

Design and Demonstration of EPA's Integrated Drive Module for Commercial Series Hydraulic Hybrid Trucks and Buses

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ABSTRACT

The United States Environmental Protection Agency's (EPA) National Center for Advanced Technology (NCAT), located at its National Vehicle and Fuel Emissions Laboratory in Ann Arbor, Michigan, has been a global leader in development and demonstration of low-greenhouse gas emitting, highly fuel efficient series hydraulic hybrid drivetrain technologies. Advances in these exciting new technologies have stimulated industry to begin manufacturing hydraulic hybrids for both commercial truck and non-road equipment markets. Development activities are continuing for other markets, including light-duty vehicles. Given the commercial emergence of these low-greenhouse gas emitting series hydraulic hybrids, EPA has passed the leadership for further development to industry.

This paper focuses specifically on the design and demonstration of the final series hydraulic hybrid drive for commercial trucks and buses as designed, built and demonstrated by EPA, incorporating many of innovative hydraulic technologies designed and advanced throughout EPA's hydraulic hybrid program. The unique integrated hydraulic drive module and its transmission in a series hydraulic hybrid vehicle (HHV) configuration were installed in a 30-foot class 6 diesel midibus. This HHV was able to achieve 50-180% better mpg over various urban stop-go drive cycles and 30% better mpg over the EPA highway cycle in chassis dynamometer testing. The paper shows design, control and integration techniques necessary for a cost-effective series hybrid for the commercial truck and bus market. Benefits include significant improvements in hydraulic pump/motor efficiency, maximum fuel economy for stop-go cycles while also improving mpg on highway operation, simple installation and removal of system components, and incorporation of safety features to address on-highway application of hydraulic hybrid technology.

CITATION: Kargul, J., Moskalik, A., Newman, K., Barba, D. et al., "Design and Demonstration of EPA's Integrated Drive Module for Commercial Series Hydraulic Hybrid Trucks and Buses," *SAE Int. J. Commer. Veh.* 8(2):2015, doi:10.4271/2015-01-2850.

1.0. INTRODUCTION

NCAT, formerly known as EPA's Clean Automotive Technology program, has been researching technology systems to improve vehicle fuel economy and reduce greenhouse gases since the early 1990's. In 1993, President Clinton initiated the Partnership for a New Generation of Vehicles (PNGV), a cooperative research and development program comprised of several Federal Agencies and the U.S. Council for Automotive Research (USCAR), which was comprised of the three U.S.-based car companies. The centerpiece of PNGV was to "Develop vehicles to achieve up to three times the fuel efficiency of comparable 1994 family sedans." ([National Research Council of the National Academy of Sciences 2001](#)) The EPA played a key role in this public-private partnership and directed substantial research activities towards demonstrating a new type of hybrid technology that used hydraulic rather than electric components.

From 1993 through 2004, NCAT worked through various automotive industry partnerships to demonstrate the potential of hydraulic hybrid vehicle (HHV) technology to significantly reduce greenhouse gases (GHGs) and increase fuel economy in light-duty passenger vehicles, sport utility vehicles and pickup trucks. From 2005 through 2012, NCAT demonstrated series HHV solutions for commercial package delivery vehicles, non-road yard-hostler service trucks, and finally, passenger shuttle buses. Descriptions of EPA's demonstration vehicles can be found at: www.epa.gov/otaq/technology/ or www.archive.epa.gov/otaq/technology

During the HHV research program, EPA obtained over 50 patents for hydraulic components and control strategies. ([Gray Jr, "Methods of operating a series hybrid vehicle" 2008](#)) ([Gray Jr, "Hydraulic hybrid vehicle method of safe operation" 2012](#)) The work in this area has stimulated a wide range of other research, demonstration, and commercialization projects. ([Beretti 2012](#)) ([Gallo 2014](#))

During the time of EPA's work, several companies were developing HHV technologies for vehicle applications including class 8 refuse, class 5-6 delivery vehicles, class 4-7 transit and shuttle bus, non-road equipment (excavators, lifters, hostler trucks), and b/c-class passenger cars (potentially for European applications), including:

