Assessment of Methane Emissions – Impact of Using Natural Gas Engines in Unconventional Resource Development

FINAL TECHNICAL REPORT

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Principal Authors: Andrew C. Nix, Derek R. Johnson, Robert Heltzel, and Dakota Oliver

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Center for Alternative Fuels, Engines, and Emissions
Department of Mechanical and Aerospace Engineering
West Virginia University
271 ESB Annex, Box 6106
Morgantown, WV 26506-6106

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ABSTRACT:

Researchers at the Center for Alternative Fuels, Engines, and Emissions (CAFEE) completed a multi-year program under DE-FE0013689 entitled, "Assessing Fugitive Methane Emissions Impact Using Natural Gas Engines in Unconventional Resource Development." When drilling activity was high and industry sought to lower operating costs and reduce emissions they began investing in dual fuel and dedicated natural gas engines to power unconventional well equipment. From a review of literature we determined that the prime-movers (or major fuel consumers) of unconventional well development were the service trucks (trucking), horizontal drilling rig (drilling) engines, and hydraulic stimulation pump (fracturing) engines. Based on early findings from on-road studies we assessed that conversion of prime movers to operate on natural gas could contribute to methane emissions associated with unconventional wells. As such, we collected significant in-use activity data from service trucks and in-use activity, fuel consumption, and gaseous emissions data from drilling and fracturing engines. Our findings confirmed that conversion of the prime movers to operate as dual fuel or dedicated natural gas – created an additional source of methane emissions. While some gaseous emissions were decreased from implementation of these technologies – methane and CO_2 equivalent emissions tended to increase, especially for non-road engines. The increases were highest for dual fuel engines due to methane slip from the exhaust and engine crankcase. Dedicated natural gas engines tended to have lower exhaust methane emissions but higher CO_2 emissions due to lower efficiency. Therefore, investing in currently available natural gas technologies for prime movers will increase the greenhouse gas footprint of the unconventional well development industry.

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EXECUTIVE SUMMARY:

Due to technology developments in horizontal drilling and hydraulic stimulation, a majority of new natural gas resources are from unconventional wells. Unconventional well development is an energy intensive process and includes three prime mover categories – trucking, drilling, and fracturing engines. In an effort to reduce costs, reduce emissions, and use their own natural gas as a fuel. Industry has examined the use of dual fuel and dedicated natural gas engines. These options would replace conventional Tier 2 diesel engines, which dominate the market. Researchers at the Center for Alternative Fuels, Engines, and Emissions at West Virginia University undertook a multi-year program aimed at assessing the impacts on emissions – especially methane – associated with implementing these technologies.

Our initial goal was to collect in-use activity data to examine these implications within laboratory conditions and extrapolate to the real world. However, we worked diligently with industry leaders to obtain access to six sites across the United States, five of which were actively drilling or stimulating unconventional natural gas wells. We developed a mobile laboratory system capable of measuring engine activity, fuel consumption, and exhaust emissions during in-use activities. We collected data from six prime-mover engines. These included a simulated fracturing engine operated as diesel only and dual fuel, two in-use drilling rigs operating as diesel only and dual fuel, and one in-use fracturing engine operated as diesel only and dual fuel. In addition, we expanded our initial scope and collected in-use data from two dedicated natural gas drilling rigs. Emissions data were collected both pre- and post- aftertreatment catalysts where applicable. In addition, we collected large quantities of additional prime mover activity data, which were used with a Markov Chain Monte Carlo method to generate test cycles for use on scaled engines within laboratory environments.

Regarding diesel only operation, we found that in-use Tier 2 diesel engines typically produced regulated emissions that were at or below regulated standards. In addition, we showed that diesel only drilling rig and fracturing engines experienced the highest fuel efficiencies – ranging from 38-40%.

Regarding dual fuel engines, we saw trends that matched with literature. When operating as dual fuel, engine out emissions of CO increased significantly; however, for those engines equipped with diesel oxidation catalysts (DOCs) – CO and NMHC emissions experienced net reductions. As such, Tier 2 diesel only engines would benefit from use of DOCs even when not operated as dual fuel. We completed a measurement campaign on an early dual fuel conversion that did not include a DOC and saw CO emissions above the Tier 2 standard. The practice of using dual fuel conversions without DOCs should be avoided. In either case, dual fuel engines typically saw decreased efficiencies – ranging from 26-27%. This decrease in efficiency was due to a decrease in combustion efficiency, excessive methane slip from the exhaust, and some methane slip from the engine crankcases. Methane slip from the engine crankcases was typically only 1-2% of the fuel supplied to the engine with the bulk being from the exhaust. Total methane slip rates ranged from 14-22% of the fuel supplied to the engine. In addition to lower overall fuel efficiency, this methane slip should be included in a corrected representation of natural gas substitution rates.

Regarding dedicated natural gas engines, we were only able to obtain access for two different rigs. Both of the engines employed closed crankcase operation, which eliminated this added source of methane emissions. One of these rigs appeared to have air fuel ratio controller, oxygen sensor, or catalysts that were not operating properly. The emissions from this rig were higher than expected and above the advertised and regulated values. However, the second engine that was operating properly had regulated emissions well below the standards. In fact, due to the ability of these engines to use three-way catalysts, NO_x emissions that were nearly two orders of magnitude lower than conventional Tier 2 diesel engines. This issue may be beneficial for industry operating in areas with air quality issues. However, both natural gas engines suffered from low fuel efficiencies – ranging from 13-20%. Unlike dual fuel engines, the main contributor was not methane slip. These engines operated as rich burn, throttled engines with lower compression ratios, which contributed to lower efficiencies.

In addition, we developed an emissions inventory model that was based on our newly collected activity and emissions data along with an extensive literature review of unconventional well development activities. The model was developed to assess emissions associated with each prime mover and presented cumulative site emissions on a per well and annual basis. We examined the effects of market penetrations of these technologies from 0-100%. As expected both technologies offer reductions in diesel fuel consumption, which is attractive from a cost perspective. However, the model showed that the required natural gas increased the total energy required to develop sites – due to dual fuel and dedicated natural gas engine inefficiencies. When including all three prime movers only diesel fuel and NO_x emission tended to decrease with increasing natural gas utilization. The most dramatic increases were in total hydrocarbon emissions, which were dominated by methane for natural gas fuels. Methane emissions increased at a faster rate for dual fuel engines than dedicated natural gas engines. Additional details are included in the report below. While there are some benefits from these technologies, there are also points to consider regarding net increases in GHG emissions, best practices, and decreased efficiency.

Our findings suggest that the current versions of these technologies do offer economic incentives to industry but a complete analysis must address issues associated with natural gas fuel delivery, storage and processing, and address the cost of increased emissions. Future research should include: 1.) collecting additional data to make emissions models and inventories more robust, 2.) examining aftertreatment and engine technologies to decrease methane slip from dual fuel engines, 3.) examine methods to increase the efficiency of dedicated natural gas engines, 4.) examine in-site methods to monitor system effectiveness and emissions, and 5.) examining additional technologies that could be used to improve efficiency or offset the efficiency penalties of current technologies. Such activities could benefit from using the developed cycles and inventory data, which may allow for pre-deployment research and modeling campaigns.

REPORT DETAILS:

Prior to our experimental field and laboratory work, we conducted a literature review regarding the onsite activities and technologies options available. These reviews were conducted to fulfill the requirements of Tasks 2 and 3. A review publication was completed and published in *Energy Technology* – see Appendix A. We have included a brief summary of the findings, which were used to shape our methods for the remaining in field and laboratory research.

Based on literature we found the prime movers of unconventional well development to be the trucking, horizontal drilling, and hydraulic fracturing engines. Table 1 presents a summary of average fuel consumption by prime mover[1-3]. Note that vertical drilling rigs are similar to those used in conventional well development and saw little conversion to operate as dual fuel – therefore our focus was on the horizontal drilling and fracturing engines. In addition, the Center for Alternative Fuels, Engines, and Emissions (CAFEE) at West Virginia University (WVU) had already collected significant emissions data for on-road dual fuel and dedicated natural gas engines – so our focus was to only collect activity data from those engines.

Table 1: Fuel Consumption per Well by Prime Movers[4].

Prime Mover	Trucking	Vertical Drilling	Horizontal Drilling	Hydraulic Fracturing
Fuel Consumption (gallons per well)	4,787	13,440	61,434	21,000

We identified that there were multiple aftermarket conversion kits for pre- and post-2010 heavy-duty diesel engines used in over-the-road trucks. In addition, industry is now producing two dedicated natural gas engines – the Cummins-Westport 8.9L and 11.9L[5,6]. These engines operated on compressed natural gas (CNG) or liquefied natural gas (LNG). These engines operated stoichiometrically and included exhaust gas recirculation and threeway catalysts (TWCs) to reduce emissions. For drilling engines, there were also multiple dual fuel conversion kits available including those from Caterpillar and Altronics-GTI among others[7,8]. Dedicated natural gas drilling engines were available and included both lean burn and rich burn options[9,10]. Dual fuel conversions were also available from multiple companies for fracturing engines and we focused on those from Caterpillar and Cummins/ComAP[11,12]. There has been even more limited investment in dedicated natural gas fracturing fleets – likely due to fuel requirements and logistics – therefore we excluded these from our study. Older reports estimated that 4-6% of drilling rigs operated as dual fuel with only 2% having the capability of using dedicated natural gas engines[13-15]. The numbers were even lower for fracturing engines (3% for dual fuel and less than 1% for dedicated natural gas[11].

Though the level of market penetrations was low – we saw that numerous industry operators had examined or deployed such technologies. These companies included but were not limited to: Cabot[16], Scandrill[17], Precision[17], EQT[18], Noble Energy[19], Apache[20], CONSOL Energy[20], Anadarko[17], Southwestern Energy[17], Ensign[17], Patterson[17], Halliburton[17,19], Baker Hughes[19], Schlumberger[21], Chesapeake Energy[22], and Antero Resources[17].

Based on our literature reviews and prior experience with on-road engines we developed the capabilities to collect engine activity data, fuel consumption data (both diesel and natural gas), exhaust emissions, and crankcase emissions. Literature on in-use drilling and fracturing engines was very limited. Our focus also included the capability to distinguish differences in methane (CH_4) emissions as opposed to regulated non-methane hydrocarbon (NMHC) emissions. The following sections discuss in more detail the experimental methods that were required to collect these data.

Experimental Methods:

Activity Data

Initially we focused on the collection of in-use activity data from the prime movers. To collect on-road data we deployed a series of J1939 Mini Loggers™ from HEM Data on fleets operating in the greater Marcellus Shale region. These data loggers were capable of recoding J1708 or J1939 engine parameters along with vehicle speed and position from internal GPS units. We solicited regional service companies and provided them with a brief overview of the study goals. No service companies received any payment for participation in the study. In total, 1,296 hours of in-use trucking activity were collected from 13 trucks equipped with varying model year engines and certification levels. Table 2 includes a summary of the engines from this data collection campaign and includes their certification emissions. Figure 1 presents an example of truck routes within the Marcellus and Utica region.

***Table 2: Engine Information for Trucking Data Colletion*[23].**

	Model	Year	BSFC (NG)	BSFC (Diesel)	CO_2	CO	NO_x	THC	CH_4
			g/ kw-hr	g/ kw-hr	g/ kw-hr	g/ kw-hr	g/ kw-hr	g/ kw-hr	g/ kw-hr
Engine 11	**ISX15**	**2005**	0.00	209.7	815.3	2.95	1.34	1.21	0.01
Engine 12	**ISX15**	**2008**	0.00	223.7	765.7	2.55	0.10	1.21	0.01
Engine 13	**ISX15**	**2009**	0.00	224.5	852.9	1.48	0.27	1.21	0.01
Engine 14	**ISX15**	**2010**	0.00	227.4	836.8	1.48	2.28	0.24	0.00
Engine 15	**ISX15**	**2011**	0.00	223.4	823.4	1.48	1.34	0.23	0.00
Engine 16	**ISX15**	**2012**	0.00	218.1	836.8	1.34	0.27	0.23	0.00
Engine 17	**ISX15**	**2013**	0.00	199.3	836.8	1.48	0.30	0.23	0.00
Engine 18	**C15**	**2006**	0.00	223.2	745.6	3.22	2.15	0.94	0.00
Engine 19	**C15**	**2009**	0.00	223.2	745.6	1.21	2.01	1.21	0.01
Engine 20	**C15**	**2010**	0.00	237.8	745.6	1.21	1.61	3.49	0.02
Engine 21	**D13**	**2002**	0.00	212.3	681.2	1.00	1.74	3.35	0.02
Engine 22	**D13**	**2012**	0.00	212.3	681.2	1.00	0.16	3.35	0.02
Engine 23	**MP8**	**2011**	0.00	210.5	794.7	1.78	1.12	0.16	0.00

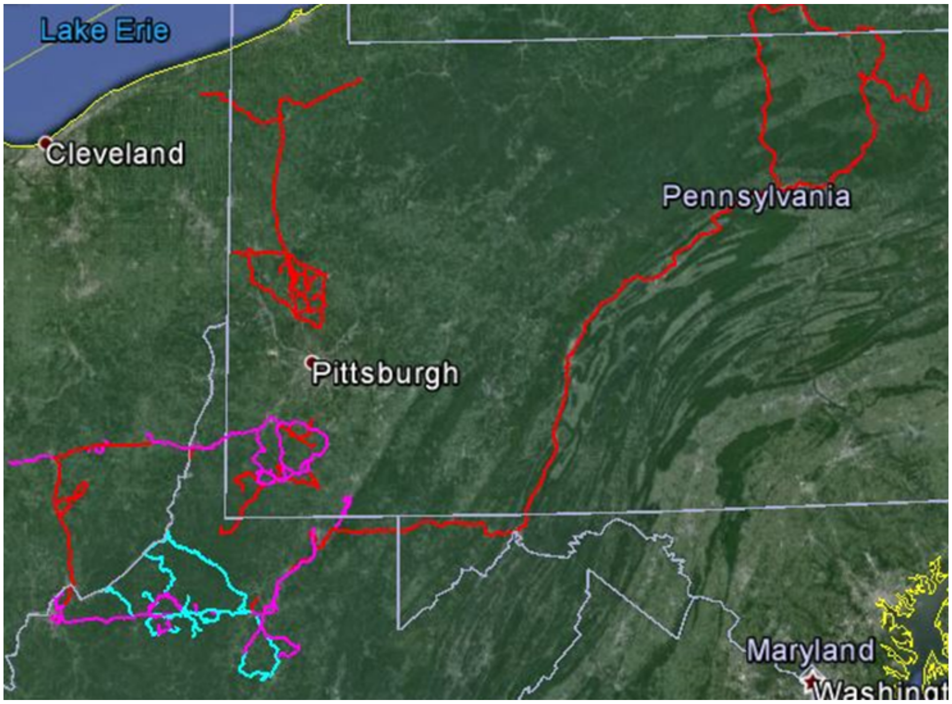

Figure 1: Examples of various trucking routes in red, white, and blue – across the greater Marcellus and Utica region.

Alternative approaches were used to collect engine activity data from drilling and hydraulic fracturing engines. For diesel only and dual fuel engines, a Vehicle Interface Adapter (VIA) from B+B SmartWorx was connected to the engine communications port and a laptop. Engine speed and load were the targeted messages though others that were publicly broadcast over J1939 were collected. Data were collected and processed with in-house software. For dedicated natural gas engines – the data collection computer was wired directly into the MODBUS communications port on the engine panel. Researchers collaborated with the engine operator to ensure proper connectivity and processing of the engine messages. Using these data collection methods over 66 hours of activity data were collected from hydraulic fracturing engines across the Marcellus and 234 hours of drilling activity data were collected across the Marcellus, Permian, and Haynesville plays. In addition, many of these activity data were collected in conjunction with fuel and emissions data.

Fuel Consumption Data

Engine and conversion kit manufacturers typically provide data regarding their diesel fuel consumption based on certification data or natural gas substitution rates. However, in-use engines operate differently than steady-state emissions certification so we deployed fuel meters to accurately account for fuel (energy) supplied to diesel, dual fuel, and dedicated natural gas engines. To collected diesel fuel consumption we deployed KRAL OME20 and OME 32 flowmeters. These were positive displacement meters using low resistance turbine screw meters. Each system included a supply and return meter. Measuring diesel fuel consumption accurately can be difficult due to the differencing of two similar numbers that may be low or high. However, each meter has an accuracy of 0.1% and included temperature correction. Therefore, when temperature, density, pressure, and each meters uncertainty were accounted for – the net uncertainty of fuel consumption measurements was ±2%. Figure 2 shows an example of the return meter attached on the return line of a diesel drilling engine.

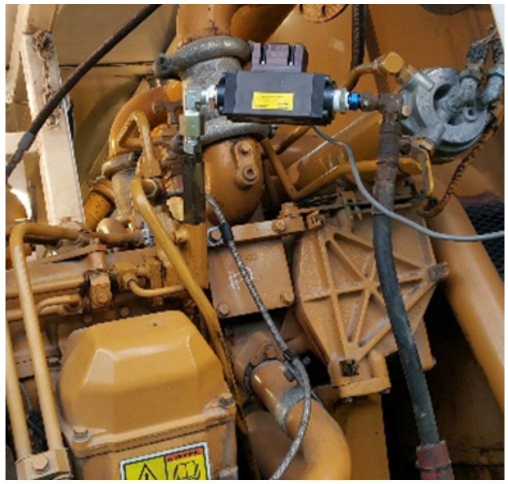

Figure 2: Return line KRAL flowmeter installed during rig move.

To measure natural gas consumption, we deployed a KURZ™ MFT-B thermal mass flow meter capable of measuring 0-252 standard cubic feet per minute (SCFM) of natural gas. The flow meter was calibrated on pure CH_4 and gas composition data were collected for density corrections. The accuracy of the natural gas flow meter also depended on composition and temperature, but under in-use conditions, accuracy was also on the order of ±2%.

Exhaust Emissions Data

We worked collaboratively with industry to develop a small emissions measurement trailer that was deployed at six sites across the United States (US). Note that drilling and fracturing operators did not receive payment for participation in this study. We deployed a small trailer, which housed all emissions measurement analyzers, electrical communications equipment, and data collection computers. Figure 3 shows an example of the trailer during in-use data collection. One site was a hydraulic fracturing test facility where a dual fuel, fracturing engines were commissioned. Ten hours of fuel consumption and emissions data were collected across common engine operating load points. In addition, 24 hours of fuel consumption and emissions data were collected from in-use fracturing engines in the Marcellus and 112 hours of in-use drilling fuel consumption and emissions data were collected in the Marcellus, Permian, and Haynesville plays.

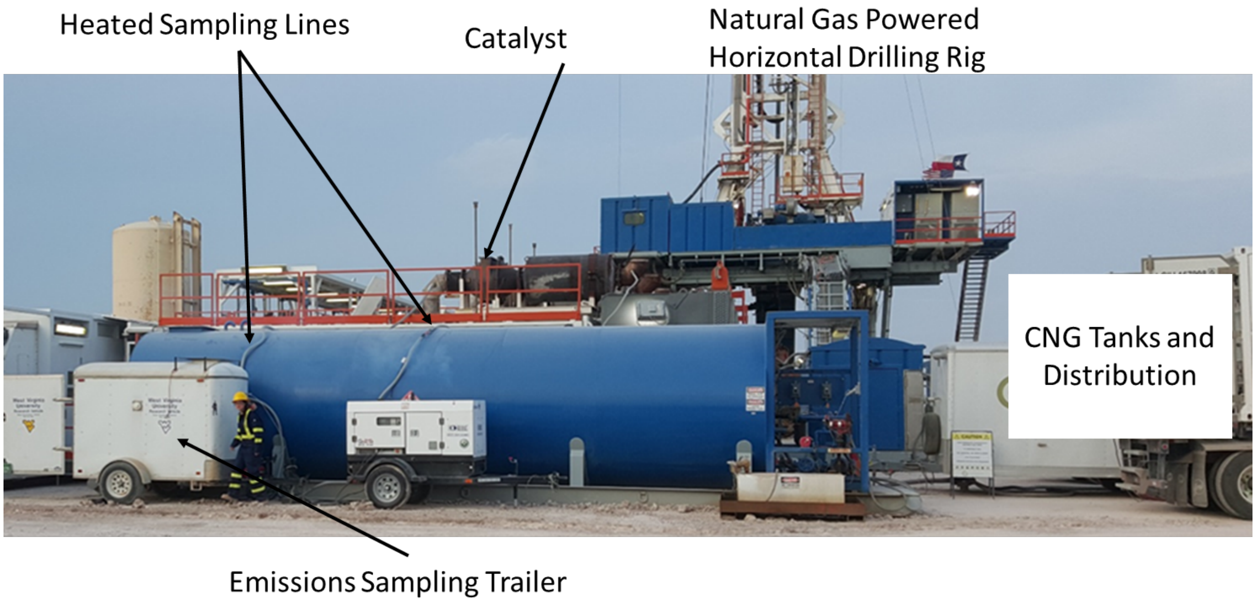

Figure 3: Emissions trailer and equipment deployed to assess fuel efficiency and emissions from a drilling rig powered by three dedicated natural gas engines.

During our initial deployment at the hydraulic fracturing test facility, emissions were measured with a SEMTECH®-DS and a California Analytical heated flame ionization detector. The SEMTECH-DS measured CO, CO_2, THC, and NO_x emissions. The California Analytical analyzer measured CH_4 emissions. This method required the use of multiple onsite calibration bottles and was determined to be too cumbersome for in-use deployment. Modifications were made to the emissions collection system for the five remaining field campaigns. Emissions were subsequently measured with a MKS Multigas™ 2030 Fourier Transform Infrared (FTIR) analyzer. This method required only ultra-high purity compressed nitrogen and liquefied nitrogen. In both cases, emissions were sampled via heated lines and filters that were connected to the engine exhausts. Where applicable ports were welded during rig moves so that emissions could be assessed before and after aftertreatment catalysts. For dual fuel engines, data were collected in diesel only and dual fuel modes.

Crankcase Emissions Data

Based on other research campaigns, we knew that engine crankcase vents might be open to the atmosphere and serve as an additional source of CH_4 emissions for dual fuel and dedicated natural gas engines. All dual fuel engines operated with open crankcases but the dedicated natural gas drilling engines utilized closed crankcase ventilation systems. To quantify the CO_2 and CH_4 emissions from open crankcases we deployed a full flow sampler (FFS). Details on its operation are found in literature[24]. The system used an explosion proof flower that was capable of capturing the entire crankcase effluent stream from an engine being tested plus dilution air. The total sample flowrate was measured with a calibrated mass airflow sensor. An Ultraportable Greenhouse Gas Analyzer (UGGA) from Los Gatos Research was used to measure the concentrations of CO_2 and CH_4. Together with flow rate, mass emissions were calculated.

Table 3 presents a summary of the six field campaigns. Engine specifications are provided along with fuel source. In some cases, CNG was used as the fuel, in other cases engines were fueled with field gas (FG) from nearby wells or pipelines. Note that drilling activity was separated into two distinct modes of operation – higher load steady-state operation (SS) and lower load transient operation (LLT).

Table 3: Campaign specifications for in-field data collection efforts[25].

Campaign	Activity	Engine Activity Type	Engine Make	Engine Model	Rated Speed (rpm)	Rated Power (kW)	CR	Average Load (%)	Average Power (kW)	Combustion Type	Dual-Fuel Kit	Modes Sampled	Fuel
1	Hydraulic Fracturing	SS	Cummins	QSK50	1900	1678	15:1	71	1189	CI	ComAP	DO	Diesel
												DF	CNG+Diesel
2	Drilling	SS	Caterpillar	3512C	1200	1101	13:1	55	613	CI	Caterpillar	DO	Diesel
		LLT						23	267			DF	FG+Diesel
3	Hydraulic Fracturing	SS	Caterpillar	3512B-HD	1800	1678	14:1	76	1292	CI	Caterpillar	DO	Diesel
												DF	FG+Diesel
4	Drilling	SS	Caterpillar	3512C	1200	1101	13:1	47	544	CI	Altronic GTI	DO	Diesel
		LLT						18	220			DF	FG+Diesel
5	Drilling	SS	Waukesha	L7044GSI	1200	1253	8:1	55	677	SI	N/A	DNG	CNG
		LLT						14	171				
6	Drilling	SS	Waukesha	L7044GSI	1200	1253	8:1	56	725	SI	N/A	DNG	FG
		LLT						21	308				

Cycle Development Methodology

An objective of collecting in-use data was to understand better the real world behavior of the prime movers. We used these data to create a thirty-minute engine test cycle based on speed and load. Development of representative tests allowed us to conduct scaled testing within a laboratory environment to evaluate the effects of fuel quality on emissions. In addition, these cycles can be used by future researchers that seek to develop and evaluate technologies that can be deployed in the unconventional well development field. A detailed analysis of the cycle development is include in an article published in the *Journal of the Air and Waste Management Association* – see Appendix B. A brief overview of the methodology follows.

Engine activity data collection was discussed early. The primary engine parameters recorded were speed and load. Data were collected and processed at 1 Hz. Data were then filtered to remove anomalies and processed based on minimum speed and load requirements. With the processed data, we employed a Markov Chain, Monte Carlo (MCMC) method to create a large population of possible cycles. MCMC methods have been deployed in the development of engine and vehicle test cycles[26-29]. Our method used one-second concatenation and transition probability matrices defined by the statistics of the collected data. Both speed and load were normalized to values between zero and 1. A total of 10,000 possible cycles were created for each prime mover. Each cycle was 1800 seconds in length – which was recommended by others[30].

With the cycle generation completed, we used a performance value (PV) (which was the sum of a statistical value and distribution value) to analyze how well the cycles represented the in-use data statistics. Such statistics included average speed, average load, average non-idle speed, normalized idle time, and other parameters. PV values ranged from zero to one with zero being a perfect match. The PV values of trucking, drilling, and fracturing cycles were 0.0327, 0.0038, and 0.0323, respectively.

To further improve the PV values we implemented a genetic algorithm (GA) on one hundred sample cycles of the 10,000 population. GAs are used to mimic the survival of the fittest qualities of a population and have been used in cycle development[31-33]. The GA used both elitist and roulette wheel selections. A sensitivity analysis showed that the GA had converged at the 50th generation and used genetic operation rates of 40% for crossover and 20% for mutation. The GA improved the PVs for trucking, drilling, and fracturing by 18, 62, and 65%, respectively. Additionally, multiple smoothing techniques were used on the trucking cycle to meet cycle regression criteria on an engine within the laboratory. A Savitsky-Golay method provided the best results. The final normalized cycles are included within the JAWMA article. These cycles were used to test a dedicated natural gas engine within the Engines and Emissions Research Laboratory at WVU.

Fuel Quality Methods

To assess cycle generation and fuel quality, we used a scaled dedicated natural gas engine. The test engine was an 8.9L Cummins-Westport ISL-G. This engine is commonly used in the trucking sector and also used technologies similar to the dedicated natural gas drilling engines tested in the field. Table 4 presents engine specifications. The engine was operated on three fuel blends, which represented conventional CNG and two blends that included higher concentration of ethane (E12) and propane (P5) – which may be experienced when using field gas. Table 5 presents specifications on the fuel blends.

Table 4: ISL-G Engine Specifications[34].

Specification	Value	Unit
Horsepower	208.8	kW
Peak Torque	1220	N-m
Governed Speed	2200	rpm
Ignition	Spark	
Arrangement	Inline - 6 Cylinder	
Intake	Turbocharged	
Displacement	8.9	L
Bore	11.4	cm
Stroke	14.5	cm
Oil Capacity	29.2	quarts
Coolant Capacity	13.1	quarts
System Voltage	12	V
Aftertreatment	TWC	
Fuel Used	CNG	

Table 5: Fuel composition for CNG, the high propane blend (P5) and the high ethane blend (E12). Note that Cummins does not recommend using fuels with a methane number of less than 75, so our blends were limited by this requirement[34].

Component	P5	E12	CNG
CH_4 (%)	86.3	86.0	95.0
C_2H_6 (%)	2.6	12.0	3.2
C_3H_8 (%)	5.2	1.0	00.6
N_2 (%)	1.5	0.5	0.5
CO_2 (%)	4.4	0.5	0.3
MN (-)	75.5	75.3	85.2
HHV (MJ/kg)	49.21	53.63	54.33
Wobbe (MJ/m3)	39.24	41.40	39.14
H/C	3.67	3.83	3.92

The engine and aftertreatment system were installed on a 500 HP AC dynamometer as shown in Figure 4. The exhaust emissions were ducted to a CFR Part 1065 compliant dilution tunnel and constant volume sampling system that used a MEXA 7200 D emissions analyzer. Crankcase emissions were measured with an FFS. The engine was tested using CNG for the three developed cycles, the FTP transient cycle, and the D-2 steady-state cycle. The Federal Test Procedure (FTP) cycle was selected to compare how the developed trucking cycle compared with the certification cycle. The D-2 cycle is used for certification of drilling and fracturing engines and was compared with those cycles, respectively. In addition, the newly developed cycles were repeated with the additional fuel blends to assess impacts of fuel quality. Figures 5 to 8 show the transient cycles and Table 6 presents the test points of the D-2 cycle.

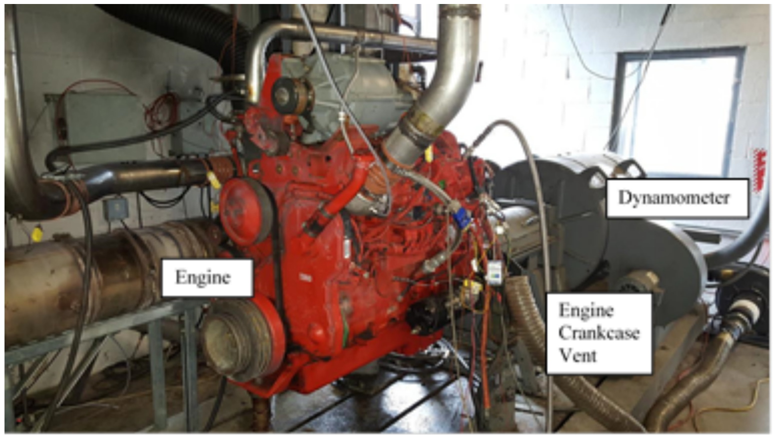

Figure 4: Dedicated natural gas engine setup for laboratory research[34].

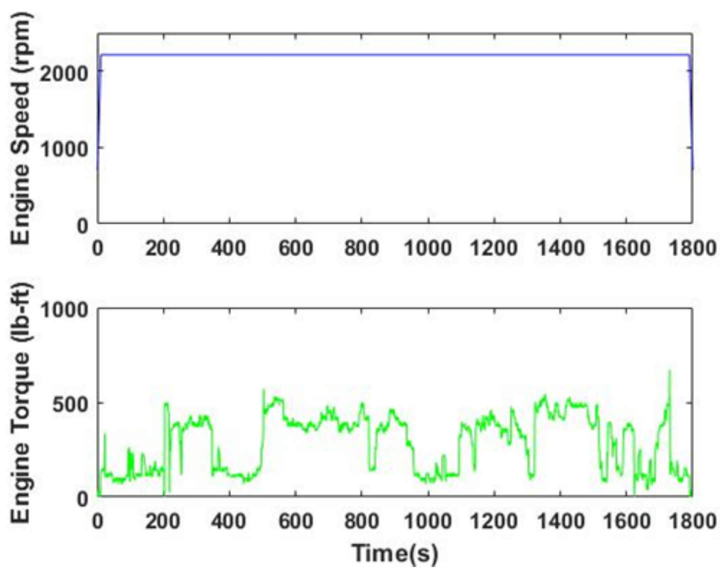

Figure 5: Denormalized engine speed and load for the drilling cycle. Note - in-use drilling engines were operated at a constant rated speed with variable load[34].

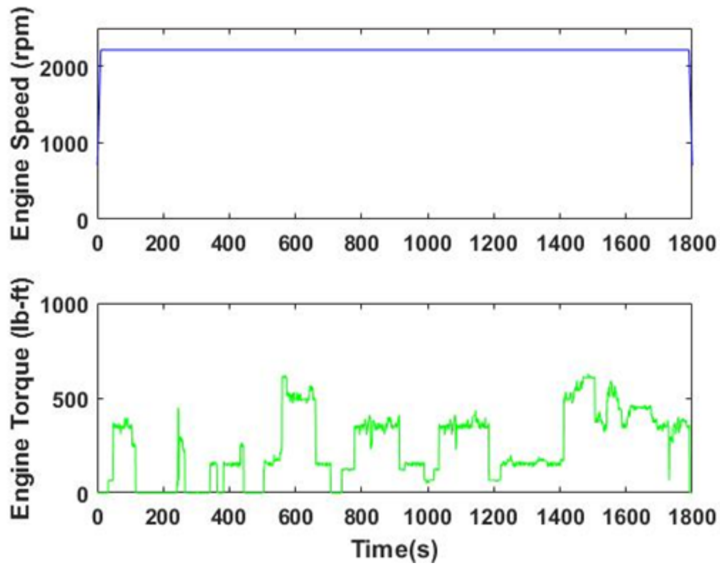

Figure 6: Normalized engine speed and load for the fracturing cycle. Note - in-use fracturing engines were operated at a constant rated speed with variable load[34].

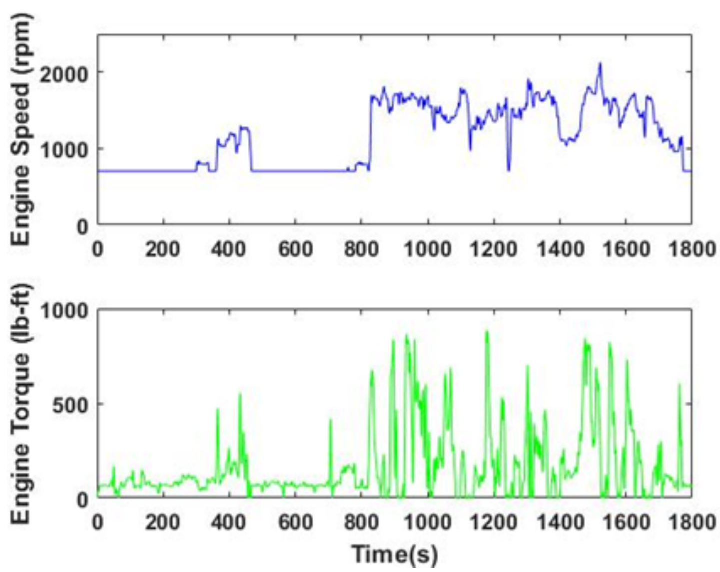

Figure 7: Normalized engine speed and load for the OTR truck cycle. Note - in-use truck engines were operated at a variable speed and load[34].

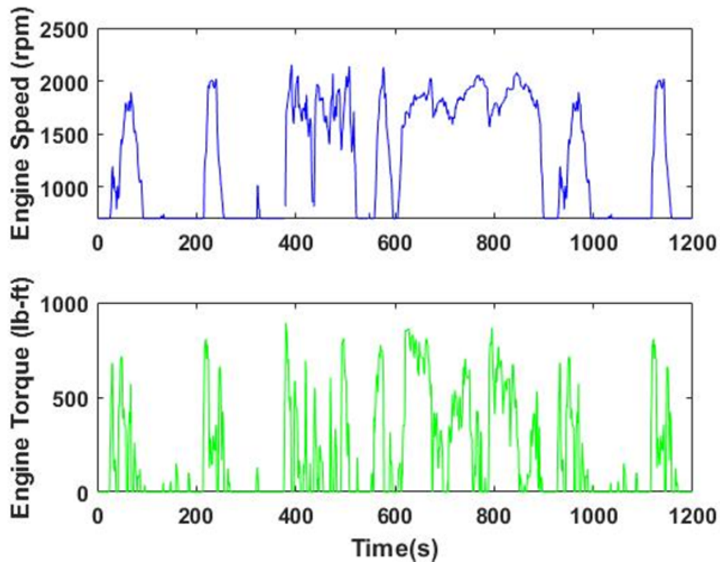

Figure 8: Denormalized engine speed and torque for the heavy-duty FTP transient cycle[36].

Table 6: Speed and torque set points for the D-2 cycle[34].

Mode	1	2	3	4	5
Torque (%)	100	75	50	25	10
Torque (N-m)	852	677	451	226	90
Power (kW)	198	157	105	52	21
Speed (rpm)	Rated Speed - 2215				
D-2 Weighting Factors	0.05	0.25	0.3	0.3	0.10

Inventory Methods

One of the last major goals of the project was to use data collected from field campaigns to develop an emissions inventory to estimate per well and national emissions from currently available technologies. We used activity and emissions data collected from in-field diesel, dual fuel, and dedicated natural gas engines to develop emission factors and activity factors. We developed activity factors for the trucking industry and used their various emissions certifications to calculate their contribution. For dual fuel and dedicated natural gas engines – we used recently collected data from other WVU projects. Figure 9 shows an overall schematic of the inventory model.

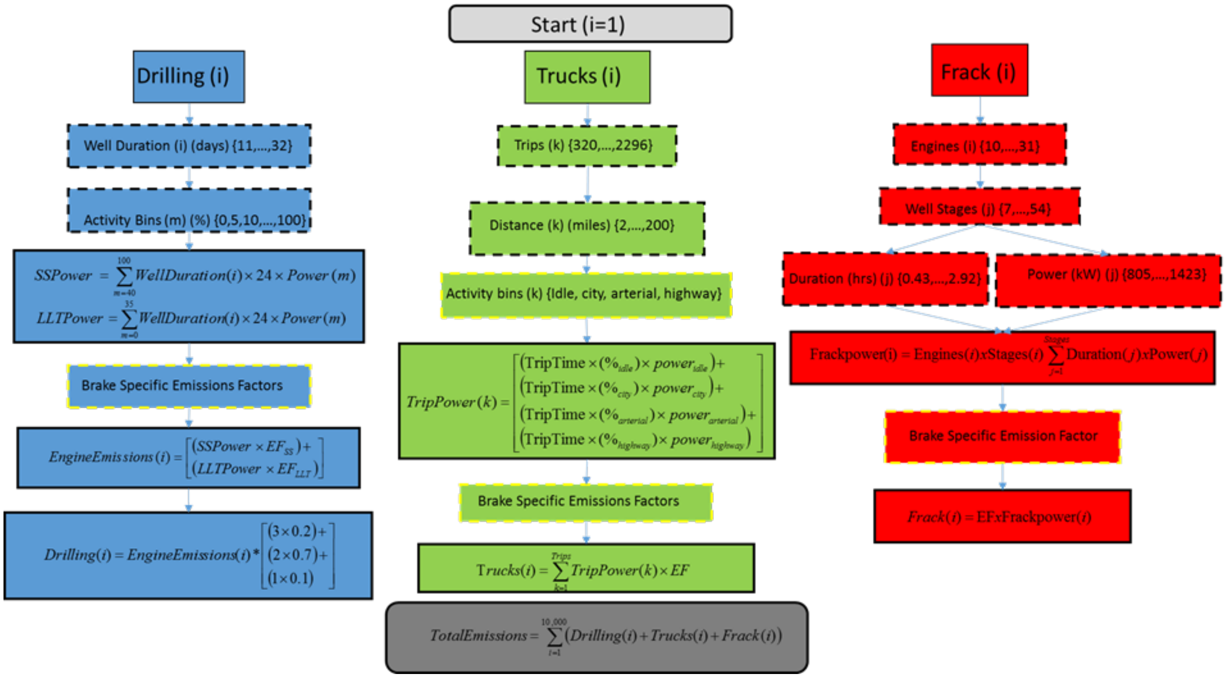

Figure 9: Overall hierarchy for the emissions inventory model[20].

We reviewed literature to obtain additional data on trucking[35-47], drilling[47-52], and hydraulic fracturing[52-55] activity from across the US. The model combined our new data with literature trends to develop an initial population of 200,000 diesel only wells. This value was selected based on a convergence analysis with populations from 1x101 to 5.5x105 wells. In addition, a population of 200,000 duel fuel and dedicated natural gas wells were produced. Note that in the case of hydraulic fracturing – dual fuel data were used for both scenarios since no in-field data or literature data were available for dedicated natural gas fracturing fleets.

In addition to these scenarios, we examined the impacts on fuel consumption and emissions as a function of market penetration for each of the technologies. Data were analysed on a per well basis and for an average year. The number of wells drilled and completed in years 2014, 2015, and 2016 were, 18,664, 11,536 and 6774, respectively[56]. Therefore, we selected an annual population of 12,325 to represent an average of the last three years. To assess annual variability we generated 20 different average year cases. Additional model details are presented in a just accepted manuscript to *Environmental Science and Technology* – see Appendix C.

Results and Discussion:

Following are the key results from both in-field research and laboratory research. Results and discussion are broken down into four major categories.

Regulated Emissions

Detailed results and discussion of regulated gaseous emission from the prime movers are presented in the article published in the *Journal of Pollution Effects and Control* – see Appendix D. Regulated emissions include NMHC+NOx and CO emissions. Emissions were collected from six different drilling and fracturing engines. We collected pre- and post- diesel oxidation catalyst (DOC) emissions from a Tier 2 diesel engine that operated as dual fuel and diesel only. The second drilling engine did not include a DOC but data were collected in both diesel only and dual fuel modes. Pre- and post-catalyst emissions data were collected for two different hydraulic fracturing engines which both operated as diesel only and dual fuel. Pre- and post- catalyst emissions data were also collected for two dedicated natural gas engines. Please refer to Table 3 for additional engine and test configuration details. We compared the in-use regulated emissions with the standards for Tier 2 Compression Ignited (CI) and Tier 2 Spark Ignited (SI) engines.

Table 7 presents the average NMHC+NOx and CO emission from drilling and fracturing engines operating as diesel only. For comparison with Tier 2 – only data collected before added DOCs are presented. The Tier 2 standard for CO emissions for CI engines is 1.5 g/kW-hr while NMHC+NOx is 6.4 g/kW-hr. Note that in all cases of diesel only operation, the in-use emissions were well below the standards even during the LLT operation of drilling engines 2 and 4. Note engine numbers align with those reported in Table 3.

Table 7: Regulated emissions results for Tier 2 CI drilling and fracturing engines. Both the average (ave.) and standard deviations (std.) are presented. Also for reference, average engine load data are presented[57].

		2 SS		4 SS		1 SS		3 SS		2 LLT		4 LLT	
		Ave.	**Std.**	**Ave.**	**Std.**	**Ave.**	**Std.**	**Ave.**	**Std.**	**Ave.**	**Std.**	**Ave.**	**Std.**
Load	**(%)**	55.7	0.97	49.4	2.17	70.8	13.7	77.0	12.3	24.3	1.99	20.0	1.12
CO	**(g/kW-hr)**	1.18	0.09	1.38	0.08	1.18	0.07	0.65	0.04	2.23	0.14	1.59	0.12
NO_x	**(g/kW-hr)**	3.56	0.17	3.53	0.08	5.97	0.22	3.21	0.23	3.74	0.49	2.87	0.27
NMHC + NO_x	**(g/kW-hr)**	3.57	0.17	3.54	0.08	6.12	0.28	3.23	0.23	3.77	0.49	2.90	0.27

Table 8 presents the regulated emissions for these four engines when operated in dual fuel mode. For these data, emissions were collected after the catalyst where applicable. Note that engine 4 was a drilling engine that was converted to operate as dual fuel years ago and did not include a DOC. DOCs are typically deployed on these engines so that emissions standards for CO are not exceeded. It is clear to see that the black italicized entries for CO are well above the standard by nearly an order of magnitude. These data also show that NMHC+NOx emissions were also above the standard of 6.4 g/kW-hr though to a lesser extent than the CO emissions. While a DOC could be installed to reduce CO emissions, DOCs have little effect on NO_x emissions[58,59] but can reduce NMHC[60-62]. However, this conversion exceed the combined threshold with NO_x alone which likely means that the dual fuel conversion kit would require reprogramming to reduce the natural gas substitution rate in order to decrease in-cylinder temperatures and NO_x emissions.

Table 8: Regulated emissions results for Tier 2 CI drilling and fracturing engines while operating as dual fuel. Both the average (ave.) and standard deviations (std.) are presented. Also for reference, average engine load data is presented[57].

		2 SS		4 SS		1 SS		3 SS		2 LLT		4 LLT	
		Ave.	**Std.**	**Ave.**	**Std.**	**Ave.**	**Std.**	**Ave.**	**Std.**	**Ave.**	**Std.**	**Ave.**	**Std.**
Load	**(%)**	54.6	1.88	43.6	0.56	71.6	12.3	74.8	10.4	22.2	1.75	16.4	1.71
CO	**(g/kW-hr)**	0.14	0.01	***12.78***	0.16	0.60	0.04	0.57	0.03	0.08	0.02	***12.24***	2.99
NOx	**(g/kW-hr)**	3.02	0.08	***6.52***	0.13	3.83	0.50	3.17	0.51	4.13	0.35	***8.03***	0.47
NMHC + NOx	**(g/kW-hr)**	3.40	0.20	***6.62***	0.13	3.83	0.50	4.02	0.90	4.39	0.37	***8.11***	0.49

Table 9 presents a summary of the regulated emissions for the SI or dedicated natural gas engines. The Tier 2 standards and advertised emissions values are included. Note that for SI engines the NMHC+NOx emissions standard is lower than CI standards while the CO standards are higher. SI engines can also use a combined emission criteria based on Equation 1.

$$(HC + NOx) * (CO)^{0.784} \leq 8.57 \qquad (1)$$

Our data set is small but we see that one of the dedicated natural gas engines was significantly exceeding the emissions standards for both methods. However, the properly operating engine and catalyst of campaign six had emissions that were well below the individual and combined standards. We examined additional data catalyst efficiency data to examine what the cause could be for the excessive emissions from the engines of Campaign 5. A catalyst efficiency paper is currently under review for publication in the *SAE International Journal of Engines* – see Appendix E.

Table 9: Regulated emissions results for Tier 2 SI dedicated natural gas drilling engines[25].

Campaign #	**Fuel**	**Operation Type**	**Emissions (g/kW-hr)**		**Value from Equation 1**
			$NMHC+NO_x$	**CO**	
5	**CNG**	**SS**	3.28	43.64	***63.37***
		LLT	2.99	86.62	***98.65***
6	**Field Gas**	**SS**	0.07	1.50	0.10
		LLT	0.06	2.89	0.13
Standard	**N/A**		0.80	20.60	8.57
Advertised			0.94	1.61	1.37

As a part of the additional catalyst efficiency analysis, we found two key findings. Firstly, for engines that were converted to operate as dual fuel and included a DOC, there were emissions benefits even when not operating in dual fuel mode. Therefore, Tier 2 diesel engines could be retrofitted with DOCs to reduce NMHC and CO Emissions. We examined both pre- and post-catalyst data when engines operated in diesel only mode. Data shows that engine out CO emissions can be reduced by 48 to 99% while engine out NMHC emissions can be reduced by 44 to 100% - dependent upon operating conditions. While DOCs were able to reduce NMHC emissions, when operating as dual fuel, THC emissions were dominated by CH_4 (>90%) which is not easily oxidized. Additional information on greenhouse gas (GHG) emissions is discussed later.

Secondly, we saw that for properly operating dedicated natural gas engines with TWCs were effective in reducing NMHC, CO, and NO_x. Conversion efficiencies ranged from 90-100% for all species. In addition, due to the high exhaust gas temperatures (>600 °C) the properly operating catalyst and engine showed reductions in CH_4 by 44%. Upon discussions with the operator, it was determined that the catalyst of campaign six underwent regular maintenance. In addition, we saw that the lambda sensor of the "good" system varied significantly with load changes while the lambda sensor of the "bad" system did not. This may suggest that there is an issue with the air fuel ratio control system for the engines of campaign five or a possible issue with the lambda sensor itself.

Fuel Consumption and Greenhouse Gas Emissions

Natural gas is often touted as a low carbon fuel, especially when compared to diesel fuel. Therefore, the displacement of diesel fuel with natural gas should lead to a lower carbon footprint due to a reduction in GHG emissions of CO_2. However, there are two major downfalls associated with its use as a fuel for the prime movers. Firstly, when used as a fuel for dual fuel options CH_4 slip occurs within the exhaust and engine crankcase. Since CH_4 is a potent GHG, it can cause a significant increase in CO_2 equivalent emissions. The Environmental Protection Agency currently assigns CH_4 a global warming potential of 25, which aligns with older values presented by the International Panel on Climate Change[63]. For our analysis, we used this value. Secondly, when dedicated natural gas engines are used, CH_4 emissions were lower but since these engines were rich burn, throttled, and used lower compression ratios - they achieved lower overall efficiencies, which contributed to increased CO_2 emissions. Additional details on fuel consumption and GHG emission were published in an article in *Applied Energy* – see Appendix F.

Regarding dual fuel engines, natural gas is substituted within the engine intake, which reduces the demanded diesel fuel flow rate. The ratio of displacement can be presented in multiple ways. Table 10 presents the results from three methods. The first method is based on the energy provided by both fuels and this method yields the highest results, which are often presented by industry. However, due to the CH_4 slip in the exhaust and crankcase, the useful natural gas is lower than that provided to the engine. Method 2 accounts for the CH_4 losses and presents more realistic substitution rates. An alternative approach is to compare the diesel fuel consumption rates at similar load points when the engine is operated in both modes.

Table 10: Various methods of calculated a natural gas substitution rate[64].

Method	Definition	Campaign –SS Operation			
		1	2	3	4
(1) Industry	$\frac{NG\ Power\ In}{Total\ Fuel\ Power\ In}$	67%	76%	72%	65%
(2) Corrected	$\frac{(NG\ Power\ In - CH_4\ Loss)}{Total\ Fuel\ Power\ In}$	54%	66%	58%	56%
(3) Brake-Specific Fueling	$1 - \frac{DF\ Diesel\ Fuel\ Rate}{DO\ Diesel\ Fuel\ Rate}$	51%	64%	57%	54%

The second method accounts for the CH_4 slip. Typically, CH_4 slip is dominated by the exhaust portion while the crankcase emissions are usually only around 1-2% of the fuel delivered to the engine. Figure 10 shows that the combined CH_4 slip ranged from 14 to 22% of the natural gas supplied to the dual fuel engine.

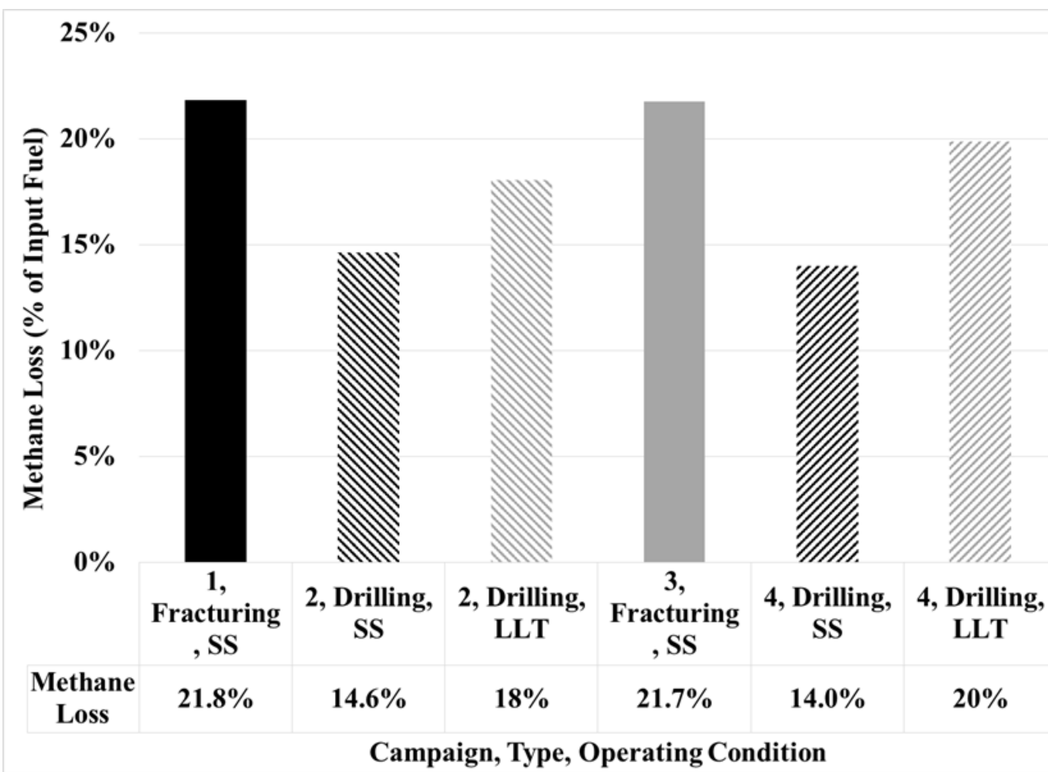

Figure 10: Methane slip from dual fuel engines as a percentage of fuel supplied to the engines[64].

When accounting for the CH_4 slip of dual fuel engines and the lower efficiency of natural gas engines we showed that overall efficiency decreased. Figure 11 shows that diesel efficiency is on the order of 40% but is reduced to around 26% by converting engines to dual fuel. Dedicated natural gas engines had the lowest efficiency ranging from 13-20%. Figure 12 shows the trends for GHG emissions. Even though the dedicated natural gas engines had the lowest efficiency, their CO_2 equivalent emissions were lower than dual fuel engines because they had lower CH_4 slip. Therefore, these technologies do not offer reductions in either CO_2 or CO_2 equivalent emissions or overall improvements in efficiency. However, from a fuel cost perspective they still offer fuel cost reductions even with lower efficiencies.

