DEVELOPMENT OF A DATA COLLECTION METHODOLOGY FOR EXAMINING CONSTRUCTION EQUIPMENT EMISSIONS AND IN-CAB AIR QUALITY

A Thesis

by

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ABSTRACT

In the United States heavy duty diesel equipment (HDDE) is a contributor of greenhouse gases (GHG) in the transportation sector. Carbon dioxide (CO_2), nitrogen oxides (NOx), hydrocarbon, carbon monoxide (CO), and particulate matter (PM) are a concern for the operators of the equipment. The major objective of this study is to investigate the relation between tailpipe emissions from the equipment and the corresponding air quality inside the cab. The question we are looking to answer is: can we develop a methodology for data collection by utilizing portable emissions measurement systems (PEMS) and other small data collection devices to collect emissions data directly from the exhaust pipe of the equipment and air quality inside the cab? In this project we will look at what data collection equipment is needed and how to create a methodology to collect HDDE tailpipe emissions and the in-cab air quality. The outcome from this project will be a methodology for measuring in-cab air quality and tailpipe emissions on HDDE for potential human health studies for construction workers.

ACKNOWLEDGMENTS

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NOMENCLATURE

CARTEEH	Center for Advancing Research in Transportation Emissions, Energy, and Health
TTI	Texas A&M Transportation Institute
EPA	Environmental Protection Agency
HDDE	Heavy duty diesel equipment
PEMS	Portable emissions measurement system
GHG	Greenhouse gases
CO_2	Carbon Dioxide
NO_x	Nitrogen Oxides
NO	Nitrogen Monoxide
NO_2	Nitrogen Dioxide
CO	Carbon Monoxide
PM	Particulate matter
DPM	Diesel particulate matter
BC	Black carbon
UFP	Ultrafine particles
RPM	Rotations per minute
ECM	Electronic control module
Mg/m^3	Milligrams per cubic meter
GPS	Global positioning satellite

TABLE OF CONTENTS

LIST OF FIGURES

Page

LIST OF TABLES

Page

CHAPTER I

INTRODUCTION

The United States Environmental Protection Agency (US EPA) categorizes air pollution into three main groups: mobile, stationary, and area sources [Environmental Protection Agency, 2004]. Nonroad heavy duty diesel engine (HDDE) construction equipment falls into the mobile source group. In 2016 there were around 250 million on-road vehicles registered in the United States [U.S. Department of Transportation Federal Highway Administration, 2017]. In 2005, it was estimated that there were roughly two million units of construction and mining equipment in operation [Bardia, et al., 2015]. According to the United States Bureau of Labor Statistics in 2020 there where currently 457,200 construction equipment operators, that number is expected to increase by 5 percent from 2020 to 2030 [United States Department of Labor, 2022].

HDDE construction equipment are categorized as nonroad engines. The EPAs definition of a nonroad engine is based on the principle of mobility or portability. This includes engines installed on equipment that is propelled while performing its function or on equipment that is portable or transportable, as indicated by the presence of wheels, skids, carrying handles, dolly, trailer or platform [Environmental Protection Agency, 2004]. Due to the large difference in numbers between on-road vehicles and nonroad HDDE vehicles; HDDE lagged behind when it came to engine emissions regulations and updates. It was not until the mid-1990's that the Tier 1 standard was established for emissions from HDDE. The current regulatory Tier 4 standards went into effect starting with all 2008 models [Environmental Protection Agency, 2004]. Tier 4 emissions require different types of exhaust aftertreatment to meet the standard. The following are different types of strategies and devices used to achieve compliance with the Tier 4 standards: selective catalytic reduction (SCR) and diesel particulate filter (DPF) [Jaehoon, et al., 2017]. Table 1 shows a breakdown of the tier standards with engine power size.

Table 1. EPA exhaust emission regulation (Modified from Hassani, 2020)

Standard	**Adoption Date**	**Progress**
Tier 1	1998-2000	Limitation of substantial reductions of NOx & PM for diesel engines with a engine power range of 8-560 kW.
Tier 2	2001-2006	Limitation of substantial reductions of NOx & PM for diesel engines with a engine power range of 8-560 kW.
Tier 3	2006-2008	Limitation of substantial reductions of NOx & PM for diesel engines with a engine power range of 37-560 kW.
Tier 4	2008-2015	Delamination of substantial reductions of NOx & Pm for diesel engines with a engine power range of 56-560 kW.

Different manufacturers use different combinations of devices and strategies to achieve the regulatory standard. Despite the drastic regulatory reductions in engine emissions, questions remain regarding the exposure of the operator. The operator may spend 8 – 12 hours per workday in the cab of equipment, sitting only a few feet away from the exhaust pipe. The primary HDDE pollutant emissions of concern to construction equipment operators include carbon monoxide (CO), carbon dioxide (CO_2), nitrogen monoxide (NO), nitrogen dioxide (NO_2) and particulate matter (PM).

Carbon monoxide is a colorless, odorless, and tasteless gas that can cause detrimental health effects when exposed. Signs of CO poisoning include dizziness, chest pain, upset stomach and possibly death [Center for Disease Control and Prevention, 2021]. Nitrogen monoxide (NO) and nitrogen dioxide (NO_2) can irritate the human respiratory tissues. Short term exposure to NO_2 can lead to coughing, wheezing and difficulty breathing. Long term exposure can lead to asthma and respiratory infections [Environmental Protection Agency, 2021]. Operator cabs found in HDDE provide a barrier between the operator and the equipment's exhaust emissions; however, that alone may not be a sufficient barrier as wind speed and direction may also factor into the level of emissions penetrating the cab. A study in 2015 focused on the infiltration of vehicle-emitted PM, black carbon (BC), and ultrafine particles (UFP) for passenger vehicles and school buses. The study suggested that replacing the vehicle's cabin air filter with a high efficiency cabin air filter a significant drop in the in-cab PM, BC, and UFP [Zhu, et al., 2015]. Another study in 2007 investigated the truck drivers' exposure levels to PM inside the cab at the Port of Oakland in Oakland, California. The air quality was monitored inside the cab of trucks ranging in age from 1981 – 2006. The results found that the average levels of BC measured were 10 times higher than background levels found in a residential area of Oakland, California [Bailey, et al., 2007]. While there has been significant research on in-cabin emissions for on-road vehicles, there is very little research on HDDE construction equipment. To-date, there has not been a standardized methodology developed for collecting the necessary data to perform these studies on construction equipment. Therefore, we propose to develop such a methodology to collect real-world data that enables other researchers to conduct exposure studies for construction equipment operators.

To properly evaluate the pollutant exposure levels of HDDE operators working within an enclosed cab, it is necessary to collect the tailpipe emissions data directly from the equipment while simultaneously collecting air quality samples from inside the cab. This will allow the data to be compared simultaneously to determine if there is a relationship between tailpipe emissions and in-cab pollutant levels. There are two commonly employed types of emissions measurements; the first is laboratory testing, which includes regulatory style testing, emissions research, combustion research, and development for engines, catalytic converters, or complete exhaust aftertreatment systems. The other type is field testing, which includes mobile emissions labs, on-vehicle measurements, vehicle inspections, vehicle maintenance, remote emissions sensing, and occupational health measurements [Kasab, et al., 2020]. Laboratory testing requires use of a chassis dynamometer to test the engine and powertrain along with large non-portable emissions testing equipment. This type is commonly used for regulatory testing of light-duty, on-road vehicles. Field testing is considered to be more relevant for the in-use operation of both on-road and non-road vehicles. For that reason, the measurements from this type of testing are often referred to as "real world emissions" or RWE because the vehicles are tested on the road or construction site using portable emissions measurement systems (PEMS) as they are operated.

A study for the Federal Motor Carrier Safety Administration conducted by Texas A&M Transportation Institute (TTI) performed emissions infiltration measurements of heavy-duty trucks in a climate-controlled chamber at the Environmental and Emissions Research Facility [Zietsman, et al., 2018]. The Weiss Envirotronics environmental chamber is capable of temperatures between -15 and 130-degrees Fahrenheit and a relative humidity range of up to 70 percent at 104 degrees Fahrenheit. At 75-ft long, 23-ft wide, and 22-ft tall, the chamber is large enough to fit an entire tractor trailer inside [Zietsman, et al., 2018]. This work showed that a newer model truck does not necessarily provide better protection (for the operator) against emissions entering the cab [Zietsman, et al., 2018]. An older model year vehicle with tighter window and door seals tighter and provides more insulation in the cab had less pollutant infiltration than a newer model with looser seals and less insulation.

