Air Emissions Characterization and Management

For Natural Gas Hydraulic Fracturing Operations

In the United States

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AACOG	Alamo Area Council of Governments
BHP	Brake horsepower
BPM	Barrels per minute
BSFC	Brake-specific fuel consumption
CAA	Clean Air Act
CARB	California EPA, Air Resources Board
CH_4	Methane
CI	Compression Ignition Engines
CO	Carbon monoxide
CO_2	Carbon dioxide
CSM	Conceptual site model
DF	Engine Deterioration Factor
DEP	Department of Environmental Protection
EF	Emission Factor
EIA	Energy Information Administration
EPA	Environmental Protection Agency
E&P	Exploration and Production
GHG	Greenhouse gas
GHGRP	Greenhouse Gas Reporting Program
HAP	Hazardous air pollutant
HC	Hydrocarbon
HP	Horsepower
LF	Load Factor
LFA	Load Factor Average
NO_x	Nitrogen oxides
NTEL	Not to Exceed Limits
O&G	Oil and Gas
OT	Operating time
PM	Particulate matter
RPM	Revolutions per minute
SO_2	Sulfur dioxide
SOC	Sources of contamination
TAC	Texas Administrative Code
TCEQ	Texas Commission on Environmental Quality
VOC	Volatile organic compounds

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ABSTRACT

Advanced petroleum and natural gas production technologies are increasingly used to help meet the demand for energy in both the United States and globally. As conventional resources become more scarce, research and innovation by the oil and gas industry has resulted in techniques for tapping unconventional resources, including hydrocarbons trapped in shale formations found in a number of locations throughout the United States. A key technology for accessing such resources is hydraulic fracturing (fracking), which has transformed natural gas production over the past several years and is also being applied for oil production. These new energy supply technologies also bring new environmental management challenges. Among the issues of concern are the air pollution emissions from fracking operations and whether they can potentially impact air quality at well sites and in surrounding communities.

A significant opportunity exists to improve the sustainability of energy production by reducing the air emissions from fracking operations. This Master's Project focuses on the characterization and modeling of these air emissions to help improve environmental management efforts by the industry and to inform the application of regulations for guiding efforts to reduce emissions. The emissions addressed include criteria air pollutants and their precursors. The work involved identifying major sources of emissions during fracking operations, evaluating current models used for air emissions characterization, and developing refinements to the models to enable better emissions management. The project team travelled to a well site and to testing facilities to learn about operations in two different shale formations and to gather data needed to improve emissions characterization. These visits enabled the team to gain a deeper understanding of the nature of fracking equipment, operations and air emissions test protocols.

The project results include an improved characterization of air emissions from equipment used in fracking, specifically for the high-power diesel frac pumps that were found to be responsible for the largest portion of emissions. The project also developed recommendations for improving the existing air emissions models for purposes of regulatory reporting and compliance, and also for potential ways to decrease air emissions from fracking operations.

INTRODUCTION

In a world where access to many forms of reliable and affordable energy is critical to economic growth and social welfare, the environmentally sensitive development of unconventional resources, such as shale gas, is crucial for shaping sound energy systems. Although forecasts of various energy agencies predict that natural gas will be an important energy resource during the coming decades that future hinges critically on the successful development of unconventional resources. Such development is possible due to the technological advances in operational techniques such as horizontal drilling and hydraulic fracturing. Applied together, these technologies enable hydrocarbons (such as natural gas) to be produced in commercial quantities from shale formations and subsequently used directly or transformed to other forms of energy such as electricity. Displacing coal-based electric generation with natural gas can be beneficial for reducing a number of environmental impacts including both criteria air pollution and greenhouse gas emissions.

Hydraulic fracturing (fracking) involves the high pressure injection of a mixture of water, sand and chemicals, to create fissures or fractures in a tight shale formation. These fractures lead to an increase in the flow of natural gas and other hydrocarbons from the formation to the well; without such technologies, these tapping reserves would not be economically feasible to produce. The increase in exploration and production of shale gas has, in turn, resulted in expanded hydraulic fracturing operations. However, this expansion has also increased concerns from federal, state, local agencies, and the public, about related potential environmental impacts on land, water and air, leading to scientific investigations and regulatory action at both state and federal levels.

In view of the concerns surrounding this process, a significant opportunity exists to improve the sustainability of energy production by reducing the air emissions from fracking operations. This is important for both, energy industry officials who seek to lower emissions from energy production as a matter of good stewardship and energy producers and their servicing suppliers who strive for business continuity, while minimizing their environmental footprint. Other stakeholders include the general public, who may benefit if those valuable energy resources are accessible and deliverable with lower environmental impacts. However, realizing the needed improvements requires a thorough continuing evaluation of relevant emissions data and workable guidelines for monitoring and emissions reduction.

One of the targets in our client's operational portfolio is fracking operations and unconventional resources development. Therefore, the client has an interest in obtaining the best possible characterization of air emissions from their operations as well as in assisting energy officials with the development of sound guidelines to reduce the potential emissions associated with the operations.

This research focuses on the characterization and modeling of the air emissions from fracking operations to improve environmental management efforts by the O&G industry and to inform the application of regulations for guiding efforts to reduce emissions. With this aim in mind, the project team travelled to a well site and to testing facilities to learn about the operations at two different shale formations (Eagle Ford and Marcellus Shale plays) and to gather data needed to improve emissions characterization. This on-site/field characterization work allowed the team to create a detailed list of the equipment (inventory) and their operating conditions. Together with an evaluation of the applicable government regulations and the current models used for estimating air emissions, this characterization work permitted to the team to better estimate the major sources of emissions from the equipment used in fracking. The emissions analyzed include criteria air pollutants and their precursors for the equipment used, specifically for the high-power diesel frac pumps that were found to be responsible for the largest portion of emissions.

Based on the results from the initial research, the team evaluated air emissions models in two categories: models based on activity levels per source and models based on fuel consumption per source. The team also analyzed the main factors affecting the variability of the resulting air emissions obtained from each model. In an effort to compare our results with others we found that few studies discuss the air emissions resulting from fracking operations, and surprisingly their results are usually based on assumptions and data developed for equipment similar to that used for fracking but used under different operational conditions. The team's work, in contrast, offers results based on real-world field data for fracking operations and characterizations specific to the on-site operations in the shale gas fields studied. The resulting scenarios used for analysis were defined on the basis of a thorough assessment of client's operational records, including client private data that remain confidential for the purposes of this report.

Based on our analysis of the air emission models and given the important role that fracking plays in energy sustainability as well as in our client’s businesses, the team developed recommendations for improving air emissions models that can be used by the client for the purposes of regulatory reporting and compliance. The team also suggested potential ways to reduce the impacts of hydraulic fracturing operations on air quality, as given in the final section of this report.

BACKGROUND

In general, the air emissions involved in fracking operations can include:

1. On-site criteria pollutants and their precursors: carbon monoxide (CO), lead, nitrogen oxides (NOx), ozone, particulate matter (PM), sulfur dioxide (SO_2), volatile organic compounds (VOC);
2. Air toxics and other hazardous pollutants, including fugitive emissions from mixing chemicals, spills and flow-back fluids (which can also include VOCs);
3. Greenhouse gas (GHG) emissions such as carbon dioxide (CO_2) and methane (CH_4).

Sources of these emissions can include combustion engines powering onsite equipment, transportation equipment; underground/downhole sources such as flow-back fluids, fugitive emissions from sand, dust, mixing chemicals, spills or other uncontrolled gas releases.

Our research focuses on several air quality concerns associated with fracking and related activities. Based on the scope of analysis requested by the client, we restricted the investigation to regulated on-site criteria pollutants, especially those from the high-power fracking equipment which is the main source of air emission during fracking jobs. Specifically, we looked at EPA regulations regarding CO, HC, NOx and PM and so did not air toxics and greenhouse gases. Analysis of air emissions for other processes, such as flowback, production, etc, are not addressed in this study; those processes are not within the operational dominion of our client. More detail is provided in the following text.

Hydraulic Fracturing Air Emissions – Conceptual Site Model

To plan the information gathering needed to develop a detailed characterization of the air quality impacts from hydraulic fracturing operations, we constructed a Conceptual Site Model (CSM). CSMs are widely used tools in environmental assessments. The CSM presented in Figure 1 represents the environmental system surrounding hydraulic fracturing operations. It includes the biological, physical and chemical processes that determine the transport and fate of contaminants through environmental media. In this case, we focus on air as the media through which emissions move.

The main components of the CSM represent fracking operational stages. The principal Sources of Contamination (SOC) are described as equipment, chemicals, and fluids that are pumped, returned and produced. SOCs have different likely pathways of environmental transport or migration to ecological and human receptors. These pathways are known as “exposure routes.” Our study area or system boundary as defined by client meetings and site visits includes well site surface sources during the fracturing operation itself.

This diagram illustrates a source-receptor framework as traditionally used for representing the effects of environmental contaminants on human health and ecosystems. For analyzing GHG emissions, a source-receptor framework is not applicable because the environmental concern is the effect on global radiative forcing of increasing atmospheric concentrations of greenhouse gases. We will not analyze these issues because our analysis is restricted to quantification of criteria pollutants rather than GHG emissions.
As highlighted in red in the following model diagram, our research scope is based on “on-site operations,” which includes equipment rig-up and rig-down, chemical mixing and high pressure pumping. The primary SOC is the fracking equipment, which is the dominant source of air emissions during the overall fracking process.

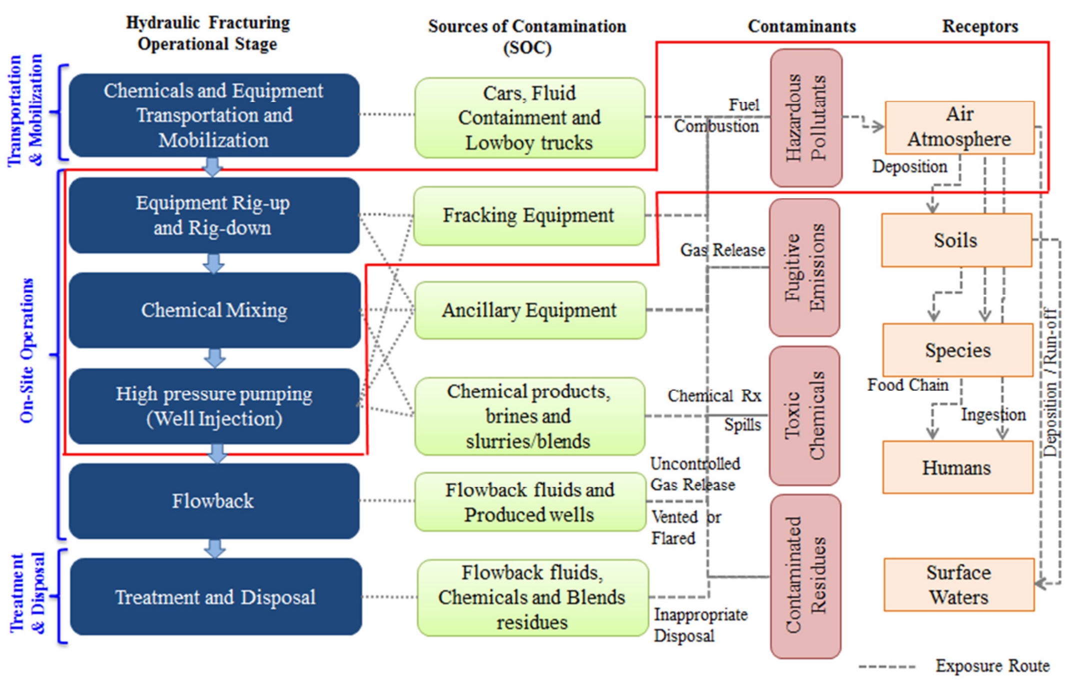


Figure 1. Air Emissions Characterization – Conceptual Site Model

Release of air contaminants happens in several procedures during the fracking process. Figure 2 illustrates the major steps in well development and production processes at a hydraulic fracturing site. The steps outlined in red, namely hydraulic fracturing is the focus of our research.

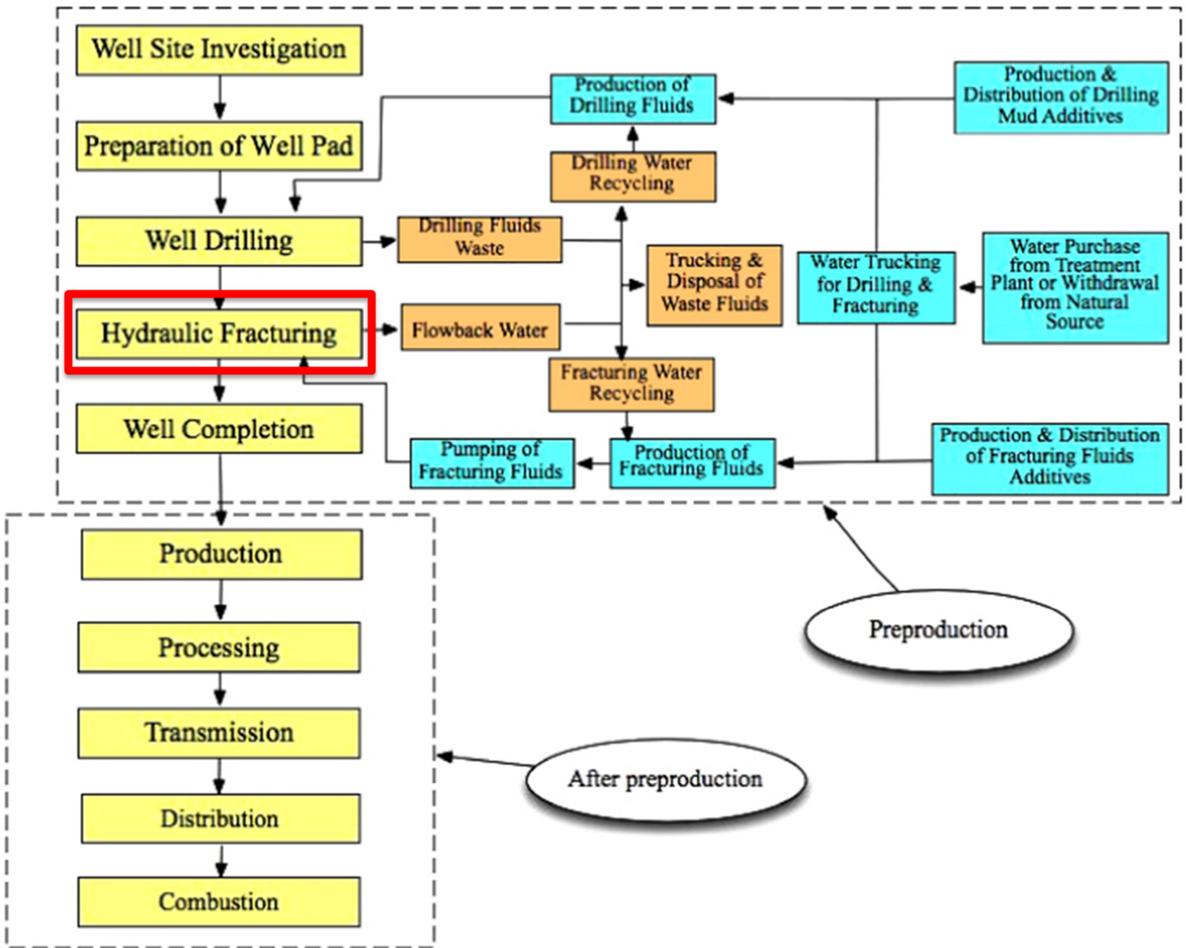


Figure 2. Major process diagram of hydraulic fracturing[1]

Federal regulations of hydraulic fracturing

Hydraulic fracturing has been used in the US oil and natural gas industry since 1940[2]. Although air emissions from domestic oil and gas operations had been regulated for many years, existing rules were largely based on operations and equipment different than what is used for hydraulic fracturing. The recent expansion of fracking operations has prompted federal and state agencies to release new regulations and programs to more specifically address emissions from these operations. Air emissions regulations relevant to fracking operations are mainly set by the U.S. Environmental Protection Agency (EPA). Over the years, the regulations established by EPA have reduced air emissions from oil and natural gas production and so fostered more sustainable practices in the business. On April 17, 2012, EPA updated regulations as required by Clean Air Act for better reducing air emissions from oil and gas operations including fracking [3].

Besides EPA regulations, several other government programs are pertinent to the research and analysis for this project, as summarized here in Figure 3.

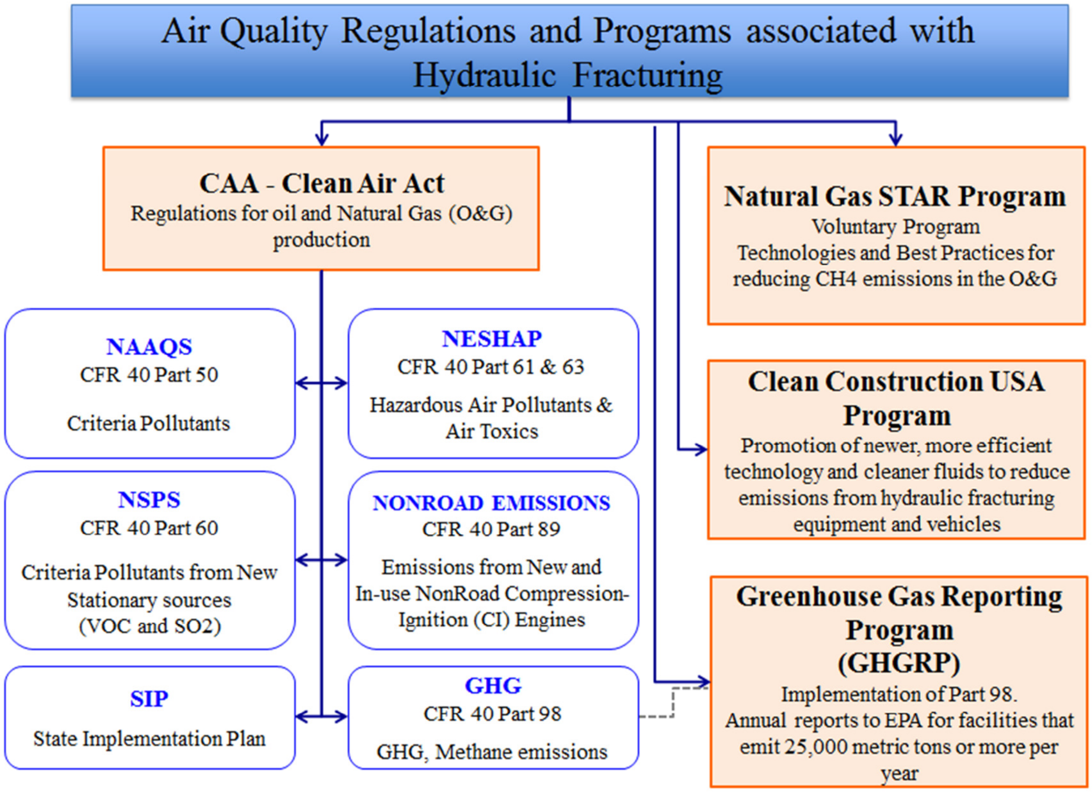


Figure 3. Research Regulatory Framework

Although EPA has overall regulatory authority, application of the regulations is largely left to the states. Moreover, in some cases fracking may have exemptions from major federal environmental statutes, such as the National Environmental Policy Act.[4] However, although the CAA provides authority for regulating emissions from oil and gas wells, EPA has historically written the regulations in such a way that oil and gas wells are not required to obtain a permit for HAP emissions. The CAA is also the basis for recent regulations on reporting greenhouse gas (GHG) emissions through Greenhouse Gas Reporting Program (GHGRP)[5], administered by the EPA. Natural Gas STAR[6] is a voluntary program administered by EPA, with the involvement of partner companies to identify technologies and practices that can cost-effectively reduce methane emissions from the oil and natural gas sector in the U.S. and abroad. The Clean Construction USA is another program through which the EPA promotes newer, more efficient technology and cleaner fuel sources. These programs identify ways in which oil and gas production operations, including hydraulic fracturing can reduce emissions.

State regulations of hydraulic fracturing

The client asked the team to review operations in the Marcellus Shale and Eagle Ford Shale. As highlighted in the Figure 4, these shale plays span a diverse set of state regulatory environments. The Marcellus Shale is located in the eastern US and spans Maryland, New York, Ohio, Pennsylvania, Virginia and West Virginia. The U.S. Energy Information Administration (EIA) divides the Marcellus into an Active Area and an Undeveloped Area[7]. Most activity is in the active area, which to date is mainly located in West Virginia and Pennsylvania. While the Eagle Ford Shale is located entirely in Texas and so is governed by only one state's regulations, whereas we have to consider both West Virginia and Pennsylvania regulations for the Marcellus Shale. As seen in Figure 4, some shales are primarily liquid (oil) plays and others are gas; although the Eagle Ford is classified on this map as a liquid play, actually it produce natural gas as well[8]. The air emissions as considered here can occur from fracking operations designed to produce either liquids or gas.

