Hybrid Electric Drivetrain Testing and Design

Cooperative Research and Development Final Report

CRADA Number: CRD-17-00699

NREL Technical Contacts: Jonathan Burton and Riley Abel

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Contract No. DE-AC36-08GO28308

Technical Report
NREL/TP-5400-77715
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Cooperative Research and Development Final Report

Report Date: **August 25, 2020**

In accordance with requirements set forth in the terms of the CRADA agreement, this document is the final CRADA report, including a list of subject inventions, to be forwarded to the DOE Office of Science and Technical Information as part of the commitment to the public to demonstrate results of federally funded research.

Parties to the Agreement: Efficient Drivetrains, Inc.

CRADA number: CRD-17-00699

CRADA Title: Hybrid Electric Drivetrain Testing and Design

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Sponsoring DOE Program Offices:
Office of Energy Efficiency and Renewable Energy, Vehicle Technologies Office (In conjunction with the Small Business Administration (SBA), Small Business Voucher Pilot Program)

Joint Work Statement Funding Table showing DOE commitment:

Estimated Costs	NREL Shared Resources a/k/a Government In-Kind
Year 1	$140,000.00
TOTALS	$140,000.00

Executive Summary of CRADA Work:

Hybrid electric drivetrains have recently become of a great interest in the medium and heavy-duty vehicle market as it enables substantial reduction of petroleum use, vehicle level fuel use and criteria pollutant emissions. These vehicle performance improvements are not only economically beneficial for business operations relying on large fleets of vehicles, they are also paramount for curbing energy use and the negative effects of vehicle operations on the environment.

Efficient Drivetrains, Inc. (EDI), acquired in July 2018 by Cummins, Inc., is a small company focused on development of medium and heavy-duty hybrid electric drivetrains. EDI has already developed the general hardware architecture of their drivetrain system, but there is still a significant effort to be done on optimizing the system in terms of control strategies and component sizing in order to maximize the benefits of the hybrid drivetrain.

Historically, hybrid electric systems have proven to deliver better fuel economy in certain applications than their conventional counterparts. Particular areas of advantageous applications are vocations with kinetically intensive transient duty cycles and operations requiring some sort of power take off whose power demand is not well matched to the size of the vehicle's main engine, thus forcing it to operate in extremely inefficient operating modes. Hybrid drivetrains can be at a disadvantage when pressed into duty cycle operation consisting of extensive steady state highway cruise due to various design compromises optimized for more transient operation. This can also lead to increase in vehicle emissions if the system is not optimized properly. Ample opportunity for extensive optimization is needed to overcome these obstacles.

Summary of Research Results:

Task 1: Analyze vehicle performance data and select drive cycles

Task 1 was to characterize the driving of class 4-6 delivery trucks, it involved three sub-tasks. The first was to identify three existing drive-cycles that could approximate the driving behavior of the work trucks for chassis dynamometer testing. The second task was to develop a drive-cycle which represents a full workday for parcel, food, and linen delivery vehicles. The third task was to compress the full-day drive cycle into a drive-cycle short enough for dynamometer testing.

To characterize the driving behavior of the test vehicle in its target vocation, over 31,000 days of in-use Class 4-6 delivery truck data was evaluated. For each vehicle day, truck speed recorded at 1-second intervals during field use was obtained from NREL's Fleet DNA database. From the 1Hz speed trace, a set of metrics was calculated to summarize the driving behavior of each vehicle day. These metrics include driving average speed, stops per mile, average acceleration, kinetic intensity, and total idle time. The results from clustering analysis can be seen in Table 1. These metrics were compared to the standard chassis dynamometer test cycle statistics. It was determined the closest matching cycles were the UDDS, HHDDT Composite, and OCTA. This project included drivetrain modeling activities.

Table 1. Results from the clustering analysis.

Cluster	Vocation	Vehicle days	Driving Avg. Speed [mph]	Kinetic Intensity [1/mi]	Stops per Mile
0	Linen	1	17	3.0	4.40
	Parcel	260			
1	Food	29	22	1.1	2.62
	Linen	118			
	Parcel	285			
2	Food	237	33	0.40	0.972
	Linen	263			
	Parcel	18			

Rather than model 31,000 vehicle days of driving data, a representative day was developed using NREL's Drive-Cycle Rapid Investigation, Visualization, and Evaluation (DRIVE) processing tool. By testing with this representative day, more attention can be paid to the specific periods of driving that the vehicle may struggle with. To create a representative day, DRIVE selects a subset of microtrips (driving data between stops) from the entire set of recorded speed to compress hundreds of hours of driving data into a drive cycle less than 2 hours long. The challenge is to select discrete microtrips that, when aggregated, produce a cycle with statistics matching those of the original, full-length speed trace. In this case, a drive cycle was generated for each of the 3 clusters identified in the previous section as seen in Figure 1.

