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Hydraulic Hybrid and Conventional Parcel Delivery Vehicles' Measured Laboratory Fuel Economy on Targeted Drive Cycles

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ABSTRACT

This research project compares laboratory-measured fuel economy of a medium-duty diesel powered hydraulic hybrid vehicle drivetrain to both a conventional diesel drivetrain and a conventional gasoline drivetrain in a typical commercial parcel delivery application. Vehicles in this study included a model year 2012 Freightliner P10HH hybrid compared to a 2012 conventional gasoline P100 and a 2012 conventional diesel parcel delivery van of similar specifications.

Drive cycle analysis of 484 days of hybrid parcel delivery van commercial operation from multiple vehicles was used to select three standard laboratory drive cycles as well as to create a custom representative cycle. These four cycles encompass and bracket the range of real world in-use data observed in Baltimore United Parcel Service operations. The New York City Composite cycle, the City Suburban Heavy Vehicle cycle, and the California Air Resources Board Heavy Heavy-Duty Diesel Truck cycle as well as a custom Baltimore parcel delivery cycle were tested at the National Renewable Energy Laboratory's Renewable Fuels and Lubricants Laboratory. Fuel consumption was measured and analyzed for all three vehicles. Vehicle laboratory results are compared on the basis of fuel economy. The hydraulic hybrid parcel delivery van demonstrated 19%-52% better fuel economy than the conventional diesel parcel delivery van and 30%-56% better fuel economy than the conventional gasoline parcel delivery van on cycles other than the highway-oriented HHDDT cycle.

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INTRODUCTION

Hybrid drivetrains have shown significant promise as part of an overall petroleum reduction fleet strategy [1, 2, 3, 4, 5, 6]. Hybrid drivetrains consist of an energy storage device and a motor integrated into a traditional powertrain and offer the potential fuel savings by capturing energy normally lost during deceleration through the application of regenerative braking. Because hybrid technologies, especially hydraulic hybrids, have low adoption rates in the medium-duty vehicle segment and because fuel savings from hybrids are highly dependent on the duty cycle they are driven on, there are still questions to be answered about when and where this technology offers a valuable return on investment in the form of fuel savings as well as which type of system works best in this application.

The objective of this project was to evaluate the in-use fuel economy of a hydraulic hybrid vehicle (HHV) compared to two conventional powertrain options operating over a range of representative standard chassis test duty cycles through chassis dynamometer testing under laboratory conditions.

Background and Methods

United Parcel Service (UPS) placed 20 new Parker Hannifin infinitely variable transmission (IVT) hydraulic hybrids into service in the Baltimore area in November 2012 as part of a purchase of 40 new HHV parcel delivery vans. These HHVs include an “engine off at idle” function and meet 2010 emissions standards. UPS also deployed gasoline-powered conventional parcel delivery vans around the same time to the Baltimore depots. Because UPS moved to using a gasoline engine in this application as the standard specification, no diesel vehicles were available within the Baltimore fleet; therefore, a diesel-powered conventional vehicle of similar specification was secured from an alternative parcel delivery van fleet for laboratory testing. The National Renewable Energy Laboratory (NREL) also evaluated hybrid electric vehicles (HEVs) in UPS service in this class of parcel delivery van previously in Phoenix, Arizona, and Minneapolis, Minnesota [3, 4, 5, 6].

Vehicle Selection and Details

The Parker Hannifin IVT HHV was compared to the UPS standard gasoline conventional drivetrain as well as a conventional diesel drivetrain commonly used for this vocational application. Table 1 lists the vehicles' specifications. The HHV uses a 280 HP ISB calibration instead of a 200HP calibration used in the diesel conventional because that was the only calibration being offered for hybrid applications by Cummins. The payload estimate used for testing is the result of discussions with UPS as an average daily load and is directly comparable to a previous dynamometer test series [3, 6].

Table 1. Study van details

Parcel Delivery Van Specification	Conventional Diesel Van	Conventional Gasoline Van	Hydraulic Hybrid Van
Chassis Manufacturer	Freightliner	Workhorse W62	Freightliner
Van manufacturer	Utilimaster Corp.	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	280 HP
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 rating	19,500 lbs	23,000 lbs	23,000 lbs
Vehicle Test Weight	15,410 lbs.	14,160 lbs.	18,015 lbs.
Payload for Testing	4,000 lbs.	4,000 lbs.	4,000 lbs.

Table 2 lists pertinent Parker Hannifin IVT hydraulic hybrid system details. This system is a “powersplit,” or a combination of parallel and series in architecture. It is a dual path system capable of transmitting power hydraulically or mechanically or a combination of both. The system uses a gear box to mix power input from both the diesel engine and the hydraulic motor to the wheels, to the hydraulic motor from the wheels for regeneration or from the hydraulic motor to the engine flywheel to start the engine. The system also shuts off the diesel engine when it is not needed. According to Parker Hannifin, the system supplies 100% of the power hydraulically from a stop and ramps down to less than 10% of power transmitted hydraulically at 30 mph with a 50% mechanical / hydraulic pathway split at 15 mph. This system is intended to capture energy during slow speed stop-and-go driving, but to provide for mechanical power transmission at higher speeds.