In general, states are relatively free to administer their own regulations as long as they follow the minimum requirements of applicable federal regulations. Based on their different circumstances, different states may apply the regulations through programs of greater or lesser effective degrees of stringency. This variability in approach adds complexity to the regulatory process. Some states have specific rules related to hydraulic fracturing, while others regulate it solely under their general oil and gas permitting requirements[9]. Some states are reluctant to permit fracking because of local concerns about potential harmful effects. For example, in New York, a moratorium to suspend the issuance of new permits for natural gas or oil drilling involving hydraulic fracturing is in place[a,b], until more conclusive scientific evidence that the fracking operations, especially the drilling technologies would not affect the underground water supply or public health and safety.

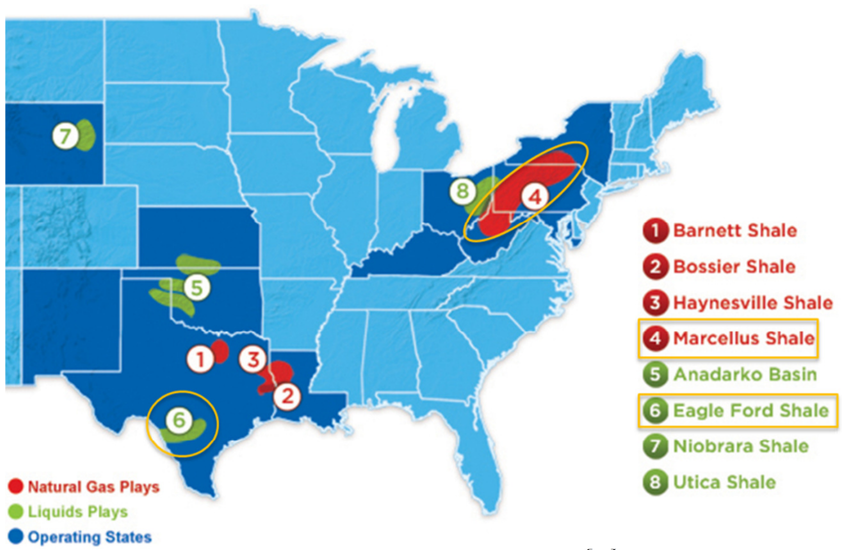


Figure 4. National shale Plays [10]

Pennsylvania

In Pennsylvania, the Department of Environmental Protection (DEP) administers regulations pertinent to oil and gas drilling in the state. No person is allowed to drill a well unless they obtain a permit from the DEP[11]. The DEP may deny a permit application if "the issuance of such permit would result in a violation of the [Pennsylvania Oil and Gas Act] or any other applicable environmental statute, rule, or

[a] Assembly Speaker Sheldon Silver and Environmental Conservation Committee Chair Robert K. Sweeney announced legislation to "suspend the issuance of new permits for natural gas or oil drilling involving hydraulic fracturing, known as hydrofracking, until May 15, 2011"

[b] On March 6, 2013, Speaker Silver announced an intent to "pass legislation that would suspend the issuance of certain types of natural gas drilling permits in the State of New York until May 15th of 2015

regulation"[12]. In the Marcellus Shale, for example, the DEP requires applications for drilling permits to include a mandatory plan for water withdrawal and disposal[13].
Pennsylvania does not have specific regulations on air emission thresholds for fracking and so EPA regulations govern the situation in the state, as indicated in Table 1.

<u>West Virginia</u>

West Virginia requires prior notice from fracking industry to people living nearby to warn of potential emission[14]. It also ensures that land owners are notified of hydraulic fracturing. In July 2011, the state filed an emergency rule with the Secretary of State's Office to increase the DEP's regulatory "oversight of horizontal well development in the state" [15]. The rule was intended to help better regulate increased oil and gas activity in the state. However, much like Pennsylvania, West Virginia has few regulations regarding air emissions thresholds from hydraulic fracturing, and so we consider EPA regulations as the default.

<u>Texas</u>

Texas has been the state with the greatest number of natural gas fracturing fields. In the Texas Administrative Code (TAC) specifies sections of the Code of Federal Regulations which oil and gas field operators are required to follow. [16] The TAC stipulates that the National Primary and Secondary Ambient Air Quality Standards as promulgated pursuant to section 109 of the Federal Clean Air Act, as amended, will be enforced throughout all parts of Texas[17]. Given the variability of the many oil and gas companies operations and conditions, in Texas, the state has not attempted to issue regulations with emission thresholds more specific than those given by EPA.

<u>California</u>

Besides the states above, the group also took a look at California, since some fracking operations are also underway in the state. California had been approving new non-road diesel engines that meet the EPA standards since 1992, starting with the Tier 1 standards. More recently, however, on December 9, 2004, the state's air board adopted a fourth level of stringency, the Tier 4 emission standards, which require engine manufacturers to "meet after-treatment-based exhaust standards for particulate matter (PM) and NOx starting in 2011 that are over 90 percent lower than current levels, putting off-road engines on a virtual emissions par with on-road heavy-duty diesel engines".[18] The Tier 4 standard for nonroad diesel engines greater than 750 horsepower will come into formal effective in 2015[19].

<u>Regulations summary</u>

Table 1 summarizes the relevant air emissions regulations and particular standards that apply to frack pumps (Tier 1 and Tier 2); greater detail on the EPA non-road standards and their interpretation can be found in Appendix A. Note that the Tier 1 regulations has separate NOx and HC standards limits, but that the Tier 2 program regulates only the sum of NMHC+NOx is regulated.

			EPA		PA	TX	CA		WV
Regulation			Clean Air Act and the National Environmental Policy Act		The Pennsylvania Oil and Gas Act	Texas Administrative Code	Clean Air Act Amendments		West Virginia DEP
Governing			Requirements for equipment that may vent or leak VOCs or air toxics		Rely on EPA regulations	Rely on EPA regulations	Rely on EPA regulations with exceptions, some are more strict		Rely on EPA regulations
Air emission of non-road diesel engine standards	Pollutant (g/bhp·hr)		Tier 1	Tier 2	(b)	(b)	Tier 1	Tier 2	(b)
		PM	0.54 (0.4)	0.20 (0.15)			0.54	0.20	
		NOx	9.2 (6.9)	-	(b)	(b)	9.2	-	(b)
		CO	11.4 (8.5)	3.5 (2.6)	(b)	(b)	11.4	3.5	(b)
		NMHC +NOx	-	6.4 (4.8)	(b)	(b)	-	6.4	(b)
		HC	1.3 (1.0)	-	(b)	(b)	1.3	-	(b)

Table 1. Summary of air emissions regulations applicable for hydraulic fracturing equipment at federal and state level.

a. The engine type we are investigating are mostly Tier1 and Tier2 types.
b. Same as EPA standard, and can only be more strict.
c. TAC (Texas Administrative Code) regulations should be relyed on EPA regulations, however exemptions may be possible because of the tenuous relationship between Texas and Federal.
d. Numbers in parenthesis are voluntary standard levels.

Air Emissions Characterization Model Overview

Models are integral components of conceptualizing and understanding how mathematical or physical systems work. Models are needed to characterize air emissions from hydraulic fracturing activities and the choice of models depends on the objectives and the types of input data that will be available for analysis.

Models have a long history of helping to explain scientific phenomena and of predicting outcomes and behavior in settings where empirical observations are limited or not available. The use of models has resulted in great advances in scientific understanding and in improvements in a wide array of endeavors. However, by their very nature, all models are simplifications and approximations of the real world. Many quantitative characterization methods are based on interpreting data from computer models.

It is important to note that: models are a simplification of reality that can be compared to maps. Road maps indicate certain aspects of reality (for example, roads of a certain size) and not others (for example, sewer lines, power lines, and buildings). No one map can include all aspects of reality and, similarly, all models, no matter how complex, are constrained by basic assumptions, structure, and uncertainties. Model development involves the definition of model objectives, conceptualization of the problem, translation into a computational model, and model testing, revision, and application. Although almost all model development follows these general steps, models designed for regulatory purposes are subject to constraints in addition to those for models developed strictly for research.

We reviewed the models currently used by regulatory officials as illustrated in Figure 5. These models fall into broad categories according to source of air emissions: 1) transportation emissions from the transportation of product and production materials and 2) site-specific emissions from components and equipment used in operations. The models also address the chemical characteristics of the emission of concern.

Aspects of a site are also necessary for characterizing overall emissions from hydraulic fracturing, enabling the model to be used in ways that account for variations among well pad or drill sites. Key inputs for this aspect of modeling are: time-step considerations such as daily, monthly, annual or real-time measurements.

Next, models account for variation in types of pollutants and their residence time within the atmosphere. The calculated quantities of each type of pollutant are computed individually by multiplying the nominal emissions rates by specific deterioration factors.

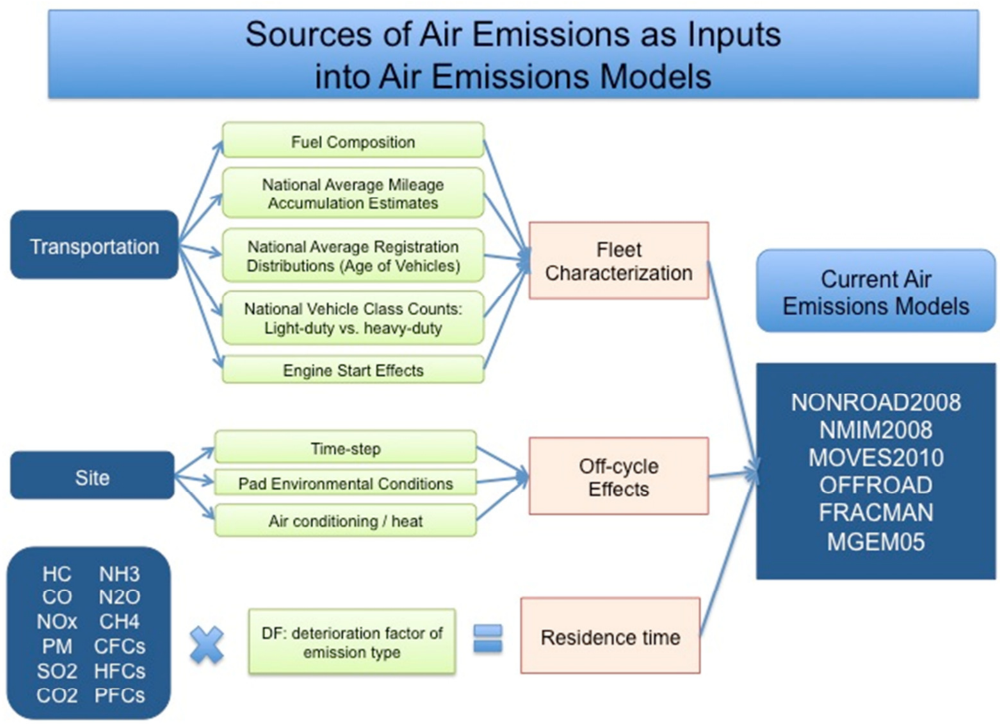


Figure 5. Sources of Air Emissions as Inputs into Air Emissions Models

ANALYSIS

Models used for our analysis

From the public models, the O&G industry has been using mainly EPA methods to estimate total emissions from hydraulic fracturing equipment. The models chosen for analysis in our study were classified into two main categories: the models that calculate emissions *based on activity level per source* and, the models that calculate emissions *based on fuel consumption per source*. Both of these categories, are focused on nonroad or offroad sources, which is the equipment category that encompasses the hydraulic fracturing equipment.

Air emissions models *based on activity level per source* are models that, for calculating emissions, take into account emissions factors and, defined time and set of conditions per source analyzed. These defined time and set of conditions, consistent with EPA studies[20], are called per-source usage rate and activity level. The product of the hours of use, the average rated horsepower, and the load factor is referred to as the *per-source usage rate.* The product of the population and the per-source usage rate is referred to as the *activity level.* In other words, in these models the emissions can be estimated by multiplying the operating hours by their engine rating, equipment load factor and respective emission factors.

There are many models available, including the CalEEMod (the State of California's emission calculation for VOCs and HAPs); the TCEQ model (the Texas Commission on Environmental Quality's emission calculations for VOCs and HAPs); California's OFFROAD 2007 for any type of emissions. These models may use different approaches to estimate activity levels, i.e. different load factors and total power output, and also use different emission factors. However, most of these emission models follow the same mathematical basis for their emissions calculations. An overarching model across the industry in the United States is the EPA AP-42 model, which is widely used for national emissions inventories and permitting. Our research encompasses the analysis of the three air emissions models that have been most widely used: the EPA AP-42, a modification of this model using average load factors and the EPA NonRoad Model, as listed in Table 2.

Nonroad engine emissions are usually expressed as tons per year (tpy), except when emissions are adjusted for seasonal usage patterns to reflect tons per summer day (tpsd) or tons per winter day (tpwd). For the purpose of this study, we have adapted the formulas for each model in the table above to fit our period of usage analyzed, namely, emission per hydraulic fracturing job rather than annual emissions. The operating time factor (OT, total hours per fracturing job) in the model formula enables one to extrapolate the results to estimate annual emissions per shale area if needed. Also, in order to be consistent in the units used, we have removed some coefficients, i.e. 0.002205-conversion factor from grams to pounds and we are providing the EFi in lb/hp-hr instead of g/hp-hr.

Model 1 EPA AP-42 (Uses emissions factors from AP-42 and assumes 100% Load Factor in estimations)	Model 2 EPA AP-42 with LFA (Uses emissions factors from AP-42 and activity levels, which includes Average Load Factors)	Model 3 EPA NONROAD2008 (Uses Adjusted Tiered engines exhaust emission factors and Average Load Factors)
$\boldsymbol{Ei = EF_i \times [PO \times (LF/100) \times OT]}$ Where, Ei = Total emissions of Pollutant (lb /job) EFi = Pollutant emission factor (lb /hp-hr) PO = Power output of the equipment engine (hp) LF = Load Factor (% of Maximum Power) 100 = Factor for converting percent to a fraction OT = Hours of use (hrs/job)	$\boldsymbol{Ei = EF_i \times Activity\ Level}$ $\boldsymbol{Ei = EF_i \times \{per\ source\ usage \times Population\}}$ $\boldsymbol{Ei = EF_i \times \{[P \times (LFA/100) \times OT] \times N\}}$ Where, Ei = Total emissions of Pollutant i (lb/job) EFi = Pollutant i emission factor (lb/hp-hr) P = Brake horsepower of the equipment engine (hp) LFA = Average Load Factor $\{\sum_1^n(\%\ of\ Maximum\ Power \times OT\ (hrs)/Total\ hrs\}$ 100 = Factor for converting percent to a fraction OT = Operating time (hrs/job) N = Number of Units	$\boldsymbol{Ei = EF_{i\,Adj} \times [RP \times (LFA/100) \times OT] \times Pop}$ Where, Ei = Total emissions of Pollutant i (lb/job) EFi = Pollutant i Adjusted emission factor (lb/hp-hr). See Appendix C. PO = Power output of the equipment engine (hp) LFA = Average Load Factor $\{\sum_1^n(\%\ of\ Maximum\ Power \times OT\ (hrs)/Total\ hrs\}$ 100 = Factor for converting percent to a fraction OT = Operating time (hrs/job) Pop = Equipment Population (Units)
* i = Pollutants of interest: NOx, VOC/HC, CO and PM.		

Table 2. Air Emission Models based on activity level per source

For the purpose of consistency, we have used these three models as a tool to predict emissions of hydrocarbons, carbon monoxide, oxides of nitrogen and particulate matter from the equipment analyzed and for the scenarios described as "typical operational conditions" at the Eagle and Marcellus Shale plays.

Air emissions models *based on fuel consumption per source* are models that includes fuel consumption rates or fuel usage as an input in the mathematical model. In Table 3 below, two models are presented. In Model 1, when the fuel consumption rate data is not available the emission can be calculated by converting overall fuel usage into a power output (i.e., horsepower-hours). Actual emissions of pollutants for the specific equipment type can be calculated by multiplying the power output by the applicable emission factors, which are given on a per horsepower hour basis.[21] In Model 2, the emissions are calculated in a similar fashion, the difference is that fuel consumption rate data are available and can be multiplied by the operating time to compute the total fuel used per job. As discussed for the previous models, we adapted the formulas to fit our period of usage analyzed, which is emission per hydraulic fracturing job.

There are both two constants in these models; one is the fuel density, which is 7.11 lb/gal modified to suit the model. The other is the typical brake-specific fuel consumption (BSFC, lb fuel/hp-hr) for the equipment, which enables the calculation to be consistent with the input data units to yield result units of pounds of pollutant emitted per job (lb/job).

Model 1 Converting Fuel usage into a power output, hp-hr – when fuel consumption rate is not available	Model 2 Using Fuel Consumption Rate
$Ei = EF_i \times [(FU \times FD)/BSFC]$ $Ei = EF_i \times [FU \times 7.11/BSFC]$ Where, Ei = Total emissions of Pollutant i (lb i/job) EFi = Pollutant i emission factor (lb i/hp-hr) FU = Fuel Usage (gal fuel/job) FD = Fuel density (lb fuel/gal fuel; default value for diesel: 7.11) BSFC = Typical brake-specific fuel consumption for the equipment (lb fuel/hp-hr)	$Ei = EF_i \times [(FC \times FD \times OT)/BSFC]$ Where, Ei = Emissions of Pollutant i (lb i/job) EFi = Pollutant i emission factor (lb i/hp-hr) FC = Fuel consumption rate (gal fuel/hr) FD = Fuel density (lb fuel/gal fuel; default value for diesel: 7.11) OT = Operating time (hrs/job) BSFC = Typical brake-specific fuel consumption for the equipment (lb fuel/hp-hr)

Table 3. Air Emission Models based on fuel Consumption per source

According to EPA nonroad vehicles and equipment model, the variable "fuel consumption" is an average amount of fuel used in a year, e.g., gal fuel/year. In our modified model, we changed the fuel consumption to fuel consumption rate, and the unit is "gal fuel/hr". In the equation on the right in Table 3, the fuel consumption rate is a sum of fuel assumed under different load conditions, taking into account that frac pumps have both pumping mode and reserve power mode. Therefore the fuel consumption rate equation should be:

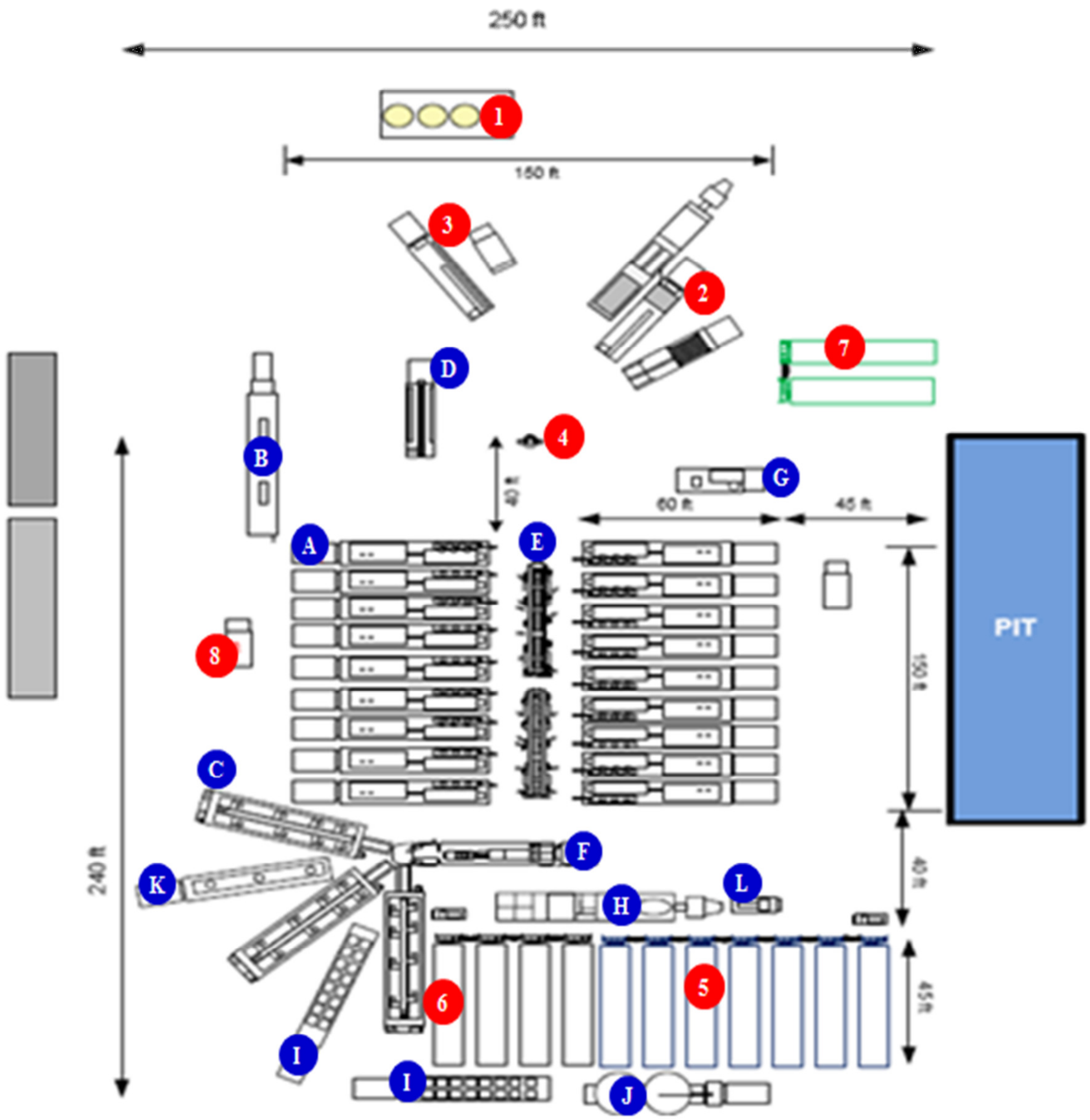
$$FC = \begin{bmatrix} (FC \times LF_{Pumping} \times OT_{Pumping} \times \#Units_{Active\ @pumping}) + \\ (FC \times LF_{Reserve\ Power} \times OT_{Pumping} \times \#Units_{Reserve\ Power\ @pumping}) + \\ (FC \times LF_{Reserve\ Power} \times OT_{Reserve\ Power} \times \#Units_{Reserve\ Power}) \end{bmatrix}$$

In this equation, we consider the variables of Load Factor (LF) under different conditions and number of engines (#Units). To be consistent with the units, the 0.002205 lb/g conversion factor has been removed, and the units of the emissions factor (EF) are lb/hp-hr instead of g/hp-hr. These two models are used to estimate the emissions of hydrocarbons, carbon monoxide, oxides of nitrogen at Eagle Ford and Marcellus Shale Plays and compared with models based on activity level.