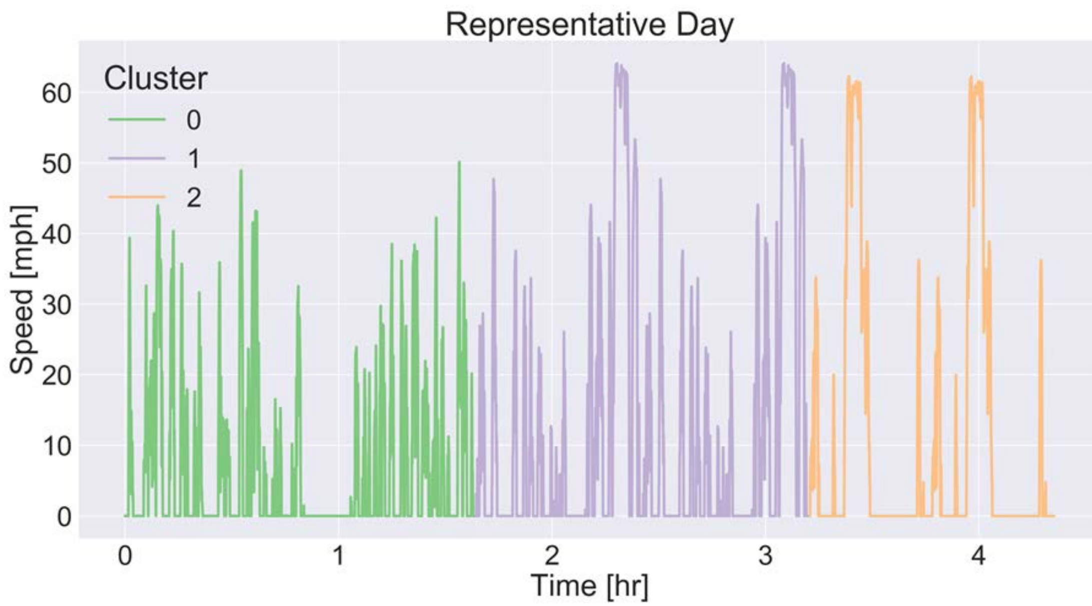

Figure 1. Representative day drive cycle with the three combined cluster groups.

The custom cycle developed for Cluster 0 is the longest, lowest-speed cycle with the highest kinetic intensity. It incorporates the most stops per mile when compared to the other two clusters. The custom cycle developed for Cluster 1 includes medium speed components, coupled with a higher driving average speed. Cluster 1 includes a greater number of idle segment time when compared to Cluster 0. Additionally, the custom cycle developed for Cluster 2 yielded the lowest kinetic intensity with the highest average driving speed. These three distinct custom cycles were combined to form a representative workday. For dynamometer testing, a drive cycle less than one hour in duration is necessary in order to repeat multiple tests in a day. DRIVE was used to condense the representative driving day into a representative drive cycle as seen in Figure 2

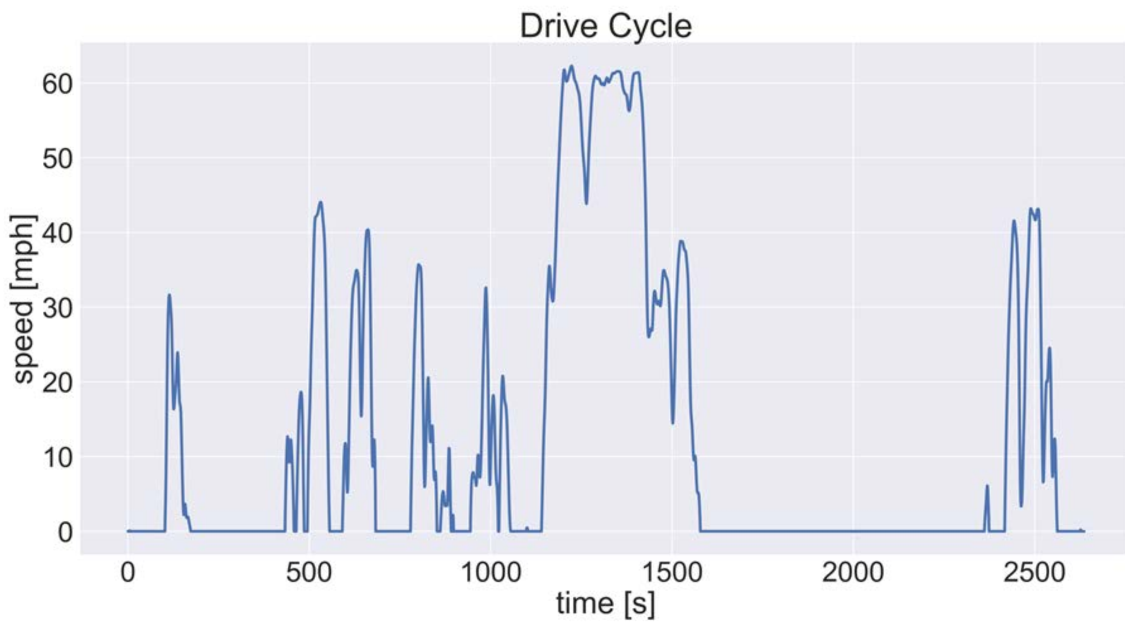

Figure 2. Representative all day drive cycle condensed to 2700 seconds

Task 2: Test EDI Class 4 PHEV truck against a baseline truck using NREL's chassis dynamometer

Task 2 was to determine the overall vehicle performance, fuel economy, and criteria emissions for both vehicles using NREL's ReFUEL laboratory chassis dynamometer. More specifically, data captured during each vehicle test was analyzed in order to calculate overall NOx and CO emissions, fuel consumption, and total fuel energy measurements for each individual drive cycle.