Table 2. Hybrid system details

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
	3,500–4,000 psi nominal pressure range
	5,400 psi max pressure

Duty-Cycle Analysis and Test Cycle Selection and Creation

GPS and J1939 Vehicle Data Logging

Isaac Instruments DRU900/908 data logging devices with global positioning system (GPS) antennas and J1939 controller area network (CAN) bus connections were deployed to the UPS Baltimore fleet to collect operational data. This information was combined with a month of telematics data provided by Parker Hannifin from systems already installed on the Baltimore HHVs. In total, 484 vehicle days of HHV operation on 20 parcel delivery vans were documented. The GPS and J1939 channels collected as part of this project were recorded at a 1-Hz sampling rate. J1939 controller area network bus channels collected included wheel-based vehicle speed, engine speed, and engine fuel rate among others (see Appendix Table A1 for a complete list). The same data collection devices and channel settings (minus GPS) were used during laboratory dynamometer testing to capture vehicle systems activity during the test runs.

Data Analysis Using DRIVE™

Filtration and analysis of the 484 days of in-use field data collected as part of the study were performed using NREL's Drive-Cycle Rapid Investigation, Visualization, and Evaluation (DRIVE™) analysis tool [7, 8]. Employing NREL's DRIVE analysis tool, researchers were able to explore daily vehicle operation and ensure data quality through analysis of approximately 150 drive cycle metrics calculated by the tool. The 150 drive cycle metrics calculated ranged in scope from high-level route descriptors such as average driving speed (mph) and stops per mile, down to vehicle energy level metrics such as kinetic power density consumed (W/kg) and kinetic intensity (1/mile), most of which were calculated using different formulations of the fundamental road load equation [9]. When performing the road load equation calculations, it was assumed the effects of road grade were negligible. However, road grade effects and their contributions to vehicle power demand have been explored in prior research, and associated fuel economy penalties have been documented [10, 11].

Laboratory Standard Test Cycle Selection

In an effort to select standard chassis test cycles that reflect the aggregate in-use data, a multivariate least squares selection method was employed. Through a comparison of drive cycle metrics such as average driving speed, stops per mile, and others, a representative set of test cycles was chosen representing the range of driving conditions. The corresponding cycles chosen to bracket and represent the range of driving observed were the California Air Resources Board (CARB) Heavy Heavy-Duty Diesel Truck (HHDDT), City Suburban Heavy Vehicle Cycle (CSHVC), and New York City Composite cycle (NY Comp). (See Appendix Figures A1, A2, A3 showing the cycles).

DRIVE™ Custom Test Cycle Generation

The DRIVE tool employs a deterministic multivariate hierarchical clustering method to generate representative drive cycles from source data [12]. Starting with source in-use data, the tool generates representative cycles of user-specified durations by first analyzing the drive cycle characteristics of a composite "super" cycle containing the driving profile of each input drive cycle concatenated together. In generating a composite cycle this way, time-based weighting is achieved, with the duration of each source cycle influencing the underlying metrics of the composite "super" cycle, as opposed to the common approach of non-weighted averages being computed from a set of cycle metrics representing each source cycle. The non-weighted approach can result in composite cycles that can disproportionally weight the metrics of the composite cycle toward the components with short durations. Once the "super" cycle has been characterized over more than 150 drive cycle metrics, the tool then decomposes the composite cycle into its component microtrips, which are individually analyzed over the same set of operational drive cycle metrics. This set of statistics includes well-known metrics such as average driving speed, stops per mile, and zero speed time as a percentage of cycle operation, as well as specialized metrics such as kinetic intensity, aerodynamic speed, and characteristic acceleration, which are used to characterize energy consumption [8]. Having been characterized, the individual microtrips undergo an iterative multivariate k-means clustering process in which they are grouped into clusters and ranked based on a set of predefined performance metrics. Upon ranking, the ideal microtrip from each cluster is selected and concatenated to form a representative cycle. This clustering process is iterated over a chosen number of clusters, with the upper limit on the number of clusters calculated as the product of the desired representative cycle duration, the number of stops per mile for the "super" cycle, and the average speed over the "super" cycle. As a final step in the generation of a representative drive cycle, zero speed time is either added or removed from the final drive cycle output to match the percentage found in the original data "super" cycle. (See Appendix Figure A4 showing the cycle).

Laboratory Chassis Dynamometer Testing Procedures

Dynamometer testing methods recommended in SAE J2711 "Recommended Practice for Measuring Fuel Economy and Emissions of Hybrid-Electric and Conventional Heavy-Duty Vehicles" [12] were used as a guide. Vehicles are secured to the dynamometer with the drive axle(s) over the rollers. The vehicle is driven by a driver following a prescribed speed trace that is defined by the previously selected/generated drive cycles. A three-foot diameter 2-HP fan is used to force cooling air onto the test vehicle's radiator to simulate the ram cooling effect of a vehicle in motion. Emissions measurements are collected from the exhaust dilution system for analysis, and various vehicle parameters (J1939) are monitored and logged by the Isaac DRU908 data acquisition system.

