Investigation of Emissions Impacts from Hybrid Powertrains

Adam Ragatz, Jonathan Burton, Eric Miller, and Matthew Thornton

National Renewable Energy Laboratory

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Strategic Partnership Project Report
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List of Acronyms

AC	Air Conditioning
AER	All Electric Range
CARB	California Air Resources Board
CV	Coefficient of Variation
CVS	Constant Volume Sample
CO_2	Carbon Dioxide
EGR	Exhaust Gas Recirculation
EPA	U.S. Environmental Protection Agency
ePTO	Electric Power Take-Off
GVWR	Gross Vehicle Weight Rating
HDV	Heavy-Duty Vehicle
HEV	Hybrid Electric Vehicle
HHDDT	Heavy Heavy-Duty Diesel Truck
HHV	Hydraulic Hybrid Vehicle
HNCO	Isocyanic Acid
HVIP	Hybrid and Zero-Emission Truck and Bus Voucher Incentive Project
ITR	Innovation Technology Regulation
KI	Kinetic Intensity
MY	Model Year
N_2O	Nitrous Oxide
NH_3	Ammonia
NO	Nitric Oxide
NO_x	Oxides of Nitrogen
NO_2	Nitrogen Dioxide
NREL	National Renewable Energy Laboratory
OBD	On-Board Diagnostics
OEM	Original Equipment Manufacturer
PEMS	Portable Emissions Measurement System
PHEV	Plug-in Hybrid Electric Vehicle
PKE	Positive Kinetic Energy
PTO	Power Take-Off
ReFUEL	Renewable Fuels and Lubricants
SAE	Society of Automotive Engineers
SCR	Selective Catalytic Reduction
UDDS-HD	Heavy-Duty Urban Dynamometer Driving Schedule
ZEV	Zero Emissions Vehicle

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Project Background and Objective

The National Renewable Energy Laboratory (NREL) under California Air Resources Board (CARB) Agreement Number 14-613, NREL Contract Number FIA-15-1802, has performed a series of chassis dynamometer and portable emissions measurement system (PEMS) studies to better understand how tailpipe NO_x emissions are affected by the addition of a hybrid propulsion system as compared with conventional medium-duty and heavy-duty diesel vehicles operating in the same vocations. Previous work has demonstrated the addition of an aftermarket hybrid propulsion system can provide a significant fuel economy advantage under the right drive cycle conditions. However, many vehicles also exhibited an increase in tailpipe NO_x emissions. This work, under CARB Agreement Number 11-600, NREL Contract Number FIA-11-1763 demonstrated an increase in tailpipe NO_x across a number of vocations and vehicle body styles. The emissions increase was also observed using various test methods including chassis dynamometer, PEMS, and in-use on-board diagnostics (OBD) NO_x sensors (Thornton et al. 2014). The work presented in this report represents a continued effort to better understand the cause of this emissions increase and steps that can be taken to ensure the issue is addressed for future vehicles going forward.

Project Summary

This study focused on the core areas of interest which required additional investigation after the first phase of the Hybrid and Zero-Emission Truck and Bus Voucher Incentive Project (HVIP) project.

1. The work is broken into two primary tasks: (i) provides technical guidance and feedback to CARB during the crafting of the Innovative Technology Regulation (ITR). The ITR provides certification flexibility for medium-duty and heavy-duty vehicle hybrid conversion systems. As part of this support NREL PEMS tested a HINO 195 (diesel conventional) and vertically integrated HINO 195h (diesel-electric hybrid) to demonstrate the feasibility of achieving the ITR criteria that had been drafted. The results of this task are summarized in number 2, below; and (ii) performs chassis dynamometer studies on current medium- and heavy-duty hybrid vehicles and their conventional baseline to better understand the main driving factors that contribute to the hybrid vehicle NO_x emissions increase observed under the preceding HVIP evaluation project. To achieve the objective of this task, three different hybrid/conventional vehicle configurations were considered: (i) Hino 195h hybrid and conventional diesel Hino; (ii) Parker Hannifin RunWise hydraulic hybrid refuse truck and conventional diesel refuse truck, and (iii) Odyne hybrid utility truck with electric power take-off (ePTO). The results of this task are summarized in numbers 3 through 5, below.

2. NREL successfully vetted and validated the ITR's PEMS hybrid test procedure through testing a HINO hybrid and a conventional vehicle using PEMS. The vehicles were simultaneously PEMS tested, using routes and drive cycle metrics developed by NREL, in a leader-follower configuration to minimize the impacts of differences in traffic and weather conditions. The HINO 195h hybrid demonstrated a 12.2% fuel economy increase on the transient route, and 10.4% fuel economy increase on the highway test route. The HINO hybrid had a statistically significant NOx increase both on the transient and highway routes. However, it is important to stress that this increase is a large percentage, but absolute magnitude of these emissions from both the hybrid and conventional are drastically lower than the selective catalytic reduction (SCR) equipped vehicles tested under HVIP-1

3. The SCR inlet exhaust temperatures for the HINO hybrid and conventional configurations were examined to see if the powertrain architectures were impacting the exhaust temperatures and thus the emissions performance. No significant differences in the exhaust temperatures between the hybrid and conventional Hino trucks were observed. In addition, the warm-up time was similar across the two architectures and there was no evidence of the hybrid vehicle spending any more time with an exhaust temperature below 200°C than the conventional vehicle. Finally, diesel particulate filter (DPF) regeneration events had an equivalent influence on the SCR inlet temperature traces for the hybrid and the conventional Hino trucks. To isolate specific components that could be contributing to the NOx increase the following parameters were also evaluated:

    - SCR bricks were swapped to rule out SCR catalyst poisoning
    - The doser nozzles and decomposition tubes were inspected to rule out defects, deterioration or other anomalies

- HINO diagnostic software DXII was purchased and was used to determine if there were any faults with the various subsystems
- Urea injection test were performed to determine if proper amounts of ammonia were injected.

4. NREL instrumented a series of conventional and hydraulic hybrid refuse trucks in the Miami-Dade municipal fleet to collect real-world activity that was used to develop a custom refuse drive cycle and conducted chassis dynamometer emissions testing of a conventional diesel refuse truck and a diesel hydraulic hybrid refuse truck at NREL's Renewable Fuels and Lubricants (ReFUEL) laboratory. The hybrid vehicle showed consistently higher NOx emissions results over the conventional vehicle across all cycles. These NOx increases were primarily attributed to the poor match between the hybrid vehicle and baseline vehicle. The baseline vehicle was of a significantly newer vintage than the hybrid, exacerbating the emissions comparison. NREL evaluated a number of indicators of SCR health for the hybrid refuse truck to determine the root cause of the increased NOx emissions. These indicators included ammonia (NH3) slip, isocyanic acid (HNCO) slip (indicator of incomplete urea decomposition), nitrous oxide (N2O) formation over the catalyst, and SCR inlet NOx emissions. Slightly elevated levels of NH3 and N2O were observed at parts of the cycle but nothing of significant concern.

5. An Odyne plug-in hybrid electric (PHEV) utility truck with ePTO was studied on NREL's heavy-duty chassis dynamometer. The vehicle had the capability of enabling or disabling the hybrid system so that NOx emissions could be studied in either PHEV or conventional operating modes on the same vehicle. The study demonstrated that the vehicle driving in hybrid mode resulted in slightly lower NOx emissions for most drive cycles when compared to the conventional vehicle mode, though the NOx differences were very small. It was shown that with the implementation of the battery powered ePTO system large improvements were made in NOx emissions over a conventional stationary PTO operation.

Project Results by Task

Benchmark a Vertically Integrated Hybrid Following the Proposed Innovative Technology Review Procedure

The main objective of this task was to benchmark a vertically integrated hybrid electric vehicle (HEV) such as the Hino 195h versus the conventional diesel Hino 195, using the proposed version of the ARB interim PEMS hybrid test procedures that are part of the "California Certification and Installation Procedures for Medium- and Heavy-Duty Vehicle Hybrid Conversion Systems" ITR (https://www.arb.ca.gov/regact/2016/itr2016/appe.pdf). The purpose of this benchmark testing was to vet and verify the applicability of the proposed PEMS hybrid test procedure. Between performing these verification tests and the publication of this report, this proposed ITR has since been adopted by the ARB, as of October 2016. These tests served both as a data point for the performance of the HINO vehicles and a method for validating the interim ITR hybrid test procedure. In developing the ITR, CARB asked for NREL's technical guidance to recommend drive cycle metrics and acceptable levels of variation to constitute a valid run. Part of the challenge in generating these criteria is to put limits in place which are stringent enough that someone could not "cheat" the test by intentionally driving the conventional and hybrid vehicles differently, but not so stringent that normal run-to-run variability would disqualify an otherwise valid test. The approach was to first procure the test vehicles, and then identify a local PEMS on-road test route near Denver, Colorado, which shared similar drive cycle characteristics to the urban dynamometer driving schedule for heavy-duty vehicles (UDDS-HD) test cycle. Once an appropriate route had been identified and the target metrics were solidified, the vehicles were simultaneously PEMS tested in a leader-follower configuration to minimize the impacts of differences in traffic and weather conditions.

ITR Overview

California has determined that it needs to transition to zero and near-zero emission transportation and freight movement technologies to meet its air quality and climate goals. These goals include:

- Reducing greenhouse gas emissions to 40% below 1990 levels by 2030
- Reducing greenhouse gas emissions from the transportation sector to 80% below 1990 levels by 2050
- Deploying 1.5 million zero emission vehicles (ZEV) by 2025, as directed in Executive Order B-16-2012, and the related goal of deploying one million ZEVs and near-ZEVs by January 1, 2023, as codified in Health and Safety Code Section 44258.4(b). The California Sustainable Freight Action Plan also includes a related goal of deploying 100,000 freight vehicles and equipment capable of zero emission operation by 2030
- Meeting federal health-based eight-hour ozone standards, as required, by 2023 and 2031 in the South Coast, which will require a reduction in oxides of nitrogen (NO_x) emissions of approximately 70% by 2023 and 80% by 2031 from today's levels.

While a diversity of new zero and near-zero emission trucks and buses will be needed to meet these goals, the ARB's comprehensive heavy-duty engine and vehicle certification requirements may deter some manufacturers from developing promising new heavy-duty vehicle technologies, including advanced hybrids for heavy-duty vehicles (HDVs), in part because of high initial certification costs and engineering challenges. One element of certification—OBD requirements—can be particularly resource-intensive and can pose engineering challenges for some new technologies. OBD is a critical emission control program consisting mostly of added software to identify and address potential engine and aftertreatment failures that can lead to an increase in emissions. The initial challenge of OBD compliance could lead a manufacturer to choose not to develop, or to delay introduction of, innovative new truck or bus technologies that are uncertain to achieve market acceptance.

To address these challenges and encourage additional needed technology innovation, the ITR would provide a more flexible short-term certification pathway for hybrid conversion systems. This applies to hybrid conversion systems installed on an ARB-certified vehicle between 6,001 and 14,000 pounds Gross Vehicle Weight Rating (GVWR) or on an ARB-certified engine installed in a vehicle over 8,500 pounds GVWR. The work under this task was in direct support of the hybrid conversion system and specifically the hybrid technology emissions test procedure discussed previously and on page E-21 of the ITR.

The ITR's PEMS hybrid test procedure incorporated the SAE J1526 "JOINT TMC/SAE FUEL CONSUMPTION IN-SERVICE TEST PROCEDURE TYPE III" procedure. This dictated many of the criteria for acceptable test conditions and following distance (within visual contact, but not interfering with aerodynamics) and is a widely accepted standing precedent. NREL has extensive previous experience using this standard for on-road aerodynamics testing. In addition, the procedure requires that the vehicles used are to be as similar as possible--same base components, gearing, engine if possible, and similar mileage. The vehicle requirements are detailed in the "Vehicle Selection and Preparation" section on page E-25 of the ITR. The test plan also requires using an approved PEMS device, such as the Semtech-DS NREL used for this task, leader-follower method to minimize impacts of variations in weather and traffic and two routes (i.e., transient and highway steady-state). The primary metric selected for verifying repeatability were coefficient of variation (CV) of average vehicle speed and CV of positive kinetic energy (PKE). To demonstrate compliance with this procedure, an OEM must demonstrate a 10% fuel savings without backsliding on NO_x emissions relative to the baseline vehicle. The following sections discuss the NREL testing approach and results of the ITR outlined PEMS hybrid procedure.

Test Vehicles

The test vehicles that met our specifications (Table 1) were sourced from a California rental company in the San Francisco Bay area. The vehicles were nearly identical conventional/hybrid counterparts except for being a couple years apart. This was the best match that could be sourced from available vehicles in the rental fleet; however, it is anticipated that an OEM should be able to match the year as well for an official approval test.

Table 1. PEMS ITR Test Vehicle Specifications

	Conventional Diesel	Hybrid Diesel-Electric
		
Vehicle Year	2015	2013
Model	HINO 195	HINO 195h
GVWR	19,500 lbs. (Class 5)	19,500 lbs. (Class 5)
Curb Weight	6,854 lbs.	7,304 lbs. (Conv. +450 lbs.)
Test Weight	15,390 lbs.	15,615 lbs. (Conv. +225 lbs.)
Engine Year	2015	2012
Engine Model	J05E-TP (5.123 L) 210 HP	J05E-TP (5.123 L) 210 HP
Engine Family	FHMXH05.1JTP	CHMXH05.1JTP
Transmission	Aisin 6-speed Auto	Aisin 6-speed Auto
Rear Ratio	5.571	5.571
Hybrid Battery		Ni-MH, 288V
Hybrid Traction Motor		36kW (48.3 HP)
Other		Idle stop engine shutdown

Route Selection

For vehicles undergoing certification on a chassis dynamometer the UDDS-HD is a well-established test cycle which is appropriate for a wide range of medium- and heavy-duty vocational vehicles (Dynamometer Schedules 1977). Additionally, from the first phase of HVIP work the UDDS-HD was found to be a good fit to the real-world operation of the instrumented vehicles (Figure 1) (Dynamometer Schedules 1977).

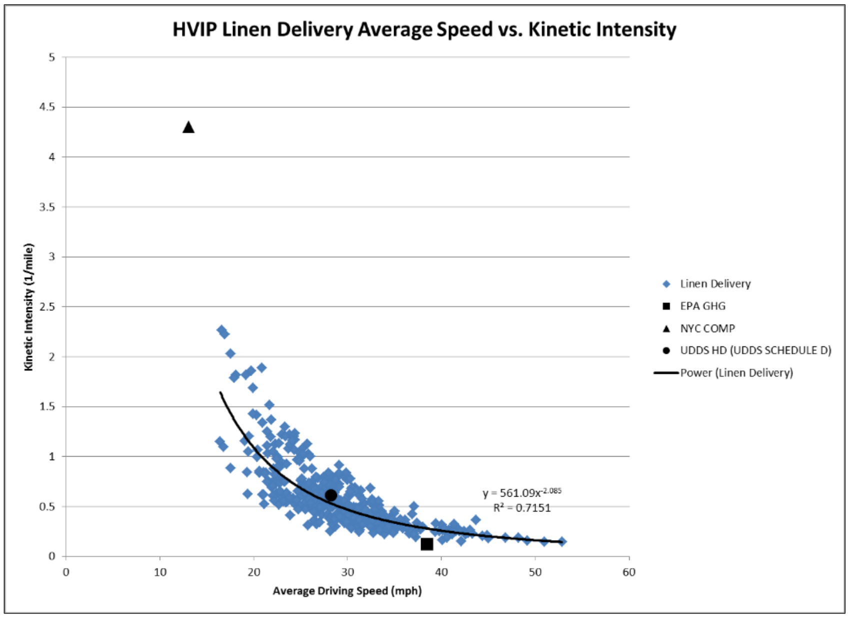


Figure 1. Example of HVIP In-use date and standard drive cycle comparison

For this reason, it was decided that the transient test route should have similar characteristics to the UDDS-HD. A local route in the Denver area was identified with proximity to the NREL ReFUEL lab. An overview and close-up map are shown in Figure 2. In addition to the transient route a steady-state highway test is also required as part of the interim ITR. The results from the highway portion have a much smaller weighting factor but are used to ensure that a hybrid system optimized for transient operation does not have a drastic unintended impact during highway operation. Even though most vocational vehicles spend most of their time under transient conditions, it is not uncommon for this to be bookended with highway travel as vehicles go from the main depot to where the route where work is performed and then back to the depot at the end of the day.

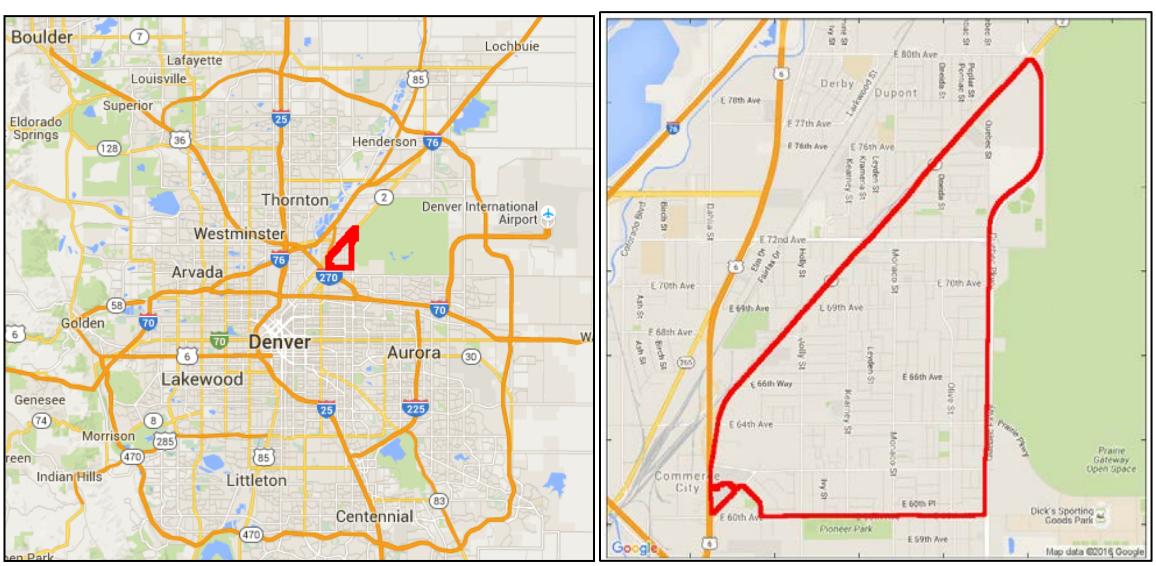


Figure 2. PEMS route

An example vehicle speed trace for this route is shown in Figure 3, for comparison with the UDDS-HD test cycle.

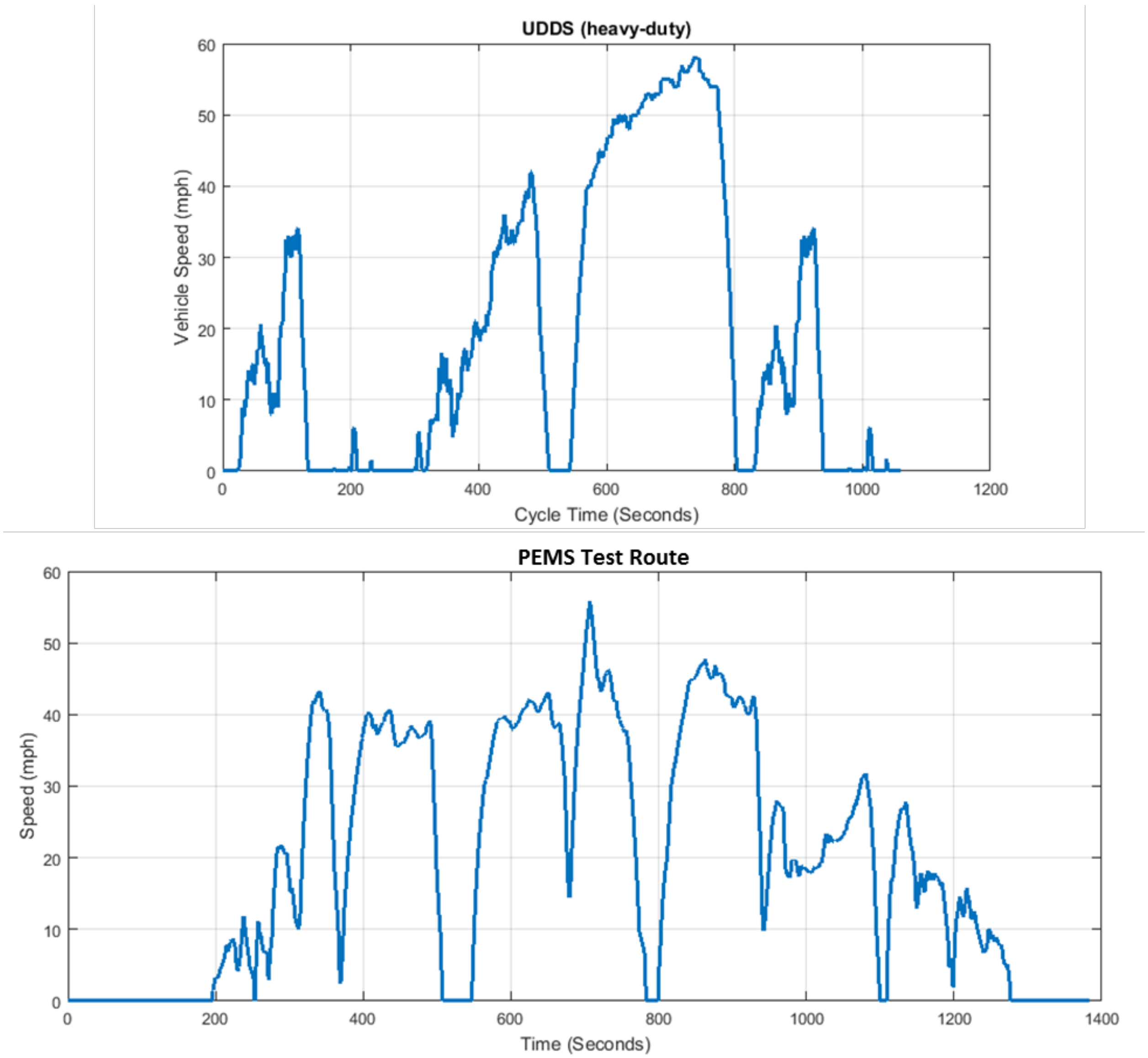


Figure 3. PEMS route comparison with UDDS-HD

The highway route map out-and-back starting from the west side (Watkins) and turning around on the east side (Strasburg) is shown in Figure 4.