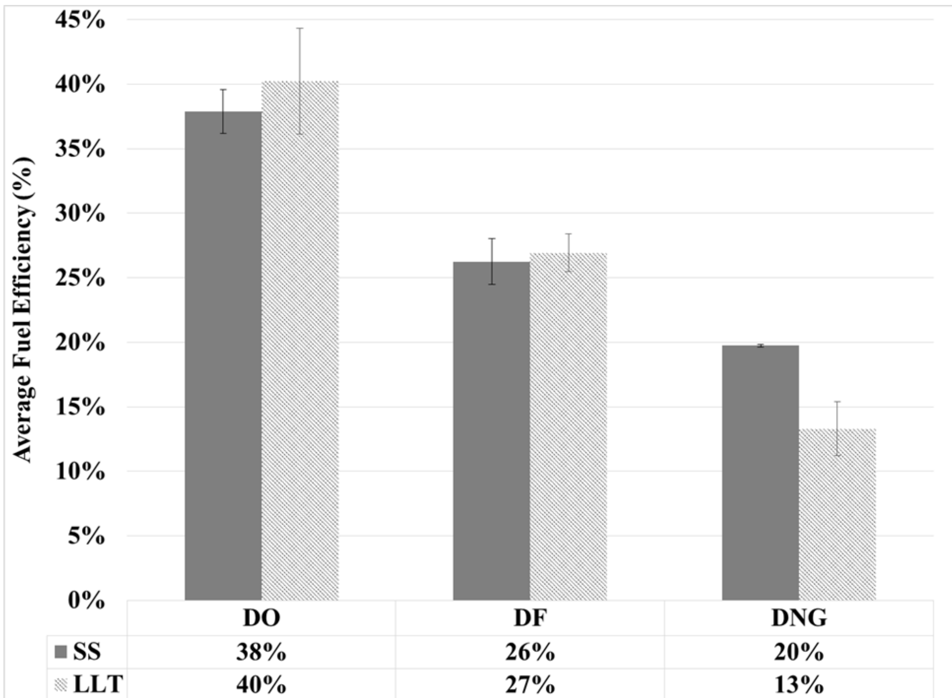

Figure 11: Impact of technologies on fuel efficiency[64].

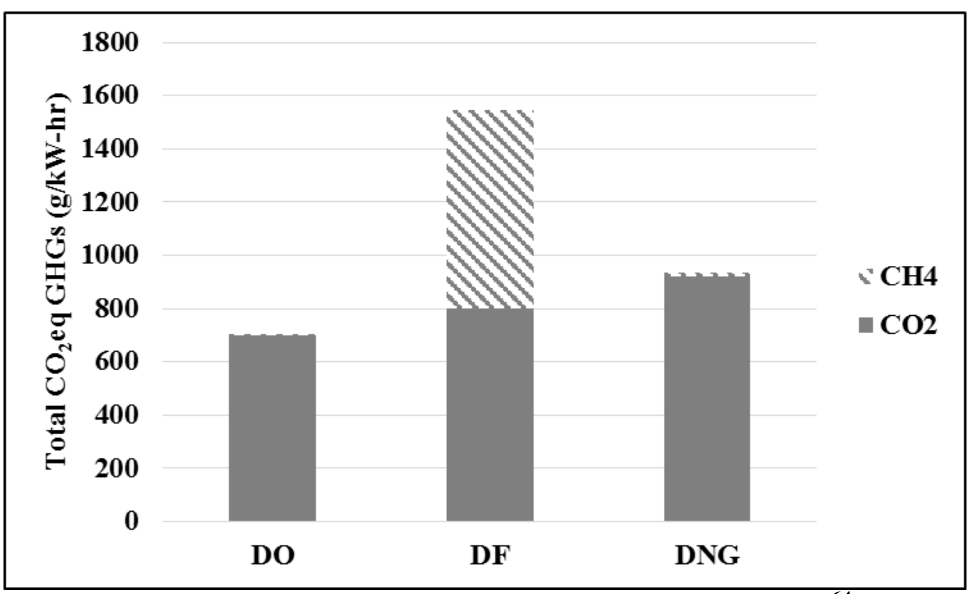

Figure 12: Impact of technologies on GHG emissions[64].

Laboratory Results

We conducted laboratory testing on an 8.9L dedicated natural gas engine to evaluate the differences between certification cycles and newly developed real world cycles and to evaluate the effects of fuel quality on emissions. Table 11 includes the results for the comparison of the trucking cycle and the FTP cycle and the results for comparison between the D-2 cycle and the drilling and fracturing cycles. For these comparisons, the engine used standard CNG. As discussed in the field result section, both diesel and dedicated natural gas engines that were properly operating yielded lower in-use emissions compared to the certification standards. We see that the trucking cycle consumed more fuel and therefore yielded higher CO_2 emissions, the same was true for both CO and NO_x. However, the trucking cycle generated lower THC and CH_4 emissions. For the drilling and fracturing cycles CO_2, THC, and CH_4 were lower than the average D-2 emissions. CO emission did tend to increase in both cases and the NO_x emissions were below the detectible limit for the D-2 cycle. While the developed cycles were representative of in-use activity – we showed that the difference between certification cycles and the developed cycles could impact all gaseous emissions.

Table 11: Results for comparison of developed cycles with certification cycles[34].

		FTP	Trucking	(% Difference)	D-2	Drilling	(% Difference)	Fracking	(% Difference)
CO2	**g/kW-hr**	606	638	5.30	688	616	-10.4	652.62	-5.13
CO	**g/kW-hr**	1.65	1.88	14.2	1.10	1.96	77.8	1.68	52.3
NOx	**g/kW-hr**	0.20	0.24	18.8	0.00	0.00	NA	0.02	NA
THC	**g/kW-hr**	1.90	1.18	-37.7	1.86	1.42	-23.5	1.40	-24.6
CH4	**g/kW-hr**	1.78	1.10	-37.9	1.76	1.34	-23.9	1.33	-24.5

We then operated the engine over the developed cycles with two fuel blends that could represent higher ethane (E12) and propane (P5) compositions indicative of various field gases. We conducted a statistical analysis (t-test) to determine if variations were significant or not. Statistically different values had a p value less than 0.05. Following are the statistically different impacts of fuel composition.

- CO_2 Emissions – the P5 blend yielded a 2.4% increase in emissions for the drilling cycle.
- CO Emissions – the E12 blend yielded a 44.5% increase in emissions for the drilling cycle.
- NO_x Emissions – the E12 blended yielded a 70% reduction in emissions for the trucking cycle and an 80% reduction in emissions for the fracturing cycle. The P5 blend yielded a 72.8% reduction in emissions from the fracturing cycle.
- THC Emissions – the E12 blend yielded a 17% reduction in emissions for the fracturing cycle.
- CH_4 Emissions – the E12 blend yielded a 17.4% reduction in emissions for the fracturing cycle.

When the significance criteria are extended to include marginal differences, the following general conclusions were found[34]:

- General trends match well with those in literature[65,66].
- The high propane blend tended to yield the highest increase in CO_2 emissions as expected based on H/C ratio.
- Both blends yielded lower NOx emissions, and the high ethane blend typically yielded the lowest.
- Both blends typically produced lower THC and lower CH_4 emissions as the fuels had lower CH_4 content and higher hydrocarbons are more easily oxidized in the TWC.
- For the drilling and fracking cycle, the high ethane blend tended to decrease both THC and CH_4 more so than the high propane blend.

Inventory Results

As discussed earlier, we use the newly collected prime-mover activity data with in-use emissions data where possible to create an emission inventory. In addition, the inventory used data presented in literature, emissions certification data for trucking engines, and research data for dual fuel and dedicated natural gas trucking engines. The goal of the inventory was to estimate the emissions per well for diesel only operation, with dual fuel conversion, and with conversion to dedicated natural gas. Detailed analysis of the model and results are presented in just accepted manuscript in the journal *Environmental Science and Technology* – see Appendix C.

We compared diesel only portions of the fracturing model with other reported literature. Rodriguez and Ouyang developed emissions estimates for the Marcellus and Eagle Ford Shale plays[53]. They used conventional emissions factors and activity factors. Table 12 presents a comparison of our model results with the various results developed by different methods of Rodriguez and Ouyang. We see that our results tend to align with their lower values, which lends confidence to our model given that in-use emissions were typically lower than certification values.

Table 12: Comparison of fracturing emissions with those presented in literature[23].

Emission	Min	Max	Worst Case	Our Estimate
NO_x (tonnes)	1.71	3.24	14.85	1.91 ± 0.56
CO (tonnes)	0.30	1.40	6.38	0.38 ± 0.11
THC (tonnes)	0.06	0.17	0.78	0.04 ± 0.02

Additionally, Vafi and Bradnt developed the open-source *GHGFrack* model to estimate the energy requirements and GHG emissions for unconventional drilling operations[67]. *GHGFrack* is a data intensive model that requires 32 input variables as opposed to our more generalized model, which is based on activity. Table 13 shows their results for four case studies and the overall average results from our model ran with an average population of 12,325 wells. Our average CO_2 equivalent emissions tended to be higher than their average values but well within their 95% CI for all case studies.

Table 13: Comparison of drilling CO2 equivalent emissions with those presented in literature[23].

	Drilling CO_{2eq} (%)	Fracturing CO_{2eq} (%)	Total Mean CO_{2eq} (tonnes/well)	95% CI of CO_{2eq} (tonnes/well)	Our Mean CO_{2eq} (tonnes/well)	Our 95% CI (tonnes/well)
Bakken 1	76	24	417	155-1243	612	±88
Bakken 2	53	47	316	233-1333		
Eagle Ford 1	25	75	419	221-798		
Eagle Ford 2	38	62	510	190-1168		
Average	48	52	416	--		

Since our results tended to align with those presented in literature we used the model to estimate per well fuel consumption and gaseous emissions and then used an average well count of 12,325 to estimate annual emissions rates. Note that a well count of 12,325 reflected the average well count of drilled and completed wells from 2014-2016. Since our in-use emissions and activity were different from certification estimates, we first present a case of diesel only operation which is based on our Tier 2 in-use data. Table 14 presents the results on an annual and per well basis.

Table 14: Emissions inventory model results for the diesel only case – includes both annual (12,325 wells) and per well values[23].

	Diesel	CO_2	CO	NO_x	THC	CH_4
	(TJ)	(kilo-tonnes)	(tonnes)	(tonnes)	(tonnes)	(tonnes)
Annual	166,000	12,700	20,600	65,600	3,040	192
95% CI	72,800	5,560	9,020	28,300	1,330	114
Per Well	9.31	0.71	1.15	3.62	0.17	0.01
95% CI	1.46	0.12	0.02	061	0.09	0.00

Since industry is seeking to reduce fuel costs and possibly emissions, we used our dual fuel and dedicated natural gas data to examine the effects of increasing market penetration of these technologies. We examined two scenarios, the first examined if all engines were converted to operate as dual fuel. The second scenario is the dedicated natural gas scenario, where trucking and drilling engines were converted to operate as dedicated natural gas but fracturing engines were converted to operate as dual fuel since no data were available for dedicated natural gas fracturing fleets. Table 15 presents a summary of the relative changes with respect to the base diesel only case. Market penetration levels were varied from 0-100% and average percent change per market penetration increase were calculated. As expected for both cases the diesel fuel demand decreases but the total fuel energy required increases. The net fuel energy increase was attributed to CH_4 slip of dual fuel engines and lower efficiency of dedicated natural gas engines. We show that CO_2 and CO increased for both scenarios while NO_x emissions tended to decrease. The most significant reduction in emissions was for NO_x emissions and the dedicated scenario. This was because implementing natural gas engines that used TWCs offered significant emissions reductions. The most dramatic increases were for THC and CH_4 emissions. For the diesel only case, THC emissions were dominated by NMHC while for dual fuel and dedicated natural gas scenarios they were dominated by CH_4. Both scenarios increased these emissions but the dual fuel led to the most significant increase due to excessive CH_4 slip.

It is important to note that the dual fuel engines did not include data from an engine converted without a DOC, as this practice should be avoided. We estimated that if just 10% of the dual fuel drilling rigs operated without a DOC – they would more than offset any reductions in CO emissions provided by dual fuel operation with a DOC.

Table 15: Relative changes in diesel fuel, total required fuel energy, and gaseous emissions due to dual fuel and dedicated natural gas market penetration[23].

	Diesel Energy	**Total Fuel Energy**	**CO_2**	**CO**	**NO_x**	**THC**	**CH_4**
	%/%MP	**%/%MP**	**%/%MP**	**%/%MP**	**%/%MP**	**%/%MP**	**%/%MP**
Dual-Fuel Scenario	-0.49	+0.46	+0.11	+0.31	-0.13	+6.28	+32.5
Dedicated Natural Gas Scenario	-0.78	+0.66	+0.25	+0.84	-0.58	+5.11	+20.0

By implementing these current technologies, fuel energy and gaseous emissions (except NO_x) tend to increase with increasing utilization. However, even when including the inefficiency losses for the technologies - both offer significant reductions in diesel fuel. For the extreme case that all prime movers were dual fuel, we estimated the industry could save $1.26 Billion annually while savings increased to $2.04 Billion for the dedicated natural gas scenario. These figures could be enticing to industry as they seek to further reduce unconventional well development costs. However, these savings are only based on current diesel and natural gas prices and do not include additional capital or rental costs for natural gas fuel equipment. In addition, we do not assess any costs for increased or decreased emissions – such as a social cost of carbon.

Conclusion:

Researchers at the CAFEE completed a multi-year program assessing the impact on CH_4 emissions from using dual fuel and dedicated natural gas technologies within the prime movers of unconventional well development. We collected, what we believe are the most current, representative, and perhaps only in-use emissions data for Tier 2 diesel engines, Tier 2 diesel engines converted to operate as dual fuel, and Tier 2 dedicated natural gas engines – that were actively operating at unconventional well sites across the US. Most emissions estimates rely on older activity and emission factors or certification standards to estimate emissions. However, we present real in-use emissions to augment current inventory methods. Our main conclusions are as follows:

1.) In-use horizontal drilling rigs operate transiently as opposed to steady state operation of certification standards. We separated drilling into SS operation with average load of greater than 40% and LLT operation with average loads below 40%.

2.) In-use, regulated gaseous emissions from Tier 2 drilling and fracturing engines tended to be lower than certification standards. Therefore, inventories that use certification standards to estimate emissions are likely conservative and may over predict these emissions.

3.) Diesel oxidation catalysts could be deployed on any Tier 2 diesel engine to lower CO and NMHC emissions.

4.) Diesel oxidation catalysts should be included in dual fuel conversion kits in order to avoid excessive CO emissions.

5.) Current dual fuel conversion technologies lose fuel and produce methane emissions from methane slip in the exhaust and crankcase. Fuel slip rates ranged from 14-22% of the fuel supplied to the engine. Therefore, substitution rates should be corrected to account for this inefficiency so that operators do not assume a reduction in diesel fuel energy is equal to the natural gas energy consumed. This current downfall is difficult to remedy with aftertreatment catalysts alone and future work should focus on multiple approaches to reduce methane slip and improve dual fuel engine efficiency.

6.) Overall, drilling and fracturing fuel efficiencies decrease with dual fuel technologies and further decrease with dedicated natural gas technologies. If natural gas prices increase and diesel prices remain low, the efficiency penalties could offset cost benefits.

7.) Properly operating Tier 2 dedicated natural gas engines had in-use emissions at or below advertised values and emissions standards. Significant reductions in NO_x emissions from dedicated natural gas drilling rigs could benefit operations where air quality is of concern. However, just as in automotive applications we show that engine and catalyst issues can contribute to excessive emissions of CO and NO_x – well above regulated standards.

8.) Industry and regulators should be cognizant of the impacts of increasing the use of currently available technologies – especially from a GHG footprint perspective. Future research should address methane slip issues and focus on methods to improve the fuel efficiency of natural gas as a fuel.

9.) Modeling shows that fuel costs can be reduced by deploying natural gas as a fuel. However, implementing natural gas requires additional equipment, which may have associated capital or rental costs. A full cost analysis should be conducted to determine costs associated with impacts on emissions.

10.) The composition of natural gas can impact emissions and fuel consumption, however, on road and non-road engine manufacturers recommend minimum methane numbers for fuels. So long as these standards are followed, only slight mixed impacts were seen.

We present Figures 13 and 14 as qualaltive tools to present the impacts of dual fuel and dedicated natural gas technologies from perspectives of regulated and GHG emissions. Following these figures are suggested areas of future research.

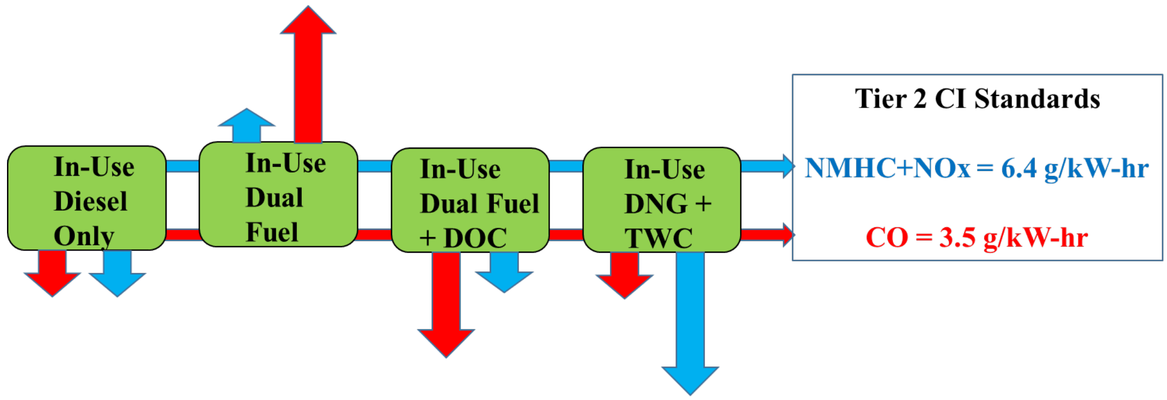

Figure 13: Qualitative impacts of current engine technologies used in unconventional well development with respect to Tier 2 regulated emissions standards.

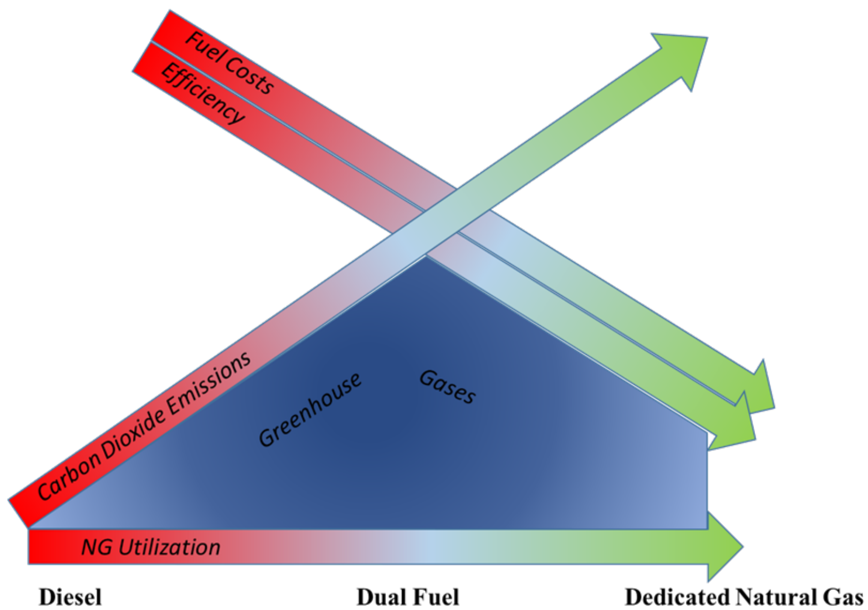

Figure 14: Qualitative impacts of current engine technologies used in unconventional well development with respect to CO2, GHGs, efficiency, and fuel costs.

Future Research Topics:

1.) Improved catalysts to reduce methane slip.
2.) Closed crankcase operation to reduce emissions.
3.) Improved dual fuel engine technologies focused on improving efficiency and reducing methane.
4.) Engine technologies to increase the efficiency of dedicated natural gas engines.
5.) In-situ emissions monitoring to alert operators of emissions and fuel performance issues from new dual fuel and dedicated natural gas engine technologies.
6.) Methods to improve the overall fuel and energy efficiency of on-site prime mover operations – such as combined heat and power systems, drill rig hybridization, thermoelectric generators, alternative fuels, and energy solutions.

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LIST OF ACRONYMS AND ABBREVIATIONS:

Avg	Average
CAFEE	Center for Alternative Fuels, Engines, and Emissions
CH_4	Methane
CI	Confidence Interval
Cm	Centimeter
CNG	Compressed Natural Gas
CO	Carbon Monoxide
CO_2	Carbon Dioxide
CO_{2eq}	Carbon Dioxide Equivalent
DF	Dual Fuel
DNG	Dedicated Natural Gas
DO	Diesel Only
DOC	Diesel Oxidation Catalyst
FFS	Full Flow Sampler
FTIR	Fourier Transform Infrared
FTP	Federal Test Procedure
GA	Genetic Algorithm
GHG	Greenhouse Gas
GPS	Global Positioning Unit
H/C	Hydrogen- Carbon Ratio
HP	Horsepower
hr	Hour
Hz	Hertz
JAWMA	Journal of the Air & Waste Management Association
kW	Kilowatt
L	Liter
LLT	Low Load Transient
LNG	Liquified Natural Gas
M	Meter
MCMC	Markov Chain, Monte Carlo
N	Newton
NMHC	Non-Methane Hydrocarbon
NOx	Oxides of Nitrogen
OTR	Over the Road
PV	Pressure Volume
RPM	Rotations per Minute
SCFM	Standard Cubic Feet per Minute
SI	Spark Ignition
SS	Steady State
Std	Standard Deviation
THC	Total Hydrocarbon

TJ	Terajoules
TWC	Three-way Cataylist
UGGA	Ultraportable Greenhouse Gas Analyzer
US	United States
V	Voltage
WVU	West Virginia University

APPENDICES:

APPENDIX A

Trends in Unconventional Well Development – Methane Emissions Associated with the Use of Dual Fuel and Dedicated Natural Gas Engines

Derek Johnson*[a], Robert Heltzel[b], and Andrew Nix[c]

Lead-in: The process of unconventional natural gas recovery is becoming increasingly popular as the world's demand for alternative fuels continues to grow. Natural gas has the potential to be a widely used fuel in the near future due to its availability and potential to displace petroleum-based liquid fuels. As energy companies extract natural gas, current fuels, such as diesel, are consumed in mass quantities for drilling and hydraulic fracturing operations. In order to save on costs and in an attempt to reduce emissions, many companies are investing in dual fuel and dedicated natural gas engines to power operations. This trend results in new sources of methane emissions, which can contribute significantly to global warming. West Virginia University is aware of the potential impact of these emissions and is conducting research funded by the Department of Energy to assess methane emissions from dual fuel and dedicated natural gas technologies, as industry moves towards more extensive use of natural gas as a fuel for onsite power production.

1. Unconventional Natural Gas Potential

The recovery of unconventional natural gas is a growing industry in the United States (US) and around the world. As high-energy demands become a prevalent issue worldwide, the search for cheaper and cleaner alternative fuels becomes more critical. Natural gas is an option that is now becoming more widely available due to advances in the technologies required for its recovery. These technologies include horizontal drilling and hydraulic fracturing. According to the Energy Information Administration (EIA), there is as much as 1,193 trillion cubic feet of natural gas in the US recoverable from unconventional sources [1]. The extraction of this natural gas results in high-energy demands and using natural gas as a fuel to power these operations leads to new sources of methane emissions. The three main sources of methane emissions include leaks and losses from onsite fueling equipment, methane vented from the crankcase, and uncombusted methane in the engine exhaust.

1.1. Objective

West Virginia University's (WVU) Center for Alternative Fuels, Engines, and Emissions (CAFEE) is currently working with the Department of Energy (DOE) and National Energy Technology Laboratory (NETL) to assess the methane emissions from the use of natural gas as a fuel in unconventional well development. WVU recognizes that the current standard in the industry is to use diesel fuel to power natural gas well construction, drilling, and stimulation equipment. Therefore, a quantification of usage and an evaluation of emissions is being conducted for both the current industy standard equipment (diesel-fueled) and the growing trend (dual fuel and dedicated natural gas). This research will produce first of its kind in-use emissions measurements that will help guide the continued use, research, and development assoicated with these emerging technologies.

Dr. Derek Johnson is a Research Assistant Professor in the Department of Mechanical Aerospace Engineering at WVU. Dr. Johnson conducts research at the Center for Alternative Fuels, Engines, and Emissions His primary research is in the area of engines, emissions, and retrofit aftertreatment devices along with natural gas as an alternative fuel. Dr. Johnson is currently the PI or Co-PI on three major programs assessing methane emissions from engines and equipment. Previous research focused on retrofit aftertreatment devices for the reduction of NO_x emissions from marine vessels. Dr. Johnson has also acted as a technical writer and curriculum developer at WVU's National Alternative Fuels Training Consortium.

Mr. Robert Heltzel is a graduate research assistant working under Dr. Johnson. Mr. Heltzel has been working at CAFEE for over a year as an undergraduate and graduate assistant. Mr. Heltzel graduated with is BS in Mechanical Engineering in the spring of 2014 and is currently pursuing his Master's Degree in Mechanical Engineering.

Dr. Andrew Nix joined the faculty at WVU in the Center for Alternative Fuels, Engines, and Emissions in Fall of 2006 as a research assistant professor. In 2012, he accepted a position as an assistant professor and is continuing research in gas turbines for propulsion and power, as well as research in wind energy, emissions measurements from transit buses, hybrid-electric vehicle systems and shale gas.

2. The Unconventional Natural Gas Industry

2.1. Introduction

The US has become a major player in the unconventional natural gas industry. There were 482,822 natural gas producing wells in the US in 2012, and this number continues to grow [2]. The total withdrawal of natural gas in the US was 2,380,940 million cubic feet in February of 2014 alone. Much of this gas comes from the major shale plays in the US which include: Marcellus, Barnett, Woodford, Haynesville, Bakken, Fayetteville, and Eagle Ford. Estimates show that 26% of the world's energy will be from natural gas in 2030 and that 50% of the US' natural gas will be from

[a] Dr. Derek Johnson
Mechanical and Aerospace Engineering Department
Center for Alternative Fuels, Engines, and Emissions at West Virginia University
151 ESB, 395 Evansdale Drive, Morgantown, WV 26505
E-mail: derek.johnson@mail.wvu.edu

[b] Mr. Robert Heltzel
Mechanical and Aerospace Engineering Department
Center for Alternative Fuels, Engines, and Emissions at West Virginia University
151 ESB, 395 Evansdale Drive, Morgantown, WV 26505
E-mail: rheltzel@mail.wvu.edu

[c] Dr. Andrew Nix
Mechanical and Aerospace Engineering Department
Center for Alternative Fuels, Engines, and Emissions at West Virginia University
271 ESB Annex, 395 Evansdale Drive, Morgantown, WV 26505
E-mail: Andrew.nix@mail.wvu.edu

unconventional sources [3]. Although there are a number of advantages to using natural gas, the process of extraction is not perfect. Billions of dollars are spent on millions of gallons of diesel fuel used by energy companies to power equipment needed to obtain unconventional natural gas.

In order to make extraction as cost effective as possible, industry is now looking to use natural gas to displace diesel at well-sites by using dual fuel or dedicated natural gas engines. This will reduce the cost and regulated emissions of unconventional natural gas extraction. However, with the use of natural gas as a fuel there may result in significant increases in methane (CH_4) emissions to the atmosphere. Methane emissions can come from the leaks and losses of fuel systems, crankcase vents, and the engine exhaust. These emissions are problematic because methane is a greenhouse gas (GHG) with a global warming potential (GWP) higher than carbon dioxide (CO_2). The Environmental Protection Agency (EPA) assigns methane a GWP of 21 times that of carbon dioxide (CO_2) on a 100-year basis [4]. The International Panel on Climate Change has assigned methane a GWP of 30 for 100 years and 85 for 20 years, from fossil fuels [5].

Well development and extraction are major fuel consumers in the process of obtaining natural gas. There are a number of critical steps in unconventional well development that have high energy demands. These aspects of well development previously utilized diesel fuel, however, the trend toward natural gas is growing rapidly. The number of new sources of methane emissions depends largely on the type and quantity of power required for each of the processes. Drilling a well requires a number of steps and is energy and fuel-intensive. Unconventional wells generally consist of two sections of drilling: vertical and horizontal. The total length drilled can vary greatly depending on the region in which the well is located and the depth of the shale gas. Barnett region wells generally only require up to 3,000 feet of vertical drilling, but Haynesville region wells can require up to 13,500 feet of vertical drilling [6]. If horizontal drilling is used, additional length will increase fuel consumption. The horizontal portion of the well can be drilled for extensive lengths of anywhere from 1,000 to over 10,000 feet [6]. Drilling longer horizontals allows potential for far more natural gas to be extracted from a single well. Once the drilling process is complete, the next major step in the recovery of unconventional gas is hydraulic fracturing. The hydraulic fracturing process is the biggest difference between the extraction of conventional and unconventional gas. Hydraulic fracturing is required because of the low permeability of the shale deposits in which the natural gas exists [6]. This means that the gas is naturally stored in pockets deep in the shale layer. These pockets are disconnected and must be combined so that the gas can flow out of the shale formation. Connecting these pockets is accomplished by pumping large volumes of sand and water into the drilled well. In hydraulic fracturing, sand is used as a proppant to provide a network of extraction pathways. The fracturing fluid is pumped in by a fleet of large pumps. High horsepower engines that operate continuously, consuming large amounts of diesel fuel, power these fracturing pumps. Hydraulic fracturing fleets are typically composed of between 10 and 20 flatbed mounted engine driven pumps. These engines operate at high power levels, around 2,250 horsepower (HP) [7].

The combined time of drilling and hydraulically fracturing a well, typically lasts two to three months [7]. During this process, large amounts of truck traffic moves to and from well sites. These heavy-duty trucks are large consumers of diesel fuel. The industry move to natural gas could result in engine conversion of these trucks and in turn another source of methane emissions. There are four prime movers of diesel fuel in the natural gas recovery sector, which each consume millions of gallons of fuel across the US, including: over-the-road tractors, vertical drilling rigs, horizontal drilling rigs and hydraulic fracturing fleets. The estimated values of diesel fuel consumption by each prime mover per well is shown in Table 1 as collected from [6-8]. If industry trends continue to move toward the displacement of diesel fuel with natural gas, a number of new sources of methane emissions will occur.

Table 1. Diesel fuel Consumers in Natural Gas Recovery [6-8]

Prime Mover	Over-the-Road Tractors	Vertical Drilling Rigs	Horizontal Drilling Rigs	Hydraulic Fracturing
Fuel Consumption (gal) [a]	4,787	13,440	61,434	21,000

[a] Fuel Consumption is based on estimated average fuel consumption per well based on a survey a published literature

2.2. On-Road Industry Technologies

A number of companies are working to develop alternative technologies for on-road diesel-fueled engines that utilize natural gas. These technologies primarily consist of dual fuel conversion kits, dedicated natural gas engines, and high pressure direct injection (HPDI) engines. On-road natural gas engines and conversion kits are being developed and implemented by both original equipment manufacturers and heavy-duty truck fleets. Cummins, for example, is a leader in on-road dedicated natural gas engine development. Cummins-Westport have been producing an 8.9 liter (L) dedicated natural gas engine since 2007 [9]. Their newest engine is an 11.9 L dedicated natural gas engine [9]. While many consider these engines cleaner, they have the potential to produce more methane emissions than similar diesel-fueled engines. Another recent technology is the high pressure direct injection (HPDI) system. The HPDI engines use natural gas as the primary fuel in a compression ignition cycle. The current HPDI systems are produced by Westport Innovations and utilize "pilot diesel" for ignition [10]. In addition to developing engines that are capable of using both diesel fuel and natural gas, many companies are producing dual fuel conversion kits for existing engines. These kits allow engines currently operating on diesel fuel to be converted and operate on diesel fuel and natural gas, simultaneously. American Power Group (APG) has recently developed a dual fuel conversion kit that it is marketing for use in glider trucks [11]. According to APG, these systems produce about 30% fewer emissions than "pre-emission" diesel fuel equipment; however, this does not include methane emissions. APG is currently the largest holder of EPA-approved retrofit kits; however, conversion kits by other companies are also available.

Another large potential for methane emissions related to over-the-road trucks is through the fueling infrastructure. The EPA states that on a “well-to-wheel” basis approximately 1.5% of methane is lost, this includes extraction from all sources, including unconventional wells, and distribution. A 2012 study lead by the Environmental Defense Fund (EDF) states that the EPA’s estimate is about 50% too low [12]. These studies show that as the unconventional well development industry attempts to convert over-the-road fleets to natural gas, the potential for methane emissions may further increase the GHG footprint of unconventional well development. Methane emissions associated with the on-road fueling infrastructure are beyond the scope of this research, but an alternative project at WVU is examining these emissions [13].

2.3. Off-road Technologies

The drilling and fracturing industry is also moving towards displacing diesel fuel in off-road engines. These engines and conversions are especially attractive to the unconventional well development industry due to operating fuel costs. Dual fuel technology is currently the more popular trend in off-road applications at well sites due to its diesel fuel back-up ability. Since the dual fuel engines can run on both diesel fuel and natural gas, they are much safer from a productivity standpoint. If the source of natural gas is unavailable the engines can continue to operate on 100% diesel fuel, which is critical for the minimization of downtime. There are multiple dual fuel conversion kits available to drilling and hydraulic fracturing companies and several companies are beginning to produce dedicated high horsepower natural gas engines. An increase in the use of these technologies increases sources of potential methane emissions. Popular engine manufacturers for unconventional well development applications include Caterpillar, Waukesha, and Cummins.

Caterpillar’s new Dynamic Gas Blending (DGB) Kit allows for dual fuel conversion of their engines. The DGB kit offers diesel fuel displacement of up to 70% [14]. They also offer the G3516 engine manufactured to operate as a lean-burn dedicated natural gas engine [15]. APG has developed a system to control the amount of gas fed to a dual fuel engine utilizing a conversion kit. The APG system was used in Oklahoma on a rig using three converted dual fuel 3512 Caterpillar engines drilling a horizontal well. The average substitution during this time was between 50% and 55% [16]. Waukesha has developed a spark ignited, dedicated natural gas engine. The engine operates as rich-burn or stoichiometric and includes a three-way catalyst for emissions control. The natural gas fuel consumption of this engine at rated power is about 220 cubic feet per minute [17]. The GE Jenbacher J320 is a similar natural gas engine for drilling operations [18]. Another engine used in generator sets to power drilling and hydraulic fracturing fleets is the Cummins QSK50. Cummins has recently modified this engine to operate in dual fuel mode with substitution of diesel fuel up to 70% with equivalent power output [19]. ComAp offers conversion kits that they refer to as Bi-Fuel. The conversion kits can operate with substitution rates up to 70%-90% with no reduction in the engine power or efficiency [20]. Altronic’s GTI Bi-Fuel System conversion can displace up to 70% of diesel fuel and reduce diesel exhaust emissions [21].

Increasing the use of these types of technologies is attractive to industry due to the reduced cost and regulated emissions. However, these types of technologies increase the risk of methane emissions from uncombusted methane slip in the exhaust and losses through crankcase venting. Since the EPA does not currently regulate dual fuel conversion systems for methane emissions, there is little incentive for industry to attempt to minimize these losses.

2.4. Industry Investments in Technologies

A number of drilling and fracturing companies are currently utilizing dual fuel and dedicated natural gas technologies. Although industry figures from 2013 show that dual fuel accounts for only 5% of the more than 8,000 fracturing pumps currently in service in North America, this percentage is expected to reach 40% in the next two years [22]. As of March 2013, over 300 fracturing jobs were completed using these new natural gas technologies with an average diesel fuel displacement of 40% [23]. Cabot, Scandrill, Precision, EQT, Noble Energy and Apache are all currently utilizing dual fuel applications to power drilling rigs. Cabot Oil & Gas was one of the first companies to make the switch to dual fuel in the Marcellus region. While many operators attempting to convert to natural gas in remote areas are using LNG, Cabot is utilizing CNG and field gas. The gas used by Cabot is approximately 97% methane and consists of only 3% higher hydrocarbons. This allows Cabot to retrofit generators on drilling rigs with dual fuel technology [24]. The dual fuel technology being utilized by Cabot allows for displacement of 30-40% of Cabot’s usual consumption of 2,000 gallons of diesel fuel per day. Cabot currently has four drilling rigs operating on dual fuel and in 2013 successfully drilled 19 wells [24]. Scandrill, a company that is prevalent in the Marcellus and Eagle Ford regions, began implementation of its first dual fuel retrofits in late 2012. They are now running at least five dual fuel rigs, four in the Marcellus region and one in the Eagle Ford region [16]. Scandrill is using a prototype gas conditioning skid from Pro-Gas Services to condition field gas from the pipeline. In 2011, Scandrill and Anadarko agreed to participate in field testing of Caterpillar’s DGB kit as well as with the APG system. The company reported substitution rates of greater than 60% with the Caterpillar kit and greater than 40% with the APG kit. In September of 2013, Precision Drilling was utilizing four dual fuel rigs in the US, two with Noble Energy and two with Southwestern Energy [16]. According to the company’s manager of engines, many contractors are hoping that they’ll have 10 to 20 dual fuel rigs in operation by late 2014. They have also been using a dual fuel kit for EnCana since 2008 [16]. CONSOL Energy has also began utilizing natural gas in the form of LNG and field gas for dual fuel engines powering drilling rigs in the Marcellus region [25]. EQT has also utilized dual fuel engine operation for drilling. They drilled using the Caterpillar and APG dual fuel kits utilizing LNG or field gas [26]. Noble Energy has begun utilizing dual fuel systems for drilling and pressure pumping. As of September 2013, they were operating four dual fuel rigs. The dual fuel rigs are utilizing GTI Altronic’s kits on three Caterpillar 3512 engines. The rigs in the DJ Basin operated on diesel fuel and LNG and experienced diesel fuel displacement between 25-40% [27]. Southwestern Energy Company recently began utilizing the Caterpillar DGB kit to utilize dual fuel in their operations. Apache is currently operating four dual fuel rigs between 1,500 and 2,000 horsepower in western Oklahoma and the Texas Panhandle. These dual fuel rigs were fitted with Caterpillar dynamic gas-blending kits and utilized LNG and diesel fuel. Apache has drilled over 10 wells with this dual fuel power and is averaging greater than 50% displacement [16].

Companies are also looking to take the next step in eliminating diesel fuel consumption by converting to dedicated natural gas engines for drilling. Precision and Ensign are experimenting with dedicated engines for drilling. Precision has retrofitted two rigs with dedicated natural gas Waukesha engines [16]. Antero Resources is also working with Patterson UTI Drilling, which began using three dedicated Waukesha VHP L7044GSI engines on an unconventional operation in West Virginia [16]. Ensign drilling is utilizing dedicated natural gas engines to power their drilling rigs. As of September 2012, they had 15 dedicated natural gas rigs in operation across the country. Ensign is currently operating three large drilling rigs in the Marcellus region, which utilize GE Jenbacher natural gas engines to power the drilling rigs [28].

In addition to drilling, companies are also looking to displace diesel fuel in fracturing and pressure pumping applications. Halliburton and Baker Hughes are currently using dual fuel to power fracturing pumps in collaboration with a number of drilling companies. Noble has also partnered with Baker Hughes and Halliburton to power fracturing pump spreads with dual fuel. In doing this, Noble has outfitted Cummins engines with ComAp conversion kits and Caterpillar engines with APG kits. These fracturing spreads have different consumption patterns than drill rigs, which makes dual fuel a more viable option than dedicated engines [27]. Halliburton has been partnering with Apache and Caterpillar since January of 2012 to create dual fuel technologies for pumping equipment. The Q10 is a 2,000 horsepower dual fuel fracturing pump that can substitute up to 60% of diesel fuel with natural gas at full load [16]. Halliburton and Apache have developed a complete fracturing spread of 12 Q10 pumps that have now completed over 35 fracturing jobs with a substitution rate over 50% [16]. Fracturing with dedicated natural gas engines is also being explored, although not yet as extensively as dual fuel. Chesapeake Energy plans to convert all of their fracturing to dedicated natural gas [23].

It has become common for the unconventional well development industry to use natural gas as a fuel for drilling and fracturing. The technologies are touted to reduce fuel costs but are also “greener” than conventional diesel-fueled rigs, which makes them more appealing to industry leaders. There is limited information on the methane emissions from these engines and GHG emissions such as CO_2 and CH_4 are currently unregulated by the EPA. The widespread use of these technologies may produce significant CH_4 emissions that are currently unreported or simply unchecked. Steps must be taken to quantify these emissions to determine the magnitude of the unconventional well development GHG footprint. Quantification is the first step to understand and eventually reduce these new sources of methane emissions.

3. WVU’s Study of Natural Gas Used as a Fuel for Unconventional Development and Extraction

3.1 Introduction

In collaboration with project partners, WVU’s CAFEE will provide an assessment of methane emissions from the prime movers of unconventional well development sites that utilize natural gas. Specifically, CAFEE will identify and characterize the methane emissions of equipment using dual fuel (natural gas and diesel fuel) or dedicated natural gas engines as replacements to the diesel-fueled units that currently dominate unconventional operations. This effort will include the methane emissions related to the prime movers at unconventional well site locations and include the onsite fueling equipment, engine fuel lines, crank case vents, and unburned fuel in the exhaust. Through this characterization, WVU’s objective is to provide industry the data, assessment, and mitigation strategies of methane emissions to inform and help guide the continued use and development of these technologies. WVU has experience in this field already as a number of campaigns conducted by CAFEE have studied the natural gas industry from natural gas transmission to end use by heavy-duty transportation. In collaboration with a number of organizations, WVU’s CAFEE has conducted leak/loss audits of natural gas compressor stations in the Barnett shale region, as well as collected emissions from dual fuel, HPDI vehicles, and dedicated natural gas vehicles.

3.2 Methane Emissions

The CH_4 emissions from unconventional well development have not yet been quantified through in-use emissions measurements. The potential for CH_4 emissions exists at well sites through engine fuel lines and crankcase vents, and through losses of unburned CH_4 from the exhaust of the large high horsepower off-road engines. A recent MIT study claims that using natural gas in a similarly efficient diesel engine will yield the potential to lower GHG emission by 10-15%. However, it also states that including the CH4 emissions from the production and use of natural gas as an engine fuel may completely negate this effect [29]. WVU has conducted numerous research projects characterizing the exhaust emissions of unburned CH_4 from dual fuel engines used to power on-road vehicles. For example, the CH_4 emissions from dedicated stoichiometric natural gas engines and dual fuel conversion heavy-duty engines are significantly different, as indicated by Figure 1. The emissions of unburned CH_4 from dual fuel engines are usually higher than spark-ignition stoichiometric engine operation especially when the SI engine is equipped with a three-way catalyst. As shown in Figure 2, the significantly higher engine out CH_4 emissions from dual fuel engines are due to the unique feature of the formation of the combustible mixture of diesel, CH_4, and air in the engine cylinder [30].

Since both of these technologies are being used by industry for unconventional well development, the CH_4 emissions of both types of engines must be quantified. The significant difference in CH_4 emissions shown in Figure 1 are also due to the observed exhaust temperatures between the two technologies and partly due to the catalyst formulation of the dual fuel engine oxidation catalyst system. Catalyst formulations consisting of high palladium loading has shown significant improvements in CH_4 reduction for lean-burn engines, but are susceptible to catalyst destruction due to higher exhaust water content and possible sulphur poisoning [31, 32]. The oxidation of methane is highly dependent on exhaust gas temperature [33].

Early work by WVU examined dual fuel operation of on-road dual fuel engines utilizing technology similar to current off-road dual fuel kits. It was shown that CO emissions increased by 390% and NMHC increased by 52% without the use of an oxidation catalyst [34]. More recent research for on-road dual fuel engines was conducted at WVU. An 11.9L Mack engine was converted to operate as dual fuel and was tested over the European Stationary Cycle. Mode 9 of this cycle saw a natural gas substitution rate of over 40% but also yielded a methane emissions rate of over 20 g/bhp-hr [35]. It is shown from this research that the general trend from these new dual fuel technologies is not only increased methane emissions but also increases in non-methane hydrocarbon (NMHC) and CO emissions. It is also noted that these programs did not include the contribution of crankcase methane slip. See Figure 3 for the modal crankcase emissions as compared with exhaust emissions.

Ideally GHG emissions from methane will be eliminated during combustion when in dual fuel operation with advanced engine control and exhaust aftertreatment, however, there are likely to be emissions from crankcase blow-by. The addition of methane in dual fuel engine operation makes these emissions of greater concern due to the higher GWP of methane. The blow-by emissions of a compression ignition engine are generally small compared to that of the exhaust, only about 0.4-0.8% of exhaust levels [35]. Although this is a small percentage it can significantly contribute to GHG emissions for large, continuously operating dual fuel or dedicated engines. According to Caterpillar, the blow-by rates can be estimated by formulas using engine rated power. This estimation varies between new and worn engines [36]. For estimating crankcase emissions from non-road compression-ignition engines with open crankcases, the EPA estimates that the crankcase emissions are equal to 2.0% of the exhaust hydrocarbon emissions [37]. The estimated crankcase emissions from worn engines are double those of newer engines. WVU recently participated in the Environmental Defense Fund Barnett Coordinated Campaign. The focus of this study was leak and loss audits at natural gas compressor station and storage facilities powered by natural gas engines [38]. WVU measured the methane concentration from two CAT G3612 engines, a CAT G3512 engine, and three CAT G3516 engines. The methane slip from these engine exhausts varied from between 1.5 to 5.4% of the fuel consumed [39]. In addition, the engine crankcases emissions were also measured. The crankcase emissions, on average, were 14% of the exhaust methane emissions. For these reasons, WVU will conduct research aimed at in-use quantification of the exhaust emissions, crankcase emissions, and any methane emissions associated with onsite fueling equipment.

3.3 Field Measurment Campaign

CAFEE research focuses on the CH_4 emissions of the prime movers associated with unconventional well development that have recently begun implementing natural gas as a fuel. These emissions include those from both diesel fuel, dual fuel, and natural gas engines. WVU will obtain this data from vertical and horizontal drilling operations and hydraulic fracturing equipment when available. WVU will also collect engine activity from these prime movers as well as truck activity common to well sites. WVU will test diesel fuel only engines, dual fuel engines, and dedicated natural gas engines when possible to assess the overall emissions profiles and fuel consumption of these developing technologies. In order to report accurately to the industry, WVU will obtain engine data from the field such as engine speed, fuel rate, engine load, boost pressure, intake air manifold temperature, and other broadcast parameters that will assist in the development of representative engine test cycles for laboratory research. The emissions measurements will include gaseous exhaust emissions such as: carbon monoxide (CO), carbon dioxide (CO_2), total hydrocarbons (THC), methane (CH_4) and oxides of nitrogen (NO_x). In addition to gaseous exhaust emissions, WVU will also collect particulate matter (PM) emissions, crankcase methane emissions, and additional information such as diesel fuel flow rate, natural gas fuel flow rate, a leak/loss audit of fueling equipment, and natural gas fuel samples. By measuring both diesel and natural gas-powered engines, WVU will be able to compare the emission of the older technologies (diesel fuel) with the newly implemented natural gas technologies. This will allow WVU to quantitatively report on these new sources of CH_4 emissions and overall efficiency of these technologies. These findings will be invaluable to the growing unconventional well development and natural gas industries.

3.3 Laboratory Research

In addition to the field data collection campaign, WVU will conduct laboratory research under the second half of this research program. The engine activity of the prime movers collected in the field will be used to create representative duty cycles to operate a scaled engine at WVU's transient engine dynamometer test cell. These test cycles will be developed for heavy-duty trucks, drilling engines, and hydraulic fracturing engines. WVU has obtained a 15L over-the-road engine, rated at 475 hp. The engine will be outfitted with a dual fuel retrofit kit. WVU has also obtained an 8.9L dedicated natural gas engine. The stoichiometric engine will include its three-way catalyst. These engines will be used as scaled test platforms for controlled experiments. This research will be conducted using WVU's Code of Federal Regulations 1065 compliant emissions measurement systems under controlled conditions. The research will examine the methane emissions associated with the scaled engines exhaust and crankcase. Many modern engines use closed crankcase ventilation and WVU will examine the total potential for methane emissions reductions available by this practice. WVU has collaborated with Hypercat Advanced Catalyst Products to examine the effect of a low temperature methane catalyst for its ability to reduce these new sources of methane emissions. Hypercat will utilize field data and conduct reactor tests to develop a catalyst formulation to test in WVU's research effort. WVU will report on the initial findings of this option for emissions reduction.

The last major area of research will be to operate the laboratory engines using a variety of fuel blends. It is realized that many companies are looking to use local pipeline, gathering, or well-head gas in order to realize the most savings. The variation in gas composition could significantly affect the performance, regulated emissions, and methane emissions from these emerging technologies [40-42]. WVU will operate the engine using pure methane which represents operation on LNG, pipeline quality natural gas representing those fleets using compressed natural gas, and three blends of natural gas representing various shale plays. See Table 2 for the major component compositions of the major US shale plays.

Table 1. Variation in composition of major components of US Shale Gas, major components shown as percentages [43].

Shale Play	Components				
	C1	C2	C3	CO_2	N_2
Barnett	80.3-90.7	2.6-11.8	0-5.2	0.3-2.7	1.0-7.9
Marcellus	79.4-95.5	3-16.1	1.0-4.0	0.1-0.9	0.2-0.4
Fayette	97.3	1	0	1	0.7
New Albany	87.7-92.8	0.8-1.7	0.6-2.5	5.6-10.4	N/A
Antrim	27.5-85.6	3.5-4.9	0.4-1.9	0-9.0	0.7-65
Haynesville	95	0.1	0	4.8	0.1

3.3 Conclusion

The natural gas extraction industry continues to move in the direction of utilizing domestic natural gas to displace diesel fuel in order to reduce operating costs. Ideally, local wellhead gas would be utilized, but this is beset with engine control and fueling road blocks in the near term. Additionally, pending and future greenhouse gas emission regulations, of which methane is a major contributor, have the potential to slow this change as risks to the industry. This is due to the fact that these new technologies currently do not apply aftertreatment or crankcase methane emissions reduction techniques. WVU's CAFEE believes that dual fuel retrofit strategies will be implemented in the near term due to lower risk to the producers, but unconventional gas producers will migrate to dedicated stoichiometric natural gas engines in the long term to realize the largest cost benefit of utilizing domestic natural gas. The migration from diesel fuel to dual fuel or dedicated natural gas engines also has the potential to reduce currently regulated emissions from these sites. The impact of shifting from diesel fuel only to dual fuel or dedicated natural gas engines, however, has not been fully quantified for pending methane and other non-regulated emissions that may have direct site, local community, or global impacts. WVU's CAFEE continues to investigate and assess methane emissions resulting from industry trends. The findings of this study will be available in early 2016.

Figure 1: Comparison of tailpipe methane emissions from dual fuel conversion and dedicated natural gas vehicles.

Figure 2: Schematic of in-cylinder plume for dual fuel combustion.

Figure 3: Crankcase methane emissions as compared to exhaust methane emissions from a dual fuel conversion.

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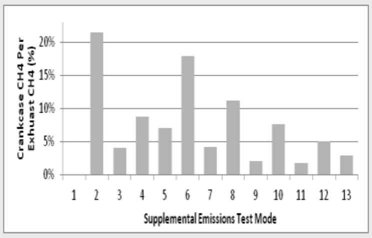
REVIEW

Shale gas production continues to grow and will dominate natural gas production for the foreseeable future. Advances in horizontal drilling and hydraulic fracturing are driving this trend but these energy intensive processes have typically been fuelled by diesel. The current trend from producers and operators is to convert equipment to operate as dual fuel or dedicated natural gas to achieve economic savings; however, these technologies result in new sources of methane emissions.



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Trends in Unconventional Well Development – Methane Emissions Associated with the Use of Dual Fuel and Dedicated Natural Gas Engines

APPENDIX B

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Development of engine activity cycles for the prime movers of unconventional natural gas well development

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TECHNICAL PAPER

Development of engine activity cycles for the prime movers of unconventional natural gas well development

Derek Johnson, Robert Heltzel, Andrew Nix, and Rebekah Barrow

Center for Alternative Fuels, Engines, and Emissions, West Virginia University, Morgantown, WV, USA

ABSTRACT

With the advent of unconventional natural gas resources, new research focuses on the efficiency and emissions of the prime movers powering these fleets. These prime movers also play important roles in emissions inventories for this sector. Industry seeks to reduce operating costs by decreasing the required fuel demands of these high horsepower engines but conducting in-field or full-scale research on new technologies is cost prohibitive. As such, this research completed extensive in-use data collection efforts for the engines powering over-the-road trucks, drilling engines, and hydraulic stimulation pump engines. These engine activity data were processed in order to make representative test cycles using a Markov Chain, Monte Carlo (MCMC) simulation method. Such cycles can be applied under controlled environments on scaled engines for future research. In addition to MCMC, genetic algorithms were used to improve the overall performance values for the test cycles and smoothing was applied to ensure regression criteria were met during implementation on a test engine and dynamometer. The variations in cycle and in-use statistics are presented along with comparisons to conventional test cycles used for emissions compliance.

Implications: Development of representative, engine dynamometer test cycles, from in-use activity data, is crucial in understanding fuel efficiency and emissions for engine operating modes that are different from cycles mandated by the Code of Federal Regulations. Representative cycles were created for the prime movers of unconventional well development—over-the-road (OTR) trucks and drilling and hydraulic fracturing engines. The representative cycles are implemented on scaled engines to reduce fuel consumption during research and development of new technologies in controlled laboratory environments.

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Introduction

The United States has experienced growth in the natural gas industry over the past decade. Annual gross withdrawals of natural gas in the United States have increased 25% since 2005 from 23 million to over 31 million cubic feet (U.S. Energy Information Administration [EIA], 2016). The U.S. Energy Information Administration (EIA) also estimates that there are about 2.276 trillion cubic feet (Tcf) of recoverable resources of dry natural gas in the United States, which at the current rate of consumption is enough to last about 84 years (EIA, 2015). These advances are a product of the new technologies of horizontal drilling and hydraulic fracturing. In order to utilize these resources, strategies are being implemented to reduce costs and emissions. One strategy involves displacing diesel fuel with natural gas in the prime movers associated with well development via either dual-fuel or dedicated natural gas applications. These prime movers, or major diesel consumers, include heavy-duty over-the-road (OTR) trucks and high-horsepower drilling and fracturing engines.

The process of unconventional well development consists of four major steps: planning and preparation of the well pad site, drilling, casing and cementing, and completion and stimulation (Canadian Society for Unconventional Resources, 2012). The primary consumer of fuel during preparation of the site is OTR trucks. Heavy-duty OTR trucks transport gravel, dirt, and other materials to and from the site. Vertical and horizontal drilling applications use high-horsepower engines to power rigs. Heavy-duty OTR trucks also haul water, drilling fluids, and other supplies during drilling. The drilling company often performs casing and cementing that involve the same engines as drilling, with an increase in truck traffic. Hydraulic fracturing is the most energy-intensive step in the process and involves the use of high-horsepower fracturing engines and large amounts of truck traffic for the delivery of water, sand, and fracturing chemicals. It is estimated that a Marcellus Shale well pad with four wells requires 20,000–30,000 truck trips during the completion of those wells—yielding up to 4 million truck trips per year for the entire Marcellus region

CONTACT Derek Johnson derek.johnson@mail.wvu.edu Center for Alternative Fuels, Engines, and Emissions, West Virginia University, PO Box 6106, Morgantown, WV 26505, USA.