Laboratory testing on a chassis dynamometer could be done on HDDE but it would fail to account for the many variables that effect the exhaust emissions of the construction equipment during operation. Three of the main variables are operator technique, machine application, and machine configuration. Operator technique differs between operators. One operator may choose to run the equipment at full engine speed in revolutions per minute (RPM) while another operator may run the equipment only at the necessary RPM to complete the task. Machine application can be affected by the type of task. For example, the difference in a loader working in a sand and gravel pit versus a loader that is loading trucks in aggregate yards. Figure 1 shows the different ways the exhaust emissions of HDDE can be affected.

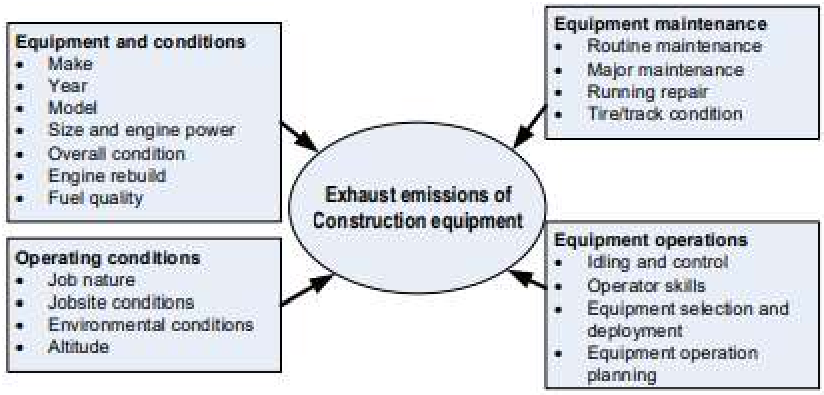

Figure 1. Factors affecting emissions (Reprinted from Fan, 2017)

Load factor is defined as “the ratio of the average horsepower during a working period to the maximum horsepower for the given engine” [Cao, et al., 2016]. An engine that is continuously producing max rated horsepower would have a load factor of 1.0. A bulldozer may reach a load factor of 1.0 occasionally but will seldomly maintain a 1.0 load factor [Caterpillar, 2021]. During normal operation HDDE engine load factor is constantly changing based on how the equipment is used. It may see a load factor of 1.0 while pushing a large pile of dirt, but the load factor will drop significantly when going in reverse. To replicate this extra load in laboratory testing would be next to impossible. Therefore, field testing is the preferred method for testing HDDE.

Field testing HDDE presents its own set of challenges. It requires using equipment that is portable, durable and capable of handling the rough terrain and harsh environment of a construction site. PEMS equipment is widely used in field testing as it can identify real world driving emissions and fuel economy, while maintaining portability [Kasab, et al., 2020].

CHAPTER II

RESEARCH QUESTION

The relationships between tail pipe emissions, in-cab air quality, engine data, wind speed, and direction are unaddressed for HDDE construction equipment. There is a large amount of data collected regarding the tail pipe emissions of the HDDE, but a limited amount of data regarding the air quality inside the cab. The goal of the proposed project is to develop a measurement methodology that will collect data from HDDE related to in-cab air quality based on tailpipe emissions. The research question is: Can we develop a reproducible, data collection methodology that will simultaneously collect real-world data for tailpipe emissions, engine activity, in-cab air quality, and ambient environmental conditions to be used for construction equipment operator exposure studies?

CHAPTER III

EXPERIMENTAL METHODS

We are seeking to develop an effective methodology for collecting the data needed to determine the relationship between tailpipe emissions, engine activity, environmental conditions, and in-cab air quality. The size and portability of the equipment used for testing is crucial for this method, because there is limited space for instrumentation installation on the HDDE construction equipment.

The parSYNC, PEMS will be used to collect the data from the HDDE exhaust pipe. This device is capable of recording CO, CO_2, NO and NO_2 in one-minute intervals. The parSYNC is also small enough to mount securely on the outside of the HDDE equipment and capable of recording data for more than 10 hours. Its specifications can be found in Table 2. Three separate instruments will be used to collect the air quality data inside the cab. A gas detector, referred to as the MX6 iBrid, will be used to collect NO, NO_2, CO, and CO_2 inside the cab. The specifications for the MX6-iBrid are shown in Table 3. Black carbon data will be collected by a pocket-sized monitor called an Aethlabs MicroAeth AE51; its information can be found in Table 4. A Thermo Fisher pDR-1000AN is a personal sized monitor that collects data for $PM_{2.5}$. Information on the pDR-1000AN is shown in Table 5. The engine data will be collected using a HEM Data OBD Mini Logger that connects to the engine's diagnostics port. Providing the HEM Data OBD Mini logger with the correct protocol any engine parameter monitored by the ECM can be recorded, such as engine RPM. Its specifications can be found in Table 6. A portable weather station called the Davis Vantage Pro2 will be on location to record weather data. It is capable of recording temperature, relative humidity, wind speed, and wind direction. The specifications on the Davis Vantage Pro2 are shown in Table 7. All the equipment can collect the necessary data including a date and time stamps to allow for an accurate time alignment and analysis.

Table 2. parSYNC Information (Modified from 3DATX Corporation, 2021)

3DATX parSYNC PLUS				
Measurement Principle	3 Electrode Electro-Chemical	3 Electrode Electro-Chemical	Non-Dispersive Infrared Spectrometer	Non-Dispersive Infrared Spectrometer
Measurement Range	Nitrogen Dioxide (NO_2)	Nitric Oxide (NO)	Carbon Monoxide (CO)	Carbon Dioxide (CO_2)
	0 - 300 ppm	0 - 5000 ppm	0 - 15%	0 - 20%
Data Logging Interval	1-minute averages			
Run Time	12V Lithium Battery			
	8 - 10 hours			

Table 3. MX6 - iBrid Information (Modified from Industrial Scientific, 2018)

Industrial Scientific MX6 - iBrid				
Measurement Principle	Electrochemical	Electrochemical	Electrochemical	Infrared
Measurement Range	Nitrogen Dioxide (NO_2)	Nitric Oxide (NO)	Carbon Monoxide (CO)	Carbon Dioxide (CO_2)
	0 - 150 ppm	0 - 1,000 ppm	0 - 1,500 ppm	0 - 5% vol
Data Logging Interval	1 - 300 seconds			
Run Time	AA Battery pack	Lithium-ion Battery pack	Lithium-ion Battery pack	
	10.5 hours without pump	20 hours with pump	36 hours without pump	

Table 4. AE51 Information (Modified from AETHLABS, 2016)

MicroAeth - AE51					
Measurement Principle	800 nm interpreted as Concentration of Black Carbon				
Measurement Range	avg. 5 ug BC/m^3 @ 24 hours @ 100 ml/min				
	avg. 100 ug BC/m^3 @ 3 hours @ 50 ml/min				
	avg. 1 mg BC/m^3 @ 15 minutes @ 50 ml/min				
Data Logging Interval	1, 10, 30, 60, 300 seconds				
Data Storage	1 week @ 60 second time base				
Run Time		50 ml/min	100 ml/min	150 ml/min	200 ml/min
	1 second	> 21 hours	> 18 hours	> 14 hours	> 12 hours
	10 seconds	> 21 hours	> 19 hours	> 15 hours	> 12 hours
	30 seconds	> 23 hours	> 19 hours	> 15 hours	> 13 hours
	60 seconds	> 28 hours	> 24 hours	> 20 hours	> 15 hours

Table 5. pDR-1000AN Information (Modified from Thermo Fisher Scientific Air Quality Instruments, 2013)

Thermo Scientific pDR-1000AN	
Measurement Principle	Single beam nephelometry
Measurement Range	$PM_{2.5}$
	.001 mg/m^3 - 400 mg/m^3
Data Logging Interval	1 - 600 seconds
Data Storage	99 sets of 13,391 data points
Run Time	9V battery pack
	< 20 hours

Table 6. OBD Mini Logger Information (Modified from HEM Data Corporation, 2021)

HEM Data OBD Mini Logger	
Data Logging Interval	1 Second
Data Storage	4GB internal storage
Run Time	Powered off of the equipment's battery

Table 7. Davis Vantage Pro2 Information (Modified from Davis Instruments, 2019)

Davis Vantage Pro2			
	Range	Accuracy	Update Interval
Temperature	-40°F - 150°F	±0.5°F	10 - 12 Seconds
Relative Humidity	1% - 100% RH	±2%	50 - 60 Seconds
Wind Speed	0mph - 200mph	±2mph	2.5 - 3 Seconds
Wind Direction	1 - 360°	±3°	2.5 - 3 Seconds

Figure 2. parSYNC

Figure 3. MX6 - iBrid

Figure 4. AE51

Figure 5. pDR - 1000AN

Figure 6. OBD Mini Logger

Figure 7. Vantage Pro2

Engine data will help in determining if the HDDE was running or turned off, and duration of activity and inactivity. The engine data will provide the HDDE engine RPM, and this will assist in showing the correlation between the HDDE emissions and equipment usage.