Equipment Analyzed

The team took three field trips: 1) to a wellsite in the Eagle Ford Shale; 2) to an equipment parking and maintenance bay and; 3) to an equipment testing bay. The survey and data audit completed during these field trips allowed us to establish the typical equipment set, or fleet, used by the client during its hydraulic fracturing operations. Figure 6 is a picture of the main equipment used during a hydraulic fracturing operation at the Eagle Ford Shale. Figure 7 illustrates a typical equipment layout for the operations also conducted in the same area; the equipment analyzed in this study is listed as items A to L in this figure. On-road emission sources, such as supply trucks, pick-ups, crew vans, fuel trucks, are not part of this research; neither are fugitive emissions due to any potential leaked from valves or pipe/equipment accessories, nor methane or any other possible emissions associated with the fluids flowback or with any other wellsite process/equipment supplied by other parties (i.e. drilling and well completion, perforation or production stage).

Figure 6. Photo of hydraulic fracturing at night in the Eagle Ford Shale.
Source: BHP Billiton Petroleum – The New Era of Shale



Fracturing Service Company Equipment

A. Frac Pumps
B. Data Monitoring and Recording Van
C. Sand Chief (Proppant Loading and Unloading)
D. Boom Truck
E. Frac Missile
F. Frac Blender
G. Casing Pump
H. Hydration Unit
I. Chemical Float
J. Gel Mixer
K. Chemical Transport
L. High Rate Skid

Other Parties Equipment

1. Production Tank
2. Coiled Tubing
3. Wireline
4. Wellhead
5. Frac Tanks – Stimulation Fluid Storage
6. Acid Tanks
7. Flow back Tanks
8. Fueling Truck

Figure 7. Hydraulic fracturing wellsite layout: example for Eagle Ford Shale

Equipment inventories and associated emissions

To focus our analysis, we started with an inventory of the equipment used at a fracking site, including key equipment used in the operations as well as the ancillary equipment required. Key sources of air emissions on a hydraulic fracturing site are: frac pumps; frac blenders; frac control, monitoring and recording unit; hydration unit; sand chief, frac missile: high pressure manifold, chemical float, chemical transport, hose trailer, iron trailer, iron truck and crane, parts trailer, skid, water transfer pump, boom truck and forklift, and the light tower. Tables 4 and 5 below list the types of equipment used in the hydraulic fracturing operations at the Eagle Ford and Marcellus shale, respectively. The potential on-site emissions from the Fracturing Service Company Equipment are categorized into two main categories: 1) exhaust emissions from engines that power the equipment and 2) emissions from dust or particulate matter, e.g., from the loading and unloading of frac proppant (that is sand, as handled by a piece of equipment known as the sand chief) and from chemicals or fluids used for the hydraulic fracturing process. Our research focuses on air emissions from engine exhausts, which is the primary source of emissions from all the equipment present at the wellsite while performing fracking jobs.

		Engine Specifications					
Equipment	**No. of Units**	**No. of Engines/Unit**	**Engine Make/Model**	**Engine Tier**	**Fuel Type**	**Engine Rating (hp)**	**Emissions Category**
Operation Equipment							
Frac Pumps	14	1	Caterpillar 3512C	Tier 2	Diesel	2,250	Engine Exhaust Emission
Frac Blender	1	2	Caterpillar C13	Tier 2	Diesel	475	Engine Exhaust Emission
Frac Control and Recording Van	1	1	Kubota	Tier 2	Diesel	75	Engine Exhaust Emission
Hydration Unit	1	1	Caterpillar C13	Tier 2	Diesel	475	Engine Exhaust Emission
Sand Chief (Loading/Unloading proppant)	2	1	Caterpillar 3054C	Tier 2	Diesel	120	Engine Exhaust Emission and Silica/Dust Emissions
Ancilary Equipment							
Water Transfer Pump	1	1	John Deere	Tier 2	Diesel	384	Engine Exhaust Emission
Boom Truck / Big Forklift	1	1	The emissions associated with this equipment are due to exhaust emissions from the truck engine that mobilizes the truck bed. Crane and forklift have one single engine for mobilization and on-site operations. Those emissions are accounted within the On-road emissions inventory, therefore, are not part of this study.				NA
Iron Truck / Crane	1	1					NA
Frac Missile (Low/High Pressure manifold)	1	1					NA
Chemical Float	1	1					NA
Chemical Transport	2	2					NA
Iron & HoseTrailer	1	1					NA
Parts Trailer	1	1					NA
Skid	1	1					NA

Table 4. Equipment inventory for hydraulic fracturing in the Eagle Ford Shale

Equipment	No. of Units	Engine Specifications					Emissions Category
		No. of Engines/Unit	Engine Make/Model	Engine Tier	Fuel Type	Engine Rating (hp)	
Operation Equipment							
Frac Pumps	16	1	Caterpillar 3512C	Tier 2	Diesel	2,250	Engine Exhaust Emission
Frac Blender	1	2	Caterpillar C13	Tier 2	Diesel	520	Engine Exhaust Emission
Frac Control and Recording Unit	1	1	Kubota	Tier 2	Diesel	75	Engine Exhaust Emission
Hydration Unit	1	1	Caterpillar C13	Tier 2	Diesel	475	Engine Exhaust Emission
Sand Chief (Loading/Unloading proppant)	2	1	Caterpillar 3054C	Tier 2	Diesel	127	Engine Exhaust Emission and Silica/Dust Emissions
Ancilary Equipment							
Water Transfer Pump	1	1	John Deere	Tier 2	Diesel	384	Engine Exhaust Emission
Boom Truck / Big Forklift	1	1	The emissions associated with this equipment are due to exhaust emissions from the truck engine that mobilizes the truck bed. Crane and forklift have one single engine for mobilization and on-site operations. Those emissions are accounted within the On-road emissions inventory, therefore, are not part of this study.				NA
Iron Truck / Crane	1	1					NA
Frac Missile (Low/High Pressure manifold)	1	1					NA
Chemical Float	1	1					NA
Chemical Transport	2	1					NA
Iron & HoseTrailerTrailer	1	1					NA
Parts Trailer	1	1					NA
Skid	1	1					NA

Table 5. Equipment inventory for hydraulic fracturing in the Marcellus Shale

We calculated the total emissions for the complete fleet for a typical operation at the Eagle Ford and Marcellus Shale. The total emissions were estimated using the EPA NONROAD emissions model (Model 3 in Table 2) using the emissions factors for nonroad compression-ignition engines[22]. The total emissions from the hydraulic fracturing fleet revealed that fracture pumps contribute the highest amount of emissions (From 79% to 95% of the total emissions depending on the pollutant; see Figures 10 and 11, below). Also, based on the number of units on-site and the engine size from the equipment inventory above, it is clear that frac pump engines are the dominant source of air emissions and, in turn, are the focus of our work.

Frac Pump Engine Types and Ratings

The biggest engines at the wellsite, especially when comparing with the rating of the other wellsite equipment, are the engines from the frac pumps. They are designed for supplying high-horsepower, hp, during the frac operations and are manufactured mainly by Caterpillar, Detroit (MTU Detroit in North America is currently named Tognum America) and Cummins. These engines are diesel (compression ignition) type. The engines examined in our field trips were all 2,250 hp, and their rating was either B or C.[23] See Appendix D for details about these engine types.

Engine Tier Classification for Emission Standards

Nonroad diesel emission standards vary by engine tier, which depends on the model year and horsepower rating of the engine. Figure 8, shows the nonroad diesel engine emission standards which are being phased in over an 19-year period, culminating in 2015 with Tier 4 final.[24] Further details on the applicable emissions standards are given in Appendix B.

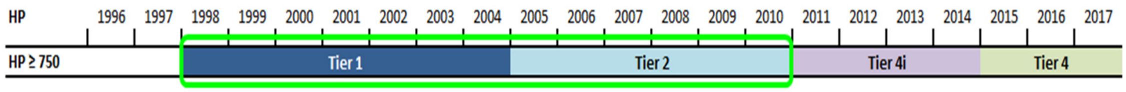


Figure 8. Nonroad diesel engine standards: Emissions Tier by year

As of January 1, 2011, engine manufacturers are required to produce engines certified to the following levels: Engines rated 50 to 74 bhp - Interim Tier 4; Engines rated 75 to 174 bhp: Tier 3 and Engines rated 175 bhp and over, such as the frac pump engines: Interim Tier 4[25], However, these rules only apply to new engines. Existing engines are exempt unless there are some local or state regulations that target them. Our study focused on the existing engines used by our client in their U.S. hydraulic fracturing operations, which are governed by the Tier 1 and Tier 2 standards as highlighted in green in the figure above. However, after reviewing the inventories of the pumps population use to operate at the Eagle Ford and Marcellus Shale specifically, our focus of analysis was limited to the analysis of emissions from Tier 2 frac pumps.

Engine Test Procedures

In order to quantify the exhaust emissions from frac pump engines, manufacturers and the industry uses the ISO 8178 Standard. The ISO 8178 is an international standard designed for a number of nonroad engine applications. It is used for emission certification and/or type approval in many countries worldwide, including the USA, European Union and Japan. Depending on the legislation, the cycle can be defined by reference to the ISO 8178 standard, or else by specifying a test cycle equivalent to ISO 8178 in the national legislation (as it is the case with the US EPA regulations).

For frac type applications, the nonroad engine emissions are measured on a steady-state test cycle known as the D-2 cycle[26]. Table 6, shows a representation of the several steady-state modes and different weighting factors for these cycles. For more details about the test cycles and fuels see Appendix E.

Mode number	1	2	3	4	5
Torque (Engine Load), %	100	75	50	25	10
Speed	Rated speed				
Weighting Factor	0.05	0.25	0.30	0.30	0.10

Table 6. Test cycle for frac pump engines: the D-2 Cycle

This test cycles are used widely to estimate engine emission factors and in turn calculate emissions inventories based on assumed weighted average operating conditions when records of the actual operational parameters are not available. However, this does not mirror the reality of how frac pumps operate. As presented in Table 7, frac pumps at the wellsite do not operate all times, either at the same rated speed (RPM) or load (% load factor). Rather than using averaged emission factors using the weighting factors of Table 6, we developed estimates based on data reflecting typical frac pump operations. This is discussed in more details in the results section.

Scenarios Analyzed

In order to identify the operational parameters that influence air emissions the team gathered and analyzed operational profiles and records from different operations in both of our areas of study. The total power, and therefore the number of frac pump engine units of a given horsepower, required for fracturing can vary from well to well because it depends on the depth, injection rate, surface treating pressure required for fracking the specific targeted underground formation. The number of hours of pumping needed also depends on various parameters: number of fracking stages (#), number of barrels of frac fluid pumped per stage (bbl), frac fluid injection rate (bbl/min), fracking interval (ft). Also, these parameters depend on the type and properties of the shale formation being fractured (i.e., formation resistance).

After operational conditions were understood, data gathered during the field visits was compared with our client's activity records, in order to define our "typical" operational scenarios for each of our shale plays in study. Although every fracking job is different, two illustrative scenarios were defined for modeling. As presented in Table 7, Scenario 1 represents operating conditions in the Eagle Ford Shale and Scenario 2 represents conditions in the Marcellus Shale. Both shale plays use multi-stage fracking, with jobs in the Eagle Ford usually having more fracking stages than jobs in the Marcellus; typical jobs might have 17 vs. 13 stages, respectively. On the other hand, the total frac fluid volume per job is slightly lower in the Eagle Ford compared to the Marcellus, with 127,500 vs. 150,000 barrels, respectively. An average fracking operation in the Marcellus Shale uses a total of 16 frac pumps, of which 14 are active, one is available as ready-reserve power pump and one pump is usually shut down (no emissions associated) but available as a back-up unit in case any of the other reserve pumps are down. In the Eagle Ford Shale, this frac pump set is usually decreased to 14 units, of which 12, 1 and 1 units are active, ready-reserve and back-up, respectively.

	Scenario 1 Eagle Ford	Scenario 2 Marcellus
Job parameters & Activity		
Number of Fracking Stages per Job (#)	17	13
Frac Fluid Volume per Stage (barrels, bbl)	7,500	8,000
Total Frac Fluid Volume per Job (barrels, bbl)	127,500	150,000
Job Average Pumping Rate (barrels per minute, bpm)	80	80
Pumping hours per job (hrs)	27	31
Time at "Reserve power" mode - between Stages (hrs)	51	26
Standby Time (No emissions associated)	20	25
Total Hours per Job (hrs)	98	82
Frac Pump Engine Parameters		
Frac Pumps Horsepower (#)	2,250	2,250
Model Year (Y)	2005-2010	2005-2010
Engine Tier (T1 or T2)	Tier 2	Tier 2
Number of Frac Pumps per Job (#)	14	16
Number of Active frac Pumps per Job (#)	12	14
Number of frac Pumps as "Reserve power" per Job (#)	1	1
Number of back-up pumps per Job (#)	1	1
RPM @ pumping mode (rpm)	1800	1800
Engine Load @ pumping mode (%)	60%	50%
RPM @ "reserve power" mode (rpm)	700	700
Engine Load @ "reserve power" mode (%)	5%	5%
Median Life at Full Load (hrs)	8,000	
Fuel Parameters (Diesel)		
Fuel Usage per Job (gal)	22,100	20,800
Fuel Density (lb/gal)	7.11	7.11
Fuel sulfur (ppm)	14	14
Fuel sulfur weight percent (%)	0.0014%	0.0014%

Table 7. Illustrative operating scenarios at Eagle Ford and Marcellus Shales

Variability of Models and Emissions

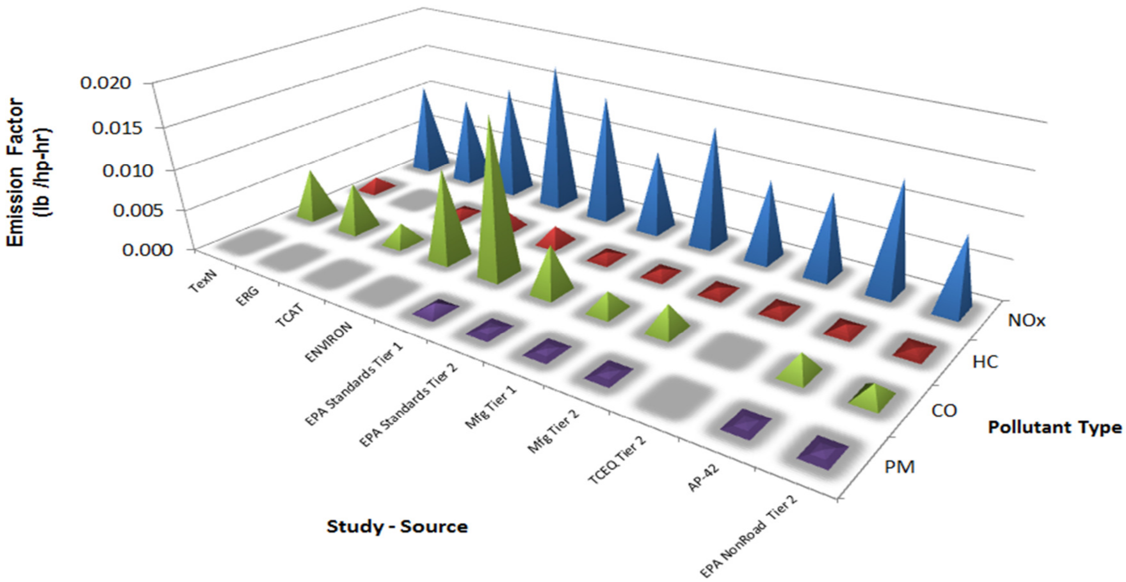
Variability of Air emissions models based on activity levels per source

As presented previously in the model equations in Table 2, air emissions based on activity level per source are generally modeled by multiplying emissions factors and, defined time and set of conditions per source analyzed. When modeling emissions from field equipment, specifically from frac pumps, the input parameters used in each model are generally the same: emission factors, power output of the equipment engine, engine load factor, hours of use (multiplication of the last three is generally called per-source usage rate of the equipment) and the number of units or population (when population is multiplied by the per-source usage rate it is known as activity level of the equipment). The variability of emissions computed under each model depends on the parameter values input to the model. The main factors/parameters to consider when estimating emissions are:

Emission Factors

As defined by EPA, an emission factor relates the quantity of a pollutant released to the atmosphere to a pollution-causing activity. These factors are usually expressed as the weight of pollutant divided by a unit weight, volume, distance, or duration of the activity emitting the pollutant[27]; for fracking pumps these factors are usually expressed in grams or pounds of pollutant emitted per horsepower-hour.

General emission factors are available to the public. In most cases, these factors are simply averages of all available data of acceptable quality, and are generally assumed to be representative of long-term averages for all facilities in the source category. Frac pumps are categorized as nonroad, compression ignition (CI) sources. We compiled emissions factors corresponding to this category from various public sources including manufacturers, EPA and state air emissions studies.[28], [29], [30], [31], [32] As shown in Figure 9, those emission factors can greatly differ between sources, and when they are not locally available, sometimes tiered engine emission standards (NTEL: Not to Exceed limits) are used as emission factors[33]. The extent of the variability that exists, even among similar individual sources such as frac pumps, can depend on engine maintenance, engine age, engine operational conditions (load, speed), combustion temperature, ambient conditions (altitude, humidity), emissions controls installed on the engine (e.g., filters), fuel composition and the type of pollutant. Whenever possible, in order to report more accurate emissions inventories it is highly desirable to develop local emission factors.