(Carr et al., 2012). Drilling engines operate continuously from rig setup until drilling, casing, and cementing are completed. The Texas Commission on Environmental Quality, in a survey of 1261 wells, found that the average drilling duration for a well was between 8 and 27 days depending on the depth of the vertical section and length of the horizontal sections. On average, the drilling rigs consisted of 2.15 engines, with an average size of 1381 horsepower (hp) each. These engines operate on average 62.6 hr per 1000 feet drilled at an average load of 48.5% (Baker and Pring, 2009). A report by Global Hunter Securities in collaboration with Prometheus Energy states that the average drilling rig uses between 62.5 and 83.3 gallons of diesel fuel per hour, resulting in 1500–2200 gallons of diesel per day (Kelly, 2012). A study by Argonne National Laboratory (ANL) assumed that a rig ran on one 2000-hp engine at 45% load and consumed 0.06 gal/hp/hr in its analysis. The study focused on four major shale plays and the fuel consumed in these plays depended mostly on the depth of the well and the amount of time required for drilling. Diesel fuel consumption by shale play ranged from 43,041 gallons for the Fayetteville Shale to 85,845 gallons for the Haynesville, with the Barnett and Marcellus within this range (Clark et al., 2012).

High-horsepower diesel engines also power hydraulic fracturing pumps. A typical fracturing fleet features engine capacities over 20,000 hp. An average site requires 8–12 fracturing pumps, but some require up to two dozen, each rated between 1500 and 2500 hp. Fracturing a well can consume between 2000 and 8000 gallons of diesel fuel per day. The University of Michigan performed site surveys in the Marcellus and Eagle Ford shale plays and showed average fleet sizes of 14 and 16 engines, respectively. The average fuel consumption during stimulation of a well in these shales was 20,800 and 22,100 gallons, respectively. The engines at both sites were Caterpillar 3512Cs (Peoria, IL) rated at 2250 hp.

Prime mover engines are subject to emissions compliance regulations as tested over specific engine cycles. The primary engine test cycle over which on-road heavy-duty diesel engines are certified is the transient Federal Test Procedure (FTP) engine dynamometer test cycle defined in Code of Federal Regulation (CFR) Title 40 Subchapter C Part 86 Appendix I. The new greenhouse gas (GHG) standards also use the FTP cycle for certification of vocational engines. This cycle is a series of speed and torque points normalized to a percentage for applicability to all engines (DieselNet, 1999). As a result of the consent decrees, engine certification also involves the Supplemental Emission Test (SET) and not-to-exceed (NTE) testing, in addition to the FTP cycle (DieselNet, 2015). Certification of nonroad engines is also based on the emissions standards outlined by the CFR. Engine tests occur on dynamometers based on the procedures of CFR Title 40 Chapter I Subchapter U Part 1039. Certification of Tier 1–3 engines requires operation over steady-state tests. The International Organization for Standardization ISO 8178 is the standard for nonroad engine emissions testing. This test, also known as the Non-Road Steady Cycle (NRSC), consists of five modes of steady-state operation and is applicable to both drilling and hydraulic fracturing engines (DieselNet, 2001).

Although these cycles are well defined, they may not be representative of in-use operation. Additionally, research and development on full-scale engines is energy intensive and cost prohibitive from a fueling standpoint. Therefore, our goal was to collect representative in-use activity data and develop a method to create representative cycles for application on scaled engines within our test cell.

Data collection

OTR trucks

Collection of data from OTR trucks servicing the unconventional well development industry was performed over a 6-month period, beginning June 6, 2014, and concluding January 9, 2015. The vehicles targeted for data collection were heavy-duty diesel vehicles that were travelling to and from unconventional natural gas wells in the Marcellus Shale region. These heavy-duty OTR trucks consisted of those hauling water, sand, and gravel. Over 100 companies in the Marcellus and other shale plays were contacted. Seven different companies located throughout Ohio, Pennsylvania, and West Virginia provided access to 25 vehicles for data collection. Vehicle instrumentation was random within each fleet, and no specifications on vehicle age, mileage, or other variables were required. Of the 25 vehicles, 18 were water haulers, 6 were sand haulers, and 1 carried gravel for site preparation. The engines populating the vehicles consisted of 18 Cummins ISX-15 (Columbus, IN) engines, 4 Caterpillar C-15 (Peoria, IL) engines, 2 Volvo D13 (Greensboro, NC) engines, and 1 Mack MP8 (Greensboro, NC). Table 1 provides a summary of the vehicles instrumented. It is noted that the vehicles all operated within the greater Marcellus region and their activity may not be representative of all unconventional natural gas shale plays. The number of truck trips varies by well pad, region, infrastructure, and other logistical variables. Three studies have estimated that a majority of truck trips per well development are attributed to hauling water to and from sites (67–78% of all truck trips) (Maryland Department of the Environment [MDE], 2014; Felsburg Holt and Ullevig, 2013; Massachusetts Institute of Technology [MIT], 2011). Of the 25 random vehicles in this program, 68% were water-hauling trucks.

Table 1. Well service vehicle data collection information.

Truck no.	Comp.	Hauling service	Make	Model	Size (hp)	Chassis	Vehicle year	Start date	End date
1	A	Water	Cummins	ISX-15	500	Peterbilt	2012	5-Jun	30-Jun
2	A	Water	Cummins	ISX-15	500	Peterbilt	2012	7-Jul	16-Jul
3	A	Water	Mack	MP8	505	Mack	2011	7-Jul	16-Jul
4	A	Water	Cummins	ISX-15	500	Freightliner	2012	7-Jul	16-Jul
5	A	Water	Cummins	ISX-15	500	International	2005	7-Jul	16-Jul
6	B	Gravel	Volvo	D13	435	Volvo	2002	29-Jul	31-Jul
7	C	Sand	Cummins	ISX-15	500	Kenworth	2013	1-Aug	13-Aug
8	C	Sand	Cummins	ISX-15	500	Kenworth	2013	1-Aug	13-Aug
9	C	Sand	Cummins	ISX-15	500	Kenworth	2009	1-Aug	13-Aug
10	C	Sand	Cummins	ISX-15	500	Kenworth	2008	1-Aug	13-Aug
11	D	Water	Caterpillar	C-15	550	Peterbilt	2012	15-Aug	28-Aug
12	D	Water	Cummins	ISX-15	500	Kenworth	2013	15-Aug	26-Aug
13	D	Water	Caterpillar	C-15	550	International	2009	15-Aug	28-Aug
14	E	Sand	Caterpillar	C-15	550	Peterbilt	2006	18-Sep	24-Sep
15	E	Sand	Cummins	ISX-15	500	Peterbilt	2009	26-Sep	22-Oct
16	F	Water	Cummins	ISX-15	500	Peterbilt	2013	19-Nov	2-Dec
17	F	Water	Cummins	ISX-15	500	Peterbilt	2013	19-Nov	2-Dec
18	F	Water	Cummins	ISX-15	500	Peterbilt	2013	19-Nov	2-Dec
19	F	Water	Cummins	ISX-15	500	Peterbilt	2013	19-Nov	2-Dec
20	G	Water	Cummins	ISX-15	500	Freightliner	2012	17-Dec	5-Jan
21	G	Water	Caterpillar	C-15	550	Peterbilt	2010	17-Dec	5-Jan
22	G	Water	Cummins	ISX-15	500	Kenworth	2011	17-Dec	5-Jan
23	G	Water	Volvo	D13	500	Kenworth	2012	17-Dec	5-Jan
24	G	Water	Cummins	ISX-15	500	Peterbilt	2010	5-Jan	9-Jan
25	G	Water	Cummins	ISX-15	500	Peterbilt	2013	5-Jan	9-Jan

Data collection occurred at a rate of 1 Hz using DAWN J1939 Mini Loggers (HEM Data, 2015). Although dozens of engine control unit (ECU) parameters were available and ultimately collected, the only parameters relevant to the creation of engine test cycles under this work were engine speed and percent load at current speed. The resulting data set included 4,724,800 data points, or over 54 days of data. The International Society of Automotive Engineers (SAE) under J1939 protocol defines the parameters as follows:

Engine percent load at current speed—SPN 92: The ratio of actual engine percent torque (indicated) to maximum available at the current engine speed, clipped to zero torque during engine braking.

Engine speed—SPN 190: Actual engine speed calculated over a minimum crankshaft angle of 720 degrees divided by the number of cylinders ("Vehicle Application Layer"; SAE, 2015).

Drilling

Drilling activity data collection occurred during the drilling of two horizontal wells in Westover, West Virginia. The collection of data occurred over a period of 11 days from September 9, 2015, to September 21, 2015. The rig used three Caterpillar 3512C generator units, rated at 1101 kW. These engines were outfitted with dynamic gas blending (DGB) kits allowing the engines to run in either dual fuel or diesel only mode. Data collected occurred on a single engine that operated continuously during rig setup, preparation, pipe tripping (PT), and steady-state drilling (SSD).

The engine control unit broadcasted data, which were recorded using a nine-pin Deutsch connector and a VIA HDV100A1 from B&B Electronics (Ottawa, IL). An in-house software recorded SAE J1939 parameters. After conversion of data to CSV format, it was determined that only 233 of the 311 hr were valid.

Use of activity logs from the drilling company assisted in sorting data. Table 2 presents a breakdown of the engine activity. This breakdown shows the amount of time spent performing each type of activity necessary for the completion of drilling. Note that data were obtained during the horizontal portions of the wells and may not be representative of the vertical or conventional drilling portion. In addition, drilling activity varies by well, depth, operator,

Table 2. Drilling activity breakdown.

	ECU collection		Overall	
Activity type	Hours	Percent	Hours	Percent
Rig up	4	1%	101	12%
Drilling	160	51%	216.5	25%
Reaming	3	1%	8	1%
Coring	0	0%	19	2%
Condition and circulate	16.5	5%	56.5	6%
Trips	21	7%	126.5	14%
Lubricate rig	10.5	3%	14.5	2%
Repair rig	9	3%	17.5	2%
Cut off drilling line	1	0%	3	0%
Wireline logs	0	0%	105.5	12%
Run casing and cement	27	9%	77	9%
Wait on cement	8.5	3%	8.5	1%
Nipple up B.O.P.	5	2%	16.5	2%
Test B.O.P.	12	4%	25.5	3%
Directional work	13	4%	21	2%
Other	20.5	7%	58.5	7%
Total	311	100%	875	100%

Note. B.O.P. = blowout preventer.

and shale play; but in discussions with the site operators, the activities were typical for the Marcellus region.

Hydraulic fracturing

Collection of hydraulic fracturing activity occurred during two separate campaigns with two different fracturing fleets. Collection of data was similar to drilling: with a nine-pin Deutsch connector, serial cable, VIA model HDV100A1 from B&B Electronics (Ottawa, IL), and a laptop computer. The first data collection effort occurred over 21 days between July 19, 2015, and August 8, 2015, from a well pad in central West Virginia. Data collection occurred on four different hydraulic fracturing pumps during the stimulation of six wells. Cummins QSK50 engines, rated at 1678 kW, powered these pumps.

The second data collection effort occurred at a well pad near Morgantown, West Virginia. Data collection occurred on a Caterpillar 3512B-HD engine rated at 1678 kW over a period of 7 days from November 5, 2015, to November 12, 2015. The engine included a dynamic gas blending kit allowing it to operate in either diesel only or dual fuel mode. We collected data from 12 fracturing stages. We eliminated data from three stages due to erratic values. The hydraulic fracturing engines operated at rated speed except for when the engines were idling between stages, which was limited. Table 3 presents a summary of the data. Since the engines typically operated at rated speed, the most important engine parameter was percent load at current speed. Note that all OTR and drilling data were collected at 1 Hz. In some cases of hydraulic fracturing, data were collected at 10 Hz (due to hardware), but a 10-point average was used to down-sample the data for use as 1 Hz. Both data sets were collected in the Marcellus Shale region. In addition, hydraulic stimulation activity varies by well, depth, operator, and shale play; but in discussions with the site operators, the activities were typical for the Marcellus region.

Cycle development

Numerous approaches are available to create engine or chassis dynamometer test cycles, including Markov chain Monte Carlo simulations, micro-trips, or day-in-the-life cycles (Clark et al., 2007; Steven, 2001; Ullman, 1999). The technique selected was a stochastic second-by-second concatenation, which utilized Markov chain theory. We applied the same method to all three types of cycle development. We selected a starting period of engine idle and from there the Markov chain technique was allowed to progress freely based on the transition probability matrix of each of the respective data sets. We imposed a time limit of 30 min (1800 sec) on each of the cycles. The FTP cycle is 20 min long (DieselNet, 1999); however, research suggests that longer Markov chains were more representative when attempting to match a distribution (Geyer, 1992; Smith, 2003). Previous studies on cycle development used 30 min as the time of the cycle (Steven, 2001). We selected 30 min to align with Steven (2001) and to provide a longer than conventional engine cycle length. Longer cycles should be examined under future work, but due to fuel restrictions, we retained 30 min as the upper limit such that a single cold start and three repeated hot starts could be conducted using the same compressed natural gas cylinder bank.

Table 3. Hydraulic fracturing data collection information.

Stage	Site	Engine make	Model	Data rate (Hz)	Length of stage (sec)	Average speed (rpm)	Average load (%)	Average power (kW)
1	A	Caterpillar	3512B	1	5209	1842	66.37	1114
2	A	Caterpillar	3512B	1	4672	1873	52.32	878
3	A	Caterpillar	3512B	1	4001	1937	79.57	1335
4	A	Caterpillar	3512B	1	4914	1866	60.45	1014
5	A	Caterpillar	3512B	1	5226	1936	79.69	1337
6	A	Caterpillar	3512B	1	4638	1936	84.81	1423
7	A	Caterpillar	3512B	1	6271	1842	66.57	1117
8	A	Caterpillar	3512B	1	5134	1823	73.76	1238
9	A	Caterpillar	3512B	1	5234	1936	77.28	1297
10	A	Caterpillar	3512B	1	4879	1602	73	1223
11	B	Cummins	QSK50	10	4860	1937	56.31	945
12	B	Cummins	QSK50	10	5810	1948	50.71	851
13	B	Cummins	QSK50	10	10770	1466	49.5	831
14	B	Cummins	QSK50	10	6130	1947	50.47	847
15	B	Cummins	QSK50	10	5130	1950	49.27	827
16	B	Cummins	QSK50	10	2380	1948	52.82	886
17	B	Cummins	QSK50	10	5910	1949	52.5	881
18	B	Cummins	QSK50	10	5890	1946	48	805
19	B	Cummins	QSK50	1	2507	1949	54.48	914
20	B	Cummins	QSK50	1	3093	1947	53.01	890
21	B	Cummins	QSK50	1	1555	1950	50.09	841
22	B	Cummins	QSK50	10	6850	1944	50.26	843
23	B	Cummins	QSK50	10	5080	1950	54.73	918
24	B	Cummins	QSK50	1	3657	1942	51.31	861

Review

Wide varieties of sciences use Markov chain Monte Carlo (MCMC) simulations as a way to estimate probabilities and perform numerical integration. MCMC is "a general method for the simulation of stochastic processes having probability densities known up to a constant proportionality" (Geyer, 1992).

The theory behind MCMC is subdivided into Markov chain techniques and Monte Carlo simulations. A Markov chain is a stochastic process that has stationary transition probabilities. The Markov chain is a string of concatenated values from a defined "state space," or data being sampled (Smith, 2003). A Markov chain is often described by saying that there exists some state, or event, and that state contains a transitional probability matrix, which gives the likelihood of the next state.

The next state in the chain depends only on the current state and its transition probability matrix. The Markov chain is "stationary" if any state in the chain has a transitional probability distribution that is independent of the location of the state. Thus, probability of reaching the next state is the same for all states in the chain and likely independent on initial distribution. If a Markov chain is not stationary, then the transition probabilities change as the chain moves further from the initial state. As the length of the chain increases, the distribution of the states becomes less dependent on the initial state and more dependent on the transition probabilities (Geyser, 2011).

If an overall distribution defines each states transition probability matrix and if the chain becomes "long," the distribution of the chain itself will approach the overall distribution (Smith, 2003). The most effective way to reach this desired distribution is by allowing the Markov chain array to grow large. The actual size necessary to properly represent a distribution will be dependent on the size of the data set, and the problem at hand. Cycle development extensively employs Markov chains, as shown in the next section. MCMC simulations expand on the idea of Markov chains, but flip the objective of the problem. Rather than attempting to find the distribution of a specific Markov chain, MCMC starts with a defined distribution and attempts to create a Markov chain that has this same distribution (Smith, 2003). When this is the case, one knows the distribution of interest and the Markov chain proceeds in the same stochastic manner until it has an array length, which is long enough to adequately represent the distribution. Researchers employ MCMC techniques to genomics, variable selection in regression, spatial statistics, longitudinal studies, mathematical chemistry, statistical physics, or when more simplistic techniques cannot be used.

The work performed by Smith is the most relevant example of engine test cycle development using a MCMC method for heavy-duty on-road vehicles (Smith, 1978). Researchers commonly use MCMC for generation of drive cycles. Ohio State University's Center for Automotive Research generated driving cycles of plug-in hybrid electric vehicle (PHEV) using a Markov chain technique. Researchers collected data from nine PHEV passenger cars consisting of over 70,000 miles of data that were segmented into 530 "sessions" defined from key-on to key-off (Gong et al., 2011). Dembski et al., also of Ohio State University, used similar techniques and calculations of sequence occurrence probabilities to analyze drive cycles for passenger cars. Kinematic sequences defined by velocity and acceleration were developed and linked together based on the probability of each type of sequence occurring, essentially utilizing a Markov chain to create drive cycles (Dembski et al., 2002). Researchers at University of California–Davis used Markov chains to produce drive cycles for a number of research programs from light-duty vehicles and chase vehicles (Lin and Niemeier, 2002; Lin and Niemeier, 2003; Dai et al., 2008).

Data processing and second-by-second concatenation

OTR trucks

We used MATLAB (MathWorks, Natick, MA) for data processing and cycle development algorithms. Normalization of engine data is necessary to compare engine operation between different sizes, makes, and models. All normalized data points contain a value from 0 to 1, representing 0–100% of the maximum possible value. The parameter percent load at current speed is an example of a normalized parameter. This parameter is based on the lug curve of the engine and is broadcasted as a percentage of the maximum possible load at a given engine speed. Previous studies considered this value similar to percent engine torque, especially at high loads (Clark et al., 2007). We used this parameter as an equivalent value of normalized percent torque for this methodology. Engine speed normalization was based on the equation used for denormalizing speed from the CFR Title 40 Chapter I Subchapter C Part 86 Subpart N Section 86.1333. Normalizing engine speed was performed using eq 1. It is noted that these engines were all diesel fuel engines, which typically include a factor of 112% of rated speed. Any data within ±2% of 0% speed were set to 0, and the same was done for engine percent load. Any speed between rated and 102% of rated was set to rated speed or 1. Of the over 4 million data points collected, speeds between rated and governed only represented 0.29% of activity and were excluded. It is also noted that all OTR data were collected in the Appalachian Basin and OTR activity may differ by shale play.

$$\text{Normalized Speed (\%)} = \frac{[\text{Engine Speed (rpm)} - \text{Idle Speed(rpm)}]}{[\text{Rated Speed (rpm)} - \text{Idle Speed (rpm)}]} \quad (1)$$

Elimination of some data was necessary because the engines often broadcasted false data or trended to an infinite value if the size of the file became too large. Data were deemed invalid if the broadcasted value was outside of the defined limits of a specific parameter and the cause was not known. The second source of invalid data was due to hardware and software issues where an error in recording caused subsequent data to increase in value through the duration of the recording. After filtering of invalid data, speed and load were arranged in a two-column array and concatenated, for each engine.

Data binning used 5% increments for both speed and load. The bins contained values of speed and load greater than or equal to the governing value of the current bin and less than the governing value of the next highest bin. Figure 1 shows the distribution of data. Note that nearly 20% of the activity data occurred in a single bin. This was bin (1, 3) and it contained nearly all of the points that occurred at idle engine speed.

Once the algorithm binned the current point in the distribution matrix, analysis of the next point occurred. The algorithm binned this data point into the transition matrix of the bin of the previously selected point and the overall distribution matrix. The program used a multi-layered structure to allow each bin of the overall distribution matrix to also contain a secondary transition matrix of the same size. This was necessary because of the stochastic logic of the Markov chain technique. Once the entire length of the array was binned, a normalized distribution was created by dividing the size of each data bin by the total length of the array. Statistics of the data set were calculated. In addition, tabulated were average speed and load, and time at idle. The idle data points were excluded from a second calculation so that the non-idle speed and load averages could be determined (see Table 4).

Drilling engines

Drilling engines operated at nearly constant rated speed and in this study operated at 1200 revolutions per minute (rpm). The binning logic used was similar to that used for OTR trucks except that it focused only on load. Figure 2 shows the distribution of engine load bins.

We further subdivided data into two categories of load, high load and low load, for the purpose of calculating statistics. High load was any value at or above 40% and low load below 40%. We selected 40% to ensure that all steady drilling operations were high load. Some of these events occurred at steady-state values below 50%, but none occurred below 40%. The idle time of the data was also calculated and included operation at 0% load—a small overall portion of the time. The average value and the normalized time of high- and low-load operations were calculated. Table 5 shows the statistics of these data.

Hydraulic fracturing engines

Hydraulic fracturing data binning used the same methodology as drilling. Data bins were in 5% increments, forming an overall distribution matrix by stepping through each point of the array. Figure 3 shows the distribution of these data.

Data were sorted into idle (0% load), low load (points below 40% load), and high load (points at or above 40% load). The average overall load, high load, and low load as well as normalized idle, low-load, and high-load times were calculated. Table 6 provides the tabular statistics of these data.

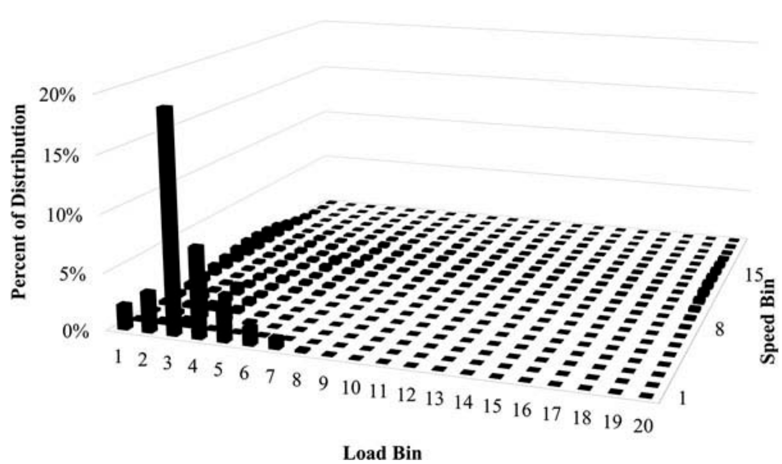

Figure 1. Truck data distribution.

Table 4. Trucking data statistics.

Parameter	Value
Average speed (%)	29.2
Average load (%)	23.1
Average non-idle speed (%)	46.9
Average non-idle load (%)	28.3
Normalized idle time (%)	37.6
Normalized non-idle time (%)	62.4
Total time (sec)	4,724,800

Table 5. Drilling data statistics.

Parameter	Value
Average load (%)	43.0
Average high load (%)	60.2
Average low load (%)	19.0
Normalized high-load time (%)	58.4
Normalized low-load time (%)	41.2
Normalized idle time (%)	0.4
Total time (sec)	840,238

MCMC

The cycle began with a period of idle, and from there the Markov chain technique progressed freely based on the transition probability matrix of each of the respective data sets. Based on the nature of driving and observations made during data collection, it was determined that, at a minimum, the first 30 sec should be idle. Therefore, the algorithm sampled points between 1 and 30 from the zero-speed row of the distribution matrix and weighted on the transition probability matrix of the current bin.

Once 30 sec of idle were completed, the overall distribution matrix was open for sampling and the Marko chain proceeded. We employed a weighted sampling technique to pseudorandomly select the next bin of the cycle. Columns and rows had separate weights. The weights of each were a function of the ratio of the time in a given bin to the total time spent in the column or row. Then, the row of the next bin was selected by sampling 1–20 (the number of rows), based on the weights of the rows developed previously. Selection of the next column bin used the same manner. Once the row and column of the next bin were found, the bin was defined and the algorithm randomly selected from the bin's population. This point represented the next point in the cycle and was added to the end of the current cycle array. The transition matrix of the selected bin then governed the weights used for selection of the next bin.

The Markov chain continued to sample using the defined method up to 1770 sec. It was determined that the vehicle should return to a state of idle 30 sec before the end of the test to simulate real-world activity and also mark the end of the cycle. If the speed bin of the cycle at this point was above 10, meaning normalized speed was above 50%, an intermediate point was required at point 1771, to create an acceptable derivative of speed. Sampling for that bin moved to the row that was five bins lower than the current bin. Once the current speed bin was below 10, the speed row was forced to 1, the idle speed row, and the process continued as it did in the first 30 sec of cycle construction, with selection of points based only on the load columns until the cycle reached a length of 1800 sec.

With the cycle completed, we imposed limitations on the cycles in two steps. The first was to search the

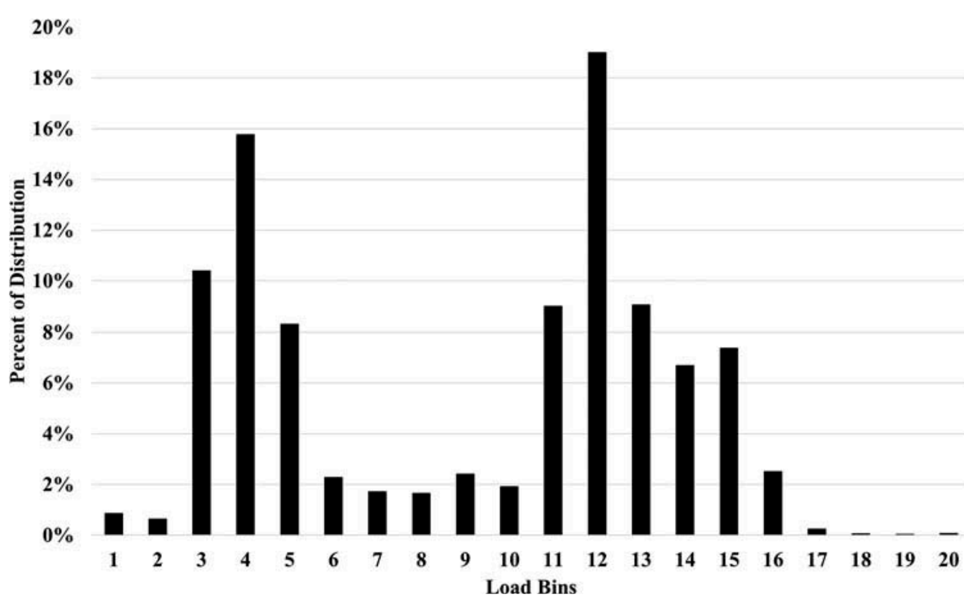

Figure 2. Drilling data distribution.

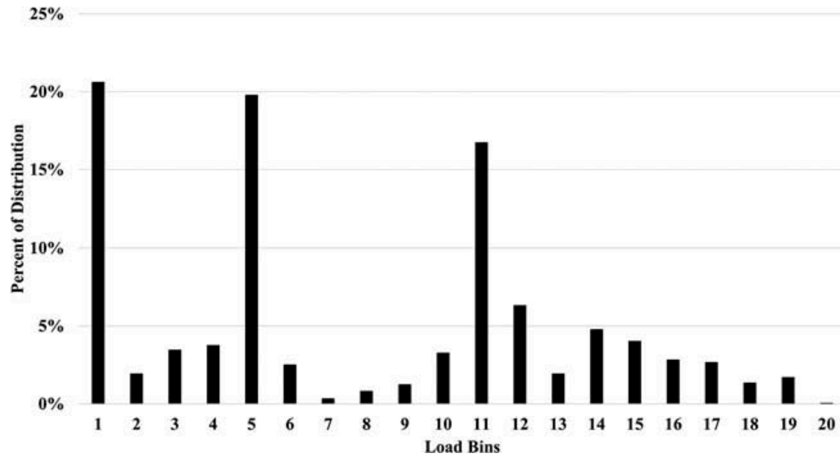

Figure 3. Fracturing data distribution.

Table 6. Fracturing data statistics.

Parameter	Value
Average load (%)	35.5
Average high load (%)	61.5
Average low load (%)	20.3
Normalized high-load time (%)	46.8
Normalized low-load time (%)	33.2
Normalized idle time (%)	19.9
Total time (sec)	239,905

cycle and determine if there were any single points of nonzero speed between points of zero speed. This type of activity made segmentation of cycles, discussed later, difficult and was not necessary to represent real-world engine operation. Once located, we forced these points to zero speed. As an example, in the creation of 100 cycles, each with a length of 1800 sec, only 29 of these points occurred (0.016%) and were forced to zero. The second step was that all points below 2% normal speed or load were forced to zero. The reduction of these points did not change the overall distribution of the cycle and had no effect on idle time, and we verified this by applying the change to a randomly generated sample population of 100 cycles.

We created a distribution of each cycle by stepping through the cycle and binning its points in the same manner as the overall in-use data. The same average statistics were determined from the cycles as from the data. These values included average speed, average load, average non-idle speed, average non-idle load, and normalized idle time. We compared the distribution and average statistics with those of the data and calculated values that defined the representativeness of the individual cycles. These values included the "statistical value" (SV), the "distribution value" (DV), and the "performance value" (PV). Absolute differences between the desired data set and the created cycles defined these values. The DV was defined by taking the absolute difference between the cycle and data of the time distribution of each bin. Each absolute difference was multiplied by 0.05 (equal weighting factor for each of the 20 bins, summing to unity), and the sum of those weighted absolute differences determined the value. Equation 2 gives the definition of DV.

$$\mathrm{DV} = \sum_{i=1}^{20}\sum_{j=1}^{20} 0.05 \times \left|\mathrm{bin}(i,j)_{\mathrm{cycle}} - \mathrm{bin}(i,j)_{\mathrm{data}}\right| \quad (2)$$

The SV was similar except that it used the absolute differences of the statistics. Each of the five statistics previously defined were given an equal weighting of 0.2 (equal weighting factor for the five statistical categories, summing to unity), and the sum of the weighted differences was used to calculate the SV, as shown by eq 3.

$$\mathrm{SV} = \sum_{i=1}^{20} 0.2 \times \left|\mathrm{stat}(i)_{\mathrm{cycle}} - \mathrm{stat}(i)_{\mathrm{data}}\right| \quad (3)$$

The PV was calculated by combining the DV and SV with equivalent weights of 0.5 and summing them, as shown by eq 4.

$$\mathrm{PV} = 0.5 \cdot \mathrm{SV} + 0.5 \cdot \mathrm{DV} \quad (4)$$

We used the above approach for drilling and fracturing engines, with the only major difference being idle time at the beginning and end of each cycle. Based on in-use statistics, we determined that only 10 sec of low load were required at the beginning and end of the cycle.

The use of Markov chain logic should create cycles, which have a similar distribution to that of the overall data. Sometimes, however, a cycle can be stuck in a certain bin or "space," or a cycle may move through the space while choosing low probability events—a side effect of the random nature of the Markov chain. MCMC simulation is the idea of creating a Markov chain that has an equivalent distribution to the one desired. This can theoretically be accomplished with the creation of one long chain or several smaller chains. Ideally, a cycle constructed under the logic of a Markov chain would exactly match the desired distribution if the cycle grew to infinite length. The other option available to best represent the desired distribution would be to create a "large" number of cycles until one matches the desired distribution. The first option could not be applied, as cycles must have a reasonable length. The second option raised a number of questions. Since an infinite number of cycles could not be created, the main issue was answering the question: "How large must the sample size be for a cycle of optimal representation to be found?" It was not practical to create hundreds of thousands of cycles to find an ideal candidate. In an initial attempt to find the optimal cycle for each of the three prime movers, we used Monte Carlo simulation to create populations of 10,000 cycles for each prime mover. The best PV from these populations of OTR truck, drilling, and hydraulic fracturing cycles were 0.0327, 0.0038, and 0.0323, respectively.

Optimization with a genetic algorithm

Review

The concept of the genetic algorithm (GA) stems from Darwin's theory of evolution, developed in 1859. The governing principle of the theory is survival of the fittest. The key aspect that separates GAs from algorithms that are more traditional is the use of the population rather than analyzing one individual at a time (Sivanandam and Deepa, 2008). GAs are advantageous in solving complex problems for several reasons. These advantages include their ability to discover global optimum solutions, their ability to handle large and poorly understood search spaces, their performance with large-scale optimization, and their easy application to a large variety of problems (Sivandam and Deepa, 2008). These advantages make GAs a choice for difficult problems such as cycle development. Several works from West Virginia University (WVU) have used GAs for problems involving cycle development (Marlow, 2009; Perhinschi et al., 2011).

Design

The first issue encountered was determining how to define the chromosomes and genes of the GA population. The overall cycles constructed by the Markov chain technique defined the chromosomes or individuals. The individuals were composed of 1800-point arrays of speed and load pairs. These individuals all had SVs, DVs, and PVs associated with them as well as distribution matrices and average cycle statistics. We created genes from these individuals. Typically, when using GAs, individuals are converted to binary strings and bits in the strings represent the genes. It was impractical to convert the entire array to binary representation, and so another methodology defined genes. Each cycle was "segmented" into portions of different activity. We defined segments in a similar manner to "micro-trips" from previous studies (Dai et al., 2008; Clark et al., 2007; Perhinschi et al., 2011). Instead of using vehicle speed to define micro-trips, we selected engine speed. Periods of idle and non-idle represented different segments. An idle segment was any length of the cycle longer than 10 sec in which the speed remained at 0% of rated. A non-idle segment was any length of the cycle in which there were more than 10 consecutive seconds of non-idle operation. One hundred random cycles from the 10,000 cycles generated by the MCMC defined the initial population.

With genes defined, we then selected and implemented genetic operators. The GA applied mutation first. The cycles selected for mutation were randomly chosen based on the mutation rate. The GA applied a random number for each cycle in the population. If the number generated was less than the rate of mutation, then the cycle in question experienced mutation. Mutation was the replacement of a segment of the selected cycle by a segment randomly chosen from the pool of segments.

Once mutation occurred, the GA selected cycles for crossover. Determining cycles to experience crossover relied on random number generation for each of the cycles in the initial population of the current generation. Cycles added to the population due to mutation were not eligible for crossover, but the cycles from which they emanated were. If the random number applied to a given cycle was less than the defined crossover rate, then the cycle was selected for crossover. In order to perform crossover, we required another cycle from the population. The GA randomly selected this cycle from the remaining 99 cycles of the current generation.

The new population size was determined by adding the number of newly created cycles from mutation and crossover to the original population size of the generation, which we fixed at 100. We then calculated cycle statistics of the newly created cycles, since newly formed cycles did not contain any information other than the speed load array.

The next step in the GA was to sort the cycles based on their respective PVs in order to determine which individuals were most representative. The PV was desired to be as close to 0 as possible; however, it was not well scaled, between 0 and 1, over the entire population. Many of the cycles within a given population had PVs closer to 0 than 1. In order to more evenly distribute the population so that selection of the next population could be implemented, "evaluation" and "fitness" functions were defined. These functions were necessary to employ roulette-wheel selection to define the next generation. In order to map the PV over the range of [0, 1] to create selection probabilities, the largest and smallest PVs of the respective generation were defined as PV_{max} and PV_{min}, respectively. These values were then used to create coefficients a and b, and scale the PV into an "evaluation function" (EF), as shown in eqs 6, 7, and 8.

$$a = \frac{1}{PV_{max} - PV_{min}} \tag{6}$$

$$b = -\frac{PV_{min}}{PV_{max} - PV_{min}} \tag{7}$$

$$EFi = a \cdot PVi + b \tag{8}$$

The use of these equations defined an evaluation function for every cycle. Since a lower PV was desirable, it was more valuable to define the opposite of the EF desired. Equation 9 shows the definition of the inverse EF.

$$EF_{new} = 1 - EF_{old} \tag{9}$$

A total fitness (TF) value (see eq 10) and a probability array were then constructed based on each individual's evaluation function, as is shown in eq 11.

$$TF = \sum_{i=1}^{n} EFi \tag{10}$$

$$p_i = \frac{EFi}{TF} \tag{11}$$

A "q" array was defined that acted as a number line with spacing equivalent to the probabilities defined from eq 12.

$$q_i = \sum_{j=1}^{i} p_j \tag{12}$$

Equations 6–12 were all defined in Roeva et al. (2013). With the "q" array defined, roulette-wheel selection could take place to define the next population. In addition to roulette-wheel selection, the GA used elitist selection to ensure the cycle with the lowest PV advanced to the next generation. Elitist selection improves exploitation and reduces variability between generations (Roeva et al., 2013). Roulette-wheel selection defined the remaining population. To implement the selection process, we generated a random number between 0 and 1, and placed it on the "q" number line as described above. The index of the "q" value falling directly to the right of the random number was the index of the cycle that advanced. Note that we performed this without removal of the cycle from the pool. This meant that it was possible for the same cycle to have multiple copies in the next generation and that other cycles not selected became extinct. This process continued to define the entire new population of the next generation.

One issue in defining the GA was finding genetic operation rates that most efficiently found a solution. In other words, it was necessary to select the best form of the GA to use in cycle development. We applied several iterations of the GA in an attempt to find the best performing genetic operation rates. During these iterations, the GA ran for a life span of 30 generations with the fixed population of 100. The genetic operation rates varied during these iterations, and each of the iterations was ranked based on the value of the elite PV that was produced. The final GA used the operators that produced the lowest average PV amongst the three cycles. Table 7 shows the results of this analysis.

Based on the analysis, the final genetic operation rates of 0.4 or 40% for crossover and 0.2 or 20% for mutation yielded the best results. For each of the three types of cycles, an initial population of 100 cycles was applied to the final GA. Each final GA had a life span of 50 generations. We extended the life span of the GA with the goal of giving better results than those seen in the initial iterations, which were shorter to save computational time.

Table 7. Genetic algorithm iteration results.

GA	Rates of operators		Drilling		Fracking		Trucking		Total
Rank	Crossover rate	Mutation rate	Elite PV	Rank	Elite PV	Rank	Elite PV	Rank	PV
1	0.4	0.2	0.0025	1	0.0314	5	0.0301	1	0.0640
2	0.4	0.25	0.0031	2	0.0302	1	0.0336	5	0.0669
3	0.35	0.2	0.0031	2	0.0324	7	0.0322	2	0.0677
4	0.4	0.15	0.0032	3	0.0308	3	0.0340	6	0.0680
5	0.45	0.2	0.0032	3	0.0321	6	0.0335	4	0.0688
6	0.2	0.1	0.0044	4	0.0312	4	0.0334	3	0.0690
7	0.3	0.2	0.0044	4	0.0329	8	0.0322	2	0.0695

Results

OTR trucks

The initial population of 100 truck cycles had an average PV of 0.0910, and after 50 generations the average PV reduced by 61% to 0.0354. The elite PV of the initial population was 0.0388 and reduced by 18% to 0.0320 by the final generation. Figure 4 shows the improvements of the average and elite PVs as a function of the GA generation. At the 50th generation, the average PV improved by only 0.35% from the previous generation and the elite PV did not improve. Figure 5 shows the elite OTR truck cycle. Table 8 presents the statistics of the elite OTR truck cycles as compared with the in-use data.

Drilling

The initial population of 100 created drilling cycles had an average PV of 0.0249. After 50 generations, the average PV reduced by 82% to 0.0044. The elite PV of the initial population was 0.0075 and reduced by 65% to 0.0026 by the end of the 50th generation. The average PV at the 50th generation actually was worse than it was in the 49th generation, and the elite PV showed no improvement. Figure 6 shows the elite drilling cycle, and Table 9 presents the statistics of the elite drilling cycle as compared with in-use data.

Hydraulic fracturing

The initial population of 100 hydraulic fracturing cycles had an average PV of 0.0762. After 50 generations, the average PV reduced by 54% to 0.0347. The elite PV of the initial population was 0.0406 and reduced by 25% to 0.0305 by the end of the 50th generation. The 50th generation elite PV showed no improvement over the 49th generation, and the average PV only improved by 0.55%. Figure 7 shows the elite hydraulic fracturing cycle, and Table 10 presents the statistics of the elite cycle and the in-use data statistics.

Implementing the dynamometer cycles

We exercised a test engine over the elite cycles to ensure their applicability to an engine dynamometer configuration. The engine used for the purpose of cycle verification was a 2008 Cummins 8.9-L ISL-G, rated at 280 hp. Table 11 provides engine specifications. A GE 800-hp dynamometer controlled engine speed, and load was measured via side-arm torque. Note that eq 1 was directly applicable to the ISL-G, which operates over the Otto cycle. Typically, denormalization for diesel engines includes values up to 112% of rated speed, but data beyond rated speed only represented 0.29% of over 4 million data points and were excluded from this analysis. In the case of diesel-fueled engines

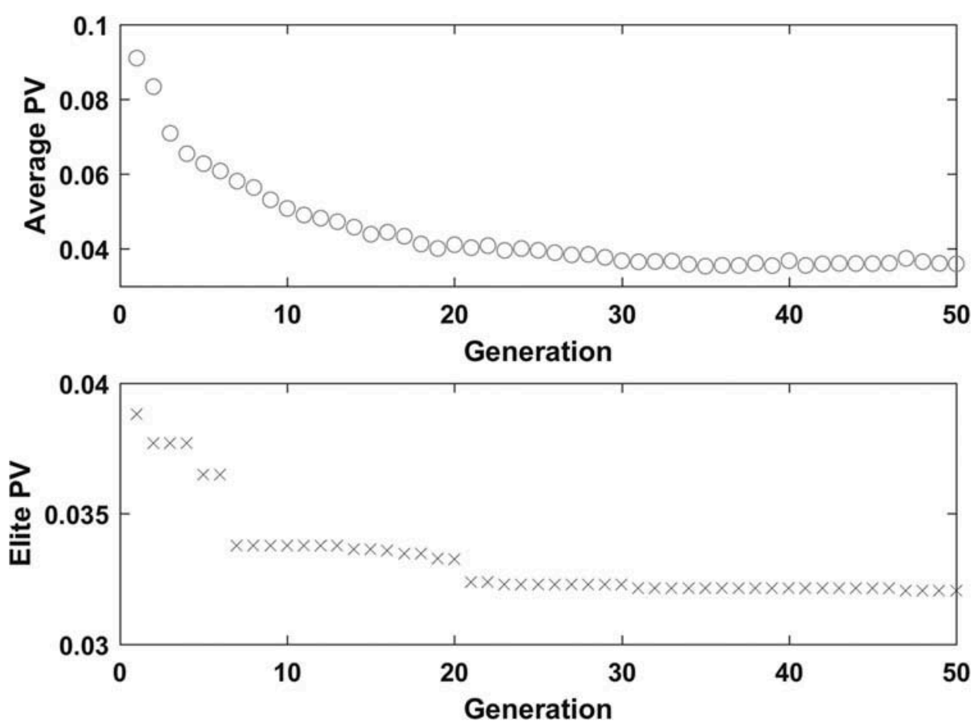

Figure 4. OTR truck GA improvements.

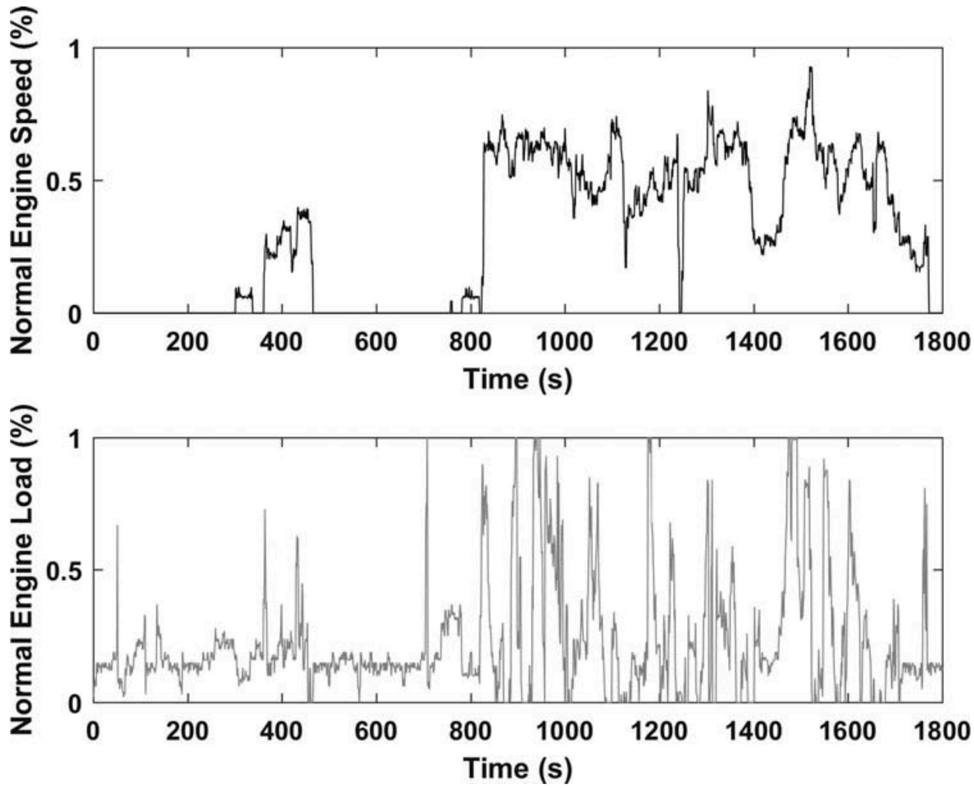

Figure 5. Elite OTR truck cycle.

Table 8. OTR truck cycle and data statistics.

		Value	
Metric		Cycle	Data
Average	Speed	0.2911	0.2923
	Load	0.2269	0.2312
	Non-idle speed	0.4665	0.4685
	Non-idle load	0.2649	0.2826
Time	Idle	0.3761	0.3762
	Non-idle	0.6239	0.6238

for drilling and fracturing, operation only occurred at rated speed.

Regression and smoothing

Before use for research or measurement of emissions, a cycle regression analysis must occur. Regression statistics must be within a certain range according to the CFR for validation of the cycle. Table 12 provides the validation criteria as defined by CFR Title 40 Chapter I Subchapter U Part 1065 Subpart F Section 514.

Drilling and fracturing cycles

Tables 13 and 14 provide the passing results for the drilling and hydraulic fracturing cycles, respectively.

Application of smoothing for the OTR truck cycle

The elite OTR truck cycle did not meet regression criteria in original form. The failure of regression for this cycle was most likely the result of the second-by-second concatenation technique. This technique allowed activity points to sometimes jump by intervals of as much as 10%. This did not allow the engine to respond to the dynamometers signals in time to meet the desired set points. We decided to implement a smoothing technique to reduce the rate of change between certain points of both speed and load. Several smoothing and filtering techniques were considered for this application, including moving average, Savitsky-Golay (SG), and local regression methods (loess and lowess). These techniques smoothed the speed and load array with the defined function and parameters and calculated the new statistics of the cycle. An analysis determined how the different smoothing techniques affected the cycle with different levels of span and degree. We performed a sensitivity analysis of the various techniques to examine their effects on the cycle PV. The goal was to apply a technique, which smoothed the cycle with minimal effect on the PV. Based on the analysis, the SG13-7 was determined to be the best method. The SG13-7 smoothing technique had an effect on

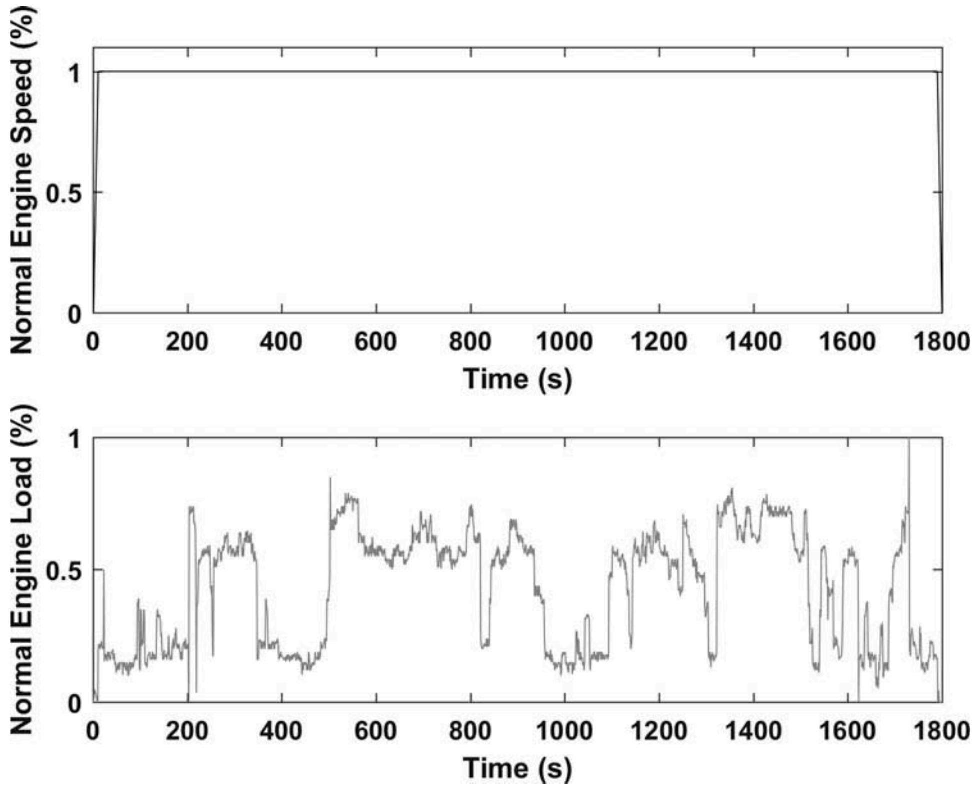

Figure 6. Elite drilling cycle.

Table 9. Drilling cycle and data statistics.

Metric		Value Cycle	Data
Average	Load	0.4295	0.4298
	High load	0.5997	0.6024
	Low load	0.1934	0.1895
Time	High	0.5850	0.5837
	Low	0.4067	0.4123
	Idle	0.0083	0.0040

1799 of 1800 cycle points. The smoothing technique changed the affected speed points by an average of 4% and the load points by an average of 15%. Table 15 provides the statistics of the smoothed elite OTR truck cycle and in-use data. Table 16 presents the passing results of the regression test, and Figure 8 displays the final normalized OTR truck cycle.

Comparison of the generated cycles with current cycles

OTR and FTP. As the 8.9-L ISL-G is a heavy-duty engine used in OTR trucks, we compared both the cycle statistics and emissions results from the OTR truck cycle and the standard FTP. Table 17 presents both the statistics and emissions comparisons with the FTP values as reference. Emissions data were collected using a 40 CFR 1065–compliant dilution tunnel and constant-volume sampling system ("Code of Federal Regulations"; Wu et al., 2009). Carbon monoxide (CO), oxide of nitrogen (NO_x), carbon dioxide (CO_2), and total hydrocarbon (THC) emissions were measured with a Horiba MEXA 7200 D analytical bench. Brake-specific emissions results are only shown for hot-start tests and are the average of three repeated tests. The OTR cycle has decreased time at idle in comparison with the FTP and therefore produces slightly higher CO_2 emissions (2.9% higher than FTP), which correlates to a slight increase in brake-specific fuel consumption. Of greater concern are the increases in CO, NO_x, and THC emissions over those produced from the FTP. The certification levels for CO and NO_x for this engine were 14.4 and 0.2 g/bhp-hr, respectively. We see that the FTP values are below or near the certification levels. However, when operated on the OTR cycle, CO, THC, and NO_x emissions increased by factors of 1.69, 2.85, and 1.79, respectively. Therefore, inventories that utilize FTP emissions values to represent this particular trucking sector could be significantly underestimating these regulated

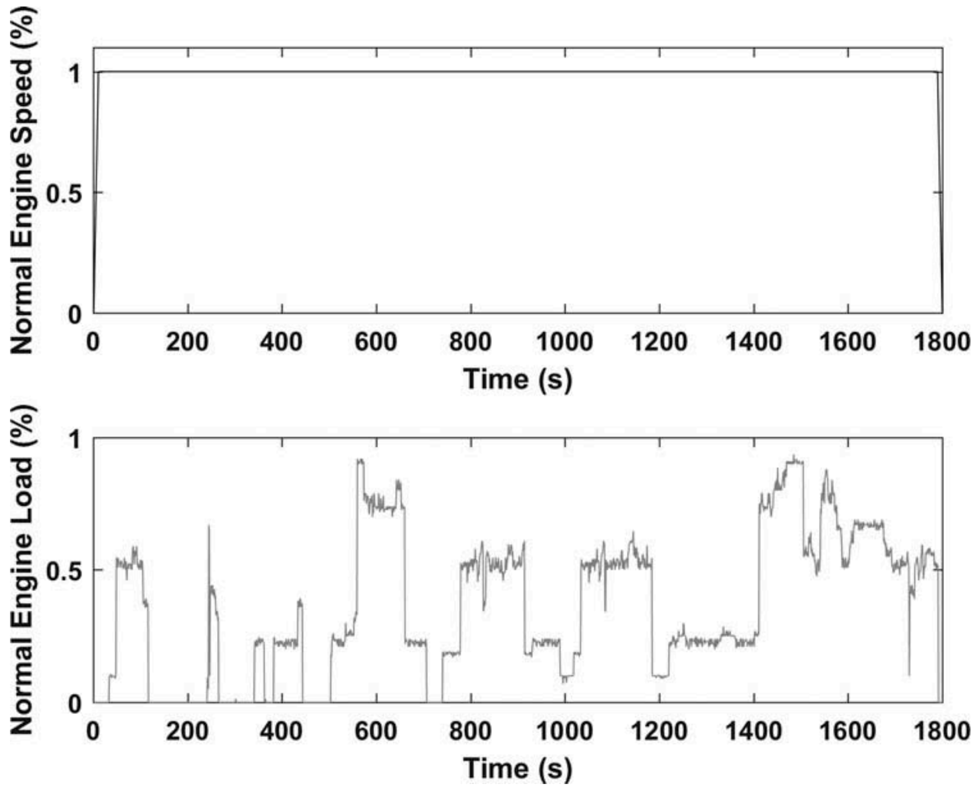

Figure 7. Elite fracturing cycle.

