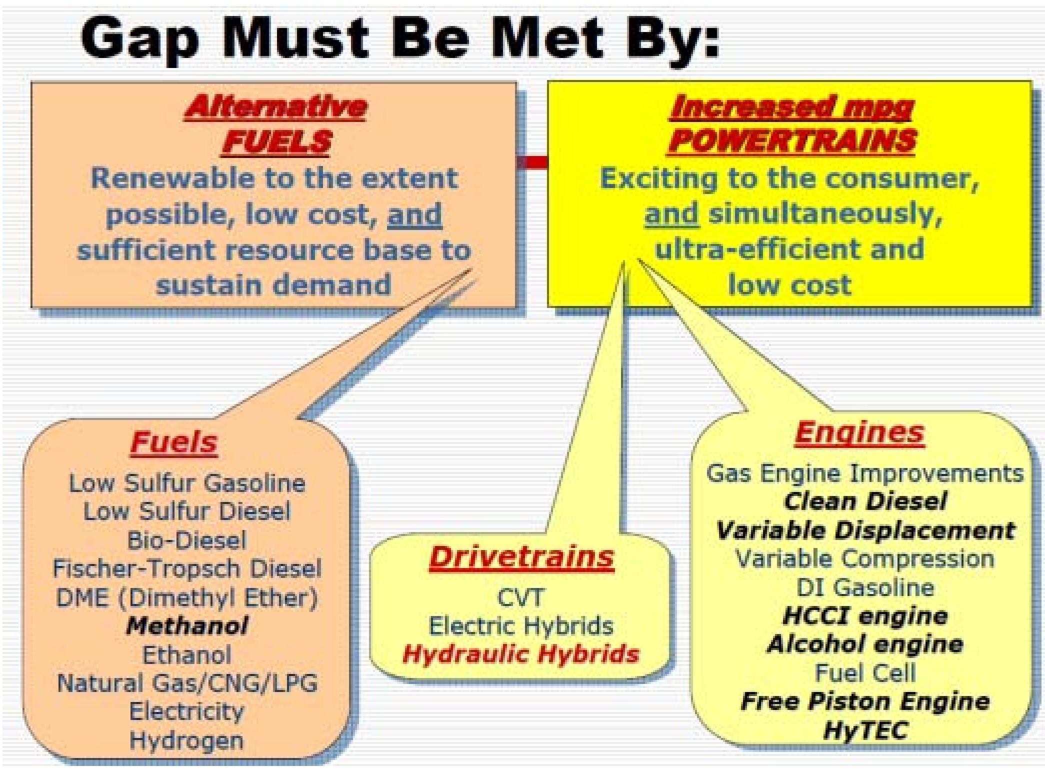
Report-out – this program was designed to support tasks and not phases, as a result, all reports were completed and submitted as part of the quarterly reviews.

5) A final report at the conclusion of the program.

Report-out – this report summaries and completes this requirement for a final report, any additional questions can be directed to the PI and will be addressed timely.

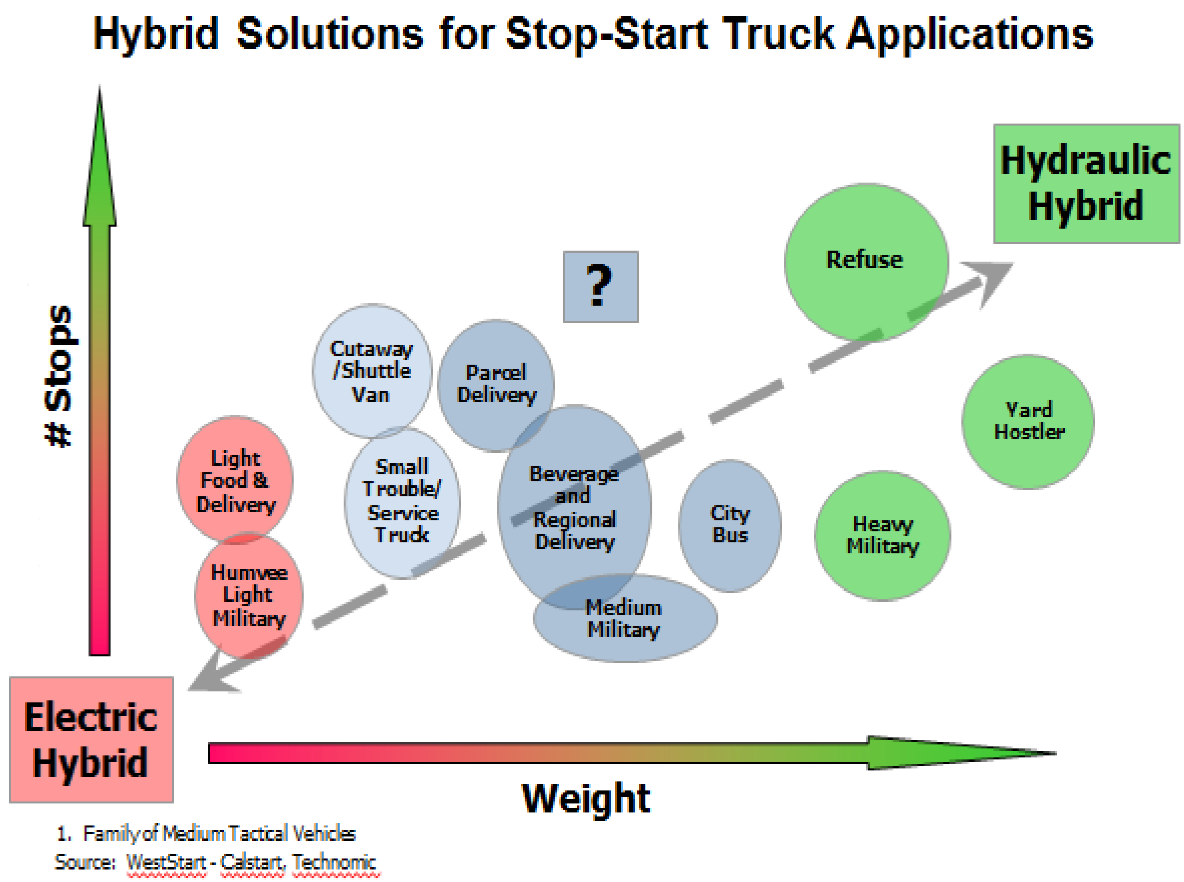
## Literature Review

A detailed review of technologies in the marketplace today will lead the reader to see that there are competing technologies in electric hybrids, hydraulic hybrids, and other technologies. The US EPA detailed out a Roadmap that identifies these areas for improvement in technology areas.




Gray, 2006, p2

Technologies that have entered the marketplace have addressed the following roadmap pretty closely in terms of start/stop platforms.




Maxwell, 2008, p26

The following is an interesting guide developed comparing some of the technologies developed supporting some of the platforms showcased above.