To assure the accuracy and consistency of road load simulation used during chassis dynamometer testing, the dynamometer is subjected to various procedures and checks. The daily testing routine consists of the following steps: 1) In the morning, the vehicle is lifted off the rollers, and the dynamometer is subjected to a warm-up procedure until the parasitic losses stabilize. 2) The unloaded coastdown procedure is used to verify that the parasitic losses did not change from previous testing and that load cell calibration has not drifted. 3) Following this verification, the vehicle is placed back on the rollers and driven for 20 minutes to warm up. 4) A conditioning test run is performed to stabilize the vehicle's temperature over the test cycle. 5) After the warm-up cycle the dynamometer road load simulation is verified via loaded coastdown. Once the road load is verified as accurate, testing can start. 6) Test runs are considered usable provided the road load simulation proves consistent in the previous step. This is verified after each test. To maximize consistency, the soak period between engine-off of one test and engine-on of the following is kept at 20 minutes.

Emissions Measurement

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

Gaseous exhaust emissions are analyzed by a Horiba MEXA 7100 series system which includes measurements of total hydrocarbons, oxides of nitrogen (NO_x), carbon monoxide, and carbon dioxide. The gas analytical system was verified prior to beginning the testing period, including linearization checks and a NO_x converter efficiency test. On a daily basis, the analyzers are zero and span calibrated, and each test was bracketed by zero, span, and background readings used for corrections. The emissions measurement data are then reduced to distance specific mass results using the Code of Federal Regulations-recommended calculations, including humidity, dry to wet, zero, span, and background corrections.

Fuel Consumption Measurement

The primary fuel consumption measurement approach applied in this project was gravimetric-based analysis. Engine fuel supply and return lines were connected to a fuel container placed on a scale, where scale mass measurements were collected and recorded in real time along with all the test data.

The difference between the beginning and the end test mass measurements indicated the mass of fuel consumed during the test. Prior to testing, the scale calibration was verified with a known calibration weight. A Sartorius Midrics MAPP1U-60ED-L scale was used for this test.

State-of-Charge Considerations

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

RESULTS

Parcel Delivery Van In-Use Duty Cycle Results

For the observed 484 days of operation, the collected in-use HHV driving routes averaged 56 miles per day with an average driving speed of 18 mph. Figure 1 shows the average distance (as a percentage of total daily distance) that HHVs drove at different vehicle speeds and also shows the zones of the HHV operation (data supplied by Parker Hannifin).

- The HHV parcel delivery vans drove 20% of their miles below 15 mph, where the IVT transmits more than 50% of the power hydraulically.
- The HHV parcel delivery vans drove 35% of their miles between 15 mph and 30 mph, where the IVT transmits 10%-50% of the power hydraulically.
- The HHV parcel delivery vans drove 45% of their miles above 30 mph, where the IVT transmits over 90% of the power mechanically, and there is less opportunity for savings from a hybrid system.

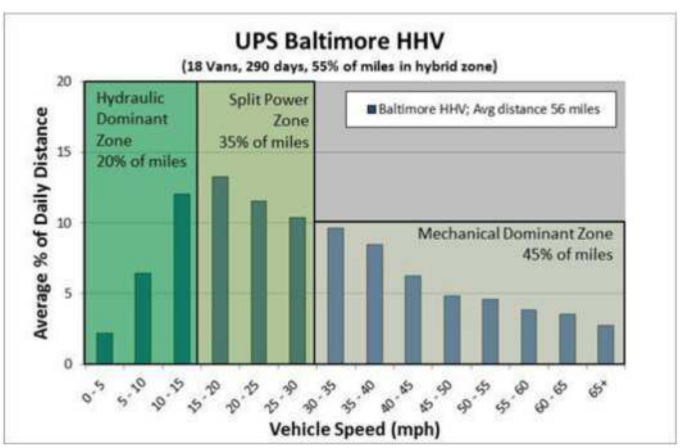

Figure 1. HHV duty cycle breakdown by percent miles traveled

Table 3 lists specific drive cycle statistics from the Baltimore HHVs. These statistics and those above indicate that the Baltimore HHVs were not operating on ideal routes for hybrid advantage to be maximized. A denser, more urban assignment with lower speed operation and a higher number of stops per mile would provide more opportunities for the HHVs to capture braking energy, save fuel, and potentially reduce emissions.