Table 10. Fracturing cycle and data statistics.

Metric		Value	
		Cycle	Data
Average	Load	0.3583	0.3554
	High load	0.6174	0.6149
	Low load	0.2167	0.2033
Time	High	0.4606	0.4681
	Low	0.3411	0.3324
	Idle	0.1983	0.1994

Table 11. Cummins ISL-G engine specifications.

Specification	Value	Unit
Horsepower	280	hp
Peak torque	900	lb-ft
Governed speed	2200	rpm
Ignition	Spark	
Arrangement	Inline—6 cylinder	
Intake	Turbocharged	
Displacement	540	in^3
Bore	4.49	in
Stroke	5.69	in
Oil capacity	7.3	US gal
Coolant capacity	13.1	US qts
System voltage	12	V
Aftertreatment	TWC	
Fuel used	CNG	

Note. CNG = compressed natural gas; TWC = three-way catalyst.

pollutants. Greater than 90% of the THC emissions from this engine was methane, a potent greenhouse gas, and its relative increase should be addressed for any greenhouse gas inventories or when reporting CO_2-equivalent emissions.

NRSC and drilling and fracturing cycles. Both drilling and hydraulic fracturing engines are subject to certification when operated over the NRSC. The NSRC cycle consists of five modes, with torque set points of 100, 75, 50, 25, and 10%. The weighting factors for each mode are 0.05, 0.25, 0.3, 0.3, and 0.1, respectively. The average time-weighted load of the NSRC is 47.25%. The average load of the drilling cycle was 42.95%, and the average load of the hydraulic fracturing cycle was 35.83%. We set a high-load and a low-load threshold of 40% based on operating statistics from in-field data. The NSRC yields 60% time of high-load operation and 40% low-load operation. The time of high-load operation for drilling was 58.5%, whereas low-load was 41.5%. The time of high-load operation for hydraulic fracturing was 46.1%, whereas low-load was 53.9%. The in-use engines are not subjected to transient operation but do experience transient operation in the field and within the newly developed cycles. The transient operation of the drilling cycle reflects activities such as drilling, pipe connections, operation of draw works, circulation of fluids, and other intermittent activities. The transient operation of the hydraulic fracturing cycle reflects multiple stages of stimulation, which may occur at different loads due to

Table 12. Cycle regression validation criteria for Cummins ISL-G.

Cycle validation criterion		Acceptable range	
		Minimum	Maximum
Speed	Intercept	−70.1	70.1
	Slope	0.95	1.03
	R^2	0.97	1.00
	SEE	0.00	110.35
Torque	Intercept	−18.0	18.0
	Slope	0.83	1.03
	R^2	0.85	1.00
	SEE	0.00	90
Power	Intercept	−5.70	5.70
	Slope	0.83	1.03
	R^2	0.91	1.00
	SEE	0.00	28.50
Work	Actual bhp-hr	Within 5%	

Note. SEE = standard error of the estimate.

Table 13. Drilling cycle regression results.

Criterion		Min	Value	Max
Speed	Intercept	−70.1≤	−24.187≤	70.1
	Slope	0.95≤	1.011≤	1.03
	R^2	0.97≤	0.998≤	1
	SEE	0≤	5.994≤	110.35
Torque	Intercept	−18.0≤	2.786≤	18.0
	Slope	0.83≤	0.988≤	1.03
	R^2	0.85≤	0.941≤	1
	SEE	0≤	35.969≤	90
Power	Intercept	−5.7≤	1.584≤	5.7
	Slope	0.83≤	0.986≤	1.03
	R^2	0.91≤	0.948≤	1.03
	SEE	0≤	14.198≤	28.5
Work	Actual bhp-hr	57.85≤	60.816≤	63.94
	Reference		60.897	

Note. SEE = standard error of the estimate.

Table 14. Hydraulic fracturing cycle regression results.

Criterion		Min	Value	Max
Speed	Intercept	−70.1≤	−22.419≤	70.1
	Slope	0.95≤	1.010≤	1.03
	R^2	0.97≤	0.998≤	1
	SEE	0≤	6.113≤	110.35
Torque	Intercept	−18.0≤	0.335≤	18.5
	Slope	0.83≤	1.000≤	1.03
	R^2	0.85≤	0.962≤	1
	SEE	0≤	34.967≤	90
Power	Intercept	−5.7≤	0.346≤	5.7
	Slope	0.83≤	0.999≤	1.03
	R^2	0.91≤	0.966≤	1.03
	SEE	0≤	13.738≤	28.5
Work	Actual bhp-hr	48.26≤	50.677≤	53.34
	Reference		50.803	

Note. SEE = standard error of the estimate.

Table 15. Smooth OTR truck cycle and data statistics.

Metric		Value	
		Cycle	Data
Average	Speed	0.291	0.292
	Load	0.227	0.231
	Non-idle speed	0.463	0.469
	Non-idle load	0.264	0.283
Time	Idle	0.372	0.376
	Non-idle	0.628	0.624
Values	Statistical	0.039	
	Distribution	0.026	
	Performance	0.032	

Table 16. Smooth OTR truck cycle regression results.

Criterion		Min	Value	Max
Speed	Intercept	−70.1≤	0.666≤	70.1
	Slope	0.97≤	0.999≤	1.03
	R^2	0.97≤	0.999≤	1.00
	SEE	0.0≤	10.083≤	110.35
Torque	Intercept	−18.0≤	0.286≤	18.0
	Slope	0.83≤	0.973≤	1.03
	R^2	0.85≤	0.919≤	1.00
	SEE	0.0≤	54.134≤	90.0
Power	Intercept	−5.7≤	−0.052≤	5.7
	Slope	0.83≤	0.983≤	1.03
	R^2	0.91≤	0.934≤	1.00
	SEE	0.0≤	15.462≤	22.1
Work	Actual bhp-hr	20.819≤	22.186≤	23.011
	Reference		21.915	

Note. SEE = standard error of the estimate.

varied pressures and gear selection of the pumps. Transient operation of turbocharged diesel engines can produce higher combustion temperatures, which lead to increased NO_x and particulate matter emissions (Rakopoulos and Giakoumis, 2006). Off-road spark ignited engines have also shown to increase THC plus NO_x emissions by a factor of 6 and CO emissions by a factor 5 when comparing real in-use transient operation with those emissions produced from the C2 NRSC (U.S. Environmental Protection Agency [EPA], 2001). Future work will examine NSRC emissions from the 8.9-L ISL-G engine as compared with those from this work.

Summary

To reduce fuel costs and emissions, the unconventional well completion industry has been attempting to utilize produced natural gas to meet power demands for cost savings. Several companies are doing this by displacing diesel fuel normally used for engines. The primary consumers, or prime movers, of diesel fuel in unconventional natural gas well development are OTR trucks, and high-horsepower drilling and hydraulic fracturing engines. In order to conduct cost- and time-effective research and evaluations, we developed a method to create engine test cycles for application to scaled engines in a laboratory setting.

We collected in-use engine activity data for the three prime movers. Data collected included engine speed and load from OTR trucks traveling to and from well sites hauling water, sand, and gravel, hydraulic fracturing engines used to power pumps for several jobs on two separate pads, and drilling engines used to drill two wells on a single pad. We employed a MCMC technique to create cycles. The goal was to replicate data by creating a large number of potential cycles. A Markov chain utilized second-by-second concatenation and a transition probability matrix. We combined the Markov chain technique with Monte Carlo simulations to create a

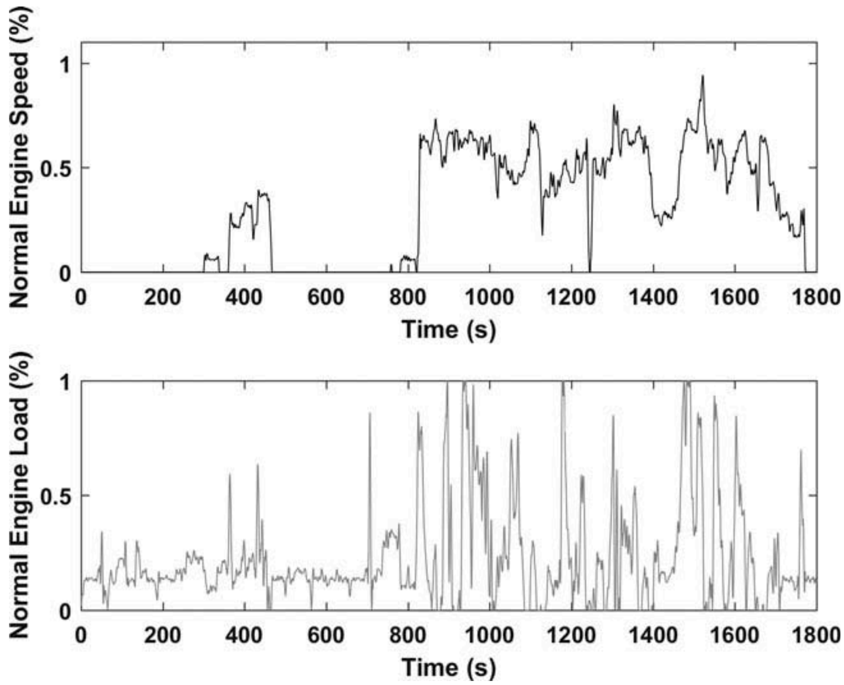

Figure 8. Normalized OTR truck cycle with SG13-7 smoothing.

Table 17. Smooth OTR truck cycle regression results compared with FTP.

Metric		Value		
		OTR	FTP	% Difference
Average	Speed	0.291	0.415	−42.6%
	Load	0.227	0.241	−6.17%
	Non-idle speed	0.463	0.719	−55.2%
	Non-idle load	0.264	0.397	−50.3%
Time	Idle	0.372	0.423	−13.8%
	Non-idle	0.628	0.577	8.1%
Values	Statistical	0.039	0.173	−342%
	Distribution	0.026	0.072	−183%
	Performance	0.032	0.123	−279%
Emissions (g/bhp-hr)	CO	3.19	1.89	40.8%
	CO_2	460	447	2.83%
	HC	2.26	0.910	59.7%
	NO_x	0.430	0.240	44.2%

population of 10,000 cycles for each prime mover. The elite PVs of the populations of OTR truck, drilling, and hydraulic fracturing cycles were 0.0327, 0.0042, and 0.0072, respectively. We then used a GA to optimize the cycle selection process. The GA employed elitist and roulette-wheel selection to determine the members of the population allowed to advance to the next generation. The final GA used genetic operation rates of 40% for crossover and 20% for mutation. It utilized an initial population of 100 cycles and had a life span of 50 generations.

After completion of the GA, the elite OTR truck cycle, drilling cycle, and hydraulic fracturing improved PVs by 18%, 62%, and 65%, respectively. The GA reduced PVs from 0.0388 to 0.0320 for OTR trucks, 0.0079 to 0.0030 for drilling, and from 0.0155 to 0.0054 for hydraulic fracturing. We exercised the cycles on an engine and dynamometer to confirm that they met regression criteria for transient cycles defined by the CFR.

The elite drilling and hydraulic fracturing cycles passed the regression criteria needed as initially defined. The OTR cycle, however, failed regression based on the R^2 of torque and power criteria. We applied a smoothing technique to the normalized cycle speed and load arrays. A sensitivity analysis determined the effect of smoothing techniques on the PV of the cycles. A SG filter with a span of 13 and polynomial degree of 7 was implemented. The smoothing resulted in a 1.25% increase in the PV from 0.0320 to 0.0324. We then exercised the smoothed OTR truck cycle on the same engine and dynamometer platform, and it passed all necessary criteria.

Based on our analyses, we feel these cycles are representative of actual engine operation in the field and will use them for research related to unconventional natural gas well development. We also provide the final cycles in tabular format for evaluation and use by other researchers. Cycle development will continue to be necessary for research as emissions standards become more stringent and different industries come under the scrutiny of regulatory institutions. For these reasons, it is important to look for new ways to apply and optimize the techniques of in-field data representation. Future research should also include catalyst temperature as a cycle metric. Older off-road engines are typically Tier 2 with no aftertreatment; however, newer engines that can be run on dual fuels have diesel oxidation catalysts (DOCs) and new Tier 4 engines may have both diesel particulate filters (DPFs) and selective catalytic reduction (SCR)—the efficiency of both are correlated with exhaust energy.

In addition, we have shown that from an emissions perspective, a dedicated natural gas engine operated over our OTR cycle produced more CO, NO_x, and THC emissions compared with the conventional FTP cycle. Although we did not compare the drilling and hydraulic fracturing cycle emissions with those from the NRSC, we plan to do so in the future. The drilling cycle high-load and low-load time distribution is similar to the NRSC but includes realistic transient operation. The hydraulic fracturing cycle yielded increased low-load operation compared with the NRSC. The transient nature of the in-use engines and our cycles will likely increase emissions over those collected during NRSC certification tests. As such, current test methods and inventory methods, which utilize current emissions factors, may be underreporting regulated emissions compared with those that occur in use.

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About the authors

Derek Johnson, Ph.D., is a research assistant professor at West Virginia University (WVU) conducting research focused on methane and other emissions associated with the use of natural gas.

Robert Heltzel, M.S.M.E., is a research assistant at WVU's Center for Alternative Fuels, Engines, and Emissions.

Andrew Nix, Ph.D., is an assistant professor at WVU conducting research on natural gas reciprocating engines and gas turbines.

Rebekah Barrow is an undergraduate research assistant pursuing bachelor's degrees in mechanical and aerospace engineering.

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APPENDIX C

Estimated Emissions from the Prime-Movers of Unconventional Natural Gas Well Development Using Recently Collected In-Use Data in the United States

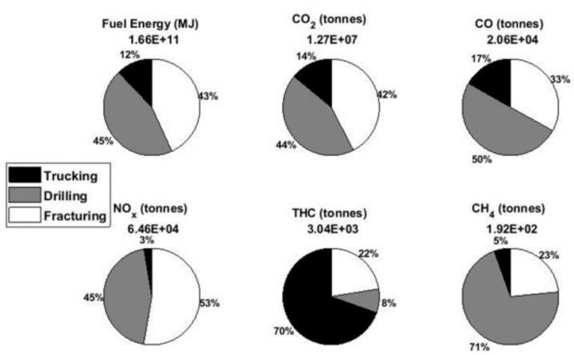
Derek Johnson, Robert Heltzel, Andrew Nix, Mahdi Darzi, and Dakota Oliver*

West Virginia University, PO Box 6106, Morgantown, WV 26506.

*Derek.Johnson@mail.wvu.edu, 304-293-5725

KEYWORDS Unconventional well development, natural gas, emissions, dual-fuel, dedicated natural gas

TOC ART



ABSTRACT

Natural gas from shale plays dominates new production and growth. However, unconventional well development is an energy intensive process. The prime movers, which include over-the-road service trucks, horizontal drilling rigs, and hydraulic fracturing pumps, are predominately powered by diesel engines that impact air quality. Instead of relying on certification data or outdated emission factors, this model uses new in-use emissions and activity data combined with historical literature to develop a national emissions inventory. For the diesel only case, hydraulic fracturing engines produced the most NO_x emissions, while drilling engines produced the most CO emissions, and truck engines produced the most THC emissions. By implementing dual-fuel and dedicated natural gas engines, total fuel energy consumed, CO_2, CO, THC, and CH_4 emissions would increase, while NO_x emissions, diesel fuel consumption, and fuel costs would decrease. Dedicated natural gas engines offered significant reductions in NO_x emissions. Additional scenarios examined extreme cases of full fleet conversions. While deep market penetrations could reduce fuel costs, both technologies could significantly increase CH_4 emissions. While this model is based on a small sample size of engine configurations, data were collected during real in-use activity and is representative of real world activity.

INTRODUCTION

Due to technology developments in unconventional drilling and well stimulation, the US is estimated to have proven natural gas reserves that will last 100 years[1]. Recently, the effects of these unconventional resources on emissions from the natural gas sector have been scrutinized. Studies have focused primarily on methane emissions from production sites[2,3], gathering and processing[4,5], transmission and stroage[6-8], distribution[9], and even the use of natural gas in the transportation sector[10]. The construction, drilling, stimulation, and other site activities required for the development of unconventional wells are energy intensive. Natural gas production from these wells currently dominates US production and this trend is expected to increase though 2040[11]. Through a review of literature, the prime-movers (or major fuel consumers) for unconventional well development were identified as over-the-road trucks servicing these sites, the drilling rig engines, and the hydraulic fracturing pump engines, see Table S1. Currently, diesel-fueled engines dominate all three markets. Emissions from these prime-movers include oxides of nitrogen (NO_x), carbon monoxide (CO), carbon dioxide (CO_2), total hydrocarbons (THC), and methane (CH_4) among others. Note that non-methane hydrocarbons (NMHC or volatile organic compounds - VOCs) are determined by the difference between THC and CH_4.

In-use engines vary in age, power, activity, and certification level. Numerous studies have suggested that emissions from unconventional resource development can affect local and regional air quality[12-18]. Reactive hydrocarbons, NO_x, and CO react in the atmosphere to produce secondary pollutants such as nitrogen dioxide (NO_2) and ozone (O_3) – both are criteria pollutants for which regional thresholds are set by National Ambient Air Quality Standards[16,19]. The RAND Corporation published a study examining the air quality impacts of unconventional well development in the Marcellus Shale – specifically Pennsylvania[14]. The emissions inventory used on-road data from a New York impact study[20], Environmental Protection Agency (EPA) GREET[21], and a National Research Council study[22]. Their estimates for drilling and fracturing were developed by data supplied by the Pennsylvania Department of Environmental Protection[23]. The Arkansas Department of Environmental Quality conducted a similar study and reported data for drilling and hydraulic fracturing engine emissions for the Fayetteville Shale in 2008[24]. The Arkansas Department of Environmental Quality estimated relative contributions of NO_x, VOC, and CO_2 emissions from drilling and fracturing engines[24] – see Table S2. Note that percentages do not sum to unity since other sources beyond our prime-movers were included within their study bounds (such as production and compression engines). A similar study was completed for the Eagle Ford shale and showed that drilling and hydraulic fracturing engines contributed minimally to total VOCs but about represented about 33% of total NO_x emissions[25]. Another study for the basins of the Rocky Mountain region estimated the 2006 NO_x emissions from the oil and gas production and the range of NO_x emissions attributed to drilling rigs are included in Table S2[12,14].

Inventory studies typically use emission factors (EFs) for the prime-movers combined with activity data to estimate mass emissions. An example of such calculation is shown in Equation 1.

$$\text{Emissions} = EF \times P \times AF \times t \qquad \text{Equation 1}$$

Where P is the rated engine power, AF is an activity factor – typically, a dimensionless number from 0-1 that represents average engine power or load, t is the total time of the given activity, and EF is an emission factor for a particular prime-mover and pollutant. EFs typically have units of mass per brake-specific energy consumed (e.g. Lb/Bhp-hr or kg/bkW-hr). Common sources for EFs include AP-42[26], EPA emissions certification results[27], EPA emissions standards[28,29], CARB[30], and EPA models such as MOVES[31], GREET[21], and NONROAD[32] or other literature. An example calculation is given below to estimate the mass emissions of NO_x for a Caterpillar 3512C drilling engine operating for 24 hours, at 50% load, using the EPA EF for NO_x.

$$NO_x = (5.04\ \text{g/kW-hr}) \times (1101\ \text{kW}) \times (0.5) \times (24\ \text{hr}) = 66{,}590\ \text{grams/day}$$

Other methods can be found in literature and may use a variety of conversion or scaling factors to achieve dimensional homogeneity. For example, one study normalized emissions based on well depth[33]. A recent study by Texas A&M examined the difference in predicted emissions for a Caterpillar 3512C engine used in drilling rigs using EFs from EPA, CARB, and AP-42[34]. They developed EFs from in-use data that tended to be lower than those from AP-42. In addition, they suggested that fuel consumption should be used instead of power. However, fuel delivered to drilling sites is loaded into a bulk storage tank. The tank feeds the drilling rig engines, but also fuels construction equipment, light towers, boilers, and other equipment that have different EFs and AFs.

This study focuses on the emissions from the prime-movers of unconventional well development. As opposed to using outdated EFs or total fuel delivered to a site, our model is based on newly collected in-use activity data[35] and in-use emissions data for Tier 2 drilling and fracturing engines, engines converted to operate as dual-fuel, and Tier 2 dedicated natural gas engines[36,37]. The goal was to produce a more realistic emissions estimates that are representative of current industry practices. In lieu of emissions data from trucks, the model used data from other research campaigns and certification data for current engine types used by service companies. Our new EFs and AFs are combined with literature, specifically estimates of total time, in order to provide mass emission rates.

Based on a review of literature, we found data regarding national emissions are limited. Regional studies rely on conventional AFs and EFs, which may not be representative of in-use activity. A recent thesis focused on developing emissions inventories for hydraulic fracturing engines. They examined a variety of EFs and focused on activity within the Marcellus and Eagle Ford Shale plays, and provided emissions estimates per “job” which is for all stages of a given well[38]. Table S3 presents a summary of reviewed publications and their sources used for EFs.

Table S4 presents some of the EF, AF, and other values presented from reports in Table S3 for diesel only drilling and hydraulic fracturing engines.

METHODS

Collecting Emissions, Fuel Consumption, and Activity Data.

Emissions data collection methods are detailed elsewhere[36,37,39], see the SI. To estimate national emissions from the prime-movers of unconventional well development, data were collected totalling over 1,296 hours of trucking activity data from the Marcellus and Utica regions, 66 hours of activity data from fracturing engines in the Marcellus, 24 hours of emissions data from fracturing engines in the Marcellus, 10 hours of emissions data of a fracturing engine operated over common load points, over 234 hours of drilling activity data and over 112 hours of emissions data from the Marcellus, Permian Basin, and Haynesville plays. Data were collected from two different drilling engines operating in both diesel only and in dual-fuel mode, two different hydraulic stimulation engines operating as diesel only and in dual-fuel mode, and two different dedicated natural gas drilling engines. Table S5 presents the new EFs for all types of drilling engines from which emissions were collected. Drilling activity data were binned into two types of activity – low load transient (LLT) operation and steady state drilling (SSD) operation. SSD operation typically represented nearly half of the drill engine activity, with near steady operation at loads greater than 40%. LLT operation represented periods of operation with typically lower steady state loads and higher load transients. The average load during LLT operation was less than 40%. This method allowed EFs to be developed for different types of drilling operation, which provided more granular data than a single

EF applied to all activity. Hydraulic fracturing of individual stages generally occurred at steady state operation, however, loads varied based on the number of engines and stage requirements. Table S6 provides our EFs for hydraulic fracturing.

EFs for heavy-duty diesel trucks were based on certification emissions available from the US EPA[27]. EFs for dual-fuel engines were taken from literature[40]. Emissions from dedicated over-the-road natural gas engines were taken in the West Virginia University Engines and Emissions Research Laboratory. Emissions from ISL-G engines can be found in literature[41]. Trucking EFs are presented in Table S8.

Note, we have shown that natural gas fuel composition can affect emissions[41]; however, analyzing its impact on total emissions is beyond the scope of the model. Gas compositions were collected during data collection efforts and the compositions were used in the development of EFs, see Table S7.

Emissions Estimation Model

The inventory model included a module for each prime-mover which used the respectively developed EFs and activity data based on literature. While activities may correlate with each other, the model did not constrain correlations among the prime-mover activities. For example, it was possible for a shorter well to have a high number of stages and low truck trips. Such a case would represent a newer, engineered stimulation that uses water from a nearby source and only requires limited sand deliveries.

The model was developed so that an individual well's emissions for each prime-mover were determined for each iteration of the model. A general flow diagram is shown in

Figure S1 and additional details for each module follow. Since the research and literature sample sizes were relatively small, the model employed bootstrapping[42] to randomly generate a population of wells for each fuel type: diesel, dual-fuel, and dedicated natural gas. Bootstrapping has been used by other studies to estimate inventory emissions based on small sample sizes[2]. Even though the in-use sample sizes were small, the total number of possible well scenarios that could be generated for the diesel only case was over 7.5×10^{16}. To determine an adequate sample size the model generated sample population sizes for diesel only operation – from 1×10^{1} to 5.5×10^{5} wells. Figure S2 presents the relative change in average CO_2 emissions per well until convergence at a population of 200,000. Figure S3 also presents the sensitivity analysis results for the relative change standard deviation in CO_2 emissions per well. This population of 200,000 wells served as the initial pool. The statistics of the entire diesel only sample population is presented in Table S9. Once a well was selected from the population for a given year, it could not be selected again for that given year; however, it could be selected again in subsequent years. Selection without replacement is a common method used to ensure adequate exploitation of the population[43]. The number of wells drilled and completed in years 2014, 2015, and 2016 were, 18,664, 11,536 and 6774, respectively[44]. A sample year pulled the average number of wells – 12,325. To assess annual variability, the average year was generated 20 times. The selection of 20 different years ensured that each well could be selected at least once. Constants used in the model included the lower heating value (LHV) of diesel fuel as 42.80 MJ/kg or 138.5 MJ/gallon and a LHV for natural gas of 54.69 MJ/kg.

Over-the-Road Trucks

For each well, a random number of truck trips was selected using a log normal distribution based on average truck trips per well from literature[20,45-56]. A trip distance, which was fixed for a given well based on the assumption that trucks travel the same routes from a water source or company yard to the well and back, was then randomly generated with data obtained from literature[45,49,50,56]. Based on typical truck activity data presented in a previous study[35], the total trip time and time in each activity bin were calculated. For each given trip (k), within a specific well iteration (i), a random vehicle engine was selected from engines 11-23 for diesel-only wells, 24-26 for dual-fuel wells and 27 or 28 for dedicated natural gas wells. The corresponding trip power was integrated and engine specific EFs were used to determine the total emissions from all truck trips of a well.

Drilling Engines

For each well, a random drilling duration (in days) was generated using data from literature[56-61]. Once the total duration of a given well (i) was determined, a data distribution was applied to the duration to distinguish between types of drilling operation. Instead of averaging all loads into a single AF, data were divided into LLT or SSD operating modes. Typical drilling fleets consist of three high horsepower engines; however, these engines were rarely operated simultaneously. Literature suggests a variety of operating engines but the model targeted 2.1 active engines to match literature[27] and based on data collection campaigns, where the dominant number of operational engines was two. Once the power and energy (kW-hr) in each mode were determined for the entire well duration the model randomly selected the EFs. For diesel-only, dual-fuel and dedicated natural gas engines, either engine 1 or 2, 3 or 4, and 5 or 6 were selected, respectively. The EFs were then multiplied by the energy of the respective operating modes and the total emissions of the well were determined.

Hydraulic Fracturing Engines

Fracturing emissions were calculated in similar fashion to drilling. Based on a review of literature, we found no specific correlations between duration to drill a well, depth or length, and number of fracturing stages. Therefore, a random number of stages and engines were selected for the given well iteration from a log normal distribution of data from literature[38,61-63]. Each stage was assigned a random stage time and average engine power. The model was based on the observation that fracturing engines generally run at steady state and rated speed for the duration of each stage. Then, a total fracturing power and energy (kW-hr) was calculated and EFs were applied. Engines 7 or 8 were selected for diesel-only iterations. Engines 9 or 10 were selected for both dual-fuel and dedicated natural gas iterations. No examples of dedicated natural gas fracturing engines were observed over the course of data collection and were therefore excluded from the model. Note that the model only presents data for non-idle engine operation during a stage. It is realized that some fleets idle back-up engines during a stage or idle engines between stages. This was not seen in our data collection efforts. In addition, based on idle emissions obtained for a fracturing engine – an idled engine would be required to operate for an entire day to produce equivalent mass emissions from a single powered engine operated for a fracturing stage duration of one hour.

Comparisons with Literature

Rodriguez and Ouyang developed emission estimates for fracturing fleets in the Marcellus and Eagle Ford Shale Plays[38]. Their work used three models with a variety of EFs. The models analyzed were EPA AP-42 (Worst Case), EPA AP-42 with an average load factor and the EPA NONROAD2008. EFs used included EPA Standards Tier 2, Mfg. Tier 2, TCEQ Tier 2, AP-42 and EPA Nonroad Tier 2. They analyzed CO, NO_x, and THC emissions for a job – the same as per well. Table S13 presents their minimum, maximum, and worst case data for NO_x, CO, and THC emissions. Our per well estimates on a national basis (regardless of play details) were within the minimum and maximum for both NO_x and CO emissions. However, our diesel-only estimate for THC emissions was 66% of their minimum value. This gives confidence to our range of values for the base diesel case.

Vafi and Brandt developed an open-source model for estimating greenhouse gas (GHG) emissions from drilling and fracturing operations[64]. Their model required additional information such as well bore and 31 other variables and did not evaluate other gaseous emissions. Table S14 presents a comparison of our average diesel only per well estimates compared with their four case studies. We see that the average CO_{2eq} emissions from their four scenarios are nearly equally distributed between drilling and fracturing as shown also by our model. Our average CO_{2eq} emissions tended to be 32% higher than the mean of their four scenarios. However, even when we included our 95% CI, our average fell within all of their scenarios ranges – again building confidence in our model.

RESULTS and DISCUSSION

Diesel Fleet

As a baseline, the total emissions were analyzed as if all wells were drilled and completed using exclusively diesel engines. The contributions of each of the prime-movers to annual emissions are shown in Figure 1. The total emissions and fuel energy used are displayed above the pie charts with the respective contribution by each of the prime-movers. Additional Tables and Figures for diesel only operation are presented in the SI. The error bars and uncertainty represent the 95% confidence interval of the respective value. Verification of the model was performed using data from a well in which extensive data was collected for both drilling and hydraulic fracturing.

Total annual estimated energy consumed by diesel fuel for all prime-movers was 1.66×10^{11} mega-Joules (MJ) or 0.157 quadrillion British Thermal Units (quads). Average annual domestic energy production for 2014-2016 was 86.71 quads[65]. The prime-movers accounted for the consumption of 0.18% of total energy production. A majority of the fuel energy was consumed by unconventional drilling – 45% but was similar to hydraulic fracturing – 44%. Total annual diesel fuel consumed was 1.2 ± 0.7 billion gallons. Since all prime-movers used diesel, a slight variation resulted in the distribution of CO_2 emissions likely because trucking engines experienced more transient behavior and may be less efficient than larger bore engines. The nature of transient operation also showed the trucking sector dominated THC emissions. Note that trucking data were collected for a variety of model year trucks, which included data and activity for both pre- and post- 2010 compliant vehicles. Methane emissions were low since natural gas was not used, thus CH_4 only contributed to 6.3% of THC emissions. NO_x emissions were dominated by hydraulic fracturing engines due to high load operation and total amount of energy consumed combined with more lenient off-road emissions standards. NO_x emissions were the largest contributor to annual regulated emissions with all prime movers accounting for

64,600 ± 38,400 metric tons (tonnes). Table 2 presents the EFs per year and per well for the diesel only case. See Figures S4 and S5 and the attached SI workbook for additional diesel only information.

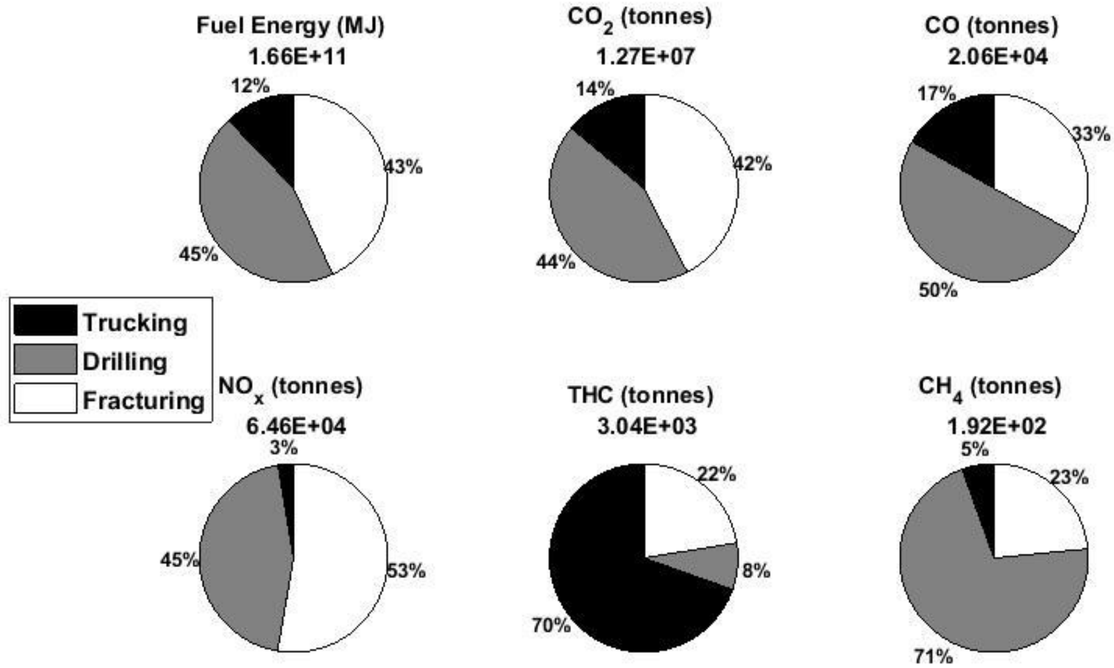


Figure 1. Estimated annual emissions for an average well count of 12,325 along with distribution by prime-mover – diesel-only.

Table 2. Diesel-only fuel consumption and gaseous emissions on an annual and per well basis for an average of 12,325 wells. Note that diesel consumption is in tera-joules (TJ – 10^9 Joules)

	Diesel	**CO_2**	**CO**	**NO_x**	**THC**	**CH_4**
	(TJ)	**(kilo-tonnes)**	**(tonnes)**	**(tonnes)**	**(tonnes)**	**(tonnes)**
Annual	166,000	12,700	20,600	65,600	3,040	192
95% CI	72,800	5,560	9,020	28,300	1,330	114
Per Well	9.31	0.71	1.15	3.62	0.17	0.01
95% CI	1.46	0.12	0.02	061	0.09	0.00

Total fuel costs are driving the conversion from diesel only operation to dual-fuel and dedicated natural gas operation. Analysis of fuel costs was performed using the average retail diesel prices 2014-2016[66]. While it is recognized that this is not the price that large-scale drilling and fracturing operations pay per gallon of diesel fuel, it was representative for trucks and serves as a comparison with natural gas. The natural gas prices used for analysis were the average Henry Hub spot prices for 2014-2016[67]. We note that the price of natural gas varies by operator and the attached spreadsheet allows for users to change the base prices in the highlighted cells. Fuel costs by activity are found in Table S10 for the diesel only case. The estimated diesel fuel costs for all prime-movers was \$198,370 ± \$31,089, per well. Note, this value includes only the prime-movers and excluded onsite fuel consumption and costs associated with auxiliary equipment such as boilers, light-towers, and other on-site equipment.

Effects of Natural Gas Technology Penetration

The model examined the effects of natural gas technologies on emissions as a function of market penetration (MP). There are limited data on the number of dual-fuel and dedicated natural gas drilling rigs and hydraulic fracturing fleets. Estimates from 2014 suggested that the percentage of drilling rigs capable of dual-fuel operation was between 4 and 6%, while only 2% operated exclusively on natural gas[68-70]. Dual-fuel hydraulic fracturing was estimated to represent 3% of the total US fleet while dedicated natural gas operation has yet to reach 1%[69]. As opposed to examining these reported penetration levels, the model created a population of 200,000 of each well type – diesel only, dual-fuel, and dedicated natural gas. The model then replaced the selected percentage of diesel wells with dual-fuel or dedicated natural gas wells. For the case of hydraulic fracturing engines, the dedicated natural gas scenario included operation of those engines as dual-fuel since no data were available for dedicated natural gas engines. Data for each percentage of market penetration (%MP) is included in the attached Spreadsheet and Figures are presented in Figures S6-S8. Literature reported varied impacts of dual-fuel engines on reducing CO_2 emissions[71,72] and literature reported higher CO_2 emissions for stoichiometric dedicated natural gas engines[73]. Note the drilling engines in our research were rich-burn. From this analysis, CO_2, CO, THC, and CH_4 emissions increased with increasing MP. NO_x emissions decreased with increasing MP. The most significant increase in gaseous emissions was for CH_4. Table 3 presents a summary of the impacts on energy consumption and gaseous emissions based on %MP for both dual-fuel and dedicated natural gas cases.

Table 3. Impact on Energy and Emissions Based on Market Penetration (MP in percentage) of Dual-Fuel and Dedicated Natural Gas Scenarios. Values represent the relative change (%) from the base case of diesel only with respect to increasing MP (%). Note that THC and CH_4 increase dramatically during early market penetration and their relative increase is the average of relative increases from 1-100% MP. See Figure 2 for graphical trends.

	Diesel Energy	**Total Fuel Energy**	**CO_2**	**CO**	**NO_x**	**THC**	**CH_4**
	%/%MP	**%/%MP**	**%/%MP**	**%/%MP**	**%/%MP**	**%/%MP**	**%/%MP**
Dual-Fuel Scenario	-0.49	+0.46	+0.11	+0.31	-0.13	+6.28	+32.5
Dedicated Natural Gas Scenario	-0.78	+0.66	+0.25	+0.84	-0.58	+5.11	+20.0

Figure 2 presents the impact on greenhouse gas (GHG) emissions in tonnes per well based on MP of the two available technologies. The left side shows GHG emissions as a function of MP for the dual fuel scenario while the left shows GHG emissions as a function of MP for the dedicated natural gas scenario. The International Panel on Climate Change assigns CH_4 a global warming potential (GWP) of 86 or 34 for 20 and 100-year periods[74]. However, the EPA uses

GWP of 25 to account for CH_4 emissions for GHG emissions compliance[75] and we used this value. For the dual-fuel case of 100% MP, GHG emissions more than doubled. CO_2 emissions for the dual-fuel trucking sector were the only source of GHG emissions that decreased but these reductions were offset by the increased CO_{2eq} methane emissions. Note that for the dedicated natural gas scenario the hydraulic fracturing engines still operated as dual-fuel since no data were available for dedicated natural gas fracturing engines. For this scenario, GHG emissions increased by a factor of 1.82 mainly due to dual-fuel fracturing engines. Net drilling GHG emissions would increase mainly due to increased CO_2 emissions from lower engine efficiencies as opposed to CH_4 slip for the dual-fuel case. The trucking sector would see a net reduction of GHG emissions of about 20%.

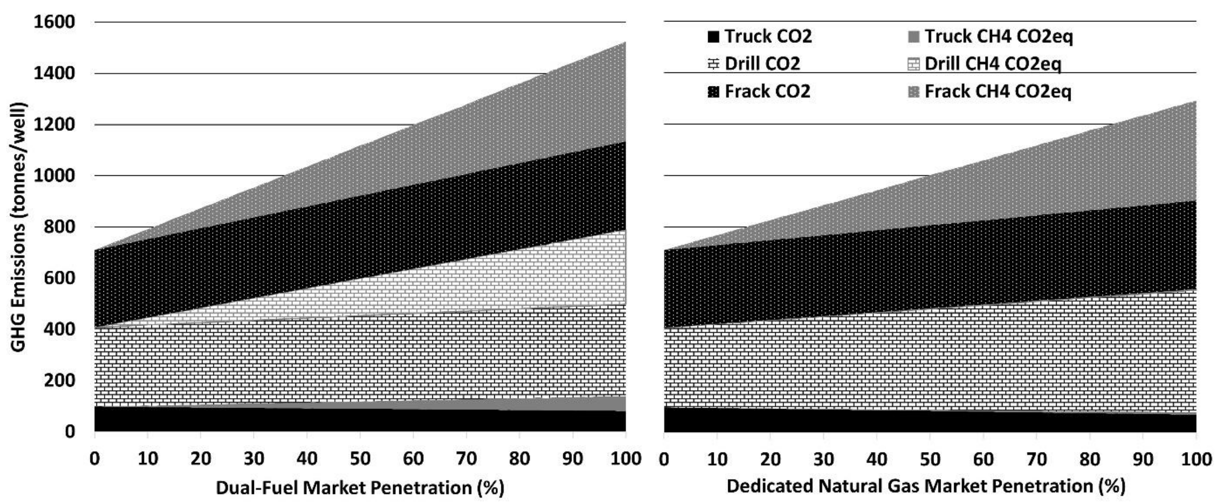


Figure 2. Effects of technology market penetration on GHG emissions per well. Data include both exhaust and crankcase emissions. A GWP of 25 was used to convert CH_4 to CO_{2eq}.

Extreme Case – All Dual-fuel Operations

Since dual-fuel conversion systems are currently available for all prime-movers, we modelled an extreme MP case to examine the effects if all were operated on dual-fuel. For this analysis, any on-road dual-fuel kit could be used but drilling and fracturing engines were limited to those that used diesel oxidation catalysts (DOCs). Figure 3 shows the national estimate of annual emissions if all prime-movers were converted to operate as dual-fuel for the average well count of 12,325. Due to the inefficiency of dual-fuel operation and CH_4 slip, the net fuel energy consumed increased by 46% while CO_2 emissions increased by 11% due to the lower carbon content of natural gas. Net CO emissions increased by 31% while NO_x emissions saw slight reduction of 13%. The most significant increases would be for THC and CH_4 emissions. THC emissions increased by a factor of 177 while CH_4 emissions increased by a factor of 2742. Annual diesel fuel consumption decreased from $1.20x10^9 \pm 5.25x10^8$ gallons to $6.11x10^8 \pm 3.62x10^8$ gallons – an average reduction of 589 million gallons for 12,325 wells. This displaced diesel was offset by the use of $1.5x10^8 \pm 8.92x10^7$ MMBTU of natural gas. Based on 2014-2016 average fuel prices, complete conversion to dual-fuel from diesel only would reduce annual fuel costs from \$3.53 ±1.55 Billion to \$2.28 ± 1.11 Billion – an average savings of \$1.26 Billion. Figures S9 and S10 present trends by prime-mover and Table S11 presents data on fuel costs for dual-fuel scenario.

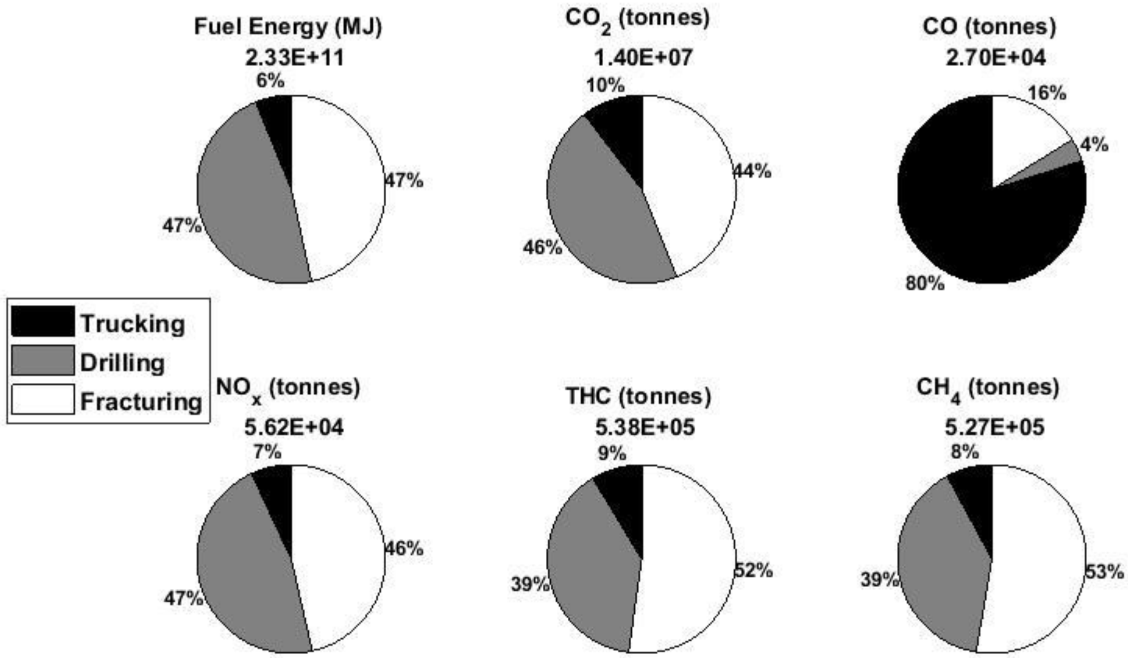


Figure 3. Estimated annual emissions for an average well count of 12,325 along with distribution by prime-mover – dual-fuel.

Using a GWP of 25, the annual CO_{2eq} emissions for diesel only wells would be 1.27×10^7 tonnes. If all wells were dual-fuel, annual CH_4 emissions would increase to $5.27 \times 10^5 \pm 3.13 \times 10^5$ tonnes (13.2 MMT of CO_{2eq}). The average annual CO_{2eq} emissions would increase by a factor of 2.14 to 2.72×10^7 tonnes (27.2 MMT). The most recent GHG inventory data is for 2015[75]. The natural gas infrastructure produced 162.4 MMT of CH_4 as CO_{2eq}. Therefore, dual-fuel CH_4 emissions would represent about 8% of the entire natural gas system CH_4 emissions as CO_{2eq}. Dual-fuel CH_4 emissions would be about 1.9 times stationary combustion CH_4 emissions (7.0 MMT of CO_{2eq} in 2015) and 6.6 times mobile combustion CH_4 emissions (2.0 MMT of CO_{2eq} in 2015).

Extreme Case – Dedicated Natural Gas Scenario

Dedicated natural gas engines are available for both on-road trucks and drilling rig engines and in some cases for hydraulic fracturing engines. However, since no data were available for dedicated natural gas hydraulic fracturing engines, we used only the dual-fuel data for these engines within this scenario. Figure 4 shows the national estimate of annual emissions for this case and for the average well count of 12,325. Since fracturing engines were still dual-fuel, they dominated production of NO_x, THC, and CH_4 emissions. Dedicated natural gas engines saw lower CO_{2eq} emissions since CH_4 slip was lower than dual-fuel engines but saw lower overall efficiency due to limited compression ratios, throttling losses, and stoichiometric/rich operation of current engines. Thus, net fuel energy consumed increased by 66% compared to diesel only and 14% over the dual-fuel case. CO_2 emissions increased by 25% over the diesel only case due to the lower carbon content of natural gas. Net CO emissions increased by 83% while NO_x emissions saw significant reduction of 58%. These reductions were possible through stoichiometric/rich operation and three-way catalysts (TWC) for on-road and drilling engines. THC emissions increased by a factor of 95 while CH_4 emissions increased by a factor of 1489 – both factors lower than the dual-fuel case because of significant elimination of CH_4 slip from trucking and drilling engines. Annual diesel fuel consumption decreased from $1.20x10^9 \pm 5.25x10^8$ gallons to $2.60x10^8 \pm 1.54x10^8$ gallons – an average reduction of 939 million gallons for 12,325 wells. This displaced diesel was offset by the use of $2.28x10^8 \pm 1.35x10^8$ MMBTU of natural gas. Based on 2014-2016 average fuel prices, complete conversion to dedicated natural gas from diesel only would reduce annual fuel costs from \$3.53 ±1.55 Billion to \$1.49 ± 0.63 Billion – an average savings of \$2.04 Billion. Figures S11 and S12 present trends by prime-mover and Table S12 presents data on fuel costs for dedicated natural gas.

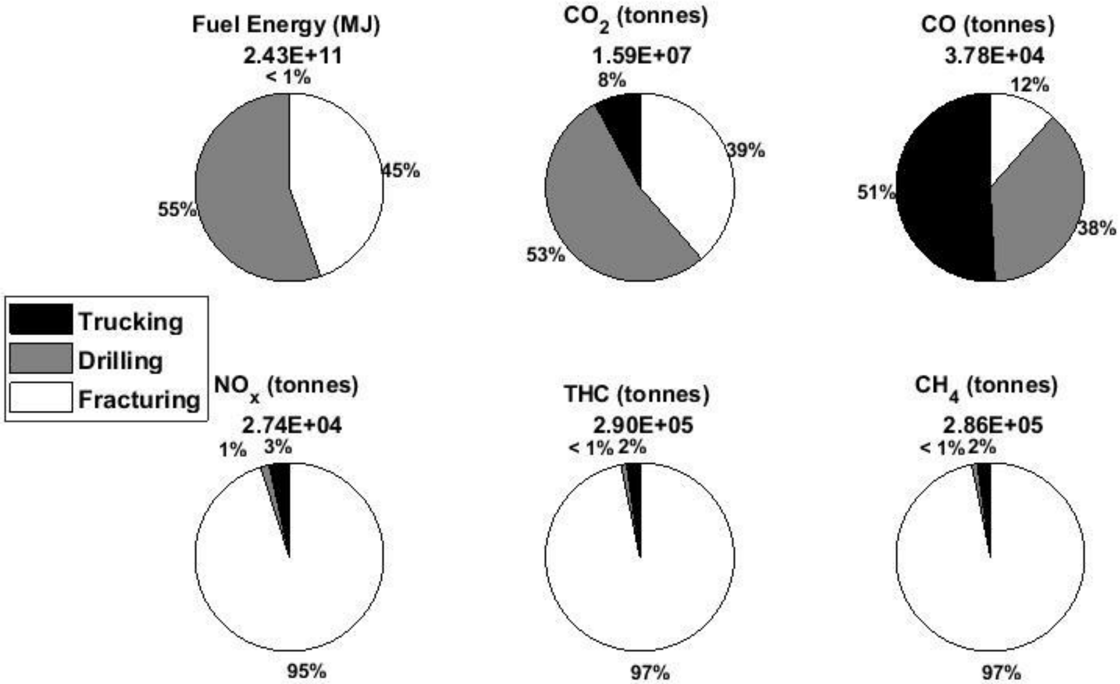


Figure 4. Estimated annual emissions for an average well count of 12,325 along with distribution by prime-mover – dedicated natural gas.

For this scenario, annual CH_4 emissions would increase to $2.86\text{x}10^5 \pm 1.70\text{x}10^5$ tonnes (7.2 MMT of CO_{2eq}). The average annual CO_{2eq} emissions would increase by a factor of 1.82 to $2.30\text{x}10^7$ tonnes (23.0 MMT) when compared to diesel only. Therefore, the CH_4 emissions would represent about 4.4% of the entire natural gas system CH_4 emissions as CO_{2eq}. The CH_4 emissions for this scenario would be about equal to stationary combustion CH_4 emissions (7.0 MMT of CO_{2eq} in 2015) and 3.6 times mobile combustion CH_4 emissions (2.0 MMT of CO_{2eq} in 2015). Therefore, dedicated natural gas engines offer the most fuel savings with a lower GHG penalty as compared to current dual-fuel technologies.

Current Technologies, Effects of Aftertreatment, and Efficiency

Current dual-fuel technologies are retrofit kits applied to conventional compression ignition diesel engines[76]. These types of retrofit kits have been shown to increase CO and NMHC engine out emissions[40,77-79]. To overcome this weakness industry has implemented DOCs to reduce CO emissions[80-83]. Based on literature, there are methods to reduce dual-fuel emissions through engine optimization and sophisticated system integration. Such methods have shown decreased CH_4 slip[84-86]. Our in-use data showed dual-fuel drilling and hydraulic fracturing engines had methane slip rates of 14 to 19% and 22%, respectively. Alternative technologies, such as heavily integrated high-pressure direct injection “HPDI” engines, which use dual-fuel combustion, offer reduced CH_4 emissions compared to retrofit kits (1.74% slip rate for HPDI versus 3-47% for on-road retrofit engines)[10]. However, these technological developments are not currently available for heavy-duty off-road engines which to-date have been dominated by the conversion of Tier 2 engines using currently available technologies.

Due to the downward rig counts and limited market penetration of the technologies, data were collected from a limited number of engines. Of four dual-fuel engines tested, only three had DOCs. Earlier conversions like one drilling rig examined during field measurements may not have installed a DOC during conversion. Due to significantly increased CO emissions, this practice should be avoided. Due to the limited sample size, we cannot speculate on the current inventory of dual-fuel engines without DOCs. Data showed that the major emissions benefits of dual-fuel kits with DOCs to be reductions of CO emissions[36]. Using data and the model, it is determined that the CO reduction benefits from dual-fuel drilling fleets would be negated if 8.1% of conversions did not use DOCs, see Figure S13. On-road dual-fuel engines spanned multiple certification years and were all included for dual-fuel trucking.

In addition, one of the two dedicated natural gas drilling rigs had a catalyst or air fuel control system that was defective or needed service. NO_x emissions from dedicated natural gas drilling engines with properly operating catalysts were nearly two orders of magnitude lower than Tier 2 diesel NO_x emissions[36]. Even with the poorer performing dedicated natural gas engine produced similar or lower NO_x emissions compared to diesel. Benefits could be seen at any market penetration level and malfunction rate. However, in addition to NO_x reductions, properly operating TWC also reduced THC and CO emissions. Catalyst maintenance procedures should be followed to maximize emissions benefits. It is noted that lean-burn engines are available for drilling engines[76], but, based on communications with industry, the trend was to utilize stoichiometric/rich burn engines, which offered lower emissions. A similar trend has occurred in switching from lean-burn truck engines to stoichiometric engines with TWCs.

Data were presented from both a CO_2 and CO_{2eq} perspective. Both are measures of an engines fuel conversion efficiency. The results showed that as more dual-fuel engines were utilized both their CO_2 and $CO_{2\text{-}eq}$ emissions tended to increase. In field measurements showed that diesel engines operating at steady-state had efficiencies of about 38%[37]. The conversion to dual fuel engines decreased overall efficiencies to about 26%[37]. We showed that the decrease in efficiency is both due to lower in-cylinder efficiency and methane slip. For dedicated natural gas drilling engines, the average efficiency was about 20% or about 47% lower than diesel drilling engines[37]. The natural gas drilling engines suffered their lowest efficiencies (around 13%) during transient operation when the engine was throttled[37]. Future research should examine methods to eliminate transient operation of natural gas engines through use of rig hybridization to ensure peak efficiency of current engine technologies is realized by industry.

ASSOCIATED CONTENT

Supporting Information.

The following files are available free of charge. Additional model details and data are provided as supporting information (PDF).

AUTHOR INFORMATION

Corresponding Author

*Email: derek.johnson@mail.wvu.edu, Phone: 304-216-6592

Author Contributions

The manuscript was written through contributions of all authors. All authors have given approval to the final version of the manuscript.