## Heavy-Duty Vehicle Application Overview

The following list provides an overview of popular alternative fuel and advanced vehicle options for several common applications:

| | |
|---|---|
| **School Bus** | Compressed natural gas (CNG) and propane (also known as liquefied petroleum gas, or LPG) are popular alternatives to gasoline and diesel fuel for school buses. Hybrid electric buses and plug-in hybrid electric buses are also available. |
| **Shuttle Bus** | CNG, propane, hybrid electrics, and fuel cells are potential options for shuttle buses and large passenger vehicles that provide transportation on standard routes. |
| **Transit Bus** | Hybrid transit buses, along with those powered by CNG or liquefied natural gas (LNG), are available. Fuel cell demonstrations are also in progress. |
| **Refuse Truck** | Many fleets have refuse trucks with CNG engines, and they can even run on landfill gas where biomethane processing facilities are in operation. Regular routes and stop-and-go operation make refuse haulers a good application for hybrid operation as well. Hydraulic hybrid systems are well suited to refuse service. |
| **Tractor** | Diesel electric hybrids offer fuel-saving hybrid operation with the convenient availability of diesel. CNG and LNG systems are also attractive options. |
| **Van** | Step vans that service a set route, such as a package delivery service, may find all-electric battery operation an effective alternative to conventional vans. CNG and propane operation are also popular alternatives. |
| **Vocational Truck** | CNG, LNG, propane, all-electric, and hybrid vehicles operate in a variety of roles, from beverage delivery to utility boom trucks, paint striping trucks, and merchandise delivery. |

Clean Cities, 2013, p4

Some of the technology and players that have entered the all-electric and electric hybrid market include those in the following slides to show the diversity, you can see that there are hybrid electric, plug-in hybrids, and all electric hybrids:

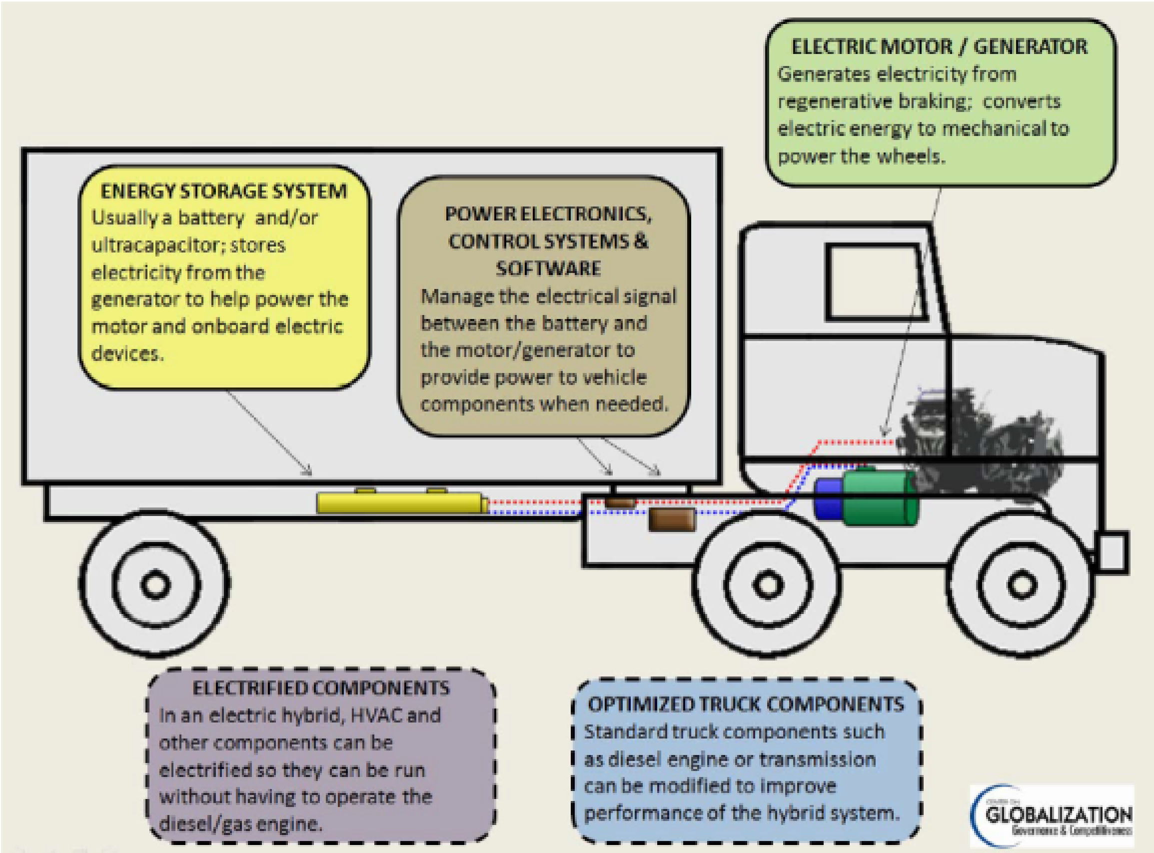
| Hybrid Propulsion System Manufacturers | | | |
|---|---|---|---|
| **Manufacturer** | **Model** | **Type** | **Website** |
| **Allison Transmission** | Allison H 40 EP | 2-mode split parallel | *www.allisontransmission.com* |
| **Allison Transmission** | Allison H 50 EP | 2-mode split parallel | *www.allisontransmission.com* |
| **BAE Systems** | HybriDrive Propulsion System | Series, parallel | *www.baesystems.com/ProductsServices/bae_prod_eis_hybridrive.html* |
| **DesignLine International** | ECOSaver IV | Series | *www.designlinecorporation.com* |
| **Eaton** | Eaton Hybrid Drive System | Parallel | *www.eaton.com* |
| **Eaton** | Eaton Hybrid HLA | Parallel | *www.eaton.com* |
| **Eaton** | Eaton Parallel Hybrid with Power Take-Off | Parallel | *www.eaton.com* |
| **Enova Systems** | Post Transmission Parallel Hybrid Electric Drive (90kW, 120kW, 170kW, 240kW Drive Systems) | Parallel | *www.enovasystems.com* |
| **Lightning Hybrids** | Hydraulic Hybrid | Parallel | *http://lightninghybrids.com* |
| **Odyne** | Odyne Plug-in hybrid with electric PTO | Parallel | *www.odyne.com* |
| **Parker Hannifin Corp.** | RunWise Advanced Hydraulic Hybrid | Series | *www.parker.com* |
| **Quantum Technologies** | F-Drive | Gasoline plug-in hybrid (150kW parallel system) | *www.qtww.com* |
| **Quantum Technologies** | M-Drive | Diesel (JP8) series hybrid system with 8-mile EV range | *www.qtww.com* |
| **Quantum Technologies** | Q-Drive | Gasoline plug-in hybrid (300kW series system) | *www.qtww.com* |
| **Quantum Technologies** | Quiet-Drive | 50kW EV drive system | *www.qtww.com* |
| **Voith** | DIWAhybrid | Parallel | *www.usa.voithturbo.com* |

Clean Cities, 2013, p16

Drivetrain Providers. At least 10 U.S. companies act as system developers that supply electric hybrid drivetrains to truck OEMs, including Allison Transmission, Arvin Meritor, Azure Dynamics, BAE Systems, Enova, Eaton Corporation and others. An additional system developer, Odyne, went out of business in 2009 and sold its assets to Dueco, with which it had developed class 6-8 aerial lift/bucket trucks. Of the remaining system integrators, only Azure Dynamics builds the hybrid drivetrain directly onto the truck chassis. More typical is the Eaton style arrangement, in which the system developer works with the truck OEM, manufacturing or modifying one or more components and sourcing the rest from other companies. The OEM generally integrates and installs the drivetrain into trucks on its production line.