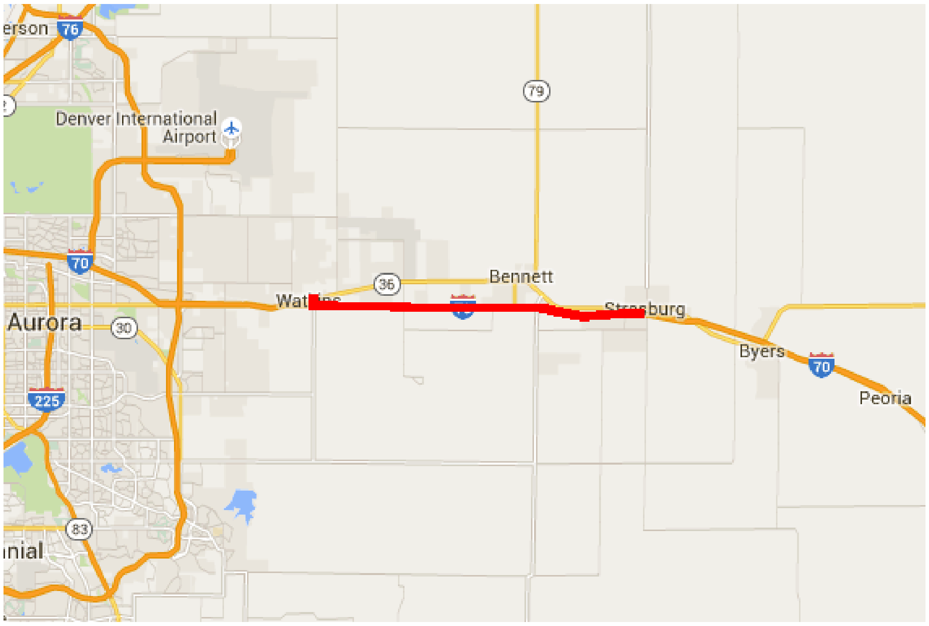


Figure 4. PEMS highway route

Drive Cycle Metrics

For the transient route it was determined that average vehicle speed along with some measure of drive cycle aggressiveness could be used to determine how similarly the vehicles drove over the same route from run-to-run and vehicle-to-vehicle. Traditionally NREL has used kinetic intensity (KI) as a measure of drive cycle aggressiveness. However, it has also been well documented that the road grade component of KI (Δh) cannot be derived from GPS alone and typically requires map matching and lookup from a road grade database such as TomTom or USGS (Wood, Burton, Duran, and Gonder 2014).

$$ki = \frac{\tilde{a}}{v_{aero}^2} \cong \frac{\sum_{j=1}^{N-1} positive\left(\frac{1}{2}\cdot\left(v_{j+1}^2 - v_j^2\right) + g\cdot\left(h_{j+1} - h_j\right)\right)}{\sum_{j=1}^{N-1} \overline{v_{j,j+1}^3}\cdot \Delta t_{j,j+1}}$$

Formula 1. Kinetic Intensity

To simplify the computational burden placed on OEMs looking to receive approval for a hybrid system through the ITR procedure a different, but related, metric, PKE was used instead.[1] Positive Kinetic Energy or "PKE" is defined as (1/total distance) * Σ[(velocity(i)^2) – (velocity(i-

[1] http://www.daham.org/basil/leedswww/emissions/drivecycles.htm

1)^2)] summed over samples where velocity(i) > velocity(i-1), for velocity data collected on the interval of i = 1 to n number of time samples, evaluated on a one hertz basis in feet/second^2.

$$PKE = \frac{\sum (V_{final}^{\ 2} - V_{initial}^{\ 2})_{a>0}}{Dist}$$

where:
V final : Final velocity
V initial : Initial velocity
a>0: For positive acceleration only
Dist: Total distance travelled in trip or microtrip

Formula 2. Positive Kinetic Energy

Both of these metrics along with a handful of standard drive cycle metrics were calculated for each individual test run. When comparing the variance from run-to-run or vehicle-to-vehicle the CV was used. The CV of a data set is the normalized measure of dispersion of probability distribution. It is the ratio of the standard deviation to the mean.

The hybrid and conventional vehicles traveled the specified local route in two different configurations with multiple repeats. The first configuration "Apart" the vehicles were spaced far enough apart that the trailing driver could not see the lead vehicle. Second "Together" the vehicles were spaced far enough apart as to not interfere with each other's aerodynamics (300 or more feet depending on the vehicle type (McAuliffe et al. 2018), but close enough that the lead vehicle could usually be seen by the trailing vehicle. Drive cycle statistics for each run are shown in Table 2, along with the same metrics for the UDDS-HD for comparison. A lumped CV was calculated for each metric of interest under the two different scenarios by pooling conventional and hybrid data together.

Table 2. PEMS Route Statistics

		Run #	Time	Zero Speed	Dist	Avg Speed	CoV	Avg DSpeed	Max Speed	KI	CoV	PKE	CoV
Vehicle	Spacing		sec	% Time	miles	mph	%	mph	mph	1/mi	%	m/s2	%
		UDDS	1,060	33.3%	5.55	18.8	NA	28.2	58.0	0.61	NA	0.27	NA
Conv	Apart	1	1,380	30.1%	7.47	20.1	3.2%	28.7	56.5	0.73	9.4%	0.24	8.7%
Conv	Apart	2	1,492	31.2%	7.47	18.5		26.9	55.1	0.86		0.27	
Conv	Apart	3	1,442	28.1%	7.47	19.2		26.7	55.0	0.84		0.25	
Hybrid	Apart	4	1,501	29.0%	7.50	19.8		27.8	54.4	0.980		0.301	
Hybrid	Apart	5	1,434	28.5%	7.50	20.2		28.2	53.8	0.894		0.277	
Hybrid	Apart	6	1,471	29.3%	7.50	19.9		28.1	55.7	0.898		0.292	
Conv	Together	7	1,246	16.7%	7.46	22.3	5.2%	26.7	55.7	0.90	6.5%	0.27	6.0%
Conv	Together	8	1,204	16.8%	7.47	23.1		27.8	55.7	0.84		0.26	
Conv	Together	9	1,386	25.6%	7.46	19.9		26.8	55.4	0.84		0.27	
Hybrid	Together	10	1,331	18.3%	7.51	21.8		26.7	55.9	0.989		0.302	
Hybrid	Together	11	1,241	19.6%	7.51	22.5		28.0	55.3	0.912		0.280	
Hybrid	Together	12	1,383	21.2%	7.51	21.1		26.7	55.8	0.936		0.293	

Although it appears for this particular set of runs the "Apart" scenario had more variation on aggressiveness, possibly a result of differing traffic conditions, but under both scenarios all pooled CVs were below 10%. Therefore, <10% was determined to not be an unreasonable target threshold for these particular vehicles on this particular route.

As to the impact this could have on fuel economy and emissions, HVIP-1 dynamometer data were leveraged to setup a hypothetical "gaming" scenario. First, the chassis dynamometer fuel economy and NO_x results for a similarly sized vehicle (Class 5 step van) were plotted against KI and a fit curve was added to both the conventional and hybrid results. This is shown in Figure 5. The vertical black lines represent the actual fuel consumption and emissions difference at KI = 0.5, 1, 2, and 4. The tipped orange lines represent a hypothetical scenario where the conventional vehicle is driven more aggressively and the hybrid vehicle less aggressively resulting in a 10% difference in KI. Although this does affect the results it's only by a couple percent over a wide range of drive cycles, and therefore reaffirmed a 10% CV allowance would most likely not allow for any drastic effects on fuel economy and emissions that could be gained through "cheating" or "gaming" the tests.

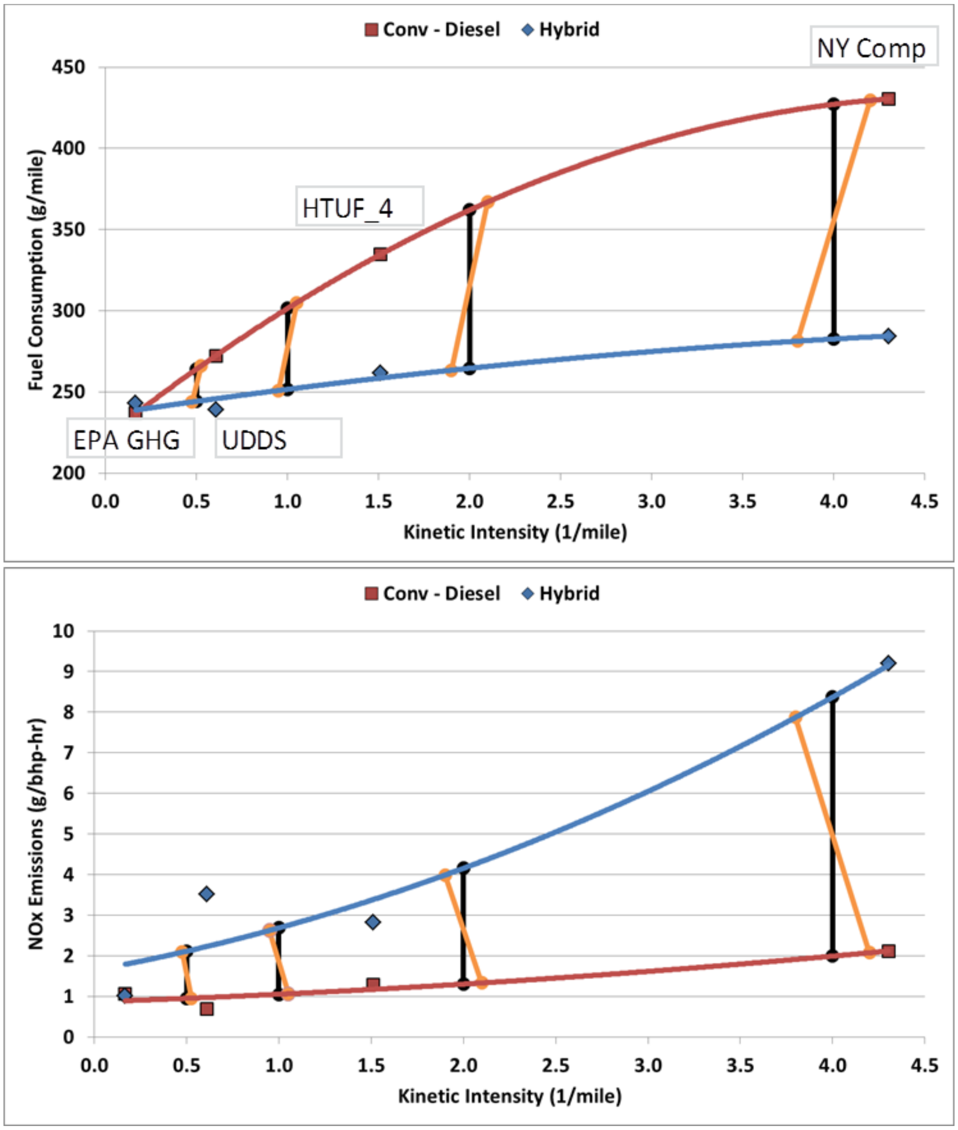


Figure 5. Fuel economy and NO_x emissions versus KI Plots for PEMS route

For the steady-state highway route a different set of drive cycle metrics were used. Since the on-highway portion should be relatively constant, average speed, standard deviation of speed, and percent of time spent within a predefined window were used to gauge compliance. An original window of ±1mph around the nominal target speed was discussed. However, even with the cruise control set, rolling hills and traffic conditions caused the speed to vary more than ±1mph for a significant portion of the drive. Figure 6, shows an example of this out-and-back trace over a stretch of highway east of Denver. The red box indicates the period spent at highway speeds and the following metrics have been calculated for the period of time spent within that box.

- Mean: 64.02 mph
- Stdev: 1.30 mph
- 64 +/- 1mph: 81.9% of time.

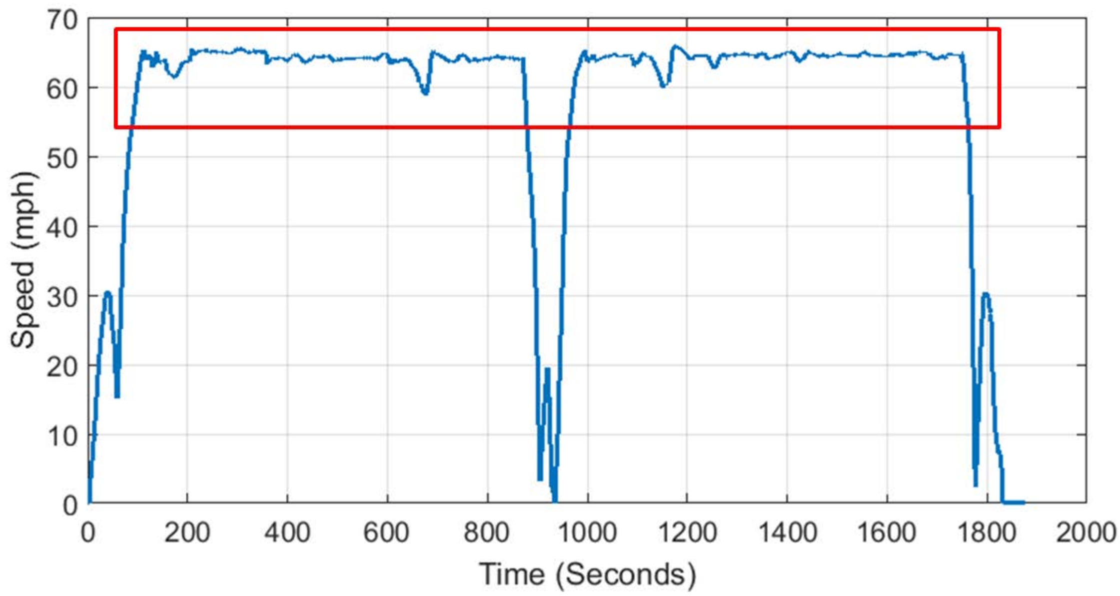
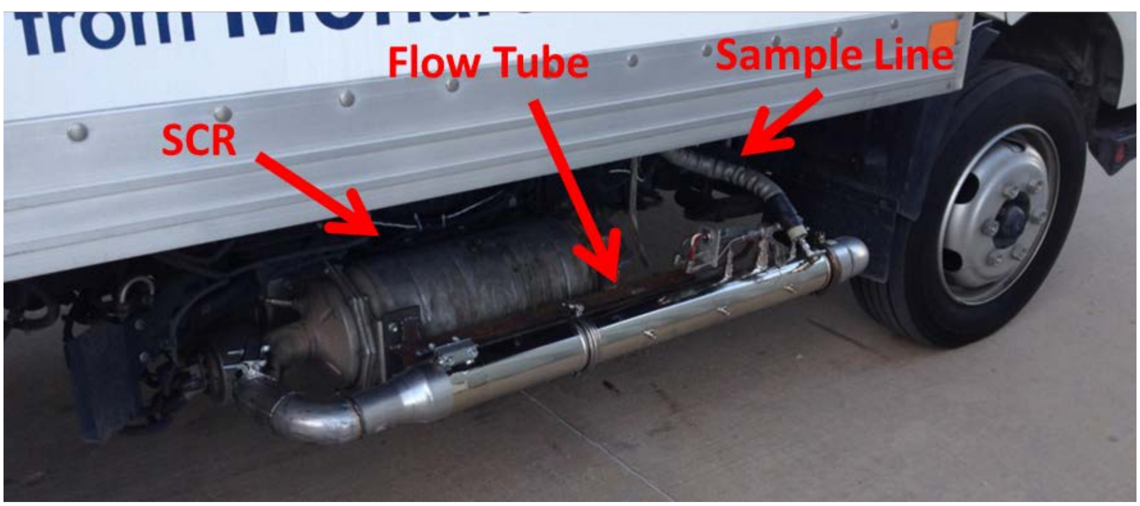


Figure 6. Example of the out-and-back trace over a stretch of highway east of Denver

The constraint of ±1mph was only achieved for ~82% of the time on a relatively gentle stretch of highway in the eastern plains of Colorado. Therefore, it was determined these criteria appeared to be unnecessarily stringent and was therefore loosened to ±2mph.

PEMS Testing

For emissions testing both vehicles were equipped with a Semtech-DS PEMS unit, as shown in Figure 7, a small Honda generator to power the PEMS, and ballasted to 50% cargo capacity. Since the hybrid vehicle is heavier to begin with the available cargo capacity is less, the 50% cargo capacity ballast (450 lbs. for the conventional and 225 lbs. for the hybrid), resulted in a final test weight of 15,390 lb. for the conventional and 15,615 lb. for the hybrid as shown in Table 1.



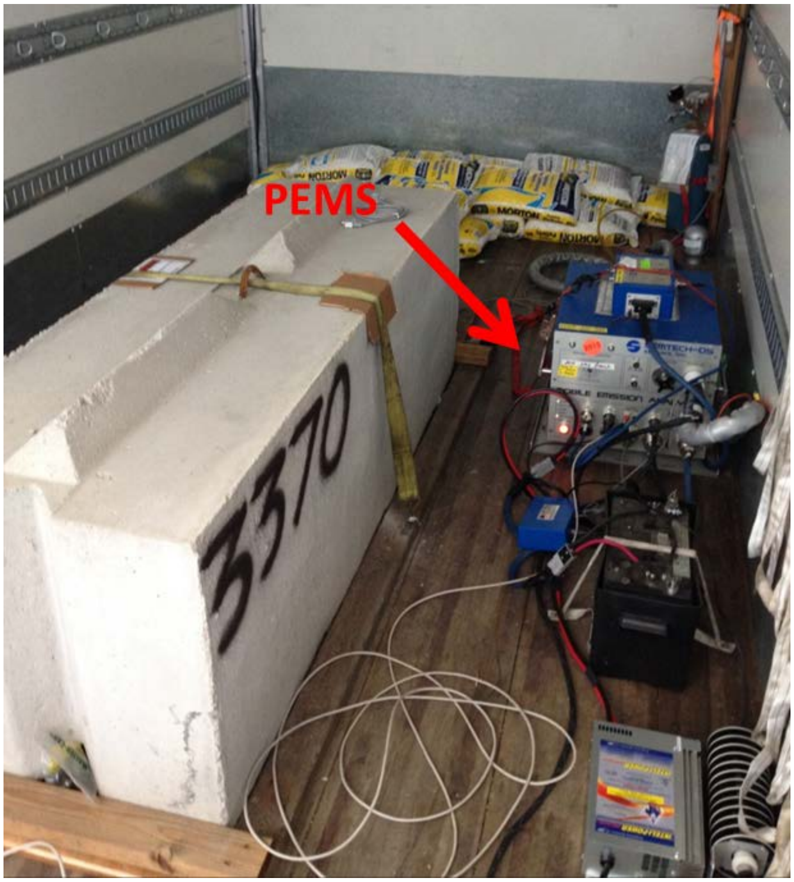


Figure 7. Photos of PEMS installation on Hino trucks

Vehicles were operated over the same transient and steady-state routes identified in the previous section using a leader-follower approach. The driver of each vehicle remained the same throughout the tests, but the leader and follower alternated for each run. Drive cycle statistics are shown in Table 3. The 10% CV limit was not exceeded by either the individual or pooled variance.

Table 3. PEMS Hino Truck Drive Route Statistics

	Time	Zero Speed	Dist	Avg Speed	CoV	Avg DSpeed	CoV	Max Speed	KI	PKE	CoV
	sec	% Time	miles	mph	%	mph	%	mph	1/mi	m/s2	%
'2016-10-21 Conv (445) Trans #1.mat'	1,366	34.3%	7.55	19.9		30.2		55.5	0.83	0.29	
'2016-10-21 Conv (445) Trans #2.mat'	1,395	34.0%	7.55	19.5		29.5		55.7	0.73	0.24	
'2016-10-21 Conv (445) Trans #3.mat'	1,345	32.2%	7.55	20.2		29.8		55.8	0.86	0.29	
'2016-10-21 Conv (445) Trans #4.mat'	1,345	32.2%	7.55	20.2	2.2%	29.8	1.3%	55.8	0.86	0.29	8.1%
'2016-10-21 Conv (445) Trans #5.mat'	1,409	35.0%	7.55	19.3		29.7		55.9	0.87	0.30	
'2016-10-21 Conv (445) Trans #6.mat'	1,363	31.6%	7.55	19.9		29.2		55.5	0.92	0.31	
'2016-10-21 Conv (445) Trans #7.mat'	1,322	31.8%	7.55	20.6		30.2		56.0	0.77	0.27	
'2016-10-21 Hyb (895) Trans #1.mat'	1,356	29.6%	7.54	20.0		28.5		56.9	0.78	0.25	
'2016-10-21 Hyb (895) Trans #2.mat'	1,394	35.2%	7.54	19.5		30.1		56.7	0.90	0.30	
'2016-10-21 Hyb (895) Trans #3.mat'	1,334	27.7%	7.55	20.4		28.2		57.3	0.92	0.28	
'2016-10-21 Hyb (895) Trans #5.mat'	1,417	33.0%	7.55	19.2	2.5%	28.6	2.8%	57.8	0.93	0.30	7.3%
'2016-10-21 Hyb (895) Trans #6.mat'	1,359	30.5%	7.55	20.0		28.8		57.3	0.86	0.27	
'2016-10-21 Hyb (895) Trans #7.mat'	1,326	31.7%	7.55	20.5		30.0		57.9	0.80	0.27	
					2.3%		2.4%				7.4%

For the steady-state highway testing 55±2mph for >80% of the time was easily achieved, as shown in Figure 8.

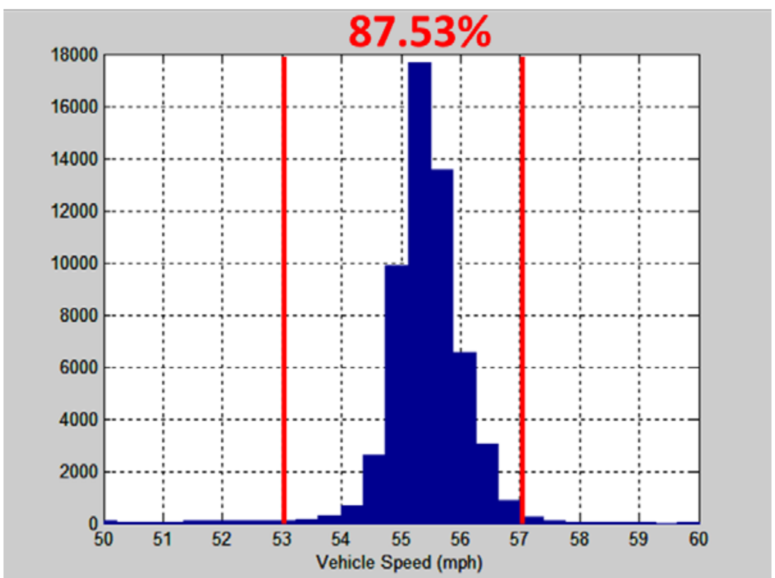


Figure 8. PEMS highway test speed histogram

The HINO 195h hybrid demonstrated a 12.2% fuel economy increase on the transient route, and 10.4% fuel economy increase on the highway test route. This is shown graphically in Figure 9, along with the chassis dyno results from HVIP-1 for a Class 5 step van over the UDDS-HD.

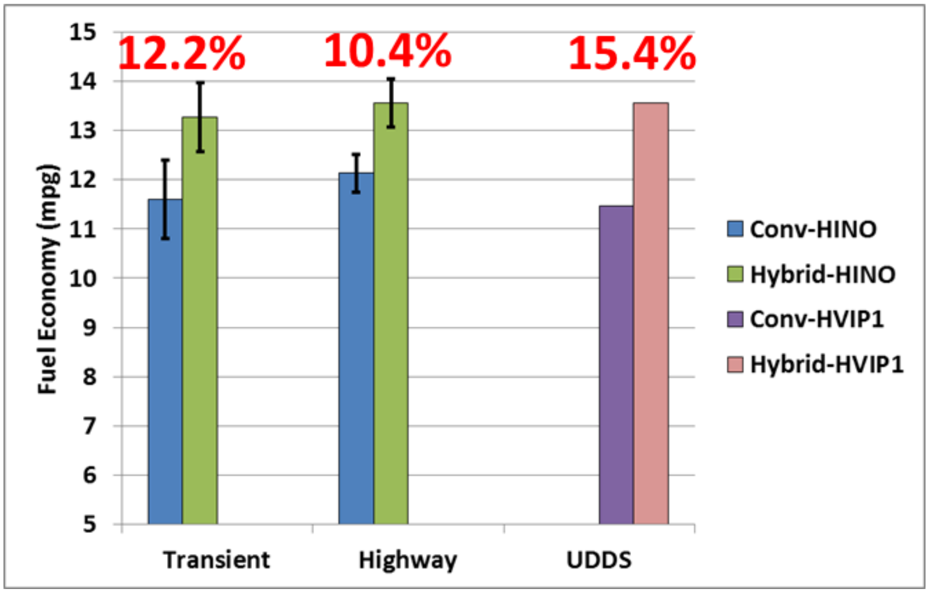


Figure 9. PEMS Hino truck test fuel economy results

Looking at the emissions results, the HINO hybrid demonstrated a statistically significant NO_x increase both on the transient and highway routes. This is shown graphically in Figure 10. However, it is important to stress that this increase is a large percentage, but absolute magnitude of these emissions from both the hybrid and conventional are drastically lower than the selective catalytic reduction (SCR) equipped vehicles tested under HVIP-1, Figure 10 and Figure 11.