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ABBREVIATIONS

AF, activity factor; BSFC, brake-specific fuel consumption; BTU, British Thermal Units; CARB, California Air Resources Board; CI, confidence interval; CO, carbon monoxide; CO_2, carbon dioxide; CO_{2eq}, carbon dioxide equivalent; CH_4, methane; DOC, diesel oxidation catalyst; EF, emission factor; EPA, Environmental Protection Agency; GHG, greenhouse gas; GWP, global warming potential; HP, engine power; Hz, hertz; kg/bkW-hr, kilograms per brake kilowatt hour; Lb/Bhp-hr, pounds per brake horsepower hour; LLT, low-load transient; M, million; MJ, mega-joules; MMT, million metric tons; MMBTU, million BTUMP, market penetration; NG, natural gas; NMHC, non-methane hydrocarbons; NO_2, nitrogen dioxide; NO_x, oxides of nitrogen; O_3, ozone; quads, quadrillion British Thermal Units; SI, supporting information; SSD, steady-state drilling; t, time; THC, total hydrocarbons; TWC, threeway catalyst; US, United States; VOC, volatile organic compounds.

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"Supporting Information"

Estimated Emissions from the Prime-Movers of Unconventional Natural Gas Well Development Using Recently Collected In-Use Data in the United States

Derek Johnson, Robert Heltzel, Andrew Nix, Mahdi Darzi, and Dakota Oliver*

West Virginia University, PO Box 6106, Morgantown, WV 26506.

*Derek.Johnson@mail.wvu.edu, 304-293-5725

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Contents

Introductory Information

Natural gas production from unconventional wells currently dominates all US production and this trend is expected to increase though 2040[1]. Through a review of literature, we found that the prime-movers (or major fuel consumers) for unconventional well development were the over-the-road trucks servicing these sites, the horizontal drilling rig engines, and the hydraulic fracturing engines. Table S1 shows an example of average fuel consumption per well as average from literature. Table S2 presents the relative contributions for unconventional well development based on the prime-movers.

Table S1: Average Diesel Fuel Consumption of the Prime-Movers of Unconventional Well Development[2]

Prime Mover	Fuel Consumption (gallons per well)
Over-the-Road Trucks	4,787
Horizontal Drilling Rigs	61,434
Hydraulic Fracturing Engines	21,000

Table S2: Relative Emissions Estimates (%) for the Prime-Movers of Unconventional Well Development from Literature.

Source	Emissions	Macrellus[20]	Arkansas[24]	Rocky Mountain Region[12]
Transportation	**VOC**	0.5-1.2		
	NO_x	3.2-3.5		
	CO_2			
Drilling Only	**VOC**		11.3	
	NO_x		26.7	2-36
	CO_2		3.9	
Hydraulic Fracturing Engines Only	**VOC**		2.4	
	NO_x		5.7	
	CO_2		0.9	
Drilling and Hydraulic Fracturing Engines	**VOC**	2.6-10.4	13.7	
	NO_x	28.9-38.8	32.4	
	CO_2		4.8	

Table S3 presents a summary of publications and their sources used for emissions factors (EFs). Table S4 presents some of the EF, AF, and other values presented from reports in Table S3 for diesel engines power drilling rigs and hydraulic fracturing pumps.

Table S3: Summary of Literature using Various EFs.

	Literature Report	EFs Used
1	*Rodriguez and Ouyang, 2013*	EPA Tier 2 Standards, Manufacturers Data, AP-42, EPA NONROAD Tier 2, ERG, ENVIRON, others
2	*Stuvar, 2015*	CARB, EPA, and AP-42 Allowable Standards
3	*Bar-Ilan, 2007*	Company Surveys and Permitting Data
4	*Litovitz et al, 2013*	NY 2011 Environmental Impact Statement, National Research Council, GREET, PA DEP Data
5	*Field et al, 2014*	US EPA National Emissions Inventory
6	*Roy et al, 2013*	AP-42 and similar engines
7	*Environ, 2009*	Bar-Ilan, 2007 and EPA NONROAD

Table S4: Summary of Literature Findings using Various EFs. Emissions are in g/kW-hr.

	Activity	Source	Power (kW)	AF	Time (hrs)	NO_x+ NMHC	NO_x	VOC (NMHC)	CO
2	Drilling	CARB Standard	3302 (3 engines)	1	--	5.3	5.04	0.27	1.6
		US EPA Standard				6.4	6.08	0.32	3.5
		AP-42 Controlled				--	7.91	0.43	3.35
		AP-42 Uncontrolled				--	14.6	0.43	3.35
6	Drilling	AP-42 and similar engines	3177 (3 engines)	0.57	624		7.78	0.81	
	Fracking		29,828 (total power)	--	--	--	7.64	0.91	
7	Drilling	Bar-Ilan	2688 (3 engines)	0.67	1500		10.73	1.34	6.71
	Fracking		745.7 (per engine)	0.5	54		10.73	1.74	6.71

Emissions Factors

Tables S5 and S6 present the EFs developed for drilling and fracturing engines based on our recent in-use measurements. Table S7 includes the gas composition for dual-fuel and dedicated natural gas engines during field work. EFs for heavy-duty diesel over-the-road trucks were based on certification emissions available from the US Environmental Protection Agency[5]. The engines were selected because vehicles were examined for activity data throughout the Marcellus and Utica used these engines. As expected, the fleet was varied and included both pre- and post- 2010 compliant vehicles. EFs for over-the-road dual-fuel engines were taken from literature from the same research institution[6]. The engines from this paper had varied substitution rates and aftertreatment systems. Emissions from dedicated over-the-road natural gas engines were taken in the West Virginia University (WVU) Engines and Emissions Research Laboratory (EERL) and from other WVU studies. Emissions from ISL-G engines can be found in literature[7]. All truck EFs used for the model are presented in Table S8.

Table S5. Emissions and Fuel Consumption Factors for Diesel, Dual-fuel, and Dedicated Natural Gas Drilling Engines Used within the Inventory Model.

Engine	Make/ Model	Fuel	Rated Power (kW)	After-treatment	Activity	BSFC (NG)	BSFC (Diesel)	CO_2	CO	NO_x	THC	CH_4
						g/kW-hr	g/kW-hr	g/kW-hr	g/kW-hr	g/kW-hr	g/kW-hr	g/kW-hr
1	Caterpillar/ 3512C	Diesel	1101	None	SSD	0.00	207.70	657.65	1.18	3.56	0.03	0.02
					LLT	0.00	230.15	738.96	2.23	3.74	0.06	0.04
2	Caterpillar/ 3512C	Diesel	1101	None	SSD	0.00	219.21	705.04	1.10	3.61	0.02	0.01
					LLT	0.00	190.92	611.20	1.48	2.94	0.04	0.02
3	Caterpillar/ 3512C	Diesel/ Field Gas	1101	DOC	SSD	186.41	77.02	763.69	0.14	3.02	27.48	27.10
					LLT	101.00	192.45	890.01	0.08	4.13	18.65	18.39
4	Caterpillar/ 3512C	Diesel/ Field Gas	1101	None	SSD	168.97	100.91	761.02	14.63	5.03	20.52	20.38
					LLT	122.13	154.16	788.33	12.37	6.74	21.86	21.77
5	Waukesha/ 7044GSI	CNG	1253	TWC (good)	SSD	282.40	0.00	973.84	1.50	0.05	0.33	0.31
					LLT	389.64	0.00	1345.6	2.89	0.04	0.40	0.38
6	Waukesha/ 7044GSI	Field Gas	1253	TWC (bad)	SSD	312.21	0.00	866.19	43.64	3.18	0.98	0.88
					LLT	544.22	0.00	1495.5	86.62	2.53	3.19	2.74

Table S6. Emissions and Fuel Consumption Factors for Diesel and Dual-fuel Hydraulic Fracturing Engines Used within the Inventory Model.

Engine	Make/ Model	Fuel	Rated Power (kW)	After-Treatment	BSFC (NG)	BSFC (Diesel)	CO_2	CO	NO_x	THC	CH_4
					g/kW-hr	g/kW-hr	g/kW-hr	g/kW-hr	g/kW-hr	g/kW-hr	g/kW-hr
7	**Cummins/ QSK 50**	**Diesel**	**1678**	**None**	0.00	217.52	697.29	1.18	5.97	0.16	0.01
8	**Caterpillar/ 3512B HD**	**Diesel**	**1678**	**None**	0.00	234.08	749.52	0.65	3.21	0.03	0.00
9	**Cummins/ QSK 50**	**Diesel/ CNG**	**1678**	**DOC**	164.25	99.21	760.16	0.60	3.83	31.45	31.45
10	**Caterpillar/ 3512B HD**	**Diesel/ Field Gas**	**1678**	**DOC**	191.47	127.14	891.97	0.57	3.17	44.02	43.18

Table S7. Fuel Composition for Dual-Fuel and Dedicated Natural Gas Drilling and Hydraulic Fracturing Engines. Note that the lower heating value (LHV) is in units of mega-joules (MJ) per standard cubic foot (SCF).

Engine	NG Source	CH_4 (%)	C_2H_6 (%)	C_3H_8 (%)	N_2	CO_2	Methane Number	LHV (MJ/SCM)	Density (kg/m3)
9	**CNG**	95.04	3.19	0.53	0.56	0.27	85.3	39.31	0.714
3	**Field Gas**	97.30	2.07	0.08	0.25	0.31	90.0	38.41	0.691
10	**Field Gas**	97.31	2.06	0.07	0.25	0.31	90.6	38.40	0.691
4	**Field Gas**	96.71	0.22	0.01	0.44	2.63	96.9	36.60	0.708
5	**CNG**	86.10	--	--	2.36	0.00	--	40.61	0.763
6	**Field Gas**	78.56	12.78	2.46	2.46	0.18	60.8	45.61	0.873

Table S8: Emissions and Fuel Consumption Factors for Diesel, Dual-Fuel, and Dedicated Over-the-Road Engines

Engine Information		Model	Year	BSFC (NG)	BSFC (Diesel)	CO_2	CO	NO_x	THC	CH_4
				g/ kw-hr	g/ kw-hr	g/ kw-hr	g/ kw-hr	g/ kw-hr	g/ kw-hr	g/ kw-hr
Diesel	Engine 11	ISX15	2005	0.00	209.7	815.3	2.95	1.34	1.21	0.01
	Engine 12	ISX15	2008	0.00	223.7	765.7	2.55	0.10	1.21	0.01
	Engine 13	ISX15	2009	0.00	224.5	852.9	1.48	0.27	1.21	0.01
	Engine 14	ISX15	2010	0.00	227.4	836.8	1.48	2.28	0.24	0.00
	Engine 15	ISX15	2011	0.00	223.4	823.4	1.48	1.34	0.23	0.00
	Engine 16	ISX15	2012	0.00	218.1	836.8	1.34	0.27	0.23	0.00
	Engine 17	ISX15	2013	0.00	199.3	836.8	1.48	0.30	0.23	0.00
	Engine 18	C15	2006	0.00	223.2	745.6	3.22	2.15	0.94	0.00
	Engine 19	C15	2009	0.00	223.2	745.6	1.21	2.01	1.21	0.01
	Engine 20	C15	2010	0.00	237.8	745.6	1.21	1.61	3.49	0.02
	Engine 21	D13	2002	0.00	212.3	681.2	1.00	1.74	3.35	0.02
	Engine 22	D13	2012	0.00	212.3	681.2	1.00	0.16	3.35	0.02
	Engine 23	MP8	2011	0.00	210.5	794.7	1.78	1.12	0.16	0.00
Dual-fuel	Engine 24*	OM-4606	2005	105.8	132.9	658.6	15.33	2.82	39.80	36.10
	Engine 25*	AC-460P	2005	93.2	143.1	673.1	8.81	2.40	15.92	14.19
	Engine 26*	MP8-505C	2011	48.1	183.2	662.1	5.31	0.11	7.97	6.62
Natural Gas	Engine 27*	ISL-G-280	2012	371.5	0.00	610.5	1.65	0.20	5.64	5.52
	Engine 28*	ISX12G-350	2013	199.0	0.00	549.2	16.03	0.67	0.47	0.46

Data collected by WVU

Methods

Collecting Emissions, Fuel Consumption, and Activity Data

Gaseous emissions were sampled pre- and post-catalyst for all engines and during both diesel-only and dual-fuel operation where applicable. Exhaust sampling ports were installed on the engine exhaust during rig move. During in-use operation, exhaust missions were sampled through a heated line and filter. Filtered gaseous emissions were measured with a SEMTECH-DS and California Analytical Heated Flame Ionization Detector or with an MKS 2030 FTIR Continuous Gas Analyser. Crankcase emissions were measured with a Full Flow Sampling System. The sampling system connected the crankcase vent to an explosion proof blower operating at a constant volume sample rate and an Ultraportable Greenhouse Gas Analyzer measured diluted CH_4 and CO_2 concentrations. Diesel fuel flow was measured with KRAL OME20 and OME Volumeters®. The combined accuracy was ±2% of the measured value. While the test engine was off, fuel flow meters were installed after the engine's fuel filter assembly and after the return manifold – prior to the cooling circuit. Note these flow meters included temperature compensation. A KURZ MFT-B flowmeter measured the flow rate of natural gas with an accuracy of ±2% of measured values. The natural gas flow meter was installed after the filter and prior to the fuel control units to collect flow rates for the single engine examined. For diesel engines, engine activity data (speed, load, fuel rate and other parameters) were collected with in-house software from the engine control unit and standard J1939 parameters. For natural gas engines, data were collected directly from the engine's serial communications port with support from the engine manufacturer. All data were collected at a rate of 1 Hz and time aligned. Data were collected from each configuration at least three times with test durations ranging from one to three hours.

Inventory Model

The inventory model was separated into three different modules defined by the prime-movers of unconventional well development. Each prime-mover had different variables affecting their contribution to total emissions. Variables between prime-movers were not related, although it is recognized that this may not be the case in some real world scenarios. The model was developed so that an individual well's emissions for each of the three prime-movers were determined by each iteration of the model. A sample population of 200,000 total wells was generated for each fuel type: diesel, dual-fuel and dedicated natural gas. These wells were used as the initial pool to be sampled from to determine average emissions per well and historical yearly emissions profiles. The average annual population was the average historical yearly emissions profiles were based on the number of wells drilled and completed each year as reported by the U.S. Energy Information Administration[4]. A general flow diagram is shown in Figure S1. Each box outlined in dash black corresponds to data collected mainly from literature. Solid boxes represent calculated data and blocks with yellow dashed borders represents EFs developed from in-use data where possible. Distributions for well duration, trips, trip distance, engines, well stages, duration, and power were empirical and based on the distribution of data presented in literature or collected from our fieldwork.

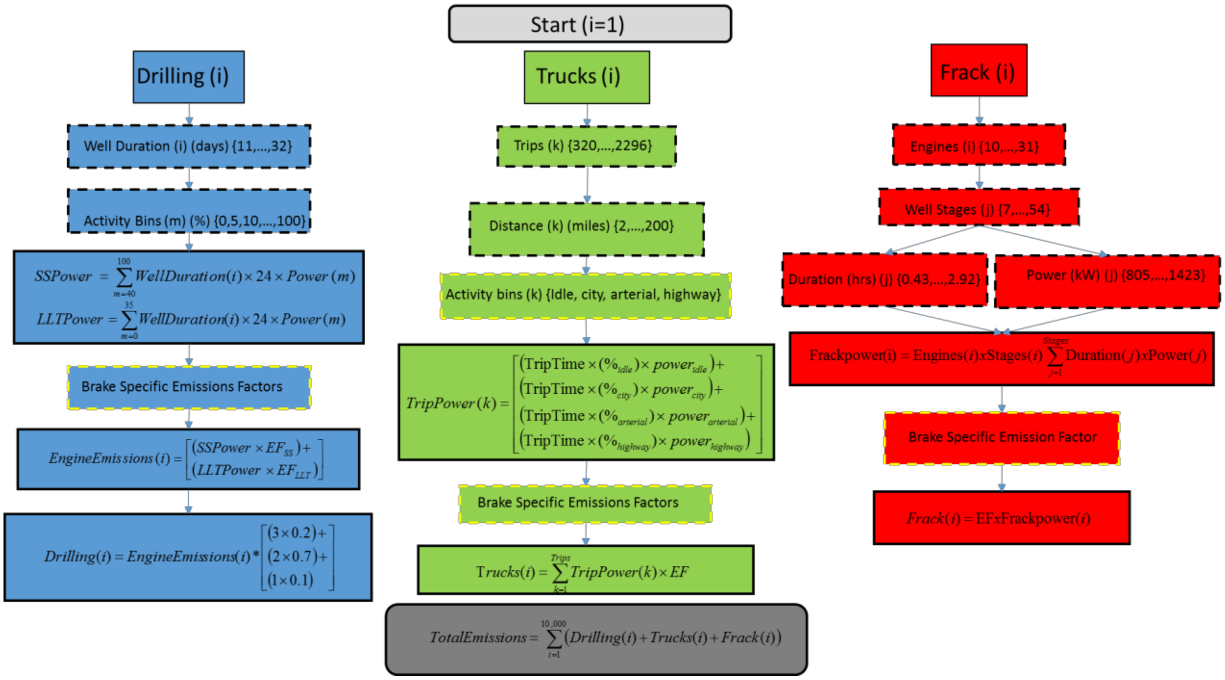

Figure S1: General Flow Diagram of Model.

Based on the diagram above and the number of available selections, there were at least 7.6×10^6 diesel only possibilities, as additional scenarios would increase the possible well scenarios. Since the distribution of all possibilities was not known, a sensitivity analysis was conducted for the diesel only case from 1×10^1 to 5.5×10^5 wells. The selected variable examined was the average CO_2 emission per well from each iteration sample population. CO_2 emissions measurements from in-use data collection tended to have less variabilities due to little impact from engine operation and aftertreatment configuration. CO_2 was also indicative of activity and fuel consumption. Figure S2 shows the relative change in average CO_2 emissions per well based on varied sample population sizes. Note the x-axis is log scale. Figure S3 shows the same data for the relative change in standard deviation of CO_2 emissions per well. We selected a sample population of 200,000. At this population size, the average change in average emissions did not change the first three significant digits of the mean CO_2 emissions.

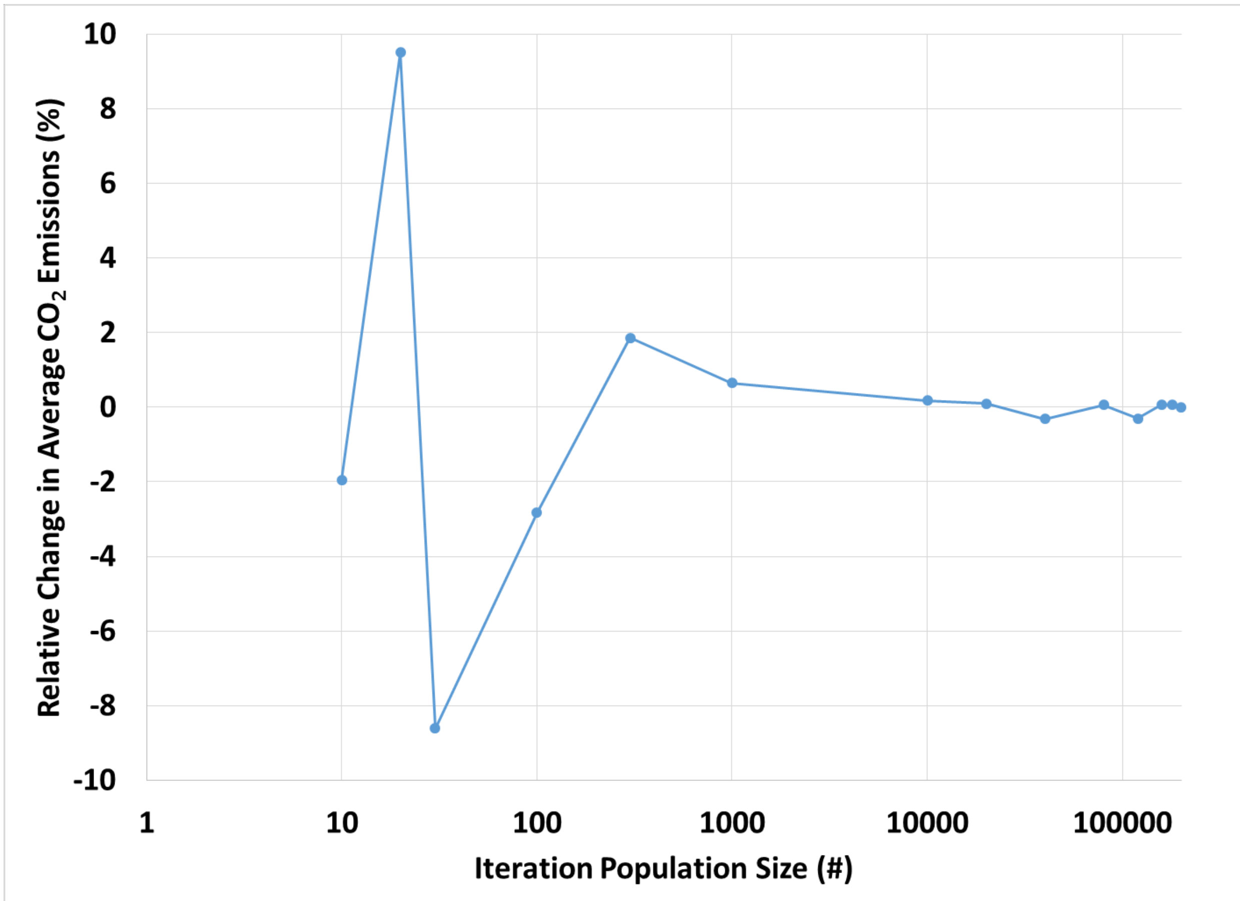

Figure S2: Relative change in average CO_2 emissions per well as a function of iteration population size.

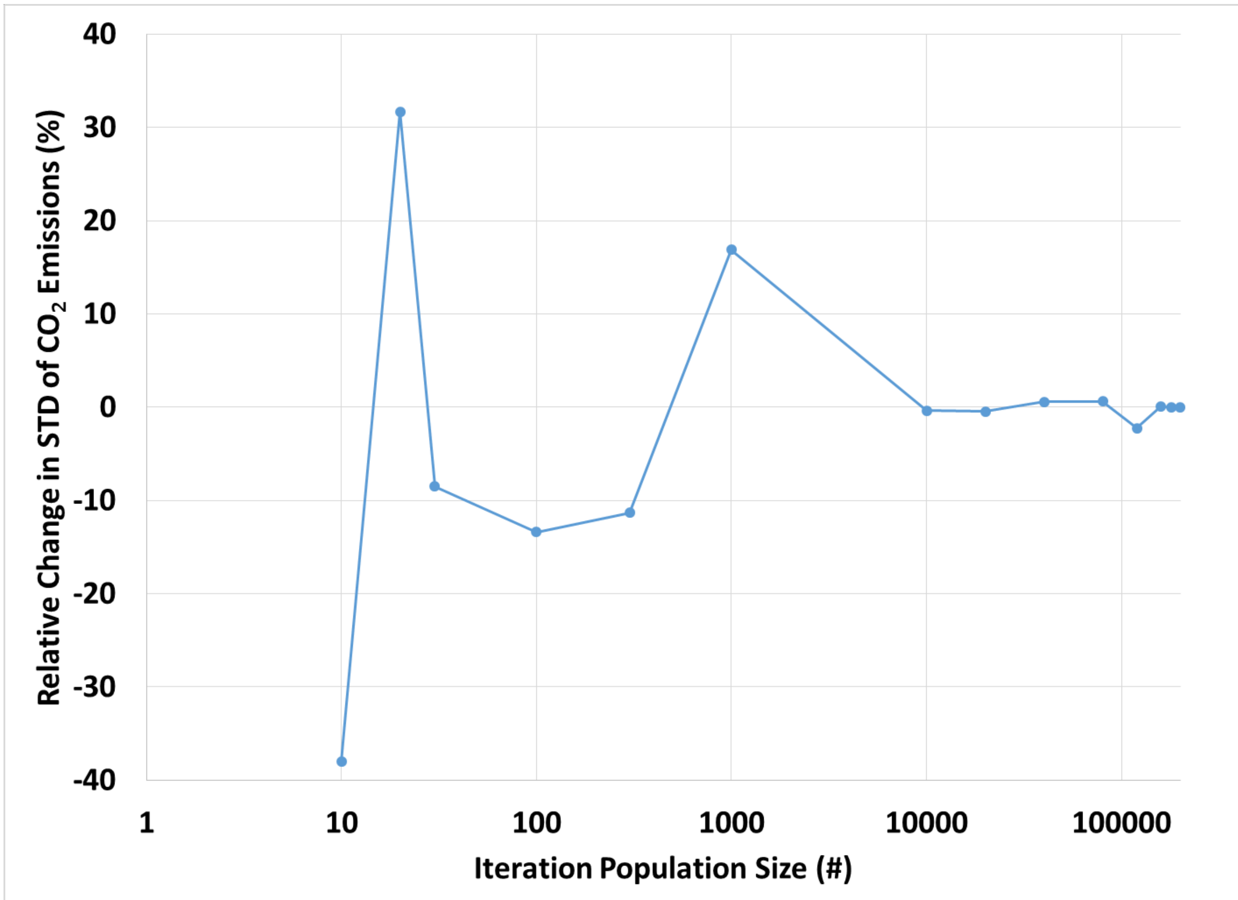

Figure S3: Relative change in the standard deviation of CO_2 emissions per well from all prime movers combined as a function of iteration population sample size.

Table S9 presents the overall results of the sample population of 200,000 diesel wells. Data are included for each prime-mover category and the total. To understand annual variation the model was ran for 20 time different year scenarios each using the average well count from the last three years – 12,325. Mean data are presented for the following scenarios and error bars on all figures represent the 95% confidence interval (CI).

Table S9: Average per well statistics for the entire sample population of 200,000 model generated wells for the baseline diesel only population.

Iterations	200,000	Diesel Only					
		Diesel (Mg/well)	CO_2 (Mg/well)	CO (kg/well)	NO_x (kg/well)	THC (kg/well)	CH_4 (kg/well)
Average	Truck	26.2	98.6	192	95.2	118	0.59
	Drill	97.1	310	579	1,620	13.6	7.65
	Frack	94.2	302	382	1,910	38.3	2.53
	Total	218	711	1,153	3,630	170	10.8
Standard Deviation	Truck	45.5	171	333	165	204	1.02
	Drill	31.8	102	196	530	4.99	3.38
	Frack	54.2	174	254	1,280	38.4	1.69
	Total	132	446	784	1,980	248	6.09
Median	Truck	13.1	49.2	95.8	47.5	58.7	0.29
	Drill	92.3	295	549	1,540	12.8	6.98
	Frack	81.8	262	317	1,590	23.1	2.10
	Total	204	663	1,070	3,340	116	10.1
Max	Truck	2,630	9,870	19,300	9,580	11,900	59.3
	Drill	371	1,190	2,370	6,220	59.6	37.1
	Frack	945	3,030	3,950	19,900	525	26.2
	Total	3,950	14,100	25,700	35,700	12,400	123
Min	Truck	0.04	0.14	0.29	0.13	0.16	0.00
	Drill	23.0	73.0	125	375	2.70	1.30
	Frack	6.12	19.6	16.9	83.8	0.69	0.11
	Total	29.1	92.7	143	459	3.56	1.41

Results

Diesel Only

Figures S4 presents the average gaseous emissions per well of each prime-movers for the baseline case of diesel only operation. Tabular data are presented for the diesel only case in the attached spreadsheet – both by year and by well. Average per well emissions were determined for each of the 20 annual samples. The average standard deviation per well was calculated as the square root of the sum of the variances annually. In all cases, the 95% confidence interval was calculated as the product of standard deviation and 1.96 divided by the square root of 20 (# of years). Note that CO_2 emissions are presented as kilo tonnes – where tonnes are metric tons or 1000 kg. Since all prime-movers are fueled with diesel, the THC and CH_4 emissions are low. We see that the largest contributor to regulated emissions was NO_x – specifically from the drilling and fracturing engines which are required to meet less stringent emissions regulations.

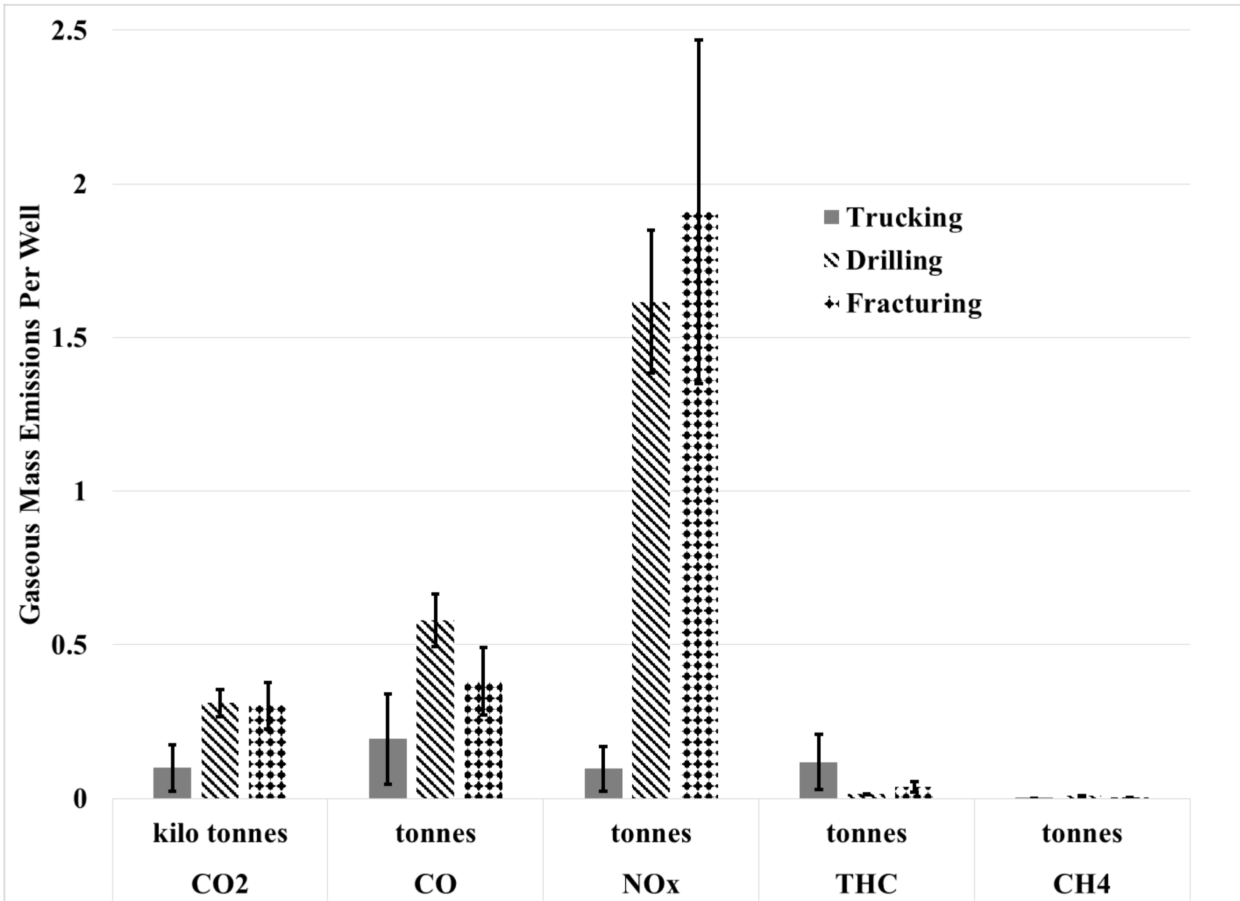

Figure S4: Diesel only scenario - gaseous emissions per well by prime-mover.

Figure S5 presents the same diesel only gaseous emissions but on a yearly average. For the annual basis, the emissions of each of the 12,325 wells were summed. Then the emissions were averaged over each 20 year sample.

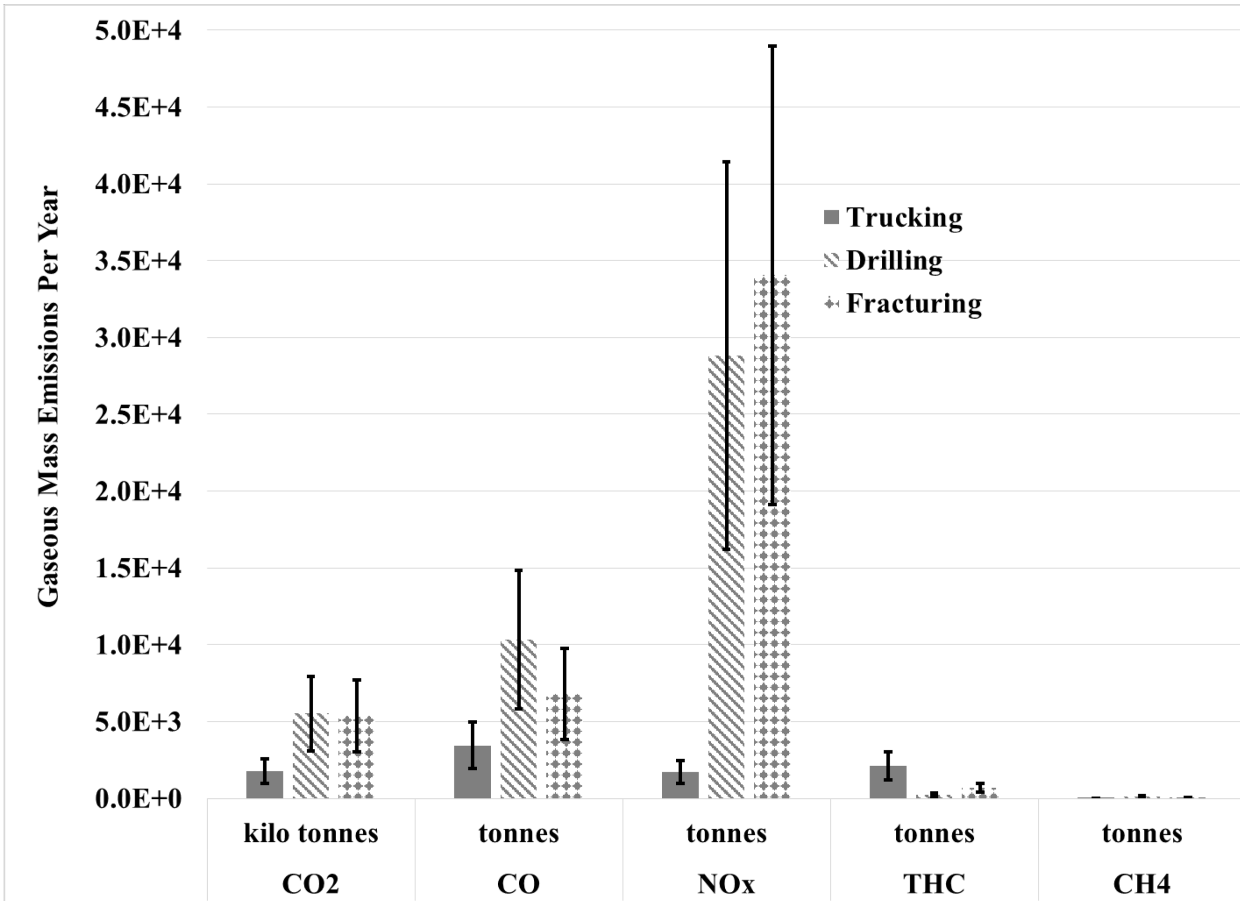

Figure S5: Diesel only scenario - gaseous emissions per year by prime-mover.

Table S10 shows the breakdown of fuel costs per well and per year. As expected, the drilling and fracturing sectors had the highest fuel costs per well and per year. Since the average annual well count of 12,325 was used – the average fuel prices for 2014-2016 were used. The attached spreadsheet includes these values and can be edited for different cost analyses.

Table S10: Fuel Costs by Prime-Mover for Diesel Only Case.

	Prime-Mover	Diesel (gal)	Cost ($)	95% CI
Per Well	Truck	8.17E+03	$24,096	$18,345
	Drill	3.00E+04	$88,535	$12,685
	Frack	2.91E+04	$85,739	$21,575
	Total	6.72E+04	$198,370	$31,089
Per Year	Truck	1.46E+08	$429,438,214	$188,209,595
	Drill	5.35E+08	$1,576,674,814	$691,008,204
	Frack	5.18E+08	$1,526,282,406	$668,922,758
	Total	1.20E+09	$3,532,395,434	$1,548,140,558

Effect of Natural Gas Technology Penetration

Figures S6 presents the trends in fuel energy (both diesel and natural gas) and the total fuel energy as a function of market penetration for both dual-fuel and dedicated natural gas scenarios. For the case of dual-fuel technology deployment, we see that natural gas fuel energy overtakes diesel energy consumption at a market penetration of 70%. This crossover point for the dedicated natural gas scenario was 45% MP. In both cases, the total fuel energy required per well increased. These trends are due to methane slip, throttled stoichiometric/rich operation of current dedicated natural gas technologies, and decreased efficiency of current dual-fuel technologies. As discussed in the text, no data were available for dedicated natural gas fracturing fleets. As such, we see that for the case of 100% dedicated natural gas penetration the diesel fuel energy is still $2.0X10^6$ MJ per well because the fracturing engines were dual-fuel and still consumed some diesel fuel. For the dual-fuel scenario, we see that per well diesel energy consumption decreased by 0.49% per each percentage increase in market penetration (%MP). For the dedicated natural gas scenario, we see that per well diesel energy consumption decreased by 0.78% for each percentage increase in market penetration. Total fuel energy per well increased for dual-fuel and dedicated natural gas scenarios by 0.46 and 0.66%/%MP, respectively.

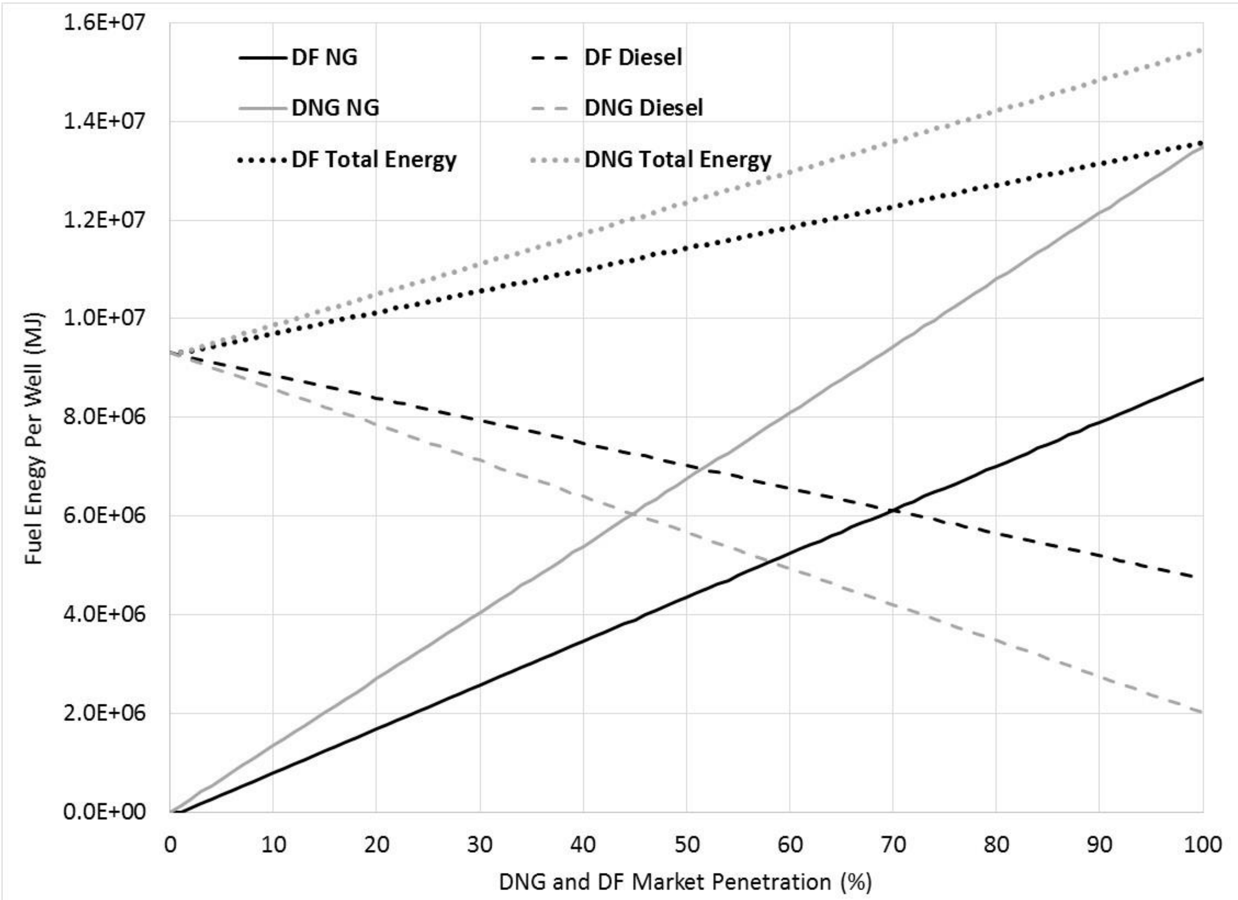

Figure S6: Fuel Energy Per Well as a Function of Dual-fuel and Dedicated Natural Gas Market Penetration.

Figure S7 presents the effects of market penetration for CO_2, CO, and NO_x emissions. Note that CO_2 emissions are presented as kilo tonnes while CO and NO_x are in tonnes. The figure shows that only NO_x emissions tend to decrease with increased use of both technologies. For the case of dual-fuel technologies, NO_x emissions tended to decrease by 0.13%/%MP. The decrease in NO_x emissions was greater for dedicated natural gas technologies – decreased at a rate 4.4 times faster than for dual-fuel. For this case, NO_x emissions decreased by 0.58%/%MP. Both CO_2 and CO increased for both technologies with CO increasing at faster rates. CO_2 emissions increased at a rate of 0.11 and 0.25%/%MP for dual-fuel and dedicated natural gas, respectively. CO emissions increased at a rate of 0.31 and 0.84%/%MP for dual-fuel and dedicated natural gas, respectively.

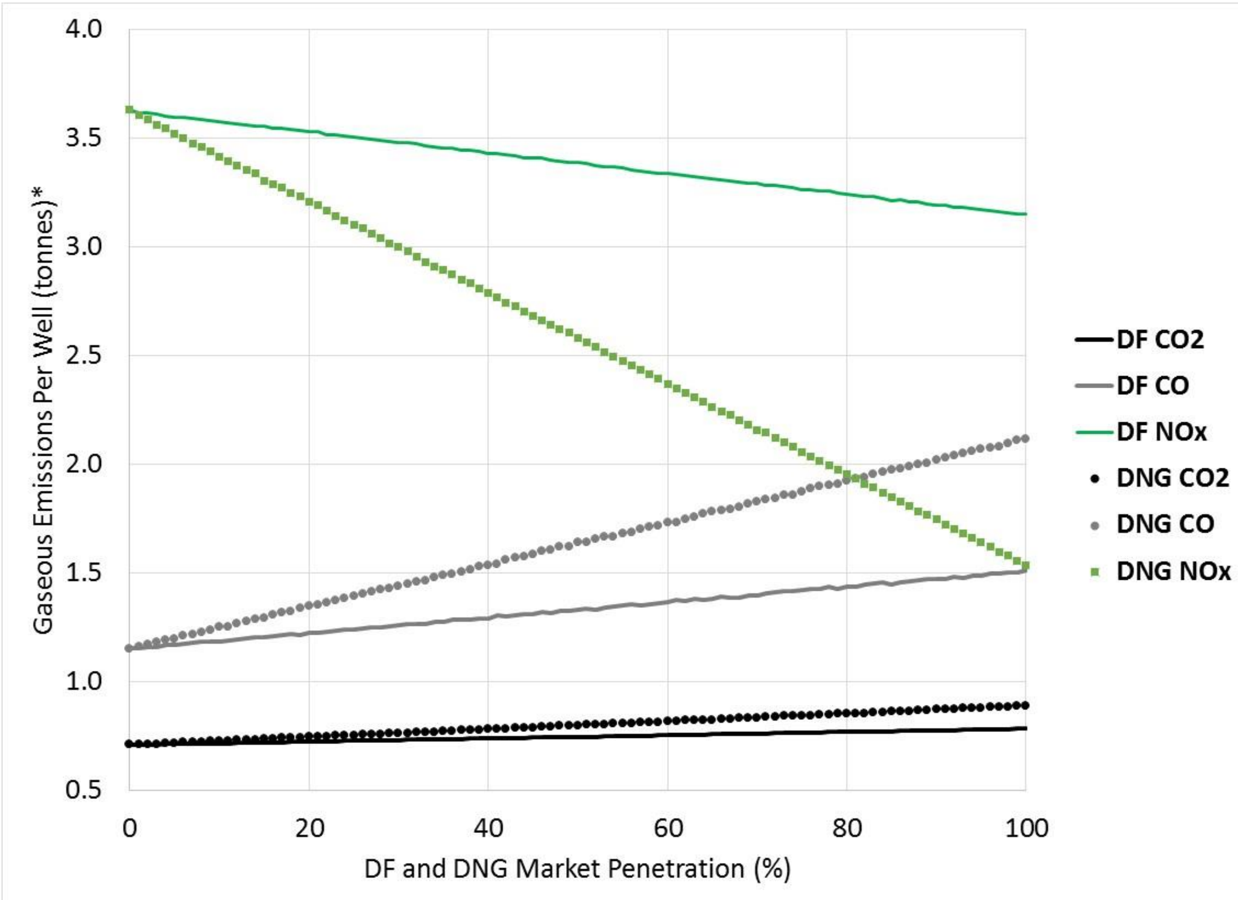

Figure S7: CO_2, CO and NO_x Emissions Per Well as a Function of Dual-fuel and Dedicated Natural Gas Market Penetration.

Figure S8 presents the effects of MP for THC and CH_4 emissions. For the diesel only case, THC emissions were predominately non-methane, as methane accounted for only about 6% of THC. For both DUAL-FUEL and DNG technologies, THC emissions are predominately CH_4. As such, the relative THC and CH_4 emissions increased rapidly at low MP levels.

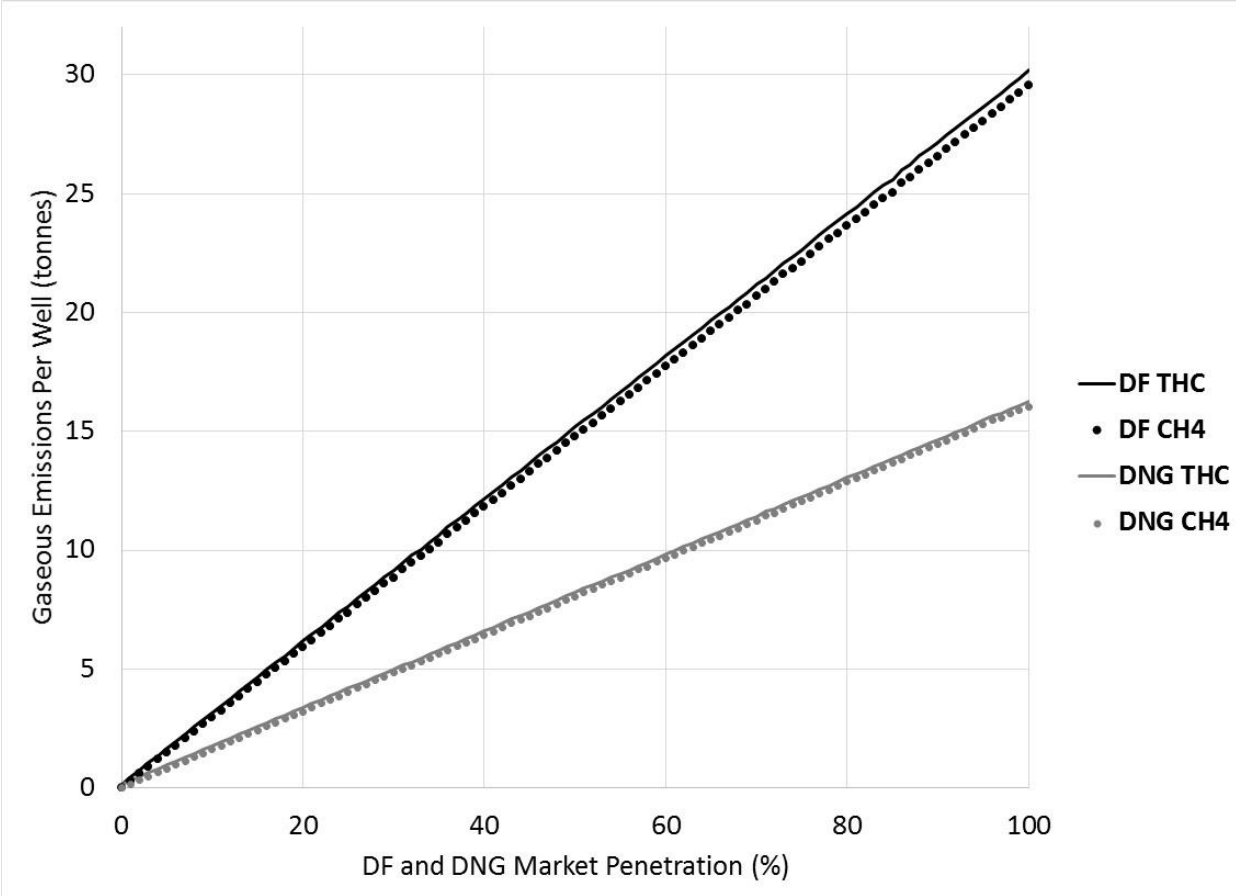

Figure S8: THC and CH_4 Emissions Per Well as a Function of Dual-fuel and Dedicated Natural Gas Market Penetration.

Extreme Case – Dual-Fuel

Figures S9 presents the average gaseous emissions per well of each prime-movers for the extreme case that all prime-movers operated as dual-fuel. Tabular data are presented for the dual-fuel case in the attached spreadsheet – both by year and by well. Average per well emissions were determined for each of the 20 annual samples. The average standard deviation per well was calculated as the square root of the sum of the variances annually. In all cases, the 95% confidence interval was calculated as the product of standard deviation and 1.96 divided by the square root of 20 (the sample size). Note that CO_2 emissions are presented as kilo tonnes – where tonnes are metric tons or 1000 kg. When comparing Figure S6 to S1, we see a slight decrease in NO_x emissions but dramatic increases in both THC and CH_4 emissions driven predominately by the increase in CH_4 emissions.

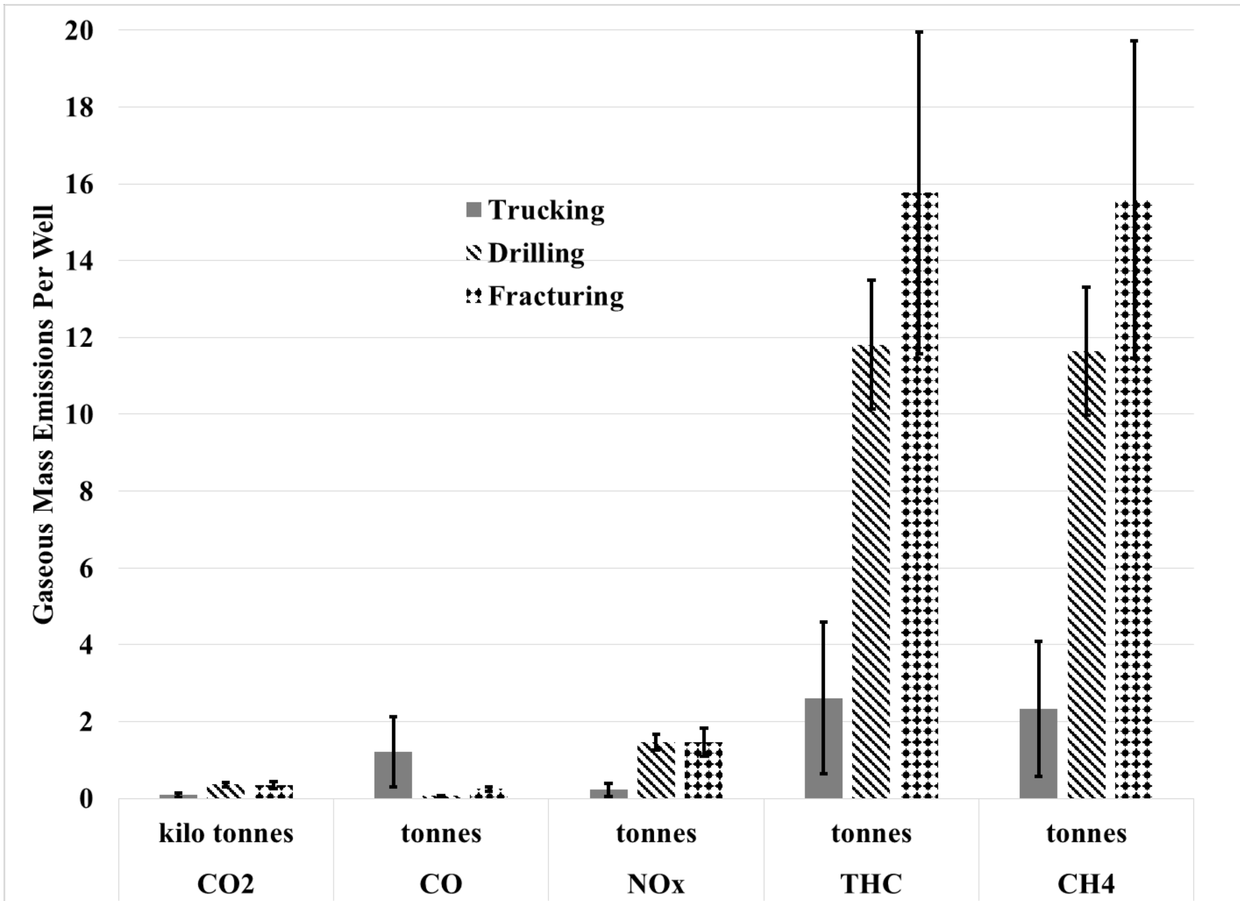

Figure S9: Dual-fuel scenario - gaseous emissions per well by prime-mover.