- Parker-Hannifin (Schoenberger 2012) and Lightning Hybrids working on commercial truck/bus solutions
- Caterpillar (Sutton 2012), Dana Spicer, Eaton, and NRG Dynamics working on non-road equipment solutions
- Bosch-Rexroth and Peugeot (Citroen 2013) working on European passenger car solutions
- Center for Compact and Efficient Fluid Power (CCEFP 2015) working on research activities

2.0. JOURNEY TO HIGHEST EFFICIENCY, LOWEST COST HYBRIDS

This paper provides an overview of three series HHV configurations that EPA studied for heavier vehicle applications as well as a deeper review of the configuration, components and results of EPA's final HHV demonstration vehicle. At this time, NCAT is not planning any additional HHV demonstrations.

In a parallel HHV, the engine provides power to the wheels through a standard transmission; however, hydraulic components are attached to the driveshaft and assist in stopping and accelerating the vehicle. Power from either source can propel the drive wheels. In a series HHV, the engine is no longer directly connected to the drive wheels. Instead a drive pump/motor, acting as a motor, uses high pressure fluid from an accumulator, or from a hydraulic pump connected to the engine, to propel the vehicle.

Initial HHV research at EPA evaluated both parallel and series hybrid configurations, as well as various methods and components to recover and store hydraulic energy on-board vehicles utilizing off-the-shelf hydraulic pump/motors. Ultimately, NCAT progressed to using highly efficient custom-designed pump/motors in a series hybrid architecture.

2.1. Exploring parallel HHVs

Parallel hybrids often represent an easy opportunity for initial fuel savings, as parallel configurations are more easily retrofitable in conventional vehicles. However, for most heavy vehicle operational duty cycles, the fuel costs saved from parallel hybrids are insufficient to recover investment for the hybrid components in a reasonable timeframe (3 to 5 years), making it difficult to develop a successful business case for this hybrid configuration.

Through testing various parallel HHVs and its relationships with commercial fleet managers, EPA learned that routine urban driving of parallel hybrids (electric or hydraulic) in commercial truck applications typically achieved 15-30% better fuel efficiency (mpg)

compared with conventional vehicles, depending on the operating environment. They can reduce criteria emissions and decrease vehicle brake wear. In addition, parallel configurations can in some cases, depending upon hardware and system controls, provide a potential limp-home mode if either the transmission or the hybrid components fail.

In 2003, EPA developed a prototype of the parallel hydraulic hybrid configuration shown in Figure 1, using a commercially available hydraulic pump and custom gear box connected to the vehicle's drive shaft. Its operation was demonstrated in a class 3 Ford F-550 truck, where it achieved 20-30% improvement in fuel economy in typical urban driving.

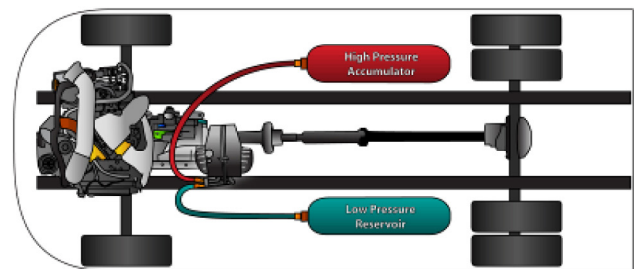


Figure 1. EPA's demonstration of parallel hydraulic hybrid technology (2003)

While the basic performance of this parallel hybrid prototype was satisfactory, with today's costs and a fuel economy gain of 20-30% it was difficult to foresee a compelling business case that could recover the initial research and development costs of the emerging technology. A more robust business case would require the implementation of series hybrid architecture which could save significantly more fuel. Thus, EPA began its journey in search of high-efficiency, low-cost, and easy-to-install series HHV technologies suitable for use in commercial truck and bus applications.