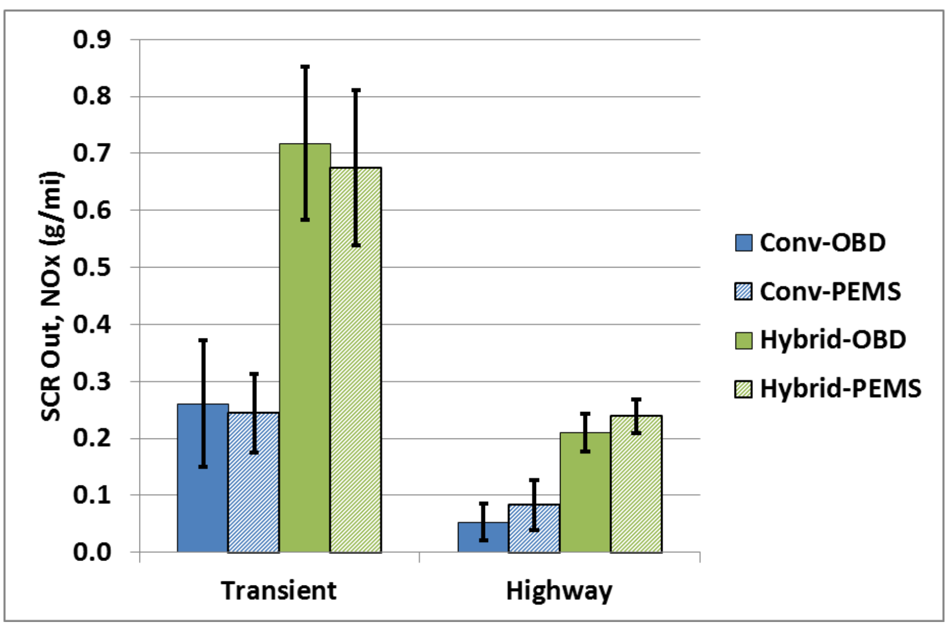


Figure 10. PEMS Hino truck NO_x emissions results

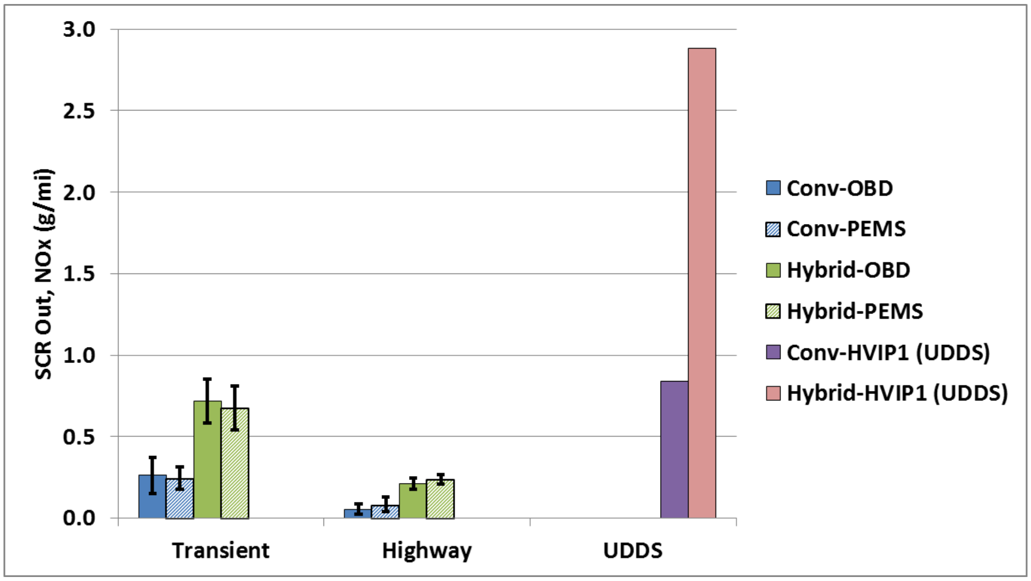
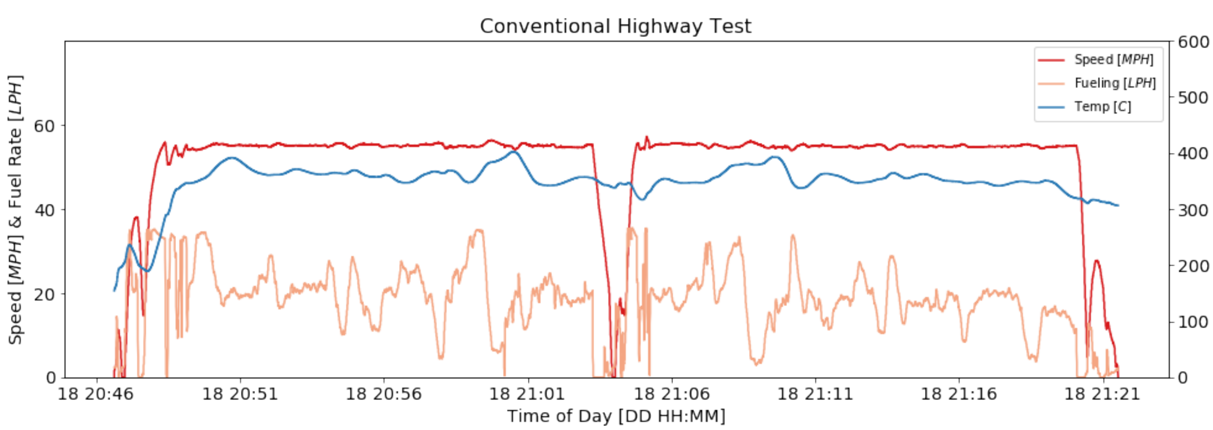


Figure 11. PEMS Hino truck NO_x emissions comparison with HVIP-1 results

As with the HVIP-1 project, the SCR inlet exhaust temperatures for the hybrid and conventional configurations were examined to see if the powertrain architectures were impacting the exhaust temperatures and thus the emissions performance. It is speculated that hybrid architectures could influence the engine load and operation over a duty cycle, resulting in lower exhaust temperatures and lower emission control conversion efficacy. Nonetheless, as was observed during the HVIP-1 project, no significant differences in the exhaust temperatures between the hybrid and conventional Hino trucks was observed during this study. This can be seen in Figure 12, where the instantaneous exhaust temperatures over both the highway and transient PEMS test routes were near identical. In addition, the warm-up time was similar across the two architectures and there was no evidence of the hybrid vehicle spending any more time with an exhaust temperature below 200°C than the conventional vehicle. This is shown in the distribution of time spent at various exhaust temperatures for the hybrids and conventional vehicles over both PEMS routes in Figure 13. Finally, as shown in Figure 14, DPF regeneration events had an equivalent influence on the SCR inlet temperature traces for the hybrid and the conventional Hino trucks.



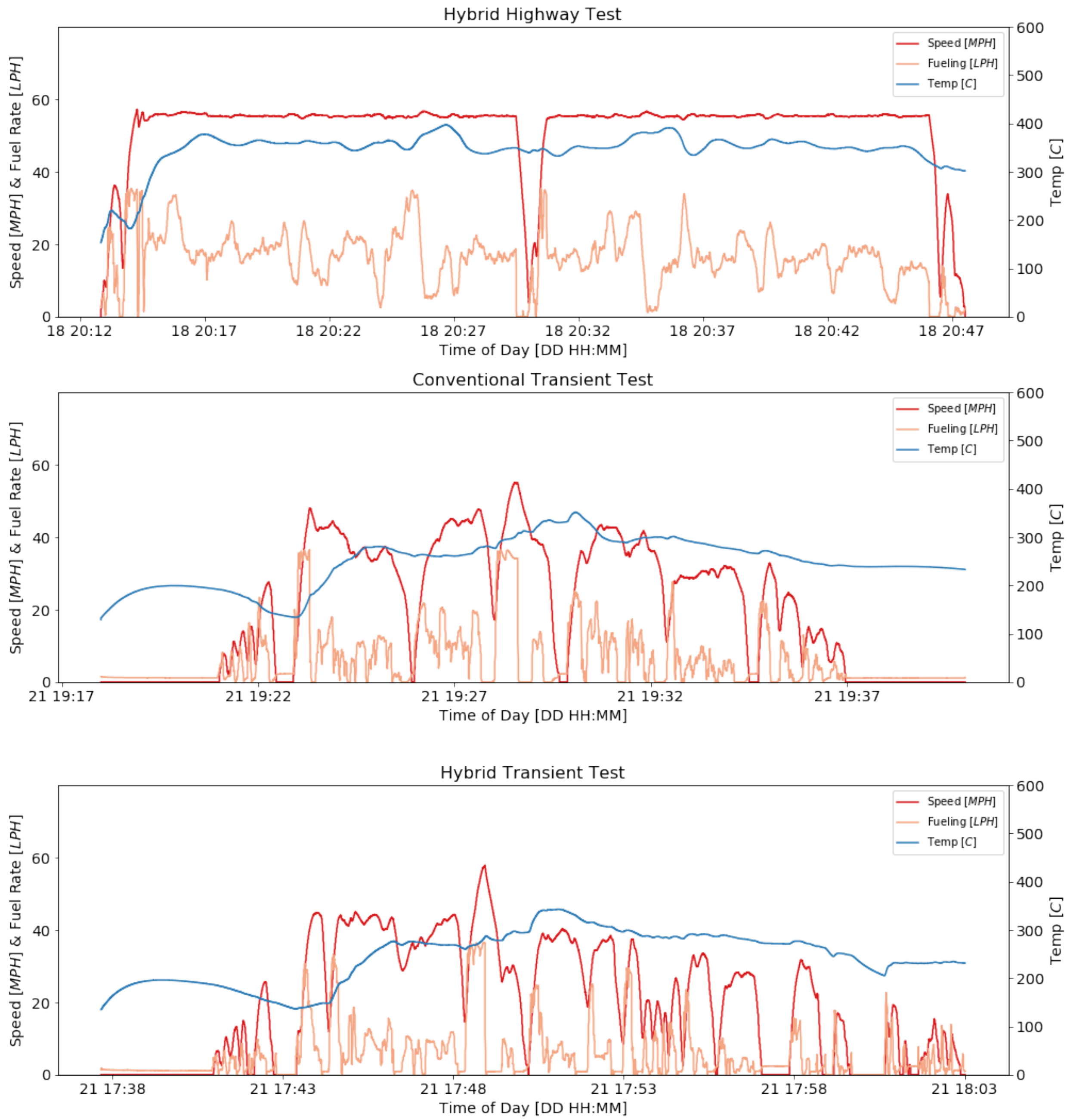


Figure 12. PEMS Hino truck hybrid versus conventional instantaneous exhaust temperature trace over the highway and transient PEMS routes

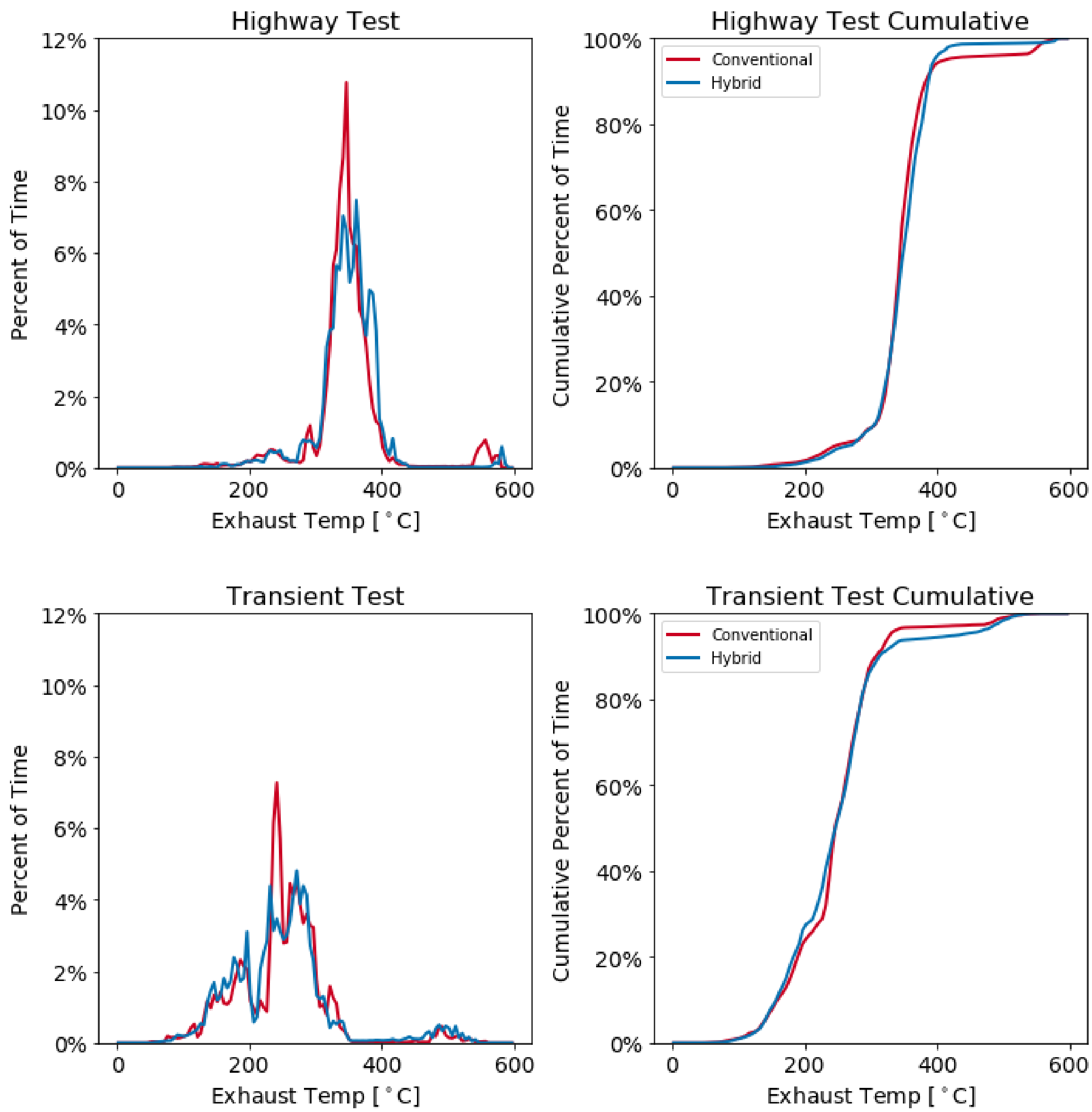


Figure 13. PEMS Hino truck hybrid versus conventional integrated exhaust temperature comparison over the highway and transient PEMS routes

Figure 14. PEMS Hino truck hybrid versus conventional instantaneous exhaust temperature trace over the highway PEMS rout with DPF regeneration event

To isolate specific components that could be contributing to the NO_x increase researchers first swapped the SCR bricks to rule out SCR catalyst poisoning. At the same time the doser nozzle and decomposition tube were inspected (Figure 15). No issues were found, and the SCR swap actually made the problem slightly worse as can be seen in Figure 16.

Figure 15. Hino SCR system diagnostic photos

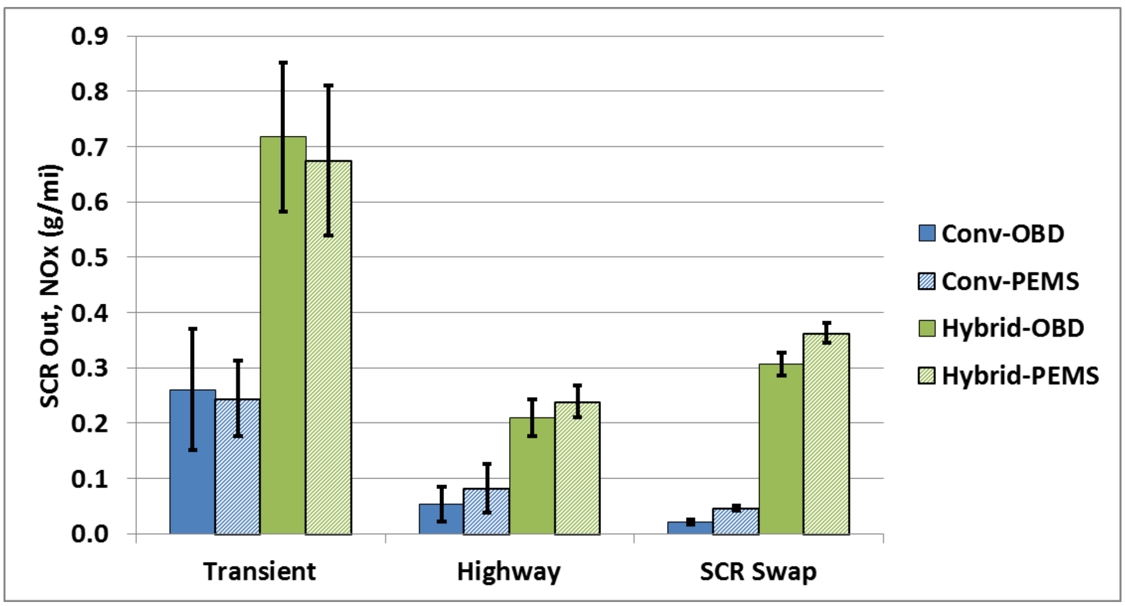


Figure 16. PEMS Hino truck NO_x emission comparison after SCR swap

Next researchers purchased a copy of the HINO diagnostic software DXII. After scrolling through the various subsystems there were no faults, and all system checks passed. Next a urea injection test was performed. For this test the injector is removed from the exhaust and placed in a graduated cylinder. Then the diagnostic software commands a specific amount of urea and the measurement in checked by the graduated cylinder. Both vehicles passed on all three predefined quantities available. The highway test was repeated and there was no statistically significant change. As the lease period was running out the trucks needed to be returned, but as one final additional check the sister truck (896) to the hybrid used in this testing (895) was rented for just one day, with NO_x result for both tailpipe and engine -out are shown in Figure 17 and Figure 18. There was not sufficient time or funding to bring this truck back to Denver, but the highway test was mimicked on a stretch of highway 101 just south of San Jose CA.

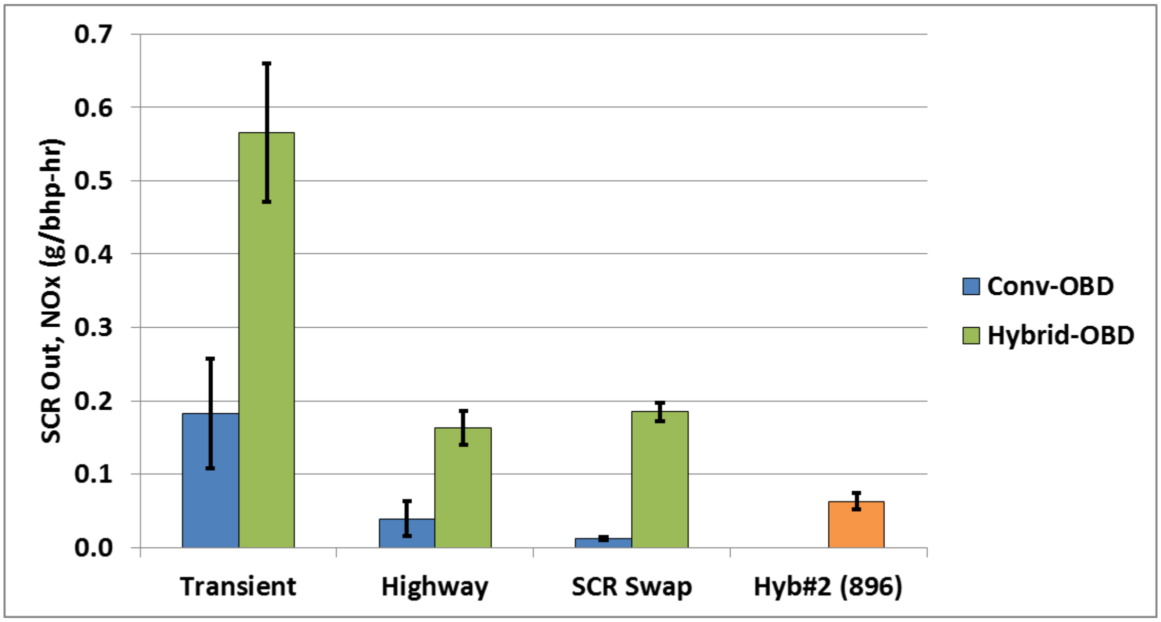


Figure 17. PEMS Hino truck tailpipe NO_x emission comparison with new hybrid truck

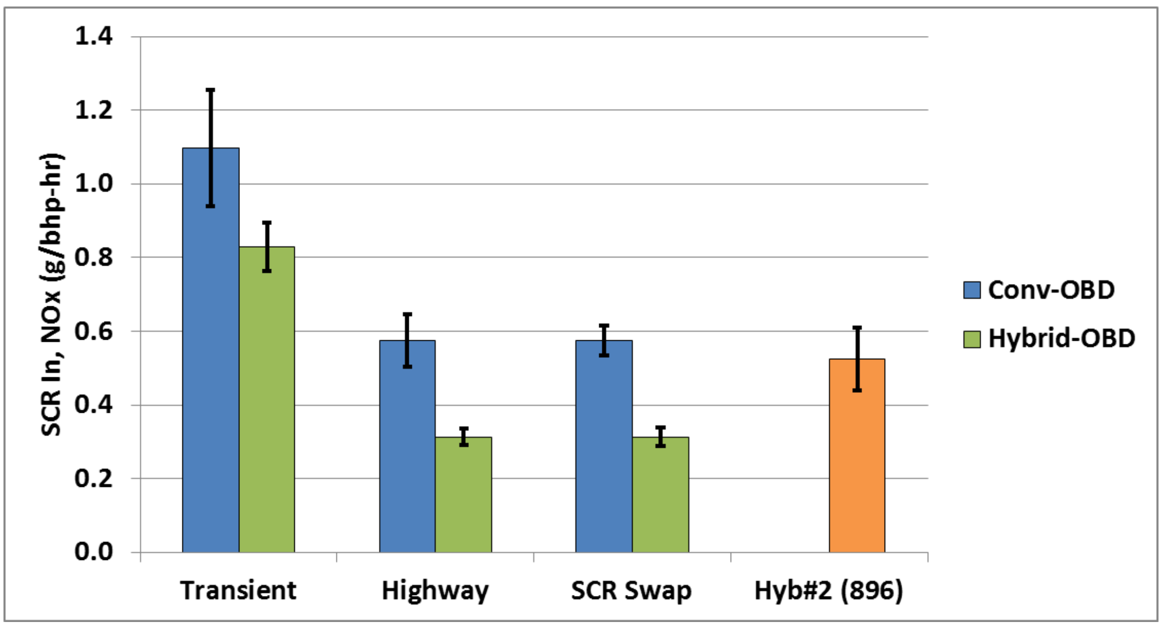


Figure 18. PEMS Hino truck engine-out NO_x emission comparison with SCR systems swapped and new hybrid truck

NO_x results from the companion hybrid vehicle, with identical specifications to truck 895, fell in between the conventional and hybrid trucks used for PEMS testing (Figure 17 and Figure 18). SCR inlet emissions reported by the on-board NO_x sensor were much closer to the conventional, hinting there could have been an issue with truck 895 that was not being captured by OBD since no faults were active. One possible explanation is that the upstream NO_x sensor on truck 895 was reading artificially low causing the perceived lower SCR in numbers and causing the SCR system to dose less. However, the detailed strategy of how the HINO aftertreatment system works is unknown. There were no active faults on any of the trucks and even though a statistically significant NO_x increase was shown, the magnitude of the increase in NO_x emissions was still far below the observed increase in HVIP-1.

Vehicles with All Electric Range and ePTO

The vehicles used for this testing did not have all electric range (AER). However, the interim ITR does have provisions for handling vehicles with AER and ePTO and NREL supplied utility curves from Fleet DNA (Figure 19) to help CARB better understand what a reasonable utility factor would be for different vocations.

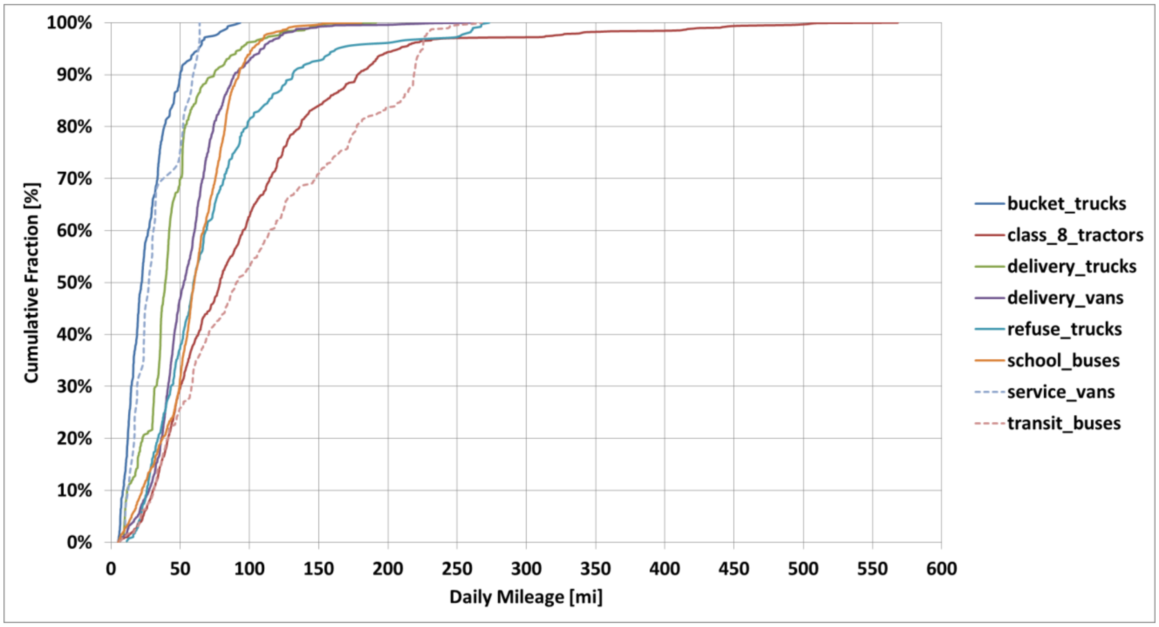


Figure 19. Vocational vehicle utility curves

Incorporated into the interim ITR by reference is a default utility factor of 37% for ePTO derived from PG&E data for the U.S. Environmental Protection Agency (EPA), feeding into the greenhouse gas phase 2 rule. EPA Code of Federal Regulations 1037.540 "Special procedures for testing vehicles with hybrid power take-off".