Figure S10 presents the same dual-fuel gaseous emissions but on a yearly average. Due to the large model sample size, we see that the trends are the same on both a per well and per year basis. For the annual basis, the emissions of each of the 12,325 wells were summed. Then the emissions were averaged over each 20 year sample.

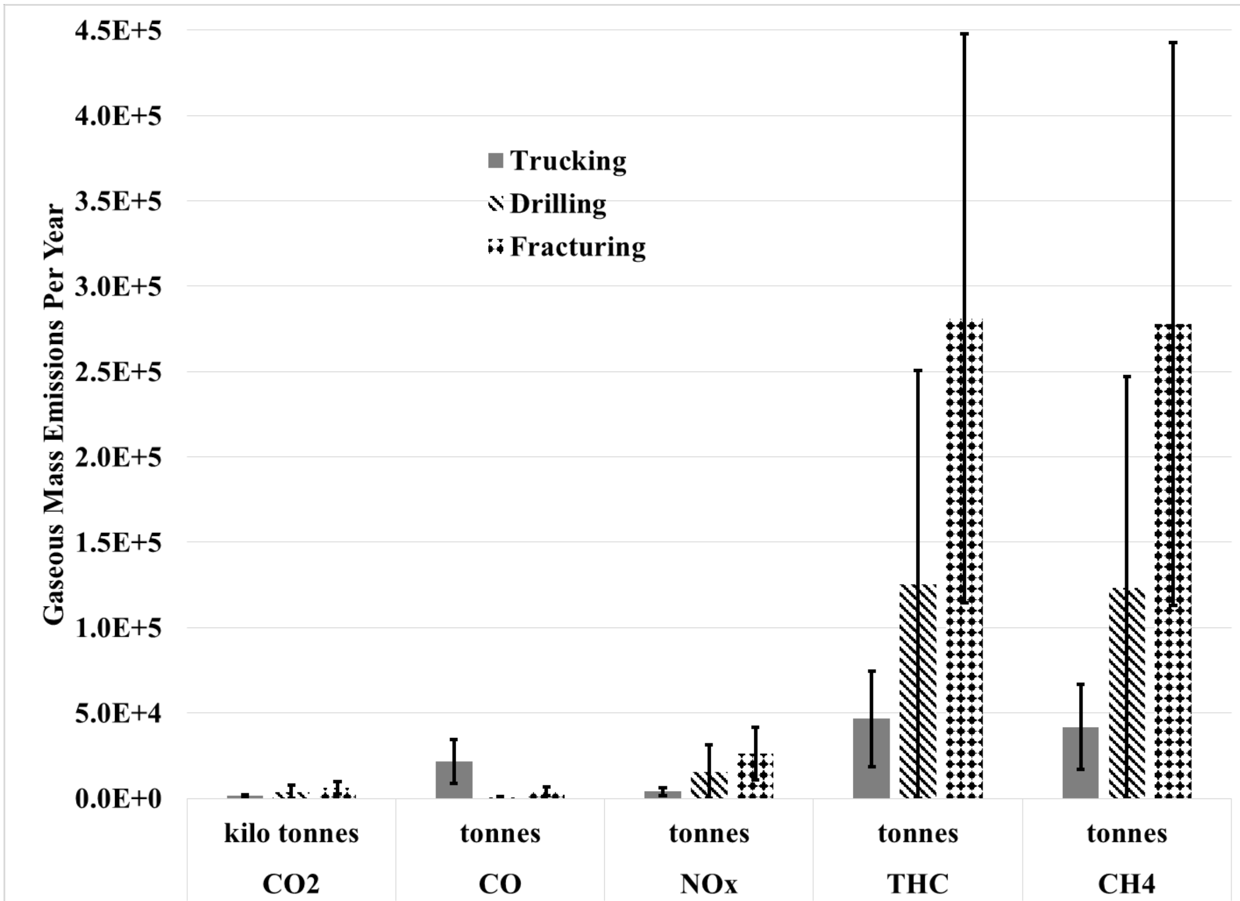

Figure S10: Dual-fuel scenario - gaseous emissions per year by prime-mover.

Table S11 shows the breakdown of fuel costs per well and per year. As expected, the drilling and fracturing sectors had the highest fuel costs per well and per year. Since the average annual well count of 12,325 was used – the average fuel prices for 2014-2016 were used. The attached spreadsheet includes the values and can be edited for different cost analysis.

Table S11: Fuel Costs by Prime-Mover for the Dual-Fuel Scenario.

	Prime-Mover	Diesel (gal)	NG (MMBTU)	Diesel Cost ($)	95% CI ($)	Natural Gas Cost ($)	95% CI ($)	Total Fuel Costs ($)	95% CI ($)
Per Well	Truck	5.81E+03	5.25E+02	$17,154	$12,944	$1,668	$1,259	$18,822	$13,005
	Drill	1.38E+04	4.04E+03	$40,725	$5,811	$12,858	$1,835	$53,583	$6,094
	Frack	1.46E+04	3.85E+03	$43,115	$11,202	$12,249	$3,125	$55,364	$11,630
	Total	3.42E+04	8.42E+03	$100,994	$18,069	$26,775	$3,834	$127,769	$18,471
Per Year	Truck	1.04E+08	5.25E+02	$306,033,169	$182,844,041	$1,668	$15	$306,034,838	$182,844,041
	Drill	2.46E+08	7.21E+07	$725,216,955	$431,121,024	$229,328,482	$136,329,314	$954,545,437	$452,162,603
	Frack	2.60E+08	6.87E+07	$767,141,484	$454,995,627	$218,307,004	$129,496,289	$985,448,488	$473,064,805
	Total	6.11E+08	1.50E+08	$1,798,391,608	$1,068,950,968	$477,443,489	$283,633,348	$2,275,835,097	$1,105,940,345

Extreme Case – Dedicated Natural Gas

Figures S11 presents the average gaseous emissions per well of each prime-movers for the extreme case that all trucking and drilling engines were dedicated natural gas and all fracturing engines were dual-fuel. Tabular data are presented for the dedicated natural gas scenario in the attached spreadsheet – both by year and by well. Average per well emissions were determined for each of the 20 annual samples. The average standard deviation per well was calculated as the square root of the sum of the variances annually. In all cases, the 95% confidence interval was calculated as the product of standard deviation and 1.96 divided by the square root of 20 (the sample size). Note that CO_2 emissions are presented as kilo tonnes – where tonnes are metric tons or 1000kg. When comparing Figure S8 to S1, we see a significant decrease in NO_x emissions for trucking and drilling engines that benefit from stoichiometric operation with TWC. We see when compared to Figure S6 that the THC and CH_4 emissions are much lower than for dual-fuel operation. However, the THC and CH_4 emissions remain unchanged for the fracturing engines.

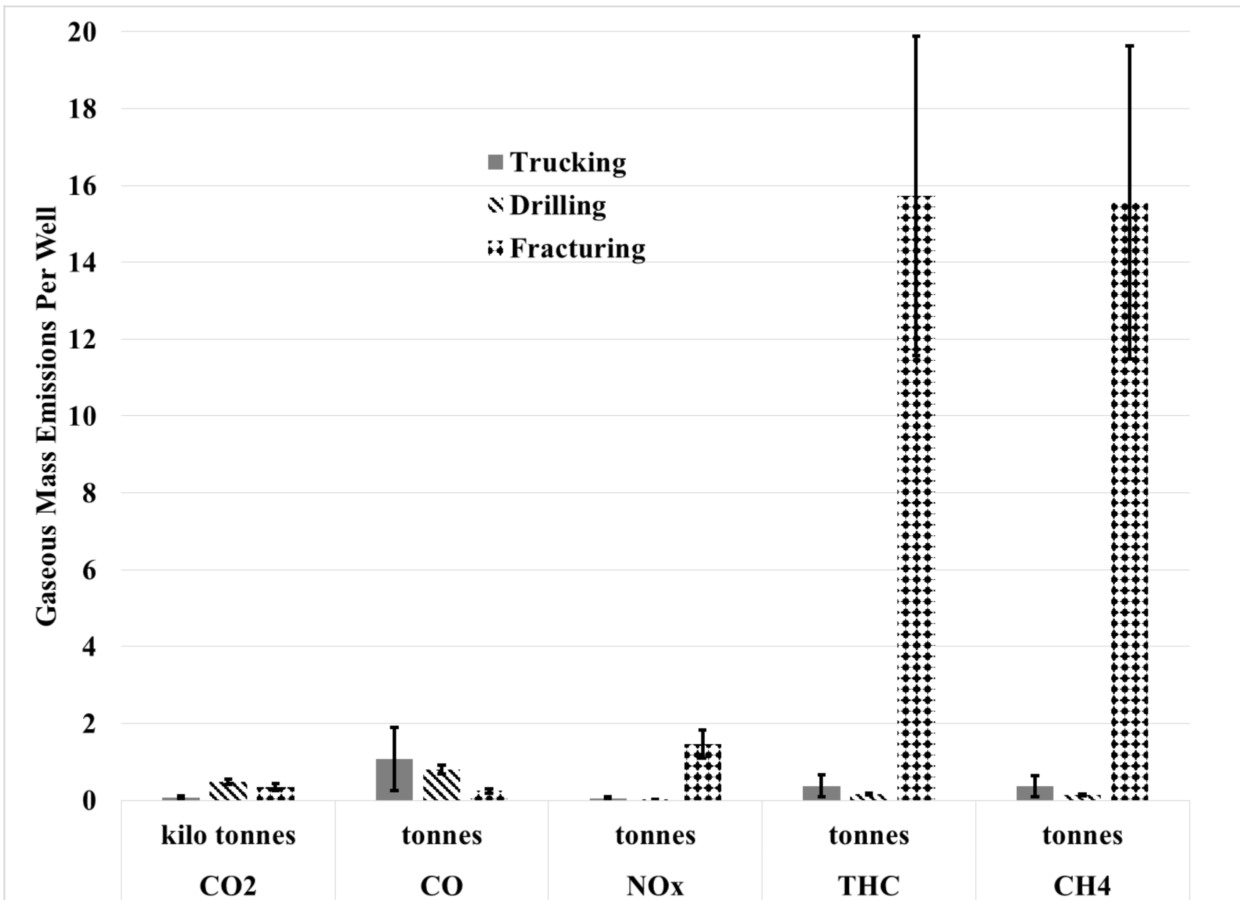

Figure S11: Dedicated natural gas scenario - gaseous emissions per well by prime-mover.

Figure S12 presents the same dedicated natural gas gaseous emissions but on a yearly average. Due to the large model sample size, we see that the trends are the same on both a per well and per year basis. For the annual basis, the emissions of each of the 12,325 wells were summed. Then the emissions were average over the 20 year sample.

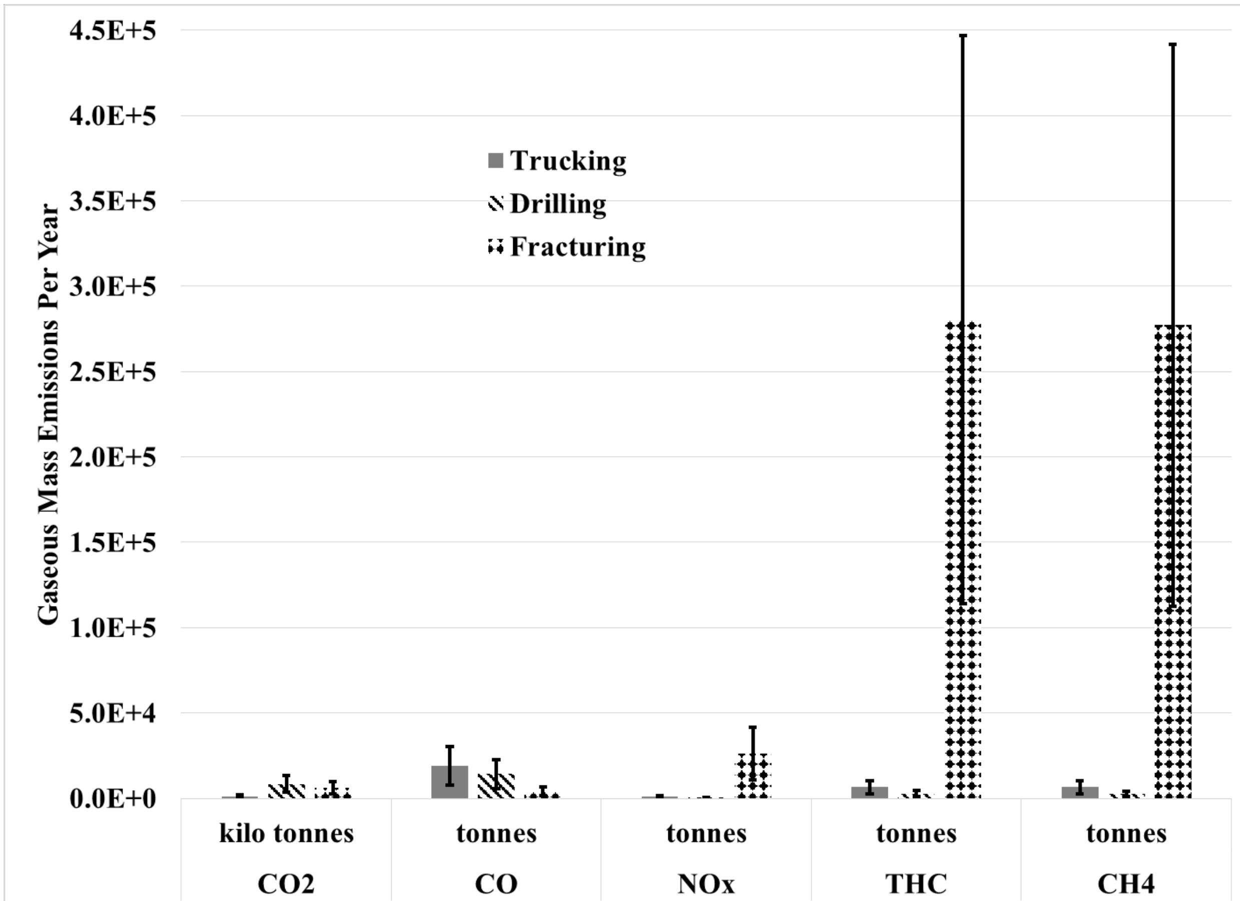

Figure S12: Dedicated natural gas scenario - gaseous emissions per year by prime-mover.

Table S12 shows the breakdown of fuel costs per well and per year. As expected, the drilling and fracturing sectors had the highest fuel costs per well and per year. Since the average annual well count of 12,325 was used – the average fuel prices for 2014-2016 were used. The attached spreadsheet includes the values and can be edited for different cost analysis.

Table S12: Fuel Costs by Prime-Mover for the Dedicated Natural Gas Scenario.

	Prime-Mover	Diesel (gal)	NG (MMBTU)	Diesel Cost ($)	95% CI ($)	Natural Gas Cost ($)	95% CI ($)	Total Fuel Costs ($)	95% CI ($)
Per Well	Truck	0.00E+00	1.80E+03	$0	$0	$5,722	$4,420	$5,722	$4,420
	Drill	0.00E+00	7.14E+03	$0	$0	$22,712	$3,256	$22,712	$3,256
	Frack	1.46E+04	3.84E+03	$43,002	$11,075	$12,218	$3,090	$55,220	$11,498
	Total	1.46E+04	1.28E+04	$43,002	$11,075	$40,652	$6,291	$83,653	$12,737
Per Year	Truck	0.00E+00	1.80E+03	$0	$0	$5,722	$35	$5,722	$35
	Drill	0.00E+00	1.27E+08	$0	$0	$405,134,495	$240,898,075	$405,134,495	$240,898,075
	Frack	2.60E+08	6.85E+07	$765,409,255	$454,431,600	$217,816,360	$129,322,399	$983,225,616	$472,474,721
	Total	2.60E+08	2.28E+08	$765,409,255	$454,431,600	$724,824,767	$430,499,066	$1,490,234,022	$625,969,268

Effects of Aftertreatment

Figure S13 shows the crossover point where dual-fuel CO benefits would be negated based on the percentage of dual-fuel drilling engines not equipped with DOC catalysts. Benefits of dual-fuel operation from a CO perspective were negated if just 8.09% of dual-fuel engines operated without a DOC. This analysis was only for drilling engines as those were the only engines that were measured without DOCs during in-field data collection.

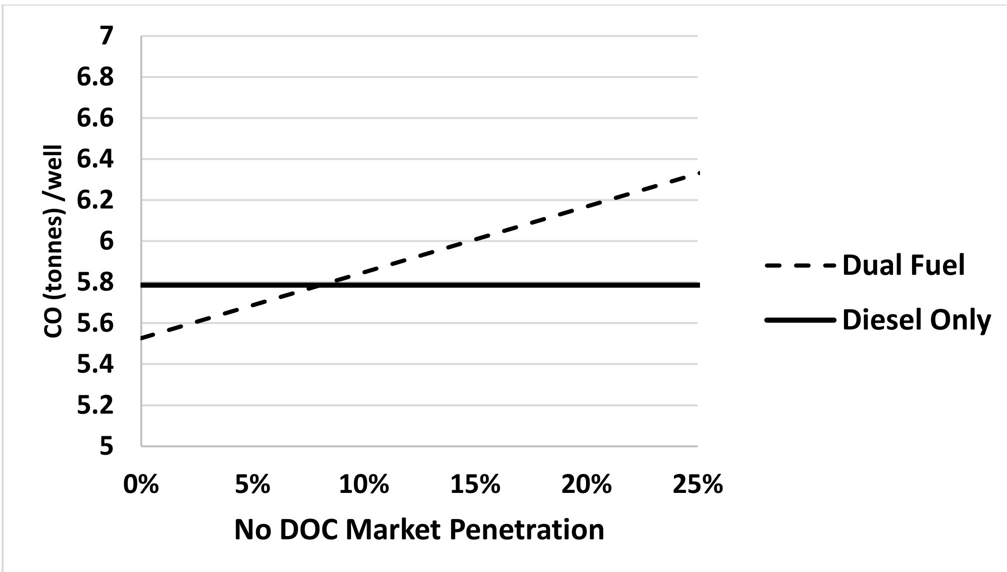

Figure S13: Drilling CO Benefits Crossover Point for Percentage of Dual-fuel Engines without DOCs.

Comparison

Rodriguez and Ouyang[8] estimated emissions from hydraulic fracturing fleets in the Marcellus and Eagle Ford Shale regions using a variety of models and EFs. The models analyzed were EPA AP-42 (Worst Case), EPA AP-42 with an average load factor and the EPA NONROAD2008. EFs used included EPA Standards Tier 2, Mfg Tier 2, TCEQ Tier 2, AP-42 and EPA NonRoad Tier 2. They analyzed CO, NO_x, and THC emissions for a job. Table S13 compares their minimum, maximum, and worst case values to our estimates.

Table S12: Comparison of Our Estimates with those of Rodriguez and Ouyang

Emission	**Min**	**Max**	**Worst Case**	**Our Estimate**
NO_x (tonnes)	1.71	3.24	14.85	1.91 ± 0.56
CO (tonnes)	0.30	1.40	6.38	0.38 ± 0.11
THC (tonnes)	0.06	0.17	0.78	0.04 ± 0.02

Vafi and Brandt developed the open-source *GHGFrack* model energy requirements and GHG emissions for unconventional drilling and hydraulic fracturing[9]. Their model required 32 input variables and included information based on site specifications such as well bore size. Their GHG values are based on EFs for GHG emissions from diesel combustion. Their model also discretized drilling data into top drive power and vertical and horizontal mud circulation. They completed four case studies for the Bakken and Eagle Ford. Table S14 presents the results of their four case studies and our per well estimates. Their average contributions by prime-mover are nearly equally split as we show with our model. Our mean CO_{2eq} per well tended to be higher than their four case studies by about 32%. However, even with inclusion of our evenly distributed confidence interval our mean falls within all of their 95% confidence intervals. We note that their model uses a CO_{2eq} EF for diesel fuel of 0.269 kg/kW-hr of which 0.264 was directly from CO_2. Our model includes in-use CO_2 measurements and our model uses a slightly different LHV for diesel fuel – both of which can contribute to our higher values. We also note that our EFs include the small CO_2 contributions from engine crankcases.

Table S14: Comparison of Our Estimates with those of Vafi and Brandt

	Drilling CO_{2eq} (%)	Fracturing CO_{2eq} (%)	Total Mean CO_{2eq} (tonnes/well)	95% CI of CO_{2eq} (tonnes/well)	Our Mean CO_{2eq} (tonnes/well)	Our 95% CI (tonnes/well)
Bakken 1	76	24	417	155-1243	612	±88
Bakken 2	53	47	316	233-1333		
Eagle Ford 1	25	75	419	221-798		
Eagle Ford 2	38	62	510	190-1168		
Average	48	52	416	--		

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APPENDIX D

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Regulated Gaseous Emissions from In-use High Horsepower Drilling and Hydraulic Fracturing Engines

Johnson DR*, Heltzel R, Nix AC, Clark N and Darzi M

West Virginia University, Mechanical and Aerospace Engineering Department, Center for Alternative Fuels, Engines, and Emissions, 263 Engineering Sciences Building, Morgantown, WV 26506, USA

Abstract

Unconventional well development is an energy intensive process, which relies heavily on diesel fuel to power high-horsepower engines. To reduce emissions and fuel costs, and increase natural gas utilization, industry has employed a limited number of dual fuel compression-ignited and dedicated natural gas spark-ignited engines. However, little in-use data are available for conventional engines or these new technologies. We measured regulated gaseous emissions from engines servicing the unconventional natural gas well development industry to understand better their in-use characteristics such that insight into real world emissions factors could be developed for use by researchers, regulators, or industry. Data collection efforts were limited by low utilization of these new technologies, therefore these data may not be representative of the current distribution of engines either nationally or by shale play. Emissions and fuel consumption were collected from two drilling engines operating as Tier 2 diesel only and dual fuel, two drilling engines that were dedicated natural gas, and two hydraulic fracturing engines operated as diesel only and dual fuel. Emissions for diesel only operation were below Tier 2 certification standards for carbon monoxide and non-methane hydrocarbon plus oxides of nitrogen. Dual fuel engines require use of oxidation catalysts to reduce carbon monoxide and non-methane hydrocarbon emissions resulting from this mode of combustion. For dual fuel engines with diesel oxidation catalysts, carbon monoxide emissions were reduced below Tier 2 diesel only standards by an order of magnitude. Dual fuel operation showed varied effects on non-methane hydrocarbon plus oxides of nitrogen emissions depending on configuration. These variations were mainly driven by some technologies increasing or decreasing oxides of nitrogen emissions. One dual fuel drilling engine failed to meet Tier 2 standards, as it did not include a diesel oxidation catalyst. Of the two dedicated natural engines tested, one had a failed catalyst and did not meet off-road standards for spark-ignited engines; however, emissions from the engine with the properly functioning catalyst were well below standards. Dedicated natural gas engines also demonstrated potential to meet Tier 2 carbon monoxide regulations while producing significantly lower oxides of nitrogen emissions than diesel only or dual fuel engines.

Keywords: Regulated emissions; Unconventional wells; Horizontal drilling; Hydraulic fracturing; Natural gas; Dual fuel

Abbreviations: CFR: Code of Federal Regulations; CI: Compression-Ignited; CH4: Methane; CO: Carbon Monoxide; CO_2: Carbon Dioxide; DOC: Diesel Oxidation Catalyst; ECU: Engine Control Unit; EPA: Environmental Protection Agency; KW: Kilowatt; LLT: Low Load Transient; NMHC: Non-Methane Hydrocarbons; NO_x: Oxides of Nitrogen; SCFM: Standard Cubic Feet per Minute; SI: Spark-Ignited; SS: Steady State; TCF: Trillion Cubic Feet; THC: Total Hydrocarbon; US: United States

Introduction

The United States (US) has experienced growth in the natural gas industry over the past decade due to unconventional well development. In 2015, SNL Financial reported that natural gas use exceeded coal for the first time in domestic electric power production [1]. The US Energy Information Administration forecasts natural gas consumption to grow in 2017 and 2018. Though natural gas production declined in 2016, it was the first time in over 10 years and net exports still increased [2]. The US Energy Information Administration also predicts natural gas production to increase through 2040 to meet energy demands [3] but that technically recoverable reserves will last for 93 years [4]. Therefore, natural gas may serve as a source of reliable energy for much of the next century. Increases in natural gas extraction are possible due to the development of technologies such as horizontal/directional drilling and hydraulic fracturing. In addition, the depth of these new wells has increased steadily over time [5]. Horizontal drilling rigs utilize high-horsepower engines to power their draw works, drills, mud pumps, and other equipment. Most current drilling rigs are electrical and use two to three stationary engines coupled to electric generators to produce this onsite electricity. On average, drilling rigs consist of 2.15 operating engines, with a per engine power of 1381 horsepower. These engines are estimated to operate 62.6 hours per 1000 feet drilled at an average load of 48.5% [6]. High-horsepower diesel engines also power hydraulic fracturing pumps. A typical fracturing fleet features total engine capacities over 20,000 horsepower. On average, each well requires 8 to 12 pumps for fracturing, but some may require up to two dozen, each rated between 1500 and 2500 horsepower [7]. As well development and completion is an energy intensive process, industry is seeking methods to reduce fuel costs. One approach is to displace some diesel fuel with natural gas using dual fuel conversion kits while another is the complete replacement of diesel fuel consumption by using dedicated natural gas engines. Little data are available on the in-use performance of these new technologies so we conducted in-use measurement campaigns to assess

***Corresponding author:** Derek R Johnson, West Virginia University, Mechanical and Aerospace Engineering Department, Center for Alternative Fuels, Engines, and Emissions, 263 Engineering Sciences Building, Morgantown, WV 26506, USA, Tel: +3042166592/3042935725; E-mail: derek.johnson@mail.wvu.edu

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the effects of these new technologies on regulated emissions as compared to conventional Tier 2 diesel only engines. Dual fuel conversions, also used for automotive applications[8], allow for substitution of natural gas into the engine intake, providing energy for combustion and in turn decreasing the diesel fuel demand. All kits tested under this work used natural gas fumigation and included two versions of the Caterpillar Dynamic Gas Blending (DGB) kit, an Altronics-GTI Bi-Fuel kit, and a Cummins-ComAP kit. Currently these systems receive exemptions from the Environmental Protection Agency (EPA) and are required to ensure their operation does not increase regulated gaseous pollutants of oxides of nitrogen (NO_x), non-methane hydrocarbons (NMHC), and carbon monoxide (CO), as well as particulate matter (PM), relative to the original diesel engine. The DGB systems are certified by the Environmental Protection Agency (EPA) and the California Air Resources Board (CARB) for Nonroad Compression-Ignition (CI) Tier 2 emissions defined by the US Code of Federal Regulations (CFR) in section 40 CFR 1039.102.

The DGB kit can be used on the land drilling Caterpillar 3512B and C and the higher horsepower 3512B-HD for hydraulic fracturing applications. The conversion kit is advertised with specifications of 70% displacement of diesel fuel for drilling applications and 60% displacement for well stimulation activities [9]. Altronic's GTI Bi-Fuel System is advertised to displace up to 70% of diesel fuel and reduce exhaust emissions and costs [10]. The QSK 50 engine with the Cummins-ComAP kit is advertised with substitution rates up to 70% with equivalent power output as similarly sized engines [11]. Generally, substitution limits are controlled by concerns that natural gas should not knock under high compression, nor fail to ignite for being too lean [12].

Due to increased availability of natural gas and possible reductions in NO_x and CO_2 emissions, the application of dual fuel conversion kits to conventional diesel engines continues to receive significant research focus [13-17]. Early research examined operation of on-road dual fuel engines utilizing technology similar to current off-road dual fuel kits. Data showed that CO emissions increased by 390% and NMHC increased by 52% without the use of an oxidation catalyst [18]. Similar results were demonstrated for older Caterpillar C-10 dual fuel engines when employed in commuter buses [19]. Another study showed the addition of catalysts reduced NMHC by 40% and reduced CO emissions by over 500% [20]. Similar trends were shown with recent dual fuel research on diesel engines that utilized alternative emissions control strategies such as exhaust gas recirculation and full 2010 compliant after treatment systems [21,22]. Overall, the general trend is increased NMHC and CO emissions from dual fuel technologies. The application of dual fuel conversion kits that are emissions compliant, require the addition of a diesel oxidation catalyst (DOC) to meet NMHC and CO Tier 2 emissions standards. DOCs typically use platinum group metals including platinum and palladium. The operation of such catalysts and their high CO and NMHC reduction potential are reported in literature [23,24]. It is noted that DOCs offer little reduction of methane (CH_4) and NO_x emissions, and are employed on lean engines where the exhaust contains excess oxygen.

To examine the effects of dual fuel operation in unconventional well development we measured exhaust emissions from four different engine and dual fuel kit configurations-two focused on dual fuel drilling and two on dual fuel stimulation. Engines of Campaigns 1-3 were equipped with DOCs while the early model conversion of Campaign 4 did not include a DOC. Engines operated in diesel only and dual fuel modes, and we collected data pre and post-oxidation catalyst for both configurations. Continuous measurements of natural gas and diesel fuel flow rates occurred in parallel along with the collection of engine control unit (ECU) data.

An alternative to dual fuel engines are dedicated natural gas engines such as the Waukesha L7044GSI engine. These engines are spark-ignited (SI) and can use various sources of natural gas-well, local pipeline, compressed natural gas (CNG) or liquefied natural gas (LNG). The engines are certified to meet the Nonroad Large SI Engine Exhaust standards defined in 40 CFR 1048.101. These engines are outfitted with three-way catalysts (TWCs) and air/fuel ratio control [25]. Applications of TWCs to stoichiometric or rich burn engines offer reductions in NMHC, CO, and NO_x and these benefits have long been established [26,27]. Waukesha advertised post-catalyst emissions of 1.61 g/kW-hr CO and 0.94 g/kW-hr NMHC+NO_x. This is a significant reduction compared to engine-out certified emissions of 15.01 g/kW-hr CO and 18.29 g/kW-hr NMHC+NO_x [25]. This shows that the engine outfitted with a catalyst could produce over 20 times less NMHC+NO_x and over 11 times less CO than one without a catalyst. To examine the effects of dedicated natural gas engines, we collected in-use data from two drilling rigs outfitted with L7044GSI engines.

Methodology

Exhaust emissions for comparison with EPA standards were sampled pre-catalyst for diesel only operation to represent Tier 2 engine-out emissions. Dual fuel engines were sampled pre and post-catalyst, but only post-catalyst emissions are presented here for comparison with certification standards. Emissions from the dedicated natural gas engines were sampled post-catalyst for comparison. ECU data were collected from diesel engines with a VIA Model HDV100A1 [28]. Dedicated natural gas engine data were collected via Modbus. These data were used to determine the speed and load of the engine allowing for the calculation of engine brake power. Diesel fuel flow was measured with meters on the inlet and return line of the engine-yielding net fuel consumption. KRAL OME20 Volumeters® provided fuel flow rates for drilling Campaigns and OME32 models for hydraulic fracturing Campaigns. The OME20 and OME32 Volumeters® measured diesel flow rates of up to 45 and 150 l/min, respectively [29]. These fuel meters each had an accuracy of 0.1% of the measured value. Temperature, pressure, and density affected accuracy and an analysis showed the combined accuracy during all data collection Campaigns was less than ± 2%. A KURZ MFT-B flow meter with a range of 0-252 standard cubic feet per minute (SCFM) of natural gas flow measured the flow rate of natural gas into the engines [30]. The natural gas flow meter was calibrated on CH_4 and as such, fuel corrections were applied. The accuracy of the thermal based flow meter was a function of temperature and an analysis showed that accuracy throughout all Campaigns was less than ± 2%. The regulated emissions recorded included exhaust CO, NO_x, and total hydrocarbons (THC). Non-regulated gaseous emissions of CO_2 and CH_4 were also measured. The measurement of both THC and CH_4 allowed for calculation of regulated NMHC emissions. Exhaust emissions were sampled through 15 meters of heated line and passed through a heated filter prior to measurement with an MKS Multigas™ 2030 FTIR Continuous Gas Analyzer [31]. It should be noted that during the first Campaign, at a hydraulic fracturing test facility, a SEMTECH-DS and California Analytical heated flame ionization detector with a CH_4 cutter were used to measure exhaust emissions.

All engines operated at rated speed. We compare our emissions with the respective CI and SI Tier 2 emissions standards. When tested for certification, these engines are subjected to the ISO-8178 D2 test cycle. This test applies to constant speed engines and the engines are subjected to the loads presented in Table 1, which also shows the emission-weighting factor for each mode.

Campaign 1 examined a dual fuel stimulation engine at a hydraulic fracturing test facility. The test engine's [11] hydraulic pump was connected to a closed circuit water system, with cooling tower, and employed a choke on the outlet of the pump to produce engine loads common to the hydraulic fracturing industry. Data from this Campaign are presented from an average load of approximately 70%.

Campaign 2 focused on a dual fuel drilling engine [9] that operated continuously during the drilling of two separate wells. Emissions were measured in three-hour windows, spanning different sampling arrangements. A total of 12 hours of data was collected at each sample position. Data were subdivided into two categories: low load transient (LLT) and steady state (SS) drilling. The average engine loads during LLT and SS operations were 23.3% and 55.2%, respectively. Figure 1 presents an example of SS and LLT drilling activity.

Campaign 3 focused on a dual fuel stimulation engine [9] that operated during hydraulic stimulation of the two wells drilled under Campaign 2. Three stages of hydraulic fracturing activity were recorded for each sampling position. The hydraulic stimulation activity was steady state during the individual stages, but not all stages occurred at the same engine load. The average engine load during the fracturing stages used for this study was 75.9%.

Campaign 4 focused on a dual fuel drilling engine [10] that operated during the drilling of a natural gas well. Note that this early dual fuel conversion did not include a DOC. Data were again categorized by engine activity type. The average engine load during LLT activity was 18.2% and during SS was 46.5%.

Campaign 5 focused on a dedicated natural gas engine [25] that operated during the drilling of a natural gas well. The catalyst on this system appeared to be faulty based on pre and post-catalyst emissions. Data were categorized by activity type with an average load of 55.1% during SS and 14.1% during LLT operation.

Campaign 6 focused on a dedicated natural gas engine [25] that operated during the drilling of a natural gas well. The engine operated

Mode	1	2	3	4	5
Torque (%)	100	75	50	25	10
Speed (rpm)	Rated Speed				
D2 Weighting Factors	0.1	0.3	0	0	0

Table 1: ISO-8178 D2 Test cycle operating points and weighting factors.

continuously and had an average SS load of 55.9% and LLT load of 20.9%. All engine emissions were processed using SS emissions calculations outlined in the CFR to determine the brake specific emissions. The emissions from Campaigns 1-4 were compared to the standards defined in the CFR for Nonroad Tier 2 CI engines greater than 900 kW. The standards for these engines were 6.4 g/kW-hr of NMHC+NO_x and 3.5 g/kW-hr of CO. Emissions from Campaigns 5 and 6 were compared to Nonroad large Tier 2 SI engines standards. The engine tags on the SI engines advertised emissions of 0.8 g/kW-hr of NMHC+NO_x and 20.6 g/kW-hr of CO. Table 2 provide a summary of the Campaigns.

Results/Discussion

Campaigns 1-4 diesel only operation emissions

Regulated gaseous emissions from diesel engines included CO, NMHC and NO_x, with the last two regulated as a mass sum, NMHC+NO_x, because of their joint contribution to formation of ozone, a regulated air quality species [32-34]. Emissions were normalized by power and time and are presented in g/kW-hr. NMHC+NO_x and CO for diesel only operation during SS and LLT operation are shown in Figures 2 and 3, respectively. The dark horizontal line represents the Tier 2 standard for these engines, but it is important to note that emissions were measured under different operating conditions than certification tests. Error bars represent the standard deviations of respective data sets. The minimum sample size for any data set was three.

Figure 2 shows that diesel drilling and fracturing engines had NMHC+NO_x emissions below the Tier 2 standard. Engine 1 had the highest emissions during SS operation at 6.12 ± 0.28 g/kW-hr. LLT operation of engines 2 and 4 showed similar emissions predominately from lower NO_x emission at lower loads.

All engines had CO emissions below 1.5 g/kWh during diesel only SS operation-well below the standard. The engines from drilling Campaigns (2 and 4) were also subject to LLT operation. Due to the transient nature of operation, the CO emissions are higher than during SS operation but well below the standard.

Campaigns 1-4 dual-fuel operation emissions

Dual fuel emissions were measured post-catalyst (where applicable) for comparison with Tier 2 standards for engines outfitted with dual fuel kits. Further investigation into the effect of the different catalysts on emissions will be examined in a future study. During dual fuel operation, CH_4 accounted for greater than 95% of THC emissions such that NMHCs were low. If THC+NO_x emissions were examined, no dual fuel engine met the 6.4 g/kW-hr standard; therefore, care must be

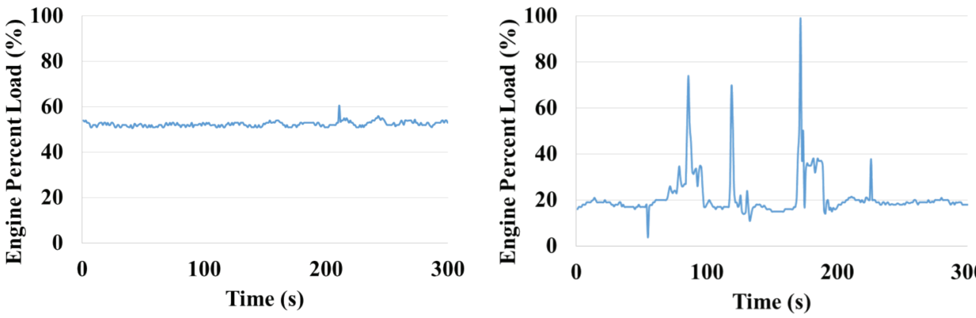

Figure 1: Example of engine activity for steady state (SS) operation (left) and low load transient (LLT) operation (right) during drilling.

Campaign	Activity	Engine Activity Type	Engine Make	Engine Model	Rated Speed (rpm)	Rated Power (kW)	Combustion Type	Dual-Fuel Kit	Modes Sampled	Fuel	Reported Exhaust Sample Location
1	Hydraulic Fracturing	SS	Cummins	QSK50	1900	1678	CI	ComAP	Diesel Only	Diesel	Pre-DOC
									Dual Fuel	CNG+Diesel	Post-DOC
2	Drilling	SS	Caterpillar	3512C	1200	1101		DGB	Diesel Only	Diesel	Pre-DOC
		LLT							Dual Fuel	FG+Diesel	Post-DOC
3	Hydraulic Fracturing	SS	Caterpillar	3512B-HD	1800	1678		DGB	Diesel Only	Diesel	Pre-DOC
									Dual Fuel	FG+Diesel	Post-DOC
4	Drilling	SS	Caterpillar	3512C	1200	1101		Altronic GTI	Diesel Only	Diesel	N/A
		LLT							Dual Fuel	FG+Diesel	N/A
5	Drilling	SS	Waukesha	L7044GSI	1200	1253	SI	N/A	Dedicated	CNG	Post TWC
		LLT									
6	Drilling	SS	Waukesha	L7044GSI	1200	1253		N/A	Dedicated	FG	Post TWC
		LLT									

Table 2: Summary of data collection campaigns. (FG: Field Gas).

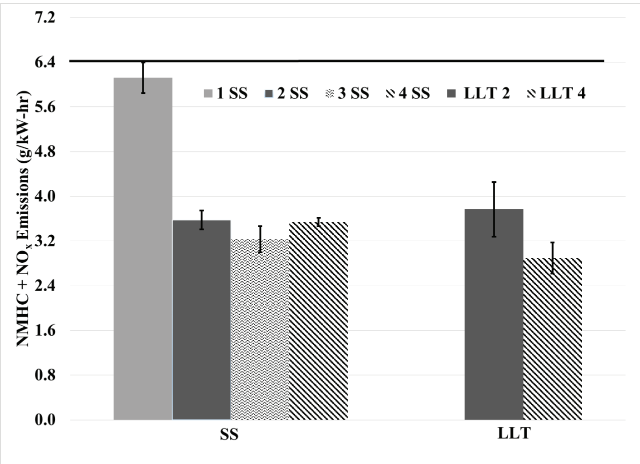

Figure 2: Diesel only, engine out (pre-catalyst) NMHC+NO_x emissions for Tier 2 operations during steady state (SS) and low load transient (LLT) operation.

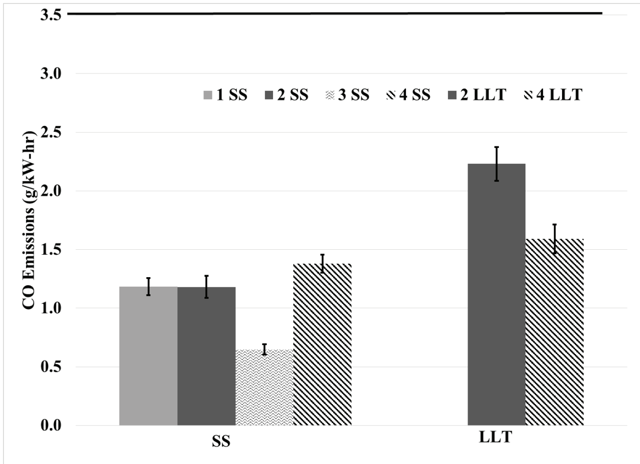

Figure 3: Diesel only, engine out CO emissions (pre-catalyst) for steady state (SS) and low load transient operation (LLT).

taken when analyzing emissions from dual fuel engines and comparing them properly to predefined standards. Methane is not regulated with NO_x as a combined standard since its reactivity to form ozone is orders of magnitude lower than other HCs. We used an FTIR analyzer, which speciated lower alkanes based on spectral measurements. For researchers that utilize heated flame ionization detectors (HFID) care must be taken when calibrating the analyzers as they inherently have different response factors based on the HC emissions measured compared to the HC on which it was calibrated.

Figure 4 presents the post-catalyst NMHC+NO_x emissions for dual fuel operation. Engine 2 was below Tier 2 standards during both SS and LLT operation. Even without a DOC, engine 4 was nearly within compliance during SS operation when accounting for variability of measurements, 6.62 ± 0.13 g/kW-hr from the engine compared to the 6.4 g/kW-hr standard. LLT operation of engine 4 exceeded the Tier 2 standard. In both cases of SS and LLT operation engine 4 saw increased NO_x emissions, which would be difficult to reduce even with the addition of a DOC. We used current or previous natural gas compositions during data processing. In-use fuel quality of natural gas and diesel fuel can directly affect NO_x and NMHC emissions, which raises an additional cautionary point when comparing in-use emissions to standards.

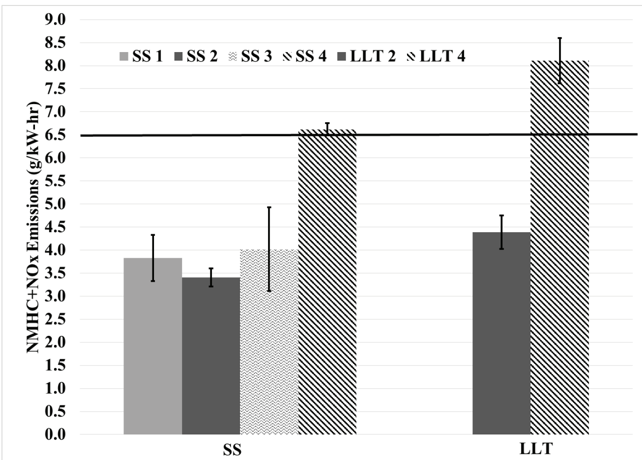

Figure 4: Post-catalyst dual fuel NMHC+NO_x emissions steady state (SS) and low load transient (LLT) operation.

We found that engine out (pre-catalyst) CO emissions from dual fuel operation were on average 22.8 times higher than diesel only.

Citation: Johnson DR, Heltzel R, Nix AC, Clark N, Darzi M (2017) Regulated Gaseous Emissions from In-use High Horsepower Drilling and Hydraulic Fracturing Engines. J Pollut Eff Cont 5: 187. doi: 10.4176/2375-4397.1000187

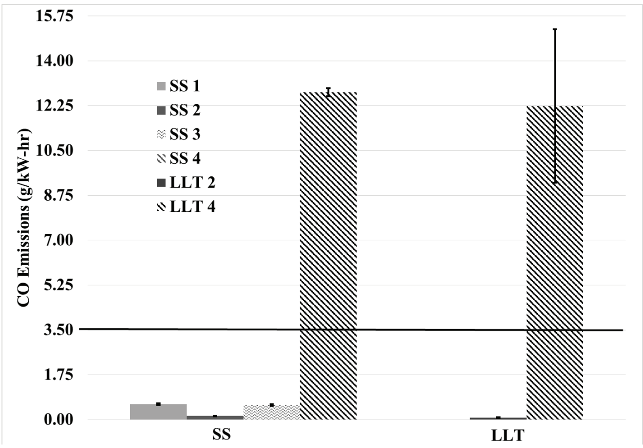

Figure 5: Post-catalyst dual fuel CO emissions for steady state (SS) and low load transient (LLT) operation.

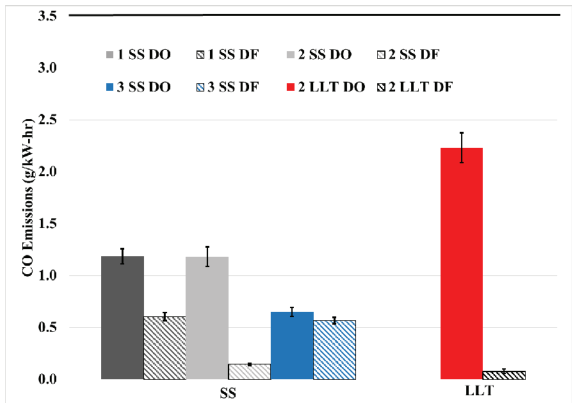

Figure 6: Comparison of diesel only (DO) and dual fuel (DF) in-use CO emissions for steady state (SS) and low load transient (LLT) operation. With DOCs, net CO reductions occur.

Figure 5 shows the significant increase in CO emissions from dual fuel engines not equipped with DOCs. Dual fuel operation without DOCs led to CO emissions nearly four times higher than the CI standard during both SS and LLT operation. Engines 1-3, with DOCs, had CO emissions eight times lower than the Tier 2 standard. Figure 6 shows the comparison of diesel only and dual fuel CO emissions for engines 1-3. With engine 4 removed, one can see that dual fuel engines with DOCs have the potential to decrease engine out CO emissions below in-use diesel only rates. Net CO reductions ranged from 13 to 97% from dual fuel operation. Although CO in high concentrations has profound health implications, impacts for long exposures at low concentrations have received less study [35]. CO emissions can be reduced with dual fuel kits that include DOCs compared to Tier 2 in-use levels, while NMHC+NO_x emissions did not show a single trend for dual fuel operation.

Campaigns 5-6 dedicated natural gas emissions

Emissions were also measured from two dedicated natural gas engines. While their fuels had different compositions, which can affect engine out emissions, it was difficult to assess these effects as these engines used closed loop control and three-way catalysts, and also due to engine-to-engine variations. The post-catalyst emissions were compared to the Nonroad Large SI Engine Exhaust standards defined in 40 CFR 1048.101. These standards allow for a number of different combinations of acceptable limits as long as the emissions comply with the following equation:

$$(HC + NOx) * (CO)^{0.784} \leq 8.57 \quad (1)$$

Where HC+NO_x and CO are in units of g/kW-hr. For engines fueled by natural gas, the only HC emissions considered are NMHCs, and for diesel engines, it is well documented that the exhaust contains very low levels of CH_4. The engine tags on both engines stated compliance with a standard of 0.8 g/kW-hr of NMHC+NO_x and 20.6 g/kW-hr of CO, and Waukesha advertised emissions of 0.94 g/kW-hr of NMHC+NO_x and 1.61 g/kW-hr of CO. These numbers represent post-catalyst emissions, highlighting catalyst abilities to reduce emissions well below current Tier 2 standards. The difference in the conditions of the two catalysts showed a significant difference in emissions, which may have correlated to their previous operation and maintenance schedules. The post-catalyst NMHC+NO_x emissions are shown in Figure 7 and CO emissions are shown in Figure 8. Figure 7 shows the advertised emissions are above the standard; however, because the advertised CO emissions are lower,

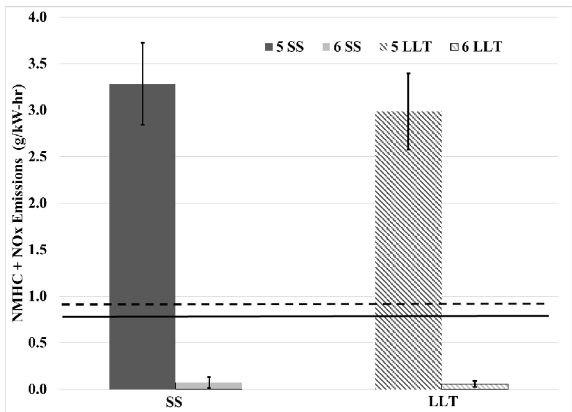

Figure 7: Post-catalyst NMHC+NO_x emissions for dedicated natural gas drilling engines during steady state (SS) and low load transient (LLT) operation. Note: the solid line represents the Tier 2 standard while the dashed line represents advertised values.

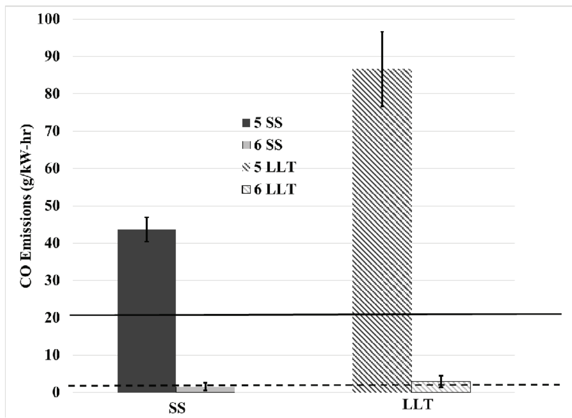

Figure 8: Post-catalyst CO emissions for dedicated natural gas drilling engines for steady state (SS) and low load transient (LLT) operation. Note the solid line represents the Tier 2 standard while the dashed line represents the advertised values. The advertised values and in-use emissions for engine 6 were not statistically different.

the alternative standard of Equation 1 is satisfied. The NMHC+NO_x emissions from the engine with the malfunctioning catalyst were 4.1 times higher than the Nonroad Large SI standards, and nearly 3.6 times higher than those advertised during SS operation. Similar trends were seen for LLT operation. The well-maintained catalyst of engine 6 had NMHC+NO_x emissions well below both the standard and advertised emissions-11.4 and 13.4 times lower, respectively. However, it must be noted that the way in which the engine was loaded did not correspond to the weighted cycle used for certification purposes.

Post-catalyst CO emissions also varied greatly depending on the catalyst. The engine with the malfunctioning catalyst showed CO emissions 27 times higher than advertised emissions and more than double the Tier 2 standard. The engine with the well-maintained catalyst showed CO emissions that were 1.1 times lower than those advertised and nearly 14 times lower than the Tier 2 standard.

Table 3 shows SI emissions from both types of operation (SS and LLT) and the results of Equation 1. Table 3 highlights the impact of catalyst failure on CO, NHMC, and NO_x emissions. Levels of CO from LLT operation are on average 1.96 times higher than those during SS operation. Dedicated natural gas engines with properly operating catalysts easily meet both Tier 2 CI and Tier 2 SI standards. These engines also offer the added benefit of significantly lower NO_x emissions as compared to Tier 2 in-use diesel only or dual fuel operation.

Tier 2 diesel engines currently dominate the off-road market and typically, emissions factors are used to estimate regulated emissions [36] for use in inventory or permitting analyses. Others have compared EPA, CARB, and AP-42 emissions factor methods for predicting emissions from CI engines and their results for a Caterpillar 3512C are shown in Table 4 along with our in-use data for diesel only operation [37,38]. The SS and LLT values are the average from two different in-use 3512C engines. We compared our NMHC emissions to VOCs. Our NO_x and VOC emissions rates were lower than all estimated values. LLT operation led to slightly higher CO emissions than the CARB emissions factor but we note that during our Campaigns the time spent in SS and LLT modes of operation were nearly equal and therefore the average value of 1.6 g/kW-hr aligns with the CARB emissions factor for CO but is less than half of the other methods [36,37]. In-use regulated emissions of Tier 2 diesel engines may be substantially below emissions standards-this fact should be addressed in any inventory analysis.

Campaign #	Fuel	Operation Type	Emissions (g/kW-hr)		Value from Equation 1
			NMHC+NO_x	CO	
5	CNG	SS	3.28	43.64	63.37
		LLT	2.99	86.62	98.65
6	Field Gas	SS	0.07	1.5	0.1
		LLT	0.06	2.89	0.13
Standard	N/A		0.8	20.6	8.57
Advertised			0.94	1.61	1.37

Table 3: Emissions from dedicated natural gas engines for steady state (SS) and low load transient (LLT) operation.

Emissions Factors	NO_x	VOC	CO
CARB	5.04	0.27	1.6
EPA	6.08	0.32	3.5
AP42-Controlled	7.91	0.43	3.4
AP42-Uncontrolled	14.6	0.43	3.4
SS	3.55	0.01	1.3
LLT	3.31	0.03	1.9

Table 4: Comparison of our diesel only in-use emissions with commonly used emissions factors. All units are g/kW-hr.

Conclusions

To reduce fuel costs and emissions, the unconventional natural gas well development industry is investing in dual fuel conversion kits and dedicated natural gas engines to power directional drilling rigs and hydraulic fracturing engines. Dual fuel and dedicated natural gas engines for unconventional well development have experienced low market penetration-only 5% in 2013. Recent data show that over 100 drilling rigs and stimulation spreads were dual fuel in 2015 and this number is expected to grow to 740 by 2024 [38]. To assess possible future impacts, emissions data were recorded during six separate campaigns, four of which utilized diesel engines outfitted with dual fuel kits and two that focused on dedicated natural gas engines. Of the six campaigns, four focused on drilling rig engines and two focused on engines used for hydraulic stimulation. For comparison with national emissions standards defined in the CFR, exhaust emissions were sampled pre-catalyst during diesel only operation for engines equipped with DOCs to represent Tier 2 engine out emissions and emissions were sampled post-catalyst for dual fuel and dedicated natural gas engines to represent engine out emissions. This study focused on regulated gaseous emissions, which included CO and the combination of NMHC+NO_x. Regarding diesel only operation, we showed that in-use emissions from Tier 2 engines may be substantially below emissions standards-this fact should be addressed in any inventory analysis that would otherwise only rely on certification standards or older emissions factors.