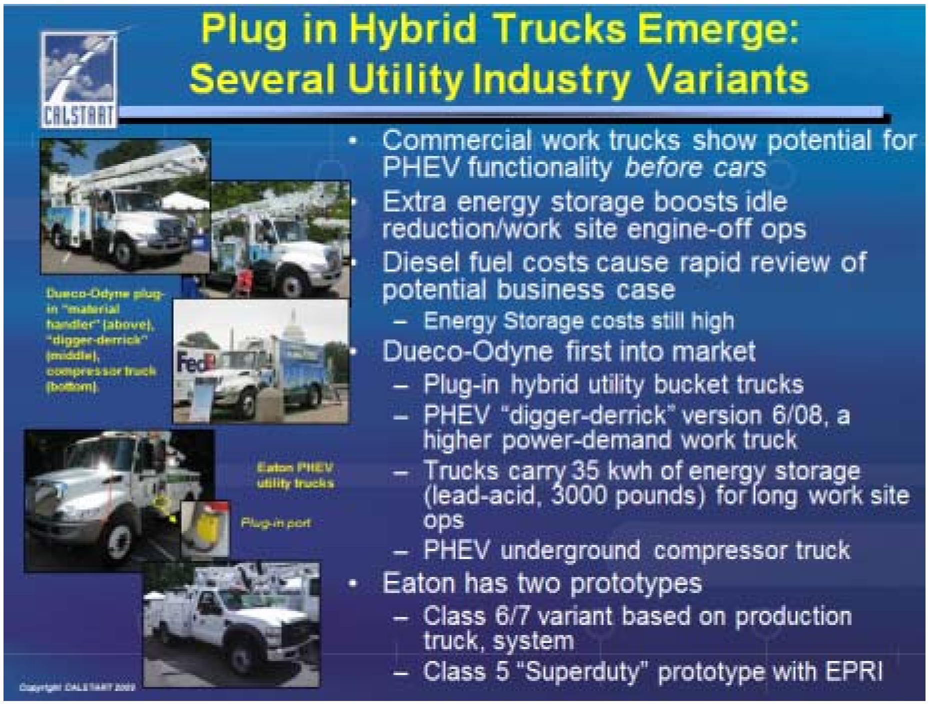
Ayee et al, 2009, p16

**Figure 2. Electric Hybrid Drivetrain for Medium- and Heavy-Duty Trucks**

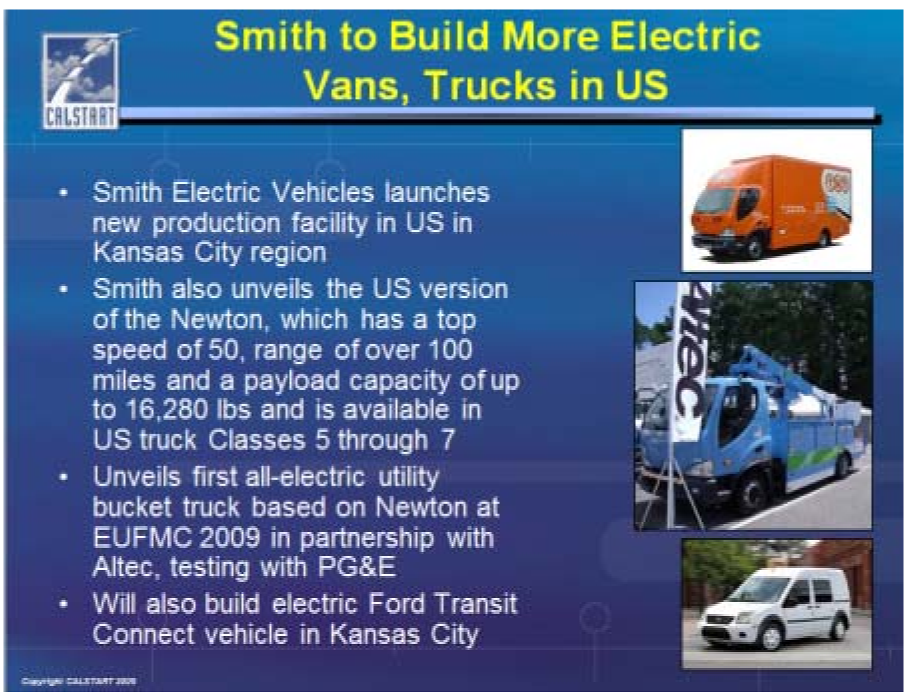



Note: This is an example of a Parallel Architecture.
Source: CGGC, based on (National Renewable Energy Laboratory, 2008).