	TexN	ERG	TCAT	ENVIRON	EPA Standards Tier 1	EPA Standards Tier 2	Mfg Tier 1	Mfg Tier 2	TCEQ Tier 2	AP-42	EPA NonRoad Tier 2
NOx	0.011023	0.010516	0.013400	0.017637	0.015125	0.009864	0.014467	0.009683	0.010053	0.013400	0.009039
HC	0.001455	Not Available	0.000707	0.002205	0.002137	0.000658	0.000658	0.000510	0.000529	0.000707	0.000368
CO	0.005886	0.005754	0.002470	0.011023	0.018741	0.005754	0.002302	0.003124	Not Available	0.002470	0.001685
PM	Not Available	Not Available	Not Available	Not Available	0.000888	0.000329	0.000296	0.000263	Not Available	0.000208	0.000290

Figure 9. Frac pump engine emission factors from various public sources

The O&G industry has been seeking to reduce variability and uncertainty in emission factors in order to improve the quality of emissions inventories submitted and to establish management practices for emissions reduction. In order to understand this variability, we witnessed some engine tests performed for our client in one of their testing facilities, in this report the name we have given for this tests is "Controlled Tests 1". During these tests the ISO8178 procedures were followed and results obtained were compared against Manufacturer data. For confidentiality reasons, the whole results of those tests are not presented in this report, however for our Scenarios in analysis, emission factors obtained in test modes 1-5 at constant speed of 1800 RPM are presented in the results section of this report.

Ideally, and as explained in the EPA methodology used for the NONROAD model, emissions factors for each type of pollutant should be adjusted using their respective equation (See Appendix C, Equations 1 and 2). The main factor influencing the adjustment of frac pump emission factors is the Deterioration Factor (DF). The DF varies as a function of engine age. For nonroad diesel engines, such as the frac pump engines, the DF is defined by the following equation: DF=1+A*Age Factor. The relative deterioration factor, constant "A" (% increase/% useful life), is available in EPA documentation for different engine tiers. For Tier 2 engines, the constants (A) are: 0.034, 0.101, 0.009 and 0.473 for HC, CO, NOx and PM, respectively. The Age Factor is the fraction of the median life expended (Age Factor=cumulative hours*load factor/median life at full load in hours). For frac pumps engines the median life at full load is ~8,000 hr; the deterioration is capped at the end of this median life (Age factor=1), under the assumption that an engine deteriorates to a point where any increased deterioration is offset by maintenance[34]. In other words, the older the engine (higher cumulative hours), the higher the DF and, in turn, higher the adjusted emission factor.

Engine Power Output

All models include engine power output as a model input. The engine power output is the rate at which work is done; the most common unit use to express engine power is horsepower[c] (hp). For frac pumps and some other oilfield equipment engine power or hydraulic power in hp is calculated[d] as injection rate (bpm) * Pressure (psi) / 40.8. Most of the air emission models include the sum of the total nominal engine power available at the wellsite in their equation factors. For example, if using 14 frac pumps of 2,250 hp, the total nominal power is 14*2,250=31,500 hp.

It is important to differentiate between the nominal horsepower (often simply "hp") and brake horsepower (bhp). Nominal horsepower (also termed "indicated" or "maximum rated" horsepower) is the theoretical power than an engine would deliver if all frictional losses were eliminated. Brake horsepower[e] is the difference the nominal horsepower minus the power required to overcome engine friction. Therefore, bhp is the actual amount of power that an engine can deliver at a certain speed with a wide-open throttle;[35] for example, based on the manufacturer's performance data, a Caterpillar 2,250 hp (nominal) frac pump engine running at 1,800 RPM can deliver output of 2,155 bhp. Air emissions models generally use nominal horsepower as input and so to indicate actual operating conditions, the engine load factor is taken into account for model computations.

Engine Load or Load Factor

Engine Load or Load Factor (LF) is a measurement of how hard an engine is working or the portion of available power at which the engine typically operates; it is expressed in percentage (%) of maximum power. For example, if a 2,250 hp frac engine is pumping at 8 bpm with a pressure of 5400 psi, the load factor, LF is approximately 40% [LF = Actual power/maximum power*100 = (7 bpm*5,300 psi /40.8)/2,250*100]. The LF is a parameter highly dependent on the specific conditions at which the frac pumps are operating, which vary during the frac job, especially between frac stages. The load factors greatly affect the estimated emissions. For example, Model 1 in Table 2 assumes a worst-case scenario, with pumps operating at full load (LF=100%) during the entire job; as discussed before, such an operational situation is not possible. Models 2 and 3 use an average load factor based on weighting different loads during different portions of the job over the total time the frac pumps are used, e.g., [$\sum_1^n(\text{Load Factor (\%)} \times \text{Time (hr)}/\ \text{Total hours (hr)}$].

Engine Usage Time

Total air emissions of course depend on the duration of engine operation. For emission inventories, engine activity is usually reported as number of hours on a specified time step. The time step can be hrs/year, hr/month, hr/well or hr/job. We have

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[c] The SI unit kilowatt "kW" is also used (1 hp = 0.745699872 kW), more commonly in Europe.
[d] Horsepower can be determined by either computing mathematically as shown above or measuring mechanically.
[e] The term *brake horsepower* is derived from the braking device (usually a dynamometer) that is applied to measure the horsepower an engine develops.

selected hr/job as period of analysis in this study. For the Eagle Ford, we found that a typical job lasts for about 98 hr. During this time, the frac pumps are pumping for 27 hrs, and may be in ready-reserve mode for up to 51 hrs (usually between frac stages while waiting for other activities to be completed) and shut down during the standby time (usually during the equipment set-up, rig-up and rig-down time) for about 20 hr. Tracking these usage periods is key for estimating total emissions. It would be inaccurate to assume that all 14 pumps were operating at a certain load for all 98 hr of the job duration; it would be also inaccurate to assume that all 14 pumps were active during the pumping time. Thus, data on time spent at each specific operating condition are key inputs for performing accurate emissions calculations.

Variability of Air emissions models based on fuel consumption per source

As seen in Table 3, Model 1 is based on fuel consumption and so involves multiplying emissions factors and average fuel usage (per job), using conversion constants for diesel fuel density and a default engine BSFC.[36] For Model 2, the calculation is similar but the inputs include fuel consumption rate and operating time.

<u>Emission factors, load factors and operating time</u>

The emission factors of models based on fuel usage per source are EPA standard emissions, and the emission factors of model based on fuel consumption rate are EPA Nonroad Tier 2 standards. Choosing different emission factors changes the results accordingly.

Load factors based on activity levels are used with the model based on fuel consumption rate. In the model based on fuel usage, load factor is left out because we simply consider the total fuel consumed by a job instead of usage under different operating conditions.

The operating time used for models based on fuel consumption per source are the same as the models based on activity level, in order to be consistent with the results. However, as mentioned before, we took into account the operating time under different working conditions.

<u>Brake Specific Fuel Consumption (BSFC)</u>

Although default values are commonly used for BSFC, the actual value can vary according to the particular manufacturer's engine.[37] BSFC is not linear with fuel consumption rate and so can change according to operating conditions. However, the variability is not large for a given engine, and so using average BSFC values results in less complex calculations and facilitates comparing results across sites. In this study we fixed the BSFC as 0.367 lb/hp-hr and take it as a default constant. If a more accurate emissions estimate is needed, the actual fuel consumption rates under load can replace the fixed default values.

<u>Fuel consumption rate</u>

The amount of fuel consumed per unit time is called the fuel consumption rate, e.g., in gallons of fuel per hour (gal/hr). Fuel consumption rates depend on working conditions, differing according to pumping and reserve power load factor and time. For the nonroad engines we studied, it is easier to measures engine speed to which fuel consumption rates are correlated based on manufacturer performance data. Fuel consumption affected the economics of engine operations, which is always a concern for the industry, and lower fuel consumption can reduce emissions. Because an engine does not only run when actively pumping, emissions during preheat or pre-work conditions must also be taken into account.

In addition to data from Marcellus and Eagle Ford scenarios, the team also considered data from the engine manufacturers (Caterpillar[38] and MTU[39]) for making comparisons. For example, given the fuel consumption rate for the Caterpillar 3512C engine of 105 gal/hour under full load, and when pumping at Eagle Ford the fuel consumption rate is 63 gal/hour and pump for 27 hours with 12 units, the total fuel consumed for these 12 units should be $(63 \times 27 \times 12) = 20412(\text{gal})$. When calculating the total fuel consumption, we add the result of fuel consumed of active engines during pumping time, engines at reserve power during pumping time and total engines at reserve power mode during the fracking stages.

Fuel usage

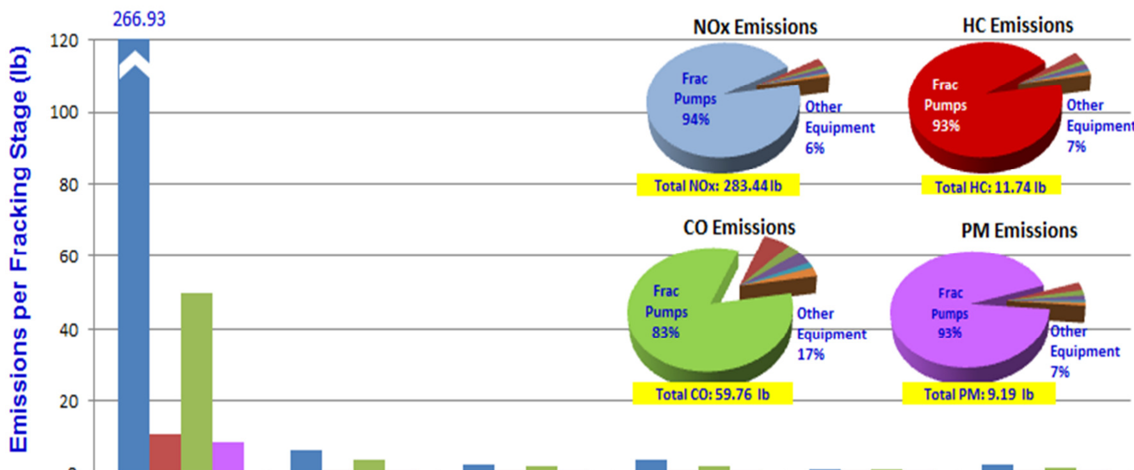
For our analysis, fuel usage represents the amount of diesel utilized during a job (difference in the amount of diesel between the beginning and the end of a job). Recording of fuel amount used in the frac pumps for an specific job is very challenging (i.e. Refueling done during the job, between stages, etc). However, in order to analyze the variability of models that use fuel usage as input, within our illustrative scenarios in Table 7, we define an average fuel used per job for Marcellus and Eagle Ford. For Scenario 1 (Eagle Ford Shale), the average fuel used per job is 22,100 gallons; for Scenario 2 (Marcellus Shale), the average fuel used per job is 20,800 gallons. Similarly we look for an external source for comparison; although we were not able to find any public source that specifies the fuel used per job for our shale plays in analysis, we found out a value reported by Apache Corp for a fracking job in a Texas Shale Play[40]. We have assumed that from the total reported, 70% of the diesel used corresponds to the diesel used in Frac pumps and the other 30% corresponds to the fuel used in backside or ancillary equipment. Simply using data for fuel usage and operating time does not reflect different working loads and so the resulting emissions estimates can be less accurate than those based on data for fuel consumption rate.

RESULTS AND DISCUSSION

Emissions from Frac Fleet

The air emissions resulting from an entire frac fleet at a typical fracking stage at the Eagle Ford Shale was estimated using the general EPA NonRoad model $\boldsymbol{Ei} = \boldsymbol{EF_i} \times [\boldsymbol{RP} \times (\boldsymbol{LFA}/\mathbf{100}) \times \boldsymbol{OT}] \times \boldsymbol{Pop}$ and standard industry information that describes the engine characteristics and operating conditions during for each item of equipment used in the fracking operation. The results obtained were: 283.44 lb of NOx; 11.74 lb of HC; 59.76 lb of CO and 9.19 lb of PM, based on equipment engine power ratings and average load factors. The emissions factors were found by looking to the respective emission standards for Tier 2 Technologies in the EPA Nonroad CI Engine Emission Standards.[f] The operating times were those defined for our Scenario Analysis. Data input, as well as the emissions standards used as emissions factors are tabulated in Appendix F.

Figure 10 illustrates the contribution to the total emissions by equipment type for each pollutant of interest. For all pollutants, the higher emissions are associated with frac pumps. As seen in the pie charts, frac pumps are responsible of 94% of the total NOx emissions, 93% of the total HC emissions, 83% of the total CO emissions and 93% of total PM emissions.

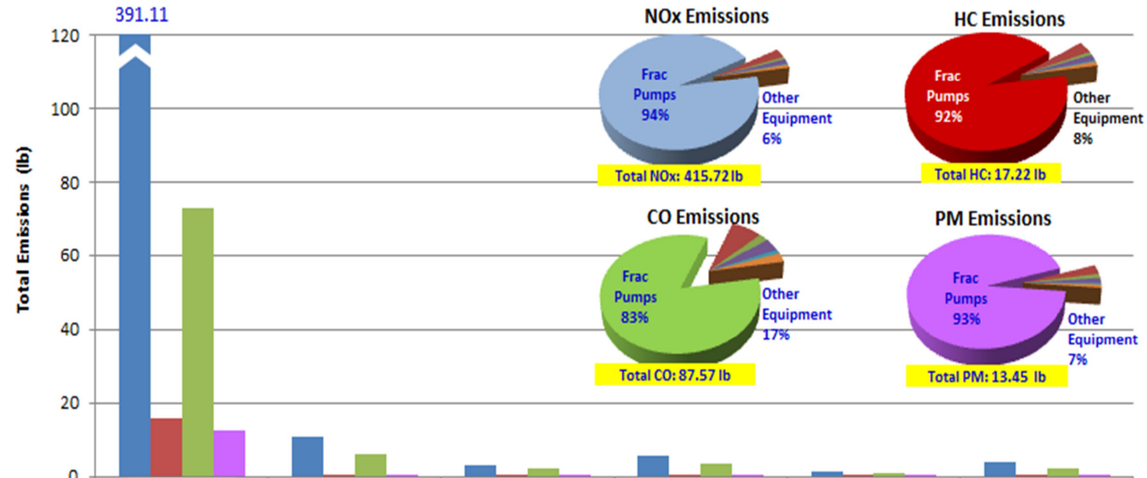


Pollutant / Equipment Type	Frac Pumps	POD Blender	Frac Control Unit	Hydration Unit	Sand Chief or Sand King	Water Transfer Pump
NOx	266.93	6.42	2.52	3.73	1.25	2.59
HC	10.87	0.34	0.13	0.20	0.07	0.14
CO	49.75	3.66	1.76	2.13	0.99	1.48
PM	8.57	0.21	0.14	0.12	0.06	0.09

Figure 10. Fleet (equipment) emissions for a fracking stage at the Eagle Ford Shale

Similar analysis was performed for a typical frac fleet in the Marcellus Shale. The number of units used in operations at Marcellus is usually higher than in the Eagle Ford. As for the analysis done for the Eagle Ford fleet, most of the emissions per fracking stage at Marcellus Shale come from the frac pump engines. From a total of 416 lb of NOx, 94% corresponds to the frac pumps; from 17 lb of HC, 92% comes from frac pump engines; from 88 lb of CO, 83% comes from frac pump engines and from a total of 13 lb of PM, 93% are emitted by frac pump engines. Data input, as well as the emissions factors used for this analysis are also tabulated in Appendix F.

[f] Table 1 from EPA-420-R-10_018 document. Emission standards are available in g/hp-hr, however, for reporting consistency we converted them to lb/hp-hr. Split for the NMHC + NOx values → NOx = 95% * NMHC+NOx; VOC=5% *NMHC+NOx (Ref 31).



Pollutant / Equipment Type	Frac Pumps	POD Blender	Frac Control Unit	Hydration Unit	Sand Chief or Sand King	Water Transfer Pump
NOx	391.11	10.81	2.78	5.74	1.29	3.99
HC	15.92	0.57	0.15	0.30	0.07	0.21
CO	72.90	6.16	1.94	3.27	1.03	2.28
PM	12.55	0.36	0.16	0.19	0.06	0.13

Figure 11. Fleet (equipment) emissions for a fracking job at the Marcellus Shale

Emissions from Frac Pumps under different air emission models

Emissions from Models based on source usage and activity levels

The frac pumps emission estimates using the models based on usage and activity levels (Table 2) and different sources for the emission factors are presented in Figures 12-15. The main reasons for variations among the estimates are the Emission Factors and Load Factors. Model 1, which is the "old" EPA model, assumes a worst-case scenario with frac pumps operating at 100% of engine load. Models 2 and 3 use an average load factor (LFA) based on averaging the load while pumping and the load while at reserve power:

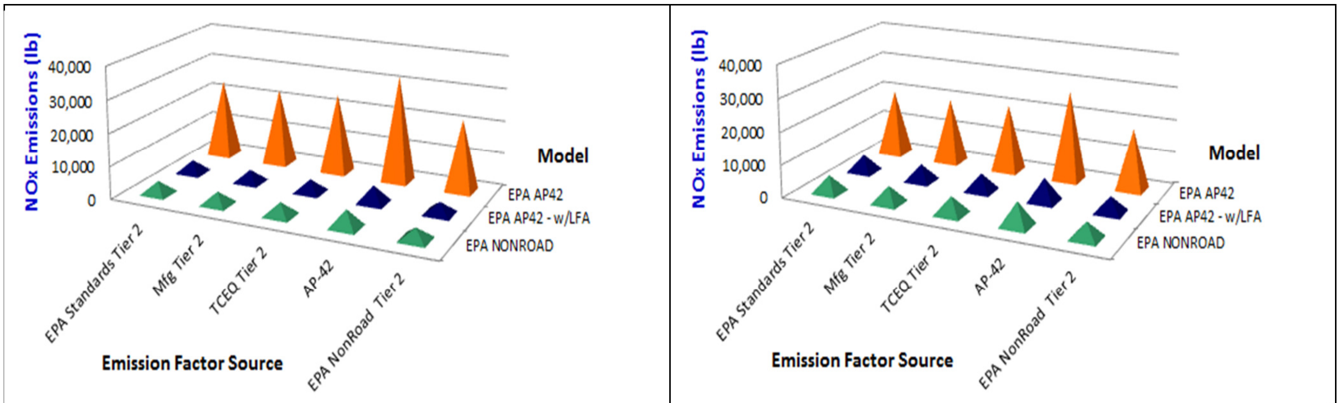
$$LFA = \frac{\left(LF_{@\ Pumping}(\%) \times Time_{Pumping}(hr)\right) + \left(LF_{@\ RP}(\%) \times Time_{RP}(hr)\right)}{Time_{Pumping}(hr) + Time_{RP}(hr)}$$

Where RP : Reserve Power

The resulting LFA values are 15.97% for the Eagle Ford Scenario and 29.56% for the Marcellus Scenario.

In order to evaluate the impact of different emission factors, we used emission factors for Tier 2 Frac Pumps from five different public sources: EF from EPA Tiered Standards (EPA Standards Tier 2); Frac pump Certified EF from manufacturer (Mfg Tier2); Texas Commission on Environmental Quality (TCEQ Tier 2); AP-42 emission factors from EPA (AP-42) and the EF used in the EPA NonRoad model (EPA NonRoad Tier 2). The EF values by pollutant per source are listed in Figure 9 data table.

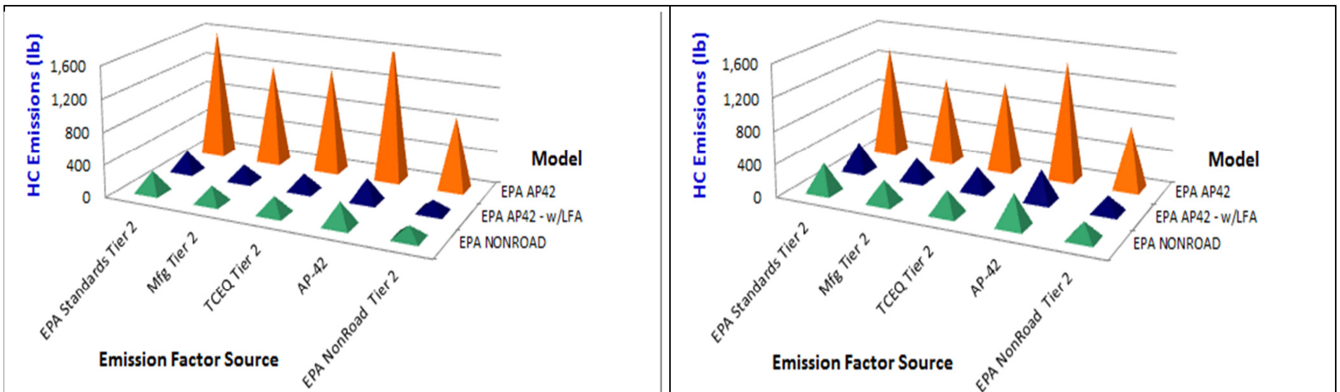
For consistency in our evaluations, the operational parameters are the same as those presented in Table 7. The resulting total pounds of each pollutant (NOx, HC, CO and PM) estimated by each model and for each specific EF source are summarized below, with estimates for the Eagle Ford Shale on the left side of each figure and estimates for the Marcellus Shale on the right.