2.2. Exploring series HHVs

Recognizing that series HHV construction held more promise for high fuel economy than parallel HHVs, EPA began a research program to optimize the series configuration in a heavy-duty truck application. From 2005 through 2012 the Clean Automotive Technology program prototyped five different series HHV configurations using custom designed and built hydraulic components and controls, and demonstrated them in heavy delivery vehicle and bus applications. Each successive demonstration focused on improving some aspect of series hybrids - fuel efficiency, energy management, energy storage, hybrid controls, cost, mass, installation, and noise, vibration and harshness (NVH). An overview of three of the prototype demonstration series HHVs (axle-mounted, frame-mounted and integrated-drive-module) will be discussed later in the paper. All of these series architectures incorporate the following basic principles of series HHV operation:

Transforming power from the engine - The crankshaft of the vehicle's engine is connected to an engine pump/motor, which can both receive power from the shaft when in pump mode and deliver power to the shaft when in motor mode. When acting as a pump, the pump/motor pressurizes the fluid used to drive the vehicle, storing any excess pressurized fluid in the high pressure accumulator. When acting as a motor, it uses pressurized fluid to restart the engine after engine-off operation.

Providing propulsion to the rear wheels - A separate pump/motor unit is connected to the rear wheels of the vehicle. This unit also operates in both pump and motor modes to receive or deliver power. When acting as a pump, the unit captures braking energy, pumping hydraulic fluid into the high pressure accumulator. When acting as a motor, it converts the pressurized hydraulic fluid into rotating power for the wheels.

Storing energy - A series HHV is configured with both high and low pressure accumulators. The low pressure accumulator holds depressurized hydraulic fluid after it has been used by the rear drive pump/motor to rotate the rear wheels. The high pressure accumulator stores captured braking energy by using hydraulic fluid to compress nitrogen gas contained inside a bladder in the accumulator. The high pressure accumulator also stores excess energy produced by the engine that is not immediately needed to propel the vehicle. In most configurations, EPA used bladders filled with polymeric foam to ameliorate thermodynamic losses. Figure 2 illustrates the condition of a low or high pressure accumulator when it is nearly full or empty of hydraulic fluid (and its nitrogen gas is under its highest or lowest pressure).

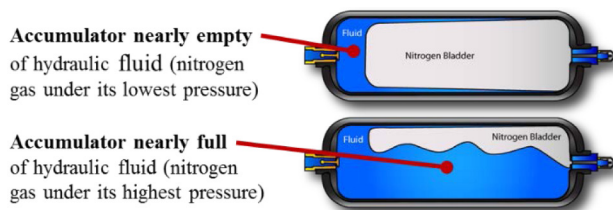


Figure 2. Accumulator and bladder configuration

Managing energy - The hybrid controller monitors the driver's acceleration and braking, and simultaneously sends operating commands to the various hybrid system components. The controller not only responds to the driver's demands, but also balances the requirements of the system to optimize fuel economy. Engine operation, accumulator limits, system pressures, and expected driver demand must all be balanced. The optimum control strategy for a series HHV can be difficult to achieve, and is apt to be unlike the strategies found in parallel or series hybrid electric vehicles. (Wu 2004) More details on controller strategy are included later in this paper.

Saving fuel - Hydraulic components are known for their ability to absorb and release high rates of energy quickly (high specific power), making HHV designs able to capture and save much of the energy normally wasted during braking events. Series HHVs can also control engine pump/motor operation in several ways to further improve efficiency.

- **Regenerative braking** quickly captures most of the braking energy, stores it in the high pressure hydraulic accumulator (similar to storing electric energy in batteries) and then re-uses it to accelerate the vehicle.
- **Engine-off control** automatically turns off the engine when it is not needed (at idle, when braking, or when running on stored energy).
- **Optimal engine control** in a *series* hydraulic hybrid allows the engine to operate at peak efficiency at a relatively high load most of the time, because the engine is not connected to the wheels and because the hydraulic accumulators are very durable and efficient at high power operation.