Ayee et al, 2009, p9

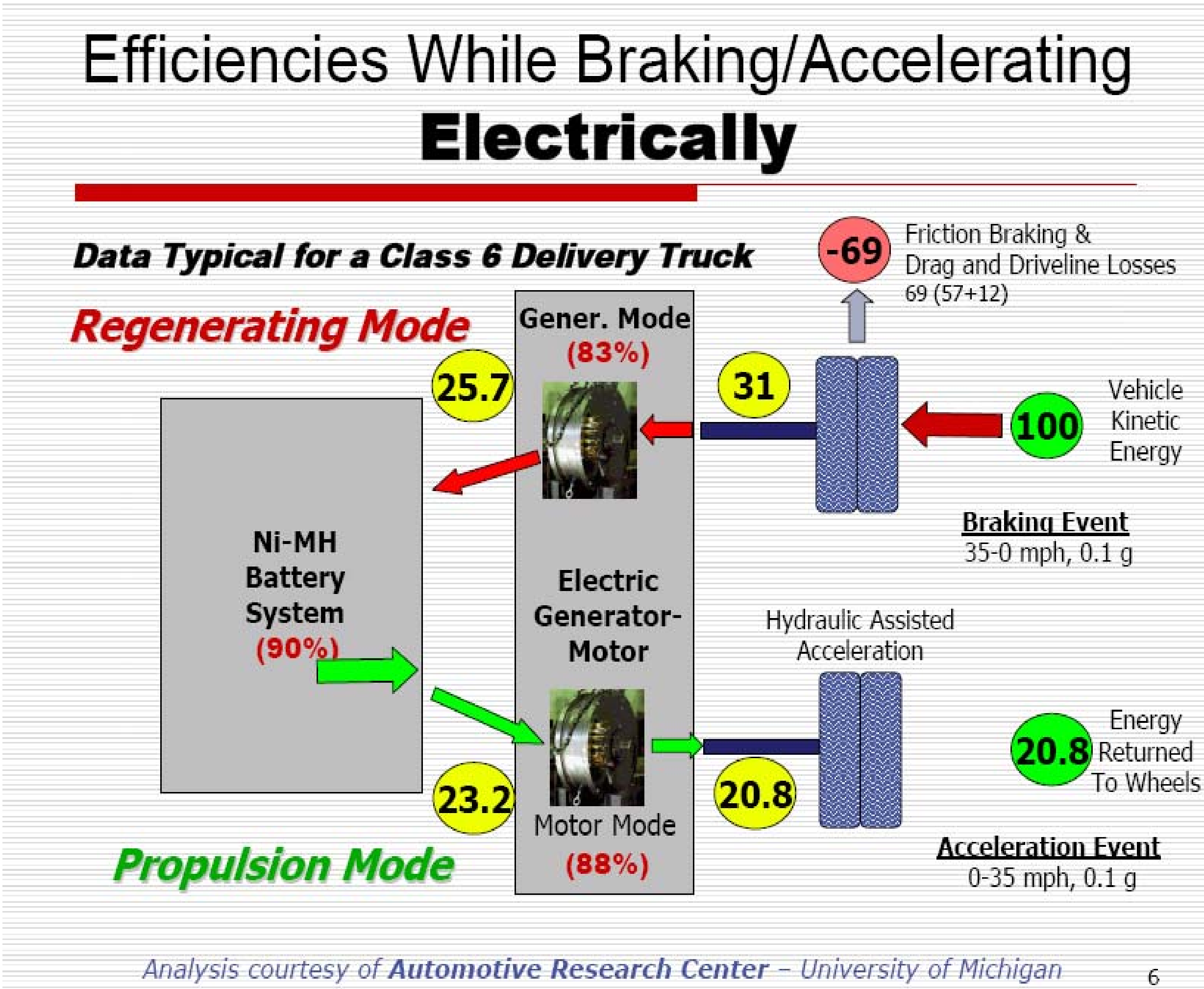



Van Amburg, 2009, p15

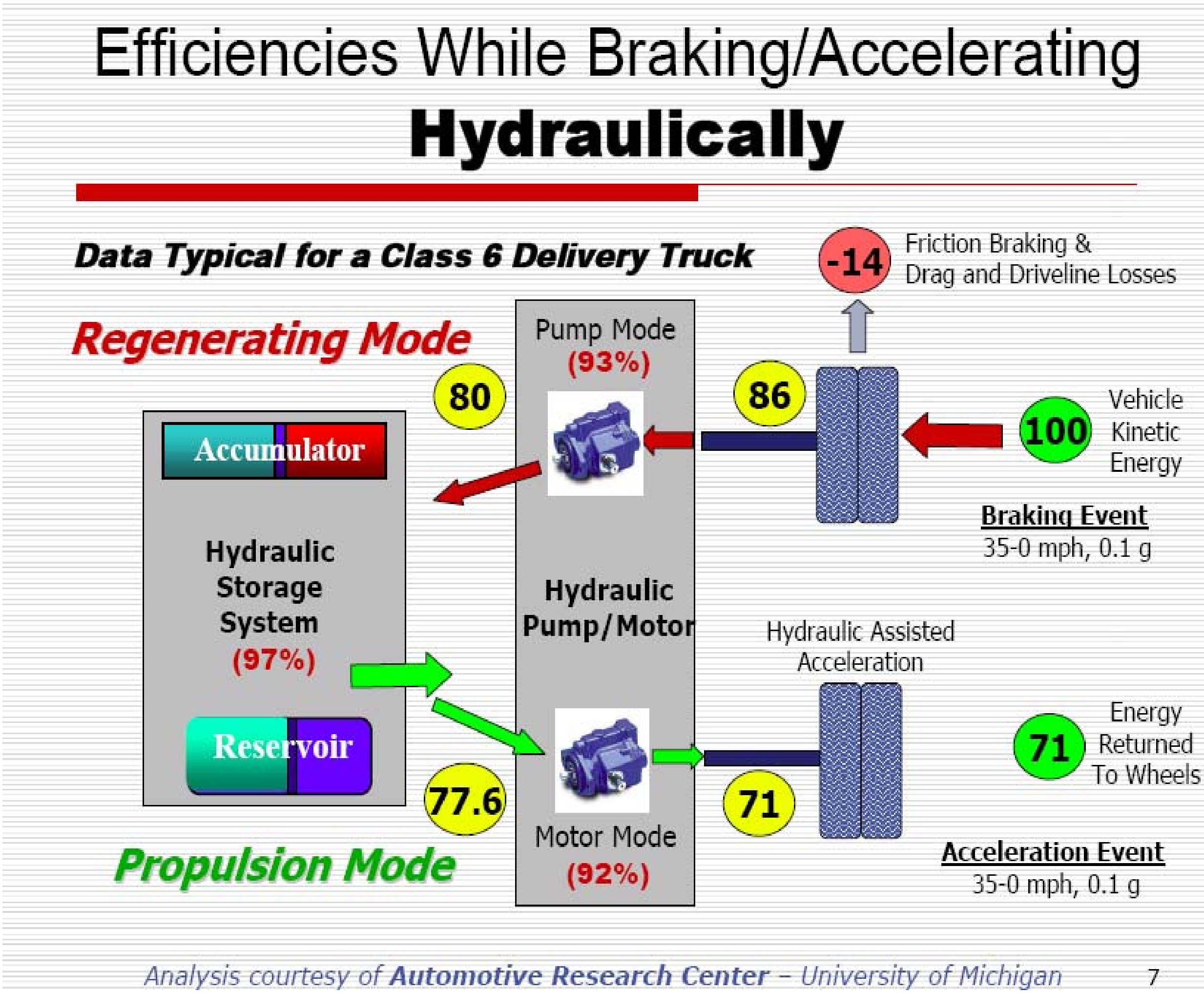



Van Amburg, 2009, p19

The above shows some of the diversity in researched and developed systems being deployed in different vehicle classes. Based on third party evaluation of technologies by the Automotive Research Center at the University of Michigan highlights the significant benefits and efficiencies while braking and accelerating leveraging hydraulic hybrids shows a 3.4+ TIMES GREATER benefit versus electric hybrids:

