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Environmentally Friendly Drilling Systems Program

White Paper – A Comparison of Air Emission Estimation Methods for Drilling Rig Emissions

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This project was conducted by the Texas A&M Institute of Renewable Natural Resources. This project is part of the Environmentally Friendly Drilling Program (managed by the Houston Advance Research Center – HARC and the Texas A&M Global Petroleum Research Institute - GPRI).

Introduction

There are three main methods for collecting air emissions data. It can be directly measured at the engine tailpipe, it can be measured through ambient downwind monitoring, or it can be estimated through a collection of engine data, fuel data and emission factors for the family of engines being studied. Emission estimation is a cost effective way to calculate emissions at a regional level and is typically why this method is used for conducting air emission inventories to determine the air quality impact from a particular industry.

The Texas Commission on Environmental Quality (TCEQ) has determined that the Eagle Ford and its supporting industry will be included in future air emission inventories. However, the current methods for calculating emissions impose error in the inventory thus leading to a compounding variance in the regional air shed models. It is believed that the variance results from the quality of data being entered into the equations as well as the equations themselves.

Based on our study, we have determined a more accurate means to estimate emissions from drilling operations. The Institute of Renewable Natural Resources (IRNR) researchers teamed with industry partners to create new methods of estimating emissions from drilling rigs via data collection directly from energy producers with active operations in the Eagle Ford Shale Play.

Since drilling engines have high variability in engine load, conducting an air emission inventory of drilling rigs requires a novel way to calculate emissions. That is, a way to estimate emissions without relying on engine load as a primary variable. The team developed a calculation, designed for drilling rigs, that used fuel consumption data rather than total horsepower and engine load data. This method appeared to minimize error and therefore gave a more accurate picture of drilling engine activity.

This project was conducted by Texas A&M IRNR which is part of the Environmentally Friendly Drilling Systems Technology Integration Program (managed by the Houston Advanced Research Center – HARC and the Texas A&M Global Petroleum Research Institute - GPRI).

Materials and Methods

Planning

Planning for the drilling rig study began with the formation of the Eagle Ford Air Emission Inventory Group. The group consisted of Texas A&M Agrilife Research, Alamo Area Council of Governments (AACOG), ConocoPhillips, Chesapeake Energy, Marathon Oil, Carrizo, EOG Resources, HOLTCAT, Pioneer Natural Resources, Energy Transfer, Plains Exploration and Production, Shell Oil and the Texas Oil and Gas Association (TxOGA).

Initial meetings consisted of introductory presentations and a description of how emissions inventories are typically calculated. This posed concern to the operators due to the fact that emissions inventories multiply total *potential* engine load by total *available* horse power. According to drilling engineers participating in the group, generator engines for electrical rigs rarely run at full engine load and there may be several engines located on site as back-up that are not running at all. Furthermore, engine load fluctuates during a drilling operation and therefore standardization would be a sizable challenge with risk of significant error. Therefore, it was agreed that using fuel consumption as an alternative method to using total potential horsepower and engine load would yield a clearer picture of actual emissions. What resulted was a refined equation for estimating emissions from drilling rigs. We refer to this new method as the "Fuel Consumption Method".

Data Collection

Fuel consumption data was simpler to obtain than engine load data and could be acquired directly from the operators without site visits or the acquisition of highly sensitive engine controller data from the service providers. This is good news since most air emission inventories are survey driven and do not include site visits or nondisclosure agreements.

Data was collected by submitting a survey to nine participating companies within the Eagle Ford Air Emission Inventory Group operating within the Eagle Ford Shale Play.

The following data was gathered on the survey for both mechanical and electric drilling rigs:

1. Company Name
2. Year for which data was given – in this case, 2012
3. Number of wells drilled in 2012
4. Number of rigs used in 2012
5. Annual hours rigs operated in 2012
6. Cumulative depth drilled (in feet)
7. Emission control type (tier 1, 2, 3 or 4)
8. Fuel type used (diesel, natural gas etc.)
9. Gallons of fuel consumed
10. Percent of time ancillary equipment (Loaders, forklifts, pumps etc.) was used

11. Percent of old engines replaced with tier 4 by 2015
12. Percent of old engines replaced with tier 4 by 2018
13. Equipment class (example Patterson, Trinidad, etc.)
14. Number of engines used in drilling operation
15. Total available horsepower of each engine
16. Engine model year
17. Engine make and model (example Caterpillar, Cummins, Detroit etc.)