A 2018 Isuzu Diesel NPRxd Class 4 vocational box truck meeting the project specifications was identified and acquired from a local rental company. The second vehicle was a 2016 Class 4 Chevrolet 4500 Low Cab Forward provided by EDI. The vehicle was equipped with a General Motors 6.0L L96 Vortec engine converted to a CNG fueling system and accompanied by a plug-in hybrid electric system designed by EDI. Specifications for each vehicle can be referenced in Table 2.

The CNG fueling system was designed, manufactured and installed by A-1 Alternative Fuel Systems, with a 23.5 GGE capacity. The low pressure and fueling calibration of the system was conducted by AGA Systems. Fuel for the EDI PHEV CNG vehicle was refueled on daily basis using fuel sourced at a Clean Energy fueling location. Redmark CNG Services took a sample from this batch of fuel and sent it to Empact to conduct a fuel analysis. Fuel for the diesel baseline vehicle study was standard pump ULSD fuel, with $B2\%$ composition.

Table 2. Test vehicle specifications.

	2018 Isuzu NPR XD	**EDI: 2016 Chevrolet 4500**
Engine	2018 Isuzu 5.2L 4HK1-TC Turbocharged intercooled diesel Engine Family: JSZXH05. 23FA	2016 General Motors 6.0L Vortec L-96 Gasoline converted to CNG Engine Group: GGMXE06.0584
Transmission	Aisin A465 6-speed auto, double overdrive and lock-up 2^{nd}-6^{th} gears	Hybrid Electric: Traction Motor Coupled with ISG Motor
Battery System	N/A	Total battery capacity 61.2 kWh SAE J1172 Level 2 Charger (6 kW)

Both vehicles were operated over the chosen representative drive cycles in order to capture total tailpipe out emissions, calculated in grams per mile. When comparing the NOx results across all the drive cycles, emissions are highest over the OCTA drive cycle, followed by the UDDS drive cycle. A table representing the total NOx results captured over the four chosen drive cycles can be referenced in Table 3.

Table 3. NOx results over the four representative drive cycles.

NOx (grams/mile)	HHDDT	OCTA	EDI_Cust	UDDS
Baseline Diesel	0.115	0.160	0.123	0.027
EDI CNG	0.129	0.280	0.123	0.122
CO (grams/mile)	HHDDT	OCTA	EDI_Cust	UDDS
Baseline Diesel	-0.010	-0.008	-0.015	-0.011
EDI CNG	34.801	5.973	20.241	10.211

A continuous second-by-second NOx emissions comparison between the diesel baseline vehicle and EDI CNG PHEV over all OCTA cycles was analyzed. The EDI CNG PHEV produces very large emissions spikes throughout the drive cycle, with two areas of interest producing heavy NOx concentration. These periods of high NOx emissions occurred at the OCTA drive cycle time of 600-1000 seconds, followed by drive cycle time of 1400-1900 seconds as seen in Figure 3.

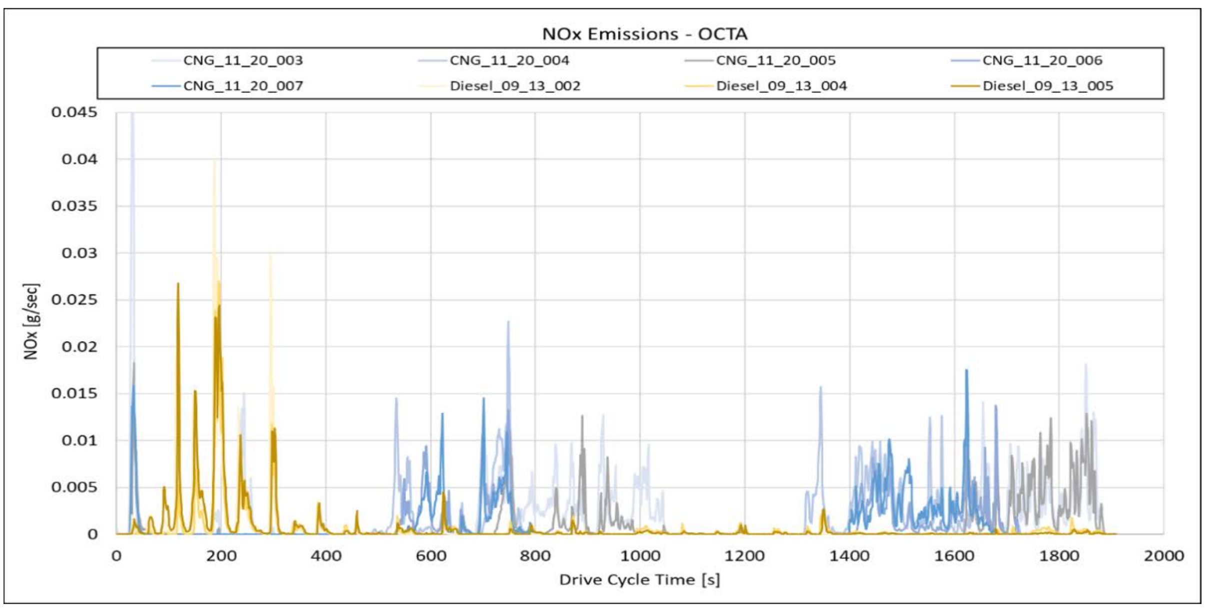

Figure 3. Continuous NOx emissions comparison between test vehicles over all OCTA drive cycles.