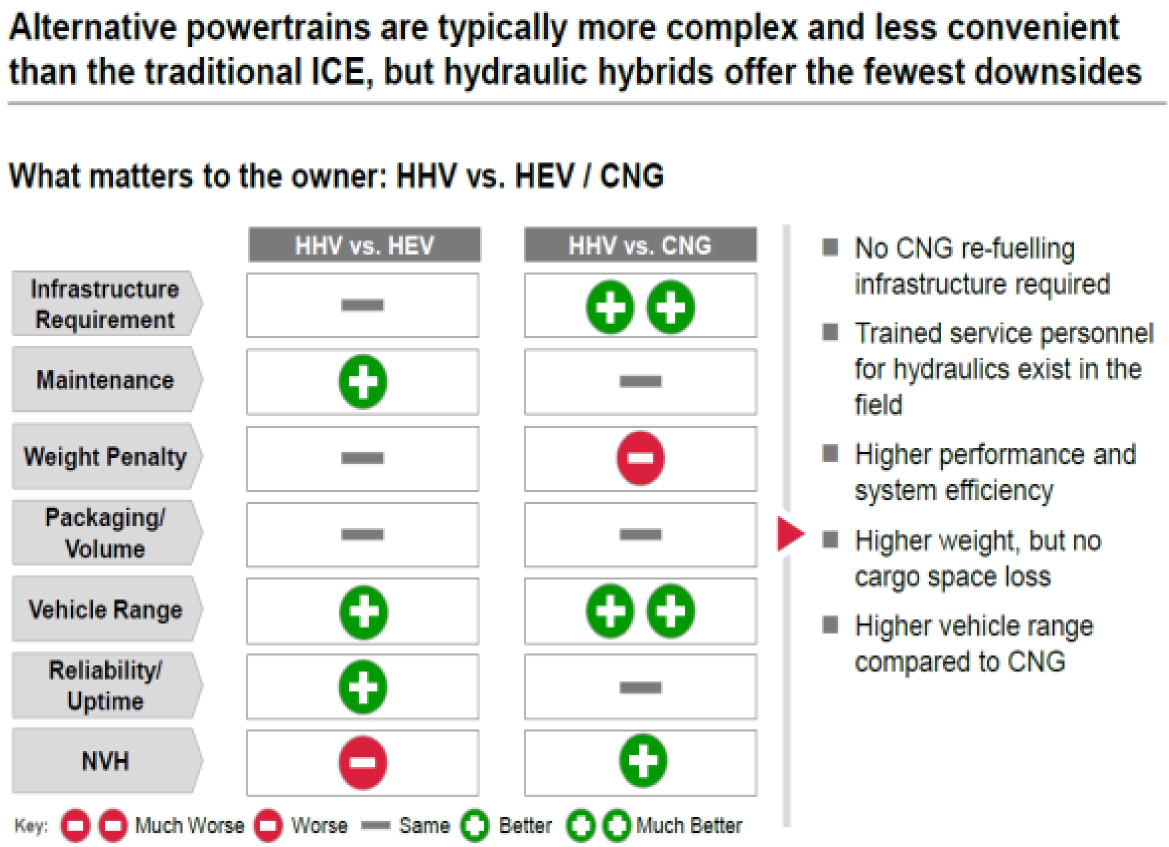



Gallo, 2014, p21



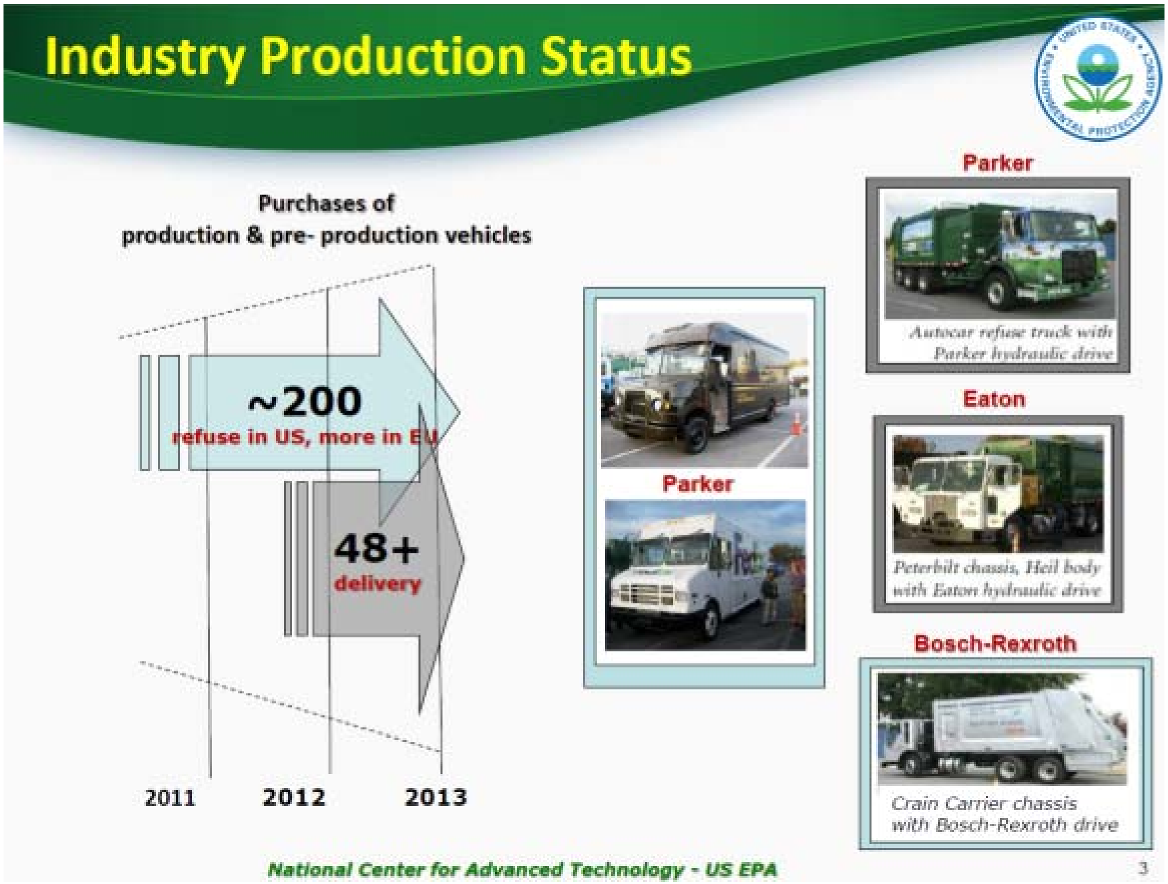

Gray, 2006, p14

Additional third party investigation highlights research performed comparing the cost of ownership of hydraulic hybrids to electric hybrids, as can be seen, hydraulic hybrids have benefits over both electric and cng applications



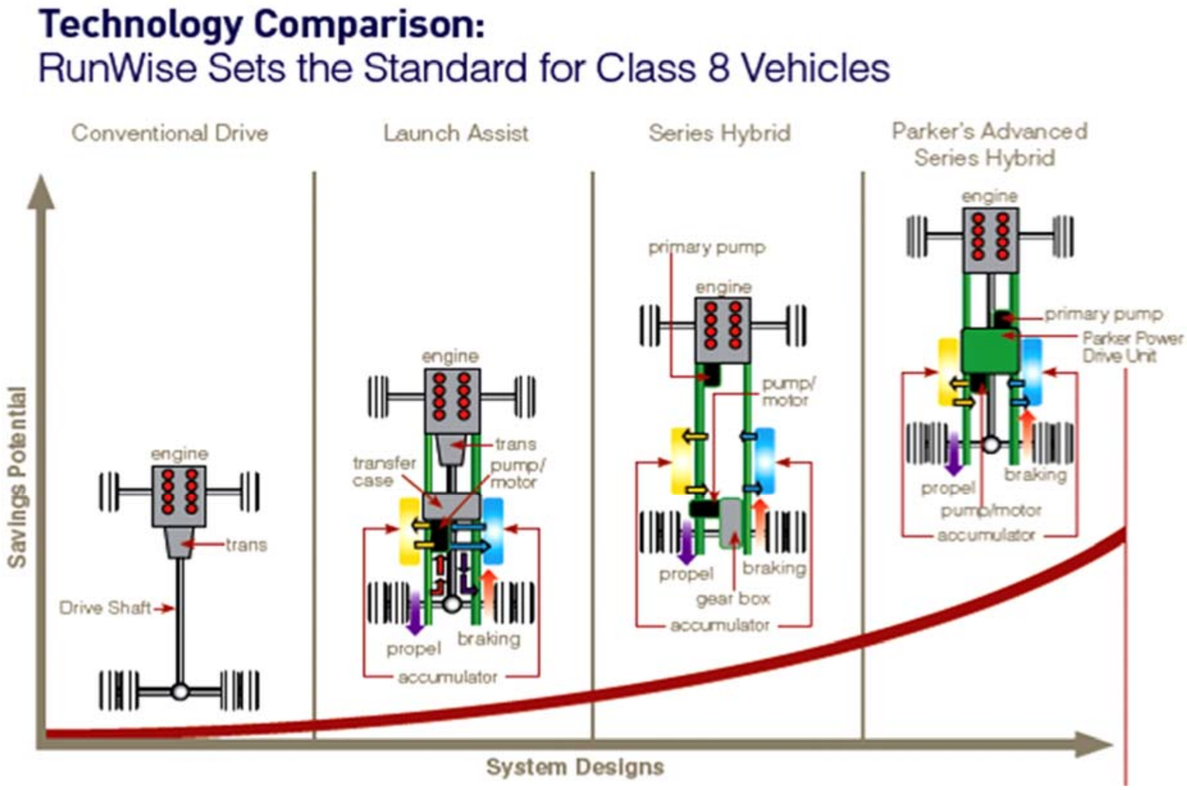

Tomazic, 2013, 21

On the hydraulic hybrid side, there has been development from the USEPA, Bosch, Eaton, Parker and a few more recently. The following showcase some of these technologies launched into the marketplace.

