CHARACTERIZATION OF PRELIMINARY DATA OF INDOOR AIR QUALITY IN DIESEL CONSTRUCTION EQUIPMENT CABS

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CHARACTERIZATION OF PRELIMINARY DATA

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CONSTRUCTION EQUIPMENT CABS

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Abstract: Indoor Air Quality (IAQ) has been the center of attention of researchers for a long period of time, but little is known about the quality of air experienced by Heavy-duty Diesel (HDD) Construction Equipment operators. Factors such as being close to diesel exhaust as well as typical existing pollutants in construction sites, increase the probability of having poor IAQ in HDD equipment cabs. This research developed a framework to answer the question of whether HDD equipment operator's exposure to pollutants are raising concerns. In total, fourteen data sets were collected at a construction site for a whole workday from each piece of equipment for Carbon Dioxide (CO_2), Carbon Monoxide (CO), Fine Particulate Matter ($PM_{2.5}$), Total Volatile Organic Compounds (tVOC), Temperature, and Relative Humidity. To determine the quality of air inside the cab, collected data was compared and assessed for compliance with IAQ limits and screening values. These values were extracted from twelve surveyed standards and guides including the Occupational Safety and Health Administration (OSHA) and the U.S. Environmental Protection Agency (EPA). Moreover, data was collected from ambient air of the construction site and four university offices to compare to the collected data from HDD equipment cabs in order to gain a better understanding of IAQ differences. Results showed that none of the measured pollutants exceeded the OSHA limits, which are set for occupational exposures and much greater than other indoor area exposure limits. However, regarding the other limits and screening values surveyed for this study, tVOC and especially $PM_{2.5}$ were high enough to exceed most of them and raise concerns. Additionally, all of the measured pollutants were at higher levels inside the HDD equipment cabs compared to the construction site ambient air outside the cab, suggesting that the tested equipment cabs may cause accumulation of pollutants inside them. Moreover, results from university offices revealed that the surveyed HDD equipment operators experienced worse IAQ than office occupants.

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LIST OF ABBREVIATIONS

IAQ	Indoor Air Quality
HDD Equipment	Heavy-Duty Diesel Equipment
EPA	Environmental Protection Agency
OSHA	Occupational Safety and Health Administration
NIOSH	National Institute for Occupational Safety and Health
ACGIH	American Conference of Governmental Industrial Hygienist
AIHA	American Industrial Hygiene Association
ASHRAE	American Society of Heating, Refrigerating, and Air Conditioning Engineers
OEHHA	Office of Environmental Health Hazard Assessment
NAAQS	National Ambient Air Quality Standards
LEED	Leadership in Energy and Environmental Design
WHO	World Health Organization
PEL	Permissible Exposure Limit
REL	Recommended Exposure Limit
TLV	Threshold Limit Value
TWA	Time Weighted Average
STEL	Short Time Exposure Limit
WEELs	Workplace Environmental Exposure Levels
OEL	Occupational Exposure Limit
PM	Particulate Matter
tVOC	Total Volatile Organic Compounds

CHAPTER I

INTRODUCTION

People spend most of their time in indoor areas, so exposure to any substance could have intensified health effects if it happens indoors. Pollutants found indoors have the potential to be toxic and are found at much higher levels than outdoors (1) which makes it crucial to observe the quality of indoor air. “Indoor Air Quality (IAQ) refers to the air quality within and around buildings and structures, especially as it relates to the health and comfort of building occupants.” (2)

Odor from exhaust emission has been evident in equipment cabs based on operator’s reports. (3) This research sought to collect data from inside the different types of non-road Heavy-duty Diesel (HDD) Construction Equipment cabs to compare them with regulatory limits. In order to find out what substances need to be assessed, the composition of diesel exhaust should be determined. In United States, more than one million workers are exposed to diesel exhaust daily (4), while diesel alone supplies about 98 percent of all energy needed in construction sector (5).

1.1 Diesel exhaust constituents

Diesel engine emissions consist of more than a hundred chemicals both in gas and particulate phases. At least 445 chemical compounds have been identified in diesel emissions (6). The composition and amount of emissions could be affected by engine type, maintenance status, and fuel additives. In the gaseous phase, the main constituents are carbon dioxide (CO_2), water vapor (H_2O), oxygen (O_2), nitrogen (N_2), carbon monoxide (CO), hydrocarbons (HCs), nitrogen oxides (NO_x), hydrogen (H_2), sulfur dioxide (SO_2), sulfates (SO42-), aldehydes (C_2H_4O), and ammonia (NH_3) (7). The Particulate phase of the diesel exhaust includes carbon, fuel-derived hydrocarbons, lubricating oil-derived hydrocarbons, soluble organic fraction, and sulfate (8, 9). Particulates have a size range of smaller than 0.01 µm to 30 µm (10). Particles with an aerodynamic diameter equal or smaller than 2.5 µm ($PM_{2.5}$) are referred to as fine particles and diameters equal or smaller than 10 µm (PM_{10}) are called coarse particles. Since particles with a diameter greater than 10 µm could be perfectly filtered and prevented from penetrating the human lung by the nasal hairs, only coarse and fine particles are usually the subjects of investigations. It has been determined that fifty to eighty percent of emitted particles have dimensions between 0.02 µm to 0.5 µm (11), which means exposure to $PM_{2.5}$ is more likely than PM_{10}. $PM_{2.5}$ is also more harmful for the human body as the particulates are able to go much deeper into the lungs and even to the blood stream. The Importance of $PM_{2.5}$ and its health effects has made the EPA, record and report live measurements of $PM_{2.5}$ in addition to general particulates from all major cities in the United States on their website (1).

In addition to $PM_{2.5}$, this research sought to measure CO_2 as the essential component of any IAQ assessment, CO to evaluate the presence of a toxic gas, total Volatile Organic Compound (tVOC) to cover all volatile substances including hydrocarbons, and temperature and relative humidity to determine convenience of the operator.