A second-by-second NOx emissions comparison between both test vehicles over all UDDS drive cycles was analyzed. Similarly, high NOx production can be seen at drive cycle times of 0-250 seconds and 590-650 seconds respectively, as seen in Figure 4. The test results indicate that for the majority of the drive cycles, the EDI CNG PHEV produced higher tailpipe out NOx emissions than the conventional diesel vehicle.

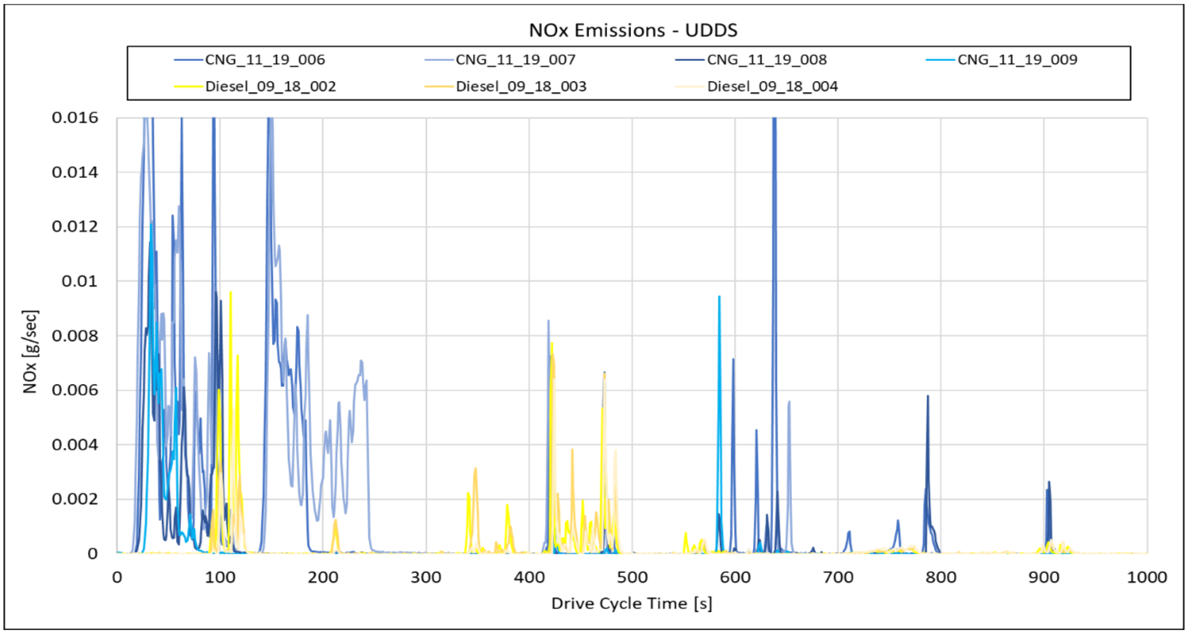

Figure 4. Continuous NOx emissions comparison between test vehicles over all UDDS drive cycles.

Carbon Monoxide emissions results for both vehicles were captured and analyzed. Notably the CO emissions of the conventional diesel vehicle are below practical detection limit of the instrumentation setup used, thus resulting in near zero negative values. Conversely, the CO emissions of the CNG fueled PHEV were spiking extremely high, causing the measurement instrument to exceed its range limits frequently. The highest production of CO emissions over all four of the drive cycles was the HHDDT cycle, followed by the EDI Custom cycle respectively. A second-by-second CO comparison between the diesel baseline vehicle and EDI PHEV CNG vehicle over all HHDDT drive cycles was analyzed as seen in Figure 5.