Field data from the surveys were compared with default data from literature using the fuel consumption method. Additionally, emission results from the fuel consumption method were compared with emission results from the horsepower method.

Data Analysis

Understanding Emission Factors

In order to understand how emissions are estimated, it is first necessary to understand emission factors. An emission factor is a representative value that relates the quantity of a pollutant released to the atmosphere with an activity associated with the release of that pollutant. 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. Such factors facilitate estimation of emissions from various sources of air pollution. 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 a particular source category. The emission factor is used to calculate the total emission from a source as an input for the emission inventory (USEPA, 2014).[1]

The general USEPA equation for emission factor development is:

E = A x EF x (1-ER/100)

Where:

E = emissions
A = activity rate
EF = emission factor
ER = overall emission reduction efficiency, %

General emission factors are available to the public. However, variations in the conditions with a given engine, such as temperature of combustion, and emission controls, can significantly affect the emissions at an individual location. Whenever possible, the development of local emission factors is highly desirable (USEPA, 2014).[2]

Emissions of criteria pollutants are usually given as mass of pollutant emitted per mechanical energy produced by the engine, (i.e. g/kWh). The energy developers participating in the study reported using Caterpillar 3512C diesel generator sets that were rated Tier 2.

Emission values that most closely represented the 3512C engines were found on the California Air Resources Board (CARB) certificate (CARB, 2007)[3]. These criteria pollutant values were derived from emission tests for zero hour steady state emissions and were performed by the manufacturer on 3512C engines operating at nominal power and speed.

Slightly more conservative than CARB, the USEPA also publishes emission standards that may be used as factors for this particular engine make and model. These values constitute allowable emissions and take such factors into consideration as engine deterioration and operations at less than nominal conditions. These values may be used in lieu of the CARB certificate values but are generally much more conservative.

Next there are the AP-42 standards which publish much generalized standards for engines greater than 750 horse power. AP-42 divides the values into controlled and uncontrolled standards for oxides of nitrogen or NOx. Controlled standards take into account associated emission controls on large engines, while uncontrolled standards make the assumption that the engine has no emission controls for NOx (ie Tier zero).

Table 1 gives the range of various emission factors and standards that are allowable for use when conducting an emission inventory with the aforementioned engine type. Note that both EPA and CARB combine the NOx and volatile organic compounds (VOCs) into a single number which the table refers to as non-methane hydrocarbon plus NOx (NMHC+NOx) where NMHC is also referred to as VOCs. The CARB Air Quality Management District guidelines were used (Moyer, 2005)[4] to separate the two values into NOx and VOC which states that emission factors for NOx equals 95% of the total sum NMHC+NOx.

The VOC values for AP-42 NOx controlled and uncontrolled engines were obtained from an EPA total organic carbon (TOC) value which according to the EPA (1996),[5] is by weight 9% methane and 91% non-methane. Therefore, the original TOC values of 0.43 were adjusted for both controlled and non-controlled engines by multiplying 0.91. The remainder of criteria pollutants (VOCs, CO and PM) are the same for both controlled and uncontrolled engines because the "controls" EPA refers to is for NOx only.

Table 1: Emission Values Available for Caterpillar 3512C Engines. Units are g/kWh

Emission Factors/Standards	NMHC NOX	NOX	VOC	PM	CO
Caterpillar 3512C Emission Factor CARB	5.3	5.04	0.27	0.14	1.6
Caterpillar 3512C Emission Standard - EPA	6.4	6.08	0.32	0.2	3.5
AP42 Controlled Engine greater than 750 hp		7.91	0.43	0.43	3.35
AP42 Uncontrolled Engine greater than 750 hp		14.6	0.43	0.43	3.35

Calculation Using Fuel Consumption Method with Field Data

The amount of No. 2 diesel (gallons) used to drill a well was averaged on a per hour basis for 41 electric rigs operating in the Eagle Ford Shale play throughout 2012. The resulting average was 55 gallons of diesel used per hour for a typical diesel Tier 2, 3512C Land Drilling Generator Set Engine. The gallons per hour (gal/hr) average was converted to pounds per hour (lb/hr) using average density for No. 2 diesel of 7 pounds per gallon (lb/gal) (API, 1988)[6].