1.2 Measured pollutants and their health effects

Adverse health effects of air pollution occur when a toxic substance enters the human body and reaches the bloodstream or organs. The entry routes of human body for a toxic substance could be through inhalation, injection, ingestion, or skin absorption, but occupational exposure is concerned when the chemical enters the body through inhalation (12). The human respiratory system consists of a series of organs including nose, throat, lung, and alveoli, where gasses are absorbed by cells. The deeper a pollutant penetrates the system, the more serious adverse effects it causes. Moreover, depending on the type of the pollutant, its concentration, and duration of exposure, both short term and long term health effects may vary in severity.

1.2.1 Carbon Dioxide

Normally CO_2 constitutes 0.035% of the outdoor air. Burning fossil fuel is main source of producing carbon dioxide, which is a colorless, odorless, nonflammable gas. Moreover, CO_2 concentration in exhaled air is higher than that of the outdoor air (13). Hence, an increase in CO_2 levels in equipment enclosed cabs caused by operator breathing and other sources on a construction site, including diesel emission, may be evident. It was reported when humans are exposed to high level of CO_2, they evaluate air quality as unpleasant and unacceptable (14). CO_2 is known as a simple asphyxiate and potential inhalation toxicant (14). It is not considered harmful for chronic exposures (15), but in the case of acute exposures, given the following percentages of CO_2 in the air, the corresponding symptoms are as follows (16):

2% ~ 3%: Shortness of breath, deep breathing. 7.5%: Headache, dizziness, restlessness, increased heart rate and blood pressure, visual distortion. 10%: Impaired hearing, nausea, vomiting, and loss of consciousness. 30%: Coma, convulsion, death

1.2.2 Carbon Monoxide

CO is a colorless, odorless, tasteless, extremely flammable, and non-irritating gas, mainly produced by incomplete combustion of liquid fuels (18). CO is highly toxic, and Like CO_2, it is not known as a carcinogen gas; however, exposure to lethal gas could result in death. CO which has entered the bloodstream through the lungs, binds to hemoglobin, a protein on red blood cells, faster than oxygen does, and makes it difficult for hemoglobin to transport oxygen to the organs, especially the heart and the brain (17). The more severe exposure to CO, the more likely heart and brain cells die. There is no certain health effect for long-term exposure, eye contact, or skin contact with CO (18). Other less severe exposure health effects are include but are not limited to headache, dizziness, fatigue, nausea, and rapid heartbeat.

1.2.3 Particulate Matter

Airborne particulate matter (PM) is part of the existing pollutants in outdoor air. It is mostly comprised of Sulfate (SO_4), Nitrate (NO_3), Ammonium, Elemental Carbon (EC), Organic mass, and inorganic material. In terms of size, commonly airborne PM splits to coarse and fine particles, where fine part refers to particles smaller than 2.5 μm in diameter (19). The EPA 2009 Integrated Science Assessment for Particulate Matter (20) has surveyed a number of studies about $PM_{2.5}$ short-term and long-term exposure health effects. They concluded that there is a relationship between short-term exposure to $PM_{2.5}$ and cardiovascular disorders like heart diseases (such as when a part of the heart does not receive enough blood) and congestive heart failure. Furthermore, relationship between $PM_{2.5}$ and respiratory infections like COPD, or asthma is likely to exist. What connects mortality to short-term exposure to $PM_{2.5}$ is death because of the previously mentioned diseases, while mortality for long-term exposure is heavily associated with lung cancer.

1.2.4 Volatile Organic Compounds (VOCs)

According to the EPA, “Volatile organic compounds (VOCs) are any compound of carbon, excluding carbon monoxide, carbon dioxide, carbonic acid, metallic carbides or carbonates and ammonium carbonate, which participates in atmospheric photochemical reactions.” (21) By measuring tVOC, most of the hydrocarbon based pollutants will be covered. VOCs are a wide range of substances from very volatile to semi-volatile (higher molecular weight) organic compounds. Some of the main sources of VOCs are car exhaust, industrial coating operations, paints, and household chemicals (20). Second-hand smoke, which is very common in equipment cabs since many equipment operators are smokers, is included in tVOC. VOC characteristics include being odorous, mostly toxic, carcinogenic, and flammable. VOCs have a wide range of health effects, including but not limited to: Headache, dizziness, visual disorders, eye and respiratory tract irritation, and memory impairment (22). The risk and effect of each VOC on human health depends on exposure time, and its compound (23).

1.2.5 Temperature and Relative Humidity

Workers may be required to work in very high or low level temperatures. When the human body becomes unable to keep its temperature at normal rate, heat or cold disorders can occur and may even result in even death. Occupational Safety and Health Administration (OSHA) does not have any regulation regarding heat stress, but heat disorders have known health effects including heat cramps, heat exhaustion, and heat stroke (24). Also the mixture of high level moisture and dust particles, which is very likely to exist in construction sites, encourages the growth of molds and viruses and can cause adverse health effects. High humidity contributes in worsening the heat stress. On the other hand, in cold stresses, when the core temperature of body drops below 90 ^{o}F, a medical condition named Hypothermia happens which could eventually be fatal. Symptoms include excessive shivering, blue lips and fingers, and confusion (24).

1.3 Research Objectives

The objectives of this research were as follows:

a) Correlate results of this research to the previous study (3), conducted as the baseline of this one, and determine whether outcomes are similar.

b) Examine operator exposure, and compare the results with existing limits and find any possible violation of theses limits.

c) Compare collected data, even if is not above the limits, to another workplace typically believed not to have poor IAQ. In this research, data collected from typical university offices to contrast to equipment cabs.