The following testing protocol will be used every day during the data collection period.

1. All equipment will be zeroed, calibrated, and time synced to the parSync's computer time.
2. The equipment will be installed on the HDDE before 6:00 AM, before the operator's shift starts.
3. The equipment will be removed from the HDDE after 4:00 PM, after the operator's shift ends.
4. The raw data will be extracted from each piece of the data collection equipment and organized by HDDE type and date.
5. The equipment will be cleaned and charged before the next use.

In addition to these data collection procedures, we will collect pictures, videos, and onsite observations to determine the equipment's usage and work environments. The objective is to collect at least five sets of data from three different units of HDDE. To succeed in collecting the necessary data for this project an agreement was made with the Texas A&M Transportation Institute Roadside Safety and Physical Security Division to allow access to their HDDE. Access to the Roadside Safety and Physical Security Division is convenient, and will allow me to install the monitoring equipment, for data collection, at a moment's notice. See Table 8 for a list of HDDE information being used for the project.

Table 8. HDDE Information

Equipment Type	Make	Model	Year
Wheel Loader	CAT	950K	2013
Motor Grader	CAT	12M3	2018
Hydraulic Excavator	CAT	320D	2010

Figure 8. Wheel Loader

Figure 9. Motor Grader

Figure 10. Hydraulic Excavator

Experimental Setup

The testing was completed at the TTI Proving Ground located on the Texas A&M University System RELLIS Campus. It is a 2000-acre complex of research and training facilities located 10 miles northwest of Texas A&M University in College Station, Texas. The HDDE being used for the testing belongs to TTI's Roadside Safety & Physical Security Division. The data collection equipment used belongs to TTI's Environmental and Emissions Research Facility.

Preliminary Equipment Testing

Before any data collection was done on the equipment, all the equipment had a baseline test completed with known gas concentrations. This ensured that all the equipment worked properly and recorded the correct concentrations. The HEM data logger was plugged into each piece of HDDE and turned on for five minutes. The data was then downloaded and verified that it was set up to record the necessary parameters. During this time, it was discovered that the data logger would not connect and record data from the hydraulic excavator. After multiple conversations with Carl at the EPA and different setups, we were still unsuccessful in connecting and recording data from the hydraulic excavator. Due to the inability to record engine parameters on the hydraulic excavator it was dropped from the list of HDDE to be tested. There were no problems getting the data logger to connect with the wheel loader and motor grader.

Daily Equipment Calibration and Installation

Every day before collecting data the equipment was calibrated, zeroed and time synced. Each piece of equipment has its own procedure that must be followed to ensure the equipment is properly calibrated and zeroed. Some equipment required only ambient air to be calibrated and zeroed while other items required calibrated gas bottles with known concentrations of NO, NO^2, CO and CO^2. The MicroAeth AE51 and pDR-1000AN only required the equipment software and ambient air. The MX6-iBrid and PEMS required equipment software and calibrated gases to be calibrated and zeroed. Figure 11 shows the MX6-iBrid in the calibration dock.

Figure 11. iBrid Calibration Dock

Due to the small physical size of some of the equipment, it was mounted inside of a hard plastic box due to the limited areas to secure the equipment inside the cab of the HDDE. This also ensured that the inlet ports of the equipment did not get blocked due to the possibility of the equipment bouncing around and into an area covering the inlet port. Figure 12 shows the MX6-iBrid and MicroAeth AE51 mounted inside the box. The inlet ports are connected to the small black hose leading to the outside of the box. A hole was drilled in the side of the box to allow the equipment to vent the air that it expels.

Figure 12. Box

The HEM DATA logger and weather station did not require daily calibration. The data logger does require an initial setup to determine what parameters need to be recorded. This does require some trial and error to configure the parameters correctly for each individual piece of HDDE. The weather station required an initial setup to determine the specific model and accessory equipment being used. This included which anemometer, wind cup size and rain collector being used. The anemometer was oriented true north per the user manual using a compass. Figure 13 shows the weather station setup outside with the wind vane on the anemometer facing magnetic North.

Figure 13. Weather Station

When installing the data collection equipment inside of the HDDE, it was placed in the same spot inside the cab every time. Figures 14 and 15 show the placement of the pDR-1000AN, data logger and box containing the MicroAeth AE51 and MX6-iBrid inside of the wheel loader and motor grader.

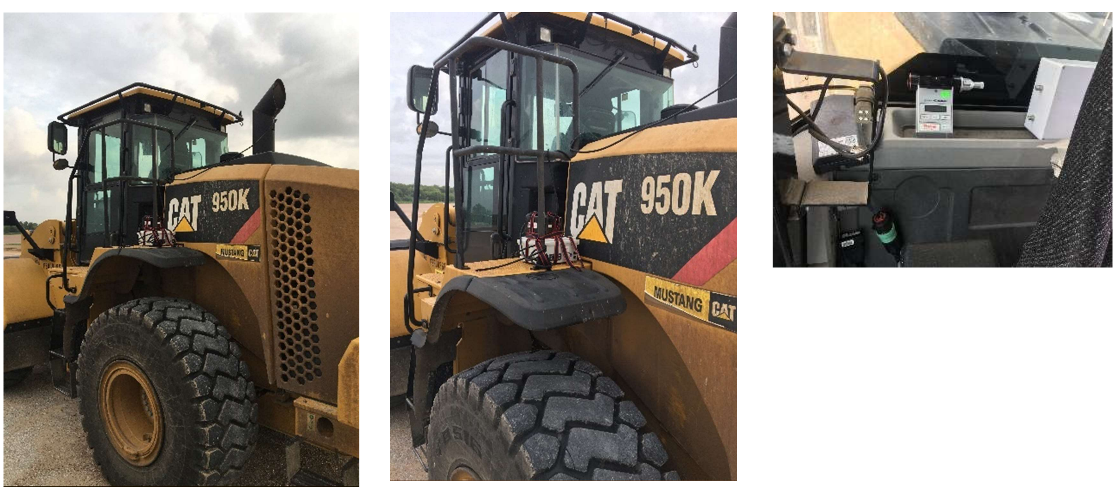

Figure 14. Wheel Loader Equipment Installed

Figure 15. Motor Grader Equipment Installed

The PEMS was mounted securely to the outside of HDDE wherever a suitable location could be found. Figure 16 shows the PEMS on the wheel loader securely mounted to the top of the rear fender. The wheel loader is equipped with an auxiliary power outlet inside the cab that can provide power to the PEMS. This enabled the PEMS to be powered by just plugging it in vs. having to provide a battery power source. The inlet probe for the PEMS was routed up to and inserted into the exhaust pipe.

Figure 16. Wheel Loader PEMS Installed

There was not a suitable location on the motor grader that allowed the PEMS to be easily installed and secured close enough to the cab. A bracket was made to attach to the roof on the back of the cab. The motor grader is also equipped with an auxiliary power outlet inside the cab the location of the bracket allowed the PEMS to be powered directly by the HDDE. Figure 17 show where the PEMS was mounted and the inlet probe installed in the exhaust tail pipe.