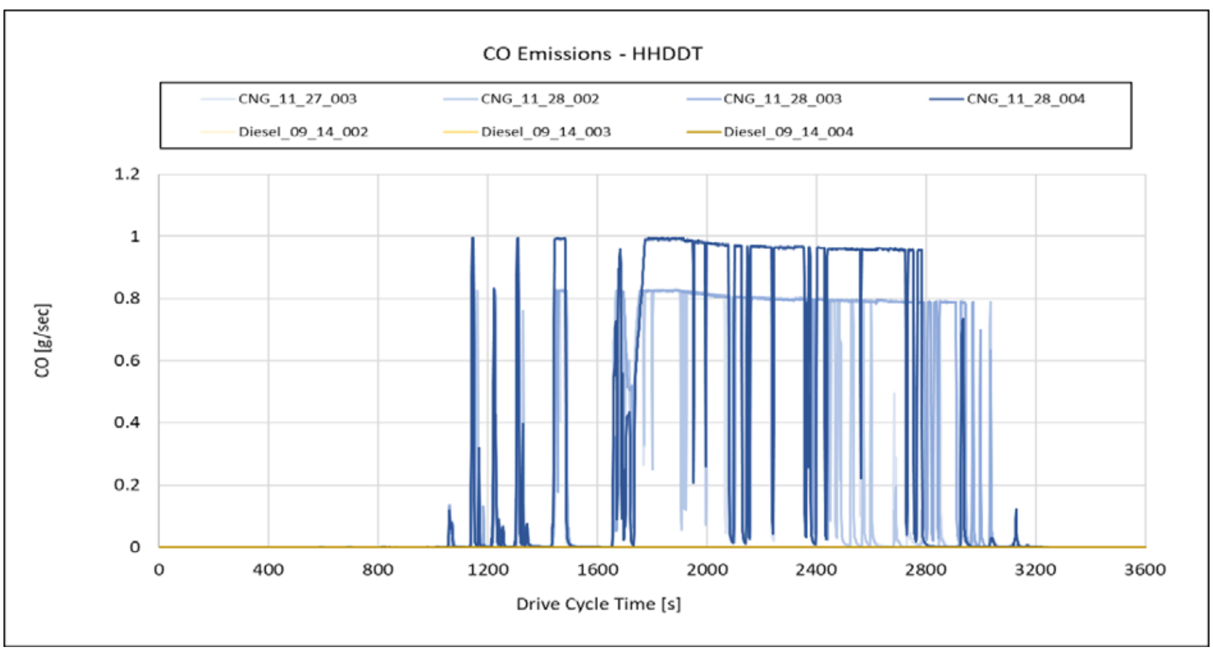

Figure 5. CO emissions comparison between test vehicles over all HHDDT drive cycles.

Table-top formation of CO measurement occurred indicating the emissions analyzer experienced complete saturation during testing. The tailpipe emissions were measured using a constant volume sampler (CVS). The CVS system nominal flowrate had to be adjusted from 1500 CFM to 2000 CFM, 2500 CFM and even to 3000 CFM on one test in an attempt to contain the CO analyzer saturation condition. It should be noted that even at the highest dilution rate the CO concentration exceeded the analyzer range. Both conditions of analyzer saturation and the very high dilution rates are a cause for reduced accuracy of the results due to inability to capture concentration peaks on the upper end and loss of sensitivity on the lower end of the concentration spectrum. One potential source for the cause of elevated CO emissions could be from an exhaust leak in the exhaust manifold outlet gasket which was observed while the PHEV-CNG vehicle was set up on the dynamometer. The leak was upstream from the three-way catalyst. A substantial amount of time was spent to repair the driver's side exhaust manifold outlet flange and get the vehicle ready for testing, but it is possible that the repair failed during testing.

If there was a leak in the exhaust fresh air could be pulled into the exhaust system if it were in a vacuum state, which only happens if the engine is being motored such as in a down-hill operation. During normal operation where the engine is producing power the exhaust would be at a positive pressure and the leak would push exhaust gases out of the exhaust pipe. Any fresh air leaking into the system before the oxygen sensor would be interpreted as a lean air/fuel ratio condition, where not enough fuel is present during combustion to burn all the available oxygen. As a result, the Engine Control Unit, detecting a false lean air/fuel ratio could respond incorrectly, adding fuel and thus pushing the air/fuel ratio into rich condition, where three-way catalysts have a low conversion efficiency of CO molecules.

Another potential cause of the elevated levels of CO could be that the retrofit engine control system for the CO conversion was not functioning properly. This conclusion could not be verified without having access to engine control commands and feedback sensor signals.

To compare fuel consumption between two vehicles with different fuels with different energy density, carbon content, mass density and cost, the fuel consumption was evaluated in terms of fuel energy. Energy consumption on a per mile basis was calculated in kilojoules (kJ) and kilowatt hours (kWh). Total fuel energy consumption was calculated for each of the four drive cycles and can be referenced in Table 4.

Table 4. Total fuel energy comparison between test vehicles over four drive cycles.

EDI CNG	HHDDT	OCTA	EDI_CUST	UDDS
Total Fuel Energy per mile (kJ)	16923.46	16475.06	18178.10	15697.37
Total Fuel Energy per mile (kWh)	4.74	4.61	5.09	4.40
Total Fuel Energy per Cycle (kWh)	123.44	30.17	44.08	24.39
Diesel Baseline	HHDDT	OCTA	EDI_CUST	UDDS
Total Fuel Energy per mile (kJ)	14869.38	15272.80	17139.99	14817.28
Total Fuel Energy per mile (kWh)	4.16	4.28	4.80	4.15
Total Fuel Energy per Cycle (kWh)	108.46	27.97	41.56	23.03

The total fuel energy consumption per cycle is represented in kWh. The highest fuel energy consumption took place over the HHDDT cycle, however, the HHDDT cycle has the longest duration over all the drive cycles and is expected to consume the greatest amount of fuel. Drive cycle fuel consumption measured in grams per mile can be seen in Figure 6. The total fuel energy consumption per mile was highest over the EDI Custom cycle as seen in Figure 7.