1.4 Research Statement:

Based on the literature review and previous study, the research statement for this thesis is that *the quality of air in construction equipment cabs is not exceeding existing limits, however equipment operators are exposed to more pollutants than typical office workplaces.*

CHAPTER II

LITERATURE REVIEW

2.1 Diesel exhaust

In 1858, while steam engines were being considered as the main source of power for industries, Rudolf Diesel invented an engine that still carries his name. Sixty nine years later, diesel engines started to be used in commercial vehicles and equipment (25). Identified as early as 1950's, emitted pollution from diesel exhaust was visible, but the effect of air pollution on human health was not the subject of attention. Typically, federal and state funds that have supported studies on the effects of air pollution on the human body has been spent on making rules and statutes for the problem (26). After a year, Kotin et al. (27) acknowledged the presence of Aromatic Hydrocarbons in diesel-engine exhaust and it was named a carcinogenic pollutant and potential hazard for public health. Kotin sparked the issue and at the time society started to realize there was a lack of information about adverse health effects of air pollution on the human body, so researchers showed interest in the topic. Fifty years after the first equipment operator exposed to diesel emissions, Decoufle et al. (28), for the first time, considered equipment operators as at-risk health groups and performed a study that revealed, by medical review, an unusual frequency of lung cancer and intestinal cancer between 2,190 deceased construction equipment operators. Since then, many researchers have focused on cause of death among equipment operators who are typically exposed to a high amount of diesel exhaust emissions. As shown in several studies, operators have higher rates of liver cancer (29). Additionally, exposure to diesel fumes could be associated with the development of prostate cancer (30), and a relationship between diesel exhaust exposure and heart diseases was identified in operators (31).

So far, the World Health Organization (WHO) (32), the International Agency for research on Cancer (IARC) (33), OSHA (34), the California Environmental Protection Agency (35), the EPA (36), and the National Toxicology Program (37) have investigated adverse effects on the human body and classified diesel exhausts as a human carcinogen and harmful substance. The EPA, in an effort to reduce non-road diesel engine emissions, introduced Tier standards on 1994 (38). Tier 1 standards were signed between the EPA and main engine makers to be phased-in from 1996 to 2000. Tier 2 and 3 standards followed Tier 1 from 2000 to 2008. The use of exhaust gas after-treatment was rarely mentioned on Tier 1 to 3 standards. Tier 1 and 2 were mostly about engine design, while Tier 3 emphasized NO_x and HC emission reduction, however, Tier 3 standards for PM were never adopted. Tier 4 standards effective from 2008 required PM and NO_x to be more reduced using advanced exhaust gas after-treatment. It also limited the use of sulfur in diesel fuels, which was not mentioned in the previous standards (38). Tier standard of engine is determinable based on engine year and horse power. All manufactured engines before 1996 are assumed as Tier 0.

Based on previous research, fatal health problems and diseases among equipment operators are identified, and have been correlated to diesel exhaust as the main cause. Therefore, to keep the operators safe, Caterpillar, as the oldest equipment manufacturer, has started using enclosed cabs for its equipment since 1950s, specifically in mining equipment (39). As Pannel et al. (40) indicate in their research, enclosed cabs could play a significant role to keep the operators protected from outside pollution. Mining equipment cabs have been shown to limit pollution concentration inside the cab as compared to outside (41). Additionally, to retrofit the cabs even more, filtration systems added to equipment air conditioners after the Mine Safety and Health Administration met with Caterpillar in 1998 (42). Filters being used in this system are usually pleated filter paper or foam (42). In order to have a comprehensive understanding of this topic, it is crucial to quantify the exposure of operators to pollution inside the equipment cab, where operators spend the majority of their workday time. This cab is considered an indoor environment for the operator, and this research sought to determine a correlation to IAQ. Throughout the history IAQ has been applied to all different types of indoor environments, however not to equipment cabs.

2.2 IAQ

EPA research on human exposure to air pollutants (43) indicates indoor air pollutants may be two to five, and occasionally more than a hundred, time more than outdoor levels. Most people in the United States spend almost 90% of their time in indoor environments, IAQ has been the subject of much research attention, but research has not focused on HDD equipment cabs. The EPA has a specific section dedicated to IAQ, with subsections including homes, schools, offices, and large buildings (44). These subsections include the home and workplace, but omit HDD equipment cabs as a potential workplace.

Office buildings are typically small environments and the presence of excess pollutants causes occupant complaints. In a case study IAQ specialists surveyed fifteen offices in order to determine why headache and nausea occurred in several company employees in Canada. Identified pollutants like CO_2, CO, particles, and tVOC were measured in their offices. In most cases, they found high levels of CO_2 and tVOC. After normalizing them by appropriate ventilation, all complaints were eliminated (45). Unlike offices, shopping malls are huge, and need precise measurements to understand their IAQ status. Research on nine shopping malls in Hong Kong showed that due to insufficient ventilation, about half of them had high levels of CO_2 and respirable particulates. They compared their data to Hong Kong Occupational Exposure Limits (OEL) (46).

Observing IAQ is very important in schools and school buses, since nearly one in thirteen school-aged children has asthma and exposure to some types of pollutants could worsen their asthma-related symptoms (43). A recent study measured indoor air pollutants in two primary schools and one kindergarten in Greece in both non-heating and heating seasons, and found that concentration of pollutants are within accepted limits reported by the World Health Organization (WHO) (47). In 2003 the California Environmental Protection Agency funded 3 studies to examine children's exposure to pollutants in school buses. Results indicated that for some buses, higher exposure occurred and main the source of the pollution was bus's own tailpipe (48). Some researchers compared different environments to each other, for instance, four IAQ investigators measured and compared some air pollutants like CO_2, PM_{10}, and VOCs in six homes, ten offices, ten schools, nine shopping malls and four restaurants. They found the CO_2 and total bacteria counts in restaurants, shopping malls and schools were not only higher than in homes and offices, but also exceeded existing standards which they believed was the result of high occupancy and inadequate ventilation (49).

IAQ specialists and researchers are mainly focused on evaluating quality of air within residential/commercial buildings, malls, schools and school buses. In recent years, the borders of IAQ-related issues have been extended a little, so some studies have considered mining and agricultural equipment operators as a group with potential exposure to indoor pollution and quantified this exposure. Tailpipe emissions not only play a significant role in a vehicle's potential poor IAQ, but polluted ambient air and contaminated workplace should also be added to the IAQ equation for heavy equipment operators.