Figure 17. Motor Grader PEMS Installed

When the shift was over, all the data collection equipment was removed from the HDDE. The data was then extracted using the interface software for each piece of equipment.

HDDE Operations / Operating Conditions

During the testing the HDDE performed the basic operations that it was designed to do. Below is a list of basic operations performed by the HDDE during the testing.

Wheel Loader

1. Load dirt into semi-trailers to be hauled off.
2. Spread out and fold dirt while it was being watered.

3. Haul debris roughly one mile from one side of the facility to the other.

Motor Grader

1. Spread fresh dirt and level the ground for proper water runoff.
2. Establish final grades on construction projects.

Figures 18 and 19 show the HDDE operating during the data collection.

Figure 18. Wheel Loader Operating

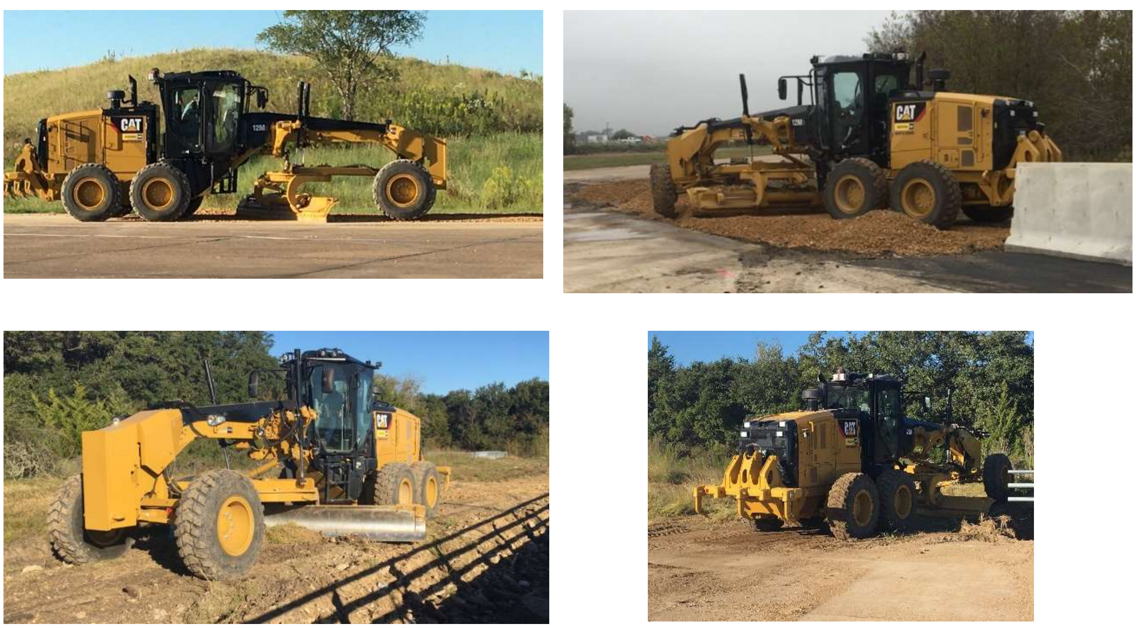

Figure 19. Motor Grader Operating

CHAPTER IV

RESULTS AND DISCUSSION

Microsoft Excel was the primary repository for all the data. Each dataset was organized by HDDE type and date. The individual emissions data had a software output of parts per million (ppm), milligrams per cubic meter (mg/m^3) and nanograms per cubic meter (ng/m^3) and time aligned in one-minute intervals. Some of the testing equipment records data on a 1-second, 10-second, 30-second, and 1-minute interval. A one-minute rolling average was used to convert it to a one-minute interval, which allowed all of the individual emissions gases to be time aligned.

During the testing, the HEM Data Logger recorded the HDDE engine parameters. The data logger would only record parameters the HDDE engine computer monitored, and it would record data in 1-second intervals. During the testing, the data logger's ability to track Latitude and Longitude was a failure. If this capability had functioned properly, it would have allowed for mapping the HDDE location on the test site with speed during the data analysis. Appendix A Table 11 shows some of the raw data collected from the testing.

The ParaSync recorded NO, NO^2 and CO^2 from the HDDE tailpipe. This data was recorded in 1-second intervals. This is the only data recording rate that this piece of equipment is capable of. The data output for the NO and NO^2 is in PPM. The CO^2 has an output reading in percent. This is believed to be an incorrect ouput parameter in the software and it should have an output of PPM, and a test was conducted to prove this. The ParaSync was calibrated and zeroed according to the manual. It then had a known

CO^2 gas of a known concentration fed into it. Two separate bottles, one with a low concentration and the second with a high concentration were used. During this time the ParaSync record a percent value of the CO^2 that equalled the PPM value on the gas bottles. Appendix A Table 12 shows the raw data colled from the testing.

The iBrid recorded the NO, NO^2, CO and CO^2 gases inside the cab were the operator was located. It is only capable of recording data on a 1-minute average. Although the output parameters does not show on the raw data, it has a output in PPM per the manufacturer. This equipment had consistent outputs of zero throughout the data collection. It verified that the equipment was working through a basic test. The equipment was calibrated and zeroed accordingly. It was then placed on a table inside of a building for 30 minutes, moved outside to ambientant air for 30 minutes, placed by the tailpipe of a running diesel truck for 30 minutes, and finally placed back inside on a table for 30 minutes. The data recorded during that time showed the gas concentrations go up when placed outside in the ambient air, increase more when placed by the tailpipe of the diesel truck, then back down when placed back inside on a table. Appendix A Table 13 shows the raw data the iBrid collected during the testing.

The pDR-1000 was placed in the cab to record PM that the operator might be exposed to. It was setup to record in 10-second average and had a data output of mg/m3. Appendix A Table 14 shows some of the raw data collected during the testing.

The MicroAeth was placed in the cab to collect black carbon data. It was configured to record in 10-second average. After the data was collected and downloaded it was run through a smoothing matrix software recommended by the EPA, called BC-

ONA. Appendix A Table shows the raw data before being run through the BC-ONA software, and Appendix A Table 16 shows the data after being run through the BC-ONA software.

The Davis Vantage Pro weather station was setup up outside at the testing facitility, where it collected data on a 1-minute average interval. Appendix A Table 17 shows a sample of data collected during the testing.

Tables 9 and 10 show the individual daily totals for each piece of HDDE while it was running. These tables show the combined daily totals for each piece of HDDE, including the minimum, maximum, average and median for each individual parameter.