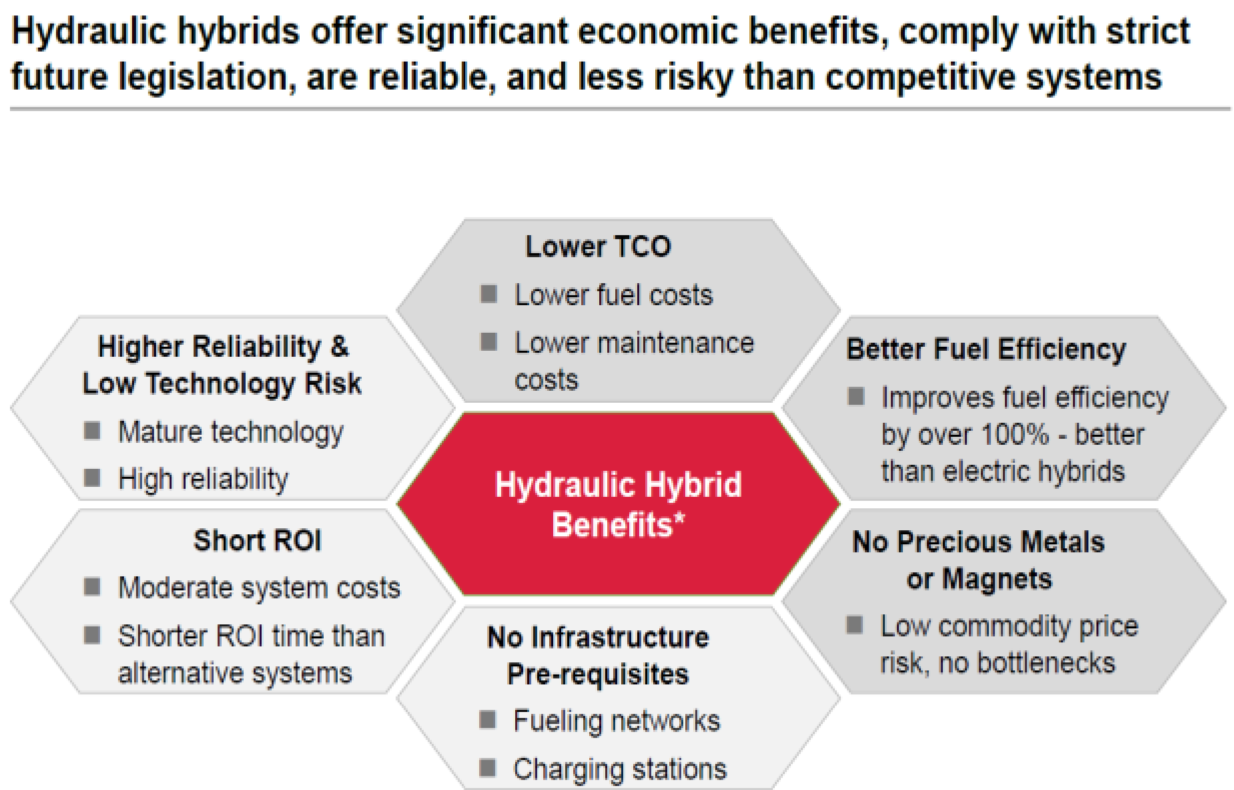



Kargul, 2013. P3

Parker has done extensive R&D in these areas and has identified the following roadmap of technologies and benefits that can be provided by hydraulic advanced series hybrid technologies:

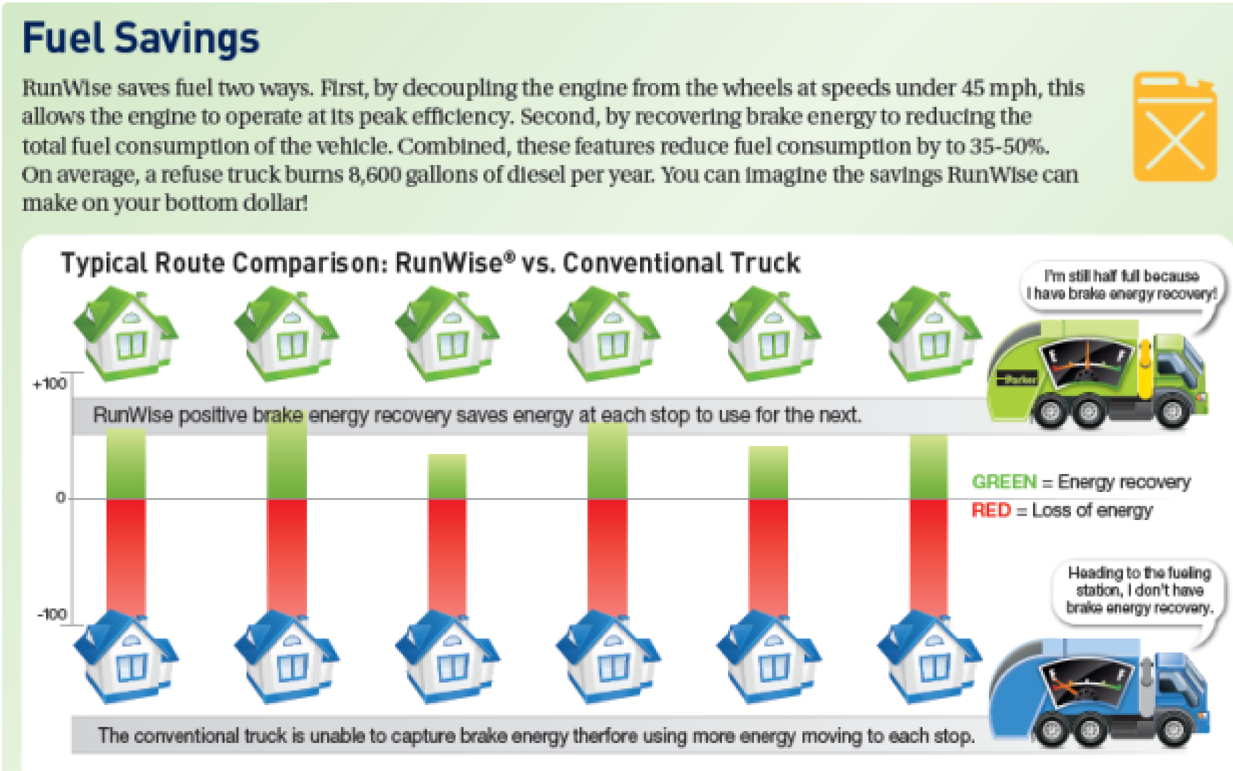



Parker has seen significant benefits in the deployment of advanced series technology in refuse applications. Additional third party research highlights additional benefits of the hydraulic hybrid technologies in many areas at a lower risk level (Tomazic, 3013, p12).




Tomazic, 3013, p12

Parker's Runwise technology has shown significant benefits in the Refuse applications, as this is a highly demanding load and mileage applications. As a result of leveraging brake energy recovery and optimized engine control with an average fuel savings of 35% - 50% based on the duty cycle, results vary as routes change.




Parker, 2013, p2

In order to evaluate the performance of the Parker RunWise system, third party evaluation of the system was performed comparing this to a conventional diesel as well as a natural gas vehicle and also a natural gas RunWise vehicle. Results were positive in these tests showing the improvements made in fuel economy as well as reductions in emission. The following are the results of this testing at the Ohio State Center for Automotive Research.

### The 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)

The testing was carried out between December 2012 and September 2013 to determine the fuel economy, carbon dioxide ($CO_2$) emissions, hydrocarbon emissions (THC), carbon monoxide (CO) and oxides of nitrogen (NOx) emissions.

The low speed comparison for fuel economy and $CO_2$ emissions clearly demonstrated the benefits of the trucks utilizing the RunWise drivetrain. The diesel hybrid achieved a low speed fuel economy of 1.31 mpg, more than double that of the CNG truck and 49% higher than the standard diesel. The diesel hybrid truck also produced just 7,800 grams of $CO_2$ per mile, a reduction of over 30% compared to the diesel configuration. Additionally, the CNG hybrid also demonstrated significant reductions over the CNG baseline, 37% reduction of $CO_2$ 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 $CO_2$ emissions were lowest with the CNG hybrid truck, followed closely by the CNG baseline at 2,035 grams per mile.

#### Low Speed Cycle

| | *mpg* | *g/mi* | | | |
|---|---|---|---|---|---|
| | Fuel Economy | $CO_2$ | CO | kNOx | THC |
| **Diesel** | 0.88 | 11,007 | 14.01 | 3.80 | 0 |
| **Diesel Hybrid** | 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 |

*Baseline CNG vehicle does not have aftertreatment catalyst.