Heavy equipment are designed for a vast variety of industries, from agriculture and forestry, to construction and earthmoving. Mining equipment operators have been the center of attention due to their extremely dusty work environment. Cecala et al. (50) tried to improve the cab filtration system for a surface drill equipment and concluded that key components to keep the operator from dust exposure were effective filtration and cab integrity. They believed their result could be applied to other types of equipment in agriculture, mining, and the construction industry. Organiscak et al. (51) measured dust and diesel particulates in four equipment cabs in two different underground silicosis mines to assess the cab filtration system performance. They found three out of four cabs were adequately protected and the high level of dust in the fourth one was due to a damaged filtration system. Moyer et al. (52) tested tractor cab filtration system in orchards to see whether operators are protected from regularly used pesticides or not. After the initial testing, no conclusive answer was determined.

With the exceptions above, there is an undeniable lack of research about the quality of air in HDD equipment cabs. As a comprehensive literature review showed, from more than ten thousand measurements collected to assess occupational exposure to diesel exhaust, none of them were specifically about construction equipment operators (53). In 2013, Hansen (54) measured carbon monoxide (CO), nitrogen dioxide (NO_2), and particulate matter in thirteen different heavy equipment cabs, including a number of construction equipment. After mentioning none of the measured pollutants could be used as a predictor of the other two, CO and NO_2 cab concentrations were correlated with American Conference of Governmental Industrial Hygienists (ACGIH) Threshold Limit Values (TLVs) and found them to be within acceptable limits. Most of equipment cab studies sought to evaluate indoor dust and particles, while it is obvious that the more pollutants measured, the better the assessment of IAQ is achieved. So this research measures four different pollutants plus temperature and humidity, inside construction equipment cabs to achieve a comprehensive IAQ assessment.

2.3 Existing Limits and Screening Values

Industrial hygiene history really began in 1970. Before that there were no federal regulations for safety and health matters except for TLVs, reported by the ACGIH. TLVs refer to "airborne concentrations of substances and represents conditions under which it is believed that nearly all workers may be repeatedly exposed day after day without adverse health effects (13)." The ACGIH emphasizes that TLVs do not indicate the boundary between safe and dangerous concentrations, so they are not the limits that are enforced by the law in the United States. Although TLVs have been reported for as many as 720 chemicals, few states had adopted TLVs as their standards, while there was no enforcement for them, neither from states nor from the federal government. On April 28 1971, OSHA came into existence by way of Department of Labor. Some of the first defined responsibilities of OSHA are as follows:

- "Empower the secretary of labor to issue safety and health regulations and standards that have the force and effect of law" (55)
- "Require employers to maintain accurate records of exposures to potentially toxic materials or harmful physical agents that are required, under the various safety and health standards, to be monitored or measured, and inform employees of the monitoring results" (55)
- "Establish a National Institute for Occupational Safety and Health (NIOSH), with the same right of entry as OSHA representatives, to undertake health studies of alleged hazardous health conditions and to develop criteria to support revisions of health standards or recommendations to OSHA for new health standards" (55)

OSHA published TLVs again as base numbers of Permissible Exposure Limits (PELs) for over four hundred chemicals and started revising them gradually. Unlike TLVs, PELs have the power of law in the United States and are mandatory federal exposure standards. Moreover, the National Institute for Occupational Safety and Health (NIOSH) was established within the Department of Health, Education, and Welfare (now known as Department of Health and Human Services). NIOSH is responsible for testing and certifying protective devices, conducting and supporting research activities to make recommendations for regulations, and training occupational health personnel. NIOSH recommendations are also known as Recommended Exposure Limits (RELs) which are basic reports of PELs. The American Industrial Hygiene Association (AIHA), founded in 1939, also has established protecting worker health as its core mission, where industrial hygienists evaluate occupational safety concerns and find solutions to prevent them (56). AIHA also published its own limits as the AIHA Guideline Foundation Workplace Environmental Exposure Levels (WEELs). The first version was published in 1978, and it has been revised a number of times. The latest version of WEELs was published in 2011. Like TLVs, WEELs do not have the power of law. In cases where a substance does not have PEL, OSHA may review available regulations and limits, where the most common ones are NIOSH RELs, ACGIH TLVs, and AIHA WEELs.

Generally, there are two types of reported limits for airborne pollutants, indoor exposure limits, which are often regulated by the EPA, and occupational or industrial exposure limits, which are mostly reported by the OSHA. Indoor limits are set for well-being and comfort of the building occupants. On the other hand, occupational limits are set just to keep workers from adverse health effects. For that reason, in most cases, indoor limits are much lesser than occupational limits.

Each limit, based on the substance that it limits, has a specific type. Some limits are for long time periods of exposure, while others are for shorter times. Typically, limits could be defined as one of these types: Time Weighted Average (TWA), Short Time Exposure Limit (STEL), Ceiling (C), Long-Term (L), or Immediately Dangerous to Life or Health (IDLH). TWA limits are based on average exposure to pollutants that targeted individual experience over a specific time period. This specific time is usually the normal work-day time period which is eight hours in the U.S., but other TWA limits have also been reported like a 1-hour TWA or even a 30-minute TWA. Generally, when it is believed that lower levels of a substance is a concern, a shorter duration TWA may be recommended (57). STEL limits refer to smaller portions of time, mostly reported over a fifteen-minute time period. So, in order to determine any violation of STEL limits, the average of the most recent 15-minute exposure should be calculated. In other words, STELs are 15-minute TWA limits. A ceiling standard is the same as the maximum acceptable limit. If a substance has a ceiling limit, this limit should never be exceeded at any time. Ceiling limits are comparable to instantaneous measurements. Long-Term limits could be associated with time periods between three months to one year, where arithmetic average concentration of the targeted substance should be below the limit. IDLH refers to condition, that poses a threat to one's life, or will cause an irreversible adverse health effects. In normal situations, it is very unlikely that any pollutant exceeds the IDLH limit.