Table 9. Wheel Loader Daily Totals

Wheel Loader Daily Totals														
	Data Logger	Ipems			iBrid				PDR	MicroAeth	Weather			
	Engine Speed	NO2	NO	CO2	NO2	NO	CO	CO2	PM	BC	Temp	Out	Heat	Wind
Date	rpm	ppm	ppm	ppm	ppm	ppm	ppm	ppm	mg/m3	ng/m^3	Out	Hum	Index	Speed
10122020	Ran 4 times during the day for a total of 121 minutes													
Min	449.20	0.42	-1.65	-33.04	0.00	0.00	0.00	0.05	0.00	295.37	74.20	64.00	76.20	3.00
Max	2321.03	101.58	182.98	36260.68	0.00	0.00	0.00	0.22	0.00	295.37	82.00	81.00	85.20	11.00
Average	1412.16	20.56	40.23	10368.51	0.00	0.00	0.00	0.16	0.00	295.37	77.13	74.83	79.50	6.85
Median	1398.57	10.42	9.64	5425.47	0.00	0.00	0.00	0.17	0.00	295.37	76.00	76.00	78.00	7.00
10202020	Ran 2 times during the day for a total of 66 minutes													
Min	699.84	0.13	1.98	143.23	0.00	0.00	0.00	0.03	0.00	166.62	73.70	48.00	75.70	2.00
Max	2255.10	17.97	101.71	11715.00	0.00	4.00	0.00	0.19	0.02	166.62	87.10	85.00	89.30	10.00
Average	1463.72	6.56	26.20	5465.95	0.00	1.86	0.00	0.10	0.00	166.62	80.91	65.05	83.01	5.20
Median	1474.27	5.79	23.58	5189.01	0.00	2.50	0.00	0.08	0.00	166.62	86.00	52.00	88.05	5.00
10262020	Ran 7 times during the day for a total of 65 minutes													
Min	692.06	0.64	-16.99	725.09	0.00	0.00	0.00	0.06	0.00	474.80	69.50	56.00	70.70	4.00
Max	2172.67	46.49	83.30	23101.37	0.00	0.00	0.00	0.14	0.02	474.80	79.00	85.00	81.00	18.00
Average	1357.03	8.45	9.45	6995.65	0.00	0.00	0.00	0.10	0.00	474.80	74.50	73.91	76.05	7.97
Median	1436.05	4.18	-0.75	5166.53	0.00	0.00	0.00	0.10	0.00	474.80	75.00	75.00	76.70	7.00
10292020	Ran 3 times during the day for a total of 84 minutes													
Min	689.96	0.59	-15.73	1222.65	0.00	0.00	-5.00	0.03	0.00	374.37	42.90	55.00	42.50	4.00
Max	2306.38	27.76	50.39	12500.22	0.00	0.00	-3.00	0.17	0.01	374.37	57.40	76.00	55.80	24.00
Average	1458.92	7.75	5.85	5516.90	0.00	0.00	-4.67	0.11	0.00	374.37	47.71	69.26	46.92	9.70
Median	1545.67	5.63	1.32	5493.77	0.00	0.00	-5.00	0.11	0.00	374.37	43.95	75.00	43.55	6.00
11042020	Ran 8 times during the day for a total of 83 minutes													
Min	525.37	0.18	-13.35	-26.55	0.00	0.00	-5.00	0.03	0.00	528.68	64.70	39.00	63.50	3.00
Max	2119.40	0.47	-8.34	810.90	0.00	0.00	-3.00	0.16	0.02	528.68	77.80	59.00	76.70	13.00
Average	1297.75	0.35	-11.01	84.03	0.00	0.00	-4.28	0.08	0.00	528.68	71.67	50.40	70.79	8.27
Median	1315.48	0.35	-11.36	-11.75	0.00	0.00	-4.00	0.09	0.00	528.68	71.50	52.00	70.60	8.00
11052020	Ran 9 times during the day for a total of 207 minutes													
Min	462.12	0.14	-4.76	-492.26	0.00	0.00	-6.00	0.03	0.00	471.99	61.40	46.00	61.90	0.00
Max	2257.02	25.97	44.84	14261.45	0.00	0.00	-4.00	0.20	0.01	471.99	79.50	92.00	79.20	10.00
Average	1239.49	1.19	2.74	51.50	0.00	0.00	-4.92	0.08	0.00	471.99	73.51	61.86	73.71	5.68
Median	1232.15	0.23	-0.03	-481.93	0.00	0.00	-5.00	0.06	0.00	471.99	75.70	55.00	75.90	6.00

Table 10. Motor Grader Daily Totals

Motor Grader Daily Totals														
	Data Logger	Ipems			iBrid				PDR	MicroAeth	Weather			
	Engine Speed	NO2	NO	CO2	NO2	NO	CO	CO2	PM	BC	Temp	Out	Heat	Wind
Date	rpm	ppm	ppm	ppm	ppm	ppm	ppm	ppm	mg/m3	ng/m^3	Out	Hum	Index	Speed
10212020	Ran 1 time during the day for a total of 60 minutes													
Min	799.92	0.65	10.58	15163.86	0.00	0.00	0.00	0.03	0.01	451.21	81.60	56.00	84.50	3.00
Max	2120.50	19.48	222.68	43537.54	0.00	0.00	0.00	0.08	0.03	451.21	84.10	65.00	87.40	11.00
Average	1515.00	7.00	39.16	24941.26	0.00	0.00	0.00	0.06	0.01	451.21	82.82	60.48	85.66	6.12
Median	1599.72	6.00	27.77	23273.80	0.00	0.00	0.00	0.06	0.01	451.21	82.90	60.00	85.65	6.00
10222020	Ran 2 times during the day for a total of 62 minutes													
Min	1.50	0.54	-1.19	5198.79	0.00	0.00	0.00	0.03	0.01	516.94	69.80	66.00	71.80	2.00
Max	2134.18	36.51	176.89	42268.39	0.00	0.00	0.00	0.06	0.02	516.94	81.70	90.00	85.10	9.00
Average	1748.96	5.57	39.07	26184.10	0.00	0.00	0.00	0.06	0.01	516.94	73.36	82.79	75.81	3.63
Median	1789.79	4.60	34.82	23538.44	0.00	0.00	0.00	0.06	0.01	516.94	70.00	89.00	72.10	3.00
11132020	Ran 5 times during the day for a total of 77 minutes													
Min	393.31	0.58	-0.89	8357.65	0.00	0.00	-5.00	0.03	0.00	918.21	64.80	86.00	66.00	1.00
Max	2131.47	188.05	497.75	42716.82	0.00	0.00	-2.00	0.37	0.04	918.21	68.00	92.00	69.50	8.00
Average	1256.53	18.83	35.25	25860.96	0.00	0.00	-4.34	0.14	0.01	918.21	65.85	90.35	67.16	4.27
Median	1125.64	11.19	12.67	25897.69	0.00	0.00	-4.00	0.09	0.00	918.21	65.10	92.00	66.30	4.00
11162020	Ran 1 time during the day for a total of 87 minutes													
Min	799.72	0.15	-18.08	15959.12	0.00	0.00	-6.00	0.03	0.00	267.39	38.90	46.00	38.40	1.00
Max	1937.44	94.88	943.22	45069.30	0.00	0.00	-5.00	0.06	0.07	267.39	52.20	74.00	50.50	6.00
Average	1343.65	26.09	166.43	29949.12	0.00	0.00	-5.98	0.05	0.01	267.39	44.83	59.21	43.90	2.54
Median	1372.17	25.55	115.87	28967.47	0.00	0.00	-6.00	0.06	0.01	267.39	44.90	56.00	43.90	2.00
11182020	Ran 2 times during the day for a total of 78 minutes													
Min	80.59	0.35	-4.39	10009.64	0.00	0.00	0.00	0.03	0.00	499.18	43.20	53.00	42.80	0.00
Max	2145.07	152.42	1031.49	53667.05	0.50	5.00	0.00	0.06	0.06	499.18	55.90	75.00	54.20	5.00
Average	1413.93	16.83	159.40	30999.08	0.04	0.60	0.00	0.05	0.01	499.18	49.89	65.96	49.07	0.65
Median	1466.31	6.76	91.85	29362.74	0.00	0.00	0.00	0.06	0.01	499.18	50.45	67.00	49.85	0.00
11202020	Ran 5 times during the day for a total of 139 minutes													
Min	92.48	0.89	-5.14	3389.82	0.00	0.00	-5.00	0.03	0.00	445.85	64.20	57.00	65.20	2.00
Max	2150.25	41.71	446.98	54894.43	0.00	0.00	0.00	0.09	0.05	445.85	77.90	91.00	78.40	12.00
Average	1526.46	8.69	50.63	31855.90	0.00	0.00	-3.73	0.06	0.00	445.85	68.58	82.02	69.63	5.65
Median	1564.96	4.35	33.90	30583.89	0.00	0.00	-5.00	0.06	0.00	445.85	64.90	91.00	66.00	5.00
11232020	Ran 4 times during the day for a total of 85 minutes													
Min	0.00	0.75	-16.40	2822.91	0.00	0.00	-6.00	0.03	0.00	446.25	53.50	75.00	53.30	2.00
Max	2150.80	25.44	461.13	58096.34	0.00	0.00	-5.00	0.09	0.02	446.25	59.70	84.00	59.20	8.00
Average	1636.05	7.84	65.25	33283.71	0.00	0.00	-5.28	0.06	0.01	446.25	56.37	79.48	56.03	4.95
Median	1730.78	6.89	51.46	31574.98	0.00	0.00	-5.00	0.06	0.01	446.25	56.80	79.00	56.40	5.00

CHAPTER V

CONCLUSION

We developed a methodology for collecting data needed to determine the relationship between tailpipe emissions, engine activity, environmental conditions, and in-cab air quality. During the research process we learned that it is imperative to check all data equipment output measurements prior to usage. This will ensure that all output measurement parameters are correct and verify communication between data collection equipment and HDDE is compatible. We also learned that the iBrid was only capable of recording higher values of NO, NO^2, CO and CO^2. Additionally, we observed that the HDDE that was used in this research was not continually operating at its intended capacity during the day. Based on these lessons learned and observations, I recommend the following changes. I recommend performing this test on equipment that will run all day, not just for 1 – 3 hours. The best place to test a wheel loader would be at an aggregate pit where it would be constantly loading trucks. Testing a motor grader that is used by a crew building a road and is needed to level out long sections of dirt is one example. I recommend replacing the iBrid with a different piece of equipment that is capable of recording lower concentrations of NO, NO^2, CO and CO^2 inside the cab if trying to replicate this study. This equipment should also be capable of recording data from a 1-second to 30-second average and able to record lower reading of PPM. It is also recommended to add an additional global positioning satalite (GPS) tracker to the HDDE. This addition would allow for mapping the physical location and speed of the HDDE during the testing period.