	EPA Standards Tier 2	Mfg Tier 2	TCEQ Tier 2	AP-42	EPA NonRoad Tier 2
EPA AP42	24,100	23,658	24,562	32,739	22,084
EPA AP42 - w/LFA	3,849	3,778	3,923	5,229	3,527
EPA NONROAD	3,867	3,796	3,941	5,253	3,544

	EPA Standards Tier 2	Mfg Tier 2	TCEQ Tier 2	AP-42	EPA NonRoad Tier 2
EPA AP42	20,330	19,957	20,719	27,617	18,629
EPA AP42 - w/LFA	5,259	5,162	5,360	7,144	4,819
EPA NONROAD	5,259	5,163	5,360	7,144	4,819

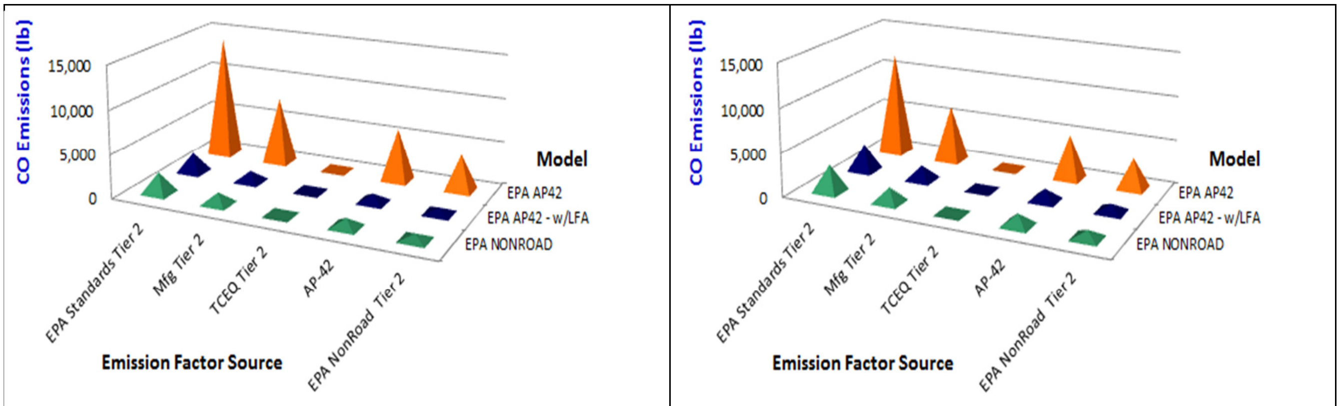
Figure 12. Total NOx Emissions per job at the Eagle Ford (Left) and Marcellus Shale (Right)



	EPA Standards Tier 2	Mfg Tier 2	TCEQ Tier 2	AP-42	EPA NonRoad Tier 2
EPA AP42	1,607	1,245	1,293	1,727	899
EPA AP42 - w/LFA	257	199	206	276	144
EPA NONROAD	261	202	210	281	146

	EPA Standards Tier 2	Mfg Tier 2	TCEQ Tier 2	AP-42	EPA NonRoad Tier 2
EPA AP42	1,355	1,050	1,090	1,457	758
EPA AP42 - w/LFA	351	272	282	377	196
EPA NONROAD	351	272	282	377	196

Figure 13. Total HC Emissions per job at the Eagle Ford (Left) and Marcellus Shale (Right)



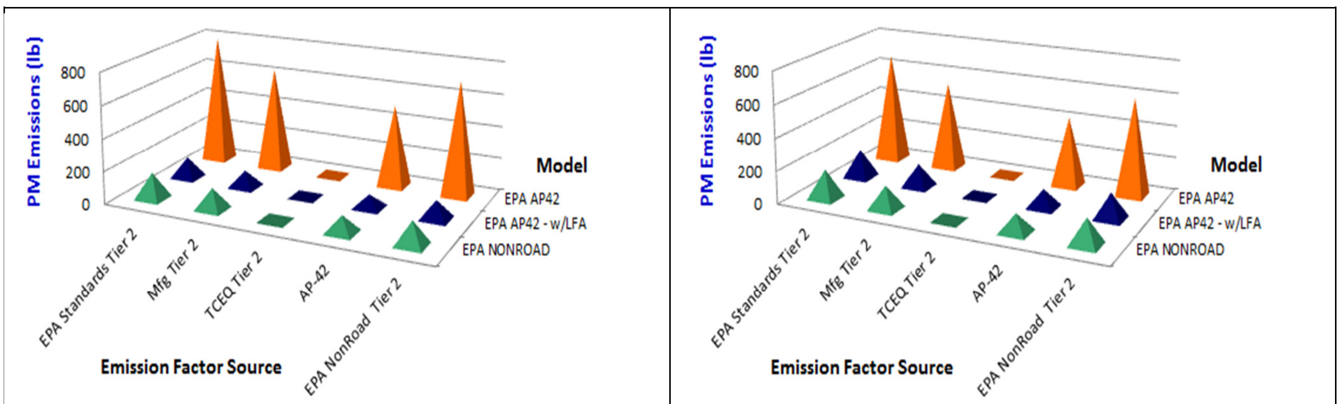
Eagle Ford (Left):

	EPA Standards Tier 2	Mfg Tier 2	TCEQ Tier 2	AP-42	EPA NonRoad Tier 2
EPA AP42	14,058	7,632	Not Available	6,035	4,116
EPA AP42 - w/LFA	2,245	1,219	Not Available	964	657
EPA NONROAD	2,364	1,283	Not Available	1,015	692

Marcellus Shale (Right):

	EPA Standards Tier 2	Mfg Tier 2	TCEQ Tier 2	AP-42	EPA NonRoad Tier 2
EPA AP42	11,859	6,438	Not Available	5,091	3,472
EPA AP42 - w/LFA	3,068	1,665	Not Available	1,317	898
EPA NONROAD	3,070	1,666	Not Available	1,318	899

Figure 14. Total CO Emissions per job at the Eagle Ford (Left) and Marcellus Shale (Right)



Eagle Ford (Left):

	EPA Standards Tier 2	Mfg Tier 2	TCEQ Tier 2	AP-42	EPA NonRoad Tier 2
EPA AP42	803	643	Not Available	508	709
EPA AP42 - w/LFA	128	103	Not Available	81	113
EPA NONROAD	160	128	Not Available	101	141

Marcellus Shale (Right):

	EPA Standards Tier 2	Mfg Tier 2	TCEQ Tier 2	AP-42	EPA NonRoad Tier 2
EPA AP42	678	542	Not Available	429	598
EPA AP42 - w/LFA	175	140	Not Available	111	155
EPA NONROAD	176	141	Not Available	111	155

Figure 15. Total PM Emissions per job at the Eagle Ford (Left) and Marcellus Shale (Right)

Discussion on models based on activity level

From these results, the model that computes the higher emissions for each of the four pollutant types analyzed is the EPA AP-42 old model, due to its assumption of a 100% Load Factor. For example, the results obtained for NOx emissions at the Eagle Ford for all the different sources are all above 22,000 lb of NOx per job (Figure 12-left). The two models that use an averaged Load Factor (LFA) estimate total emissions below roughly 5,300 lb NOx per job. Similar estimates result when calculating emission for the typical Marcellus job, for which the EPA AP-42 old model calculates emission above 18,000 lb NOx per job, whereas the other two models estimate emission below roughly 7,200 lb of NOx (Figure 12-right).

Since all the inputs in the models are multipliers, there is a direct relationship between EF values and total emission results; the higher the EF, the higher the total emissions per job. Among all of EF sources, those for the EPA AP-42 are the higher values. For all pollutants and for each of the three models, the higher total emissions per job correspond these EFs. For example, for HC emissions at Eagle Ford, the total emissions per job using each of the three models are 1,727 lb, 276 lb and 281 lb, respectively. Conversely, using the EPA Tier 2 Zero-Hour, Steady-State Emission Factors for Nonroad CI Engines, which provide the lowest emission factors among the five sources analyzed yields the lowest estimated emissions per job. In this case, HC emissions at the Eagle Ford with EPA Nonroad Tier 2 EF for the three models are: 899 lb, 144 lb and 146 lb, respectively (Figure 13-left). Similar results are obtained for the Marcellus Shale Scenario (Figure 13-right).

The main difference in the results obtained when modeling using Model 2 vs. Model 3 consists in the adjustment of emission factors. As discussed above, both models use the same LFA; In model 2 the emission factors are not adjusted, whereas in Model 3 the EF are adjusted using EPA methodology for its Nonroad model. This adjustment is mainly affected by the deterioration factors calculated based on the engines age factor (Age Factor=cumulative hours*load factor/median life at full load in hours). When comparing the difference in total emissions obtained between Model 2 and Model 3 for the Eagle Ford vs. Marcellus Job we can see that there is a higher difference between Model 2 and model 3 total emissions for the eagle ford, which is mainly due to the fact that most of the time the age factor of the frac pumps used for frac jobs at the Eagle Ford is higher than the age factor of the frac pumps used at the Marcellus Shale. This difference seems to be minimum for the Eagle Ford scenario and for the Marcellus Shale it seems to be null, however, it is important to keep into account that the emissions inventory in this analysis is done at frac job level, if the emissions inventory level were annual, the difference in total emissions when adjusting EF will be more notable. i.e. When referring to CO emissions at the Eagle Ford, the results obtained using Model 2 and 3 with EPA NonRoad Tier 2 EF for the Eagle Ford is 657lb and 692lb respectively, whereas the total emissions obtained for the Marcellus Scenario for the same models is 898lb vs. 899lb (See Figure 14).

Emissions from Models based on Fuel Consumption

The frac pumps emission outputs by pollutant using each of the models defined in the report as models based on fuel usage and fuel consumption in Table 3 and different source for emission factors are presented below in Figures 16-18. The inputs in these models are modified by units and contain EF as the same as models based on source usage and activity levels; the usage is according to the table 7 for both shale plays; the fuel consumption, fuel density and BSFC are all constants. Model 1 converted fuel usage into a power output when usage data is not available and model 2 uses the fuel consumption as an input. The difference brings variability which will be shown in the following text.

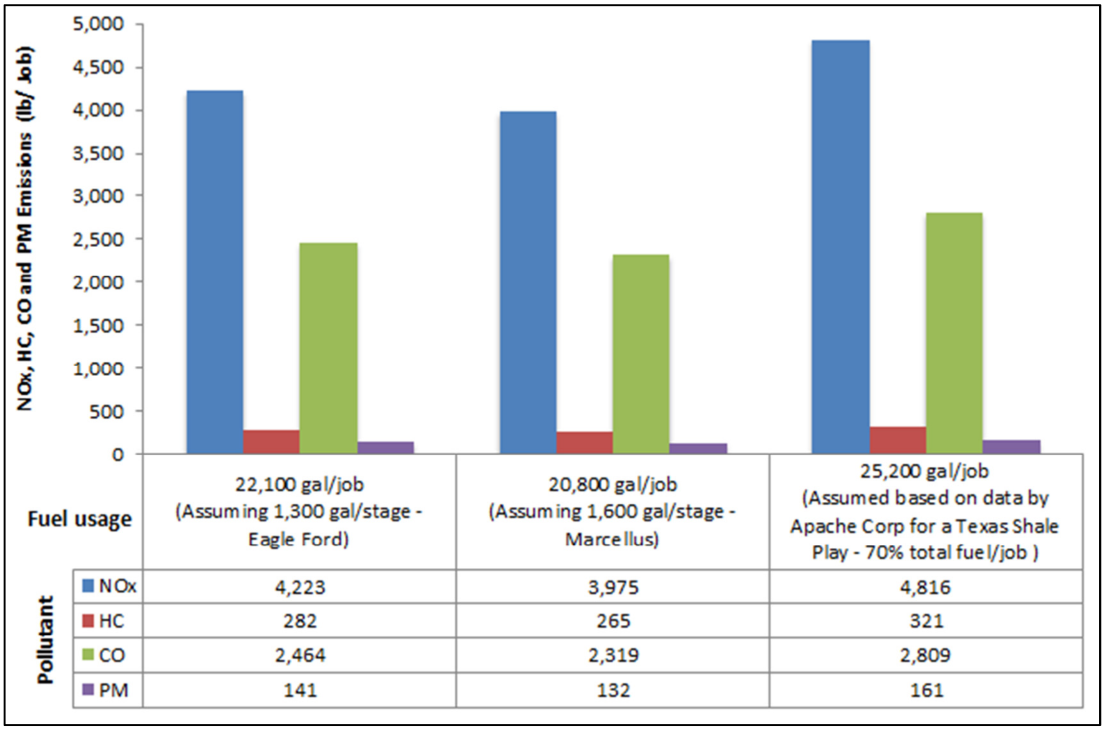


Figure 16. Emissions based on fuel usage (EF Used: EPA Standard Tier2)

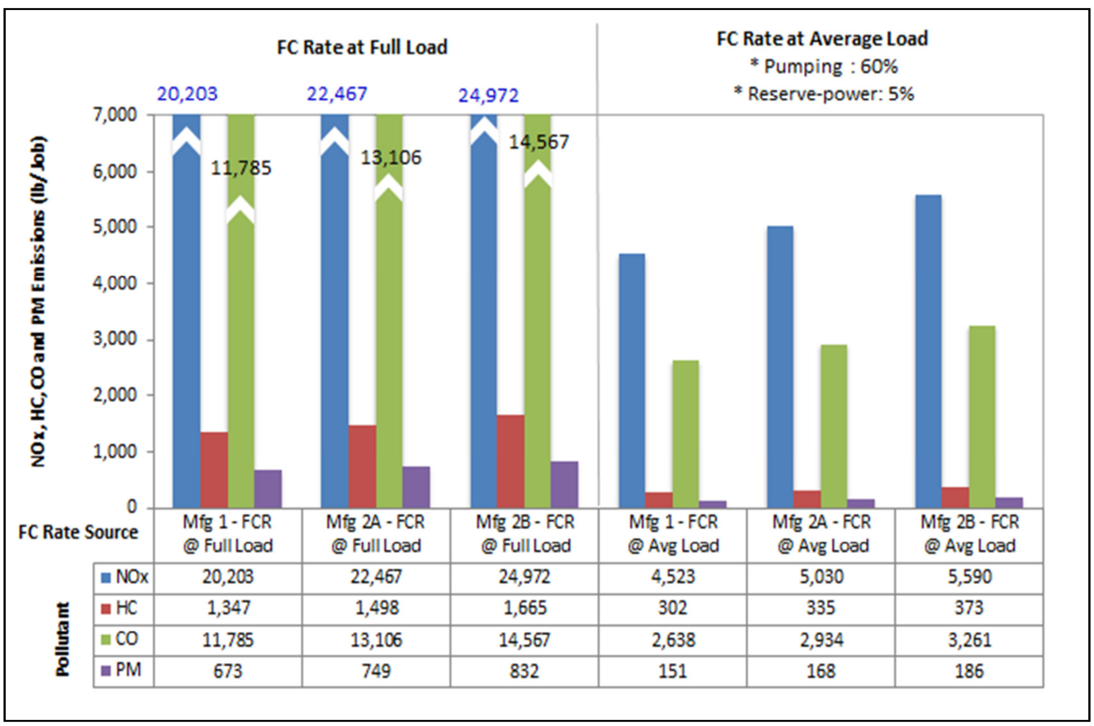
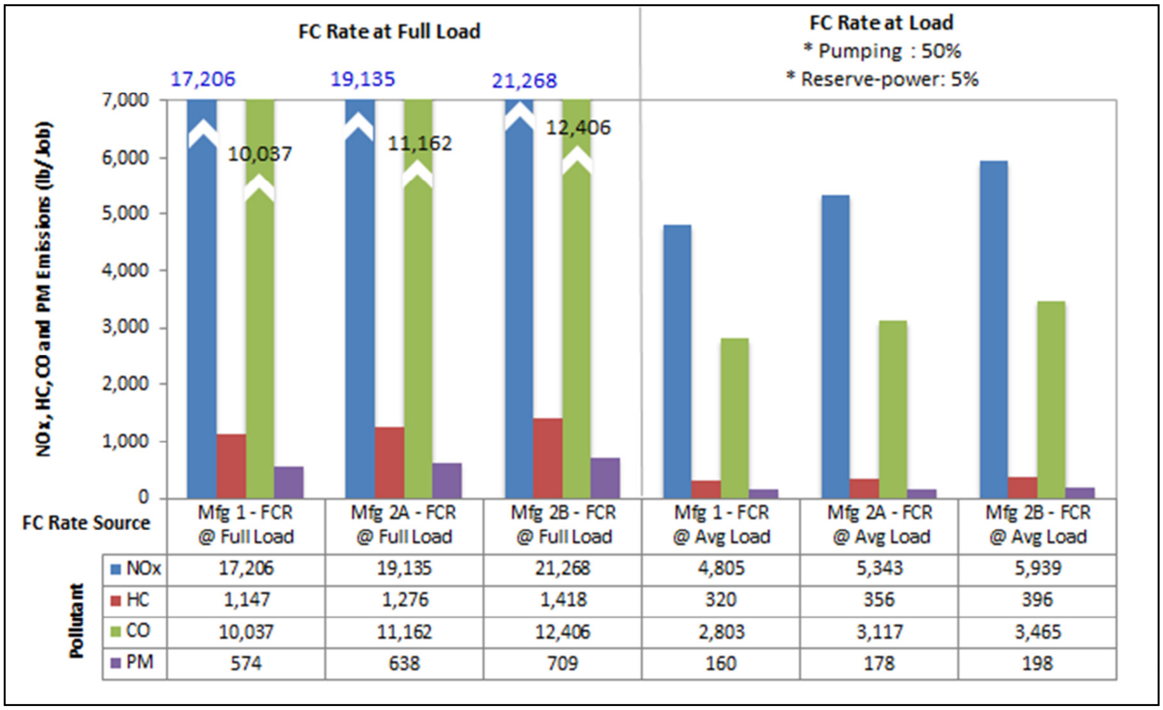


Figure 17. Emissions based on fuel consumption for Eagle Ford Shale. Fuel consumption rate at full load (Left) and at average load (Right)



FC Rate Source	Mfg 1 - FCR @ Full Load	Mfg 2A - FCR @ Full Load	Mfg 2B - FCR @ Full Load	Mfg 1 - FCR @ Avg Load	Mfg 2A - FCR @ Avg Load	Mfg 2B - FCR @ Avg Load
NOx	17,206	19,135	21,268	4,805	5,343	5,939
HC	1,147	1,276	1,418	320	356	396
CO	10,037	11,162	12,406	2,803	3,117	3,465
PM	574	638	709	160	178	198

Figure 18. Emissions based on fuel consumption for Marcellus Shale. Fuel consumption rate at full load (Left) and at average load (Right)

Discussion on models based on fuel consumption

From the equations of models in table 3, ideally the results calculated from the two models should be the same, since they are both focused on fuel use and the fuel used per job is fixed or can be measured. However, as shown in figure 16, 17and 18, the emission based on fuel usage and the emission based on fuel consumption are different from each other, for all the pollutants. Figure 16 shows the emission based on different fuel usage and the results can only be affected by fuel usage since other factors (fuel density, BSFC, EF) are the same. All these results are based on EPA standard Tier2, and fuel consumption information are from public manufacturers' sources. All the emissions factors being used are shown in figure 9, and the differences of emissions factors, together with the fuel usage, directly caused the differences between two figures. To be mentioned, the emissions factors of HC and PM are rather small, and this is the reason why it seems that the height of HC and PM on the graph are inconspicuous.

Figure 17 and 18 show the Emissions based on fuel consumption rate and using EPA Non-road Tier 2 standard for emission factors for Eagle Ford and Marcellus, respectively. On the left side of figure17 and figure 18, the results show when we assume a full load during all working conditions, regardless of operating mode (pumping or reserve power). The obtained results are huge and the magnitude is high. This is not correct and would lead to inaccurate estimation in industry. When load factor data is not available, people tend to simply calculate total emissions under full load condition, which overestimates the total emission. On the right side of figure17 and figure 18, we are assuming linear behavior in fuel consumption, so the actual fuel consumption is the fuel consumption at full load times load factor. For example, the 105 gallons per hour is according to the fuel consumption of Eagle Ford at 100% working load, and we multiplied by the load factor when pumping, which is 60%, and we get the pumping fuel consumption rate is 63 gal/hour. Similarly, under reserve power mode, the fuel consumption rate is about 5 gal/hour, since the load factor at reserve power is only 5%. Also we need to consider the number of engines, and different operating times, so the total fuel consumed in a job is:

$$\left(105\ \frac{\text{gal}}{\text{hr}} \times 60\% \times 27\text{hr} \times 12\right) + \left(105\,\frac{\text{gal}}{\text{hr}} \times 5\% \times 27\text{hr} \times 1\right) + \left(105\ \frac{\text{gal}}{\text{hr}} \times 5\% \times 51\text{hr} \times (12+1)\right) = 24034.5\left(\frac{\text{gal}}{\text{job}}\right).$$

Similarly, when calculating other emissions under various working conditions, different fuel consumption rate under reserve power hours have been taken into account. In this way we can explain why the results in figure 17 and figure 18 are much different from those in figure 16. In model 1 we simply calculated the emissions factors with the fuel usage, which is the total fuel usage per job, while in model 2 we separate the fuel consumption during working hours and reserve power hours. There might be other fuel consumptions not considered into account which being wasted during the fracking jobs so that make level of total consumption different. The data for the engine performance at those specific operating conditions should be more precise, and therefore emissions will be more accurately estimated. We will discuss about it more in the industry models.