In contrast to the series HHVs, the engine in a *parallel* hydraulic hybrid must directly power the wheels through its transmission. This means the engine operates outside of its peak efficiency zone more often, making it less efficient than the series configuration.

3.0. AXLE-MOUNTED SERIES HHV UPS PACKAGE CAR

From 2005 to 2010, EPA partnered with UPS to explore two similar versions of axle-mounted series HHV technology in a UPS class 6 diesel powered P100 "package car" delivery truck shown in Figure 3. In its conventional configuration, this truck is powered by a 6.0 liter diesel engine and a 5-speed automatic transmission. While this class 6 truck is rated for 24,000 pounds GVWR, UPS asked that comparisons be run with a test weight of 20,000 pounds.



Figure 3. Demonstration vehicle for EPA's axle-mounted series HHV

First-generation proof-of concept - The first generation prototype of the axle-mounted series HHV architecture was assembled using EPA's high efficiency pump/motors that were designed and sized for light-duty SUVs and pickup trucks. The chassis was an International 1652 chassis with a Morgan Olson body. The engine was a 6.0 liter International VT365 diesel connected to a 200cc Rexroth engine pump. The axle-mounted drive system consisted of three prototype EPA designed 117cc pump/motors. Two were configured in an

end-to-end manner and connected to the rear differential. A third auxiliary drive 117cc pump/motor also connected to the differential was needed to provide the necessary torque during launch. The high and low pressure accumulators each consisted of two 22-gallon (44-gallon total) carbon fiber tanks.

While the fuel efficiency improvement of this prototype was good and the prototype successfully proved that this series HHV concept was viable, it became apparent that a more efficient version of this series HHV was possible using hydraulic pump/motors sized and designed for commercial truck applications.

The series hydraulic hybrid partnership between UPS and EPA is described in an article in *Hydraulics and Pneumatics* (Heney 2005). A more technical article in the same publication (Kargul-EPA and Hall-UPS 2006) gives more details on the design and operation of this first-ever axle-mounted series HHV.

Second-generation fuel efficiency improvements - In 2010, EPA's second generation of the axle-mounted series HHV focused on improving fuel efficiency. Using EPA designed and fabricated high-efficiency pump/motors sized for heavy-duty truck and bus applications, EPA assembled the second generation of its axle-mounted series HHV configuration shown in Figure 4. The chassis was a Workhorse 62 with Morgan Olson body. The engine was an International 2007 International VT-275 diesel (4.5L, V6, 200 HP @2700 rpm) connected to a prototype 160cc EPA designed engine pump.

The axle-mounted drive system shown in Figure 5 consisted of two prototype EPA designed 160cc pump/motors configured in an end-to-end manner, but identically controlled, and connected to the rear differential once the conventional transmission and driveshaft were removed. The auxiliary drive pump/motor was not necessary for this design. The high accumulator consisted of two 22-gallon (44-gallon total) carbon fiber tanks. The low pressure accumulator consisted of a single 54-gallon steel tank.

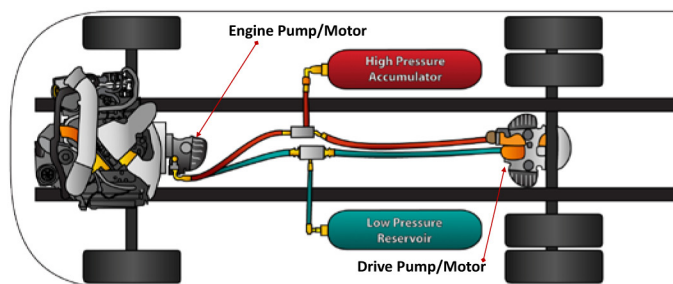


Figure 4. EPA's 2010 version of its axle-mounted series HHV in urban package delivery truck



Figure 5. EPA's prototype axle-mounted series hydraulic hybrid drive

3.1. Fuel economy benefits

A component of EPA's HHV research program involved measuring the fuel efficiency of prototype hybrids over a variety of applicable HD drive cycles. The fuel efficiency of each prototype was measured to determine its percent fuel economy improvement over UPS's comparable conventional (baseline) diesel delivery truck.