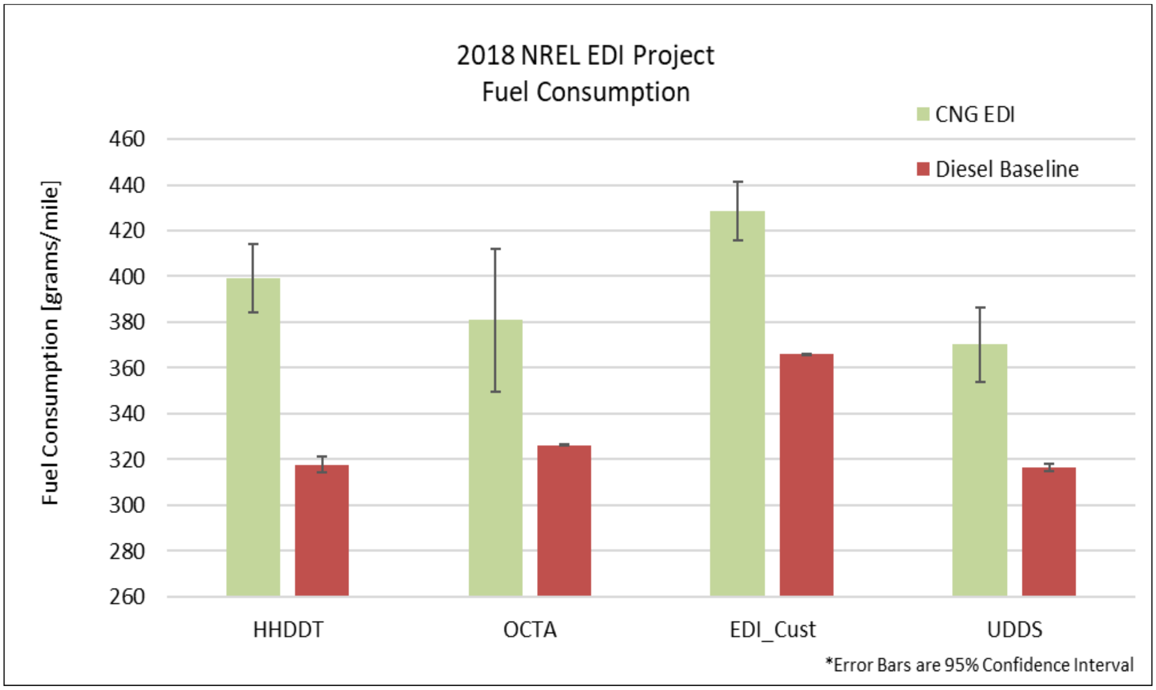

Figure 6. Drive cycle fuel consumption results.

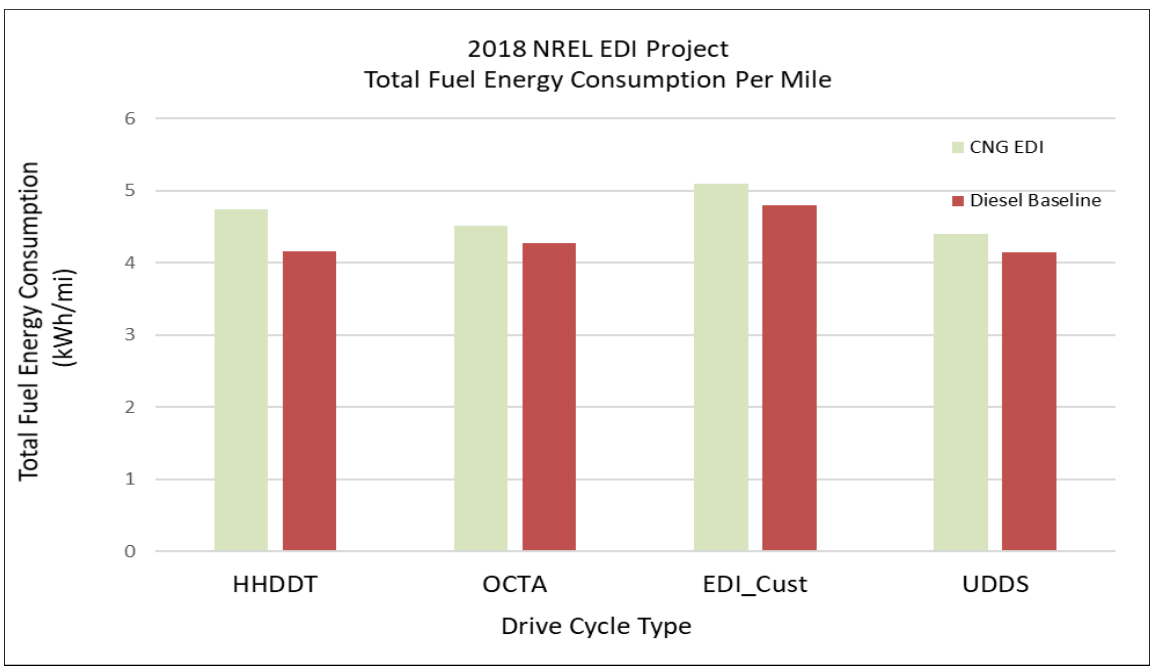

Figure 7. Drive cycle total fuel energy consumption per mile results.