Hybrid NO_x Emissions In-Depth Investigation

The main objective for this task was to better understand what the key driving factors are, contributing to elevated tailpipe NO_x emissions from some hybrid vehicles observed under the HVIP-1 phase of the project. Critical aspects of this task were to explore what opportunities may exist to lower these emissions through changes to the engine, aftertreatment, and hybrid system control strategies and determine if current state-of the-art medium-duty hybrids still suffer from NO_x increase issues or if these have been addressed by OEMs.

To achieve the objective of this task, three different hybrid/conventional vehicle configurations were considered. First, the Hino 195h versus the conventional diesel Hino 195 used for the ITR PEMS validation discussed previously was used to provide some insight to NO_x emissions veracity and considered as a basis for this task, but it did not offer a good opportunity for root cause analysis because the vehicle-to-vehicle variation was on the same order as the observed NO_x increases and therefore isolating factors affecting NO_x emissions was too difficult. The second candidate vehicle set was the HHV with the Parker Hannifin RunWise system in a refuse truck. This vehicle was tested at NREL and did provide some additional insight to hybrid related NO_x increases, but the complication with acquiring an appropriate baseline vehicle to make solid conclusions was not possible. The testing results, NO_x emission results and NO_x emission comparisons are discussed in the following section, but in the end the HHV was not an ideal candidate for this task because differences in gearing and control strategy complicate the comparison. The question of what is the "appropriate baseline" is a perpetual problem because in the field the vehicles looked comparable against a 2006 CAT powered vehicle with tall gearing, but a fuel economy conscious buyer could also go with a modern lower rear differential ratio and double overdrive and save a significant amount of fuel at a fraction of the cost. The engine test cell work was inconclusive because the identical torque/speed trace was re-played and emissions were wildly different. Even though the engine calibration was changed to be identical, differences still existed in aftertreatment packaging and configuration and possibly differences in the catalyst formulations. In addition, both emission control systems had drastically different histories and could have catalyst poisoning or plugged exhaust gas recirculation (EGR) cooler or other issues. Therefore, with concurrence from ARB we decided on a third option as the best systems to evaluate hybrid NO_x emissions. This option was the Odyne utility truck system because there are no OEM integration issues. Therefore, when the Odyne hybrid system is disabled it is essentially not there as far as the rest of the vehicle is concerned. This removes all potential unknowns for the baseline vehicle since the engine, aftertreatment and gearing are identical for hybrid and conventional, the system is simply turned on and off. The Odyne system also provide a vehicle platform that allowed the evaluation of the utility service vocation, including the worksite power take-off (PTO) operations and emissions. The following sections discuss the laboratory testing results and the NO_x emissions evaluations of both the HHV refuse trucks and the Odyne utility trucks.

Heavy-Duty Chassis Dynamometer

All of the testing of the HHV refuse truck and the Odyne utility truck, for this task, was conducted on the heavy-duty chassis dynamometer at NREL's ReFUEL laboratory. The dynamometer can simulate transient loads on heavy-duty vehicles of up to 80,000 lbs. GVW at speeds up to 60 mph. The dynamometer is an in-ground installation with 40-inch tandem diameter rolls protruding above the surface to interface with the vehicle wheels, see Figure 20. The base mechanical inertia of the dynamometer rotating components simulates 31,000 lbs. of road load force. A direct current motor (380hp absorption/360hp motoring capacity) supplements dyno forces to simulate the vehicle inertia/force to a range of 8,000 to 80,000 lbs.

To assure the accuracy and consistency of the road load simulation forces, the dynamometer was subjected to continual standard procedures and checks. With the vehicle lifted off the rolls, an automated dynamometer warm-up procedure was performed daily until the dyno temperatures stabilized and consistent measured parasitic losses in the dynamometer were reached. After each drive cycle run a loaded coastdown procedure was performed to further ensure stability of vehicle and dynamometer parasitic losses and accurate road load simulation during the study. A 20-minute soak period was used between each run. Each drive cycle was repeated for at least 3 hot tests to ensure repeatability. Prior to the first hot run, a conditioning run was performed using the same cycle to ensure the temperatures and loading of the dynamometer and the vehicle were stabilized.

The vehicles were secured to the dynamometer with the drive axle on the rear rolls. The vehicle was driven by NREL staff following a prescribed speed trace on an aid monitor. A large fan (18,000 cfm) was used to force cooling air onto the vehicle radiator to roughly simulate the ram effect of vehicle in motion. Vehicle parameters were monitored and logged by the data acquisition system.

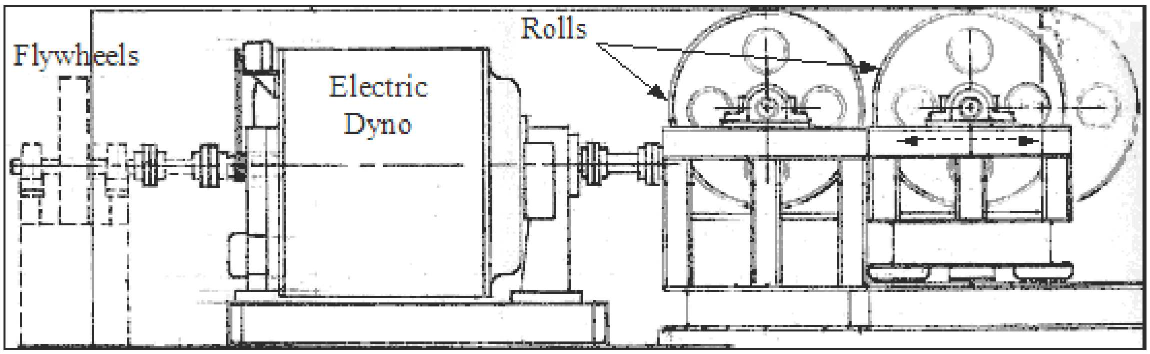


Figure 20. Drawing of ReFUEL's in-ground heavy-duty chassis dynamometer

Fuel Consumption Measurements

Vehicle fuel consumption was measured using a precision scale (Figure 21). The engine fuel supply was removed from the vehicle fuel tank and connected to an 11-gallon stainless steel fuel container placed on a scale, as shown in Figure 21. The return fuel is cooled in a liquid-to-air heat exchanger prior to reentering to the drum to keep the fuel supplied to the engine at consistent temperature. The total mass of fuel consumed was calculated by taking the difference of the fuel mass measured at the beginning and the end of the test cycle. The scale used for the transient drive cycles was a Sartorius Midrics MAPP1U-60ED-L, which has a readability of 5 grams and an uncertainty of 10.0 grams. For the stationary PTO study, which required a more precise measurement (such as engine mapping and idle tests) a Sartorius Signum 1 SIWADCP-1-16-S scale was used. This scale has readability of 0.2 grams and sub 1-gram uncertainty.

Figure 21. Fuel scale cabinet

Engine Air Handling & Conditioning

Engine intake air was conditioned per requirements in the EPA's Code of Federal Regulations. The intake air is conditioned for pressure, humidity, and temperature as well as high-efficiency particulate air filtered to eliminate background particulate matter. Engine intake air was maintained at 20°C with a dew point of 12°C, which is approximately a relative humidity of 50%. The intake air pressure was maintained at a slight positive gage pressure of about 3 mbar above ambient conditions, which is typically around 840 mbar for Denver.

Vehicle exhaust was diluted using a constant volume sample (CVS) full flow dilution system. The CVS system relies on critical flow venturis to measure and control the flow rate of the diluted exhaust. The dilution air for the exhaust is supplied by the same system mentioned previously that supplies air to the intake of the engine.

Exhaust Emissions Measurements

Gaseous emissions were measured with a Horiba MEXA 7100DEGR Bench (Figure 22). The Bench includes the following analyzers: Carbon Dioxide (NDIR, AIA-722), Carbon Monoxide (NDIR, AIA-721A for low range, AIA-722 for high range), O2 (Magnetic, MPA-720), EGR (NDIR, AIA-722), Total Hydrocarbon (Heated FID, FIA-725A), Nitric Oxides (Heated CLD, CLA-720MA).

Engine out raw NO/NO_2 exhaust emissions (pre-aftertreatment system) were also measured with a Horiba MEXA NX1170 analyzer. Raw tailpipe out emissions, including, ammonia (NH_3) (post-aftertreatment system) were measured with an MKS Multi-Gas 2030 FTIR.

All analyzers were calibrated before each testing day. A zero gas, span gas, and background check are performed automatically immediately prior to and immediately after each and every test cycle for the Horiba emissions analyzers.

Figure 22. Horiba MEXA 7100DEGR emissions bench

Data Acquisition and Instrumentation

Data were recording at a rate of 1 Hz. Chassis dynamometer cell temperatures, pressures and other parameters were measured with a National Instruments data acquisition system. Vehicle CAN data were recorded using ISAAC data loggers.

Hydraulic Hybrid Drive Cycle Data Collection and Performance Analysis

The main objective of this task was to benchmark the fuel economy and emissions performance of an HHV in a refuse truck application and compare those results with a conventional to determine if the tested HHV suffers from the same tailpipe NO_x emissions increase observed from some HEVs in the first phase of this project. The fleet selected for the in-use evaluation was Miami-Dade County Public Works. They have 190 total refuse vehicles and 64 are equipped with HHV system. The hybrid system on these vehicles is the Parker Hannifin RunWise System spanning both the model year (MY)13 and MY15 versions of the system. Details of the Parker system are listed in the following and shown in Figure 23.

- Parallel / Series combination system
  - Hydrostatic low (0–25 mph)
  - Hydrostatic high (25–40 mph)
  - Mechanical drive (40+ mph)
- 335 HP Motor
- 5,400 psi accumulator.

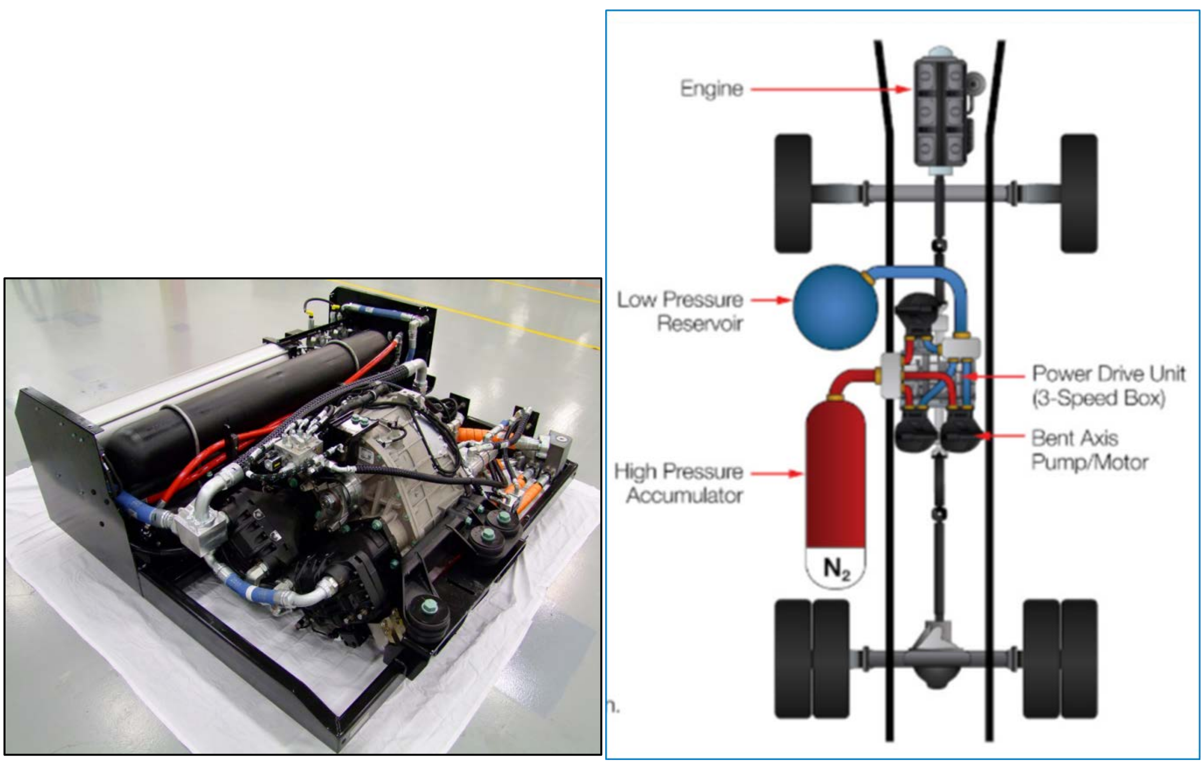


Figure 23. Parker Hannifin RunWise System design spanning both the MY13 and MY15 versions

For the field deployment and instrumentation effort, used to gain an understanding of the drive cycle and activity of these vehicles for this vocation, 37 vehicles were instrumented for several weeks to get full understanding of their typical activity and provide data for drive cycle development. In total, 645 vehicle operating days were captured. Of these instrumented vehicles, 13 were first generation HHVs (MY13), 11 were second generation HHVs (MY15) and 13 were conventional diesels. The vehicle specifications are provided in the following Table 4 and photographs of the three vehicles are shown in Figure 24.

Table 4. Parker Hannifin RunWise System and Comparable Conventional Vehicle Specifications

	Conventional Diesel	MY15 HHV	MY13 HHV
GVWR (lbs)	66,000	66,000	66,000
Chassis Make/Model	Freightliner Condor	Autocar Xpeditor E3	Autocar Xpeditor E3
Body Type	Automated Side Loader	Automated Side Loader	Automated Side Loader
Body Make/Model	LaBrie	Heil Durapack 7000	New Way Sidewinder XTR
Packer Size (cu. Yards)	31	33	31
Engine Make/Model	Caterpillar C11	Cummins ISL9	Cummins ISL9
Engine Displacement (L)	11.1	8.9	8.9
Engine Emissions Cert.	EPA 2006	EPA 2010	EPA 2010
Aftertreatment Device	DOC	EGR/DOC/DPF/SCR	EGR/DOC/DPF/SCR
Engine Horsepower (hp)	335 at 2,100 RPM	380 at 2,100 RPM	380 at 2,100 RPM
Transmission	Allison 4500	Parker RunWise Gen 2	Parker RunWise Gen 1
Number of forward speeds	6	3	3
Curb/Tare Weight (lbs)	35,540	40,600	39,900

Figure 24. Parker Hannifin RunWise System and comparable conventional vehicle photo

A summary of the field data results is the form of kinetic intensity versus average speed are provided in Figure 25. As can be seen in this plot, conventional and hybrid vehicles operate on similar routes and should provide for a good comparison.

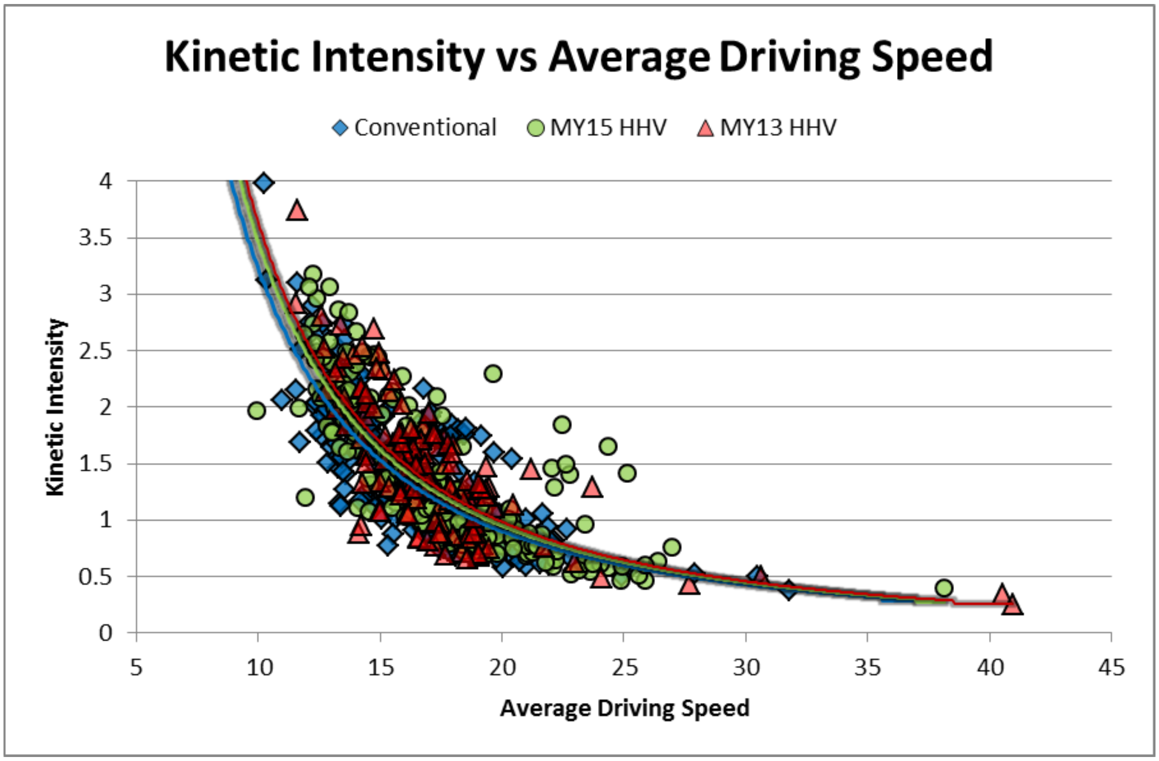


Figure 25. Parker Hannifin RunWise System and comparable conventional vehicle fleet activity—kinetic intensity vs. average speed

NREL, in coordination with CARB and the OEM, chose the NREL Refuse Truck Cycle-Neighborhood Refuse, UDDS, and heavy heavy-duty diesel truck (HHDDT) standard cycles to run on the chassis dynamometer. In addition, NRELs DRIVE tool was used with the field activity data to create a Miami custom cycle. The following Figure 26 and Figure 27 show kinetic intensity and average speed trade-off of these cycles and the cycle speed/time traces.

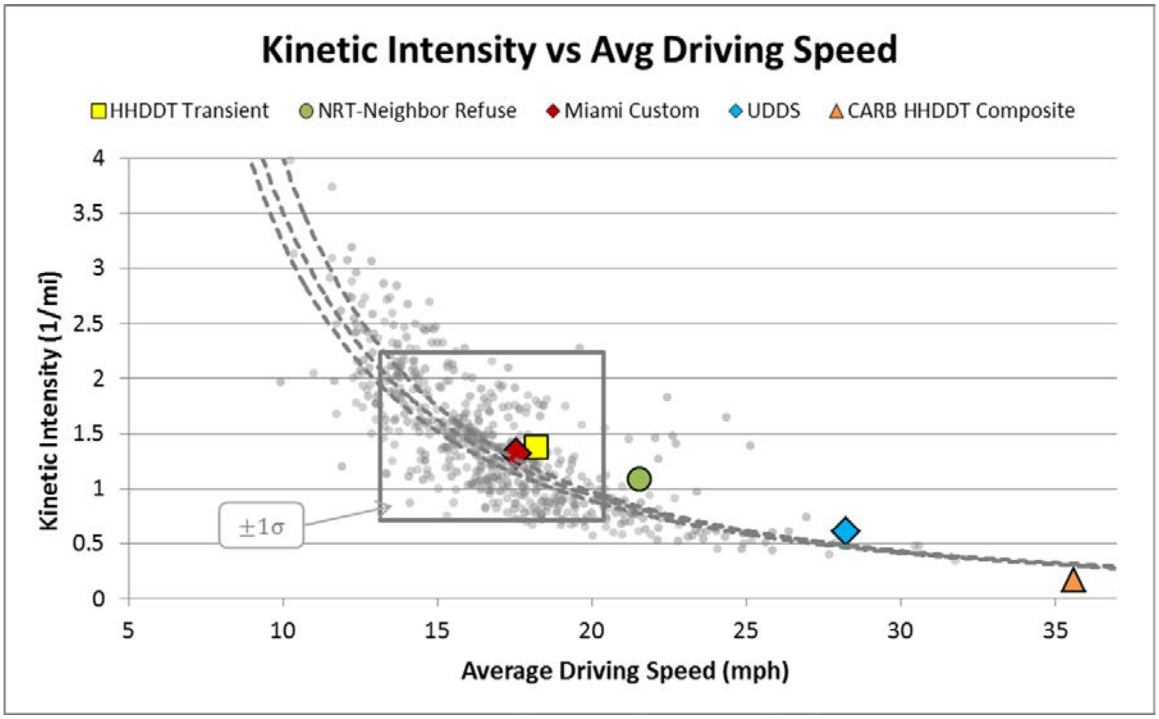


Figure 26. Parker Hannifin RunWise System chassis dynamometer test cycle selection and comparison

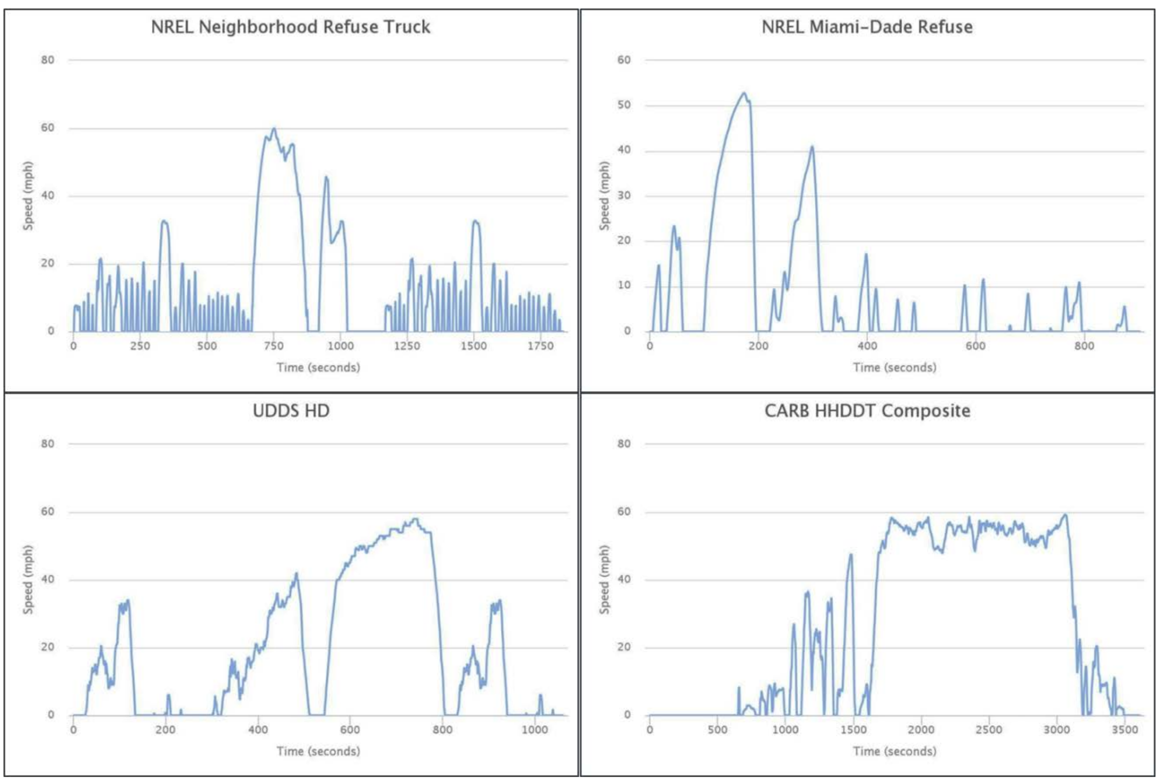


Figure 27. Parker Hannifin RunWise System chassis dynamometer test cycles

Test Vehicles

For the chassis dynamometer testing, Parker supplied the HHV vehicle and the conventional baseline vehicle was borrowed from Denver Parks and Recreation district, both certified at the EPA 2010 standard. Vehicle specifications and photos of the test vehicles are provided in the following Figure 28. It should be noted, as discussed previously, the conventional vehicle had a considerably newer engine and engine technology and the Denver Parks and Recreation district trucks are likely geared for more highway than neighborhood refuse since stops are further apart.