From these results, the model that computes the higher emissions for each of the pollutant types correspond to the higher fuel consumption and emission factors. However, since we did not change too much to the operating time in all shale plays in the model, and in real life this can be a highly various number among different sites, the results can also make difference. Also, based on different temperature, weather, working condition, engine volume (even the same type of engine) the BSFC can be different. In this study the team basically analyzed some scenarios to help the O&G industry for calculation options and comparison.

To be specific with the standards, it is without doubt that if different emission standards were chose, the results would change. This is account for the different EF between EPA Nonroad Tier 2 and other standards. Since EF is the most significant factor for comparing emissions among different standards, it is not hard to find that in both model 1 and model 2, EF is the significant factor deciding the height in the graphs, which means the amount of emissions depends on EF in both models.

When comparing the total emissions per job obtained for the Eagle Ford Scenario against the results obtained for the Marcellus Scenario (Comparing both side of the results in each of the previous figures) under the rather accurate model considering load factors, different results may due to the difference in operational conditions in each Shale play. In general, Marcellus Shale operations require more engine power at the wellsite (higher number of frac pump units), higher engine load factors and also more total operating time.

Emissions calculations improvements by the O&G industry

Frac Pump Engine Emission Rates and Factors for a Tier 2 Engine

In order to calculate and report emissions in a more accurate fashion, O&G industry and our client in particular are performing tests to develop frac pump curves with emission rates (lb/hr) and emission factors (lb/hp-hr) for each engine type and technology used for fracturing operations. The data from our study is confidential and can not be placed in the public report. For our study, we built pump emissions curves based on actual emissions measured during "controlled tests" done by a certified third party for our client. To these pump curves, we added similar tests done by manufacturer on a brand-new engine. Both tests protocols follow the ISO Test Cycle for Frac Pumps. Tests were done on a Tier 2 Engine at all 5 Test Modes for D-2 Cycle (100, 75%, 50%, 25% and 10% Engine Load) and measure the modal mass emissions[g] in lb/hr at different engine speeds: 1300, 1400, 1500, 1600, 1700, 1800 (engine speed we have assumed as "typical" for each job at both of our scenarios analyzed: Eagle Ford and Marcellus) and 1900 RPM. Additionally, one more test was run to get emissions information at "reserve power" mode.

As stated before, there is a direct relationship between Engine Load Factor and emissions rate; the highest the load factor the higher the pollutant emission rate. Emissions at mode 1 (100% LF) are higher than the emissions at Mode 2 (75% LF), Mode 3 (50% LF), Mode 4 (25% LF) and Mode 5 (10% LF) and at reserve power mode. A brand-new engine emits at lower rate than a used engine. For all pollutants type, this linear relationship is followed, however, there are some exceptions where emission rates instead of decreasing between modes increase, low emission rates (< 3 lb/hr), such as the emission rates for CO, HC and PM in some modes are slightly higher than the previous mode. This phenomena, may be attributed to either the precision measurement of the equipment used during the tests or to the non-linearity of the combustion behavior itself.

In order to perform a comparison between the magnitude of the emission factors obtained from these emission rates and the current EPA Tiered Emission Standards, we converted emission rates (lb/hr) into implied emission factors (lb/hp-hr and lb/bhp-hr) by dividing those emission rates by the corresponding engine power for the specific load at that engine speed (1800 RPM). Emission factors in lb/bhp-hr are always higher than emission factors in lb/hp-hr. Breakhorsepower is always a smaller number than the nominal horsepower (bhp<hp), since it accounts for the frictional horsepower, in turn, dividing the emission rate by a smaller number, results in a higher emission factor, that is why when accounting for total emissions per job it is necessary to make sure the emissions factors and the power used as a factors in the models are consistent in terms of units. Interestingly, emission factors obtained from the test results showed that in average for all pollutants those values are well below the standards defined by the EPA.

Although emission models use methods such as interpolation and extrapolation of data based on the assumption that the behavior of emissions is linear, the results also show that further field tests are required to evaluate and interpret the correlation between emission rates and engine load, as well as the correlation with engine speed for all different pollutants.

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[g] Modal sampling tests measure emissions on a continuous basis while the engine is operating. The conventional modal system is designed to sample exhaust gas at a constant rate.

Total Emissions per job from model based on "activity levels" with actual data from Industry tests

The emissions per pollutant per job based on data from the industry tests were computed by adding the emissions corresponding to the Pumping time, while differentiating between the frac pump engines that are as "active" and the ones that are as "reserve power" and, the emissions corresponding to the reserve power time between frac stages. In other words, the model is a modified version of the "model based on activity levels", that corresponds to the following equation:

$$Total\ Emissions\ E_i\left(\frac{lb}{job}\right) = \left[\begin{array}{c} \left(Em.Rate_{@\ Avg\ LF-pumping}\left(\frac{lb}{hr}\right) \times \#Units_{Active} \times Time_{Pumping}\left(\frac{hr}{job}\right)\right) + \\ \left(Em.Rate_{@\ RP}\left(\frac{lb}{hr}\right) \times \#Units_{RP} \times Time_{Pumping}\left(\frac{hr}{job}\right)\right) + \\ \left(Em.Rate_{@\ RP}\left(\frac{lb}{hr}\right) \times \#Units_{RP} \times Time_{RP}\left(\frac{hr}{job}\right)\right) \end{array}\right]$$

Where RP : Reserve Power

The emission rates used in this model correspond to the emission rates in lb/hr for each pollutant, interpolated from the test pump curves and the emission rates from the tests at reserve mode. The resulted emissions for each of our scenario analysis are summarized in Figure 19 and its data table below. It is interesting to highlight that there is no specific pattern or behavior between the total emissions resulted from the two tests for each Scenario. i.e. The highest total NOx emissions per Job at the Eagle Ford correspond to the values calculated based on Manufacturer Pump Curve (4,690 lb NOx), whereas the highest total NOx emissions per job at Marcellus Shale correspond to the values calculated based on the Controlled Tests Pump Curves (4,064 lb), which is consistent with the variability in the emission rates when interpolating from pump curves. In general, total emissions per job at the Eagle Ford are higher than in the Marcellus Shale, however, there is no one single parameter that we could say is responsible for this results. We could say that it is due to the fact that the frac pump load factors in the Eagle Ford is higher than the load factor in the Marcellus Shale (60% vs. 50% respectively), however the amount of units and the operating time this units are in "active" and "ready reserve" mode is different as well as the emission rates at each of those modes. These results are strong evidence of the need of using actual data when modeling, actual pump curves are great source for obtaining most accurate emission rates, but specific operating conditions for the frac pumps fleet during a fracking job is equally important, and even more taking into account that every single job requires different operational conditions even within the same shale play.

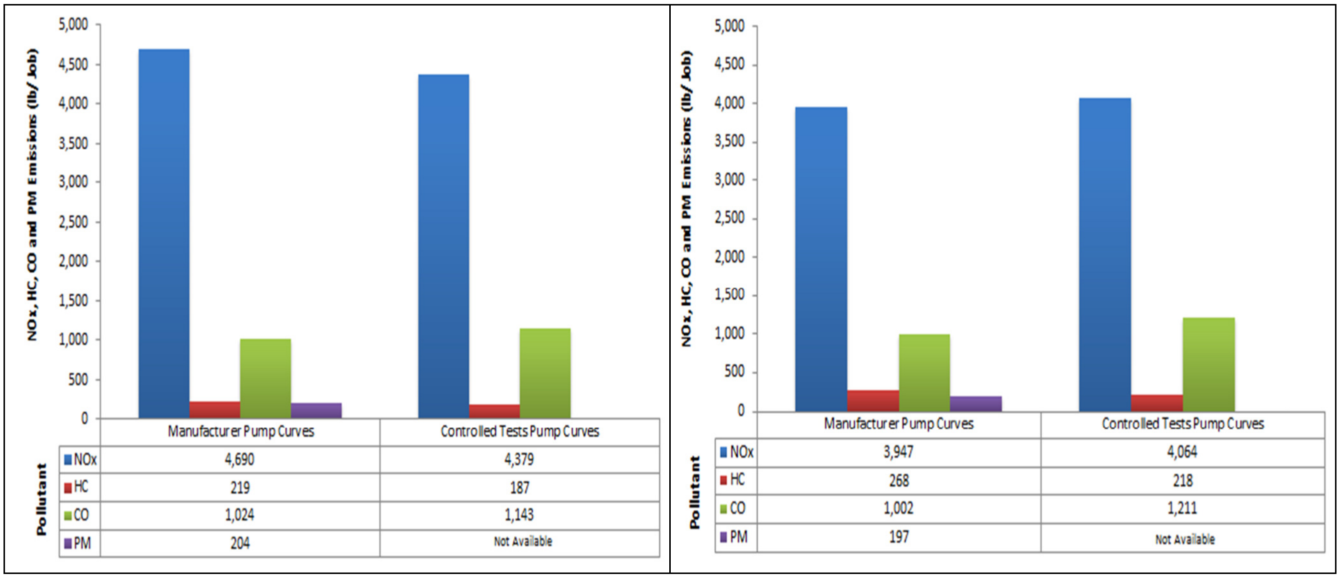
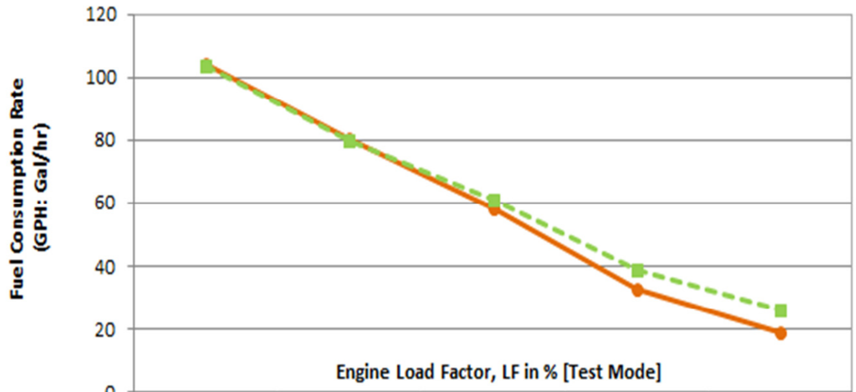


Figure 19. Total Emissions per Job at the Eagle Ford (Left) and Marcellus Shale (Right) from Industry Tests – Model based on "activity level"

Frac Pumps Fuel Consumption Rates from Industry Tests

Similar to the test protocols followed for the measurement of pollutants emission rates in lb/hr; O&G industry and our client in particular are performing tests to develop fuel (diesel) consumption curves with the consumption of diesel in gal/hr, in order to get more accurate data, representative of the real operating conditions for frac pumps. Tests protocols follow the ISO Test Cycle for Frac Pumps and were done on a Tier 2 Engine at all 5 Test Modes for D-2 Cycle (100, 75%, 50%, 25% and 10% Engine Load) to measure the fuel consumption rates in gal/hr at different engines speeds: 1600, 1800 and 1900 RPM. For this study, we built Fuel Consumption curves based on actual rates measured during "controlled tests" done by the certified third party for our client (Series named "FC Rate-Tests" in Fig. below) and based on similar tests done by manufacturer on a brand-new engine (series named "FC Rate-Mfg" in Fig. below). Figure 20 contains the fuel consumption results corresponding to each Test mode, for both of our scenarios analyzed (Eagle Ford and Marcellus) and at engine operating speed of 1800 RPM. Both tests revealed a positive correlation between fuel consumption rate and engine load, which is an expected result, since the higher the work from an engine, the higher its fuel consumption. A comparison of the two test results also shows that a high engine loads (LF > 60%), there is no significant difference between the obtained values, however at engine loads <60%, the consumption rates from the used engine are higher than the rates for the brand-new engine, which could be attributed to: the engine wear; the composition of the fuel (diesel)[h] being burned, and the fuel combustion efficiency itself, which is affected by different ambient conditions such as temperature and humidity[41].

[h] The common diesel fuel used for frac operations at these two shale plays fulfills ASTM D975 specifications; Grade D2 or ULSD#2 (Ultra low sulfur diesel); Sulfur < 15ppm (See Appendix G for more details)



	100% [Mode 1]	75% [Mode 2]	50% [Mode 3]	25% [Mode 4]	10% [Mode 5]
FC Rate - Mfg	104.0	80.3	58.4	32.9	18.6
FC Rate - Tests	103.6	79.9	60.7	39.0	26.1

Figure 20. Frac Pump Fuel Consumption Rates at 1800 RPM for different Engine Loads

Comparison of Fuel Consumption Rates - Volumetric tests UofM Team

In addition to the controlled tests and the manufacturer mentioned before, the team performed volumetric tests, to measure the diesel used by the engine in the space of an hour of testing at different engine loads and speeds. The resulted volume (gal) were divided by the test time (min) and converted to fuel consumption rates in gal/hr. The objectives of these tests were to compare the results obtained vs. to the data from previous tests; to get familiar with our client's acquisition and recording systems and, to provide feedback for the engineers whom are working in developing software that estimates emissions based on live-operating conditions. It is important to mention that the software named "Software 1" and "Software 2" in the figure below, correspond to two different software used by our client to map and record the frac pump engines operational conditions during every job. The two software are loaded with input data that is provided by the manufacturer with the "Engine General Performance Data", for confidentiality reasons the full data are not published in this report. Once the engine is powered on, the software is able to acquire and record the consumption of fuel at the specific conditions in which the engine is operating. Software 1 is able to acquire and record data every second, software 2 every three seconds. Both software average fuel consumption rate in gal/min regularly. Figure 21, displays the results obtained in our volumetric tests and how they compare to the average fuel consumption rate calculated from the two software (converted from gal/min to gal/hr). No significant difference was found between the averaged fuel consumption rates found between the two software, even though the rate of acquisition is different and it may be attributed at the conditions of the test itself, engine speed and load stable during the test duration. The most striking result to emerge from the test is that fuel consumption rate at reserve power mode calculated based on our volumetric measurements is almost 180% less than the fuel consumption reported in the Performance Data of the engine. Based on the high difference in the results, the test was re-run three more times and in different time periods and results were found to be consistent with the previous one. For all the other tests variability of our results against the data calculated from the software correspond to 3-8% more. This finding have led to additional research and tests to be run by our client, in order to get more accurate results for both emission rates (lb/hr) and fuel consumption rates at power reserve mode (~5%) and at low engine loads in general.

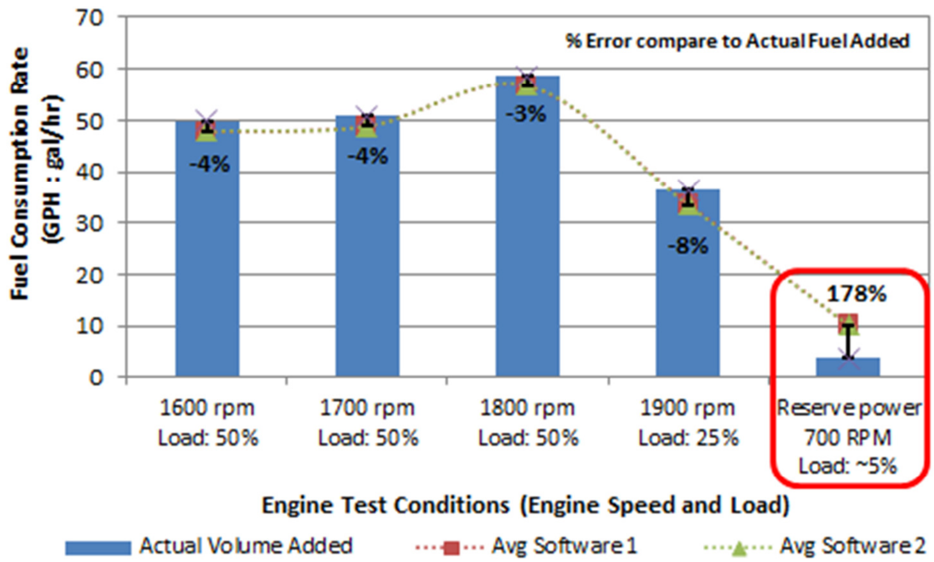


Figure 21. Frac Pump Fuel Consumption Rates Comparison from Controlled Tests

Total Emissions per job from model based on "fuel consumption" with actual data from Industry tests

The emissions per pollutant per job based on data from the fuel consumption rate tests were computed by adding the emissions corresponding to the emissions from each of the two modes: Pumping at specific engine load and RPM as per defined in our scenario analysis (differentiating between the frac pump units that are as "active" and as reserve power during the pumping stage) and at reserve power (~5% load and ~700RPM). The emissions model use for these calculations correspond to a modified version of the "Model 2 based on fuel consumption per source" discussed in the Analysis section, as illustrated in the following equation:

$$Emissions\ E_i\left(\frac{lb}{job}\right) = \sum_{1}^{n} EF_{i\ @Mode}\left(\frac{lb_i}{bhp-hr}\right) * \frac{FC_{Mode}\left(\frac{gal}{hr}\right) * Diesel\ Density\left(\frac{lb_{fuel}}{gal}\right) * Time_{mode}\left(\frac{hr}{job}\right)}{BSFC_{@\ Mode}\left(\frac{lb_{fuel}}{bhp-hr}\right)} * \#\ Units$$

The emission factors used in the model were the implied emission factors from the industry emission rates (summarized in Fig 20). Brake Specific Fuel Consumption (BSFC) values were obtained from manufacturer Engine General Performance data (0.338 and 0.365 at 1800 RPM and 700 RPM respectively). Diesel density of 7.11 lb/gal fuel, as per defined in our scenarios and consistent with averages used in various EPA analysis. Figure 22, summarizes the resulted emissions for each of our scenarios (Job @ Eagle Ford and Job @ Marcellus) and the results for each scenario using three different Fuel Consumption Rates. "Manufacturer" and "Controlled Tests1" results, correspond to rates interpolated from the curves in Figure 20 and "Controlled Tests 2" takes into account the real fuel consumption rate during the reserve mode test presented above, in Figure 21.