Table 3. Drive cycle statistics from Baltimore HHVs

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

Laboratory Drive Cycle Selection

Based on the in-field usage data and the DRIVE™ methodology used to analyze the data, three standard drive cycles were chosen to match and bracket the observed in-use data and associated statistics. The selected cycles were NY Comp, CSHVC, and CARB HHDDT, with CSHVC being the closest match to the average in-field data and NY Comp and CARB HHDDT bracketing the high and low observed data. Additionally, a custom drive cycle was created using DRIVE™ as described in the Methods section. Figures 2 and 3 show the laboratory test cycles compared to gathered field data relating to kinetic intensity, average driven speed, and stops per mile.

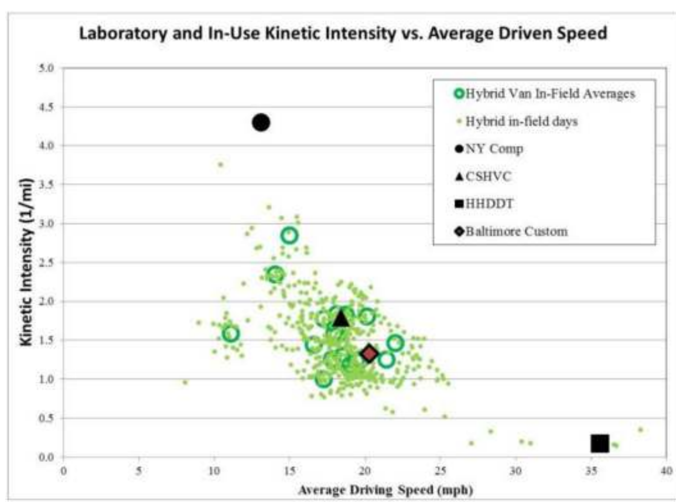

Figure 2. Laboratory cycles and field data by average driven speed and kinetic intensity

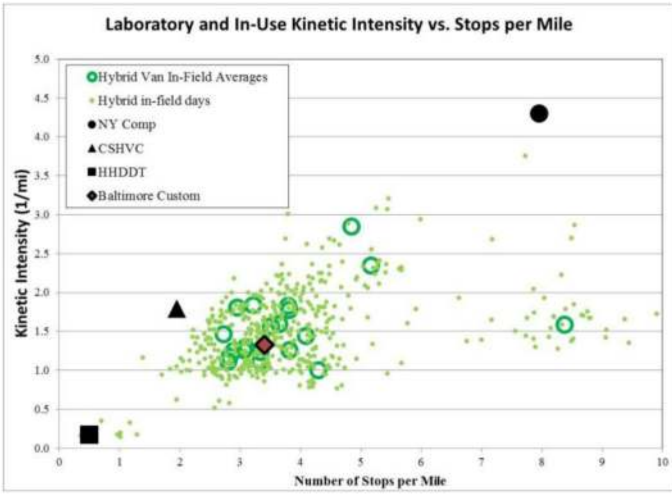

Figure 3. Laboratory cycles and field data by stops per mile and kinetic intensity

Parcel Delivery Van Fuel Economy

Laboratory Testing Gravimetric Fuel Economy

Table 4. Fuel economy (gravimetric) of hybrid and conventional parcel delivery vans on chassis dynamometer cycles

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%

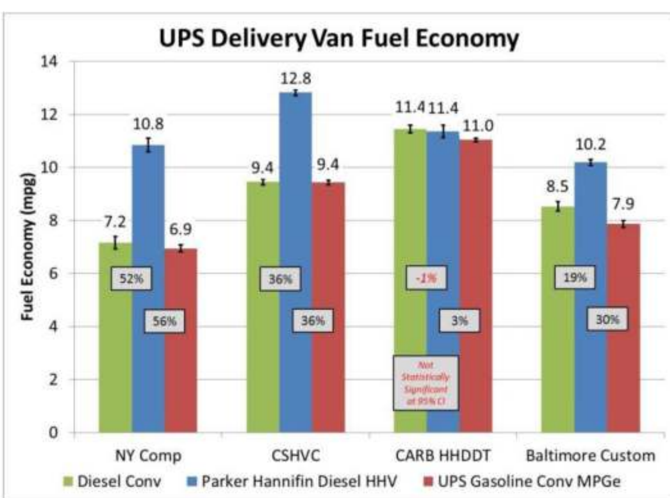

Figure 4. Laboratory Fuel Economy Results

All reported laboratory fuel economy results are average values calculated from four test runs performed on each standard cycle. Gravimetric fuel economy results for the parcel delivery vans are shown in Table 4 and Figure 4 with gasoline results shown in diesel energy equivalent units. The HHVs showed a −1% to +52% improvement in fuel economy over the conventional diesel parcel delivery van on the tested duty cycles. The HHVs showed a +3% to +56% improvement in energy equivalent fuel economy over the conventional gasoline parcel delivery vans on the tested duty cycles.