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APPENDIX A

RAW DATA

Table 11. Hem Data Logger Raw Data

Time: 11/5/2010 7:04:00 AM															
Time	Accelerator Pedal Position 1 (%)	Engine Percent Load At Current Speed (%)	Actual Engine - Percent Torque (%)	Engine Speed (rpm)	Engine's Desired Operating Speed (rpm)	Wheel-Based Vehicle Speed (kph)	Engine Fuel Rate (l/h)	Engine Throttle Valve 1 Position 1 (%)	Latitude	Longitude	Altitude	Velocity	Heading	Date
11/5/2010 7:04:01	54.4	83	95	1542.4	1647.2				0	0	0	0	0	0
11/5/2010 7:04:02	68	82	89	1849.1	1901.9	101	19	216	0	0	0	0	0	0
11/5/2010 7:04:03	73.6	90	87	1973.1	2005.8	101	19	236	0	0	0	1	0	0
11/5/2010 7:04:04	80.4	89	83	2095.4	2087.2	101	19	240	0	0	0	1	0	0
11/5/2010 7:04:05	89.6	87	81	2179.1	2237.5	101	19	238	0	0	0	1	0	0
11/5/2010 7:04:06	95.2	94	74	2227	2303.1	101	19	238	0	0	0	1	0	0
11/5/2010 7:04:07	98.4	91	69	2248.5	2308.5	101	19	230	0	0	0	1	0	0
11/5/2010 7:04:08	99.6	89	69	2254.8	2310.1	101	19	230	0	0	0	1	0	0
11/5/2010 7:04:09	98	89	67	2267.1	2306.2	101	19	228	0	0	0	1	0	0
11/5/2010 7:04:10	96	89	67	2270.5	2310.9	101	19	228	0	0	0	1	0	0
11/5/2010 7:04:11	93.2	88	65	2285.1	2306.6	101	19	228	0	0	0	1	0	0
11/5/2010 7:04:12	47.2	15	21	1833.8	1391.1	101	19	226	0	0	0	1	0	0
11/5/2010 7:04:13	0.4	6	14	816.2	800	101	19	218	0	0	0	1	0	0
11/5/2010 7:04:14	0.8	14	21	787	800	101	19	130	0	0	0	1	0	0
11/5/2010 7:04:15	13.6	32	39	803.1	1066.6	101	19	110	0	0	0	1	0	0
11/5/2010 7:04:16	70	77	84	1675.2	2009.4	101	19	104	0	0	0	1	0	0
11/5/2010 7:04:17	85.6	91	87	2013.2	2148.4	101	19	162	0	0	0	1	0	0
11/5/2010 7:04:18	92.8	94	78	2198.8	2258.5	101	19	228	0	0	0	1	0	0

Table 12. ParSYNC Data Raw Data

Time stamp	Date	Time	Bag #	Scattering (V)	Ionization (V)	Opacity (V)	Cb	Cs	Ci	Co	PSN	PSN_limit	Pass/Fail	NO2 (V)	NO2 (ppm)	NO (V)	NO (ppm)	CO2 (V)	CO2 (%)	Temperature (deg C)	ErrorCode
21638	11/5/2020	6:00:39 AM	0	0.129817	5.471258	6.195946	0	20	1	20	0	0.5	Pass	1.028181	0.22	-1.784225	-3.53	0.096508	-499.76	29	0
21639	11/5/2020	6:00:40 AM	0	0.129817	5.461197	6.195946	0	20	1	20	0	0.5	Pass	1.027985	0.2	-1.783346	-1.93	0.096117	-521.7	29	0
21640	11/5/2020	6:00:41 AM	0	0.128938	5.462759	6.195849	0	20	1	20	0	0.5	Pass	1.028083	0.21	-1.783639	-2.46	0.096996	-472.33	29	0
21641	11/5/2020	6:00:42 AM	0	0.129817	5.461099	6.195458	0	20	1	20	0	0.5	Pass	1.028865	0.3	-1.784322	-3.71	0.096801	-483.3	29	0
21642	11/5/2020	6:00:43 AM	0	0.129817	5.471062	6.195849	0	20	1	20	0	0.5	Pass	1.029451	0.37	-1.783834	-2.82	0.097289	-455.87	29	0
21644	11/5/2020	6:00:44 AM	0	0.129328	5.486496	6.196337	0	20	1	20	0	0.5	Pass	1.028865	0.3	-1.784225	-3.53	0.096801	-483.3	29	0
21644	11/5/2020	6:00:45 AM	0	0.129524	5.474676	6.195751	0	20	1	20	0	0.5	Pass	1.02906	0.33	-1.784029	-3.18	0.096703	-488.79	29	0
21645	11/5/2020	6:00:46 AM	0	0.130598	5.486593	6.195458	0	20	1	20	0	0.5	Pass	1.029548	0.39	-1.783834	-2.82	0.096899	-477.81	29	0
21646	11/5/2020	6:00:47 AM	0	0.129817	5.492064	6.195653	0	20	1	20	0	0.5	Pass	1.028767	0.29	-1.783639	-2.46	0.096313	-510.73	29	0
21647	11/5/2020	6:00:48 AM	0	0.128645	5.484444	6.195946	0	20	1	20	0	0.5	Pass	1.029158	0.34	-1.783053	-1.39	0.096313	-510.73	29	0
21648	11/5/2020	6:00:49 AM	0	0.129035	5.47956	6.195849	0	20	1	20	0	0.5	Pass	1.028865	0.3	-1.783541	-2.28	0.09641	-505.24	29	0
21649	11/5/2020	6:00:50 AM	0	0.129426	5.483663	6.195556	0	20	1	20	0	0.5	Pass	1.029158	0.34	-1.784127	-3.35	0.096801	-483.3	29	0
21650	11/5/2020	6:00:51 AM	0	0.129915	5.490501	6.195849	0	20	1	20	0	0.5	Pass	1.028571	0.27	-1.783443	-2.11	0.096996	-472.33	29	0
21651	11/5/2020	6:00:52 AM	0	0.129426	5.49177	6.195751	0	20	1	20	0	0.5	Pass	1.028474	0.26	-1.783736	-2.64	0.096801	-483.3	29	0
21652	11/5/2020	6:00:53 AM	0	0.129133	5.491868	6.195849	0	20	1	20	0	0.5	Pass	1.029646	0.4	-1.783736	-2.64	0.097387	-450.38	29	0
21653	11/5/2020	6:00:54 AM	0	0.128742	5.497143	6.195556	0	20	1	20	0	0.5	Pass	1.028962	0.32	-1.783834	-2.82	0.096801	-483.3	29	0
21654	11/5/2020	6:00:55 AM	0	0.129328	5.496264	6.195458	0	20	1	20	0	0.5	Pass	1.028474	0.26	-1.782662	-0.68	0.096606	-494.27	29	0
21655	11/5/2020	6:00:56 AM	0	0.129621	5.489622	6.196142	0	20	1	20	0	0.5	Pass	1.029255	0.35	-1.783443	-2.11	0.097094	-466.84	29	0
21656	11/5/2020	6:00:57 AM	0	0.129915	5.476239	6.195946	0	20	1	20	0	0.5	Pass	1.028962	0.32	-1.783541	-2.28	0.097289	-455.87	29	0
21657	11/5/2020	6:00:58 AM	0	0.129915	5.472234	6.196044	0	20	1	20	0	0.5	Pass	1.029158	0.34	-1.783541	-2.28	0.097289	-455.87	29	0
21658	11/5/2020	6:00:59 AM	0	0.13011	5.481709	6.195849	0	20	1	20	0	0.5	Pass	1.029158	0.34	-1.783932	-3	0.097485	-444.9	29	0
21659	11/5/2020	6:01:00 AM	0	0.130598	5.4737	6.195458	0	20	1	20	0	0.5	Pass	1.028767	0.29	-1.784518	-4.07	0.097289	-455.87	29	0
21660	11/5/2020	6:01:01 AM	0	0.130012	5.470476	6.195946	0	20	1	20	0	0.5	Pass	1.027692	0.16	-1.783736	-2.64	0.097778	-428.44	29	0