While our limited study identified a dedicated natural gas engine with a failed catalyst, the other data highlight that these new technologies have potential to reduce regulated emissions. Dual fuel operation with DOCs can decrease CO emissions below Tier 2 in-use levels, while NMHC+NO_x emissions did not show a single trend for dual fuel operation. Dual fuel operation without DOCs significantly increased CO and THC emissions and should be avoided. The use of dedicated natural gas drilling engines are capable of meeting both Tier 2 CI and Tier 2 SI CO standards while offering further reduced NO_x emissions-two orders of magnitude compared to diesel only or dual fuel operation less than 0.1 g/kW-hr SS and LLT operation. These advantages are already of interest to on-road vehicles converting from older diesel to newer natural gas technologies [39,40]. Such technology implementation would be beneficial in regions where air quality standards for ozone and NO_2 are of concern. The data set is small and future work should include additional in-use measurements, as these data may not represent all technologies or the exact distribution of engines currently employed by industry. See Figure 9 for general in-use emissions trends. Further analysis and data are required to develop

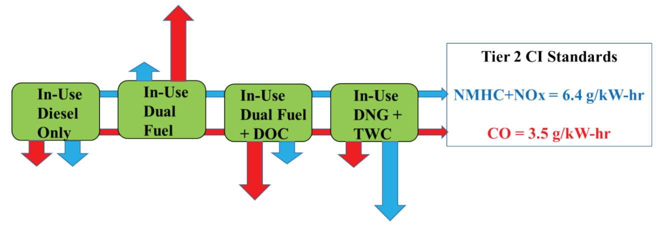

Figure 9: General Trends of In-Use Emissions by Technology.

more robust emissions factors compared to conventional methods or certification standards.

Author Information

Dr. Derek Johnson* is a research assistant professor at West Virginia University (WVU) conducting research focused on emissions associated with the use of natural gas a fuel for internal combustion engines. Mr. Robert Heltzel, MSME, and Mr. Mahdi Darzi, MSME, are graduate research assistants at WVU's Center for Alternative Fuels, Engines, and Emissions working towards their doctoral degrees. Dr. Andrew Nix is an assistant professor at WVU conducting research on natural gas reciprocating engines and gas turbines. Dr. Nigel Clark is a professor at WVU with extensive experience alternative fuels with specific focus on natural gas engines and vehicles.

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APPENDIX E

In-Use Efficiency of Oxidation and Three-way Catalysts used in High-Horsepower Dual Fuel and Dedicated Natural Gas Engines

Author, co-author (Do NOT enter this information. It will be pulled from participant tab in MyTechZone)

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Abstract

Directional drilling and hydraulic stimulation utilize diesel fueled compression ignition (CI) engines to power drilling rigs and pumps. The majority of these engines are compliant with US Environmental Protection Agency (EPA) Tier 2 standards. To reduce costs, industry is investing in dual fuel (DF) and dedicated natural gas (DNG) engines. DF engines use diesel oxidation catalysts (DOCs) to reduce CO and NMHC emissions. DNG engines may be either lean-burn or rich-burn and the latter uses three-way catalysts (TWC) to reduce CO, NMHC, and NO_x emissions. This research presents in-use emissions data collected pre- and post-catalyst for three DF engines and two DNG engines. One DF engine was converted earlier and did not include a DOC. Data were collected from six Tier 2 engines, two CI drilling engines converted to operate as DF, two CI hydraulic fracturing engines converted to operate as DF, and two SI DNG drilling engines. One DNG catalyst did not effectively reduce emissions. DF engines with DOCs were able to reduce CO and NMHC during DF operation by >90 and >50%, respectively. The DOCs did not reduce methane and NO_x emissions. Properly functioning DNG engines and TWCs decreased engine out CO, NMHC, and NO_x emissions all by >90%. It is important to note that DOCs could be added to Tier 2 diesel engines regardless of combustion mode to reduce emissions. DNG engines offered the lowest NO_x emissions, which could be important in certain air districts. Research should focus on improved oxidation of methane emissions from DF engines.

Introduction

Unconventional natural gas resource development has led to a US energy revolution. Oil and gas can now be produced from shale plays and most growth in natural gas production is from unconventional resources [1]. The development of unconventional resources requires the use of directional drilling rigs and hydraulic stimulation equipment. Drilling rigs are typically equipped with compression-ignition (CI) diesel engines certified to meet Tier 2 emissions standards when operated over the ISO 8178 (D-2 5 mode) cycle [2]. These rigs are typically equipped with three engines of around 1000 kilowatt (kW) [3]. Once unconventional wells are drilled, they must be hydraulically stimulated to increase natural gas production rates. Stimulation requires the use of pumps to pressurize fracturing stages up to 62 mega-Pascal (MPA) [4]. CI diesel engines that may be rated up to 1864 kW power these pumps. Typical fracturing fleets for a well may require anywhere from eight to 24 of these engine and pump combinations [5]. A majority of drilling and fracturing engines are Tier 2 engines, which do not include any aftertreatment devices. Table 1 shows the Tier 2 and 4 non-road diesel emissions regulations and the year in which they came into effect [6]. Table 2 includes the D-2 test conditions for certification engine certification. Note that for certification and during in-use operation, these engines operate at rated speed but in-use operation led to varied loads and transient operation. Tier 4 CI engines are currently available from multiple manufacturers [7, 8]. Cummins has selected to meet Tier 4 compliance using selective catalytic reduction (SCR) systems with urea. Caterpillar has instead used exhaust gas recirculation (EGR) and diesel oxidation catalysts (DOCs). Table 1 also includes Tier 2 non-road large spark-ignited (SI) emissions standards [9]. Note that regulations only apply to new production engines. Alternatively, SI engines may also be certified to meet the criteria given in Equation 1 as long as $NMHC+NO_x$ emissions are lower than 2.7 g/kW-hr and CO emissions are less than 20.6 g/kW-hr [9].

Table 1. Tier 2 and Tier 4 gaseous emissions standards for CI and SI non-road engines applicable to drilling and hydraulic fracturing engines (>900 kW).

Engine Type	CI		SI
Tier	2	4	2
Year	2006	2011	2007
CO	3.5	3.5	4.4
NMHC	--	0.40	--
NOx	--	3.5	--
NMHC+NOx	6.4	--	2.7

Table 2. D-2 power modes for engine certification including modal weighting factors.

Mode	1	2	3	4	5
Torque (%)	100	75	50	25	10
Speed (rpm)	Rated Speed				
D-2 Weighting Factors	0.05	0.25	0.3	0.3	0.10

$$(NMHC + NO_x)*(CO)^{0.784} \leq 8.57 \quad (1)$$

Due to the volatility in oil prices and desire to reduce operating costs, industry is investing in dual fuel (DF) conversion kits that can be installed on Tier 2 diesel engines. The DF kits fumigate natural gas within the intake system, which reduces the diesel fuel demand. Advertised substitution rates are up to 70% [10, 11, 12]. The application of DF kits to diesel engines has long been shown to significantly increase NMHC and CO emissions [13, 14, 15]. Such conversion kits are not required to undergo Environmental Protection Agency (EPA) certification but must be tested to ensure conformity with Tier 2 emissions and receive letters of conformity from the EPA or from California Air Resources Board (CARB). To meet CO and NMHC standards, the conversion process typically requires the installation of DOCs. The conversion kits are also required to demonstrate that NO_x emissions are not beyond standards and DOCs have little effect on NO_x emissions. DF kits are not required to demonstrate or meet any standards for CO_2 or methane (CH_4) emissions. DF kits saw limited early market penetration but more penetration than dedicated natural gas engines; because of their ability to revert to diesel only (DO) operation when natural gas supplies are unavailable.

Where natural gas sources are readily available, some companies have opted to invest in drilling rigs powered by dedicated natural gas (DNG) engines. Currently, lean-burn and rich-burn (stoichiometric) engines are available [16, 17]. Lean-burn natural gas engines also use an oxidation catalyst to control emissions while rich-burn engines are equipped with three-way catalysts (TWCs) for the simultaneous conversion and reduction of CO, NMHC, and NO_x emissions. While lean-burn engines are available, these types of engines were not tested under this research program. Data on TWC efficiency are presented for two rich-burn DNG engines. Neither lean-burn nor rich-burn DNG engines are required to meet any standard for CO_2 or CH_4.

Diesel Oxidation Catalysts

Oxidation catalysts are used to convert CO and NMHC emissions to CO_2 and water [18, 19]. These technologies can be applied to lean burn engines, either diesel or natural gas fueled. Due to the excess oxygen, simultaneous conversion of CO and NMHC with reduction of NO_x emissions is difficult. DOCs have been successfully employed to on-road engines for over a decade. Non-road regulations standards have previously been met through engine controls. However, new non-road regulations require PM and NO_x emissions reductions of 95% compared to Tier 1 regulations introduced in the 1990's [20]. As such, new non-road engines are now using proven on-road technologies such as EGR, DOCs, diesel particulate filters (DPFs), and SCR systems.

As mentioned previously, dual fuel (DF) combustion can increase CO and NMHC emissions by orders of magnitude [13, 14, 15]. CO emissions are especially high during part load operation and THC emissions easily increase by an order of magnitude due to CH_4 emissions. Research has suggested these emissions are likely due to the homogenous lean fuel air mixture within the cylinder that is below the flammability limits of the mixture, which does not allow for flame propagation [21]. At the same time, reductions in PM and NO_x emissions have been shown in addition to cost benefits from reduced diesel fuel consumption [21]. Research that is more recent has examined DF effects on emissions from heavy-duty on-road engines. This included engines with and without aftertreatment systems. Even the engine equipped with a DOC and DPF saw increased CO, NMHC, and CH_4 emissions. Peak CO emissions increased by 16x while peak NMHC increased by 31x over DO operation. CH_4 emissions were below detection limits for DO operation but ranged from 6.6 to 36.1 g/kW-hr for DF operation [22].

Currently, CH_4 emissions are not regulated but DOCs are employed on DF conversions to ensure CO and NMHC emissions are reduced. DOCs use platinum group metals (PGM), especially platinum (Pt) and palladium (Pd). The main reactions are shown in Equations 2-9 of Table 3 [23, 24].

Table 3. Main reactions for HC and CO oxidation and NO reduction within DOCs.

	Reaction	Eqn.
CO Oxidation	$CO + \frac{1}{2} O_2 \rightarrow CO_2$	2
HC Oxidation	$C_xH_yO_z + (x+y/4-z/2)O_2 \rightarrow$ $xCO_2 + (y/2)H_2O$	3
Steam Reforming	$C_xH_y + (x-n)H2O + nCO_2 \rightarrow$ $(x+n)CO + (x+y/2-n)H_2$	4
HC SCR*	$(1-S_{N2O}/2)C_3H_6 + 9NO \rightarrow$ $3(1-S_{N2O}/2)\ CO_2 + 3(1-S_{N2O}/2)H_2O +$ $4.5S_{N2O}N_2O + 4.5(1-S_{N2O})N_2$	5
H_2 Oxidation	$H_2 + \frac{1}{2} O_2 \rightarrow H_2O$	6
NO Oxidation	$NO + \frac{1}{2} O_2 \leftrightarrow NO_2$	7
NO_2 Reduction by CO	$CO + NO_2 \leftrightarrow CO_2 + NO$	8
NO_2 Reduction by HC	$C_xH_y + (2x+y/w)\ NO_2 \rightarrow$ $xCO_2 + (y/2)\ H_2O + (2x+y/2)\ NO$	9

*SN2O – selectivity to N2O

Depending on temperature and catalyst formulation, DOCs have been demonstrated CO and NMHCs conversion efficiencies of 70-100% [25, 26, 27, 28]. DOCs have also been shown to decrease PM emissions mainly through reduction of soluble organic fraction (SOF). PM reductions range from 10-35% [25, 26, 27, 28]. As shown in the main equations of Table 2, DOCs have little to no effect on total NO_x emissions [25, 26]. CO and NMHC conversions are high over a broad range of temperature from 200 to 400 °C [23]. However, implementing DOCs requires the use of ultra-low sulfur fuels to prevent sulfur poisoning which reduces reduction efficiency [26, 27]. In addition to sulfur poisoning, HC conversion efficiency can also decrease with age of the catalyst as HC is adsorbed on active sites along with soot; however, exposure to temperatures of 450 to 600 °C can regain most conversion ability [29].

Though DOCs have a long and successful history of application, research continues in three key areas: 1) reducing the light off temperature, 2) reducing ultimate PGM loading requirements, and 3) reducing CH_4 emissions from DF or lean-burn natural gas engines. Varying the ratio of Pt and Pd can aid in lower temperature conversion and durability against thermal aging while decreasing the total required mass of PGM [30]. Specific focus has been on synergized PGM applied to mixed metal oxides. New catalysts using these methods have lower ultimate PGM loadings with similar behavior for CO but higher light-off temperatures for HC emissions and lower HC conversion [31]. Researchers have applied DOCs to

DF engines to examine their effects on emissions. DOCs were shown to decrease CO emissions of DF operation to those at or below DO operation. However, THC emissions did not decrease - as 90% of THC was CH_4, which is not catalyzed well at DF operating temperatures with Pt only catalysts [32]. To overcome this limitation Pd can be used to reach 100% CH_4 conversion efficiency at 600 °C with a 50% light off temperature (T50) of 480-560 °C, but sulfur inhibits catalyst performance [33]. The addition of Pd and overall catalyst volume and surface area must be designed in order to capitalize on its benefits. With optimal space velocity and a Pd to Pt ratio of 6:1, the T50 decreased to 350 °C. Such a loading ratio was able to achieve 100% reduction at 500 °C but the ultimate loading of PGMs was high and cost prohibitive [34]. An alternative method to increase PGM loading is to increase the exhaust temperature through injection of fuels (diesel) into the exhaust once the temperature has reached 200 °C. This method decreased CH_4 emissions by 70% from DF engines with a fuel penalty of 7.5% [29, 35].

Catalysts for Natural Gas Engines

For TWCs, Pd is favored for both CH_4 and NO_x reduction. Early TWC applications showed reductions of 10-60% all three based on equivalence ratio and temperature. CH_4 was still difficult to oxidize at 300 °C and NO reduction was inhibited by O_2 [36]. In addition to Pd and Pt, rhodium (Rh) is also used in TWCs however; research has shown that Rh decreased CH_4 conversion and NO_x reduction but CO conversions remained as high as 100% [37]. Though Pd may be the best for conversion of lower alkanes, its capability for dedicated natural gas engines is still reduced from sulfur poisoning which requires regeneration temperatures above 400 °C [38]. Other research has shown that Pd inhibits NO oxidation but that Pt, Pd, or Pt/Pd had NMHC and CO conversions near 100% above 200 °C. CH_4 required temperatures above 600 °C with sulfur poisoning and 500 °C without [39]. To overcome such limitations and to meet new GHG regulations, research is examining the impregnation of the zeolite pore structure itself as a method to improve active sites for CH_4 oxidation while limiting effects of sulfur poisoning [40]. Other methods for support material and Pd dispersion are being examined [41]. As such, catalysts for CH_4 conversion continue to make incremental improvements that have seen T50 of Pt/Pd catalysts trending downwards from 402 to 317 °C [42]. In addition to TWC research, other methods such as air-fuel ratio (AFR) control and fuel dithering have been shown to reduce NO_x emissions by 95% while providing CO and HC conversions of 90% and above 80% when slightly rich [43].

Methodology

Table A1 of the Appendix includes details on each measurement Campaign. These Campaigns included data collection from two in-use drilling engines outfitted with DF conversion kits that were operated as DO and DF. Note the last drilling engine of Campaign 4 was converted to operate as DF much earlier and did not include a DOC. Emissions data for these engines are presented as engine out emissions for additional reference. Two Campaigns focused on emissions collection from hydraulic stimulation engines converted to operate as DF. One of these engines used a pressure test facility to mimic typical in-use engine loads while the other data were collected during in-use stimulation. For both cases, emissions were sampled pre- and post-catalyst in both modes of operation. The remaining measurement Campaigns included the pre- and post-catalyst emissions measurements of two DNG drilling engines. In Campaigns 2-6, emissions were sampled through 15 meters of heated line and passed through a heated filter assembly prior to measurement with an MKS 2030 HS Fourier Transform Infrared analyzer. For Campaign 1, a SEMTECH DS and California Analytical heated flame ionization detector with CH_4 cutter were used for emissions measurements.

In addition to pre- and post-catalyst emissions measurements, fuel flow rates, and engine control unit (ECU) data were recorded. Diesel fuel flow was measured with KRAL OME20 and OME32 model Volumeters® for drilling and hydraulic fracturing engines, respectively. These fuel meters each had an accuracy of 0.1% of the measured value. Temperature, pressure, and density affected accuracy and an analysis showed the combined accuracy during all data collection Campaigns was ±2%. A KURZ MFT-B flowmeter measured the flow rate of natural gas into the engines. The accuracy of the thermal based flow meter was a function of temperature and an analysis showed that accuracy throughout all Campaigns was ±2%. ECU data were collected for standard J1708/J1939 parameters for diesel engines and via Modbus communication protocols for DNG engines. Methods defined in the CFR were used with collected data to determine brake-specific emissions, which are presented in the Appendix. For drilling engines, engine activity was subdivided into two categories – steady state (SS) and low-load transient (LLT) operation. The threshold between these two categories was 40% engine load as broadcast by the ECU. No emissions data were collected during engine warm-up. Data for hydraulic fracturing engines all occurred at SS operation with loads above 40%. Activity and emissions data were collected on three repeated runs for each operating mode and sampling location. Therefore, the minimum number of samples for any given metric was three. Only during Campaign 1 was the engine load targeted to be the same in all configurations. Campaigns 2-6 were collected during in-use operation and as such, data are averaged over multiple samples ranging from 1-2 hours in each mode so that similar loads occurred for all sampling configurations. Percent conversion or reductions are calculated from Equation 10. Where pre- and post- are the species concentrations upstream and downstream of the catalyst, respectively.

$$\%_{CONV} = ((Pre - Post)/Pre)*100 \qquad (10)$$

Results and Discussion

DO and DF Engines

Presented below are temperature SS and LLT operation data for DO and DF engine operation.

Campaign 1 – Temperatures

The engines tested in Campaigns 2-4 did not broadcast exhaust or catalyst temperature data; therefore, it was not measured and reported. However, the engine of Campaign 1 did broadcast exhaust temperature data and since this engine was operated in a simulated environment, data were collected at multiple loads for DO and DF operation. The modes simulated included idle, 20, 40, 60, 80, and 100% engine load. Due to the limitations of natural gas substitution during DF operation, little to no substitution occurred in modes 1, 2, and 6. During DF modes 3-4, when natural gas substitution was high, the exhaust temperatures increased by about 50 °C in each mode. Others have also reported increase exhaust gas temperatures from dual fuel natural gas combustion, which were due to longer duration of the combustion process [44]. A two-tailed, two-sample equal variance t-test was used to examine if trends were statistically significant. The values were considered statistically different if $p<0.05$ and values were marginally statistically different if $0.05<p<0.1$. For modes 3-5 the dual fuel temperatures were statistically higher based on p-values that were orders of magnitude lower than 0.05. For all power modes, the temperatures well exceeded the minimum temperature range for DOC conversion of NMHC and CO emissions [23].

Table 3. Exhaust gas temperatures by mode for Campaign 1 during DO and DF operation (°C). Note Modes 3-5 were the only modes with significant natural gas substitution.

Mode	DO		DF	
	Average	Standard Deviation	Average	Standard Deviation
1	119.5	7.7	120.0	7.0
2	411.1	5.8	413.4	4.2
3	*466.8*	*4.4*	*508.2*	*4.4*
4	*493.3*	*4.7*	*551.8*	*2.8*
5	*536.0*	*9.3*	*585.4*	*2.4*
6	573.5	5.7	570.4	4.9

Campaign 1 – Modal Emissions

Since temperature and modal data were available, granular conversion efficiency data are provided in Table 4. CH_4 emissions during the post-catalyst tests were higher during Modes 4-5 during DF operation but were all within one standard deviation of the pre-catalyst data. However, when using the t-test post-catalyst values were statistically higher. The average natural gas consumption in both modes and found that natural gas consumption was also statistically lower (about 3%) with p-values of 0.006 and 0.003, respectively. Therefore, due to variations in test conditions CH_4 emissions may have been higher due to additional leanness of the dual fuel mixture. Trends of improved combustion efficiency and lower fuel slippage with increased gas concentration have been reported in literature [45].

During power modes of DO operation, engine out CO emissions were low (<1.5 g/kW-hr). During DF operation engine out CO emissions increased to well over 21 g/kW-hr an increase in a factor of nearly 20 – which is similar to increases reported elsewhere [13, 14, 15]. Even with these elevated levels, the DOC was able to convert over 93% of CO emissions. DO engine out THC emissions were also low at less than 0.3 g/kW-hr for all power modes. During this Campaign, an alternative catalyst that focused on improved CH_4 conversion was tested. During these repeated tests, the fuel flow rate of natural gas into the engine was not statistically different based on p-values as occurred during testing of the stock catalyst. The new methane catalyst showed slight reductions of 7 and 5% were shown for Modes 3 and 4, respectively but it should be noted that these data were not statistically different based on the t-test. The average DF exhaust temperatures within these modes should have been capable of higher CH_4 oxidation based on literature if the new catalyst contained Pd [33, 34], but the PGM loading information was not available. The data in Table 4 also highlight that brake-specific CO and THC emissions from diesel only operation could be lowered by 44-70% even without the use of natural gas.

Table 4. Modal data for CO and THC conversion percentages from Campaign 1 only for DO and DF operation - given in percentages. Note Modes 3-5 were the only modes with significant natural gas substitution.

Mode	DO Conversions		DF Conversions	
	CO	THC	CO	THC
1	55	44	--	--
2	52	70	--	--
3	*48*	*67*	*98*	*23*
4	*61*	*61*	*96*	*20*
5	*63*	*51*	*93*	*6*
6	54	53	--	--

SS and LLT DO - Emissions

Tables A2 and A3 present summary emissions data for DO engines during SS and LLT operation, respectively. Engine activity emissions data for drilling engines were binned by load into SS and LLT modes of operation. Average engine power between sampling configurations were analyzed and all p-values were greater than 0.05 such that engine power was not statistically different. Note that diesel only engine out CO emissions ranged from 0.65 to 1.18 g/kW-hr – well below the standard for CI engines of 3.5 g/kW-hr. Additional analyses on engine out emissions for regulated species are presented elsewhere along with comparisons to emissions standards and emissions factors used in literature [46]. Figure 1 shows the average conversion efficiency of CO and NMHC emissions as calculated from pre- and post-catalyst data from Campaigns 1-3 – during SS operation. Engine 4 did not include a DOC. The application of DOCs to Tier 2 DO, SS operation showed CO conversions of 68-98% and NMHC conversions of 83-100%, which aligns with reported reductions in literature [25, 26, 27, 28]. Only engines of Campaigns 2 and 4 were operated under LLT operation. For Campaign 2, the DOC converted 98% of CO emissions during LLT operation.

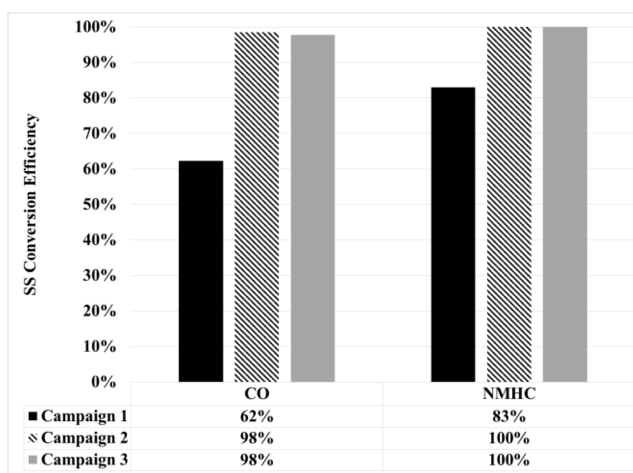

Figure 1. Average CO and NMHC emissions reductions for steady-state operation of Tier 2 diesel engines (Campaigns 1-3) outfitted with DOCs – DO.

SS and LLT DF - Emissions

Tables A4 and A5 present summary emissions data for DF engines during SS and LLT operation, respectively. In all Campaigns, engine out CO and THC emissions increased from DF operation. Engine out CO emissions increased by average factors of 20.3 and 6.9 over DO engine out emissions during SS and LLT operation, respectively. In all cases, engine out CO emissions were above the Tier 2 standard – by factors of 6.0 and 3.6 for SS and LLT operation, respectively. Even though engine out CO emissions were higher, the DOCs were effective at converting CO. DF CO conversion efficiency ranged between 97-99% yielding post catalyst emissions similar to DO post-catalyst and well below Tier 2 DO engine out levels. The results of Campaigns 1-3 align well with conversion efficiencies reported in literature [32].

During SS, DF operation - CH_4 was the predominant HC representing greater than 97% of THC emissions. These results are similar to, but higher than, those reported in literature [32]. In none of the SS, DF cases were post-catalyst CH_4 emissions statistically different from engine out values. NMHC emissions were generally low for all cases and were reduced by 52% for Campaign 2. During Campaigns 2 and 3, post-catalyst CO_2 emissions did increase by 7 and 13% even though their loads were not statistically different. These increased CO_2 emissions were likely due to the oxidation of CO to CO_2 within the DOC.

The DF kit of Campaign 4 tended to increase NO_x emissions during DF operation and brake-specific NO_x values varied greatly. Even if a DOC were installed, it would likely have no effect on NO_x emissions. Only engines of Campaign 2 and 4 experienced LLT operation. The DOC of Campaign 2 was able to decrease CO emissions by 99% and NMHC by 50% with no statistically significant change in CH_4. These conversions during DF operation are comparable with those reported by DOCs for DO operation [25, 26, 27, 28].

DNG Engines

Temperatures

For both cases of SS and LLT operation of DNG engines, the pre- and post-catalyst engine power levels were statistically similar. The DNG engines broadcast exhaust temperatures, which are shown in Table 5.

Table 5. Exhaust gas temperatures of DNG engines during SS and LLT operation for pre- and post-catalyst sampling positions (°C).

Exhaust Gas Temperature (°C)		Pre-Catalyst		Post-Catalyst	
		Average	Standard Deviation	Average	Standard Deviation
Campaign 5	SS	639.5	1.9	640.1	1.0
	LLT	588.4	3.8	591.9	8.3
Campaign 6	SS	669.1	6.7	664.9	9.3
	LLT	622.8	9.8	616.8	4.6

The DNG engines utilized TWC and AFR control as emissions control devices. Data were broadcast for both oxygen sensors (left and right banks) and lambda values are presented in Table 6. Note that the average values for right and left were the same. Pre- and post-catalyst refers to measurements corresponding to emissions sampling locations and not to the location of the oxygen sensor itself. Then engine of Campaign 5 tended to operate more rich than the engine of Campaign 6, which matches, with engine out (pre-catalyst) CO emissions nearly 3-4 times higher. This trend is expected from basic combustion theory [47]. Literature supports the decrease in TWC conversion of CO for natural gas engines that are overly rich; however, others still showed conversions of around 50% at a lambda of 0.98 for steady state, non-dithered operation [43]. The engine of Campaign 5 had small standard deviations in lambda ranging from 3.87×10^{-5} to 9.31×10^{-4} with an average of 4.85×10^{-4}. The engine of Campaign 6 had standard deviations in lambda ranging from 2.77×10^{-4} to 1.38×10^{-3} with an average of 8.27×10^{-4}. Thus, not only was the engine of Campaign 5 operating richer, it also had lower variation from AFR control. Figure 3 shows an example of continuous data from both engines during similar SS operation followed by transient behavior. The engine of Campaign 6 periodically ran with a lambda approaching 1.02, which would dramatically improve its CO conversion efficiency due to added oxygen. However, the engine of Campaign 5 remained rich even during sudden load changes, never exceeding a lambda of 0.99.

Table 6. Average lambda values during SS and LLT operation for pre- and post-catalyst sampling positions.

Lambda (-)		Pre-Catalyst	Post-Catalyst
Campaign 5	SS	0.981	0.981
	LLT	0.975	0.975
Campaign 6	SS	0.992	0.991
	LLT	0.986	0.986

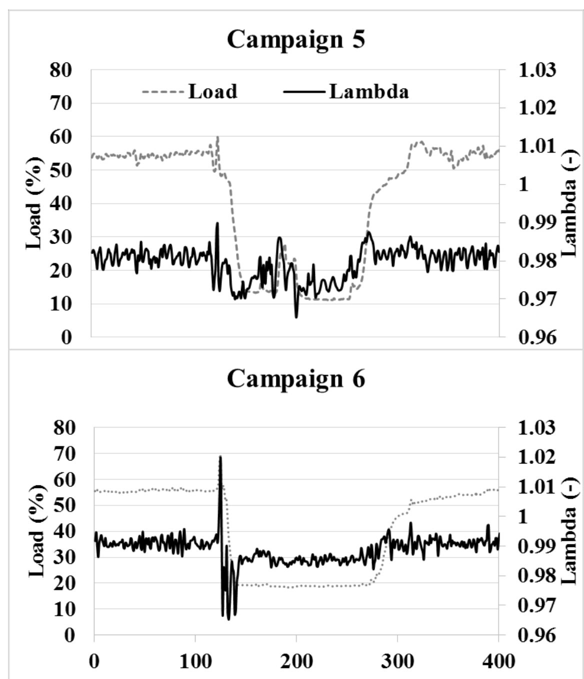

Figure 3. Example of continuous load and lambda from Campaign 5 (upper) and Campaign 6 (lower). Both graphs are periods of contiguous data (6.6 minutes) collected at 1 Hz.

SS DNG Emissions

Tables A6 and A7 present summary emissions data for DNG engines during SS and LLT operation, respectively. For SS operation, CH_4 emissions were already low (<1 g/kW-hr) and no discernable effects of the catalysts on CH_4 were seen. Figure 4 shows the changes in CO, NO_x, THC, and NMHC emissions. The TWC of Campaign 6 decreased regulated emissions by 90% or greater which is similar to reported values [37, 39, 43]. The TWC of Campaign 5 showed little impact across the board with pre- and post-catalyst CO emissions being similar. During SS operation, the TWC of Campaign 5 showed a conversion of CO emissions of 3.7% but was not statistically different based on a t-test. As expected for both catalysts, the conversion of THC was lower than NMHC because CH_4 was the predominate species.

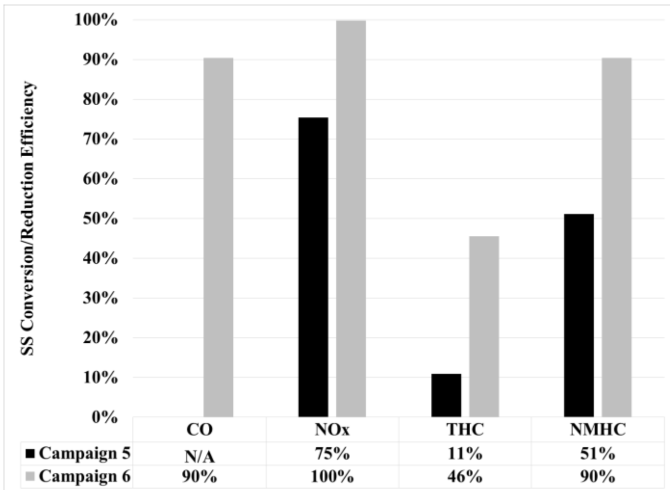

Figure 4. Emissions conversion and reduction efficiency for TWCs of two DNG drilling engines during SS operation.

LLT DNG Emissions

Figure 5 shows similar data for LLT operation but includes CH_4. Again, the TWC of Campaign 5 is shown to underperform when compared to the TWC of Campaign 6 and those in literature. The TWC of Campaign 5 showed only a 9% reduction in CO emissions and these values were not statistically different based on a t-test. In both cases, the exhaust temperatures were well above 600 °C. In addition, the second TWC also reduced CH_4 emissions by 44%.

The operator was alerted to these trends so that the TWC of Campaign 5 could be examined and replaced if necessary. The catalyst and rich operation could both have led to lower conversion efficiency. It is noted that the second TWC and the TWCs on its sister engines underwent routine inspection and maintenance. Communications with industry has shown that GE does provide catalyst maintenance procedures to overcome reduced performance from carbon-fouling, ash-fouling, oil fouling, and masking. However, as mentioned before long-term thermal aging or sulfur poisoning could cause irreversible damage. The TWCs used with these engines are thin-walled stainless steel honeycomb as opposed to ceramic honeycombs [17].

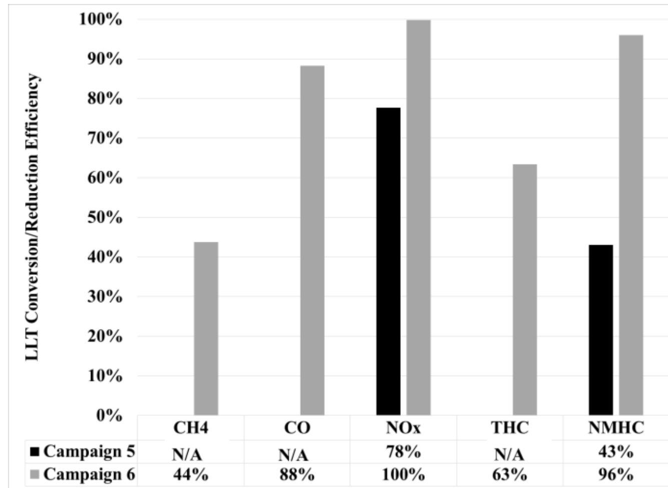

Figure 5. Emissions conversion and reduction efficiency for TWCs of two DNG drilling engines during LLT operation.

Summary/Conclusions

The unconventional well development industry is seeking methods to reduce operating costs. As such, some operators are investing in dual fuel conversion kits or dedicated natural gas engines to reduce diesel fuel consumption. Tier 2 diesel engines dominate the current fleet, which do not include any exhaust aftertreatment components. Dual fuel engines require the addition of a diesel oxidation catalyst to convert engine out CO and NMHC emissions. Lean-burn and stoichiometric/rich burn, dedicated natural gas engines are available and those that are rich burn use three-way catalysts for decreased CO, NMHC, and NO_x emissions. This study examined the in-use conversion and reduction efficiency of these catalysts. Regardless of fueling mode (DO versus DF), the addition of DOCs to Tier 2 engines were effective at converting both CO and NMHC emissions. Due to limited market penetration and drilling activity, this study includes only data from four DO/DF engines and two DNG engines. Of these engines, three were equipped with DOCs while the fourth, older conversion, was not. One DNG engine and TWC appeared to not be performing as intended. Due to the small sample size, these trends should not be extrapolated to the entire fleet. The following conclusions were found:

DOCs for DO Engines

- DOCs applied to Tier 2 DO engines have the ability to lower CO emissions due to high conversion efficiencies - 48 to 99% depending on engine out CO emissions and operating conditions.
- DOCs applied to Tier 2 DO engines have the ability to lower NMHC emissions from 44 to 100% depending on engine out NMHC emissions and operating conditions.
- No discernable trends in NO_x emissions were found.

DOCs for DF Engines

- DOCs applied to DF engines showed high CO conversion efficiency - up to 99%.
- Dual fuel operation tended to increase exhaust and catalyst temperatures for the engine of Campaign 1.

- DOCs applied to DF engines showed moderate NMHC conversion efficiency - above 50%.
- THC emissions were dominated by CH_4 (>90%).
- No discernable impacts on CH_4 emissions by DOCs.
- No discernable impacts on NO_x emissions by DOCs.

TWC of DNG Engines

- Operating temperatures of tested TWC exhausts were higher than the DF exhaust.
- Properly operating catalysts demonstrated CO conversions of 90%, NMHC conversions of 90-100% and NO_x reductions of 90-100%.
- TWCs were able to decrease CH_4 emissions by 44% depending on engine out CH_4 and operating conditions.
- THC conversion efficiency was just above 60%.

All Engines

- Campaign 5's engine operated richer than the engine of Campaign 6 and its TWC showed little CO conversion.
- DF engines without DOCs can lead to excessive CO emissions.
- DNG engines with properly operating catalysts that were operated slightly rich had lower NO_x emissions than DO or DF engines.
- For DF and DNG engines >90% of THC emissions are CH_4.
- With DOCs, DF engines can emit lower CO and NMHC emissions - below Tier 2 engine out emissions.
- Engines converted to operate as DF can experience emissions benefits from DOCs even when not operated as DF.

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Contact Information

Derek Johnson. Email: derek.johnson@mail.wvu.edu. Phone: 304-216-6592.

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Definitions/Abbreviations

CH_4	methane
CI	compression ignited
CO	carbon monoxide
CO_2	carbon dioxide
DF	dual fuel
DNG	dedicated natural gas
DO	diesel only
DOC	diesel oxidation catalyst
ECU	engine control unit
g/kW-hr	grams per kilowatt hour
H_2	hydrogen
HC	hydrocarbon
LLT	low-load transient
NMHC	non-methane hydrocarbon
NO_x	oxides of nitrogen
O_2	oxygen
Pd	palladium
PGM	platinum group metals
PM	particulate matter
Pt	platinum
Rh	rhodium
SCR	selective catalytic reduction
SI	spark-ignited
SS	steady-state
T50	50% light off temperature
THC	total hydrocarbon
TWC	three-way catalyst

Appendix

Table A1. Details of measurement Campaigns.

Campaign	Activity	Engine Activity Type	Engine Make	Engine Model	Rated Speed (rpm)	Rated Power (kW)	Compression Ratio	Combustion Type	Dual-Fuel Kit	Modes Sampled	Fuel	Reported Exhaust Sample Location
1	Hydraulic Fracturing	SS	Cummins	QSK50	1900	1678	15:1	CI	ComAP	DO	Diesel	Pre-/Post-DOC
										DF	CNG+Diesel	Pre-/Post-DOC
2	Drilling	SS	Caterpillar	3512C	1200	1101	13:1		DGB	DO	Diesel	Pre-/Post-DOC
		LLT								DF	FG+Diesel	Pre-/Post-DOC
3	Hydraulic Fracturing	SS	Caterpillar	3512B-HD	1800	1678	14:1		DGB	DO	Diesel	Pre-/Post-DOC
										DF	FG+Diesel	Pre-/Post-DOC
4	Drilling	SS	Caterpillar	3512C	1200	1101	13:1		Altronic GTI	DO	Diesel	N/A
		LLT								DF	FG+Diesel	N/A
5	Drilling	SS	Waukesha	L7044GSI	1200	1253	8:1	SI	N/A	Dedicated	CNG	Pre-/Post-TWC
		LLT										
6	Drilling	SS	Waukesha	L7044GSI	1200	1253	8:1		N/A	Dedicated	FG	Pre-/Post-TWC
		LLT										

Table A2. Diesel only operation results from Campaigns 1-4 during steady-state operation. Avg is the average data while std is one standard deviation. For all cases, the minimum number of data points were three.

			Campaign 1				Campaign 2				Campaign 3				Campaign 4	
			Engine Out		Post-Catalyst		Engine Out		Post-Catalyst		Engine Out		Post-Catalyst		Engine Out	
			Avg	Std	Avg	Std	Avg	Std	Avg	Std	Avg	Std	Avg	Std	Avg	Std
Engine	Load	%	70.84	13.67	71.56	12.31	55.70	0.97	54.62	0.79	77.00	12.32	67.46	10.77	57.13	7.08
	Power	kW	1189.12	229.50	1201.18	206.58	613.27	10.70	601.33	8.68	1292.05	206.78	1132.01	180.80	629.03	77.99
	Diesel	L/hr	312.18	60.15	314.04	60.28	151.93	2.68	150.11	2.39	359.86	31.68	318.49	26.46	165.74	15.74
Exhaust	CO_2	g/kW-hr	696.56	1.52	692.40	15.35	656.72	13.59	663.53	5.00	748.65	54.51	754.97	60.26	703.96	23.86
	CH_4	g/kW-hr	0.00	0.00	0.00	0.00	0.02	0.01	0.01	0.00	0.00	0.00	0.01	0.00	0.01	0.00
	CO	g/kW-hr	1.18	0.07	0.45	0.01	1.18	0.09	0.02	0.00	0.65	0.05	0.04	0.01	1.10	0.28
	NO_x	g/kW-hr	5.97	0.22	5.69	0.28	3.56	0.17	3.65	0.07	3.21	0.28	3.05	0.17	3.61	0.14
	THC	g/kW-hr	0.16	0.05	0.03	0.02	0.03	0.01	0.01	0.00	0.03	0.01	0.01	0.01	0.02	0.00
	NMHC	g/kW-hr	0.16	0.05	0.03	0.02	0.01	0.00	0.00	0.00	0.02	0.00	0.00	0.01	0.01	0.00

Table A3. Diesel only operation results from Campaigns 2 and 4 during low-load transient operation. Avg is the average data while std is one standard deviation. For all cases, the minimum number of data points were three.

			Campaign 2				Campaign 4	
			Engine Out		Post-Catalyst		Engine Out	
			Avg	Std	Avg	Std	Avg	Std
Engine	Load	%	24.29	1.99	24.52	1.76	21.75	1.78
	Power	kW	267.49	21.89	270.00	19.35	239.45	19.64
	Diesel	L/hr	74.28	4.90	74.69	6.85	55.06	3.58
Exhaust	CO_2	g/kW-hr	737.30	55.69	736.02	55.09	610.72	38.45
	CH_4	g/kW-hr	0.03	0.01	0.02	0.00	0.01	0.01
	CO	g/kW-hr	2.23	0.14	0.05	0.07	1.46	0.14
	NO_x	g/kW-hr	3.74	0.49	3.66	0.35	2.96	0.29
	THC	g/kW-hr	0.06	0.01	0.01	0.00	0.04	0.01
	NMHC	g/kW-hr	0.03	0.00	0.00	0.00	0.02	0.00

Table A4. Dual fuel operation results from Campaigns 1-4 during steady-state operation. Avg is the average data while std is one standard deviation. For all cases, the minimum number of data points were three.

			Campaign 1				Campaign 2				Campaign 3				Campaign 4	
			Engine Out		Post-Catalyst		Engine Out		Post-Catalyst		Engine Out		Post-Catalyst		Engine Out	
			Avg	Std	Avg	Std	Avg	Std	Avg	Std	Avg	Std	Avg	Std	Avg	Std
Engine	Load	%	70.84	13.67	71.56	12.31	61.13	5.20	54.68	1.88	74.84	4.48	74.81	10.42	47.08	2.94
	Power	kW	1189.12	229.51	1201.17	206.58	673.09	57.30	602.06	20.74	1255.79	75.13	1255.29	174.85	518.32	32.37
	Diesel	L/hr	151.69	17.13	143.23	22.24	59.82	4.42	55.73	2.09	150.26	38.69	191.83	45.88	62.95	8.06
	NG	SCFM	165.02	31.57	166.30	30.81	104.91	9.28	94.60	3.18	212.96	5.87	202.59	13.68	73.58	6.61
Exhaust	CO_2	g/kW-hr	741.65	9.11	759.45	22.24	715.81	7.56	762.64	7.91	791.93	32.40	891.12	32.16	758.29	26.85
	CH_4	g/kW-hr	35.86	9.15	34.49	7.46	25.21	1.63	25.64	3.68	42.37	5.97	42.61	12.80	17.96	2.07
	CO	g/kW-hr	23.06	1.40	0.60	0.04	20.59	1.05	0.14	0.01	25.46	2.89	0.57	0.03	14.72	1.47
	NO_x	g/kW-hr	3.53	0.35	3.83	0.50	2.78	0.15	3.02	0.08	2.40	0.34	3.17	0.51	4.96	0.85
	THC	g/kW-hr	35.04	9.11	30.76	6.85	26.01	1.67	26.02	3.80	43.75	6.14	43.46	13.19	18.10	2.10
	NMHC	g/kW-hr	0.00	0.00	0.00	0.00	0.81	0.04	0.38	0.12	1.38	0.17	0.85	0.40	0.14	0.03

Table A5. Duel fuel operation results from Campaigns 2 and 4 during low-load transient operation. Avg is the average data while std is one standard deviation. For all cases, the minimum number of data points were three.

			Campaign 2				Campaign 4	
			Engine Out		Post-Catalyst		Engine Out	
			Avg	Std	Avg	Std	Avg	Std
Engine	Load	%	24.11	2.13	22.20	1.75	16.65	1.96
	Power	kW	265.46	23.46	244.38	19.22	183.34	21.63
	Diesel	L/hr	57.27	3.28	56.53	1.38	33.97	4.70
	NG	SCFM	26.12	7.14	20.80	4.21	18.87	3.52
Exhaust	CO_2	g/kW-hr	870.05	82.70	888.00	47.37	785.89	52.80
	CH_4	g/kW-hr	18.51	4.01	16.85	0.88	19.99	3.17
	CO	g/kW-hr	12.92	2.77	0.08	0.02	12.37	2.56
	NO_x	g/kW-hr	3.98	0.42	4.13	0.35	6.74	1.28
	THC	g/kW-hr	19.02	4.14	17.11	0.90	20.09	3.19
	NMHC	g/kW-hr	0.52	0.13	0.26	0.01	0.10	0.02

Table A6. Dedicated natural gas operation results from Campaigns 5 and 6 during steady-state operation. Avg is the average data while std is one standard deviation. For all cases, the minimum number of data points were three.

			Campaign 5				Campaign 6			
			Engine Out		Post-Catalyst		Engine Out		Post-Catalyst	
			Avg	Std	Avg	Std	Avg	Std	Avg	Std
Engine	Load	%	53.99	1.80	55.13	1.16	57.83	3.02	55.85	4.78
	Power	kW	676.48	22.62	690.79	14.49	724.65	37.79	699.78	59.94
	NG	SCFM	178.77	6.16	181.78	4.21	172.37	7.67	166.57	12.23
Exhaust	CO_2	g/kW-hr	867.13	10.77	866.19	7.85	949.41	9.25	973.84	18.09
	CH_4	g/kW-hr	0.88	0.03	0.88	0.04	0.40	0.02	0.31	0.13
	CO	g/kW-hr	45.32	3.14	43.64	3.27	15.53	0.74	1.50	1.01
	NO_x	g/kW-hr	12.89	0.76	3.18	0.43	21.47	0.61	0.05	0.05
	THC	g/kW-hr	1.10	0.03	0.98	0.04	0.60	0.03	0.33	0.14
	NMHC	g/kW-hr	0.22	0.00	0.11	0.01	0.20	0.01	0.02	0.01

Table A7. Dedicated natural gas operation results from Campaigns 5 and 6 during low-load transient operation. Avg is the average data while std is one standard deviation. For all cases, the minimum number of data points were three.

			Campaign 5				Campaign 6			
			Engine Out		Post-Catalyst		Engine Out		Post-Catalyst	
			Avg	Std	Avg	Std	Avg	Std	Avg	Std
Engine	Load	%	13.68	1.36	14.12	1.10	24.62	7.00	20.87	1.79
	Power	kW	171.39	17.03	176.93	13.73	308.51	87.70	261.56	22.47
	NG	SCFM	80.13	3.12	81.16	2.95	93.71	15.96	85.90	4.18
Exhaust	CO_2	g/kW-hr	1518.21	120.44	1495.55	86.39	1230.81	109.02	1345.68	58.79
	CH_4	g/kW-hr	2.84	0.39	2.74	0.35	0.68	0.08	0.38	0.09
	CO	g/kW-hr	95.01	11.92	86.62	9.98	24.57	4.81	2.89	1.49
	NO_x	g/kW-hr	11.35	1.24	2.53	0.39	19.95	1.06	0.04	0.03
	THC	g/kW-hr	3.64	0.46	3.19	0.37	1.08	0.12	0.40	0.10
	NMHC	g/kW-hr	0.79	0.07	0.45	0.02	0.41	0.04	0.02	0.01

APPENDIX F

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Greenhouse gas emissions and fuel efficiency of in-use high horsepower diesel, dual fuel, and natural gas engines for unconventional well development

Derek R. Johnson*, Robert Heltzel, Andrew C. Nix, Nigel Clark, Mahdi Darzi

West Virginia University, Mechanical and Aerospace Engineering Department, Center for Alternative Fuels, Engines, and Emissions, 263 Engineering Sciences Building, Morgantown, WV 26506, United States

HIGHLIGHTS

- Dual fuel is advertised to reduce diesel consumption by up to 70%.
- When correcting for methane slip, peak substitutions were up to 58%.
- GHG emissions of dual fuel operation were 2.2 and 1.65 times higher than diesel only and natural gas, respectively.
- Dual fuel and dedicated natural gas engines have lower efficiencies than diesel only.
- Even when accounting for methane slip these technologies do offer economic benefits.

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ABSTRACT

We collected data focusing on in-use emissions and efficiency of engines servicing the unconventional well development industry to elucidate real world impacts from current and newly applied engine technologies. The engines examined during the campaigns were diesel only (DO) and dual fuel (DF) diesel/natural gas, compression-ignition (CI) engines and dedicated natural gas, spark-ignition (SI) engines. These included two CI drilling engines outfitted with two different DF kits, two SI drilling engines, and two CI well stimulation engines. Our data were gathered under the load and speed requirements in the field, and the engines were not under our direct control. Greenhouse gas (GHG) emissions were measured from all engines and fueling types and included both exhaust and crankcase emissions. Fuel consumption and engine data were collected to determine fuel efficiency. During steady-state operation, fuel efficiency was 38%, 26%, and 20% for DO, DF, and SI engines, respectively. The loss of efficiency during DF operation was due in part to uncombusted methane (CH_4) slip in the exhaust, which accounted for 18% of the fuel supplied. GHG emissions (carbon dioxide and CH_4) from CI engines were 2.25 times higher during DF compared to DO operation. During DF operation, substitution ratio varied depending on engine load and DF kit, ranging from 9% to 74%. GHG emissions from the SI engines were 1.33 times higher than DO due to lower efficiencies of throttled and rich operation as compared to unthrottled and lean operation for CI engines.

Abbreviations: BSFC, brake-specific fuel consumption; C_2H_6, ethane; C_3H_8, propane; CH_4, methane; CI, compression-ignition; CO, carbon monoxide; CO_2, carbon dioxide; CO_{2eq}, carbon dioxide equivalent; CR, compression ratio; DF, dual fuel; DGB, dynamic gas blending; DLE, diesel liter equivalent; DNG, dedicated natural gas; DO, diesel only; DOC, diesel oxidation catalyst; ECU, engine control unit; EIA, Energy Information Administration; EPA, US Environmental Protection Agency; FG, field gas; g, grams; GHG, greenhouse gases; GREET, greenhouse gases, regulated emissions, and energy use in transportation; GWP, global warming potential; HC, hydrocarbon; kg, kilograms; kW, kilowatts; kW-h, kilowatt-hours; LHV, lower heating value; LNG, liquefied natural gas; LLT, low-load transient (drilling operation); m, meters; m^3, cubic meters; M, million; MJ/SCM, mega-Joules per standard cubic meter; MN, methane number; MW-h, megawatt-hours; N_2, nitrogen; N_2O, nitrous oxide; NG, natural gas; NMHC, non-methane hydrocarbons; NO_x, oxides of nitrogen; rpm, revolutions per minute; SCM, standard cubic meters; SI, spark-ignition; SR, substitution ratio; SS, steady-state (drilling operation); THC, total hydrocarbons; TWC, three-way catalyst; US, United States; WVU, West Virginia University; ZECE, zero emissions conversion efficiency; °C, degrees Celsius; $, US Dollars

* Corresponding author.
E-mail address: derek.johnson@mail.wvu.edu (D.R. Johnson).

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1. Introduction and background

An energy revolution has occurred due to technological advances in directional drilling and hydraulic fracturing. These technologies have increased natural gas (NG) reserves such that they are estimated to last the United States (US) 93 years [1]. One of the key sectors benefitting from an abundance of low cost gas is power generation. Numerous analyses have been conducted examining the conversion of vehicles and/or power plants to use this new resource [2,3]. NG is touted as a low carbon fuel because it has the highest hydrogen to carbon ratio and a higher heating value on a mass basis than fuels such as gasoline. However, when switching to NG, overall system efficiency must be examined along with any NG leaks across the supply chain to assess climate benefits [4]. Alvarez et al. showed that methane (CH_4) leaks across the supply chain must be less than 1.0 and 3.2% to have net benefits for fuel switching for heavy-duty diesel vehicles and power plants, respectively [2]. Others have suggested that benefits occur if the net leakage rates are less than 2.9%, but also noted that losses are typically higher across the supply chain when NG prices are low [3]. To examine the total greenhouse gas (GHG) emissions one must include not only CH_4 leakage but also all carbon dioxide (CO_2) or CO_2 equivalent (CO_{2eq}) emissions across the entire supply chain from development to end use. Such analyses are often called wells to wheels, wells to combustion, or wells to tank [5]. Such studies require collection of an array of data sets from numerous sources and assumptions from across many sectors in order to estimate entire life cycle emissions. A recent study showed that NG from the Marcellus shale could have a GHG footprint of only 53% of coal [6]. They estimated that GHG emissions during stimulation of these new unconventional sources represented about 1.2% of the total life cycle emissions.

This subsector includes the energy consumption and GHG emissions from the development of new unconventional gas wells. On-site execution of these new extractive technologies require significant energy and are often powered by onsite compression-ignition (CI) diesel engines. On average at a site, drilling rigs consist of 2.15 engines, with an average size of 1030 kilowatts (kW). These engines operate 62.6 h per 305 meters (m) drilled, at an estimated average load of 48.5% [7]. With continued advances in technology, the length and depth of these new unconventional wells continue to increase [8]. In 2016, Halliburton completed the longest well with a lateral length of 5639 m and total length of 8244 m [9]. The well included 124 "frack" stages. High-horsepower diesel engines also power hydraulic fracturing pumps and the longest US well utilized dual fuel (DF) stimulation engines to reduce fuel consumption by 40%. Total engine capacities for fracturing spreads may be 14,914 kW or more as each site requires anywhere from eight to nearly two dozen stimulation pumps. Typically, a diesel engine rated between 1119 and 1864 kW [10] powers each pump. We reviewed recent literature and found that average fuel consumption per well for vertical drilling, horizontal drilling, and hydraulic fracturing was 50,876, 232,553, and 79,494 l, respectively [11]. Fuel consumption increases with length of the well and number of fractured stages. As such, unconventional well development is also expensive – average horizontal well costs range from $1.8 M to $2.6 M while well completion ranges from $2.9 M to $5.6 M [12]. Note $ is US Dollars.