Comparing Gravimetric and J1939 Reported Fueling During Laboratory Testing

Hydraulic hybrid fuel economy results from both the gravimetric measurement method and the J1939 reported fuel rate for the HHV during chassis dynamometer testing are shown in Table 5. The J1939 method over-reported fuel economy by 1.4%-4.0% with an average error of 3%. It is supposed that J1939 fuel rate reporting is not at a high enough resolution to accurately calculate in-use fuel economy because the error was solely in fuel consumed, not an error in miles traveled during the test. However, the run-by-run repeatability of the error was such that a correction factor can be applied to achieve more accurate in-field analysis with data logging of this channel. Applying 3% reductions to each laboratory test run resulted in reduced error values (1.5% or less); therefore, this adjustment is applied later to the in-field J1939 data analysis. With the correction factor applied, the highest remaining error is on the bracketing cycles, and the lowest remaining error is on the cycles most representative of the in-field data observed.

Table 5. Gravimetric and J1939 fuel economy on various cycles on chassis dynamometer and calculated correction factor

	NY Comp	CSHVC	CARB HHDDT	Baltimore Custom
Gravimetric MPG	10.84	12.82	11.36	10.18
J1939 MPG	11.00	13.29	11.82	10.49
J1939 Error	1.4%	3.7%	4.0%	3.0%
J1939 Corrected MPG	10.68	12.90	11.48	10.18
Remaining J1939 Error	-1.5%	0.6%	1.0%	0.0%

J1939 In-Use Fuel Economy

The fuel economy calculations from the 484 in-use days of J1939 and GPS data recording are assumed to be affected by the same offsets seen in the laboratory tests, and thus these data have been corrected using the factors discussed above. Table 6 shows the total miles driven, fuel consumed, and average fuel economy from the study vehicles during the recorded days.

Table 6. Field fuel economy (data logging with correction factor) of HHVs

Fuel Economy from GPS & J1939 Data Logging	Mileage Total	Fuel Used (gal)	MPG	Corrected MPG
Hydraulic Hybrid	20,978	2,373.8	8.84	8.58

Because detailed driving behavior is also known for each in-use driving day, comparisons of fuel economy to kinetic intensity and average driven speed are possible. Figure 5 shows individual days of operation and the corresponding vehicle average fuel economy, and the laboratory dynamometer fuel economy results presented earlier compared to the average driven speed of the drive cycle. Figure 6 shows the same data compared to kinetic intensity. There is clear indication that the laboratory results bracketed the in-use operational metrics of the study groups. The in-use daily data points clearly show the random effects of varying drivers, loads, traffic, idle time, and weather that are not captured in laboratory testing and that tend to reduce fuel economy as compared to laboratory results. Note that the laboratory tests seemed to over-predict fuel economy by the duty cycle metric chosen and that the Baltimore Custom cycle seems to more accurately represent the field data and thus seems out of line with the standardized duty cycles.

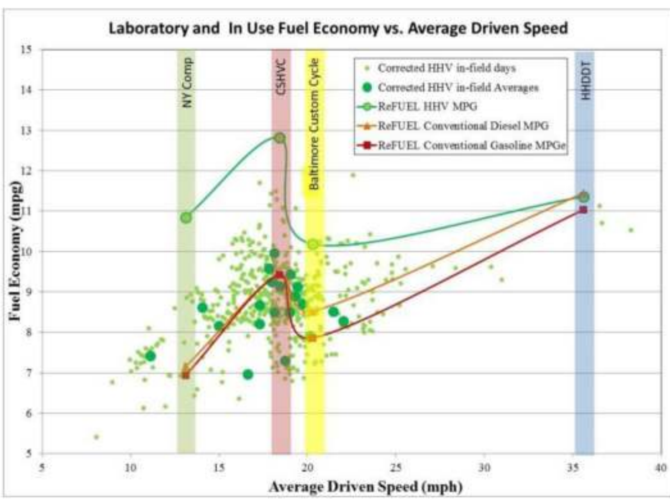

Figure 5. Laboratory and in-use fuel economy compared to average driven speed

Discussion

Hybrid powertrains save the most energy when on high kinetic intensity and high stops-per-mile routes where the repeated deceleration and acceleration events provide opportunity to capture energy through regenerative breaking that would otherwise be lost on a conventional powertrain. The HHVs in Baltimore are being deployed on routes with lower kinetic intensity, higher driven speed, and lower stops per mile than is ideal or has been seen with other studies of hybrid parcel delivery deployments [3, 4, 5, 6]. It is expected that they are not currently delivering their full potential for fuel savings. The HHV demonstrated less change in fuel economy across duty cycles than the conventional parcel delivery van, which ranged from 6.9 to 11.0 mpg with a gasoline engine and from 7.2 to 11.4 mpg with a diesel engine. The HHV ranged only from 10.2 to 12.8 mpg. If the HHVs were deployed on harder decelerating, dense stop-and-go routes with higher kinetic intensity, it would be expected they would achieve a higher percent fuel consumption savings.