The calculation for converting gal/hr to lb/hr follows:

Fuel Usage Average = 55 gal/hr x 7 lb/gal = 385 lb/hr

Engine data used was for a 2008, Tier 2, Diesel Compression-Ignition off-road engine listed as engine family: 8CPXL58.6T2X (CARB, 2007)[7]. Based on interviews with drilling engineers, 50% load for Brake Specific Fuel Consumption (BSFC) of No. 2 Diesel on the 3512C drilling rig generator sets were considered most typical for a drilling operation in the Eagle Ford.

The emission factor from the CARB certificate for the 3512C Tier 2 engine (CARB, 2007)[8] used most often by energy developers who provided data is as follows:

NMHC + NOx Emission Factor = 5.3 g/kW-hr

In order to separate oxides of nitrogen (NOx) from non-methane hydrocarbons (NMHC), also referred to as Volatile Organic Compounds (VOCs), the CARB Air Quality Management District guidelines were used (Moyer, 2005)[9] which stated that emission factors for NOx equals 95% of the total sum NMHC+NOx or:

CARB Emission Factor for NOx = NMHC+NOx EF x 95% = 5.04 g/kW-hr

Next, a conversion from g/kW-hr to lb/hp-hr was calculated:

Emission Factor for NOx = 5.04 g/kW-hr x (lb/453.59 g x kW/1.3405 hp) = 0.008280 lb = 0.008 lb_{NOx}/hp-hr

The equation for pounds of NOx per hour follows:

[E]lb_{NOx}/hr = {[Fuel $Usage_{avg}$ (lb fuel/hr)]/[BSFC (lb fuel/hp-hr)]} x (EF_{NOx} = lb_{NOx}/hp-hr)

Placing the numbers into the equation yields the following:

[E]lb_{NOx}/hr = (385 lb fuel/hr)/(0.35 lb fuel/hp-hr) x (0.008 lb_{NOx}/hp-hr) = 9.1 lb_{NOx}/hr

Carbon Monoxide (CO), VOC, and Particulate Matter (PM) were also calculated and are located in the results section of this report.

Calculation using Fuel Consumption Method and Default Data:

Emission standards from USEPA for the 1,476 horsepower 3512C Land Drilling Generator Sets were chosen as a default standard. This would be the factor most likely chosen in an emission inventory if the engine make and model was known but little else about the operation. Standards for NOx, CO, VOC and PM were calculated based on the fuel input factors provided from AP-42 (EPA, 1996)[10].

The No. 2 diesel fuel usage value of 69.5 gallons per hour was provided on the Caterpillar technical data sheet for the 3512C Land Drilling Generator Set as a “nominal” or best guess value (Caterpillar, 2013)[11].

The equation to calculate NOx emissions using default data follows:

EPA 3512C Emission Standard for NOx = 6.08 g/kW-hr

Next, a conversion from g/kW-hr to lb/hp-hr was calculated as follows:

Emission Factor for NOx = 6.08 g/kW-hr x (lb/453.59 g x kW/1.3405 hp) = 0.01 lb $_{NOx}$/hp-hr

The equation for pounds of NOx per hour follows:

[E]lb_{NOx}/hr = {[Fuel $Usage_{avg}$ (lb fuel/hr)]/[BSFC (lb fuel/hp-hr)]} x (EF_{NOx} = lb_{NOx}/hp-hr)

Placing the numbers into the equation yields the following:

[E]lb_{NOx}/hr = (486.5 lb fuel/hr)/(0.33 lb fuel/hp-hr) x (0.01 lb_{NOx}/hp-hr) = 14.74 lb_{NOx}/hr

CO, VOC, and PM were also calculated and are located in the results section of this report.