#### High Speed Cycle

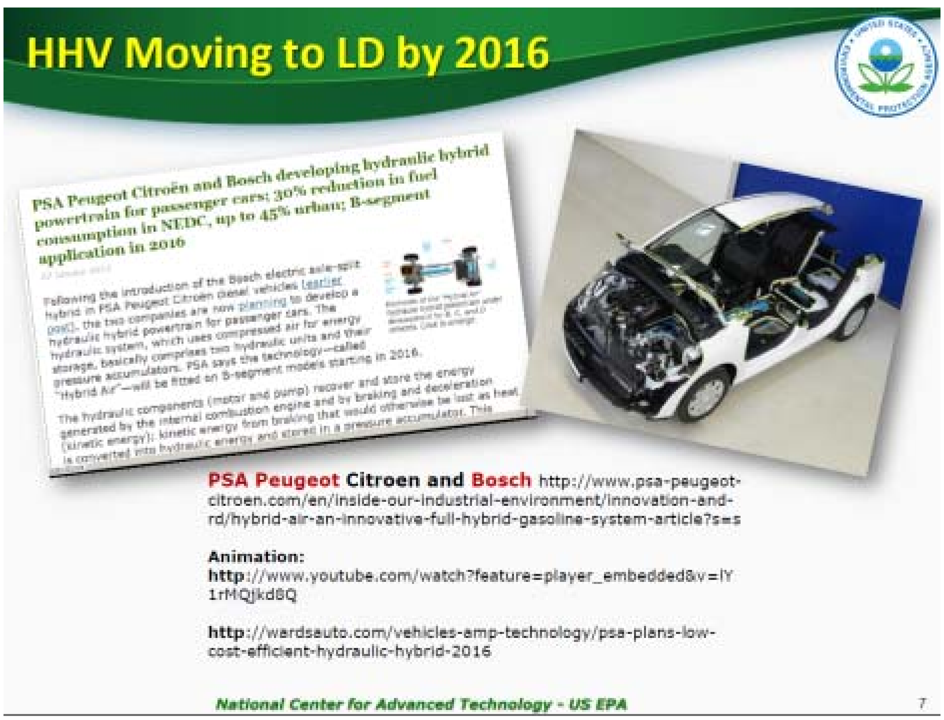
| | *mpg* | *g/mi* | | | |
|---|---|---|---|---|---|
| | Fuel Economy | $CO_2$ | CO | kNOx | THC |
| **Diesel** | 3.78 | 2,689 | 1.16 | 2.13 | 0.06 |
| **Diesel Hybrid** | 4.32 | 2,352 | 1.6 | 2.29 | 0.01 |
| **CNG** | 3.8 | 2,035 | 27.75* | 0.29* | 4.27* |
| **CNG Hybrid** | 4.06 | 1,928 | 8.33 | 0.82 | 0.11 |

*Baseline CNG vehicle does not have aftertreatment catalyst.

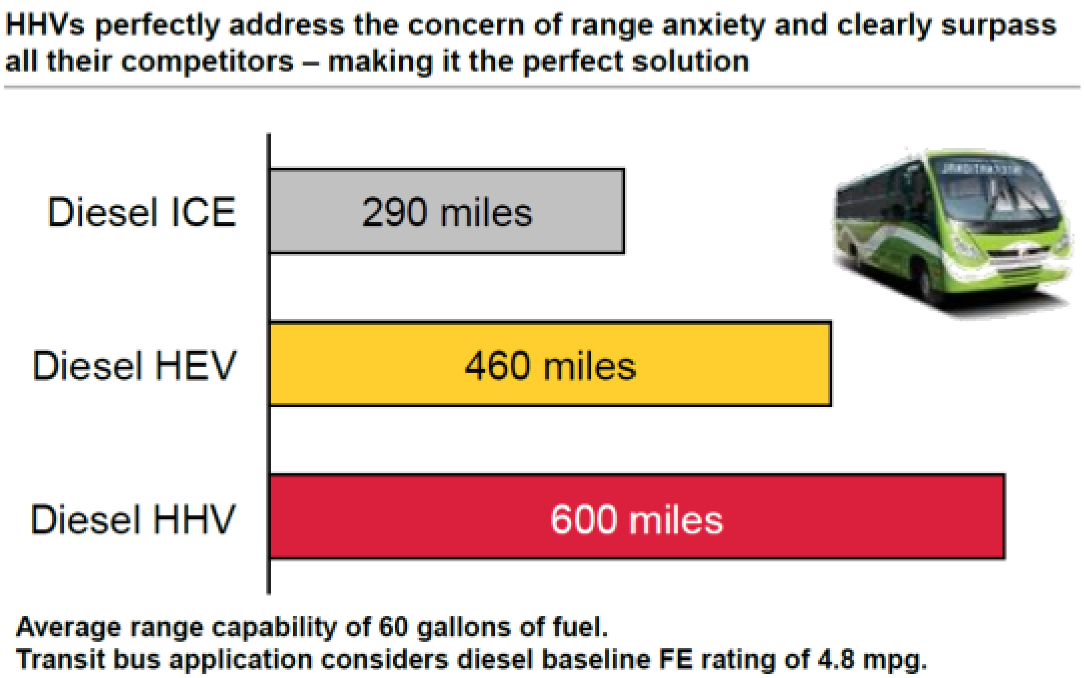
Parker, 2013, p3

More recently, additional technologies have been entering the marketplace. On the hydraulic hybrid side with additional configurations, some of these include off-road applications, transit and shuttle buses and automotive applications. In all cases, the technology benefits must positively impact the investment and savings that can be achieved,


Kargul, 2013, p6

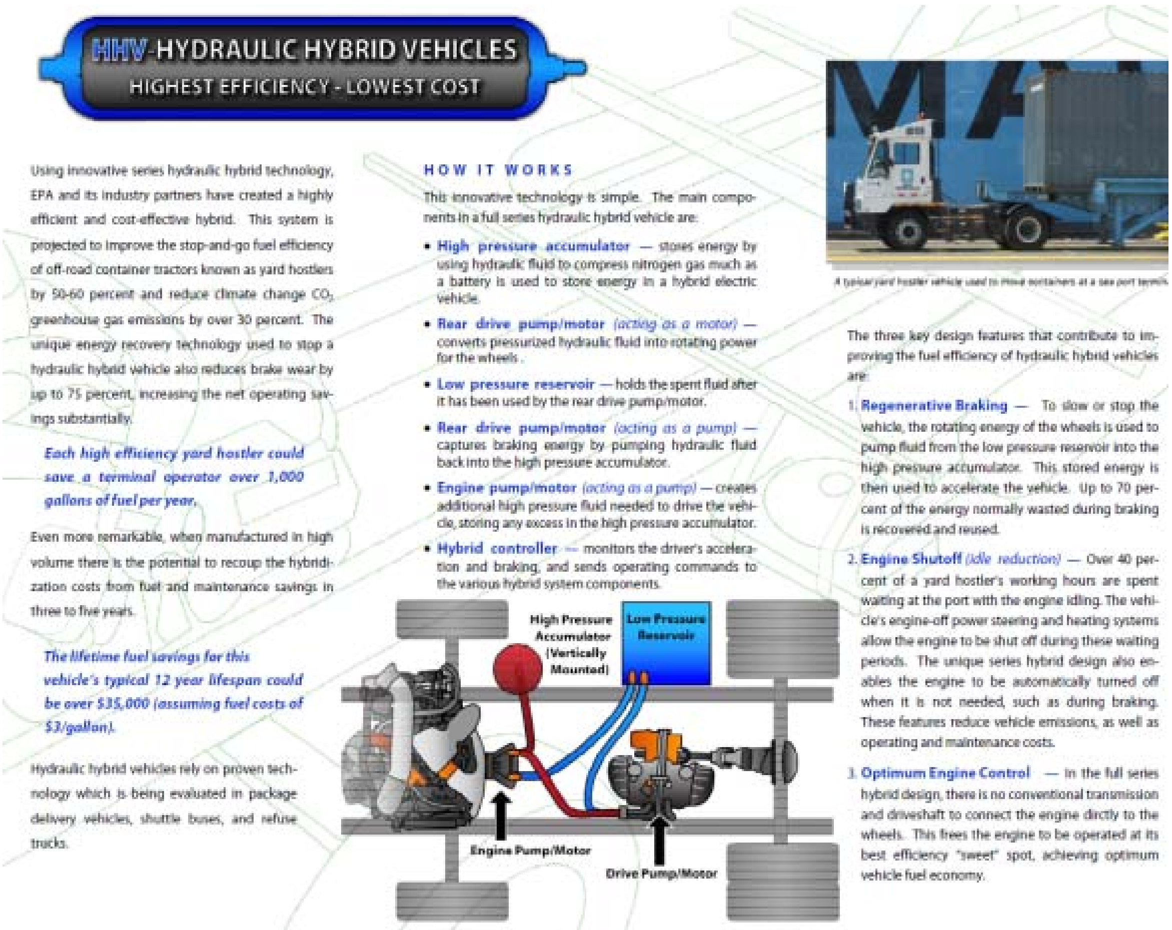



Kargul, 2013, p7




Tomazic, 2013, p16


EPA, 2009, p1



HHV-HYDRAULIC HYBRID VEHICLES
HIGHEST EFFICIENCY - LOWEST COST

Using innovative series hydraulic hybrid technology, EPA and its industry partners have created a highly efficient and cost-effective hybrid. This system is projected to improve the stop-and-go fuel efficiency of off-road container tractors known as yard hostlers by 50-60 percent and reduce climate change $CO_2$ greenhouse gas emissions by over 30 percent. The unique energy recovery technology used to stop a hydraulic hybrid vehicle also reduces brake wear by up to 75 percent, increasing the net operating savings substantially.