Vehicles were tested over several drive schedules representing different types of urban, suburban and highway driving. Figure 6 illustrates the stop-go intensity of several driving schedules used in the testing. As expected, fuel economy improvement is highly dependent on the drive cycle (Kramer 2011). Most of the chassis dyno testing was done at EPA's National Vehicle and Fuel Emissions Laboratory (NVFEL) in Ann Arbor, Michigan. The vehicles tested at NVFEL were tested at 19,944 pounds test weight on large roll chassis dynamometer with results compared to the conventional baseline diesel UPS P100 delivery truck.

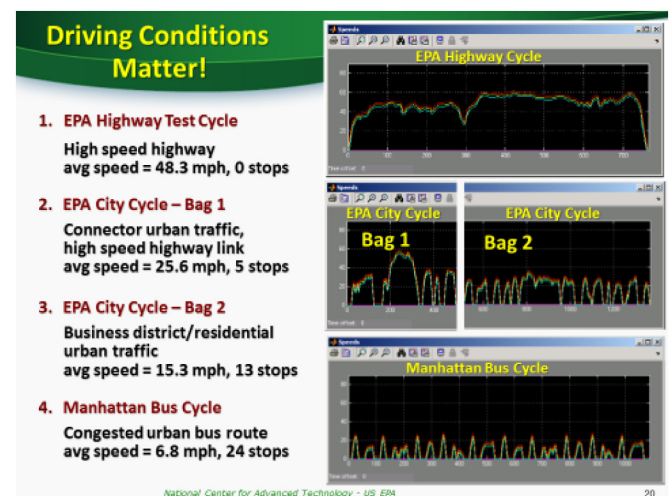


Figure 6. Examples of different urban and highway drive cycles

Fuel economy from chassis dyno tests - Figure 7 shows the percent fuel economy (mpg) improvement of EPA's 2010 second generation prototype of the axle-mounted series HHV compared to UPS' parallel hybrid electric vehicle (HEV) trucks commercially available in 2007 (1st generation HEV), and 2010 (2nd gen HEV). A larger, more readable version of this data is shown in Figure 27 Figure 23 in the Appendix. The test data show that:

- On a cold start city cycle (FTP), parallel hybrid electric delivery trucks achieved 9-18% improvement over the baseline truck, while the prototype series hydraulic hybrid vehicle achieved a 51% improvement.

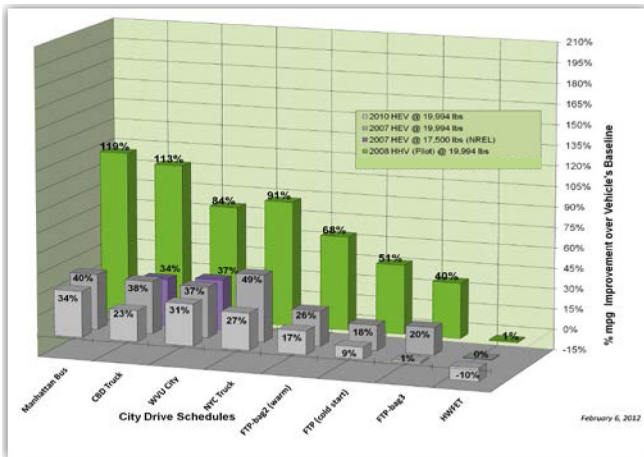


Figure 7. Fuel economy comparison of parallel HEVs and EPA's series axle-mounted HHV. A larger, more readable version of this data is shown in the chart in Figure 27 of the Appendix.