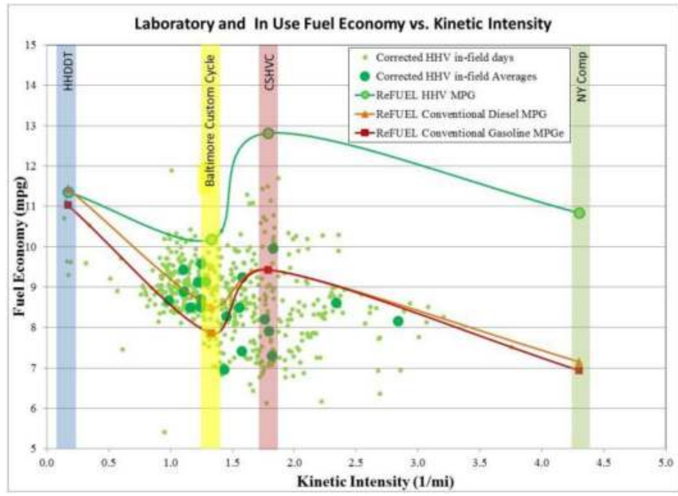

Figure 6. Laboratory and in-use fuel economy compared to kinetic intensity

SUMMARY/CONCLUSIONS

The Parker Hannifin hydraulic hybrid parcel delivery vans consistently are delivering a fuel economy advantage over comparable diesel and gasoline vehicles on all but the highway oriented HHDDT cycle. Laboratory testing demonstrated the following results.

- The hydraulic hybrid parcel delivery van demonstrated 19%-52% better fuel economy than conventional diesel on cycles other than the highway-oriented HHDDT cycle on which it achieved parity.
- The hydraulic hybrid parcel delivery van demonstrated 30%-56% better fuel economy than conventional gasoline on cycles other than the highway-oriented HHDDT cycle on which it was 3% better.
- The custom Baltimore cycle, statistically created from pieces of collected field data, most accurately matched observed in-field fuel economy.
- Both the conventional parcel delivery vans saw lower fuel economy on the custom cycle than the HHV.
- The CSHVC cycle over-predicted the fuel economy for the HHV compared to similar kinetic intensity in-use data.

Additionally field usage data indicate:

- Hydraulic hybrid parcel delivery vans could maximize their fuel saving potential if deployed on more kinetically intense routes more similar to the NY Comp test cycle and observed parcel duty cycles from previous studies [3, 6].

FUTURE WORK

Because a diesel conventional to diesel hydraulic hybrid in-field analysis is not available for any fleet we could identify, a modeled analysis approach to use the collected in-use route data for all of the tested powertrains could be undertaken to estimate their performance over the duty cycles observed. This could provide a virtual comparison of a HHV to a conventional diesel on the actual Baltimore routes.