	Conventional Diesel	Hydraulic Hybrid Diesel
Vehicle Source	City of Denver, Parks & Recreation	Parker Hannifin Engineering Development Vehicle
Engine	MY15 Cummins ISX12, 12L	MY12 Cummins ISL, 8.9L
Aftertreatment	DOC, DPF, SCR	DOC, DPF, SCR
Horsepower Rating	350 hp	380 hp
Transmission	Allison 4500 RDS	Parker RunWise
Transmission Fwd Gears	6 with 2 Overdrive	2 Hydrostic, 1 Mechanical
Rear Axle Rating	4.56:1	4.33:1

Figure 28. Chassis dynamometer refuse truck test vehicles and specifications

Refuse Truck Chassis Dyno Results

As would be expected and shown in Figure 29 the largest fuel economy improvements related to the stops/mile activity and higher kinetic intensity cycles. In some cases, the low kinetic intensity cycles showed no fuel economy improvement or even a fuel consumption increase, as shown in Figure 30, showing fuel economy versus stops per mile. This could be the result of higher vehicles mass for the hybrid, but also the engine and transmission configuration and baseline mismatch in gearing with the hybrid vehicles. The field results were higher in terms of percent improvement, which could also be related to the dynamometer comparison using an older vehicle with different gearing for the baseline.

Diesel	MPG (Fuel Scale)	UDDS	NRT	Miami Custom	HHDDT Comp	HHDDT Idle	HHDDT Creep	HHDDT Trans	HHDDT Cruise
RAR 4.56	Diesel Conv 1	4.06	2.65	2.26	5.72	0.00	0.81	3.52	6.73
350 hp	Diesel Conv 2	4.13	2.54	2.32	5.70	0.00	0.81	3.51	6.73
12L	Diesel Conv 3	4.12	2.64	2.33	5.69	0.00	0.81	3.53	6.67
	Diesel Conv 4		2.58	2.38	5.69	0.00	0.79	3.50	6.68
	Diesel Conv Avg	**4.10**	**2.60**	**2.32**	**5.70**	**0.00**	**0.80**	**3.51**	**6.70**
Diesel HHV	Diesel HHV 1	3.77	3.10	2.55	4.55	0.00	1.04	3.42	5.05
	Diesel HHV 2	3.73	3.10	2.67	4.58	0.00	1.05	3.56	5.07
RAR 4.33	Diesel HHV 3	3.74	3.12	2.59	4.59	0.00	1.14	3.47	5.09
380 hp	Diesel HHV 4	3.74	3.19	2.69					
2012-8.9L	**Diesel HHV Avg**	**3.75**	**3.13**	**2.63**	**4.57**	**0.00**	**1.08**	**3.48**	**5.07**
	% Diff Diesel Conv	**-9%**	**20%**	**13%**	**-20%**		**34%**	**-1%**	**-24%**
	Kinetic Intensity	**0.61**	**1.08**	**1.31**	**0.17**		**24.93**	**1.38**	**0.12**
	Stops/mi	**2.52**	**10.54**	**10.31**	**0.50**		**25.00**	**1.40**	**0.26**

Figure 29. Refuse truck fuel economy results

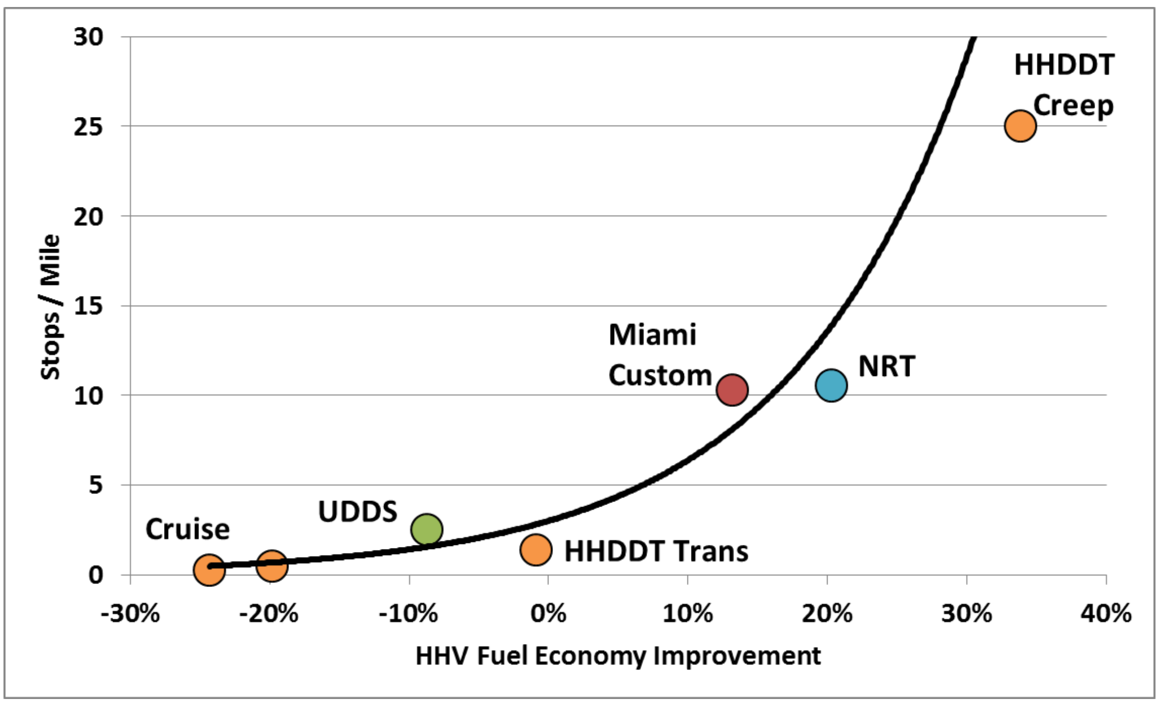


Figure 30. Refuse truck fuel economy results relative to stops per mile

The hybrid did show consistently higher NO_x emissions results with a significant increase over the conventional vehicle across all cycles as shown in Figure 31. Figure 32, also shows a consistent trend of higher NO_x emissions with increased kinetic intensity for the HHV from field testing, a trend that is not present for the conventional vehicle. The NO_x emissions modal data, shown in Figure 33, also shows high NO_x emissions during transient and low speed operation for the hybrid vehicle compared to the conventional vehicle; a trend that is not observed with the conventional vehicle. As with the fuel economy results, these figures need to be looked at in the context of the incongruence of the hybrid and baseline match regarding vintage, engine and transmission. That said, the level and consistency of the elevated NO_x emissions figures do point to an emission control issue with this platform and application.

Diesel	NOx g/mile	UDDS	NRT	Miami Custom	HHDDT Comp
RAR 4.56	Diesel Conv 1	0.83	0.42	1.26	0.20
350 hp	Diesel Conv 2	0.61	0.30	1.21	0.41
ISX12	Diesel Conv 3	0.55	0.18	0.56	0.46
12L	Diesel Conv 4	N/A	0.22	0.83	0.48
	Diesel Conv Avg	**0.66**	**0.28**	**0.96**	**0.39**
Diesel HHV	Diesel HHV 1	2.64	3.51	4.12	1.23
	Diesel HHV 2	2.56	3.47	3.74	1.42
RAR 4.33	Diesel HHV 3	2.43	3.38	3.72	1.41
380 hp	Diesel HHV 4	2.80	3.58	3.62	N/A
2012 ISL	Diesel HHV 5	N/A	N/A	N/A	N/A
8.9L	**Diesel HHV Avg**	**2.60**	**3.49**	**3.80**	**1.35**
	% Diff Diesel Conv	**294%**	**1145%**	**294%**	**247%**

Figure 31. Refuse truck NO_x emissions results

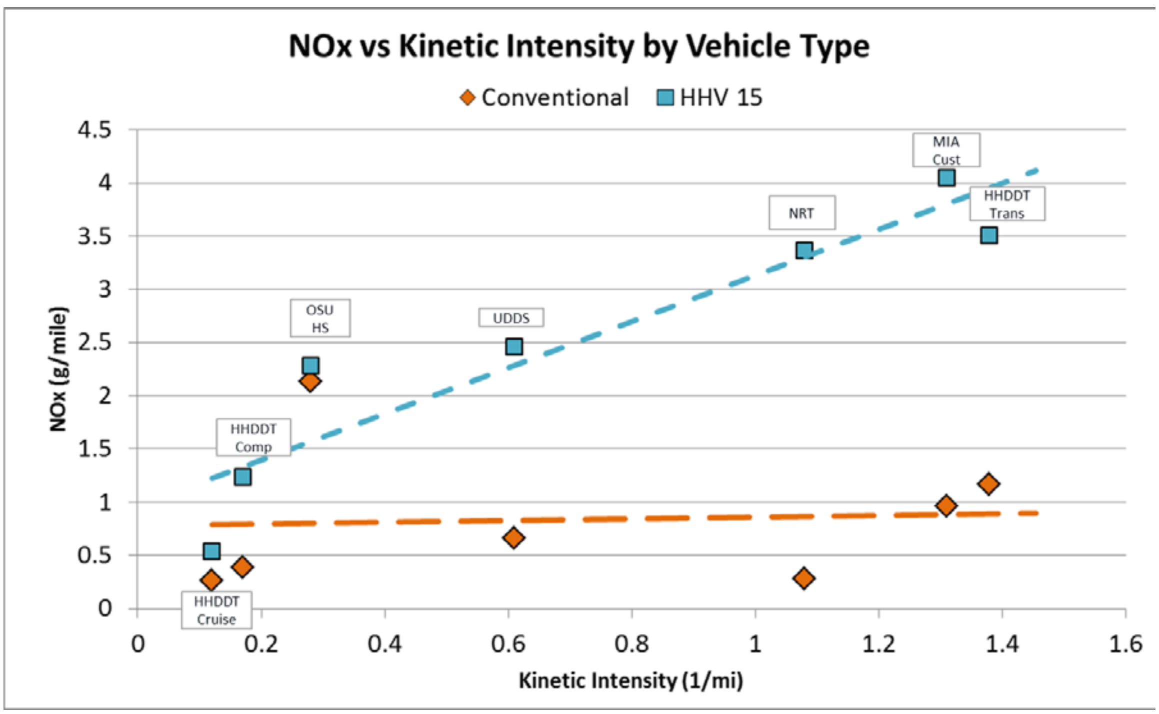


Figure 32. Refuse truck NO_x emissions results versus kinetic intensity

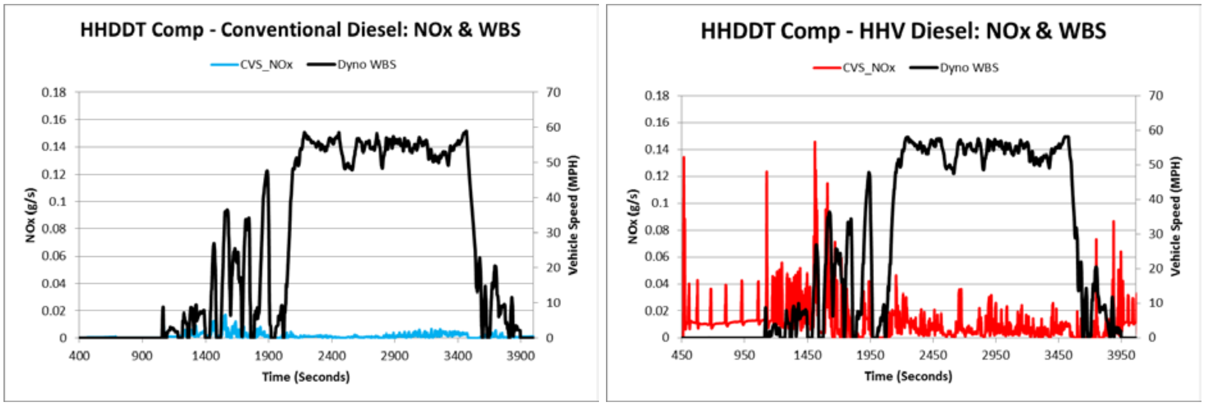


Figure 33. Refuse truck modal NO_x emissions measured dilute from the Constant Volume Sampling (CVS) System versus Wheel Based Speed (WBS) results, hybrid versus conventional

In an attempt to try and find the root cause we looked at a number of indicators of SCR health for this vehicle (Figure 34). These included NH_3 slip, isocyanic acid (HNCO) slip (indicator of incomplete urea decomposition), N_2O formation over the catalyst, and SCR inlet NO_x. Slightly elevated levels of NH_3 and N_20 were observed at parts of the cycle but nothing of significant concern.

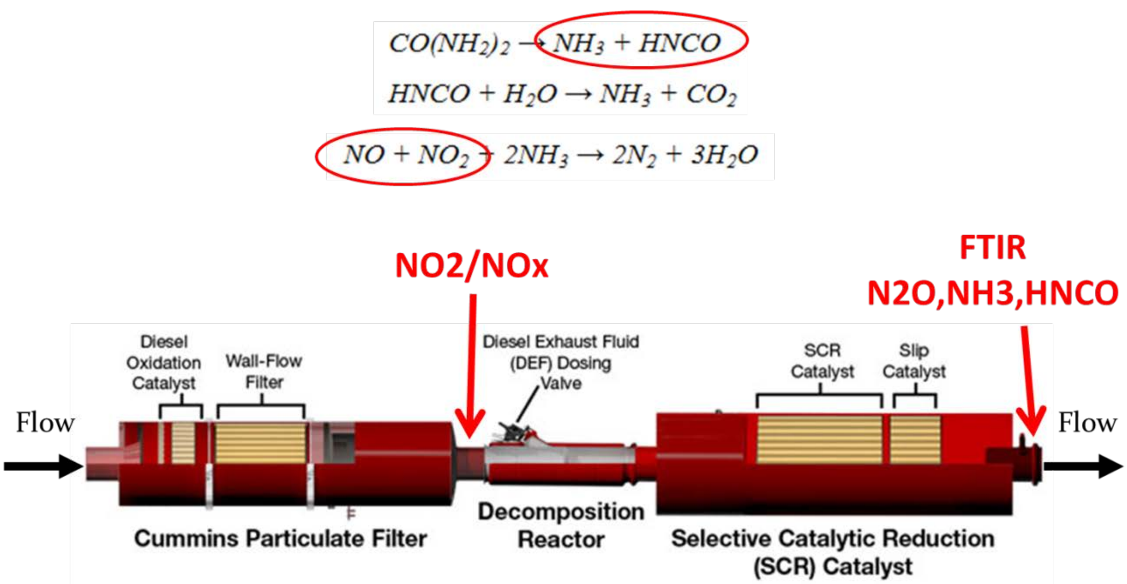


Figure 34. Emission control schematic and urea decomposition pathways

To ensure there were no calibration issues we had Cummins Rocky Mountain flash the laboratory Cummins ISL engine to ensure it had the same engine control unit calibration as the hybrid refuse truck. We then replayed the same engine speed and torque trace on the engine dynamometer, which was captured by the logger during the HHV chassis tests. SCR inlet NO_x levels were on a similar order of magnitude, but the emission control system was able to fully clean up the emissions and passed all tests below certification levels. It is not known what differences exist in aftertreatment catalyst coatings between the truck and system on the engine dynamometer. Also, the packaging and flow path configuration is different between the two vehicles, differences may also exist in the doser and decomposition tube design. In addition, the truck could be suffering from catalyst poisoning or damage, the full history was not known.

It is hypothesized that the MY15 conventional has a much more sophisticated model-based control of the aftertreatment. Cycle learning is observed on most if not all cycles where emissions consistently trend down the more times a cycle is repeated on the dynamometer. Previous work has pointed to this type of control strategy as an approach to address issues from hybrid vehicles and there is evidence that the OEM's are addressing the previously observed hybrid NO_x emission issues through such methods (Kotz et al. 2017).

Therefore, it is anticipated that the Parker MY17 systems may not suffer from the same issue if they are using the latest Cummins aftertreatment technology and control system. Nonetheless, due the issues with the baseline vehicle for this comparison is was decided to evaluate the NO_x emission performance of the Odyne utility truck hybrid system which includes ePTO operation which has the potential for significant NO_x reduction form worksite operation.

Odyne Utility Truck Project Overview

Odyne Hybrid Systems has developed a hybrid system that integrates into the PTO system on heavy-duty and medium heavy-duty utility vehicles. The system allows the PTO system to run under full battery electric conditions without using the engine, unless a battery recharge is necessary. This type of PTO is typically called electric PTO, or ePTO. The hybrid system also enables the vehicle to be operated under mild hybrid propulsion conditions while driving.

Figure 35. Odyne hybrid vehicle on NREL's HD chassis dynamometer

The Odyne hybrid system is still being optimized for peak performance. The intent of this project was to study the vehicle under multiple driving and PTO operating conditions and provide feedback as to how the system can be optimized for maximize fuel economy and minimize exhaust emissions, particularly NO_x. The vehicle study results will be used in modeling of the power and energy management strategies of the hybrid electric vehicle (HEV) drivetrain to optimize fuel efficiency and exhaust emissions. This was phase I of the project, after modeling and optimization the vehicle will return for follow-up studies.

A single utility vehicle was used for phase I of this project (Figure 35, Figure 36, and Figure 37). It was equipped with the Odyne HEV drivetrain PTO system and could be switched between operating in either a conventional diesel mode or a diesel hybrid mode. Six transient drive cycles were studied in the project. Additional PTO studies were performed to characterize stationary work of utility vehicles work simulation, hybrid vehicle battery pack stationary charging, engine efficiency mapping (emissions and fuel consumption) and vehicle idling.

This study was supported by the Department of Energy through a Funding Opportunity Agreement and as part of a California Air Resources Board Hybrid and Zero-Emission Truck and Bus Voucher Incentive Project hosted by NREL, which focused on identifying effects of hybrid drivetrains on NO_x exhaust emissions in heavy duty vehicles.

Test Vehicle

A 2017 Freightliner Class 7 cab and chassis was used for the study. The hybrid system was installed by Odyne immediately after the vehicle was built by Freightliner. After the study at NREL the vehicle was sent to Altec for installation of a large aerial boom structure and then sent to its end user, Duke Energy. The vehicle was delivered to the laboratory driven under its own power with about 1,100 miles on odometer. An additional 3 days (800 miles) of break-in were completed by aggressive driving over mountain passes to further degreen the vehicle aftertreatment and ensure the drivetrain efficiency was stabilized. Table 5 contains some of the test vehicle details.

Table 5. Vehicle specifications

Engine	2017 Cummins ISB240 Engine family HCEXH04088AT
Transmission	Allison 17E09 automatic
Axle	Meritor axle model MS2114X4DCRNN572-643
Hybrid System	Odyne PTO based drivetrain system

Figure 36. Odyne utility bare chassis vehicle prior to upfitting of utility box. Hybrid components are temporarily mounted to the frame for shipping and can be packaged in various configurations for different utilities

Figure 37. Odyne hybrid vehicle

As the vehicle had not been outfitted with the utility package yet it did not have the full PTO system yet. The proper hydraulic PTO pump was installed prior to testing to make sure the parasitic loses were accounted for during the study.

Figure 33 shows part of the hybrid system on the bare chassis vehicle. This vehicle could be fitted with multiple utility configurations with this hybrid system.

The engine exhaust aftertreatment system was one of the latest from Cummins, Single Module Aftertreatment System. Figure 38 shows the system from underneath the vehicle with the inlet on the left of the picture. It combines the DOC, diesel particulate filter, and SCR systems into one compact design.

Figure 38. Vehicle Cummins single module aftertreatment system

Fuel

Fuel for the vehicle study was standard pump ultra-low Sulphur diesel fuel. To ensure results consistency, the fuel was purchased in sufficient quantity to assure the whole project, phase I and II, can be completed with the same batch. Fuel drums 20521 & 20524 were used in phase I. It was purchased at Hill Petroleum in Arvada, Colorado, in August. As it was purchased in August it would be summer pump diesel.

Emissions Measurements

Details of the ReFUEL lab emissions equipment was described in a previous section. The Odyne vehicle study had the following emissions measurement configuration:

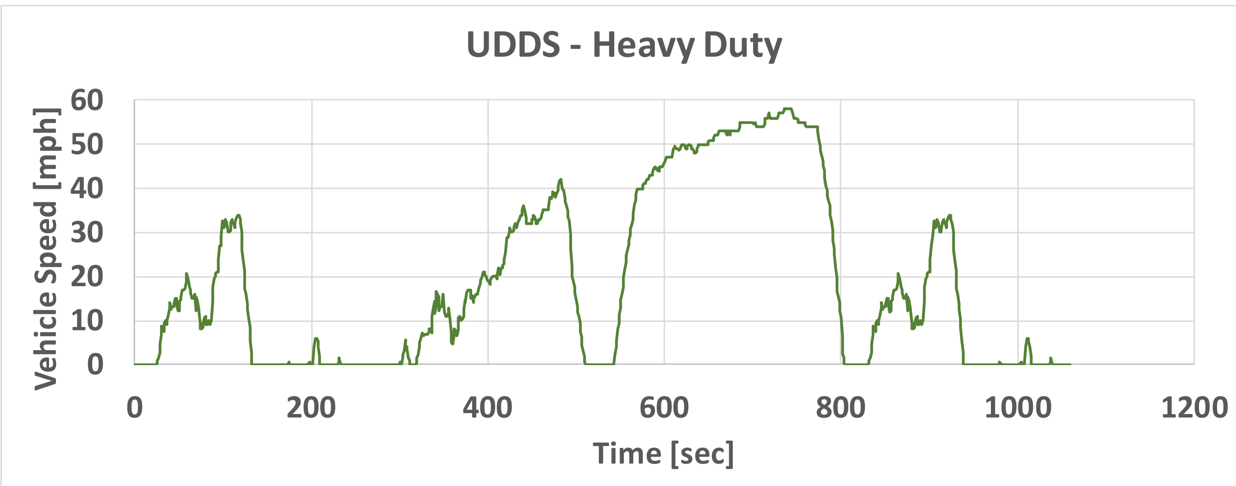
- Dilute emissions were measured from the full-flow dilution tunnel with the Horiba 7100 device.
- Raw engine out (pre-aftertreatment) NO_x emissions were measured with the Horiba 1170Nx device.
- Raw tailpipe out emissions were measured with the MKS FTIR instrument.