- During more intense stop-go traffic simulated by the FTP-bag2 (warm) cycle, the parallel HEVs achieved 17-26% improvement in mpg while the series HHV achieved 68% improvement.
- In very heavy stop-go traffic simulated by the Manhattan Bus cycle, the parallel HEVs only were able to get 34-40% better mpg, while the series HHV achieved an amazing 119% better mpg.
- While not yet considered by EPA to be great highway test results, the second-generation axle-mounted series HHV was able to match a conventional vehicle's mpg on the EPA highway cycle (HWFET), while the 2010 version of the HEV lost 10%. At the time, achieving highway results comparable to a conventional vehicle was not thought to be possible with series hybrid designs.

The fuel economy improvements demonstrated by the EPA closely match the fuel economy results predicted by a study which anticipates the fuel economy benefits in military vehicles over the urban cycle to be around 20% for parallel electric hybrids, 26% for parallel hydraulic hybrids, and 68% for series hydraulic hybrids. (Kramer 2011)

Fuel economy from UPS's field tests - Another component of EPA's technical research involved evaluating prototypes in real commercial usage. The field tests of this prototype axle-mounted series HHV UPS truck in real-world package delivery was done by UPS on one of their Detroit suburban routes. UPS' testing demonstrated a 52% fuel economy increase over a conventional diesel delivery vehicle on the same route with the same driver. Encouraged by these positive results, UPS began pursuing partnerships with industry to demonstrate series HHV technology in their package delivery vehicles.

3.2. Lessons learned from axle-mounted series HHV

The dyno and field testing of the prototype axle-mounted series HHV helped EPA identify three key areas for improvement:

- Pump/motor efficiency** - testing of the EPA prototype dual end-to-end pump/motor design clearly showed significant efficiency benefits from sharing a common output shaft and right sizing the bearings.
- Identifying pump/motor losses** - While outperforming many commercial pump/motors, testing of the EPA pump clearly identified key aspects of pump/motor efficiency and losses, and their relative importance for improving overall HHV system efficiency.
- Series controls** - The importance of precisely controlling series HHVs became obvious, highlighting several key techniques and methods for moderating engine operation where possible.
- System integration** - While the axle-mounted system had some advantages for efficiency, it required a special axle for each application, limiting the broad application of the design across the commercial market. Manufacturing, packaging and costs must be considered as part of the system design.
- Durability** - Working with industry on this project revealed how dependent the truck sector has become on suppliers to perform all research and development, as well as show viable pathways for manufacturing and durability, in addition to improved efficiency.

Understanding pump/motor efficiency - One observation from the testing of the axle-mounted series HHVs was that the efficiency of the pump/motors was critical to obtaining high fuel efficiency. Pump/motor units sized and designed for highest efficiency in heavy-duty vehicle applications are essential to the series design, as all power flows through the pump/motor units, and small increases in efficiency can have a large impact on the final fuel economy numbers.

In conjunction with hybrid vehicle development work, EPA began an empirical investigation into the losses associated with pump/motor units. A simple conceptual model of the relative magnitude of pump/motor losses was developed and used in later designs, when tradeoffs between different losses were examined.

A prototype pump/motor, consisting of two 120cc rotating groups rotating a common shaft, was tested to estimate the relative magnitudes of each type of loss. The overall efficiency of this unit was tested in a dedicated high-power test stand.

The high-power test stand consisted of a double-ended engine dynamometer connected to a slave hydraulic unit on one end and the test unit on the other. The prototype pump/motor and slave unit were hydraulically connected. A regulator controlled pressure on the high-pressure side, and a low-pressure charge unit provided make-up flow. With the proper balancing of flows through the prototype and slave units, a wide range of operating conditions could be tested.

The prototype was tested with a low pressure set at 200 psi (except for zero-load conditions) and a fluid temperature of 50 C. Losses were recorded at a series of constant speeds, high pressures, and displacements. The total losses were conceptually divided into seven areas, and a series of experiments were designed to estimate the magnitude of each type of loss as listed below.