The goal of this research is not just limited to assess IAQ of HDD equipment cabs from the legal perspective. Hence multiple number of regulatory organizations, either based in the United States or other countries around the globe that have reported limits and regulations, were used as a basis for this research. Considering identified pollutants to measure, regulatory agencies and other organizations surveyed in this research are the abovementioned OSHA (58), NIOSH (58), ACGIH (58), AIHA (59), and:

- The LEED v.3 and LEED v.4, reported by the U.S. Green Building Council (USGBC) to assure well-being of building occupants (60). The difference between two versions is that LEED v.4 focuses on increasing technical stringency from past versions and developing new requirements for some project types such as hotels, schools, and mid-rise residential.
- The National Ambient Air Quality Standard (NAAQS) table, reported by the EPA that applies to outdoor air throughout the United States (61). These limits are enforceable for cities, and set to be reviewed by the EPA every five years.
- A comprehensive report developed for nonindustrial environments by the Denmark based World Health Organization (WHO/Europe), which is intended to contain limits for both indoor and outdoor air (62).

- The MAK RELs reported by the German institute Deutsche Forschungs Gemeinschaft (DFG), which is similar to the U.S. NIOSH. This report is specifically for industrial environments, covers a very wide range of substances, and has the power of law in Germany (63).
- The advisory report on environmental and occupational health for residence, reported by Health Canada and contains maximum exposure limits (64).
- The Office of Environmental Health Hazard Assessment (OEHHA) Reference Exposure Levels, reported by the California Office of Environmental Health Hazard Assessment (65).
- The Hong Kong Occupational Exposure Limits (OEL) (66).

All mentioned sources were surveyed for each measuring pollutant. Results are shown in the following tables, where the limits and screening values are ordered from small to large. Table 1, 2, and 3 are for CO_2, CO, and $PM_{2.5}$ respectively.

Table 1: CO_2 Exposure Limits and Screen Values

#	Limit	unit	type	Source
1	700	ppm	above outdoor air	LEED v3 (2009)
2	1,000	ppm	instantaneous	EPA (Building Air Quality Guide)
3	1,000	ppm	instantaneous	ASHRAE 62.1 Standard 2013
4	1,000	ppm	instantaneous	Canadian
5	3,500	ppm	Long-term	Canadian
6	5,000	ppm	8-hr TWA	OSHA (PEL)
7	5,000	ppm	8-hr TWA	NIOSH (REL)
8	5,000	ppm	8-hr TWA	ACGIH (TLV)
9	5,000	ppm	8-hr TWA	MAK
10	10,000	ppm	1 hr	MAK
11	30,000	ppm	STEL (15-mins)	NIOSH (REL)
12	30,000	ppm	STEL (15-mins)	ACGIH (TLV)
13	40,000	ppm	IDLH (Will kill)	NIOSH (REL)

In many cases, CO2 levels are considered as an indicator of IAQ. Since measuring all potential pollutants in indoor areas could be expensive and time consuming, measuring CO2 can reveal whether ventilation is sufficient. Limit of 1,000 ppm reported by the Canadian, the ASHRAE, and the EPA is based on this definition as the EPA Building Air Quality Guide (67) mentions that peak CO2 levels above 1,000 ppm indicates inadequate ventilation.

Table 2: CO Exposure Limits and Screening Values

#	Limit	unit	type	Source
1	2	ppm	above outdoor air	LEED v.4
2	9	ppm	> 4-hr sampling	LEED v.4
3	9	ppm	8-hr TWA	EPA-NAAQS
4	10	ppm	8-hr TWA	WHO/Europe
5	11	ppm	8-hr TWA	Canadian
6	25	ppm	1-hrTWA	ACGIH (TLV)
7	25	ppm	1-hrTWA	WHO/Europe
8	25	ppm	1-hrTWA	Canadian
9	30	ppm	8-hr TWA	MAK
10	35	ppm	8-hr TWA	NIOSH (REL)
11	35	ppm	1-hrTWA	EPA-NAAQS
12	50	ppm	8-hr TWA	OSHA (PEL)
13	50	ppm	STEL (30-min)	WHO/Europe
14	60	ppm	STEL (30-min)	MAK
15	90	ppm	STEL (15-min)	WHO/Europe
16	200	ppm	ceiling	NIOSH (REL)
17	1,200	ppm	IDLH	NIOSH (REL)

Table 3: $PM_{2.5}$ Exposure Limits and Screening Values

#	Limit	Unit	type	Source
1	0.012	mg/m3	Long-Term (1 year)	EPA-NAAQS
2	0.015	mg/m3	Instantaneous	LEED v3 (2009)
3	0.035	mg/m3	24-hour	EPA-NAAQS
4	0.04	mg/m3	Long-term	Canadian
5	0.1	mg/m3	1-hour TWA	Canadian
6	1.5	mg/m3	8-hr TWA	MAK
7	3	mg/m3	8-hr TWA	ACGIH (TLV)
8	5	mg/m3	8-hr TWA	OSHA (PEL)

Limits converted from µg/m3 to mg/m3 to be consistent with EVM-7 logging unit

Since multiple number of substances could be named as VOCs, and it is not a singular gas, reporting a single limit for it is not accurate. None of the identified sources have mentioned a limit for total VOCs (tVOC), except two very general numbers. For typical VOCs, the screening value is set to be 500 µg/m^3, and for hydrocarbon based VOCs this number is 200 µg/m^3 (68). However, considering VOC substances that are emitted from diesel exhaust (69), and typical VOCs are found in construction sites (24), there are multitude exposure limits for each VOC, makes it possible to measure and correlate each one with corresponding limits. List of VOCs that are most likely to exist in HDD equipment operator's ambient air and their limits is shown in Appendix C. Additionally, isobutylene is a goof indicator of tVOC in indoor environments (Additional information on section 3.1). Field experiences have suggested the following guide to assess indoor air environments based on isobutylene measurements (70): 100~400 ppb isobutylene units: normal IAQ. 500+ ppb of isobutylene: Indicates potential of IAQ contaminants.