Recently, researchers at Stanford developed "*GHGfrack*", an open source model aimed at estimating GHG emissions from drilling and stimulation of unconventional wells [13]. Their model uses CO_2 emissions factors for diesel fuel of 0.269 kg (CO_{2eq}) per kilowatt-hour (kW-h) of lower heating value (LHV) as does the Greenhouse Gas, Regulated Emissions, and Energy Use in Transportation (GREET) Model [13,14]. *GHGfrack* requires additional information regarding details such as drill rates and flow rates to estimate the total CO_{2eq} emissions. Their results showed that, in all four analyzed cases, hydraulic fracturing yielded the highest fuel consumption and highest GHG emissions as compared to drilling. This paper will examine the CO_{2eq} emissions compared to those emission factors used in literature [13,14]. It is also noted that other studies have tried to indirectly quantify GHG emissions from well sites during the development stages [15] but such methods cannot relate GHG emissions to the prime-movers since measurement results represent the entire site. Since little in-use data are available and rely on older emissions factors, we present these in-use results to represent new emissions rates not only for prime-movers using conventional diesel fuel but also newly applied technologies that include dedicated and DF engines which are seeing additional market penetration. These data can be used by industry, regulators, and researchers to understand the current strengths and weaknesses from application of these technologies. In addition, this analysis produces the first in-use evaluation and emissions factors from these technologies. Industry is likely to continue to invest in these new technologies to reduce energy consumption and their associated costs, but such investments must include a broad understanding of the implications on GHG emissions and efficiency of new cost saving measures [16]. Accurate and direct baseline quantification of GHGs is crucial to reducing uncertainty and establishing mitigation targets [17].

One method to reduce operating costs is to reduce diesel fuel consumption by replacing it with NG. For example, a fracturing fleet of 14,914 kW could consume 3785 l of fuel per day, which is nearly $50,000 per day. Diesel fuel prices are typically more volatile than NG, which typically retains a three to one price advantage [18]. DF conversion kits allow for substitution of NG into the engine intake, providing energy for combustion thus decreasing diesel fuel demand. In addition to current cost reductions, the demand for diesel fuel is expected to grow faster than other fuels through 2040 [19]. Researchers have suggested that such an increase could disrupt the energy production sector, as the distribution of energy demand would be unbalanced [20]. The same study highlighted that DF or DNG engines and other alternative fuels could help offset this imbalance but that any analysis must include any CH_4 emissions, which could offset GHG reductions [20]. Others have also suggested that increasing the use of DF engines could offer future balance and they provide an extensive review of DF combustion and emissions [21]. DF systems are subject to the emissions standards of their respective diesel engines, but off-road engines are not subject to GHG or fuel efficiency standards.

An alternative to partial reduction in diesel fuel consumption is to use only NG as fuel. Currently this requires use of spark-ignition (SI) engines such as the Waukesha L7044GSI. Both fueling methods are also capable of using field gas depending on quality, which eliminates refining, processing, and transmission (by pipeline or truck) costs and the respective GHG emissions. For reference, the average price of diesel fuel for 2016 was $0.61/l [22]. The 2016 average Henry Hub price for NG was $8.60 per megawatt-hour (MW-h) [23]. Approximately 0.76 kilograms (kg) or 1.04 standard cubic meters (SCM) of NG yields the energy in a diesel liter equivalent (DLE) [24]. Based on the Henry Hub price, this yields a NG cost of around $0.09/DLE.

Diesel engines are typically favored for their efficiency and durability. Modern on-road diesel engines typically have efficiencies around 43–44% [25]. The most efficient four-stroke CI engine is above 50% [26]. Diesel engines are also inherently more efficient than SI engines that are impacted by compression ratio (CR) limitations, throttling, low volumetric efficiency (especially for gaseous fuels), and lean operation [27].

1.1. Dual fuel combustion

Current DF conversion kits utilize NG fumigation, which introduces NG prior to the intake air compressor. The added NG reduces the diesel fuel required to meet a target engine power. Systems are calibrated over the entire load range and utilize engine parameters to determine the substitution ratio of NG. However, the fuel substitution map is limited on the lower end due to misfire or incomplete combustion of the dilute fuel gas, and on the upper end due to knocking [28]. In some cases, increased NG substitution has been shown to decrease brake-specific

CO_2 emissions [29]. Research has shown brake-specific fuel consumption (BSFC) increases during DF operation especially at part loads due to lower combustion temperatures and increased ignition delay [30]. In addition, unburned CH_4 decreases efficiency and increases GHG emissions. This has been shown under optical investigations as due to lean operation (low equivalence ratio) [31]. The NG intake mixture is homogeneous within the cylinder and therefore CH_4 can become trapped in crevice volumes leading to increased emissions [32]. Research has shown that application of intake throttling at part loads may decrease unburned hydrocarbons and improve both combustion and indicated efficiency [33]. Although throttling lowers efficiency by demanding pumping energy from the engine, inefficiency associated with poor NG combustion may be greater. However, engines currently converted to operate as DF do not include throttling capability. Other research continues to address CH_4 emissions and reduced efficiency of DF engines. Technologies such as premixed micro pilot combustion may reduce CH_4 emissions by up to 65% and improve fuel consumption over current DF delivery strategies [34].

West Virginia University (WVU) examined emissions from DF engines powering buses that used technologies similar to those employed in current off-road engines. Results indicated decreased CO_2 during DF operation, but the total hydrocarbon (THC) emissions increased [35]. WVU also showed that both legacy and newer on-road DF engines offer CO_2 reductions but that BSFC and CH_4 emissions increased with net decreases in efficiency [36]. Similar reductions in CO_2 emissions were summarized in the review of Hegab [21]. The recent WVU research also examined the use of a diesel oxidation catalyst (DOC) to reduce carbon monoxide (CO) and HC emissions [36]. Engines of Campaigns 1–3 utilized DOCs for these emissions benefits but the earlier conversion kit applied to the engines of Campaign 4 did not use DOCs. However, exhaust temperatures during DF operation may still be below the light-off temperature for CH_4 oxidation (~450 °C) [37] and employed DOCs are not necessarily formulated to target CH_4 oxidation. These emissions further increase the GHG footprint because CH_4 has a higher global warming potential (GWP) compared to CO_2. The Intergovernmental Panel on Climate Change recommends a GWP for CH_4 of 25 for a 20 year time period and this value was used in our research [38]. Others examined GWPs of 25 and 75 for 20 and 100 year periods, and showed that GHGs increased by factors of 1.63–4.78 for DF operation [36]. A similar study showed a net reduction of CO_2 emissions for heavy-duty DF vehicles but when analyzing CO_{2eq} emissions, they increased by 50 and 127% [39].

1.2. Dual fuel conversion kits

A Caterpillar Dynamic Gas Blending (DGB) kit can be used on the land drilling Caterpillar 3512B and C and 3516B engines, which are widely used in the US for drilling and well stimulation. The conversion is advertised with specifications of 70% displacement of diesel for drilling applications and 60% well stimulation activities [40]. See Table 3 for methods to calculate the substitution ratio (SR) – advertised rates are energy based. The Altronic GTI Bi-Fuel System is advertised to displace up to 70% of diesel fuel and reduce exhaust emissions and costs [41]. The QSK 50 engine with the Cummins/ComAP kit is advertised with substitution of NG up to 70% with equivalent power output as similarly sized engines [42].

1.3. Dedicated natural gas combustion

Dedicated natural gas (DNG) engines are spark-ignition (SI) and may operate as lean or stoichiometric/rich burn. SI and CI engines that both operate at wide-open throttle and similar CRs enjoy similar efficiencies but in practical applications, SI engines are limited on CR by auto-ignition or knocking. While the main component of NG is CH_4, which is fairly knock resistant, NG fuels also contain higher alkanes and composition directly affects knock in SI engines [43]. Resistance to knocking of gaseous fuels is typically evaluated using methane number (MN). MN was calculated with the method suggested by Cummins-Westport [44]. The DNG engines examined herein also suffer from lower efficiency due to throttling at part load and operating with an equivalence ratio at or around one. Other DNG engines can operate lean to improve efficiency but lean operation may lead to incomplete combustion and higher oxides of nitrogen (NO_x) emissions. Lean DNG engines can use DOCs to reduce non-methane hydrocarbon (NMHC) and CO emissions but do not enjoy the NO_x reduction benefits of three-way catalyst (TWCs). Exhaust gas recirculation is an alternative emissions control strategy to reduce NO_x emissions that could be employed on both types of DNG but is not currently used in application. Benefits of stoichiometric operation include the ability to use TWCs to reduce HC, CO, and NO_x emissions simultaneously. Recent data from on-road engines equipped with TWCs showed they still emit average CH_4 emissions of 0.25–0.78% of the fuel – depending on vehicle type/activity [45]. One market that has seen an increase in DNG engines is the mass transit sector where compressed natural gas is used to fuel SI engines. Even with TWCs, the DNG engines typically yielded higher CO_2, CO, and THC emissions compared with conventional diesel engines but did offer benefits of reduced NO_x emissions [46]. The increase of GHG emissions, specifically CO_2, was attributed to the lower efficiency of the SI NG engine.

1.4. Crankcase GHG emissions

DF kits also produce CH_4 emissions from engine crankcase vents if the original diesel engine did not have closed crankcase provision. Crankcase HC emissions of a CI engine are generally small compared to that of the exhaust, only about 0.4–0.8% [47] and rates correlate to engine power and differs between new and worn engines [48]. For the purpose of non-road CI engines with open crankcases, the Environmental Protection Agency (EPA) estimates that crankcase HC emissions are equal to 2.0% of the exhaust [49]. Recent data collected by WVU show that on-road DF engines may have fuel specific CH_4 emissions of 1% (1% of NG substituted is lost via the crankcase) [45]. Other research on large, lean burn DNG engines showed crankcase CH_4 emissions may be up to 14.4% of the exhaust emissions [50]. On-road DNG engines that were stoichiometric were shown to have crankcase CH_4 emissions from 0.95 to 1.02% [44] of fuel consumed – nearly equal to exhaust emissions rates. DNG engines measured under this campaign were all stoichiometric/rich burn and equipped with closed crankcase ventilation systems, which negated crankcase GHG emissions.

2. Methodology

All campaigns included collection of data from the Engine Control Unit (ECU), fuel flowrates (both diesel fuel and NG), and exhaust and crankcase emissions. Exhaust emissions sampling occurred both pre- and post-aftertreatment systems. Measuring after the catalysts ensured that total tailpipe GHG emissions were captured. Pre-catalyst emissions were critical in determining fuel efficiency and CH_4 slip through the engine and in determining GHG emissions of engines operating as diesel only (DO). Exhaust emissions were sampled by an MKS Multigas™ 2030 FTIR Continuous Gas Analyzer [51] for campaigns 2–6 and a SEMTECH-DS and California Analytical heated flame ionization detection with a methane cutter for Campaign 1. Crankcase emissions from DO and DF engines were sampled using a Full Flow Sampling System [52].

ECU data were collected with a VIA Model HDV100A1 [53] from J1708/J1939 parameters. Waukesha engine data were collected via Modbus serial communication. These data were used to determine speed and load of the engine, allowing for calculation of engine brake power, although the broadcast load was inferred from operating variables and not measured independently. Diesel fuel flow rate was measured with KRAL OME20 Volumeters® for drilling campaigns and OME32 models for hydraulic fracturing campaigns [54]. The combined

Table 1
Summary of data collection campaigns. FG = Field Gas. CR = Compression Ratio.

Campaign	Activity	Engine activity type	Engine make	Engine model	Rated speed (rpm)	Rated power (kW)	CR	Average load (%)	Average power (kW)	Combustion type	Dual-fuel kit	Modes sampled	Fuel
1	Hydraulic fracturing	SS	Cummins	QSK50	1900	1678	15:1	71	1189	CI	ComAP	DO DF	Diesel CNG + Diesel
2	Drilling	SS LLT	Caterpillar	3512C	1200	1101	13:1	55 23	613 267		DGB	DO DF	Diesel FG + Diesel
3	Hydraulic fracturing	SS	Caterpillar	3512B-HD	1800	1678	14:1	76	1292		DGB	DO DF	Diesel FG + Diesel
4	Drilling	SS LLT	Caterpillar	3512C	1200	1101	13:1	47 18	544 220		Altronic GTI	DO DF	Diesel FG + Diesel
5	Drilling	SS LLT	Waukesha	L7044GSI	1200	1253	8:1	55 14	677 171	SI	N/A	DNG	CNG
6	Drilling	SS LLT	Waukesha	L7044GSI	1200	1253	8:1	56 21	725 308		N/A	DNG	FG

accuracy during all data collection campaigns was ± 2% of the measured value. A KURZ MFT-B flowmeter measured the flow rate of NG [55]. The accuracy of the thermal based flow meter was ± 2% of measured values. Values were corrected based on reported gas composition listed in Table 2.

Campaign 1 examined a DF stimulation engine at a hydraulic fracturing test facility. Data from this campaign are presented for an average load of approximately 71%, which aligned with average activity data collected in the field. Data were collected at 0, 20, 40, 60, 80, and 100% load and these granular data are included in the SR discussion below. In-use engine load and power are presented in Table 1.

Campaign 2 focused on an in-use DF drilling engine that operated during the drilling of two separate wells. Emissions were measured in three-hour windows, spanning different sampling arrangements. A total of 12 h of data was collected at each sample position. Data were subdivided into two categories: low-load transient (LLT) and steady-state (SS) drilling operation. All SS drilling operation occurred at or above an average load of 40%, which was used as the threshold to define activity type. The average engine loads during LLT and SS operations were 23.3% and 55.2%, respectively.

Campaign 3 focused on a DF stimulation engine. Three stages of hydraulic fracturing activity were recorded for each emissions sampling position. The hydraulic stimulation activity was SS during individual stages, but not all stages occurred at the same engine load. The average engine load during the fracturing stages was 75.9% – average of in-use operation.

Campaign 4 focused on an in-use DF drilling engine. Note that this engine did not include a DOC. The average engine load during LLT activity was 18.2% and during SS was 46.5%.

Campaign 5 focused on an in-use DNG engine on a drilling rig. The catalyst on this system appeared to be faulty based on the emissions pre- and post-catalyst. Data were categorized by activity type with an average load of 55.1% during SS and 14.1% during LLT operation.

Campaign 6 focused on an in-use DNG engine on a drilling rig. The engine had an average SS load of 55.9% and LLT load of 20.9%. Table 1 provides a summary of the campaigns and Table 2 presents information regarding the NG fuels used in each campaign. The composition of the fuels varied greatly and composition was used to correct fuel flow and emissions calculations. Since in-use data collection was the goal, fuel quality could not be controlled and its effects are noted but beyond the scope of this article. Fuel quality directly affects the combustion process and therefore efficiency and emissions from both DNG and DF engines [56–59]. Trends typically show increased CO_2 emission with increased higher HC content but this increase may be offset by decreased CH_4 emissions as a function of lower amounts of CH_4 in the fuel.

3. Results and discussion

Normalized fuel rates are presented in DLE per kilowatt-hour (DLE/kW-h) based on LHV. The LHV of NG varied by campaign depending on the composition – see Table 2. The diesel and NG fueling rates are presented in Fig. 1 for SS operation of DO and DF engine operation from Campaigns 1–4. Table 3 presents tabular values for data shown in Fig. 1 along with data for LLT operation.

Fig. 1 shows that DF operation required more equivalent fuel energy than DO operation – on average, 1.5 times as much. On average, 70% of the fuel energy supplied during DF operation was from NG. This number is often called the SR by industry; however, the SR can be defined in different ways. Method 1 does not account for efficiency and CH_4 losses, which gives the appearance of greater substitution. A second method to present SR is to reduce the CH_4 supplied to the engine by the ratio of CH_4 lost via the crankcase and exhaust. This corrected method decreased the SRs. The third method to define SR was the ratio of diesel fuel used during DF operation to the amount of diesel fuel used during DO operation at the same engine power. Table 4 presents a summary of each method and the results for SS operation. The average DF SRs calculated as advertised were 70% during SS operation, however, when corrected for lost CH_4 the average was 58%. Method 1 aligns with the energy SR presented in literature [38].

The third method can be difficult to complete when collecting in-field data due to varying engine loads. To compare DO and DF operation, with varying loads, fueling rates were analyzed on a brake-specific basis. This made operation at similar loads more comparable, however, since fueling is not linear with engine power some issues can arise if

Table 2
NG fuel details – major constituents shown. For the case of Campaign 5, a fuel analysis was provided by the operator and did not include a full analysis beyond data provided.

Campaign	NG source	CH_4 (%)	C_2H_6 (%)	C_3H_8 (%)	N_2	CO_2	Methane number	LHV (MJ/SCM)	Density (kg/m^3)
1	CNG	95.04	3.19	0.53	0.56	0.27	85.3	39.31	0.714
2	FG	97.30	2.07	0.08	0.25	0.31	90.0	38.41	0.691
3	FG	97.31	2.06	0.07	0.25	0.31	90.6	38.40	0.691
4	FG	96.71	0.22	0.01	0.44	2.63	96.9	36.60	0.708
5	CNG	86.10	–	–	2.36	0.00	–	40.61	0.763
6	FG	78.56	12.78	2.46	2.46	0.18	60.8	45.61	0.873

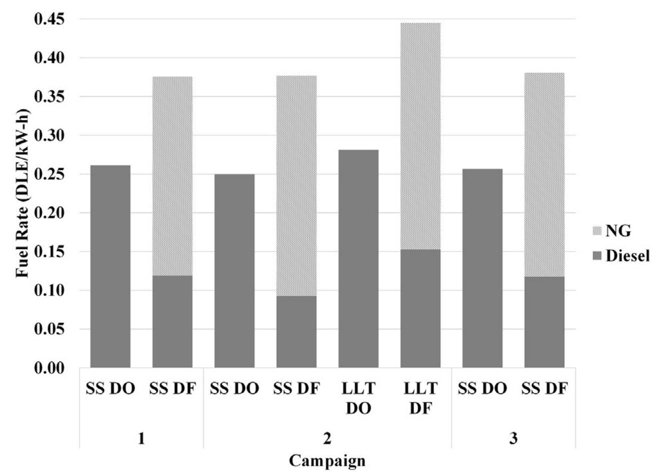

Fig. 1. BSFC for DO and DF operation from Campaigns 1–4, see Table 3 for tabular values.

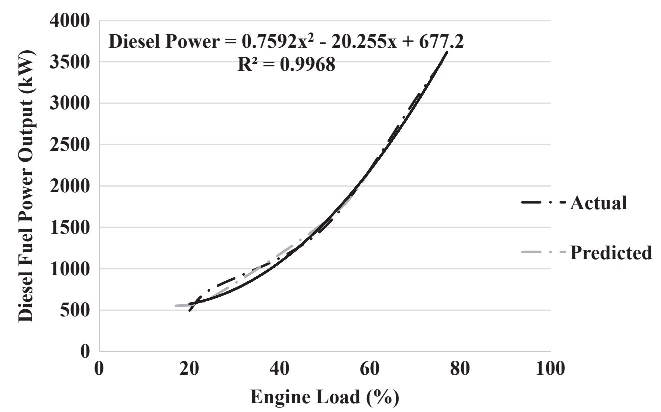

Fig. 2. Produced diesel fuel power output versus engine load (%) – data collected from all engines tested. Actual data were plotted and a second order polynomial regression fit was applied (dotted line). The gray predicted line is the expected diesel power required from the regression based on DF loading.

Table 3
Average BSFC for DO and DF operations.

Campaign	Fueling	Engine operation	NG (DLE/kW-h)	Diesel (DLE/kW-h)	Total (DLE/kW-h)
1	DO	SS	–	0.261	0.261
	DF	SS	0.256	0.119	0.376
2	DO	SS	–	0.250	0.250
		LLT	–	0.354	0.354
	DF	SS	0.284	0.093	0.377
		LLT	0.16	0.23	0.389
3	DO	SS	–	0.281	0.281
	DF	SS	0.292	0.153	0.445
4	DO	SS	–	0.257	0.257
		LLT	–	0.233	0.233
	DF	SS	0.263	0.118	0.380
		LLT	0.191	0.194	0.386

Table 4
Average SRs by campaign and method – SS operation only.

Method	Definition	Campaign –SS operation			
		1	2	3	4
(1) Industry	$\frac{NG\ Power\ In}{Total\ Fuel\ Power\ In}$	67%	76%	72%	65%
(2) Corrected	$\frac{(NG\ Power\ In - CH_4\ Loss)}{Total\ Fuel\ Power\ In}$	54%	66%	58%	56%
(3) Brake-specific fueling	$1-\frac{DF\ Diesel\ Fuel\ Rate}{DO\ Diesel\ Fuel\ Rate}$	51%	64%	57%	54%

loads differ substantially. Fig. 2 shows the correlation between DO engine load and diesel fuel power output measured from DO operation. Fig. 2 consists of average SS operating data points from all campaigns for DO operation. A least squares polynomial regression predicted power well. This allowed for comparison of a predicted diesel fuel rate at the different loads during in-use operation. In some cases (Campaign 1, 2, and 3) the broadcast engine load corresponded directly with the expected engine load and fuel power output based on conventional operation. However, in the case of Campaign 4, the engine broadcasted lower than expected load values due to the nature of integration of the dual fuel kit. Therefore, engine power output was estimated based on total fuel power and load was inferred. Defining SR as a ratio of brake-specific diesel consumption produced lower substitution rates.

Most of the engines only operated in DF mode between engine loads of 20% and 80%. Engines of Campaign 2 had the widest range of SR, ranging from 9% during LLT operation to 74% during SS operation. Engines of Campaign 4 had a much narrower band in terms of load, but had a higher SR during LLT. The hydraulic fracturing engines operated continuously as SS and had an average SR of 53%. The overall average SR across all loading types was 48%; however, the average SR during SS type operation was 59%. These rates match well with values presented for transit buses, which ranged from 40 to 61% [38]. Fig. 3 presents the SRs for the reported engine operating conditions and includes additional granular data collected for the engine of Campaign 1 – Method 3. This DF engine showed increased SR with increased load but only varied from 50 to 56% and saw no substitution at 100% load or 20% and lower.

From Fig. 1 it is seen that DF operation comes with some loss of fuel efficiency due in part to a loss of fuel energy in the form of unburned CH_4 (methane slip). Fig. 4 shows the percentage of CH_4 that is lost to the exhaust and crankcase of each DF configuration during SS operation. Methane loss is defined as the ratio of the sum of CH_4 mass emissions from the exhaust plus crankcase divided by the mass of fuel supplied to the engine, see Eq. (1).

$$\text{Methane Loss (\%)} = \left[\frac{Mass\ CH_4\ exhaust + Mass\ CH_4\ crankcase}{Mass\ Fuel}\right] \times 100 \tag{1}$$

The hydraulic fracturing engines (Campaigns 1 and 3) lost a higher percentage of CH_4 than the drilling engines. When operating in DF mode an average of nearly 22% of CH_4 passed through the engine unburned and exited via the exhaust or crankcase during hydraulic fracturing. Drilling engines experienced losses of 14.3% on average during SS operation. Methane loss was higher for drilling engines during LLT operation – 19% on average. We previously discussed that CH_4 exhaust emissions were due in part to HC emissions trapped in crevice volumes [32] and to uncombusted CH_4 due to lean mixtures and quenching [30]. It should also be noted that DF conversion kits are currently applied to CI engines that were designed with valve trains optimized for diesel only operation. Recent research has examined variable valve lift and duration and showed that when converted to operate as DF, engines that had much earlier exhaust valve closure (decrease short circuiting of the homogenous intake air and NG charge) could reduce THC emissions by 50% or more [60]. Therefore, engines that were designed to operate specifically as DF could reduce crevice volumes and alter valve timing to reduce CH_4 emissions – GHG benefits that are not afforded with current conversion kits.

CH_4 losses should be accounted for when calculating SR and overall efficiency. The ratio of engine power output to fuel energy into the engine was defined as the total fuel efficiency and is shown in Fig. 5 for SS operation. The average fuel efficiency of all engines during DO SS operation was 38% and during DF SS operation was 26%. The decrease in conversion efficiency – by nearly a third – was due in part to the CH_4

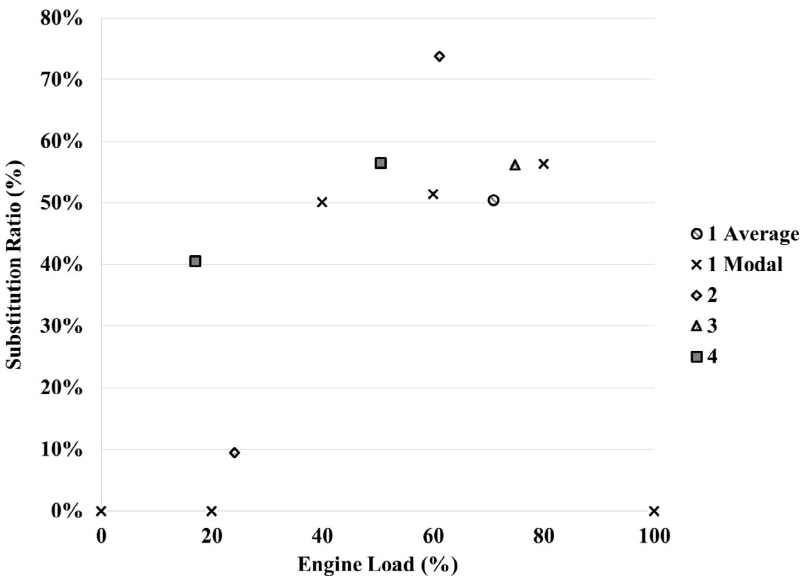

Fig. 3. SR for All DF engines as a function of load as defined by method 3.

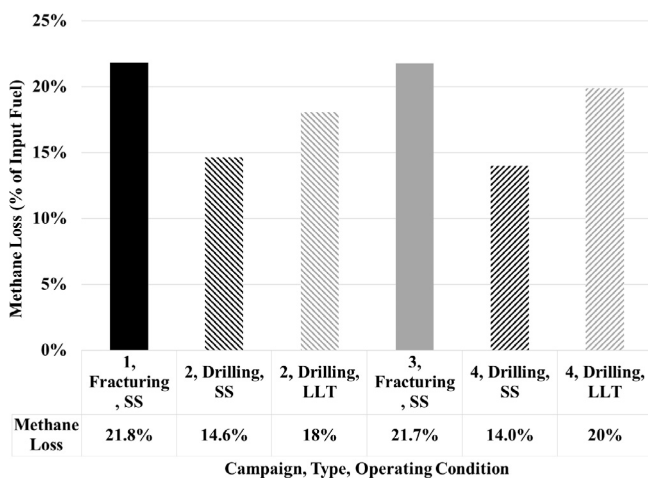

Fig. 4. Methane loss from Campaigns 1–4 during DF operation.

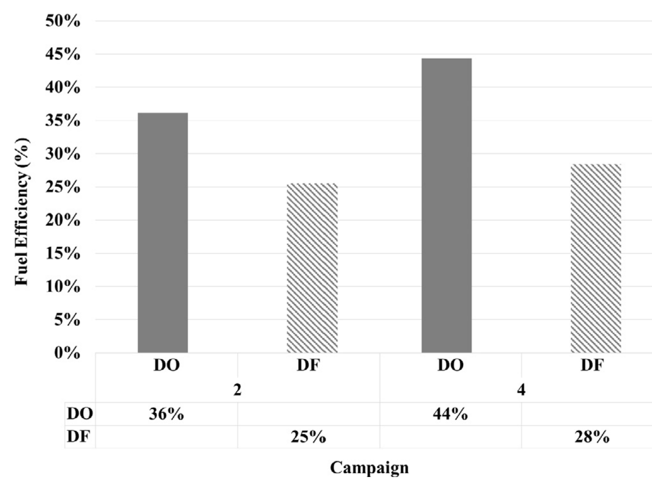

Fig. 6. Diesel and DF fuel efficiency for Campaigns 1–4, during LLT operation.

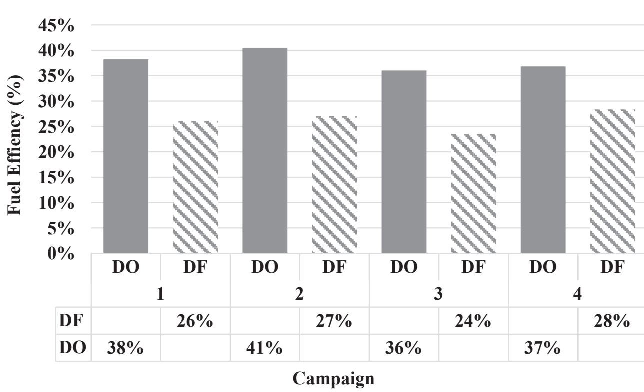

Fig. 5. Diesel and DF fuel efficiency for Campaigns 1–4, during SS operation.

slip. Fig. 6 shows the average fuel efficiency during LLT operation for the engines of Campaigns 2 and 4 – drilling engines.

Ideal efficiency of internal combustion engines can be calculated from Eq. (2). We selected $k = 1.4$ and since r_c was not known we calculated efficiency for values from 1 to 2.5. When $r_c = 1$ the equation reduces to the ideal Otto cycle efficiency which is applicable to the SI engines. CI engines have values of $r_c > 1$.

$$\eta = 1-\left[\left(\frac{1}{r^{k-1}}\right)\times\left(\frac{r_c^k-1}{k\,(r_c-1)}\right)\right] \tag{2}$$

where r is the compression ratio, r_c is the cutoff ratio, and k is the ratio of specific heats.

Fig. 7 presents the average efficiency values for all fuels and engines based on CR along with the upper theoretical efficiencies for reversible Otto (SI) and Diesel (CI) cycles. The ratio of actual efficiency to the upper theoretical efficiency denotes the Second Law efficiency (η_{II}) for the engines. The ranges of η_{II} for each CR are presented in Table 5.

To examine if other factors beyond CH_4 slip impacted efficiency, we used a zero emission conversion efficiency (ZECE) to determine the conversion of fuel consumed during DF mode by subtracting the CH_4 loss from the NG provided to the engine, see Eq. (3).

$$ZECE\ (\%) = \left[\frac{Engine\ Power\ (\mathrm{kW})}{(LHV\times\dot{m})_{diesel} + (LHV\times\dot{m})_{NG\ fuel} - (LHV\times\dot{m})_{methane\ loss}}\right]\times 100 \tag{3}$$

The ZECE values for DO in Campaigns 1 through 4 were, 38, 41, 36, and 37%, respectively – little impact for DO operation as THCs were low. The ZECE values during DF in Campaigns 1–4 were 30, 30, 27, and 31%, respectively. Thus, even when excluding the energy lost from uncombusted CH_4, the average fuel efficiency was reduced by 22%

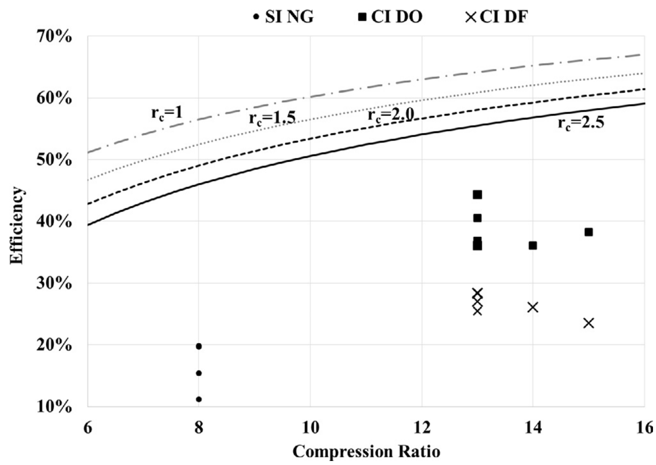

Fig. 7. Theoretical and actual efficiencies based On CR.

Table 5
Second law efficiency based on fuel and CR.

CR	Combustion	Fuel	η_{II} (%)
8	SI	DNG	19.9–35.2
13	CI	DO	56.3–79.9
13	CI	DF	39.7–51.5
14	CI	DO	55.2–63.4
14	CI	DF	40.0–45.9
15	CI	DO	57.7–65.9
15	CI	DF	35.6–40.6

from 38% for DO to 30% for DF operation. These observations show that while less diesel fuel was being used, the requirement of more NG due to loss of efficiency reduced the fuel and GHG benefits of DF operation.

The CO_{2eq} of SS DO and DF operation are shown in Fig. 8. The exhaust CO_2 and crankcase CO_2 were combined with CO_{2eq} methane emissions from the exhaust and crankcase using a GWP of 25. On average, DF operation produced 2.24 times more GHG emissions than DO operation. The ratios for engines 1–4 were 2.37, 2.17, 2.61, and 1.83, respectively. See Tables 6 and 7 for average data for all engines by fuel and activity type.

The majority of the GHG emissions during DF operation were from the exhausts. When accounting for GWP, CH_4 slip in the exhaust made up nearly the same percentage (47.11%) of total GHG emissions as CO_2 (50.75%), during SS operation. Fig. 9 shows the average contribution (Campaigns 1–4) of each component during DF SS operation (left) and

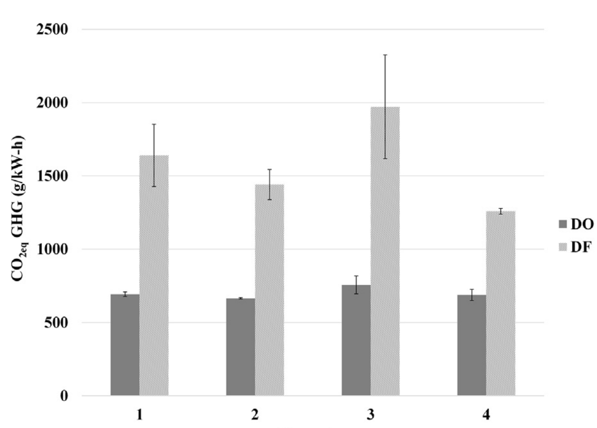

Fig. 8. SS CO_2-equivalent emissions (g/kW-h CO_{2eq}) for Campaigns 1–4, see Table 6 for tabular values.

Table 6
CO_2 and CO_{2eq} emissions factors by source for steady-state operation (brake-specific g/kW-h). Where CO_{2eq} includes CO_2 and CH_4.

SS operation	DO drilling				DO fracturing				DF drilling				DF fracturing				DNG drilling			
	CO_2		CO_{2eq}		CO_2		CO_{2eq}		CO_2		CO_{2eq}		CO_2		CO_{2eq}		CO_2		CO_{2eq}	
	Ave.	Std. Dev.	Ave.	Std. Dev.	Ave.	Std. Dev.	Ave.	Std. Dev.	Ave.	Std. Dev.	Ave.	Std. Dev.	Ave.	Std. Dev.	Ave.	Std. Dev.	Ave.	Std. Dev.	Ave.	Std. Dev.
Exhaust	675.0	21.2	675.3	21.3	723.4	37.8	723.9	37.8	776.2	7.15	1298.9	57.7	825.3	27.2	1789.1	230.4	920.0	13.0	934.8	15.1
Crankcase	1.03	0.11	1.06	0.13	0.85	0.17	N/A		1.19	0.03	51.03	3.42	0.78	0.21	16.5	3.2	N/A			

Table 7
CO_2 and CO_{2eq} emissions factors by source for low-load transient operation (brake-specific g/kW-h). Where CO_{2eq} includes CO_2 and CH_4.

LLT operation	DO drilling				DF drilling				DNG drilling			
	CO_2		CO_{2eq}		CO_2		CO_{2eq}		CO_2		CO_{2eq}	
	Ave.	Std. Dev.	Ave.	Std. Dev.	Ave.	Std. Dev.	Ave.	Std. Dev.	Ave.	Std. Dev.	Ave.	Std. Dev.
Exhaust	678.3	51.7	678.7	51.9	852.8	41.8	1292.4	115.1	1420.6	72.6	1459.6	78.1
Crankcase	1.84	0.15	1.92	0.18	2.25	0.11	39.3	13.8	N/A			

during DF LLT operation (right). It is seen that in both cases, crankcase emissions contributed only a little over 2%, which is similar to values presented elsewhere [45,49]. Exhaust CH_4 emissions tended to be lower during LLT operation.

While DF operation had high levels of CH_4 slip, the DNG engines saw almost no CO_{2eq} emissions from CH_4. Fig. 10 shows the average exhaust CO_{2eq} emissions from all fueling types in terms of CH_4 and CO_2 – during SS operation on a brake-specific basis. See Table 6 for tabular SS data and Table 7 for data during LLT operation. The only emissions from the DNG engines came from the exhaust as the engines had closed crankcases. Unlike trends in literature [21,35,36], DF operation of both drilling and hydraulic stimulation engines tended to increase CO_2 emissions – about 15%. DF GHG emissions were 2.2 and 1.65 times higher than DO and DNG, respectively. DO and DNG GHG emissions were almost entirely due to CO_2 at 99.9% and 98.4%, respectively. DNG CO_2 emissions were 1.3 times higher than DO operation.

As mentioned earlier, models such as *GHGfrack* and GREET use a CO_{2eq} emissions factor for diesel fuel of 0.269 kg/kW-h LHV where CO_2 contributed 0.264 kg/kW-h LHV [13]. The LHV used in their analysis was 35.81 MJ/l while our value was slightly higher at 35.83 MJ/l. Note that their values did not include efficiency as those losses were accounted for in emissions and activity factors of *GHGfrack*. Our fuel specific CO_2 emissions for diesel fuel were 0.26792 kg/kW-h LHV with total CO_{2eq} of 0.26799 kg/kW-h LHV. When DF emissions were analyzed with this method their CO_2 emission were 0.1965 kg/kW-h LHV, while their CO_{2eq} emissions were 0.3876 kg/kW-h LHV due to CH_4 slip. DNG engines had CO_2 emissions of 0.1913 kg/kW-h LHV and CO_{2eq} of 0.1945 kg/kW-h LHV. Methane emissions were low for DNG with properly operating TWC and closed crankcase systems and thus they obtain an advantage over both DO and DF from this perspective.

Although the DNG engines had fewer GHGs and less CH_4 slip than DF, they still saw much lower efficiencies due to the nature of their operation. Engines 5 and 6 were rich-burn, throttled engines that resulted in lower efficiencies than the lean-burn diesel or DF engines. In addition, as shown in Table 1, the CRs of the SI engines were lower which is also indicative of lower thermal efficiency [27]. Increasing the CR of the SI DNG could improve efficiency but such increases would be limited based on fuel quality and knock limits [61]. Fig. 5 showed that the average fuel efficiency for DO and DF operation was 38% and 26%,

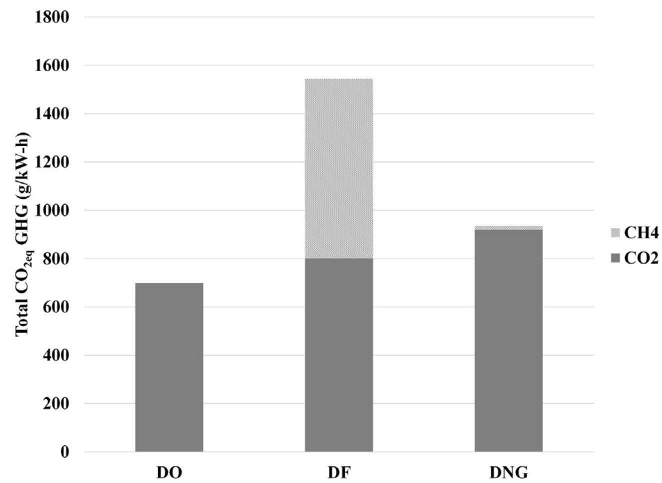

Fig. 10. Average CO_{2eq} GHG emissions by fueling type for SS operation – average from all engines, See Tables 6 and 7 for tabular values for both SS and LLT operation.

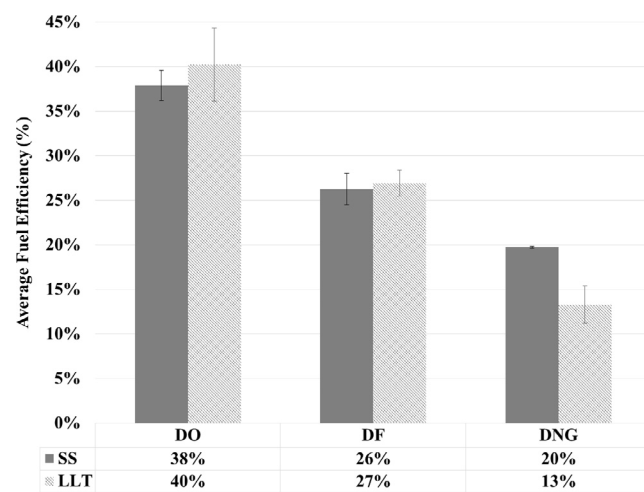

Fig. 11. Fuel efficiency by fueling type and operation.

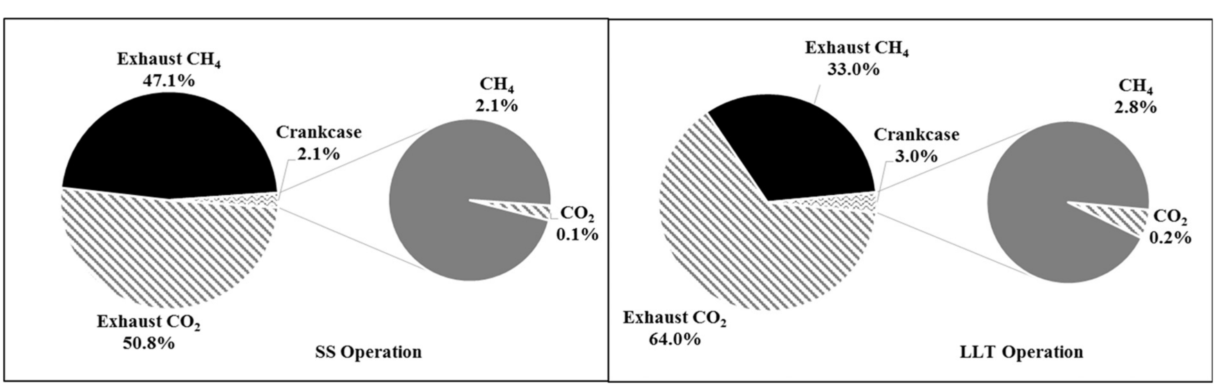

Fig. 9. DF GHG emissions contributions for SS (left) and LLT (right) operation.

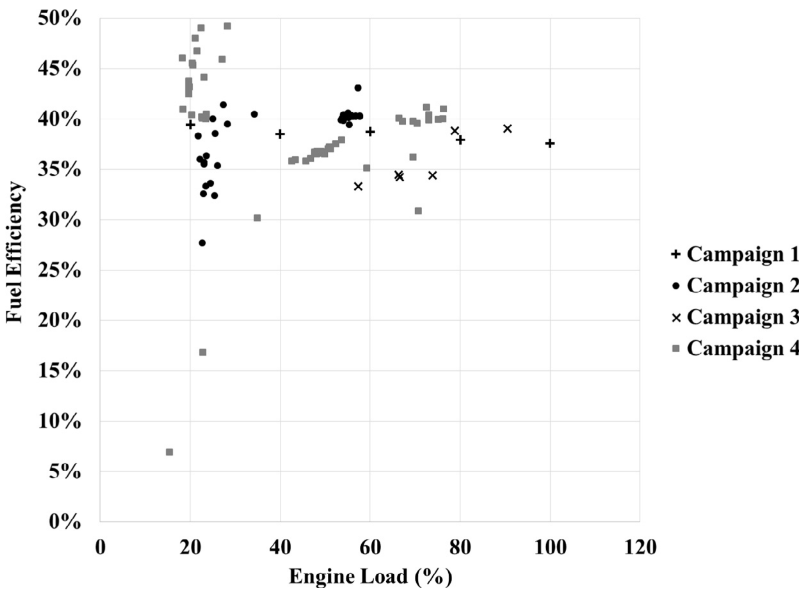

Fig. 12. Un-averaged fuel efficiency as function of engine load for DO operation.

respectively. The average DO fuel efficiency (38 ± 2%) matches well with the range of 36–42% presented in literature [12]. The average fuel efficiency of the DNG engines was only 20% during SS operation. A summary of the three fueling efficiencies is shown in Fig. 11 for both SS and LLT operation. The fuel efficiency of DO operation was 12% and 18% (absolute) higher than DF and DNG, respectively. Note that for DO and DF engines (unthrottled), engine load did not significantly affect efficiency. However, fuel efficiency of DNG engines (throttled) was only 13% during LLT compared to nearly 20% during SS operation.

Diesel engine efficiency is typically impervious to load and Figs. 12 and 13 show the efficiency as a function of load for DO and DF operation. Note that DF operation did not tend to affect this trend. Fig. 14 provides granular data for both SI DNG engines. It shows that efficiency decreases as load decreases due to throttling losses. Note for Figs. 12 and 13 the y-axis is scaled to 50% while for Fig. 14 it is scaled to 25%.

DNG engines required the most fuel energy to produce equivalent power levels of DO and DF operation. However, industry may still prefer these engines in the future due to potential cost savings. Further savings may be realized by avoiding the oversizing of engines for a particular application. Data were used from the Energy Information Administration (EIA) to evaluate potential costs of the different fueling types; average 2016 prices were used in the analysis. The price of on-road diesel ($0.61/l) was used, as EIA did not publish data for off road diesel, which could be lower based on applied taxes. The average import prices were used for pipeline NG and liquefied natural gas (LNG), which were $0.07 and $0.13 per cubic meter, respectively. Fig. 15 shows the cost of each type of operation on a brake-specific basis during higher load SS operation, which shows the economic benefits of utilizing NG as a fuel, even with efficiency losses. DNG fueling costs were lower than any other type even if LNG were used. This analysis is highly variable and total operational costs depend on a number of other factors. Note that when accounting for fuel losses the SR decreases which would yield an increase in relative NG fuel prices in $/DLE. Even with the losses in efficiency, the replacement of diesel fuel with NG provided economic benefits. Fueling costs were 1.8 and 5.3 times less than DO when DF and DNG were used with pipeline prices, respectively. Further research should focus on CH_4 catalysts, closed crankcase operation, and optimization of DF technologies to ensure that emissions reductions and the full climatic benefits from using NG are obtained. Note that the costs for DF with pipeline NG have the same cost as DNG with LNG.

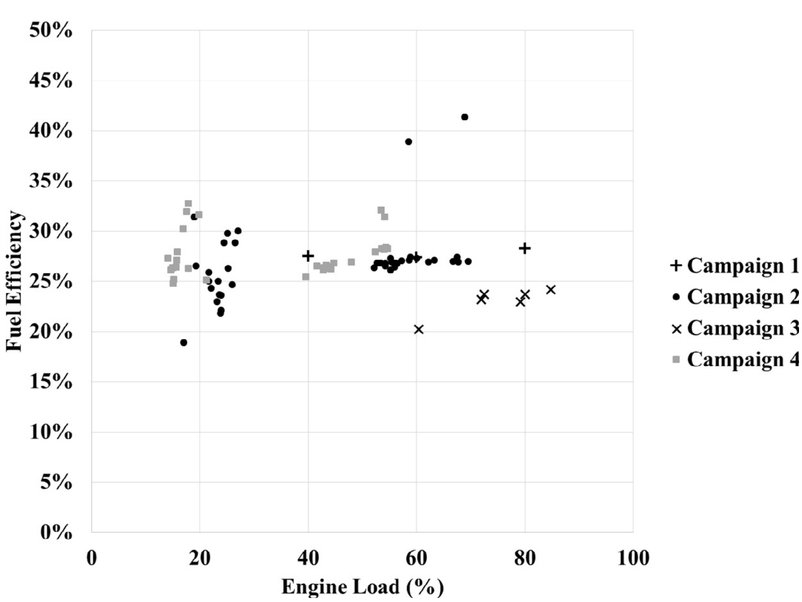

Fig. 13. Un-averaged fuel efficiency as function of engine load for DF operation.

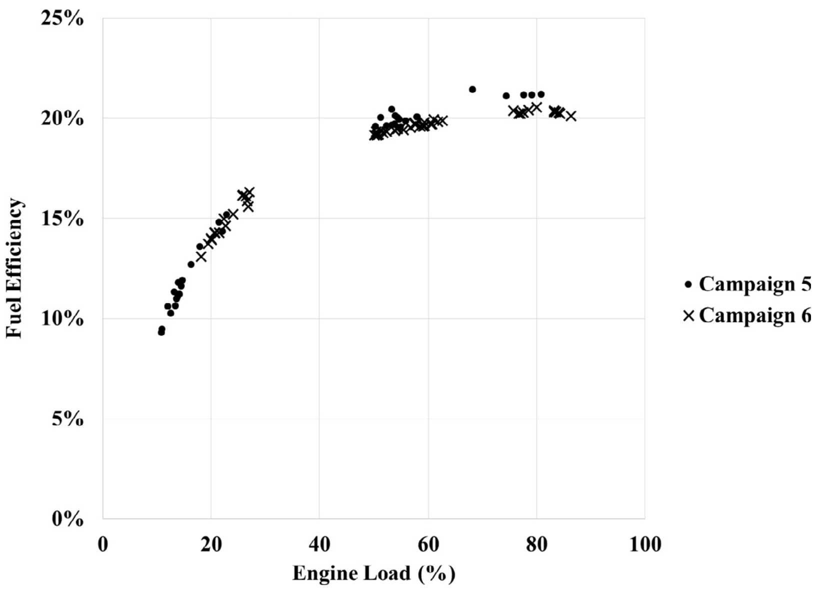

Fig. 14. Un-averaged fuel efficiency as function of engine load for DNG operation.

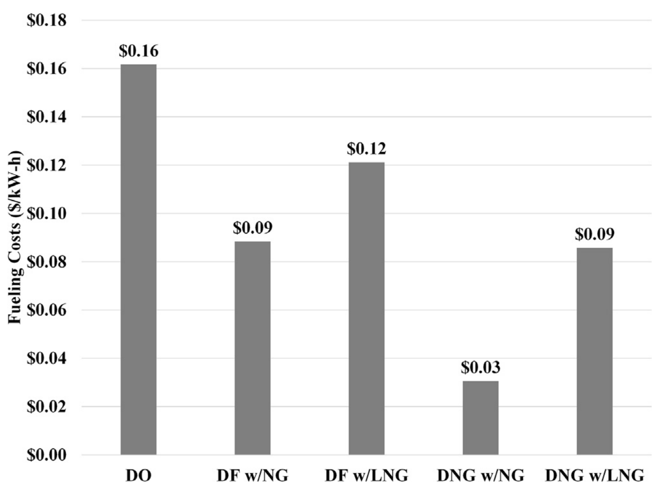

Fig. 15. Brake specific fueling costs by operation and fuel type, evaluated under field operating conditions.

Also note this analysis only includes the fuel costs and does not consider other cost factors such as NG processing equipment necessary for onsite processing or equipment rentals for LNG (tank rentals and vaporizers).

As mentioned earlier, Vafi and Brandt used their model to estimate CO_{2eq} emissions per well for diesel powered prime-movers. Our data did not include the specific granularity of drilling data necessary for the *GHGfrack* model but we did have enough activity data for a specific Marcellus shale well to estimate CO_{2eq} emissions for comparison with their estimated values. In addition, their model included N_2O, which we excluded. Their emissions per well were dominated by fracturing engine emissions which ranged from 47 to 75% (Bakken and Eagle Ford) [12] and our fracturing engines were slightly higher at 76.9% (Marcellus). The estimated emissions for an Eagle Ford well ranged from 419 to 510 metric tons of CO_{2eq} per well [12]. For the Marcellus well, we showed total CO_{2eq} emissions of nearly 983 metric tons per well. Our higher values could be due to different operation per shale play along with other variables not accounted for such as comparison of estimated and actual fracturing fleet size, fracturing stages, well bore, and total well length. Jiang et al. completed a GHG estimate for a Marcellus Shale well during pre-production, which included site preparation and well completion – beyond our system. They estimated GHG emission of 5500 metric tons with the main contributor being well completion [62]. Tables 6 and 7 present a summary of data (emissions factors) that could be used in future inventory analyses.

4. Conclusions

To reduce fuel costs, the unconventional well development industry is investing in DF conversion kits and DNG engines to power directional drilling rigs and hydraulic fracturing engines. Exhaust and crankcase emissions and fuel consumption data were recorded during six separate in-use campaigns for four different DF engine and conversion kit configurations and two DNG engines while the engines were being operated in revenue service. Both exhaust and crankcase emissions, as well as fuel consumption data were recorded from DO, DF, and DNG operating modes. The average DF SRs calculated as advertised were 70% during SS operation, however, when corrected for lost CH_4 the average was 58%. The average CH_4 loss rate during DF operation was 21.8% during hydraulic fracturing operation and 14.3% during SS drilling operation and these values were similar to on-road vehicles. These methane losses contributed significantly to the GHG profiles of the DF engines. The GHG emissions of DF operation were 1.65 and 2.2 times higher than DNG and DO operation, respectively. Of these GHG emissions, over 47% were due to exhaust CH_4 and just over 2% were due to CH_4 from the crankcase of DF engines. The GHG emissions from DO and DNG engines were almost exclusively due to exhaust CO_2. The absolute fuel efficiency of DO operation was 12% and 18% higher than DF and DNG, respectively. Even with the losses in efficiency, the replacement of diesel fuel with NG provided economic benefits. Fueling costs were 1.8 and 5.3 times less than DO when DF and DNG were used with pipeline prices. Further research should focus on CH_4 catalysts, closed crankcase operation, and optimization of DF technologies to ensure that emissions reductions and the full climatic benefits from using NG are obtained. With these new emission rates, emission models such as *GHGfrack* and others could implement new emissions factors to address the evolving landscape of drilling and hydraulic fracturing engines.

Author information

Dr. Derek Johnson is a research assistant professor at West Virginia University (WVU) conducting research focused on emissions associated with the use of natural gas a fuel for internal combustion engines. **Mr. Robert Heltzel**, MSME, and **Mr. Mahdi Darzi**, MSME, are graduate research assistants at WVU's Center for Alternative Fuels, Engines, and Emissions working towards their doctoral degrees. **Dr. Andrew Nix** is an assistant professor at WVU conducting research on natural gas reciprocating engines and gas turbines. **Dr. Nigel Clark** is a professor at WVU and holds the George Berry Chair of Engineering. He has extensive experience alternative fuels with specific focus on natural gas engines and vehicles.

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