Calculation using the Traditional Horse Power Method:

The horse power method is the traditional approach to air emission inventories. The method consists of multiplying the emission factor by the total available horsepower, by the engine load to achieve pollutant emissions in pounds per hour. Since engine load can fluctuate dramatically during a drilling operation, engine load field data is typically not an option and is therefore conservatively estimated at 100%. Hourly emission rates were calculated using conservative default emission standards for NOx controlled diesel engines found in US EPA AP-42.[12]

In order to make a clean comparison, the same generator sets were used in this method as were used in the fuel consumption method. That is the 1,476 horsepower Caterpillar, Tier 2, 3512C drilling generator sets operated with diesel fuel. There are 3 of these generator sets on site for a typical drilling operation in the Eagle Ford.

1,476 hp x 3 engines = 4,428 hp_{total}

The emission equation for NOx follows:

$E_{NOx} = EF \times HP_{total} \times LF$

Where,

E_{NOx} = NO_x Emissions (lb/hr)
EF_{NOx} = NO_x Emission Factor (lb NO_x/hp-hr)
HP_{total} = Total potential power output (hp)
LF = Load factor (assumed to be 100%)

The equation to calculate NOx emissions using default data follows:

EPA NOx Controlled Engine Emission Standard for NOx = 7.91 g/kW-hr

Next, a conversion from g/kW-hr to lb/hp-hr was calculated as follows:

Emission Factor for NOx = 7.91 g/kW-hr x (lb/453.59 g x kW/1.3405 hp) = 0.013 lb_{NOx}/hp-hr

The equation to calculate NOx using the horse power method follows:

E_{NOx} = 0.01 lb/hp-hr (100%) 4,428 Hp = 57.64 lbs_{Nox}/hr

CO, VOC, and PM were also calculated and are located in the results section of this report. Note that the AP-42 *uncontrolled* standard for NOx is twice as high as it is for controlled engines. If therefore, we were to substitute the uncontrolled engine standard into the equation, the emissions estimation for NOx would increase significantly.

For example:

EPA NOx Uncontrolled Engine Emission Standard for NOx = 14.6 g/kW-hr

Next, a conversion from g/kW-hr to lb/hp-hr was calculated as follows:

Emission Factor for NOx = 14.6 g/kW-hr x (lb/453.59 g x kW/1.3405 hp) = 0.02 lb $_{NOx}$/hp-hr

The equation to calculate NOx using most conservative values follows:

E_{NOx} = 0.02 lb/hp-hr (100%) 4,428 Hp = 106.32 lbs$_{Nox}$/hr

Results

Making the Comparisons

Calculations were performed for each of the criteria pollutants using each of the protocols described in the sections above. Results indicate that pounds of pollutants reported for the same operation could vary as much 97.21 pounds depending on the protocol chosen.

- NOx Fuel Consumption Method Using Field Data and CARB Emission Factor = 9.11 lb/hp-hr
- NOx Fuel Consumption Method Using Default Data and EPA Emission Standard = 14.74 lb/hp-hr
- NOx Horse Power Method Using AP-42 Engine NOx Controlled Emission Factor = 57.60 lb/hp-hr
- NOx Horse Power Method Using AP-42 NOx Uncontrolled Engine Emission Factor = 106.32 lb/hp-hr