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DEFINITIONS/ABBREVIATIONS

CAN - Controller Area Network

CARB - California Air Resources Board

CSHVC - City Suburban Heavy Vehicle Cycle

DPF - diesel particulate filter

DRIVE - Drive-Cycle Rapid Investigation, Visualization, and Evaluation

GPS - global positioning system

HHDDT - Heavy Heavy-Duty Diesel Truck

HHV - hydraulic hybrid vehicle

IVT - Infinitely Variable Transmission

NO_x - oxides of nitrogen

NREL - National Renewable Energy Laboratory

NY Comp - New York City Comp

SCR - selective catalyst reduction

UPS - United Parcel Service

APPENDIX

Table A1. SAE J1939 data logging channel list

Data Channel Name	Data Channel Name	Acronym	PGN#	SPN#	Units
Transmission Output Shaft Speed	TransOutputShaftSpeed_1	ETC1	61442	191	RPM
Transmission Input Shaft Speed	TransInputShaftSpeed_1	ETC1	61442	161	RPM
Accelerator Pedal Position 1	AccelPedalPos1	EEC2	61443	91	%
Engine Percent Load At Current Speed	EngPercentLoadAtCurrentSpeed	EEC2	61443	92	%
Actual Maximum Available Engine - Percent Torque	ActMaxAvailEngPercentTorque	EEC2	61443	3357	%
Driver's Demand Engine - Percent Torque	DriversDemandEngPercentTorque	EEC1	61444	512	%
Actual Engine - Percent Torque	ActualEngPercentTorque	EEC1	61444	513	%
Engine Speed	EngSpeed	EEC1	61444	190	RPM
Transmission Selected Gear	TransSelectedGear_1	ETC2	61445	524	Gear
Transmission Current Gear	TransCurrentGear_1	ETC2	61445	523	Gear
Engine Exhaust Gas Recirculation 1 (EGR1) Mass Flow Rate	EngExhstGsRcrcltionMassFlowRate	EGF1	61450	2659	kg/hr
Engine Intake Air Mass Flow Rate	EngInletAirMassFlowRate	EGF1	61450	132	kg/hr
Diesel Particulate Filter Lamp Command	DieselParticulateFilterLampCmd	DPFC1	64892	3697	-
Diesel Particulate Filter Passive Regeneration Status	DslPrtclPssvRgnrtionStatus	DPFC1	64892	3699	-
Diesel Particulate Filter Active Regeneration Status	DslPrtclActvRgnrtionStatus	DPFC1	64892	3700	-
Diesel Particulate Filter Status	DieselParticulateFilterStatus	DPFC1	64892	3701	-
Exhaust System High Temperature Lamp Command	ExhaustSystemHighTempLampCmd	DPFC1	64892	3698	-
Diesel Particulate Filter Active Regeneration Forced Status	DslPrtclActvRgnrtionFrcdStatus	DPFC1	64892	4175	-
Aftertreatment 1 Diesel Particulate Filter Outlet Gas Temperature	Aftrtrtmnt1PrtcltTrpOtltGasTemp	AT1OG2	64947	3246	deg C
Aftertreatment Exhaust Gas Temp	Aftertreatment1ExhaustGasTemp1	AT1IG2	64948	3241	deg C
Referenced Torque	ReferenceEngineTorque	EC1	65251	544	Nm
Red Stop Lamp (engine)	EngRedStopLampData	DLCD1	64773	5095	-
Amber Warning Lamp (engine)	EngAmberWarningLampData	DLCD1	64773	5094	-
Protect Lamp (engine)	EngProtectLampData	DLCD1	64773	5093	-
Nominal Friction - Percent Torque	NominalFrictionPercentTorque	EEC3	65247	514	%
Engine Coolant Temperature	EngCoolantTemp	ET1	65262	110	deg C
Engine Fuel Temperature 1	EngFuelTemp	ET1	65262	174	deg C
Engine Oil Temperature 1	EngOilTemp1	ET1	65262	175	deg C
Engine Intercooler Temperature	EngIntercoolerTemp	ET1	65262	52	deg C
Engine Fuel Delivery Pressure	EngFuelDeliveryPress	EFL_P1	65263	94	kPa
Engine Oil Pressure	EngOilPress	EFL_P1	65263	100	kPa
Wheel-Based Vehicle Speed	WheelBasedVehicleSpeed	CCVS	65265	84	km/h
Brake Switch	BrakeSwitch	CCVS	65265	597	-
Engine Fuel Rate	EngFuelRate	LFE	65266	183	l/h
Barometric Pressure	BarometricPress	AMB	65269	108	kPa
Ambient Air Temperature	AmbientAirTemp	AMB	65269	171	deg C
Engine Air Intake Temperature	EngAirInletTemp	AMB	65269	172	deg C
Engine Intake Manifold 1 Pressure	EngTurboBoostPress	IC1	65270	102	kPa
Engine Intake Manifold 1 Temperature	EngIntakeManifold1Temp	IC1	65270	105	deg C
Engine Air Intake Pressure	EngAirInletPress	IC1	65270	106	kPa
Engine Exhaust Gas Temperature	EngExhaustGasTemp	IC1	65270	173	deg C
Engine Oil Temperature 2	EngOilTemp2	ET2	65188	1135	deg C
Engine Exhaust Gas Temperature - Left Manifold	EngExhaustGasTempLeftManifold	ET	65031	2434	deg C
Engine Exhaust Gas Temperature - Right Manifold	EngExhaustGasTempRightManifold	ET	65031	2433	deg C
Engine Exhaust Gas Average Temperature	EngExhaustGasTempAverage	EAI	64851	4151	deg C
Diesel Oxidation Catalyst Intake Gas Temperature 1	Aftrtrtmnt1DslOxdtnCtlystDffPrss	A1DOC	64800	4765	deg C
Diesel Oxidation Catalyst Exhaust Gas Temperature 1	Aftrtrtmnt1DslOxdtnCtlystIntkGsT	A1DOC	64800	4766	deg C
Diesel Oxidation Catalyst Differential Pressure 1	Aftrtrtmnt1DslOxdtnCtlystOutlGsT	A1DOC	64800	4767	kPa
Diesel Oxidation Catalyst Intake Gas Temperature 2	Aftrtrtmnt2DslOxdtnCtlystIntkGsT	A2DOC	64799	4771	deg C
Diesel Oxidation Catalyst Exhaust Gas Temperature 2	Aftrtrtmnt2DslOxdtnCtlystOutlGsT	A2DOC	64799	4772	deg C
Diesel Oxidation Catalyst Differential Pressure 2	Aftrtrtmnt2DslOxdtnCtlystDffPrss	A2DOC	64799	4773	kPa
SCR Catalyst Intake Gas Temperature 1	Aftrtrtmnt1SCRCtlystIntkGasTemp	A1SCREGT	64830	4360	deg C
SCR Catalyst Exhaust Gas Temperature 1	Aftrtrtmnt1SCRCtlysOutlGasTemp	A1SCREGT	64830	4363	deg C
SCR Exhaust Gas Differential Pressure 1	Aftrtrtmnt1SCRCtlysExhstGsDffPr	A1DCREGP	64831	4358	kPa
SCR System State 1	Aftertreatment1SCRSystemState	A1SCRDS1	61475	4332	-
SCR Diesel Exhaust Fluid Dosing Requested Quantity 1	Aftrtrtmnt1SCRRqdDsngRgntQntity	A1SCRDSR1	61476	4348	g/hr
SCR 1 Diesel Exhaust Fluid Average Consumption	Aftrtrtmnt1SCRAvrgCtlystRgntCnsm	SCR1	64878	3826	L/hr
SCR Conversion Efficiency	Aftrtrtmnt1SCRCtlystCnvrsnEffcnc	SCR1	64878	4364	%
Diesel Exhaust Fluid Actual Dosing Quantity 1	Aftrtrtmnt1SCRActlDsngRgntQntty	A1SCRDSI1	61475	4331	g/hr
Diesel Particulate Filter Differential Pressure	Aftrtrtmnt1DsPrtcltFltrDffPrss	AT1IMG	64946	3251	kPa
Diesel Particulate Filter Intermediate Gas Temperature	Aftrtrtmnt1DslPrtcltFltrInt_0001	AT1IMG	64946	3252	deg C
Engine Exhaust Gas Recirculation Temperature 1	EngExhaustGasRecirculation1Temp	ET2	65188	4750	deg C
Aftertreatment 1 Outlet NH3	Aftertreatment1OutletNH3	A1SCRAI	61477	4377	ppm
Aftertreatment 1 Outlet NOx	Aftertreatment1OutletNOx	AT1OF1	61455	3226	ppm
Aftertreatment 1 Intake NOx	Aftertreatment1IntakeNOx	AT1IG1	61454	3216	ppm