For temperature and humidity, both heat and cold stresses should be taken into consideration. The heat index, which is calculated based on temperature and humidity, is the best way to express heat stress. The heat index equation (55) is valid when temperature is above 80 ^{o}F and relative humidity is above 40%. Table 4 shows the severity of heat indexes. The greater the heat index is, the more heat stress is exposed to the targeted operator.

Table 4: Heat Indexes and Corresponding Risks

HI	Risk
80-90	Caution
91-103	Extreme Caution
104-124	Danger
125-137	Extreme Danger

On the other hand, Figure 1 (24) shows the risk of cold stress based on temperature and wind speed.

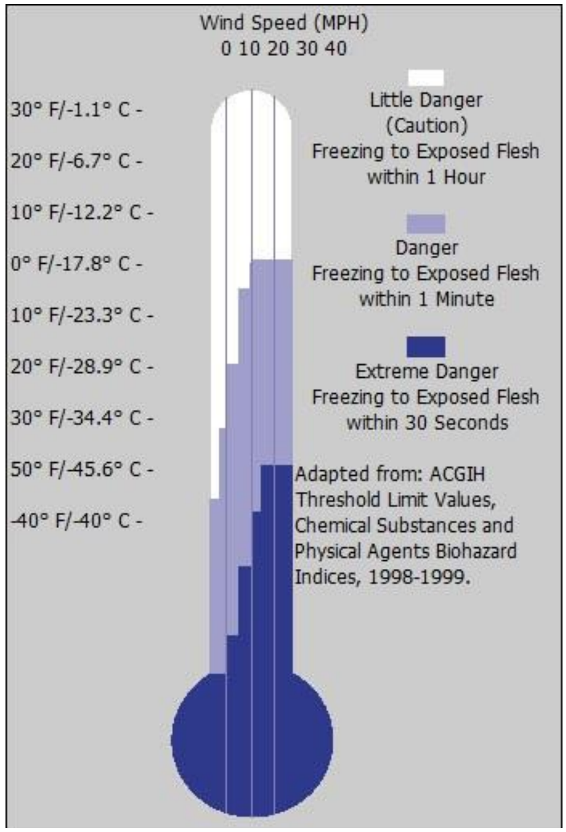

Figure 1: Cold Stress and Potential Hazard

CHAPTER III

METHODOLOGY

Output of an idealized complete combustion process in diesel engines would be just carbon dioxide (CO_2) and water vapor (H_2O), but due to an incomplete combustion process, pollutants like hydrocarbons (HC), carbon monoxide (CO), Nitrogen oxides (NO_x), and particulate matter (or dust) could be emitted from the tailpipe. These pollutants are potentially present inside the equipment cabs. Moreover, equipment processes like excavating, moving dirt, and grading, cause high chance of dust to penetrate the cab through opened windows and doors, and running air conditioners specifically set to “outdoor air”. For the pollutants being considered, the “EVM-7 Advanced Particulate, and Air Quality Monitor” manufactured by “3M solutions” had been chosen for sampling. The EVM-7 is equipped with 6 sensors, making it able to measure Carbon Dioxide (CO_2), Carbon Monoxide (CO), Dust (or Particulate Matter), total Volatile Organic compounds (tVOC), Temperature, Relative Humidity, and the Dew Point.

3.1 Sampling equipment

There are many instruments on market for measuring air pollution. Each one, based on the equipped sensors, is able to measure some specific pollutants. For instance, the research team previously rented “AdvancedSense IAQ Pro monitor and GrayWolf probes” for similar study (3), which was able to measure CO_2, CO, NO_2, tVOC, Temp, RH, and Barometric Pressure. This instrument was not a good fit for the purpose of the research, due to its limited battery life, start-up time, and complicated connections (3). To facilitate the data collection process, and be able to collect comprehensive data, two EVM-7 monitors (Figure 2) were purchased with CO_2, CO, tVOC, PM (optional between $PM_{2.5}$, PM_4, PM_{10}, PM_{100}), Temp, and RH sensors. As indicated in the user manual, the battery life is at least eight hours in running mode, however, through instrument use, it was determined it could run up to twelve hours without the power source, making it possible to measure in-cab pollutants for a complete workday.

Figure 2: EVM-7s

The EVM-7 collects particles or dust in two ways. It pumps air through a circular inlet, called impactor, designed to collect particles smaller than optional sizes of 100 µm, 10 µm, 4 µm, or 2.5 µm in diameter. There are different size plates underneath each turret, hence for pumped air to enter the instrument it has to round the grease covered plate in 90° angles, so larger/heavier particles would stick to the plate (Figure 3 and 4). Then, using the optical light scattering photometer, EVM-7 determines the total mass concentration of particulate matter in milligrams per cubic meter of air.

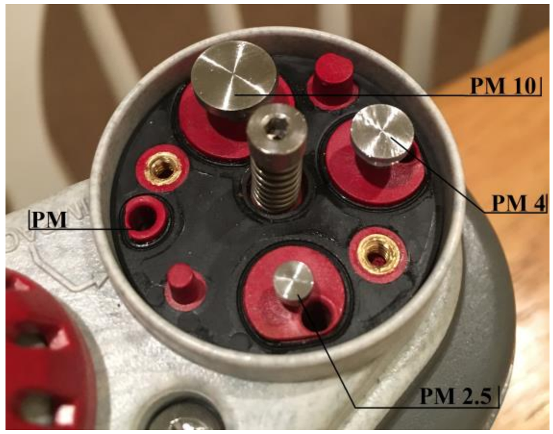

Figure 3: Greased Plates

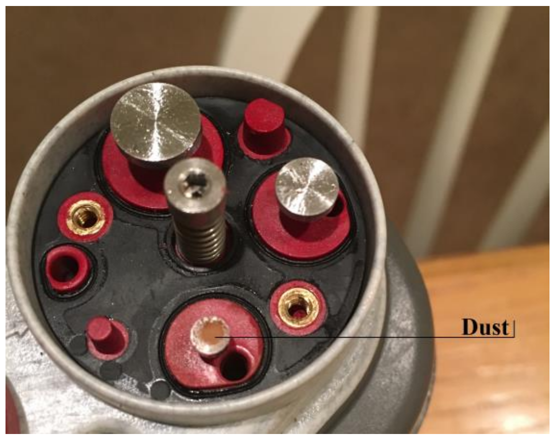

Figure 4: Dust on Plate

Through gravimetric sampling, the EVM-7 passes air through a paper filter inside a sealed cassette, where particles accumulate. The cassette should then be sent to a laboratory for results (Figure 5).