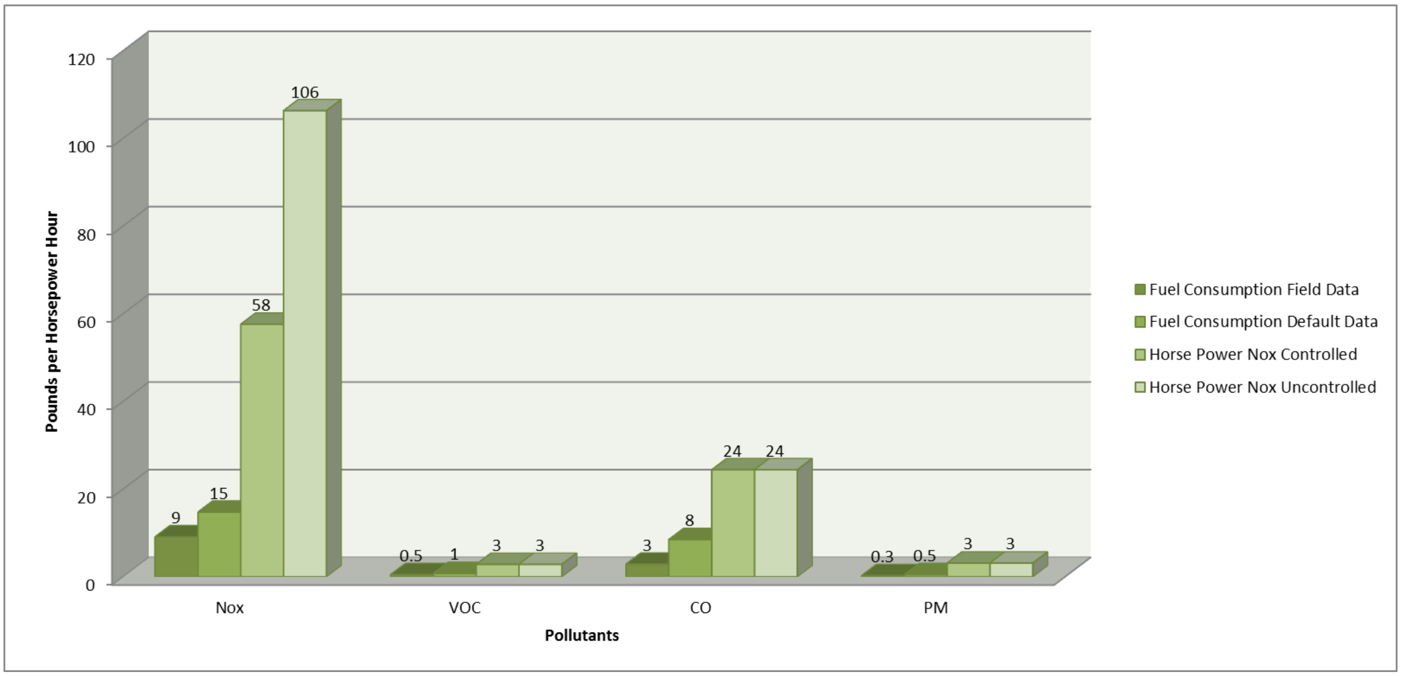
- VOC Fuel Consumption Method Using Field Data and CARB Emission Factor = 0.48 lb/hp-hr
- VOC Fuel Consumption Method Using Default Data and EPA Emission Standard = 0.77 lb/hp-hr
- VOC Horse Power Method Using AP-42 Emission Factor = 2.84 lb/hp-hr

- CO Fuel Consumption Method Using Field Data and CARB Emission Factor = 2.89 lb/hp-hr
- CO Fuel Consumption Method Using Default Data and EPA Emission Standard = 8.49 lb/hp-hr

- CO Horse Power Method Using AP-42 Emission Factor = 24.40 lb/hp-hr

- PM/PM10 Fuel Consumption Method Using Field Data and CARB Emission Factor = 0.25 lb/hp-hr
- PM/PM10 Fuel Consumption Method Using Default Data and EPA Emission Standard = 0.48 lb/hp-hr
- PM/PM10 Horse Power Method Using AP-42 Emission Factor = 3.13 lb/hp-hr

Figure 1: Comparison of Air Emission Inventory Protocols for the Same Drilling Operation units are lb/hp-hr.



Discussion

The Right Protocol for the Right Job

For the same operation, results varied from 9 to 106 pounds per hour for NOx depending on the protocol chosen. On average, using fuel consumed to calculate emissions rather than total horse power yielded a lower pound per hour rate. This was expected since the horse power method was reliant upon engine load which defaulted to 100% as well as the assumption that generators were all operational at all times. Estimating emissions using fuel consumption data was shown to better account for engine activity under field conditions.

With that said, the question often gets asked – if the fuel consumption method yields more accurate results for drilling operations, then why not use this method for fracturing operations as well? The answer lies within data availability. On a Frac Spread, acquiring fuel consumption data for a few select engines (such as the frac pumps for instance) can be quite challenging since fuel is typically supplied by 1 or 2 tanker trucks and then routed throughout the pad for a whole host of activities and many types of equipment. Engine load from frac pumps however remains fairly stable and can be estimated with some degree of confidence. Therefore, using the horsepower method may be best option in that situation.