In general total emissions in a job in the Eagle Ford Shale for most pollutants is higher than in the Marcellus Shale (Figure 22, left vs. right), which provides evidence that higher consumption rates (due to higher engine load: 60% Eagle Ford vs. 50% Marcellus Shale) and higher operational times, especially at reserve power, lead to higher total emissions per job. The variability of emissions per job between the emissions obtained from "Manufacturer" and "Controlled Tests 1" matches the variability explained before in the discussion of Figure 20. And, finally the results obtained when using a more accurate fuel consumption rate for the reserve power "Controlled Tests 2", exemplify the significant impact and risk of overestimate emissions in the absence of accurate fuel consumption rates for each engine specific mode. i.e Total NOx emissions per job based on volumetric tests for the Marcellus Shale are 3,602lb whereas the emissions calculated based on Manufacturer tests and third party tests are 5,597lb and 4,512lb. (Fig. 24-right)

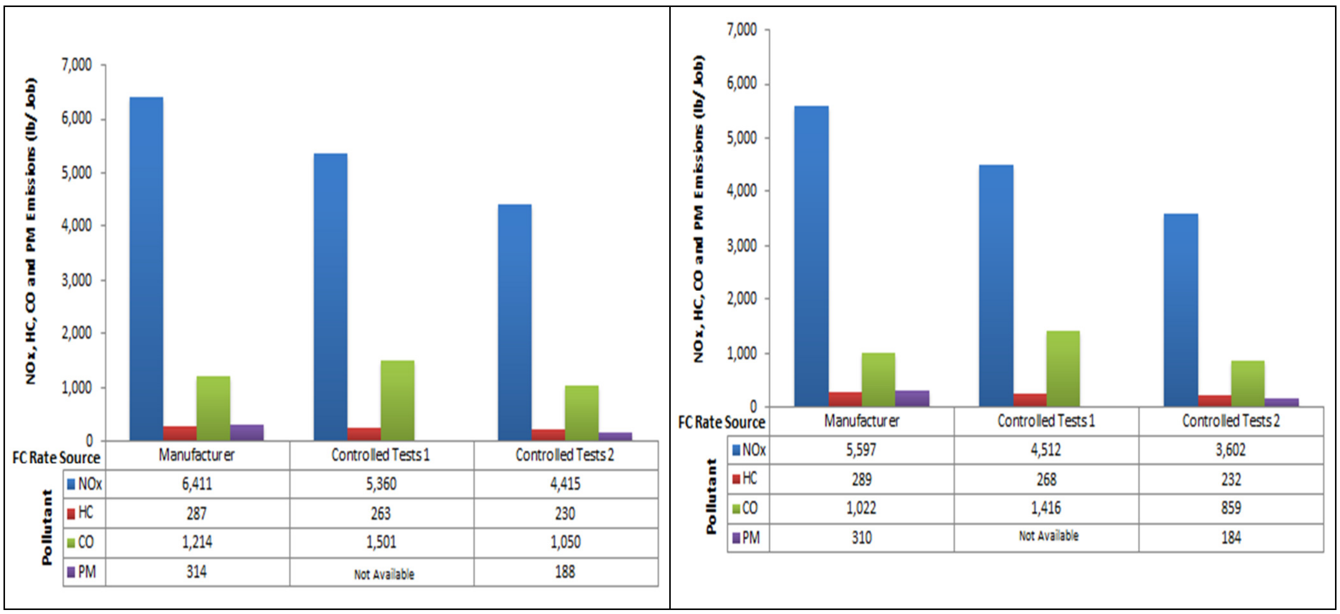


Figure 22. Comparison of Total Emission per pollutant per Job at the Eagle Ford (Left) and Marcellus Shale (Right) – Model based on Fuel Consumption Rate tests

CONCLUSIONS

The pollutant emissions from the equipment used for hydraulic fracturing operations are mainly exhaust emissions from engine fuel combustion. Not all of the equipment generates exhaust emissions; some items are passive machinery without engines, such as the high pressure manifold or frac missile, the chemical float, iron and hose trailers, etc. For the operations we studied at the Eagle Ford Shale and Marcellus Shale, frac pumps are responsible for more than 83% of the total. For that reason, the industry is interested in better characterizing and certifying these emissions. Prior analyses indicated that the emissions from frac pumps are well below the applicable nonroad engine emission standards.

Existing information on the EPA standards and federal and state policies is straightforward for O&G companies to review when planning and carrying out wellsite operations. As the standards become more strict in line with technology improvements, the industry faces ongoing challenges for reducing emissions.

As with any air emission modeling analysis, the results from this study are only as good as the assumptions upon which they rest. The extent of the variability that exists, even among similar individual sources such as frac pumps, can depend on the engine maintenance condition, age of the engine, conditions at which emissions are measured (e.g., engine load, speed), combustion temperature, ambient conditions (i.e., altitude, humidity), any emissions controls installed on the engine (i.e., filters), and the composition of the fuel being burned. To report more accurate emissions inventories it is highly desirable to develop local emission factors specific to the operations in question. When modeling air emissions, the variability of the outputs mainly depends on the following factors: assumed pollutant emission factors; engine power output, load factor, usage time and fuel usage or fuel consumption rate.

During this study we developed frac pump emissions curves based on measurements made during controlled tests in order to calculate emissions in a more accurate fashion. Such results will help the O&G industry and our client by contributing to a more up-to-date and complete data base of specific emission rates and emission factors for each engine types. This information will be beneficial for both efficiency and improved fracking operations.

A key parameter for all the air emissions models analyzed is the load factor. Different working conditions involve different load factors, resulting in different emissions. The load factor also relates to efficiency and fuel consumption. More detailed information on load factor and fuel consumption enables the calculation of more accurate results. Similarly, the more specific the data we have on fuel consumption rate, the higher the accuracy. Also under different conditions there are different BSFCs; more specific BSFC information also enables more accurate results.

With total fuel usage data alone, it is difficult to obtain accurate emissions estimates. Fuel consumption rate data better reflect the differences in various operating conditions, resulting in better estimates and also revealing opportunities for improving the efficiency of operations.

Because of the complexity of specific loading factors, some industries simply use average emission and loading factors. However, averaging emission and load factors per job lead to inaccuracy in emission models outputs. The most accurate way to estimate emissions would be having a detail engine mapping and recording of the operational parameters during a fracking job and pump curves that represent the specific emissions data for each pollutant on each engine.

RECOMMENDATIONS

The oil & gas industry wishes to have appropriate and validated procedures for reporting air emissions inventory in order to facilitate pre- and post-job permitting. For this purpose, the development of certified “pump curves” for high-power engines is crucial for accurate records. Frac equipment engines and the entire frac fleet in general have a high mobility, thus an appropriate tracking of the engines used for each specific job and their cumulative hours is important for reporting representative and consistent emissions inventories.

With the availability of engine mapping and certified pump curves emissions, air emission software that automatically calculates emissions inventories should be developed. That will enable service companies to more easily characterize and report the air emissions from their operations.

In addition to the software that calculates emissions inventories, there should be a more accurate estimation of fuel consumption or better software for monitoring fuel usage during different working conditions (ie, reserve power or pumping). Fuel can be wasted during non-working time, also resulting in excess emissions, and so companies should find ways to reduce this part of fuel usage.

Also further research on more accurate emissions rates and factors at different engine loads and speeds for those pollutants of interest is needed, particularly in anticipation of stricter emission regulations. Better knowledge of engine performance data will also enable planning more efficient working conditions. This is also important for factors that affect fuel consumption rates, since the results of this study show that higher fuel consumption rates relate to higher levels of air emisisons. Further research on improving fuel efficiency would also offer progress.

Further analysis of the factors affecting fuel combustion, such as temperature, humidity, other ambient conditions and the heat for burning the oil[42] is recommended. These factors affect combustion efficiency and the fuel consumption rate, and therefore the estimates of pollutant emissions. Companies may want to make some effect on ensuring the ideal working condition for higher efficiency, such as complete combusting, controlling the working temperature and humidity, choosing a desirable working location.

Our analysis indicated how modeled air emissions significantly depend on fuel consumption rates, emission factors and BSFC. Because under different conditions the engine can have different BSFC values, better engine manufacturer data on BSFC will lead to better modeling.

Our research focused on equipment meeting the Tier 2 standards. With the stricter Tier 3 and Tier 4 being phased in, companies should consider new generation engines, which may also offer higher efficiency as well as lower air emissions.

Other options to reduce emissions can include biofuels, compressed natural gas and liquefied natural gas (LNG). In 2012, first liquefied natural gas (LNG)-fueled hydraulic fracturing was completed in Eagle Ford Play,[43] demonstrating an opportunity for emissions reductions and lower operating costs. Solutions such as Dual-Fuel Service in fracking pumps (See Appendix H), which can allow a higher efficiency as well[44].

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APPENDICES

APPENDIX A – Applicable EPA Standards

Subpart B Emission Standards and Certification Provisions

§ 89.112 Oxides of nitrogen, carbon monoxide, hydrocarbon, and particulate matter exhaust emission standards.

Non-road Compression-Ignition Engines -- Exhaust Emission Standards [45]

Rated Power (kW)	Tier	Model Year	NMHC + NOx (g/kW-hr)	NOx (g/kW-hr)	PM (g/kW-hr)	CO (g/kW-hr)
kW > 900	1*	2000-2005	-	9.2	0.54	11.4
	2	2006-2010	6.4	-	0.20	3.5

*: For Tier 1 engines the standard is for total hydrocarbons.

Emission standards for engine (for non-road engine)

In the project, the team focused on engines where the emissions are coming from. Among the fracking industry, various types of engines are being used, and to be specific with the project engine, the group investigated the Regulations from Code of Federal Regulations (CFR) 40 part 89 to take a deep look at the Non-road Compression Ignition Engines – Exhaust Emission Standards – Oxides of nitrogen, carbon monoxide, hydrocarbon, and particulate matter exhaust emission standards. These regulations report precise standards for potential emissions that could be occurred in the fracking process that the group is researching on.

Mentioned in Appendix A to Subpart A of Part 89—State Regulation of Nonroad Internal Combustion Engines

This appendix sets forth the Environmental Protection Agency's (EPA's) interpretation of the Clean Air Act regarding the authority of states to regulate the use and operation of non-road engines.

EPA believes that states are not precluded under section 209 from regulating the use and operation of non-road engines, such as regulations on hours of usage, daily mass emission limits, or sulfur limits on fuel; nor are permits regulating such operations precluded, once the engine is no longer new. EPA believes that states are precluded from requiring retrofitting of used non-road engines except that states are permitted to adopt and enforce any such retrofitting requirements identical to California requirements which have been authorized by EPA under section 209 of the Clean Air Act.([62 FR 67736, Dec. 30, 1997])[46]

APPENDIX B – United States Emission Standards for Nonroad Diesel Engines[47]

Background

Tier 1-3 Standards. The first federal standards (Tier 1) for new nonroad (or off-road) diesel engines were adopted in 1994 for engines over 37 kW (50 hp), to be phased-in from 1996 to 2000. In 1996, a Statement of Principles (SOP) pertaining to nonroad diesel engines was signed between EPA, California ARB and engine makers (including Caterpillar, Cummins, Deere, Detroit Diesel, Deutz, Isuzu, Komatsu, Kubota, Mitsubishi, Navistar, New Holland, Wis-Con, and Yanmar). On August 27, 1998, the EPA signed the final rule reflecting the provisions of the SOP. The 1998 regulation introduced Tier 1 standards for equipment under 37 kW (50 hp) and increasingly more stringent Tier 2 and Tier 3 standards for all equipment with phase-in schedules from 2000 to 2008. The Tier 1-3 standards are met through advanced engine design, with no or only limited use of exhaust gas aftertreatment (oxidation catalysts). Tier 3 standards for NOx+HC are similar in stringency to the 2004 standards for highway engines, however Tier 3 standards for PM were never adopted.

Nonroad Diesel Fuel. At the Tier 1-3 stage, the sulfur content in nonroad diesel fuels was not limited by environmental regulations. The oil industry specification was 0.5% (wt., max), with the average in-use sulfur level of about 0.3% = 3,000 ppm.
The US nonroad emission standards are harmonized to a certain degree with European nonroad emission standards.[48]
EPA emission standards for nonroad diesel engines are published in the US Code of Federal Regulations, Title 40, Part 89 [40 CFR Part 89]

Tier 1-3 emissions standards applicable for fracturing pumps (hp≥750) are listed in Table 2. Nonroad regulations are in the metric system of units, with all standards expressed in grams of pollutant per kWh.

Engine Power	Tier	Year	CO	HC	NMHC+NOx	NOx	PM
kW ≥ 560 (hp ≥ 750)	Tier 1	2000	11.4 (8.5)	1.3 (1.0)	-	9.2 (6.9)	0.54 (0.4)
	Tier 2	2006	3.5 (2.6)	-	6.4 (4.8)	-	0.2 (0.15)

Table 2. EPA Tier 1-2 Nonroad Diesel Engine Emission Standards, g/kWh (g/bhp·hr)

Manufacturers who signed the 1998 Consent Decrees[49] with the EPA may be required to meet the Tier 3 standards one year ahead of schedule (i.e. beginning in 2005).
Voluntary, more stringent emission standards that manufacturers could use to earn a designation of "Blue Sky Series" engines (applicable to Tier 1-3 certifications) are listed in Table 3.

Rated Power (kW)	NMHC+NOx	PM
kW ≥ 560	3.8 (2.8)	0.12 (0.09)

Table 3. EPA Voluntary Emission Standards for Nonroad Diesel Engines.
Units g/kWh (g/bhp·hr)

California. In most cases, federal nonroad regulations also apply in California, whose authority to set emission standards for new nonroad engine is limited. The federal Clean Air Act Amendments of 1990 (CAA) preempt California's authority to control emissions from new farm and construction equipment under 175 hp [CAA Section 209(e)(1)(A)] and require California to receive authorization from the federal EPA for controls over other off-road sources [CAA Section 209 (e)(2)(A)].

California regulations

Maximum rated power (kW)	Tier	Model year	NOx	HC	NMHC+ NOx	CO	PM
kW>560	Tier 1	2000~2005	9.2	1.3	-	11.4	0.54
	Tier 2	2010	-	-	6.4	3.5	0.20

Table 1. Tier 1 and Tier 2 Exhaust Emission Standards (grams per kilowatt-hour)[50]

Engines of all sizes must also meet smoke standards of 20/15/50% opacity at acceleration/lug/peak modes, respectively.
The regulations include several other provisions, such as averaging, banking and trading of emission credits and maximum "family emission limits" (FEL) for emission averaging.

Fig 1, illustrates the timeline of these engine tiered standards from 2004 to 2015. The Frac Pump engines are engines above 560 Kw. Caterpillar, MTU-Detroit, Cummins are part of the engine manufacturers that signed the 1998 Consent Decrees.

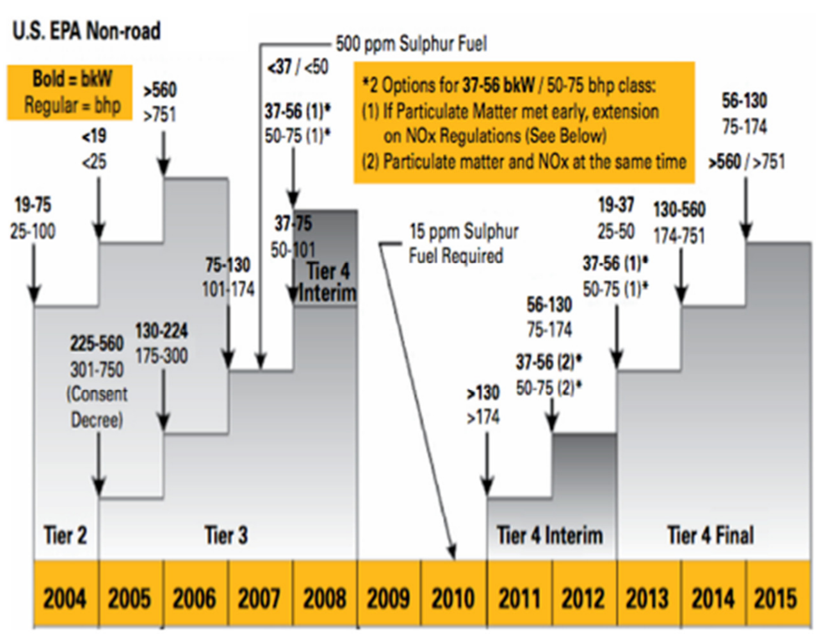

Figure 1. Tiered Emissions Standards Timeline[51]
(Tier 3 Changes for Consent Decrees Signatories)

Other Provisions. Existing Tier 2-3 smoke opacity standards and procedures continue to apply in some engines. Exempted from smoke emission standards are engines certified to PM emission standards at or below 0.07 g/kWh (because an engine of such low PM level has inherently low smoke emission).

The Tier 4 regulation does not require closed crankcase ventilation in nonroad engines. However, in engines with open crankcases, crankcase emissions must be measured and added to exhaust emissions in assessing compliance.

Similarly to earlier standards, the Tier 4 regulation includes such provisions as averaging, banking and trading of emission credits and FEL limits for emission averaging.

APPENDIX C – EPA Methodology for Calculation of Emission Factors for Non Road Engine Model [52]

EPA420-P-02-016 - Update for NonROAD 2008a model

For HC, CO, and NOx, the exhaust emission factor for a given diesel equipment type in a given model year/age is calculated as follows:

$$EFadj(HC, CO, NOx) = EFss \times TAF \times DF \qquad \text{[Equation 1]}$$

where:
EFadj = final emission factor used in model, after adjustments to account for transient operationand deterioration (g/hp-hr)
EFss = zero-hour, steady-state emission factor (g/hp-hr)
TAF = transient adjustment factor (unitless)
DF = deterioration factor (unitless)

The zero-hour, steady-state emission factors (EFss) are mainly a function of model year and horsepower category, which defines the technology type. The transient adjustment factors (TAFs) vary by equipment type. The deterioration factor (DF) is a function of the technology type and age of the engine.

Since PM emissions are dependent on the sulfur content of the fuel the engine is burning, the equation used for PM is slightly modified from equation [1] as follows:

$$EFadj(PM) = EFss \times TAF \times DF - SPMadj \qquad \text{[Equation 2]}$$

where:
SPM_{adj} = adjustment to PM emission factor to account for variations in fuel sulfur content(g/hp-hr)
PM and SO2 are the only diesel pollutants that are dependent on fuel sulfur content.

For BSFC, there is no deterioration applied, so the equation is simplified to:

$$EFadj(BSFC) = EFss \times TAF \qquad \text{[Equation 3]}$$

Emission factors for CO2 and SO2 are calculated based on brake-specific fuel consumption; therefore, the model does not require CO2 or SO2 emission factor input files.
Crankcase HC emissions are simply a fraction (2%) of exhaust HC emissions.

Transient Adjustment Factor
The Transient Adjustment Factor, TAF, is provided by the EPA as a look-up table for each nonroad application in the *EPA420-P-02-016 document.*

Deterioration Factor
For HC, CO, NOx and PM For The NONROAD model addresses the effects of deterioration in the inventory calculation by multiplying a zero hour emission factor for

each category of engine by a deterioration factor, DF (see equation 1 above). DF varies as a function of engine age. The following equation is used to calculate DF as a function of engine age:

$$DF = 1 + A * (\text{Age Factor})^b \quad \text{for Age Factor} \leq 1 \qquad \text{[Equation 4}$$
$$DF = 1 + A \quad \text{for Age Factor} > 1$$

where:

Age Factor = fraction of median life expended = $\frac{cumulative\ hours * load\ factor}{median\ life\ at\ full\ load,\ in\ hours}$

A, b = constants for a given pollutant/technology type; $b \leq 1$.

Deterioration is capped at the end of an engine's median life (age factor =1), under the assumption that an engine deteriorates to a point where any increased deterioration is offset by maintenance.

The constants A and b can be varied to approximate a wide range of deterioration patterns. "A" can be varied to reflect differences in maximum deterioration. For example, setting A equal to 2.0 would result in emissions at the engine's median life being three times the emissions when new (DF = 1 + 2). The shape of the deterioration function is determined by the second constant, "b." This constant can be set at any level between zero and 1.0. **For compression-ignition engines, b is always equal to 1.0**. This results in a linear deterioration pattern, in which the rate of deterioration is constant throughout the median life of an engine.

EPA provides look-up tables for load factor, median life at full load and A constant values in the *EPA420-P-02-016 document.*

Sulfur Adjustment for PM Emissions (SPMadj)

Since PM emissions are dependent on the sulfur content of the fuel, an adjustment (SPM_{adj}) is subtracted from the PM emission factor to account for variations in fuel sulfur content (see equation 2 above). SPM_{adj} corrects PM emissions from the default fuel sulfur level to the episodic fuel sulfur level and is calculated using the following equation:

$$SPM_{adj} = BSFC * 453.6 * 7.0 * soxcnv * 0.01 * (soxbas - soxdsl) \qquad \text{[Equation 5]}$$

where:

SPM_{adj} = PM sulfur adjustment (g/hp-hr)
BSFC = in-use adjusted brake-specific fuel consumption (lb fuel/hp-hr)
453.6 = conversion from lb to grams
7.0 = grams PM sulfate/grams PM sulfur
soxcnv = grams PM sulfur/grams fuel sulfur consumed = 0.02247 for diesel
0.01= conversion from percent to fraction
soxbas = default fuel sulfur weight percent = 0.33 for diesel
soxdsl = episodic fuel sulfur weight percent (specified by user)

APPENDIX D – Fracturing Pumps and their Engines

The pumps used in hydraulic fracture operations may be float- or trailer-mounted or on a skid configuration. The configuration most commonly used for Land jobs is the trailer-mounted. It is designed and used for high-horsepower applications. The single triplex pump delivers fracturing fluids to the well at high pressures and rates. The main manufacturers of their engines are: Caterpillar and Detroit (MTU Detroit in North America is currently named Tognum America).

The Caterpillar Frac pump Unit has a Caterpillar Diesel engine. Its rating is either B or C (Engine rating obtained and presented in accordance with ISO3046/1)[53] depending on the brake horsepower. The engines found during our field-visits/field-tests were all 2250 hp, either CAT 3512B or 3512C. See Figure 1, for details about these ratings.