Figure 5: Gravimetric Sampling Cassette

For the gaseous phase, the EVM-7 is capable of running 3 optical sensors simultaneously; One sensor for a toxic gas, selected between nine toxic gasses, one for tVOC, and one for carbon dioxide (Figure 6). One of the most important toxic gasses in diesel exhausts is nitrogen dioxide (NO_2). Results of previous research showed that NO_2 is not in dangerous concentrations and not approaching limits (3). Therefore, carbon monoxide (CO), which is also toxic, was identified, measured and correlated with limits. Additionally, the EVM-7 measures temperature and relative humidity (RH) over the time.

Figure 6: Gas Detector Sensors

All measurements, basically, are comparisons: Comparison of an unknown value with standards which are known values. In order to achieve valid and reliable comparison, the instrument performing measurements, should be calibrated (41). The instrument receives a full factory calibration before shipping. However, calibration is not a one-time process and the instrument should be calibrated regularly. The EVM-7 consists of seven parts and each part has a specific calibration requirement. The particulate sampling filter was calibrated using factory provided zero-cal filter (Figure 7).

Figure 7: Particulate Zero-cal

Pump flow rate is calibrated using a standard flowmeter calibrator. The flow rate adjusted to 1.67 liters per minute as suggested by the user manual for best functioning (Figure 8).

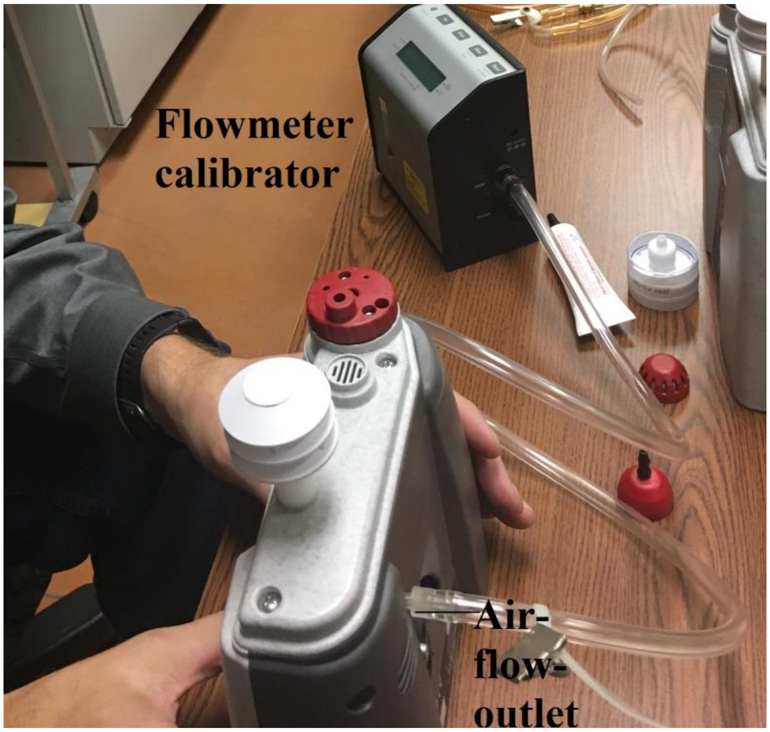

Figure 8: Flow-meter Calibrator

Two limits need to be defined by calibration for the CO, CO_2, and tVOC gas sensors, zero and span or maximum. For setting the zero limit, a nitrogen (N_2) calibration gas cylinder, which contains zero parts per million (ppm) of targeted gasses, was used for all three sensors. For identifying the maximum limit, each sensor needs its own gas cylinder. Carbon monoxide calibrated with a 100 ppm CO cylinder, which makes the maximum measurable CO hundred ppm. Likewise, a 100 ppm CO_2 gas cylinder was used for carbon dioxide span limit. For the VOC sensor, since tVOC refers to the composition of multiple number of substances, the EVM-7 user manual recommends using a substitute for the tVOC which typically is Isobutylene (C_4H_8). A 100 ppm isobutylene gas cylinder was used for VOC sensor calibration (Figure 9). As mentioned, each sensor was calibrated on a regular basis, as prescribed by the manufacturer, during the data collection process. Details on calibrations are given in the sampling strategy section.