A drilling operation is different. Fuel consumption data is fairly simple to obtain since only 2 or 3 generators supply power for the electric rigs. On the other hand, drill rig generator engine load is highly variable and changes throughout the job and can be adjusted to account for well depth, geologic formation, type of petroleum product being extracted, type of well drilled, type of mud used, type of equipment used and company philosophy. So for this type of activity, it might be best to consider using the fuel consumption method.

A Note on Tiered Engines

Tier 1-3 Standards - The first federal standards (Tier 1) for new non-road (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 non-road 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 after treatment (oxidation catalysts). Tier 3 standards for NOx and hydrocarbons are similar in stringency to the 2004 standards for highway engines; however Tier 3 standards for PM were never adopted.[13]

Tier 4 Standards - On May 11, 2004, the EPA signed the final rule introducing Tier 4 emission standards, which are to be phased-in over the period of 2008-2015.[14] The Tier 4 standards require that emissions of PM and NOx be further reduced by about 90%. Such emission reductions can be achieved through the use of control technologies—including advanced exhaust gas after treatment—similar to those required by the 2007-2010 standards for highway engines.

Conclusion

Since drilling engines have high variability in engine load, conducting an air emission inventory of drilling rigs required a novel way to calculate emissions. That is, a way to estimate emissions without relying on engine load as a primary variable. However, for other upstream operations such as completions, traditional methods that utilize horse power and engine load as variables may be better suited if fuel consumption data is unavailable.

Most importantly, the emission results of an air emission inventory can dramatically vary depending on the type of calculations and methods chosen. In order to achieve most accurate results, use as much field data as possible as well as emission factors that are best suited to the engines being inventoried.

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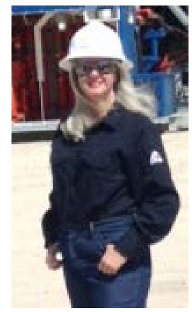

Dr. Stuver has over 25 years of experience directing the planning, acquisition, development and technical execution of environmental projects supporting the Oil and Gas Industry throughout the US and oversees. Dr. Stuver was instrumental in the development of a new methodology to estimate emissions for fracturing and drilling operations based on activity data, load factors and fuel consumption rather than worst case estimates. She was recently awarded a 1.2 million dollar contract that focuses on developing and improving a nationwide understanding of the potential challenges posed by fugitive methane emissions that occur during upstream oil and gas processes. As manager of the Environmentally Friendly Drilling Systems West Regional Center, Dr. Stuver oversees oil and gas research projects on all shale plays west of the Mississippi that reduce air emissions, enhance re-use technologies of flow back water, desalinization technologies for brine treatment, data distribution technologies and invasive species management. Dr. Stuver holds a Doctorate in Environmental Engineering and Environmental Science from the University of Texas at San Antonio (2007), a Master's of Science in Environmental Science and GIS Spatial Analysis at the University of Texas at San Antonio (2002), and a Bachelor's of Science in Biology and Chemistry from the University of Central Missouri (1994). She is an executive board member on the Alamo Area Council of Governments, Air Improvement Resources Executive Committee and has served as the Director for Relationships and Recognition on the Executive board for the Society of American Military Engineers, the President of the Air Waste Management Association and has been a board member on numerous committees to include Texas Cooperative Extension, Energy Efficiency Task Force, Clean Cities and Clean Texas. Dr. Stuver is a distinguished Veteran from the US Army and a graduate of Leadership Texas class of 2011.

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As a program manager at the Texas A&M Institute of Renewable Natural Resources (IRNR), Jesse Alonzo works on research and development projects related to air quality management and compliance. He is involved in several studies of air emissions sources at oil and gas production sites in the Texas Coastal and Eagle Ford Shale areas in association with the Houston Advanced Research Center's Environmentally Friendly Drilling program. These studies are aimed at identifying the type and amount of pollutants and developing best management practices for improving the measurement/quantification of emissions and minimizing the impact on regional air quality from these operations. Before joining the IRNR, Mr. Alonzo had worked for the Texas Commission on Environmental Quality as an air quality permit engineer and as an environmental consultant to the U.S. Department of Defense and industry clients for consulting firms. He also worked for the Texas A&M Center for Applied Technology. Mr. Alonzo received a bachelor of science in civil engineering degree in 1992 from the University of Texas at Austin. Previously, he served in the U.S. Air Force as an air traffic controller.