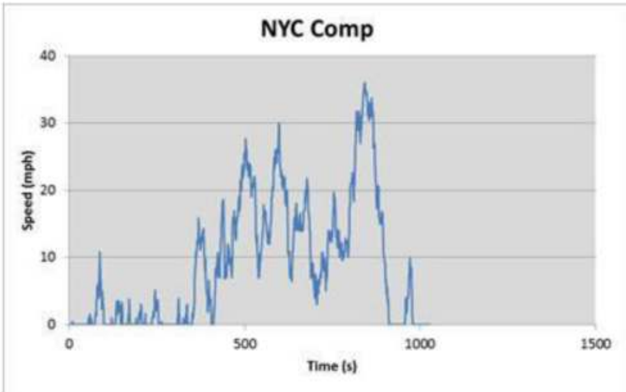

Figure A1. NY Comp Trace

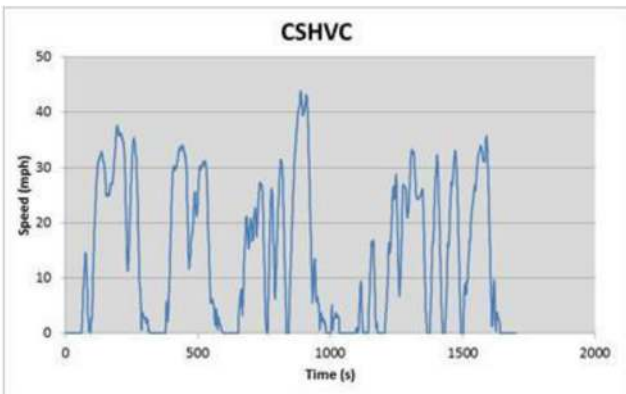

Figure A2. CSHVC Class 4 Trace

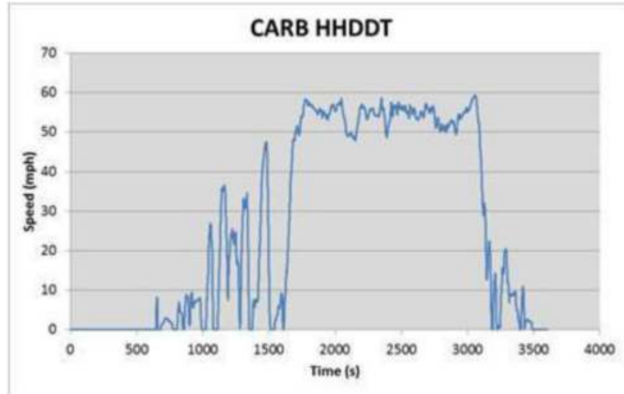

Figure A3. CARB HHDDT Trace

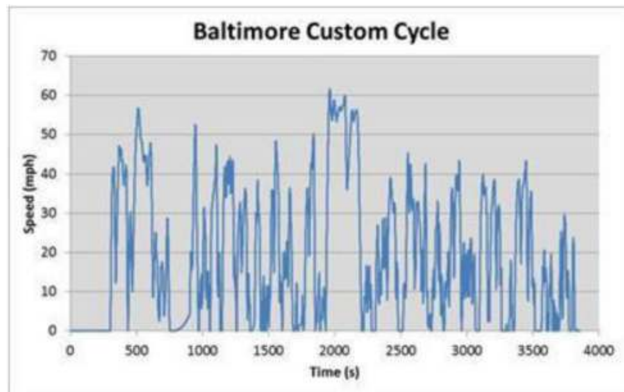

Figure A4. Baltimore Custom Cycle Trace