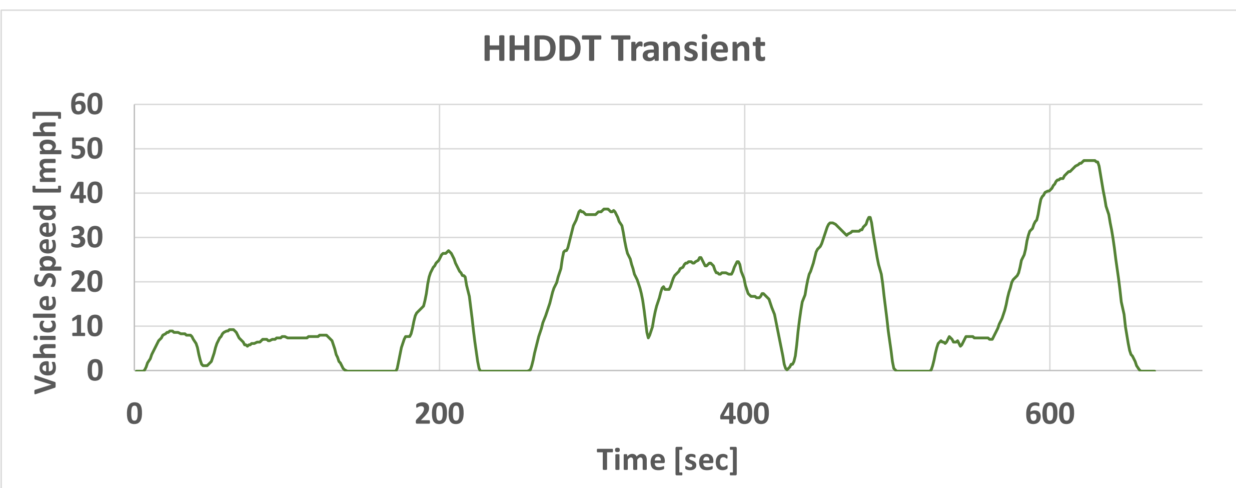
Chassis Dynamometer Drive Cycles

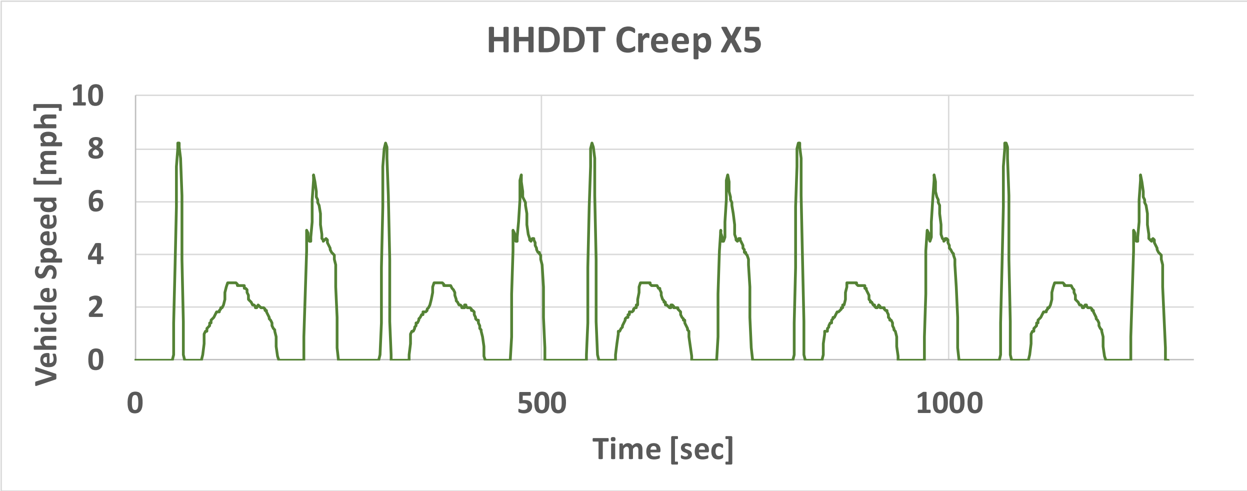
The vehicle was studied on six different chassis dynamometer drive cycles—UDDS-HD, HHDDT transient section, HHDDT creep section (repeated 5 times) and three NREL's developed custom drive cycles (Figure 39). The three custom cycles were developed using various vocational Odyne vehicle data logged in the field. The names of the custom cycles are

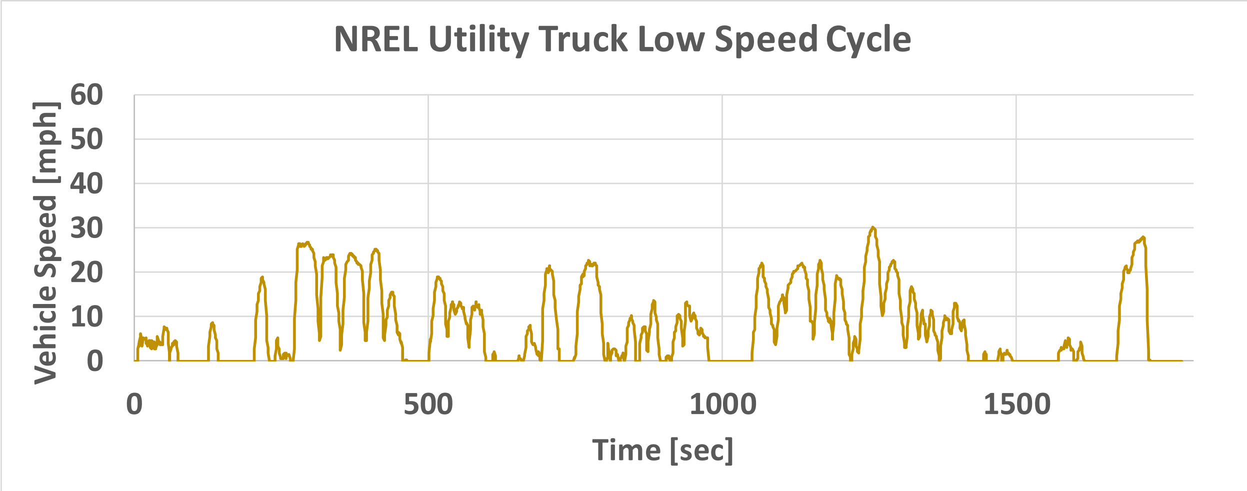
NREL Utility Truck Low Speed, NREL Utility Truck Medium Speed, and NREL Utility Truck High Speed.

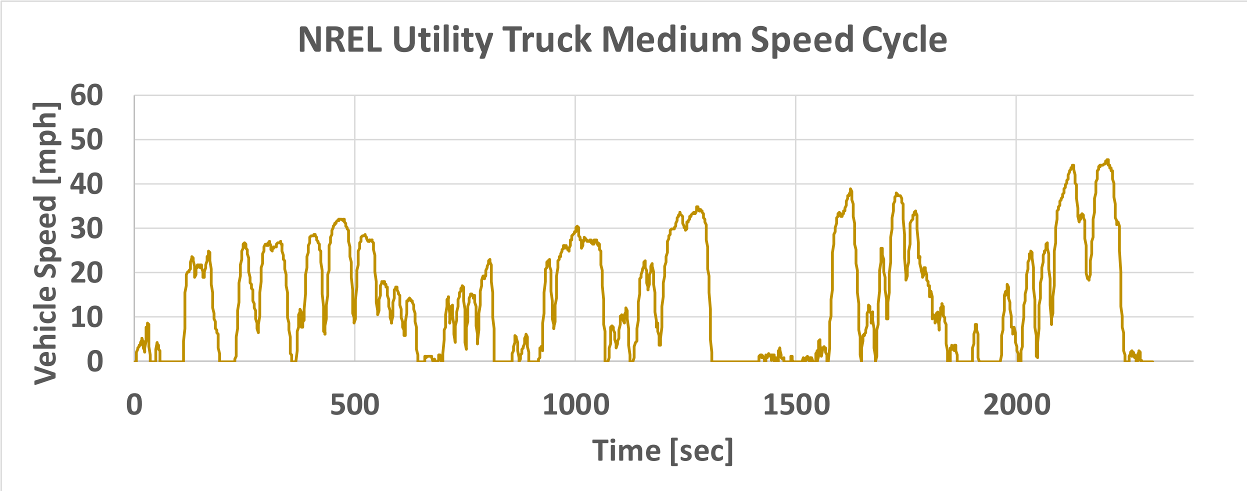
The vehicle was operated in alternating hybrid and conventional modes over the drive cycles to eliminate any changes that could potentially cause drifts in the emissions and fuel consumption. For example, run one for the NREL Utility Truck Low Speed cycle was conventional mode, run two was hybrid mode, run three was conventional, run four was hybrid, and so on until the set number of hot runs was reached for each drive cycle. A minimum of three hot runs were completed for each vehicle mode for each drive cycle (e.g., three hot UDDS in conventional and three hot UDDS in hybrid). The vehicle was configured in such a way it could be switched from conventional to hybrid mode operation with the flip of a switch.






HHDDT Creep X5
Vehicle Speed [mph]
10
8
6
4
2
0
0
500
1000
Time [sec]


NREL Utility Truck Low Speed Cycle
Vehicle Speed [mph]
60
50
40
30
20
10
0
0
500
1000
1500
Time [sec]


NREL Utility Truck Medium Speed Cycle
Vehicle Speed [mph]
60
50
40
30
20
10
0
0
500
1000
1500
2000
Time [sec]

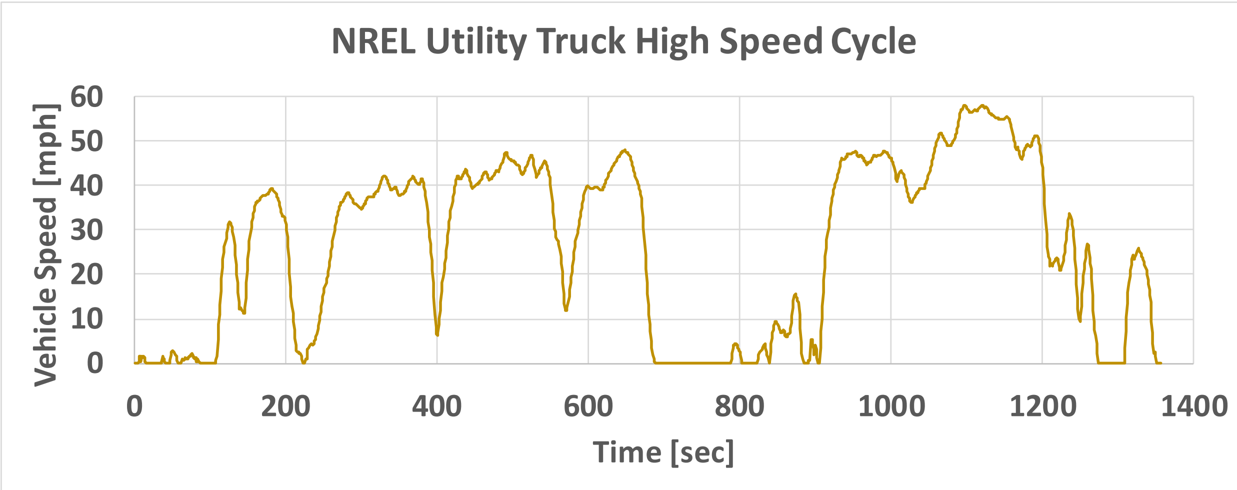


Figure 39. Chassis dynamometer drive cycles

Table 6. Chassis Dynamometer Drive Cycle Metrics

	HHDDT Transient	UDDS HD	HHDDT CreepX5	NREL Utility Truck Low Speed	NREL Utility Truck Medium Speed	NREL Utility Truck High Speed
Duration (sec)	669	1061	1270	1781	2310	1357
Distance (miles)	2.85	5.55	0.62	3.78	8.95	9.94
Total Avg. Speed (mph)	15.34	18.84	1.76	7.63	13.95	26.37
Avg. Driving Speed (mph)	18.20	28.23	3.00	11.59	18.10	32.04
Max Speed (mph)	47.50	58.00	8.20	30.08	45.57	57.99
Kinetic Intensity (1/mile)	1.38	0.61	24.93	4.39	1.64	0.56
Total # of Stops	4	14	15	29	33	12
Stops per Mile	1.40	2.52	24.14	7.68	3.69	1.21

Road Load Coefficients

Since the test vehicle was provided incomplete (only chassis-cab) it was not possible to conduct actual on-road coast down tests to determine the road load forces empirically. Theoretical forces were thus calculated using complete boom truck vehicle dimensions and typical values of rolling resistance and aerodynamic drag.

Table 7. Vehicle Test Weights and Road Load Coastdown Coefficients

Parameter	Value	Units
Vehicle Weight (lbs.)	33000	
Vehicle Mass (kg)	15000	
µ	0.007	
G	9.81	m/s^2
P	1.17	kg/m^3
A	7.432	m^2
Cd	0.7	
A (SI units)	1030.05	N
B (SI units)	0	N /(m/s)
C (SI units)	3.043404	N $/(m/s)^2$
A	231.57599	lbf
B	0	lbf/mph
C	0.1367297	lbf/mph^2

Stationary PTO

Several experiments not involving vehicle driving were performed to gather data relevant to a utility vehicle stationary PTO work with the intent to characterize the fuel consumption and exhaust emissions. The following is a list and description of each of these tests.

- Engine Mapping: The engine was operated in a matrix of 5 different engine speeds (800, 1,200, 1,400, 1,600, 2,000 rpm) and 6 different engine loadings (0, 10, 50, 100, 150, 200 Nm). These operating points are typical for PTO use and battery recharging. This map will assist in designing more optimal operating points. Each steady state mode was 180 seconds long, with a nearly instantaneous load change in between, as seen in Figure 40. The PTO hydraulic pump loading was simulated by applying load with the electric motor which then pushed the absorbed energy to the battery pack. This mapping study was operated in the diesel conventional engine mode.
- Transient PTO Cycle: Vehicle field data were used to generate a transient PTO cycle that was representative of real-world operation. The PTO hydraulic pump loading was

simulated by applying load with the electric motor which then pushed the absorbed energy to the battery pack. The electric motor loading was controlled over the prescribed torque profile, see Figure 41, by means of an external signal generated by a data acquisition system which was sent to the vehicle in analog format. The transient PTO stationary cycle was only performed with the engine operating at 1,600 RPM and was operated in the diesel conventional engine mode.

- Stationary Battery Recharging: The engine was used to recharge the HEV battery packs and data were recorded. This was done twice. The first was on a completely cold engine corresponding to a vehicle being at the work site for many hours performing electric PTO with the internal combustion engine shut off and completely cooled down. The second test was performed an hour after shutting down the engine, thus cool but not yet completely cold. These tests were intended to provide data for comparison of electric PTO operation on a hybrid vehicle to a standard engine driven PTO on conventional vehicle and can be compared to the transient PTO cycle which is full conventional diesel PTO work.
    - Idle Conditions: in following modes.
    - Idle with transmission in park, air conditioning (AC) off
    - Idle with transmission in drive, AC off
    - Idle with transmission in park, AC on

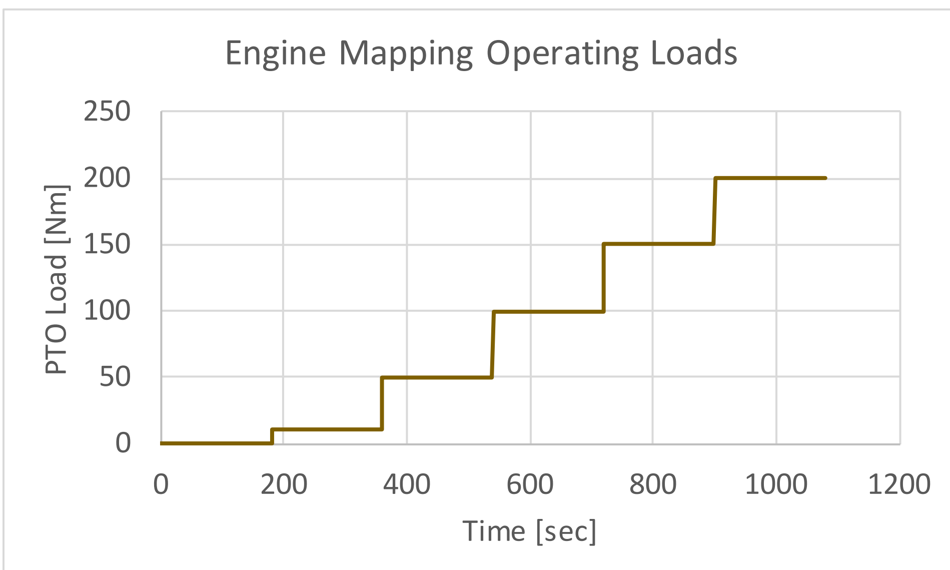


Figure 40. Steady state engine mapping cycle

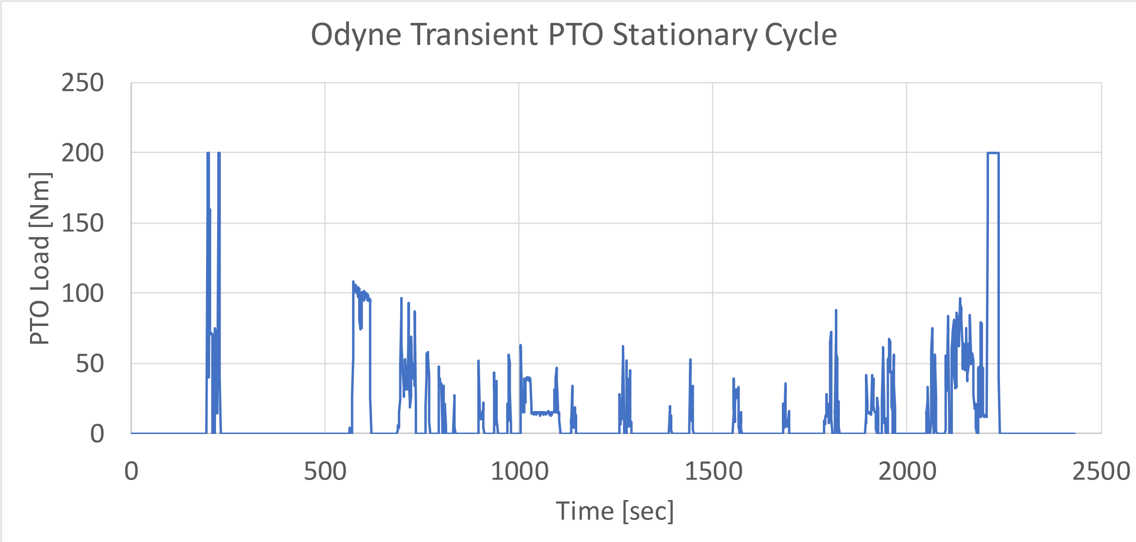


Figure 41. Transient PTO stationary cycle

Drive Cycles Dynamometer Results

Table 8, shows the results in NO_x emissions and fuel consumption for both the conventional and HEV over the tested drive cycles. Note that the HEV operates normally (unless its battery is depleted to a certain threshold) in a charge depleting mode. Hence the fuel consumption for the HEV is supplemented by a battery net energy change.

Table 8. Fuel Consumption and NO_x Emissions Results

Nox (gram/mile)						
	UDDS	Odyne Low Speed	Odyne Medium Speed	Odyne High Speed	HHDDT Transient	HHDDT Creep
Conv	0.87	2.78	1.11	0.63	1.90	7.53
Hyb	0.85	2.28	1.18	0.58	2.04	6.60
Fuel Consumption (gram/mile)						
	UDDS	Odyne Low Speed	Odyne Medium Speed	Odyne High Speed	HHDDT Transient	HHDDT Creep
Conv	523.39	768.45	536.37	430.70	553.22	1903.97
Hyb (plus batt. energy below)	513.19	708.35	514.26	430.52	519.15	1898.03
Battery Net Ener. (kW-hr/mile)						
	UDDS	Odyne Low Speed	Odyne Medium Speed	Odyne High Speed	HHDDT Transient	HHDDT Creep
	-0.02	-0.47	-0.16	0.02	-0.21	-0.78
% Hyb Improvement Over Conv						
	UDDS	Odyne Low Speed	Odyne Medium Speed	Odyne High Speed	HHDDT Transient	HHDDT Creep
NOx	2.63	17.84	-6.08	9.05	-7.11	12.31
Fuel Consumption	1.95	7.82	4.12	0.04	6.16	0.31

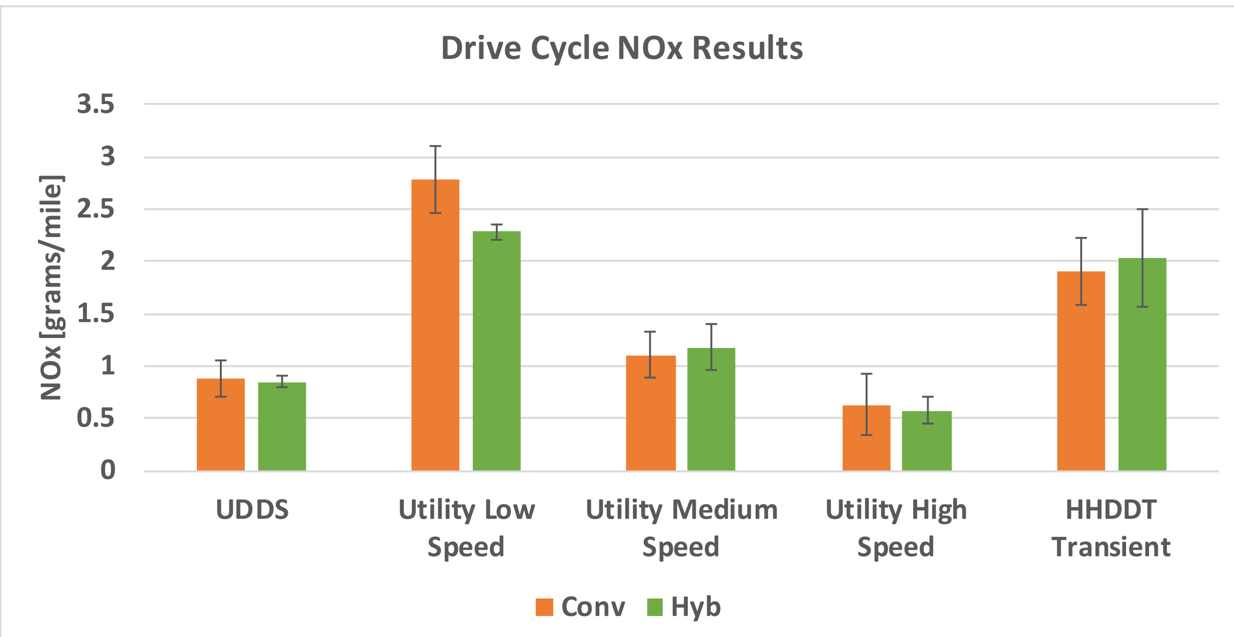


Figure 42. Drive cycle NO_x results for all six drive cycles in both conventional and hybrid modes. Error bars are 95% confidence interval

Figure 42 shows that for most of the dynamometer drive cycles the HEV performed slightly better than the conventional vehicle regarding NO_x emissions. For this phase the project the hybrid system was always active from the start of vehicle. There is potential to disengage the hybrid system during a warm up period to allow the engine and exhaust system to achieve higher temperatures faster because of the higher loading on the engine instead of being assisted from the hybrid system. This could improve the NO_x emissions.

HHDDT Creep X5 drive cycle results are only shown in the Table 8 (labeled as HHDDT Creep) and not in Figure 42, as the emissions and fuel consumption results and error bars are substantially higher than the results for the other cycles, which caused the plot resolution to diminish.

Emissions measurement taken at the tailpipe were made with the MKS FTIR instrument. Ammonia also was monitored. This vehicle demonstrated no slip of ammonia into the exhaust system during the drive cycles.

Previous studies found that some heavy-duty hybrid vehicles emitted higher NO_x emissions as a result of lower thermal loading in the catalysts affecting SCR efficiency. Hybrid vehicles can have lower exhaust temperature since some of the energy comes from the hybrid energy system instead of the internal combustion engine. Figure 40, shows the vehicle exhaust temperatures for pre and post SCR catalyst. It is seen that there is typically not a large difference between the temperatures for the conventional and the hybrid vehicles. This allows the SCR system to operate at nearly the same conditions for both vehicle configurations. This might be a result of the mild nature of this hybrid vehicle.