Task 3: Optimize motor, battery, and other component selection and configuration

The Future Automotive Systems Technology Simulator (FASTSim), was used to generate an optimized model to estimate the EDI CNG PHEV efficiency, performance, cost and battery life. Engine torque data captured from Task 2 drive cycles was used to develop an engine efficiency map. The factory GM 6.0L L96 Vortec engine and torque curve map was utilized in parallel with an engine max torque curve provided by EDI. This information was used to determine an operating horsepower and torque curve estimate at the maximum engine speed of $3000RPM$ experienced over the four drive cycle tests. Real time engine torque signals were captured on the CAN network during vehicle testing, however, a value of $120kW\ or\ 160.923hp$ estimate was used for modeling purposes by a general assumption of that CNG has a 20% less fuel energy when compared to its gasoline counterpart. Actual engine torque values after the CNG conversion kit installation was not available as the engine was never dyno-calibrated. For the lack of solid engine performance data, a simplified one-dimensional engine efficiency map was generated, indicating a maximum of 38% engine efficiency at a maximum engine power of 42% as seen in Figure 8.

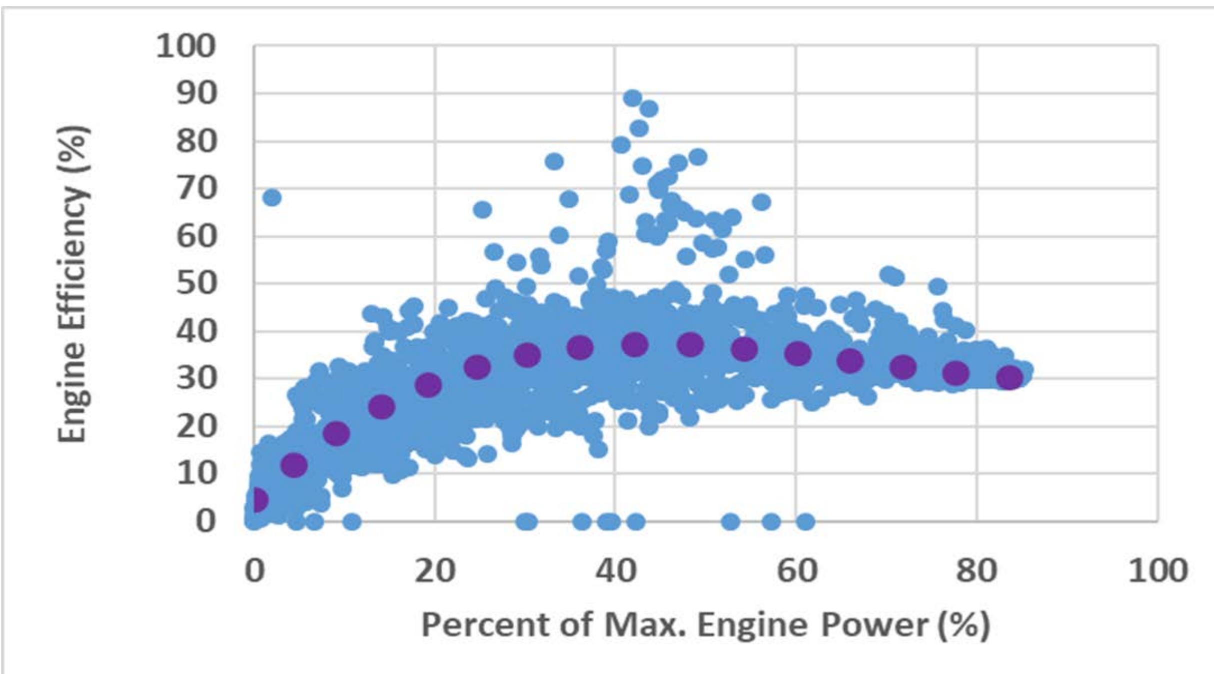

Figure 8. Engine efficiency map generated from drive cycle test data.

A vehicle model was generated from the data of one test of each drive cycle and applied to the remaining drive cycles to compare model predicted results and actual test results. Table 5 indicates the differences of the fuel efficiency, (FE), measured during testing versus FASTSim model predictions. The fuel efficiency is represented in miles per gallon gasoline gallon equivalence, (MPG GE). The simulated FE value compared to the actual FE test value produced simulation error representing how close powertrain modeling is to the actual powertrain data captured from the vehicle. The largest simulation error of -4.05% occurred over the EDI Custom cycle.

Table 5. Drive cycle test MPG GE versus vehicle model calibration results.