Table 13. iBrid Raw Data

Time	Temp ℃	Nitrogen Dioxide (NO2)	TWA (NO2)	STEL (NO2)	Nitric Oxide (NO)	TWA (NO)	STEL (NO)	Carbon Monoxide (CO)	TWA (CO)	STEL (CO)	Isobutylene (C4H8)	TWA (C4H8)	STEL (C4H8)	Carbon Dioxide (CO2)	TWA (CO2)	STEL (CO2)
11/5/2020 5:32	17	0	0	0	0	0	0	-5	0	0	-0.6	0	0	0.06	0	0
11/5/2020 5:33	17	0	0	0	0	0	0	-4	0	0	-0.7	0	0	0.05	0	0.01
11/5/2020 5:34	17	0	0	0	0	0	0	-5	0	0	-0.8	0	0	0.03	0	0.01
11/5/2020 5:35	17	0	0	0	0	0	0	-5	0	0	-0.9	0	0	0.03	0	0.01
11/5/2020 5:36	17	0	0	0	0	0	0	-5	0	0	-1	0	0	0.03	0	0.01
11/5/2020 5:37	17	0	0	0	0	0	0	-6	0	0	-1	0	0	0.03	0	0.02
11/5/2020 5:38	18	0	0	0	0	0	0	-6	0	0	-1.1	0	0	0.03	0	0.02
11/5/2020 5:39	18	0	0	0	0	0	0	-6	0	0	-1.1	0	0	0.03	0	0.02
11/5/2020 5:40	18	0	0	0	0	0	0	-6	0	0	-1.1	0	0	0.03	0	0.02
11/5/2020 5:41	18	0	0	0	0	0	0	-5	0	0	-1.2	0	0	0.03	0	0.02
11/5/2020 5:42	18	0	0	0	0	0	0	-5	0	0	-1.2	0	0	0.03	0	0.03
11/5/2020 5:43	18	0	0	0	0	0	0	-5	0	0	-1.2	0	0	0.03	0	0.03
11/5/2020 5:44	18	0	0	0	0	0	0	-5	0	0	-1.2	0	0	0.03	0	0.03
11/5/2020 5:45	18	0	0	0	0	0	0	-5	0	0	-1.2	0	0	0.03	0	0.03
11/5/2020 5:46	18	0	0	0	0	0	0	-5	0	0	-1.3	0	0	0.03	0	0.03
11/5/2020 5:47	18	0	0	0	0	0	0	-5	0	0	-1.3	0	0	0.03	0	0.03
11/5/2020 5:48	18	0	0	0	0	0	0	-5	0	0	-1.3	0	0	0.03	0	0.03
11/5/2020 5:49	18	0	0	0	0	0	0	-5	0	0	-1.3	0	0	0.03	0	0.03
11/5/2020 5:50	18	0	0	0	0	0	0	-5	0	0	-1.3	0	0	0.03	0	0.03
11/5/2020 5:51	18	0	0	0	0	0	0	-5	0	0	-1.3	0	0	0.03	0	0.03
11/5/2020 5:52	18	0	0	0	0	0	0	-5	0	0	-1.3	0	0	0.03	0	0.03
11/5/2020 5:53	18	0	0	0	0	0	0	-5	0	0	-1.4	0	0	0.03	0	0.03

Table 14. pDR-1000 Raw Data

pDR			
Tag Number: 01			
Number of logged points: 3800			
Start time and date: 05:53:14 05-Nov			
Elapsed time: 10:33:20			
Logging period (sec): 10			
Calibration Factor (%): 100			
Max Display Concentration: 1.109 mg/m3			
Time at maximum: 16:22:11 Nov 05			
Max STEL Concentration: 0.044 mg/m3			
Time at max STEL: 16:25:46 Nov 05			
Overall Avg Conc: 0.001 mg/m3			
Logged Data:			
Point	Date	Time	Avg.(mg/m3)
1	5-Nov	05:53:24	0.008
2	5-Nov	05:53:34	0.01
3	5-Nov	05:53:44	0.012
4	5-Nov	05:53:54	0.012
5	5-Nov	05:54:04	0.008
6	5-Nov	05:54:14	0.009
7	5-Nov	05:54:24	0.011
8	5-Nov	05:54:34	0.011
9	5-Nov	05:54:44	0.009
10	5-Nov	05:54:54	0.006
11	5-Nov	05:55:04	0.008
12	5-Nov	05:55:14	0.01
13	5-Nov	05:55:24	0.008
14	5-Nov	05:55:34	0.007
15	5-Nov	05:55:44	0.005
16	5-Nov	05:55:54	0.006
17	5-Nov	05:56:04	0.008
18	5-Nov	05:56:14	0.01
19	5-Nov	05:56:24	0.012
20	5-Nov	05:56:34	0.01
21	5-Nov	05:56:44	0.013
22	5-Nov	05:56:54	0.016
23	5-Nov	05:57:04	0.01
24	5-Nov	05:57:14	0.021
25	5-Nov	05:57:24	0.015

Table 15. MicroAeth AE51 Raw Data

Delimiter = ,									
AethLabs									
Device ID = AE51-S6-1163									
Application version = 2.2.4.0									
Flow = 49 ml/min									
Timebase = 10 s									
Start date = 2020/11/05									
Start time = 05:34:10									
Original date format = yyyy/MM/dd									
Original time format = hh:mm:ss									
Flow units = ml/min									
PCB temp units = deg C									
Battery units = %									
BC units = ng/m^3									
Date	Time	Ref	Sen	ATN	Flow	PCB temp	Status	Battery	BC
11/5/2020	5:34:10	919722	672245	31.345	49	23	0	100	
11/5/2020	5:34:20	919659	672194	31.346	49	23	0	100	512
11/5/2020	5:34:30	919691	672241	31.342	49	23	0	100	-2443
11/5/2020	5:34:40	919424	671598	31.409	49	23	0	100	46363
11/5/2020	5:34:50	919475	671593	31.415	49	23	0	100	4376
11/5/2020	5:35:00	919506	671661	31.408	49	23	0	100	-4697
11/5/2020	5:35:10	919482	671570	31.419	49	23	0	100	7608
11/5/2020	5:35:20	919508	671588	31.419	49	23	0	100	103
11/5/2020	5:35:30	919493	671583	31.418	49	23	0	100	-617
11/5/2020	5:35:40	919448	671520	31.423	49	23	0	100	3121
11/5/2020	5:35:50	919425	671498	31.424	49	23	0	100	539
11/5/2020	5:36:00	919425	671446	31.431	49	23	0	100	5386
11/5/2020	5:36:10	919464	671419	31.44	49	23	0	100	5747
11/5/2020	5:36:20	919459	671386	31.444	49	24	0	100	3040
11/5/2020	5:36:30	919326	671235	31.452	49	24	0	100	5583
11/5/2020	5:36:40	919403	671238	31.46	49	24	0	100	5514
11/5/2020	5:36:50	919407	671200	31.466	49	24	0	100	4240
11/5/2020	5:37:00	919381	671118	31.476	49	24	0	100	6531
11/5/2020	5:37:10	919374	671058	31.484	49	24	0	100	5689