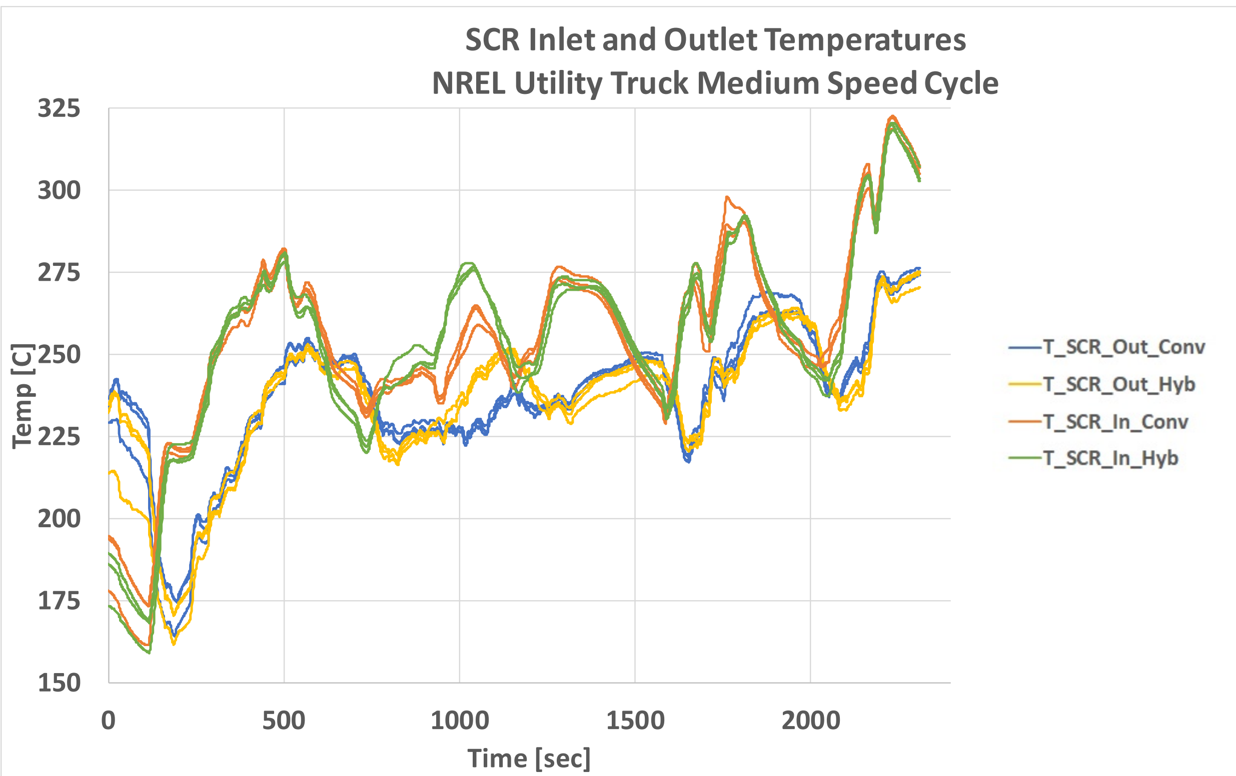


Figure 43. Exhaust gas flow SCR temperatures for the NREL utility truck medium speed drive cycle

Drive cycle fuel consumption results can be seen in Figure 44. The HEV consistently improves fuel consumption for all drive cycles when compared to the conventional vehicle. Some of the improvement is a result of regenerative braking but some of it is because of the plug-in capabilities of this vehicle. These drive cycles were operated in a charge depleting mode and thus the state of charge of the batteries at the end of the cycle was different than at the beginning.

Figure 45 shows the amount of energy that was depleted from the batteries during each drive cycle and helps to understand how much of the fuel economy improvement could have come from energy that originally came from grid electricity through the plug-in hybrid system.

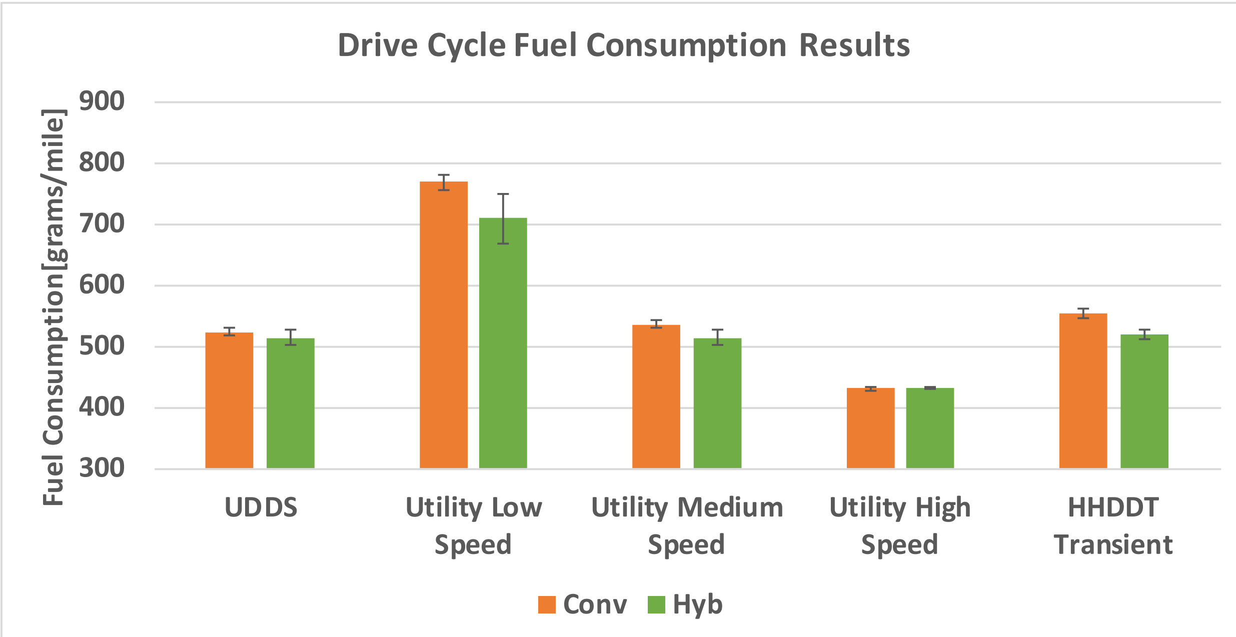


Figure 44. Drive cycle fuel consumption results for all six drive cycles and in both conventional and hybrid modes. Error bars are 95% confidence interval

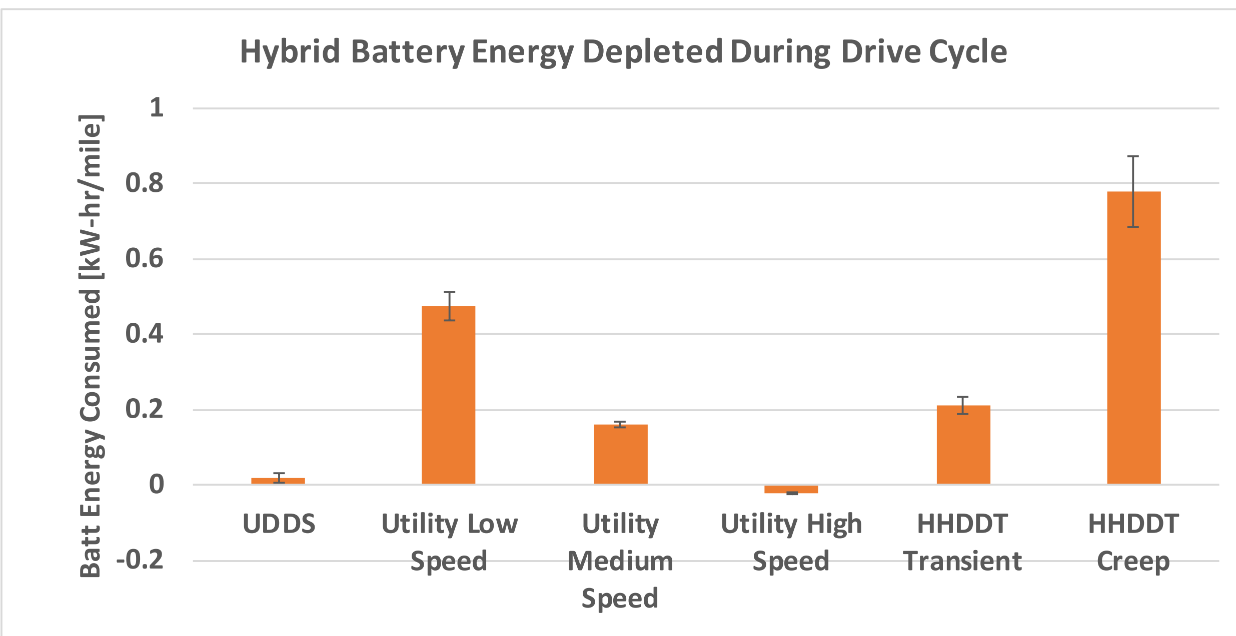


Figure 45. Battery energy consumed during drive cycle

PTO Transient Cycle and Battery Recharging Results

To demonstrate the differences in operating in a conventional diesel operating mode and the battery electric in PTO mode, the transient PTO cycle was generated. This cycle was run twice. The first run was performed immediately after driving a UDDS drive cycle to simulate PTO operation at engine/exhaust temperatures similar to a vehicle just arriving at the work site and immediately commencing PTO work. The second run was performed immediately after the first cycle at which point the engine and exhaust temperatures had settled to lower values, a result of the PTO work not being high power in general. The PTO work load never peaked above 200 Nm.

The conventional vehicle was tested operating a PTO loading cycle while the hybrid vehicle was tested for a stationary battery recharge. Equivalent PTO work specific emissions and fuel consumption rates were calculated for the hybrid vehicle using the component efficiency specs provided by Odyne. Table 9 indicates the emissions and fuel consumption results for the conventional vehicle and the calculated values for hybrid vehicle. The equivalent PTO values for the hybrid vehicle were calculated at three different component efficiency levels. Odyne supplied an estimate of 75% component efficiency for the vehicle. That was bracketed by 70% and 80% efficiency to accommodate for estimate errors. Results indicate that the hybrid vehicle produces roughly an order of magnitude less NO_x exhaust emissions and consumes 4~5 times less fuel than the conventional vehicle while operating a PTO work cycle.

Table 9. Transient PTO Work and Battery Recharging Comparisons

PTO shaft work specific results comparison							
	NO_x	THC	CO	CO_2	Fuel ConsCB	Fuel cons FS	batt->PTO eff
	g/kW-hr	g/kW-hr	g/kW-hr	g/kW-hr	g/kW-hr	g/kW-hr	%
Calculated equivalent electrical PTO from a cold start charge	3.619	0.090	0.290	1991.947	626.182	637.947	70
Calculated equivalent electrical PTO from a charge after an hour soak	3.574	0.079	0.654	1944.871	611.558	588.849	70
Calculated equivalent electrical PTO from a cold start charge	**3.378**	**0.084**	**0.270**	**1,859.150**	**584.436**	**595.417**	**75**
Calculated equivalent electrical PTO from a charge after an hour soak	**3.335**	**0.074**	**0.611**	**1,815.213**	**570.787**	**549.592**	**75**
Calculated equivalent electrical PTO from a cold start charge	3.167	0.079	0.253	1,742.954	547.909	558.204	80
Calculated equivalent electrical PTO from a charge after an hour soak	3.127	0.069	0.573	1,701.762	535.113	515.243	80
Tested conventional PTO hot immediately after arrival to site	**32.606**	**0.782**	**0.071**	**8,483.421**	**2,666.646**	**2,827.026**	
Tested conventional PTO consequent	**36.146**	**0.923**	**0.062**	**7,151.774**	**2,248.326**	**2,410.621**	

PTO Engine Mapping

The engine was operated in a matrix of 5 different engine speeds (800, 1,200, 1,400, 1,600, 2,000 rpm) and 6 different engine loadings (0, 10, 50, 100, 150, 200 Nm). To allow the results to stabilize, only data from the last half of each mode were analyzed. All modes reached relative equilibrium exhaust temperature conditions except for those at the 800-rpm case, which exhaust temperatures were still increasing when the mode switch occurred for the 100, 150 and 200 Nm points.

Figure 46 shows the resulting fuel consumption for each mode in grams per brake horsepower hour basis. Engine loads of 0 and 10 Nm were omitted from the results as they are highly susceptible to noise as a result of the denominator (torque) being very near zero. It can be easily seen that running the engine at high loads yields a substantially lower fuel consumption per unit power out. When the engine is running in a recharging or PTO mode it would be idle to run at as high of a load as possible.

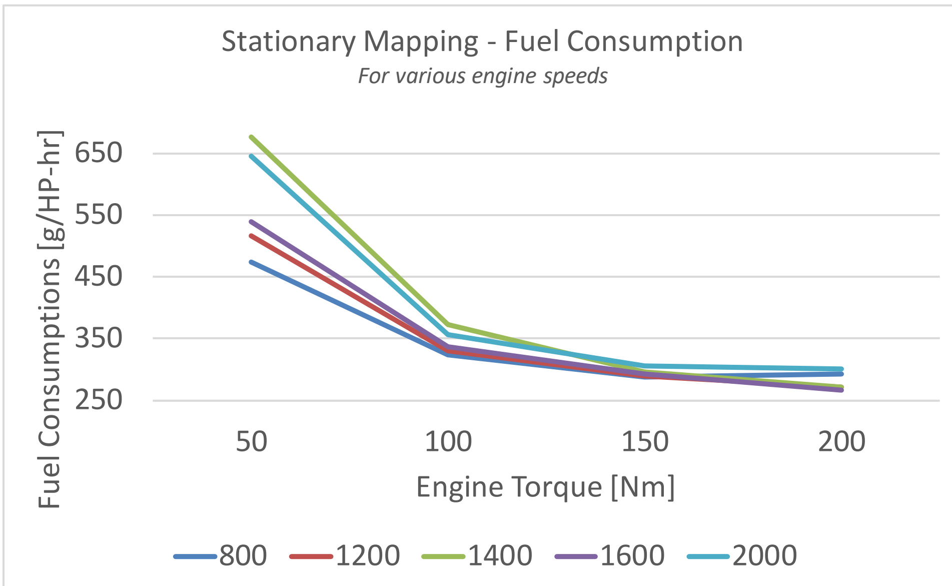


Figure 46. Fuel consumption engine map

Figure 47 shows the same results as Figure 46 but zoomed in at the higher load to better demonstrate any differences the engine speed will have. The engine will operate most efficiently in the middle speed ranges. The 800 rpm and 2,000 rpm engine speed results show a higher fuel consumption rate than the other speeds, likely because of higher friction loses on the high-speed case and possibly less than optimal turbocharger operation at the low speed case.

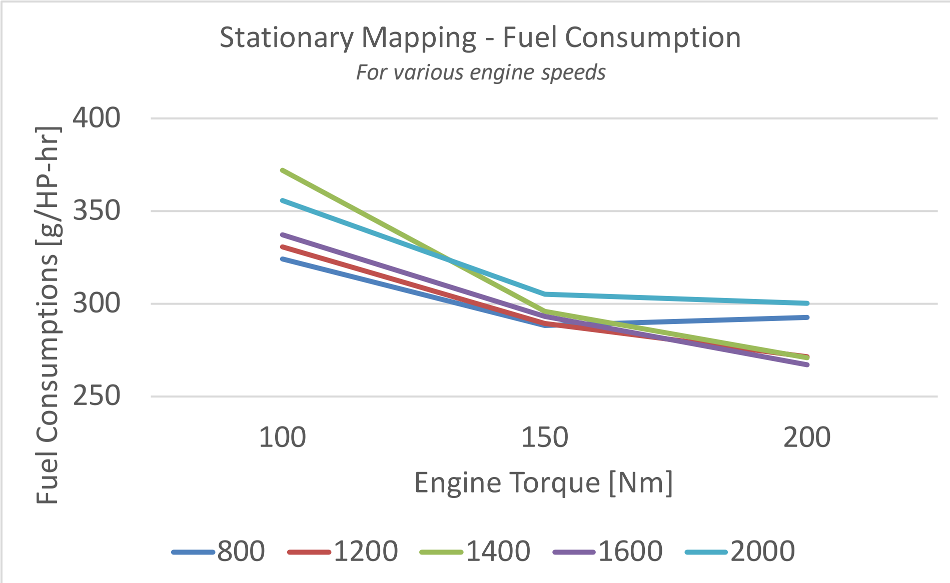


Figure 47. Fuel consumption engine map zoomed in on higher load modes

NO_x emissions were measured both pre and post exhaust aftertreatment system. NO_x conversion efficiency was calculated from these measurements and is shown in Figure 48. The NO_x conversion efficiency was consistently higher on the higher power mapping points. This is a result of the higher amount of heat carried in the exhaust at those points. SCR NO_x reduction is greatly dependent on heat for the catalyst to function optimally. Typically, the exhaust needs to be about 225°C before the SCR control system will start injecting diesel exhaust fluid (an aqueous urea mixture). The catalyst is not effective at reducing NO_x below that threshold. SCR inlet temperatures can be found in Figure 49. As is evident in the plot, there is a direct correlation between SCR inlet temperature and NO_x conversion efficiency.

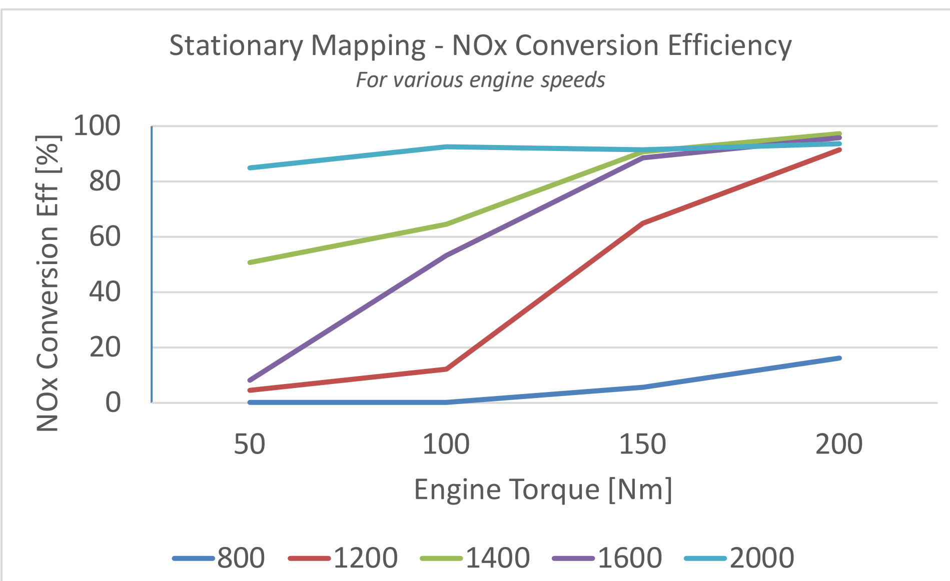


Figure 48. NO_x conversion efficiency engine mapping

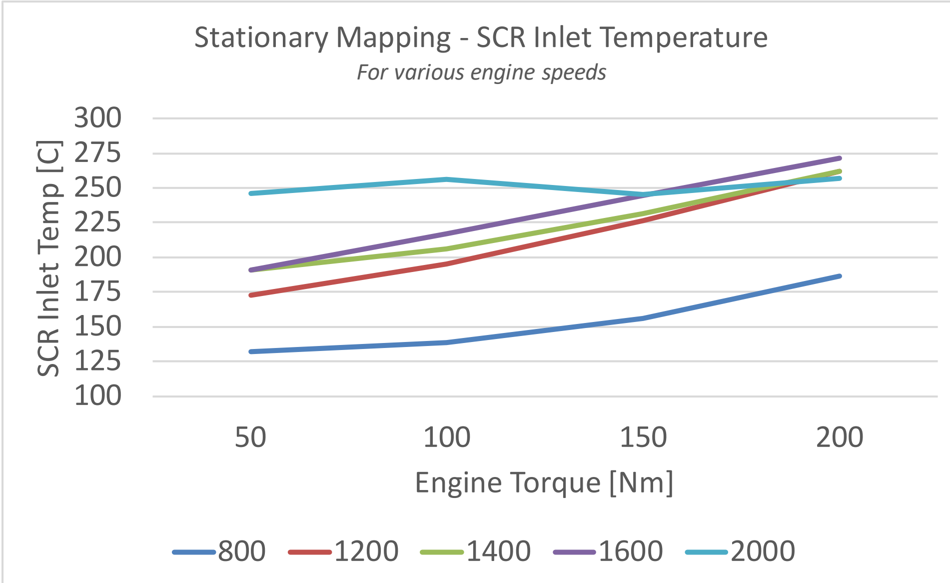


Figure 49. SCR inlet exhaust gas temperature

Engine out and tailpipe out raw NO_x emissions are shown in Figure 50 and Figure 51. Engine out raw NO_x emissions are lower for higher engine speeds and decrease with increase in load. Engine out emissions are not affected by the aftertreatment and the results are primarily a function of engine operation. Tailpipe out emissions are affected by both engine operations, lower engine out NO_x would result in less of a required reduction at the SCR catalyst but is also a function of the catalyst efficiency which as shown previously is highly dependent on the exhaust temperature. Operating at high engine power conditions delivered the optimal results for lowering tailpipe out NO_x.

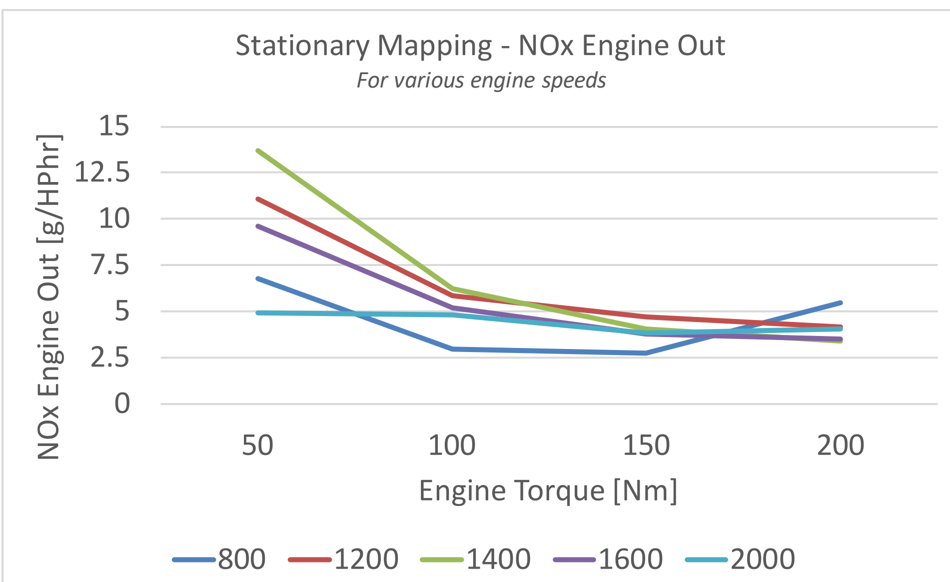


Figure 50. Engine out raw (pre-aftertreatment) NO_x

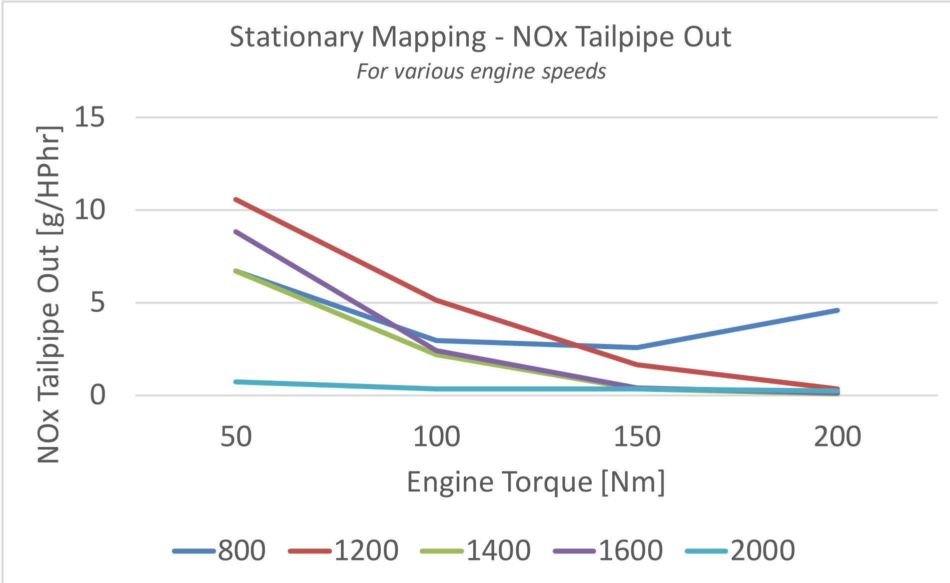


Figure 51. Tailpipe out (post-aftertreatment) NO_x

Idle Conditions

The vehicle was idled over the following three conditions. Each condition was run twice and 200 seconds of each mode were analyzed, and then combined and averaged for like modes.

- Idle with transmission in park, AC off
- Idle with transmission in drive, AC off
- Idle with transmission in park, AC on

Figure 52 shows the fuel consumption in grams per hour for all three idling conditions. The idle condition when the vehicle was in park and the AC has the lowest fuel consumption. The condition with the vehicle transmission in drive has the highest fuel consumption, approximately 65% higher than the base idle-park condition. Using the AC while in idle increased the fuel consumption, but not as much as being in drive did. At the idle-park condition the fuel consumption is roughly 0.4 gallons/hr.