Drive Cycle	All ReFUEL Test			Vehicle Model Calibration		
	Repetition Test	ReFUEL FE (mpgge)	Deviation from the Average (%)	ReFuel FE of Selected Drive Cycle (mpgge)	FASTSim Simulated FE (mpgge)	Simulation Error (%)
UDDS	1	7.66	-0.13	7.66	7.39	-3.50
	2	7.20	-6.13			
	3	7.83	2.09			
	4	7.98	4.04			
	Average	7.67	---			
OCTA	1	6.46	-11.99	7.85	7.82	-0.32
	2	7.85	6.95			
	3	6.88	-6.27			
	4	7.89	7.49			
	5	7.63	3.95			
	Average	7.34	---			
EDI Customized	1	6.70	1.21	6.25	6.00	-4.05
	2	6.80	2.72			
	3	6.24	-5.74			
	4	6.61	-0.15			
	5	6.73	1.66			
	Average	6.62	---			
HHDDT	1	7.31	2.81	6.85	6.92	0.98
	2	6.85	-3.66			
	3	7.17	0.84			
	Average	7.11	---			

An economic sensitivity analysis was conducted in order to minimize energy costs when compared to economic costs. This was developed using 2015-2017 CNG fuel and electricity costs data in order to determine an optimal energy cost per mile evaluation. The lowest and highest energy cost per dollar was averaged over the three-year period and was modeled as a current energy price. CNG and electricity prices of $\$3.03$ and $\$0.10$ were used respectively and remained fixed for the powertrain FC and battery combination analysis. A current market battery price of 150 ($\$/kWh$), and battery lifetime of eight years and $100{,}000$ miles was assumed. The minimal fuel convertor, (FC), and battery component combination was chosen to meet the power/energy requirements of the vehicle, operating on a duty cycle represented by the EDI Custom drive cycle. An optimized FC/battery sizing combination was selected for different daily driving distance scenarios ranging from 20 miles to 100 miles. The results of fuel convertor and battery system combination results can be referenced in Table 6.

Table 6. Fuel convertor and battery system combination results by FASTSim.

Daily Travel Distance	Optimization Design		CD Distance	Electricity Consumed from CD mode (kWh)	Gallons Consumed from CD mode	Gallons Consumed from CS mode	Opt. Energy Cost ($/mi)	Opt. Total Cost ($/100,000mi)
Miles	FC kW	Batt. kWh						
20	160	30	50.53	11.87	2.07	0	0.38	42034
40	160	30	50.53	23.75	4.14	0	0.38	42034
50	160	30	50.63	29.68	5.18	0	0.38	42034
55	**160**	**30**	**50.53**	**50.53**	**5.69**	**0.713**	**0.45**	**49341**
55	150	30	55.99	29.47	5.89	0	0.38	42527
60	**150**	**30**	**55.99**	**55.99**	**6.43**	**0.624**	**0.45**	**49806**
60	140	30	62.52	28.79	6.65	0	0.39	43087
65	130	30	69.53	28.04	7.42	0	0.39	43554
70	**130**	**30**	**69.53**	**69.53**	**7.99**	**0.072**	**0.45**	**49704**
80	110	30	85.76	27.98	9.58	0	0.39	44426
90	**100**	**30**	**91.60**	**91.60**	**11.14**	**0.065**	**0.47**	**51742**
90	140	40	92.35	38.98	10.78	0	0.41	47177
100	130	40	102.87	38.89	12.25	0	0.41	47177

This optimization is based purely on the economics of the battery purchase cost and the operating energy cost (overnight charging and fuel consumed). Additional parameters and variables (such as suitable engine options availability, drivability in conditions outside of the scope of EDI custom cycle, matching the engine torque profile to requirements of the drivetrain architecture) must be considered for appropriate component selection as this was beyond the scope of this study. Additionally, future changes in fuel/electricity energy cost balance would affect the optimum component selection. Therefore, there is no definite singular answer in component selection within the scope of this work, and the operating costs were based on various input parameters such as daily mileage, energy cost and component sizing.

Task 4: Project report and dataset

This report represents the final report including all study findings for this EDI CNG PHEV evaluation. It is inclusive of all study results, minus the raw dataset that was sent to EDI.

The drive cycle results demonstrate the EDI CNG PHEV fuel economy was lower when compared to the conventional diesel vehicle over all four drive cycles chosen for this study. Additionally, the exhaust emissions from the PHEV were higher than for its conventional counterpart, particularly the CO emissions where much higher. As previously mentioned, this could be a result of an exhaust leak or potentially the retrofit engine control system not functioning properly.

Additionally, this engine has been designed and optimized by GM to operate at speed over 5000 RPM while the EDI drivetrain architecture and control strategy does not operate the engine in excess of 3000 RPM. Substantial changes to the engine mechanical components (camshaft lobe profiles, valve and port sizing, etc.) would be required to optimize this engine for a duty with the EDI drivetrain.

Since the modeling and economic optimization part of this project was based on data obtained from testing a vehicle with a damaged exhaust line, the results of the optimization are also likely affected. The optimization work focused primarily on economic balance of battery pack cost and operational energy consumption costs. The suggested component size packages will have to be further reconsidered based on vehicle intended daily mileage and other factors such as minimum driving performance, operation beyond the scope of the EDI custom drive-cycle, drivetrain architecture requirements and chassis weight capacity.

Subject Inventions Listing: None

ROI #: None