Well Service Engine Ratings

bhp Range	Engine
41.6-66	C2.2
72-142	C4.4 • C4.4 ACERT
128-275	C6.6 ACERT
188-300	C7 ACERT • C7.1 ACERT
325-375	C9 ACERT • C9.3 ACERT
325-450	C11 ACERT
385-520	C13 ACERT
440-595	C15 ACERT
575-800	C18 ACERT
800-1050	C27 ACERT
800-1500	C32 ACERT
2000-2250	3512B
2150-2500	3512C HD
205-1110	Hazardous Location
205-1225	Watercooled Manifold
680-1665	Watercooled Manifold

B Rating
For service where power and/or speed are cyclic. Typical service examples are: irrigation — where normal pump demand is 85% of engine power, **oil field mechanical pumping**/drilling, independent rotary drive, well service blenders, cementers, and stationary plant air compressors. Typical load factor <85%.

C Rating (Intermittent)
Intermittent service where maximum power and/or speed are cyclic. Typical service examples are: off-highway trucks, fire pump application power, oil field hoisting, nitrogen pumping, **well service kill pumps**, cementers, and electric drill rig power (also called Prime power). Typical load factor <70%.

Figure 1. Caterpillar Well Service Engine Ratings

The Engine operation in Fracking is characterized for being continuous at varying load and speed with duration of reserve power between applied loads. Typical load factor 40-60%.

Caterpillar 3512B Engine

CATERPILLAR®

3512B Petroleum Engine

1492-1678 bkW (2000-2250 bhp) 1900 rpm

Dry Manifold with SCAC

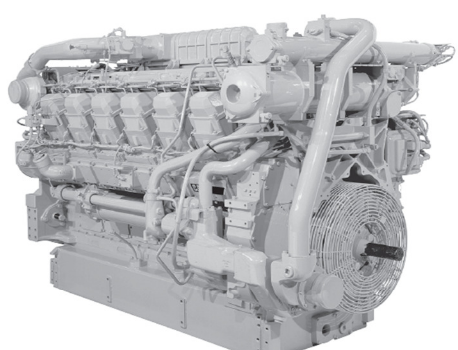

Image is a representation only, and may show optional attachments.

CAT® ENGINE SPECIFICATIONS

V-12, 4-Stroke-Cycle-Diesel
Emissions . . . Non-Current EPA, Non-Road Mobile Tier 1
Peak Torque at Speed . . . . 6219 lbs-ft
Bore . . . . 170 mm (6.7 in.)
Stroke . . . . 190 mm (7.5 in.)
Displacement . . . . 52 L (3173 cu. in.)
Aspiration . . . . Turbocharged-Aftercooled
Governor and Protection . . . . Electronic (ADEM™ A3)
Engine Weight, net dry (approx) . . . 4803.6 kg (10,590 lb)
Capacity for Liquids
Lube Oil System (refill) . . . . 151.4 L (40 gal)
Cooling System . . . . 181.7 L (48 gal)
Oil Change Interval . . . . 250 hours
Rotation (from flywheel end) . . . . Counterclockwise
Flywheel and Flywheel Housing . . . . SAE No. 0
Flywheel Teeth 151

Caterpillar 3512C Engine

3512C HD Petroleum Engine

1603-1864 bkW (2150-2500 bhp) 1900 rpm

Dry Manifold with ATAAC

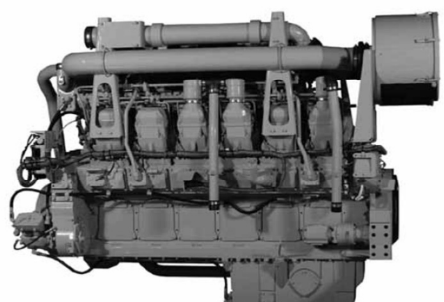

Image is a representation only, and may show optional attachments.

CAT® ENGINE SPECIFICATIONS

V-12, 4-Stroke-Cycle-Diesel

Emissions	Non-current EPA Tier 2
Peak Torque at Speed	6910 lbs-ft
Bore	170 mm (6.7 in)
Stroke	215 mm (8.5 in)
Displacement	58.6 L (3574 in^3)
Aspiration	Turbocharged-Aftercooled
Governor and Protection	Electronic (ADEM™ A3)
Engine Weight, net dry (approx)	6645 kg (14,650 lb)
Capacity for Liquids	
Lube Oil System (refill)	151.4 L (40 gal)
Cooling System	134 L (35.4 gal)
Oil Change Interval*	250 hours
Rotation (from flywheel end)	Counterclockwise
Flywheel and Flywheel Housing	SAE No. 0
Flywheel Teeth	151

*500 hours oil sump pan optional

Figure 2. Engine Specifications for CAT 3512B and 3512C Engines.

Note: For more information about the engines, please refer to its specification sheet. Available at:
http://catoilandgas.cat.com/cda/files/2123529/7/3512B+-+LEHW0055-00+P5.pdf
http://catoilandgas.cat.com/cda/files/2425722/7/3512C+HD+ATAAC+-+Final+LEHW0056.pdf

APPENDIX E – Engines Test Cycles, Certification Fuels and useful Life

Test Cycles and Fuels

ISO 8178 Standards and its use for nonroad engine emission certification

The ISO 8178 is an international standard designed for a number of non-road engine applications. It is used for emission certification and/or type approval in many countries worldwide, including the USA, European Union and Japan. Depending on the legislation, the cycle can be defined by reference to the ISO 8178 standard, or else by specifying a test cycle equivalent to ISO 8178 in the national legislation (as it is the case with the US EPA regulations).

The ISO 8178 is actually a collection of many steady-state test cycles (type C1, C2, D1, etc.) designed for different classes of engines and equipment. Each of these cycles represents a sequence of several steady-state modes with different weighting factors.

ISO 8178 test Cycles – Steady State Testing
The ISO 8178 test cycle—or its 8-mode schedule C1 in particular—can be also referred to as the "Non-Road Steady Cycle", NRSC.

The particular engine modes and their weighting factors for B-type (11 mode) test cycles are listed in Table 1. The standard also includes an A-type 13-mode cycle, which is not listed in the table (ISO standards can be ordered through the ISO website).

Mode number	1	2	3	4	5	6	7	8	9	10	11
Torque, %	100	75	50	25	10	100	75	50	25	10	0
Speed	Rated speed					Intermediate speed			Low Reserve Power		
Constant speed											
Type D1	0.30	0.50	0.20	-	-	-	-	-	-	-	-
Type D2 (Used for Frac Pumps)	**0.05**	**0.25**	**0.30**	**0.30**	**0.10**	**-**	**-**	**-**	**-**	**-**	**-**

Notes:
- Engine torque is expressed in percent of the maximum available torque at a given engine speed
- Rated speed is the speed at which the manufacturer specifies the rated engine power
- Intermediate speed is the speed corresponding to the peak engine torque.

Table 1 . ISO 8178 Test Cycles. Weighting Factors of B-Type

Nonroad engine emissions are measured on a steady-state test cycle that is nominally the same as the ISO 8178[54] C1, 8-mode steady-state test cycle. For frac type applications the test cycle used is the D-2 cycle. Other ISO 8178 test cycles are allowed for selected applications, such as constant-speed engines (D2 5-mode cycle), variable-speed engines rated under 19 kW (G2 cycle), and marine engines (E3 cycle).

Transient Testing.
Tier 4 standards have to be met over both the steady-state test and the nonroad transient cycle, NRTC[55]. The transient testing requirements begin with MY 2013 for engines

below 56 kW, in 2012 for 56-130 kW, and in 2011 for 130-560 kW engines. **Engines above 560 kW are not tested on the transient test.** Also constant-speed, variable-load engines of any power category are not subject to transient testing. The NRTC protocol includes a cold start test. The cold start emissions are weighted at 5% and hot start emissions are weighted at 95% in calculating the final result.

Tier 4 nonroad engines will also have to meet not-to-exceed standards (NTE), which are measured without reference to any specific test schedule. The NTE standards become effective in 2011 for engines above 130 kW; in 2012 for 56-130 kW; and in 2013 for engines below 56 kW. In most engines, the NTE limits are set at 1.25 times the regular standard for each pollutant (in engines certified to NOx standards below 2.5 g/kWh or PM standards below 0.07 g/kWh, the NTE multiplier is 1.5). The NTE standards apply to engines at the time of certification, as well as in use throughout the useful life of the engine. The purpose of the added testing requirements is to prevent the possibility of "defeating" the test cycle by electronic engine controls and producing off-cycle emissions.

Certification Fuels.
Fuels with sulfur levels no greater than 0.2 wt% (2,000 ppm) are used for certification testing of Tier 1-3 engines. From 2011, all Tier 4 engines will be tested using fuels of 7-15 ppm sulfur content. A transition from the 2000 ppm S specification to the 7-15 ppm specification will occur in the 2006-2010 period.[56]

A change from measuring total hydrocarbons to nonmethane hydrocarbons (NMHC) has been introduced in the 1998 rule. Since there is no standardized EPA method for measuring methane in diesel engine exhaust, manufacturers can either use their own procedures to analyze nonmethane hydrocarbons or measure total hydrocarbons and subtract 2% from the measured hydrocarbon mass to correct for methane.

Engine Useful Life
Emission standards listed in the above tables must be met over the entire useful life of the engine. EPA requires the application of deterioration factors (DFs) to all engines covered by the rule. The DF is a factor applied to the certification emission test data to represent emissions at the end of the useful life of the engine (See details about Deterioration Factor in Appendix C)
The engine useful life and the in-use testing liability period, as defined by the EPA for emission testing purposes, are listed in Table 2 for different engine categories. The Tier 4 rule maintains the same engine useful life periods.

Power Rating	Rated Engine Speed	Useful Life		Recall Testing Period	
		hours	years	hours	years
< 19 kW	All	3000	5	2250	4
19-37 kW	constant speed engines ≥3000 rpm	3000	5	2250	4
	all others	5000	7	3750	5
>37 kW	All	8000	10	6000	7

Table 2. Useful Life and Recall Testing Periods

APPENDIX F – Support Information for Results Section

Equipment	Engine Specifications					Engine Emission Factors			
	No. of Units	No. of Engines/Unit	Engine Rating (hp)	Total Time (hrs)	Load Factor Average (%)	NOx EF (lb/hp-hr)	HC EF (lb/hp-hr)	CO EF (lb/hp-hr)	PM EF (lb/hp-hr)
Operation Equipment									
Frac Pumps	14	1	2,250	27	60	0.009039	0.000368	0.001685	0.000290
Frac Blender	1	2	475	27	43	0.010053	0.000529	0.005732	0.000331
Frac Control and Recording Van	1	1	75	98	50	0.011729	0.000617	0.008157	0.000661
Hydration Unit (PCM - Precision Continuous Mixer)	1	1	475	27	50	0.010053	0.000529	0.005732	0.000331
Sand Chief (Loading/Unloading proppant)	2	1	120	20	43	0.010263	0.000540	0.008157	0.000485
Ancilary Equipment									
Water Transfer Pump	1	1	384	27	43	0.010053	0.000529	0.005732	0.000331

Table 1. Data Input, including emission factors used for calculating emissions from the frac fleet for a Fracking Stage at the Eagle Ford Shale

Equipment	Engine Specifications					Engine Emission Factors			
	No. of Units	No. of Engines/Unit	Engine Rating (hp)	Total Time (hrs)	Load Factor Average (%)	NOx EF (lb/hp-hr)	HC EF (lb/hp-hr)	CO EF (lb/hp-hr)	PM EF (lb/hp-hr)
Operation Equipment									
Frac Pumps	16	1	2,250	31	50	0.009039	0.000368	0.001685	0.000290
Frac Blender	1	2	520	31	43	0.010053	0.000529	0.005732	0.000331
Frac Control and Recording Unit	1	1	75	82	50	0.011729	0.000617	0.008157	0.000661
Hydration Unit (PCM - Precision Continuous Mixer)	1	1	475	31	50	0.010053	0.000529	0.005732	0.000331
Sand Chief (Loading/Unloading proppant)	2	1	127	15	43	0.010263	0.000540	0.008157	0.000485
Ancilary Equipment									
Water Transfer Pump	1	1	384	31	43	0.010053	0.000529	0.005732	0.000331

Table 2. Data Input, including emission factors used for calculating emissions from the frac fleet for a Fracking Stage at the Marcellus Shale

APPENDIX G –Diesel fuel Specifications[57]

In the United States, diesel fuel is controlled according the American Society for Testing and Materials Standard D975-97. This standard describes a limited number of properties that diesel fuels must meet. It should be noted that the requirements are all performance-based. They do not mandate the composition of the fuel, only the specific performance related requirements demanded of a fuel for a diesel engine. The requirements of D975-97 are described below.

ASTM Specifications for Diesel Fuel Oils (D975-97)
Diesel fuel is characterized in the United States by the ASTM standard D 975. This standard identifies five grades of diesel fuel described below.

Grade No. 1-D and Low Sulfur 1-D: A light distillate fuel for applications requiring a higher volatility fuel for rapidly fluctuating loads and speeds as in light trucks and buses. The specification for this grade of diesel fuel overlaps with kerosene and jet fuel and all three are commonly produced from the same base stock. One major use for No. 1-D diesel fuel is to blend with No. 2-D during winter to provide improved cold flow properties. Low sulfur fuel is required for on-highway use with sulfur level < 0.05%.

Grade No. 2-D and Low Sulfur 2-D: A middle distillate fuel for applications that do not require a high volatility fuel. Typical applications are high-speed engines that operate for sustained periods at high load. Low sulfur fuel is required for on-highway use with sulfur level < 0.05%.

Grade No. 4-D: A heavy distillate fuel that is viscous and may require fuel heating for proper atomization of the fuel. It is used primarily in low and medium speed engines. ASTM D975 specifies the property values shown in Table 2 for these grades of diesel fuel. The surprising aspect about ASTM D 975 is how few requirements are actually included. The standard says nothing about the composition of the fuel or its source. It only defines some of the property values needed to provide acceptable engine operation and safe storage and transportation.

Requirements for Diesel Fuel Oils (ASTM D 975-97)

	Grade	Grade	Grade	Grade	Grade
Property	LS #1	LS #2	No. 1-D	No. 2-D	No. 4-D
Flash point °C, min	38	52	38	52	55
Water and sediment, %					
vol, max.	0.05	0.05	0.05	0.05	0.50
Distillation temp., °C, 90%					
Min.	--	282	--	282	--
Max.	288	338	288	338	--
Kinematic Viscosity,					

mm^2/s at 40°C					
Min.	1.3	1.9	1.3	1.9	5.5
Max.	2.4	4.1	2.4	4.1	24.0
Ramsbottom carbon residue,					
on 10%, %mass, max.	0.15	0.35	0.15	0.35	--
Ash, % mass, max.	0.01	0.01	0.01	0.01 0.10	
Sulfur, % mass, max	0.05	0.05	0.50	0.50 2.00	
Copper strip corrosion,					
Max 3 hours at 50°C	No. 3	No. 3	No. 3	No. 3	--
Cetane Number, min.	40	40	40	40	30
One of the following					
Properties must be met:					
(1) cetane index	40	40	--	--	--
(2) Aromaticity,					
% vol, max	35	35	--	--	--

APPENDIX H – Solutions/Alternatives for Reduction of Emissions

Next Generation of Frac Pump Engines and Other "Less Emissions" Alternatives

Caterpillar – Dynamic Gas Blending[58]

Flexible Control
Lower emission levels and operating costs with a single technology. Use gas when it's available and automatically modulate gas substitution when needed. Cat® Dynamic Gas Blending continuously adjusts to changes in incoming fuel quality and pressure, allowing your engines to run on a wide variety of fuels, from associated gas to gasified LNG, all while consistently maintaining your diesel power and transient performance.

- Lower fuel costs with up to 70% replacement of diesel with gas
- Maintain existing service intervals and component life
- Improve display performance and troubleshooting capability with ADEM™ A4 and EMCP 4.4 controls
- Capability to reduce gas flaring by consuming dry field gas for less environmental impact
- Maintain original engine emissions certifications with retrofit kit

Your Cat dealer will help you implement a complete package or a retrofit kit compatible with your generator sets. Using existing Caterpillar gas engine hardware with no changes to core components, you can be up and running quickly with Dynamic Gas Blending.

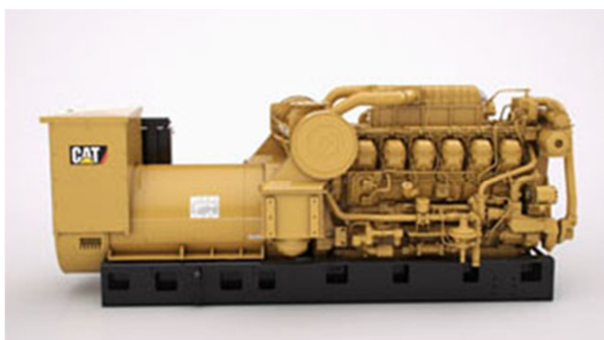

Figure 1. Cat® Dynamic Gas Blending Engines

MTU Detroit – Series 4000[59]
With the next generation Series 4000, MTU Detroit provides the perfect Tier 4-ready frac engine – hitting the sweet spot in terms of performance, reliability and life-cycle costs. Designed to meet EPA Tier 4i, MTU's Series 4000 engine is the technological base for the future requirements of Tier 4 final. It offers a solid foundation to ensure your success – today and in the future. The new MTU Series 4000 engine has been designed for the specific requirements of the frac application, offering more torque, lower fuel consumption, and no after-treatment.

MTU EGR Technology
MTU’s current engines > 560 kW (751 bhp) achieve EPA Tier 4i emissions with integrated cooled Exhaust Gas Recirculation (EGR) - without the need for additional after-treatment. So no extra tanks or fluids required.
As the key emissions control technology, MTU Exhaust Gas Recirculation (EGR) is tried and tested in the field and has successfully proven its reliability in even the toughest situations. The new MTU Series 4000 is ready to order from your MTU distributor.

MTU Series 4000 Tier 4i – Benefits:

- Cost-effectiveness
  - No additives needed for emissions control due to in-engine technologies
  - Up to 5% better fuel economy*
  - Lower life-cycle costs*
  - Uncompromising durability, availability and reliability for more uptime
  - Maintenance intervals optimized for individual application
- Performance
  - 12V 4000 T94L rated at 2500 bhp (1865 kW)
  - 12V 4000 T94 rated at 2250 bhp (1678 kW)
  - Performance map optimized for frac application: More low-end torque
  - Full performance available beyond 4,000 m (13,000 ft)
  - Optimized power-to-weight ratio
  - compared to EPA Tier 2 engine

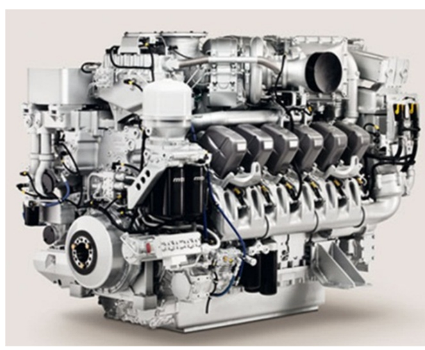

Figure 2. MTU Detroit New Generation of Frac Engines – Series 4000

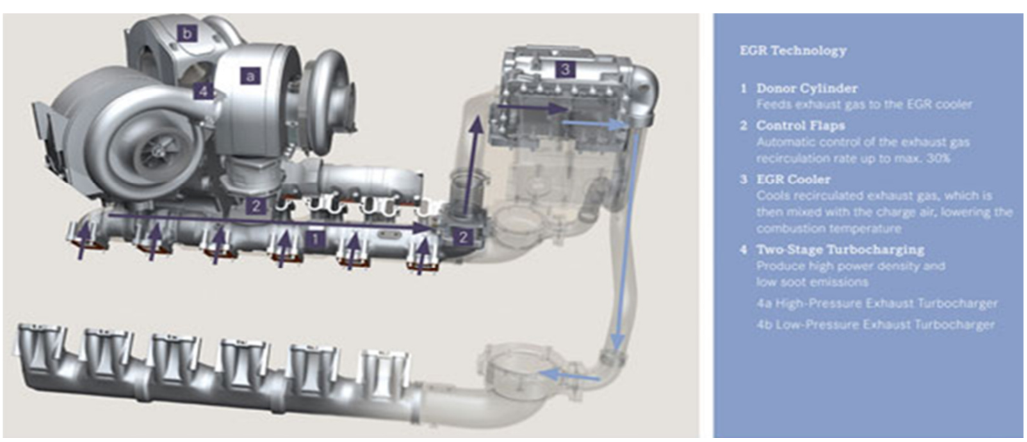

Figure 3. MTU Detroit EGR Technology – The New Tech for Frac Engines

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