Table 16. MicroAeth AE51 Post BC_ONA Raw Data

Smoothing Metrics:				
Total Number of Data Points: 3916				
Percent of original negative: 48.24				
Percent of filtered negative: 0.00				
Estimated Originai Noise: 1759.72				
Estimated Final Noise: 0.00				
Input Data Time Resolution: 10.00 seconds				
Median Averaged Time Base : 39160				
Delta Attenuation: 0.0500				
Date Time	BC_orig	BC_ONA_Mod	ATN_orig	# of points avg.
11/5/2020 5:34:10	NaN	471.9852	0	3916
11/5/2020 5:34:20	512	471.9852	0	3916
11/5/2020 5:34:30	-2443	471.9852	0	3916
11/5/2020 5:34:40	46363	471.9852	0	3916
11/5/2020 5:34:50	4376	471.9852	0	3916
11/5/2020 5:35:00	-4697	471.9852	0	3916
11/5/2020 5:35:10	7608	471.9852	0	3916
11/5/2020 5:35:20	103	471.9852	0	3916
11/5/2020 5:35:30	-617	471.9852	0	3916
11/5/2020 5:35:40	3121	471.9852	0	3916
11/5/2020 5:35:50	539	471.9852	0	3916
11/5/2020 5:36:00	5386	471.9852	0	3916
11/5/2020 5:36:10	5747	471.9852	0	3916
11/5/2020 5:36:20	3040	471.9852	0	3916
11/5/2020 5:36:30	5583	471.9852	0	3916
11/5/2020 5:36:40	5514	471.9852	0	3916
11/5/2020 5:36:50	4240	471.9852	0	3916
11/5/2020 5:37:00	6531	471.9852	0	3916
11/5/2020 5:37:10	5689	471.9852	0	3916

Table 17. Vantage Davis Pro Raw Data

Date	Time	Temp Out	Hi Temp	Low Temp	Out Hum	Dew Pt.	Wind speed	Wind Dir	Wind Run	Hi Speed	Hi Dir	Wind Chill	Heat Index	THW Index	THSW Index	Bar	Rain	Rain Rate	Solar Rad.	Solar Engergy	Hi Solar Rad.	UV Index	UV Dose	Hi UV	Heat D-D	Cool D-D	In Temp	In Hum	In Dew	In Heat	In EMC	In Air Density	ET	Wind Samp	Wind Tx	ISS Recept	Arc. Int.
11/5/2020	5:30 AM	62	62	61.9	91	59.3	6	S	0.1	8	S	62	62.6	62.6	---	30.23	0	0	0	0	0	0	0	0	0.002	0	71.9	43	48.2	70.3	8.17	0.0746	0	23	1	100	1
11/5/2020	5:31 AM	62	62	62	91	59.3	6	S	0.1	9	SSW	62	62.6	62.6	---	30.23	0	0	0	0	0	0	0	0	0.002	0	71.9	43	48.2	70.3	8.17	0.0746	0	23	1	100	1
11/5/2020	5:32 AM	62	62	62	91	59.3	5	S	0.08	7	S	62	62.6	62.6	---	30.23	0	0	0	0	0	0	0	0	0.002	0	71.9	43	48.2	70.3	8.17	0.0746	0	23	1	100	1
11/5/2020	5:33 AM	62	62	62	91	59.3	5	S	0.08	7	S	62	62.6	62.6	---	30.23	0	0	0	0	0	0	0	0	0.002	0	71.9	43	48.2	70.3	8.17	0.0746	0	22	1	95.7	1
11/5/2020	5:34 AM	62	62	62	91	59.3	5	SSE	0.08	6	SSE	62	62.6	62.6	---	30.23	0	0	0	0	0	0	0	0	0.002	0	72	43	48.3	70.4	8.17	0.0746	0	23	1	100	1
11/5/2020	5:35 AM	62	62	62	91	59.3	4	SSE	0.07	6	S	62	62.6	62.6	---	30.23	0	0	0	0	0	0	0	0	0.002	0	72	43	48.3	70.4	8.17	0.0746	0	23	1	100	1
11/5/2020	5:36 AM	62	62	62	91	59.3	4	SSE	0.07	6	SSE	62	62.6	62.6	---	30.23	0	0	0	0	0	0	0	0	0.002	0	72	43	48.3	70.4	8.17	0.0746	0	23	1	100	1
11/5/2020	5:37 AM	62	62	62	91	59.3	3	SE	0.05	6	SE	62	62.6	62.6	---	30.23	0	0	0	0	0	0	0	0	0.002	0	72	43	48.3	70.4	8.17	0.0746	0	23	1	100	1
11/5/2020	5:38 AM	62.1	62.1	62	91	59.4	4	SSE	0.07	6	SE	62.1	62.8	62.8	---	30.23	0	0	0	0	0	0	0	0	0.002	0	72	43	48.3	70.4	8.17	0.0746	0	23	1	100	1
11/5/2020	5:39 AM	62	62.1	62	91	59.3	4	SSE	0.07	7	SSE	62	62.6	62.6	---	30.23	0	0	0	0	0	0	0	0	0.002	0	72	43	48.3	70.4	8.17	0.0746	0	22	1	95.7	1
11/5/2020	5:40 AM	62.1	62.1	62	91	59.4	4	S	0.07	5	S	62.1	62.8	62.8	---	30.23	0	0	0	0	0	0	0	0	0.002	0	72	43	48.3	70.4	8.17	0.0746	0	24	1	100	1
11/5/2020	5:41 AM	62	62.1	62	91	59.3	4	S	0.07	5	S	62	62.6	62.6	---	30.23	0	0	0	0	0	0	0	0	0.002	0	72	43	48.3	70.4	8.17	0.0746	0	22	1	95.7	1
11/5/2020	5:42 AM	62.1	62.1	62	91	59.4	6	S	0.1	7	SSE	62.1	62.8	62.8	---	30.23	0	0	0	0	0	0	0	0	0.002	0	72.1	43	48.4	70.6	8.17	0.0745	0	24	1	100	1
11/5/2020	5:43 AM	62.1	62.1	62	91	59.4	5	S	0.08	5	S	62.1	62.8	62.8	---	30.23	0	0	0	0	0	0	0	0	0.002	0	72	43	48.3	70.4	8.17	0.0746	0	23	1	100	1
11/5/2020	5:44 AM	62.1	62.1	62	91	59.4	4	SSE	0.07	7	SSE	62.1	62.8	62.8	---	30.23	0	0	0	0	0	0	0	0	0.002	0	72.1	42	47.7	70.5	8.01	0.0746	0	23	1	100	1
11/5/2020	5:45 AM	62.1	62.1	62.1	91	59.4	6	S	0.1	8	S	62.1	62.8	62.8	---	30.23	0	0	0	0	0	0	0	0	0.002	0	72.1	42	47.7	70.5	8.01	0.0746	0	22	1	95.7	1
11/5/2020	5:46 AM	62.1	62.1	62.1	91	59.4	4	SSE	0.07	6	S	62.1	62.8	62.8	---	30.23	0	0	0	0	0	0	0	0	0.002	0	72.1	42	47.7	70.5	8.01	0.0746	0	22	1	95.7	1
11/5/2020	5:47 AM	62.1	62.1	62.1	91	59.4	4	SSE	0.07	5	SSE	62.1	62.8	62.8	---	30.23	0	0	0	0	0	0	0	0	0.002	0	72.1	42	47.7	70.5	8.01	0.0746	0	24	1	100	1
11/5/2020	5:48 AM	62.1	62.1	62.1	91	59.4	3	SSE	0.05	5	SSE	62.1	62.8	62.8	---	30.23	0	0	0	0	0	0	0	0	0.002	0	72.1	42	47.7	70.5	8.01	0.0746	0	22	1	95.7	1
11/5/2020	5:49 AM	62.1	62.1	62.1	91	59.4	4	SSE	0.07	5	SSE	62.1	62.8	62.8	---	30.23	0	0	0	0	0	0	0	0	0.002	0	72.1	42	47.7	70.5	8.01	0.0746	0	24	1	100	1
11/5/2020	5:50 AM	62.1	62.1	62.1	91	59.4	4	SSE	0.07	6	SE	62.1	62.8	62.8	---	30.23	0	0	0	0	0	0	0	0	0.002	0	72.1	42	47.7	70.5	8.01	0.0746	0	21	1	91.3	1