- **Zero-load spin losses** - These losses primarily come from shaft seals and bearing drag. To determine the spin losses, the pump/motor cases were drained of fluid, the displacements were set to exactly zero, and the input torque was measured as a function of speed.
- **Churning losses** - Churning losses include windage from the connecting rods and bearing rollers. To determine the churning losses, the pump/motor cases were then filled with fluid and the additional input torque required was measured as a function of speed.
- **“Zero displacement” friction losses** - The zero displacement friction losses include additional bearing and barrel/valve plate friction that occurs when these components are pressure loaded. To determine the friction losses, the rotating groups were pressurized and the additional input torque required was measured.
- **Friction Losses at Displacement** - Friction losses at displacement include the additional friction from the pistons and ball sockets. To determine this additional friction, both sides of one rotating group were pressurized, and the torque loss recorded as a function of pressure and displacement.
- **Compressibility Losses** - Compressibility losses occur when high pressure fluid flows into the dead volume above the piston when a low pressure chamber makes contact with the high pressure kidney. To determine the extent of the compressibility losses, one pump/motor rotating group was set at exactly zero displacement, pressurized, and rotated. The high pressure flow into the pump/motor was recorded as a function of speed and pressure. The resulting data gave an estimated bulk modulus of 165,000 psi.
- **Flow Losses** - Flow losses occur from a pressure drop due to flow through passages. To measure the flow losses, a low pressure was applied to the inlet of one end of the pump. The unit was placed at high displacement and spun at increasing speed until cavitation occurred, as indicated by cavitation noise and/or roll off of the flow as a function of speed.

- **Internal Leakage Losses** - Leakage losses are actual leakage flow out of the rotating group into the case. The leakage was measured as a function of pressure at zero displacement; there was very little effect on leakage with increasing displacement or speed.

Total Losses and Pump/Motor Efficiency - Each of the measured losses was approximated by empirical equations as a function of (as appropriate) speed, displacement, pressure, and/or temperature. Predicted power losses, based on these empirical equations, were calculated for a range of pump/motor operation points. The predicted power losses were compared to actual power losses recorded during efficiency testing for this unit. Sample charts of the predicted and measured power losses are shown in Figure 8 for both pumping and motoring modes. Additional charts for other operating conditions are shown in Figure 28, located in the Appendix.

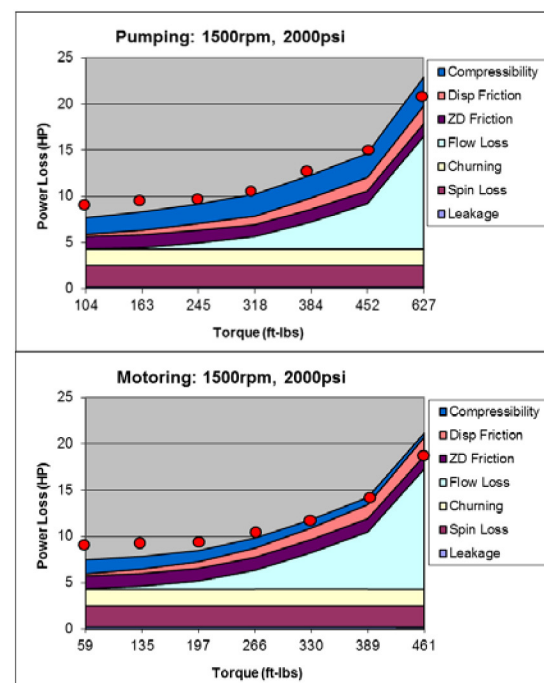


Figure 8. Pumping and Motoring loss predictions: The predicted power loss from each source is represented by the color bands. Actual measured power loss is represented by the red dots (note differences in scale for each graph).

The total predicted power losses closely match actual measured pump losses. More importantly, the figures show the relative size of each contribution to the pump/motor losses at each specific operating point. In our program we found that the best technique for maximizing overall vehicle fuel economy was to focus on minimizing overall power loss as opposed to maximizing overall efficiency, especially when looking at design trade-offs between different operating points. The individual estimates of power losses can serve as a guide for:

- Creating a vehicle control strategy, guided by understanding the effect of operating conditions on overall losses, which avoids operating the HHV system where the power loss is high.