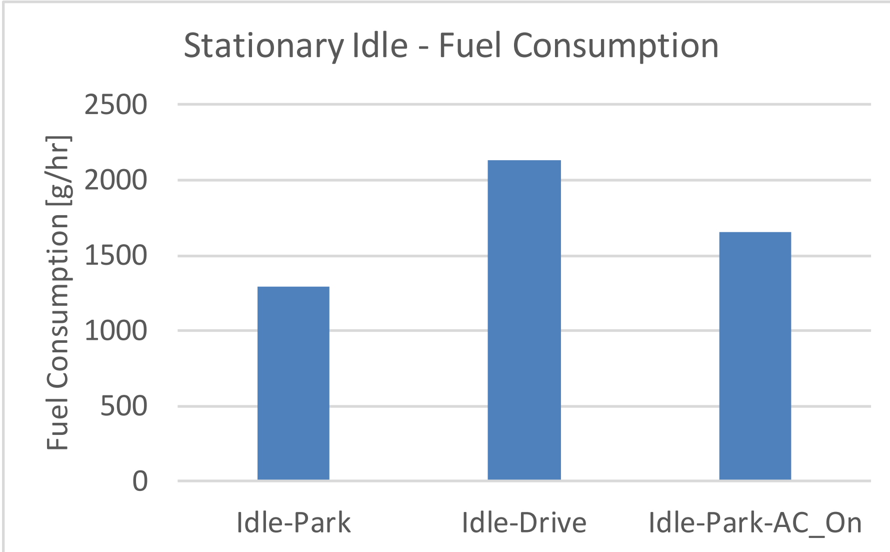


Figure 52. Idle conditions fuel consumption

Tailpipe NO_x emissions for the idle NO_x emissions are shown in Figure 53. NO_x is very similar for all conditions. Due to the lack of repeats, it cannot be determined if the drop in NO_x while the AC is on is statistically different than the other two conditions. As a result of the low exhaust temperatures at these idle conditions, the aftertreatment NO_x conversion efficiency at these conditions was effectively 0 resulting in almost all engine-out NO_x emissions making it out the tailpipe of the vehicle.

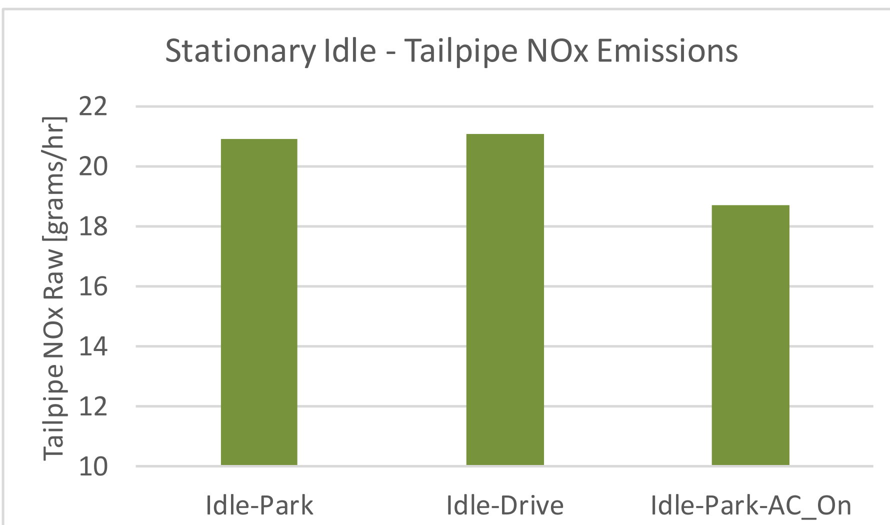


Figure 53. Idle conditions NO_x emissions

NO_x Comparison

When comparing NO_x results across all the different study conditions performed on this vehicle NO_x emissions are at the highest rate during PTO use. This is likely due the nature of the engine and exhaust operating conditions during PTO work. The engine spends a majority of the time at idle which results in low exhaust temperatures and low SCR NO_x conversion efficiency, but then work is commanded at abrupt segments very transient in nature resulting in large engine out NO_x spikes. These spikes cannot be mitigated by the aftertreatment system because of the low temperatures which then results in high NO_x concentration values out of the vehicle tailpipe.

Figure 54 shows a graph comparison of time-based NO_x emissions in grams per hour. The results show the potential ranges of NO_x emissions for conditions that were studied in this phase I part of this project. For explanation, the highest NO_x emitting drive cycle was for the HHDDT transient cycle. If this cycle were continuously operated, it would average 30.8 grams/hour of NO_x emissions out of the tailpipe. The conventional PTO work results are from the PTO transient work shown previously in Table 9. The hybrid PTO work calculations are from the battery recharging calculations also in Table 9. This is calculated by assuming all the energy used by the electric PTO system will be recharged back to the batteries via the vehicle engine, so no plug-in capabilities were considered here (e.g. if the vehicle PTO used 1kW-hr of energy then 1kW-hr of energy would be put back on the battery packs by engine recharging mode operation). The vehicle is a plug-in hybrid so in reality vehicle out emissions for this scenario could effectively go down even lower. Also, emissions during charging of the batteries could potentially be optimized to have lower NO_x emissions as shown in the engine mapping section discussed previously. Figure 54 demonstrates that the Odyne electric PTO system can have a dramatic impact of an order of magnitude on NO_x emissions from utility vehicles when performing stationary PTO work.

It can also be noted that many of the utility vehicles studied were in stationary mode for nearly 75% of the shift time. That would indicate that most of their NO_x emissions will come from either PTO work or idling with no work output at all. If this were considered, then the increase in NO_x from conventional PTO would go even higher when compared to the hybrid system.

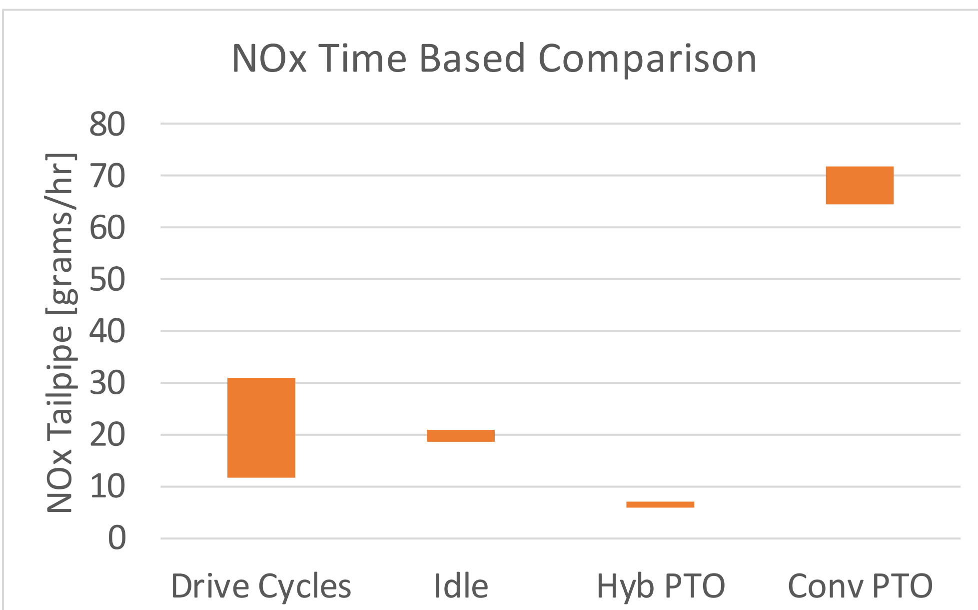


Figure 54. Time-based NO_x emissions for the various operating modes

Field Data and Modeling Results

As part of the Odyne project, vehicle field data were collected from utility vehicles of various vocations. A total of 44,000 vehicle days of data were analyzed and filtered down to 20,000 of usable data. A model was then developed from the chassis dyno results on the three NREL Utility Truck drive cycles previously described. Data from daily operation are categorized by the operation type and if the operation is driving then the data are categorized by which of the three drive cycles it matches closest, Figure 55.

The model includes NO_x calculations derived from the chassis dynamometer drive cycle study as well as the other idle and PTO studies performed on the Odyne vehicle found in this report. This model then calculates the accumulated NO_x emissions for the actual collected field data and shows the difference between the vehicle being operated in conventional engine mode and the Odyne hybrid system mode using ePTO.

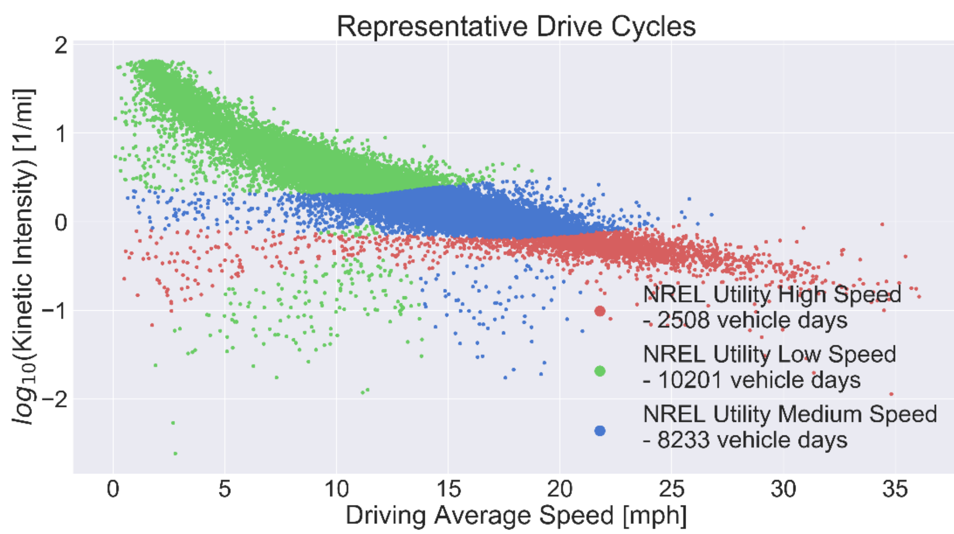


Figure 55. Field data categorized into NREL utility truck drive cycles in model

The first plot in Figure 56contains data from a vehicle that was operated for nearly an entire shift. It can be seen at the beginning and end of the day the vehicle drives and idles some. For about 5 hours in the middle of the day the vehicle is operated in PTO work mode. By operating from the ePTO system the vehicle emits drastically less NO_x emissions. The engine kicks on three times for a field battery recharge (“Fcharge”) but the rest of the time the engine is off, and all PTO work comes from the batteries. When the vehicle performs a field recharge it is done at a higher engine load than when at idle, allowing the exhaust system to be hotter and the SCR system to mitigate NO_x more efficiently because of higher catalyst efficiency.

When in conventional mode during the PTO work the engine operates at a high-speed low-load idle condition. When work is performed it creates sudden engine torque loads as shown in the transient PTO cycle in Figure 41. The continual low-load condition results in low exhaust temperatures and low SCR catalyst efficiency for converting NO_x. When the engine load is spiked with a PTO load NO_x will flow through the aftertreatment system, and due to the low efficiency conditions, most of it will not be converted in the SCR and go out the tailpipe.

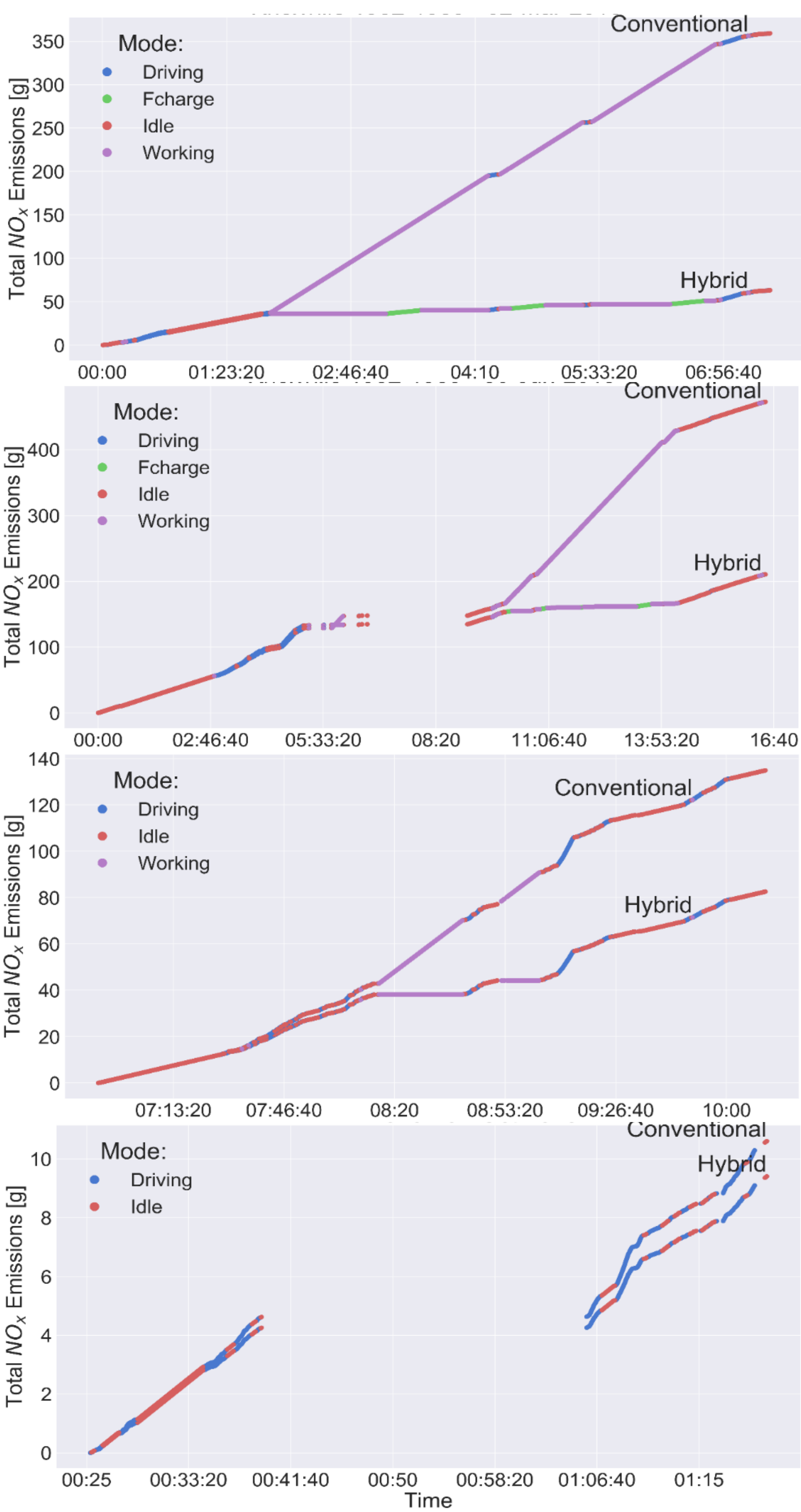


Figure 56. Comparison of total NO_x accumulation on four different days of vehicle operation for conventional and hybrid modes

The three other plots in Figure 56 show the same calculations for various types of daily operation. The gaps in the line note key-off situations where the vehicle was shut down entirely during that time. The ePTO system results in major improvements for NO_x reduction over a day. If the vehicle is only driven and no PTO work is performed then the mild hybrid system has a smaller improvement to reduce NO_x, but in all cases here it does reduce NO_x.

Figure 57 shows the amount of NO_x savings from the hybrid over the conventional vehicle categorized by which drive cycle they were matched for all 20,000 vehicle days of data.

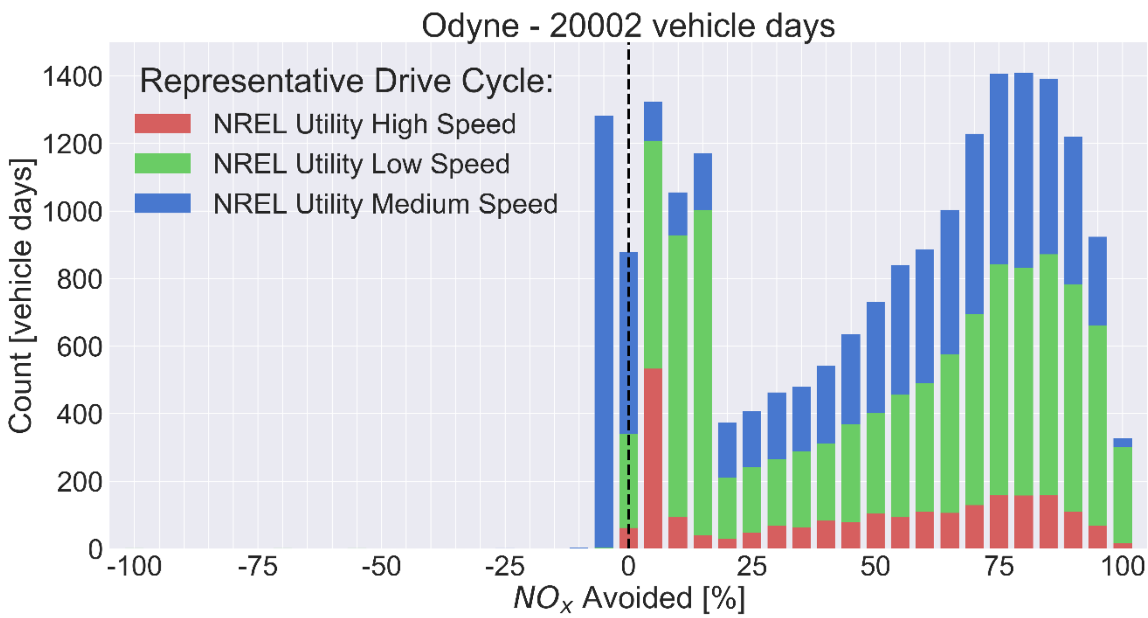


Figure 57. NO_x avoided by using hybrid system on approximately 20,000 vehicle days of field data

The Odyne hybrid ePTO system also demonstrated fuel savings. Figure 58 shows fuels savings for the 20,000 vehicle days of field data.

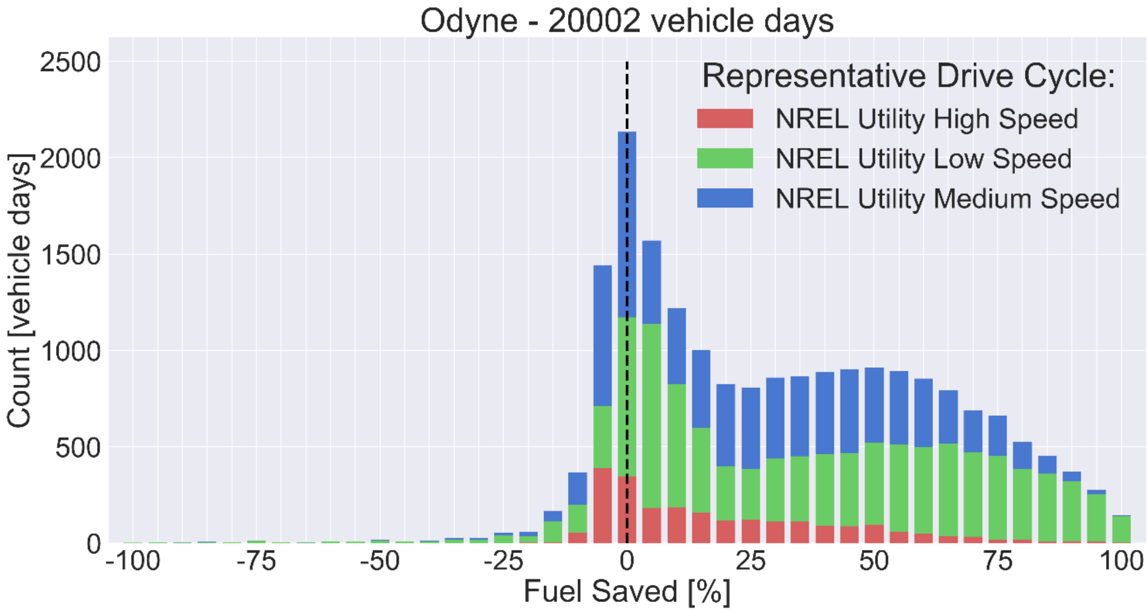


Figure 58. Fuel savings from Odyne hybrid system

Odyne Vehicle Study Summary

The following conclusions have been reached from phase I of this vehicle study:

- The drive cycle results demonstrate that the hybrid system studied either improves or has a neutral effect on vehicle fuel consumption, depending on the average speed and kinetic intensity of the cycle. Note that electrical energy from plug-in sources is not included in this calculation. There are no significant changes in vehicle NO_x emission between the hybrid and conventional systems on the drive cycles.
- It was shown that using the battery system to provide energy for the PTO system and then recharging the battery at a higher constant load (200 Nm) was extremely advantageous over operating the PTO system off engine power. Using the engine as a generator is a more efficient operation mode than having the engine running at idle mode and responding to transient PTO events. The exhaust temperatures are lower when operating at idle resulting in poor aftertreatment performance, whereas when operating at the constant higher loading during a battery recharge event the exhaust can maintain temperatures that allow higher aftertreatment conversion efficiencies. If the PTO system is operated over a full day the impact on NO_x emissions can be dramatically improved with the hybrid system.
- It was demonstrated that running the highest load possible at middle speeds is ideal for battery pack recharging from both emissions and fuel consumption perspectives.
- The Odyne hybrid showed a general small decrease in total NO_x emissions for the dynamometer drive cycles but showed a large potential for NO_x emissions reduction when using the ePTO system power from the hybrid batteries instead the standard PTO system powered from the vehicle internal combustion engine.

Report Summary

Two areas of focus were investigated in this study.

1. NREL provided technical guidance and feedback to CARB during the crafting of the ITR. NREL PEMS tested a HINO 195 (diesel conventional) and vertically integrated HINO 195h (diesel-electric hybrid) to demonstrate the feasibility of achieving the ITR criteria that had been drafted. There was some evidence of increased NO_x with the hybrid vehicle as shown with the Hino PEMS testing and HHV tests, but overall emissions levels were lower (close to certification levels, ranging from 0.20 to 0.70 g/mi) with the Hino for both hybrid and conventional powertrains when compared to the NO_x levels observed during the original HVIP study, primarily from other older vintage and no-vertically integrated electric hybrid configurations (Thornton et al. 2014). This is further evidence that OEMs are addressing past hybrid NO_x increases with better model-based urea dosing and emissions controls approaches (Kotz et al.). These enhanced model-based emissions controls approaches, combined with improved performance and emissions trade-offs and thermal management strategies have provide OEMs with tools to significantly lower engine-out and tailpipe NO_x emissions from current hybrid offerings when compared to hybrid vehicles included in the original HVIP study. This provides some evidence that current state-of the-art medium-duty hybrids will implement strategies to significantly mitigate the NO_x increase issues previously observed during the HVIP study. Particularly form vertically integrated hybrid systems such as the HINO 195h. CRAB policies to use either chassis dynamometer or in use PEMS testing to verify hybrid NO_x emissions levels and confirm anti-backsliding from new medium and heavy-duty hybrid offering will ensure that OEMs utilize the above strategies to control in-use NO_x emissions.

2. NREL carried out chassis dynamometer studies on current medium- and heavy-duty hybrid vehicles and their conventional baseline to better understand the main driving factors that contribute to the hybrid vehicle NO_x increase observed under the preceding HVIP evaluation project.

   A series of conventional and HHV refuse trucks were instrumented in the Miami-Dade municipal fleet to collect real-world activity. A conventional diesel vehicle and a diesel HHV were studied at NREL's ReFUEL laboratory for chassis dyno emissions studies. Increases in NO_x emission were observed for the hybrid vehicles compared to the conventional vehicle, but these relative increases were primarily attributed to the poor match between the hybrid and baseline vehicle. The baseline vehicle was of a significantly newer vintage from the hybrid, exacerbating the emissions comparison. Therefore, it is anticipated that the newer hybrid model (Parker MY17 systems) would not suffer from the same NO_x emission issue if they are using the latest Cummins aftertreatment technology and control system, with expected NO_x emission in the 1.0 gr/mi range. If this assumption is accurate, it would provide further support of the HINO 195h emissions results, showing that the OEMs are addressing the previously observed hybrid NO_x emission increased through new emission control systems and model-based controls on multiple vehicle platforms.

In addition, an Odyne PHEV utility truck with ePTO was studied on NREL's heavy-duty chassis dynamometer. The vehicle had the capability of enabling or disabling the hybrid system so that NO_x emissions could be studied in either PHEV or conventional operating modes on the same vehicle, removing the uncertainty of vehicle gearing, aging of the aftertreatment and engine model year. The study demonstrated that the vehicle driving in hybrid mode resulted in slightly lower NO_x emissions for most drive cycles when compared to the conventional vehicle mode, though the NOx differences were very small. It was shown, however, that with the implementation of the battery powered ePTO system large improvements were made in NOx emissions over a conventional stationary PTO operation. This portion of the study illustrated that for this vehicle the NOx emissions were similar or even slightly lower for the hybrid compared to the conventional, but also provided a potentially significant NOx benefit in certain applications, such as that under utility work site operations. This study provide evidence that these benefits can provide up to a 10X NOx reduction for the hybrid over a given day, depending on the amount and duration of work site activity.

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