*Each high efficiency yard hostler could save a terminal operator over 1,000 gallons of fuel per year.*

Even more remarkable, when manufactured in high volume there is the potential to recoup the hybridization costs from fuel and maintenance savings in three to five years.

*The lifetime fuel savings for this vehicle's typical 12 year lifespan could be over $35,000 (assuming fuel costs of $3/gallon).*

Hydraulic hybrid vehicles rely on proven technology which is being evaluated in package delivery vehicles, shuttle buses, and refuse trucks.

HOW IT WORKS

This innovative technology is simple. The main components in a full series hydraulic hybrid vehicle are:

- **High pressure accumulator** — stores energy by using hydraulic fluid to compress nitrogen gas much as a battery is used to store energy in a hybrid electric vehicle.
- **Rear drive pump/motor** *(acting as a motor)* — converts pressurized hydraulic fluid into rotating power for the wheels .
- **Low pressure reservoir** — holds the spent fluid after it has been used by the rear drive pump/motor.
- **Rear drive pump/motor** *(acting as a pump)* — captures braking energy by pumping hydraulic fluid back into the high pressure accumulator.
- **Engine pump/motor** *(acting as a pump)* — creates additional high pressure fluid needed to drive the vehicle, storing any excess in the high pressure accumulator.
- **Hybrid controller** — monitors the driver's acceleration and braking, and sends operating commands to the various hybrid system components.

High Pressure Accumulator (Vertically Mounted)
Low Pressure Reservoir
Engine Pump/Motor
Drive Pump/Motor

A typical yard hostler vehicle used to move containers at a sea port termi

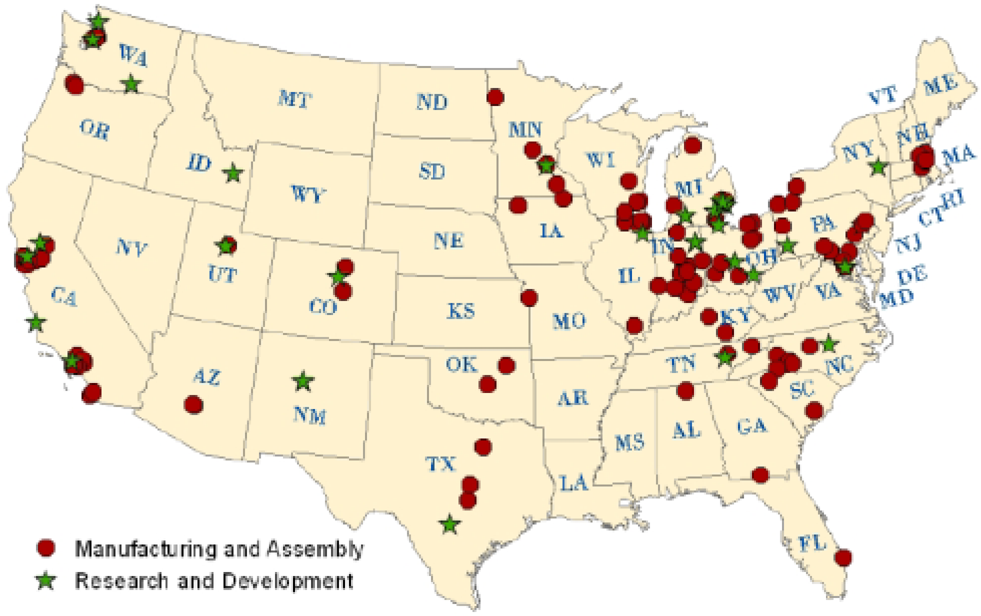
The three key design features that contribute to improving the fuel efficiency of hydraulic hybrid vehicles are:

1. **Regenerative Braking** — To slow or stop the vehicle, the rotating energy of the wheels is used to pump fluid from the low pressure reservoir into the high pressure accumulator. This stored energy is then used to accelerate the vehicle. Up to 70 percent of the energy normally wasted during braking is recovered and reused.
2. **Engine Shutoff** *(idle reduction)* — Over 40 percent of a yard hostler's working hours are spent waiting at the port with the engine idling. The vehicle's engine-off power steering and heating systems allow the engine to be shut off during these waiting periods. The unique series hybrid design also enables the engine to be automatically turned off when it is not needed, such as during braking. These features reduce vehicle emissions, as well as operating and maintenance costs.
3. **Optimum Engine Control** — In the full series hybrid design, there is no conventional transmission and driveshaft to connect the engine dirctly to the wheels. This frees the engine to be operated at its best efficiency "sweet" spot, achieving optimum vehicle fuel economy.

EPA, 2009, p2

Additionally, there is significant research and development, manufacturing, and assembly occurring in all areas of hybrid systems across the US (Ayee et al, 2009, p30). This will support job growth and technological advancement as the market grows, the following is a sample of these facilities across the US.

**Figure 7. U.S. Hybrid Medium- and Heavy-Duty Trucks: Manufacturing, Assembly, and R&D Locations**




Source: CGGC, based on Tables 3, 4, and 5 above; company interviews and websites.

Ayee et al, 2009, p30

## Conclusions

This paper reviewed the demonstration of the Parker advanced series hydraulic hybrid system placed into revenue service across the US as part of the DOE funded program for 48 vehicles. This increased vehicle count added to the quality and content of data available in this report, exposure to multiple routes, route profiles, route geography and drivers. Through the investigation of Parker, NREL, and CALSTART, significant benefits in terms of reduced fuel consumption and also reduced emissions in both revenue service and lab dynamometer testing methods. This third party investigation allowed this report to have a higher level of credibility to the system both on the lab test dynamometer stand and also in real world revenue applications. In the case of field and dynamometer testing a baseline vehicle was used to validate the current state and then compare to the future state using the Parker advanced series hydraulic hybrid system on the dynamometer stand and also in the field. This report showcased the benefits of fuel reduction, emissions reduction, while leaving room for further investigation in the areas of increased productivity, and continued study of reduced maintenance. Field testing presents unique operating parameters that are not always easily defined, as a result of looking at this data, composite custom cycles were developed reflecting these conditions and the baseline and advanced series units tested. These parallel investigations with NREL & CALSTART validated the savings potential in fuel reduction of on average of 19% to 52% over the baseline in terms of mpg (Lammert, 2014, p11), Parker data for parcel delivery vehicles in the field parallels this at a range of 35% - 50%, emissions reduction of 17.4% lower $CO_2$ per mile and 30.4% lower $NO_x$ per mile (Gallo, 2014, p15), with maintenance improvement in the areas of brake and starter replacement. Continued testing and monitoring of these vehicles will allow for the expanded research in these four areas of fuel reduction, emissions reduction, productivity, and vehicle maintenance. Future research as a result of this paper can be applied in many areas specific to the utilization of hydraulic hybrids in different vehicle types and routes, along with methods to optimize the system integration, system operation, and other methods of operation of hardware in a hybrid fashion based upon the duty cycles of the vehicles being evaluated.

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