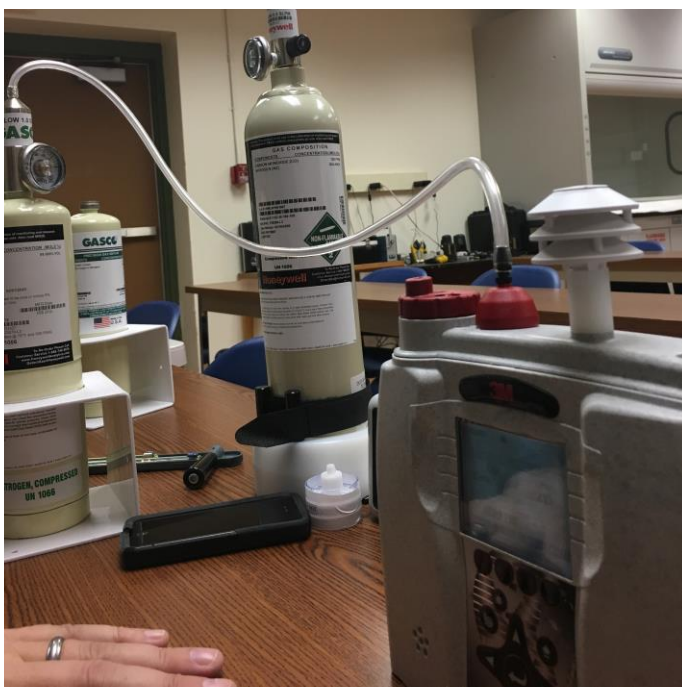

Figure 9: VOC Sensor Calibration Process

Accuracy of sensors should take into consideration as interpreting the results are highly dependent upon them. Accuracy and precision are specific for each sensor. Accuracy is typically expressed as a percentage either of the reading or the full scale of the instrument. Display resolution or precision is the decimal precision instrument reports for each sensor. Table 5 represents detailed accuracy and resolution information.

Table 5: Display Range, Precision, and Accuracy of the EVM-7s

Sensor	Display Range	Precision	Accuracy
CO2	0 to 5,000 ppm	1 ppm	±100 ppm
CO	0 to 1,000 ppm	1 ppm	±5%
Particulate	0 to 200 mg/m3	0.001 mg/m3	±15%
VOC	0 to 2,000 ppm	0.1 ppm	±5%
Temperature	14 to 140 ^{o}F	0.1 ^{o}F	± 2 ^{o}F
	0 to 60 ^{o}C	0.1 ^{o}C	± 1.1 ^{o}C
Relative Humidity	0 to 100%	0.1%	±5%

3.2 Data collection

Two instruments were used to collect data. In order to have consistent results from both, a number of tests were conducted before starting the data collection process. Both EVM-7s were placed in the exact same location to read the pollutants for a specific time period. Outputs were correlated to determine whether the units provided the same readings. Figure 10 is an example of the tests. A certified industrial hygienist observed the results. Given the accuracy of EVM-7, both instruments were reading same amounts, although the output appears slightly different. Using both EVM-7s, twenty individual samples were collected from ten different pieces of equipment, the construction site ambient air, outdoor air, and four different university offices.

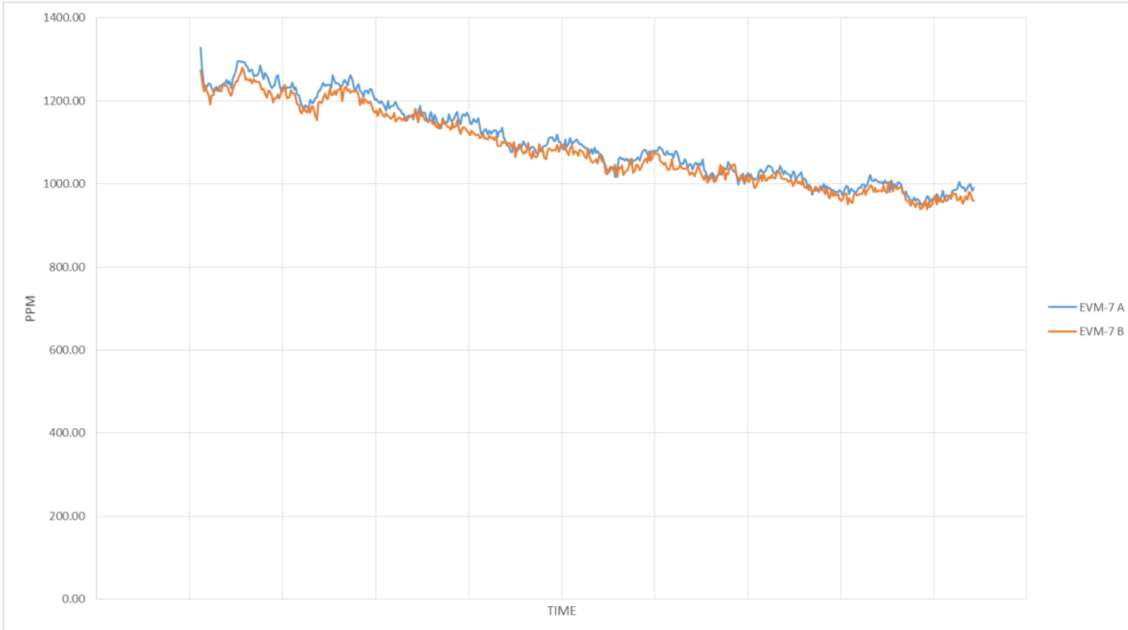

Figure 10: Comparison of CO_2 Readings over Time

3.2.1 Sampling locations

A major residential development construction site was identified in Stillwater, Oklahoma. The construction of a retirement center and residential development was progressing on the early stages. The project included excavation, roadwork, the main retirement center, and future home lots (Figures 11, 12).

Figure 11: Construction Site and Equipment Fleet

Figure 12: Aerial View: Retirement Center

HDD equipment, which participated in data collection process, were mostly working focused on dirt moving, grading, and excavation. This site was selected due to its heavy equipment variety, unlimited access to site and equipment, and short distance from Oklahoma State University. Equipment tested included excavators, loaders, backhoes, and motor graders. Ambient air test was conducted on northeast side of the site (Figure 13). Additionally, EVM-7s were placed in four typical university offices for a whole day to measure their exposure to pollutants and to act as a control.

Figure 13: Construction Site Ambient Air Sampling

3.2.2 Equipment tested

The project was in the initial stages focusing on earth moving, excavating and grading. There were a large number of related heavy equipment on site. Fourteen specific sets of data were collected from ten different pieces of equipment (Table 6).

Table 6: Equipment Sample List

Equipment Tested
Scraper #1
Scraper #2
Scraper #3
Scraper #4
Excavator #1
Excavator #2
Excavator #3
Excavator #4
Backhoe Loader #1
Backhoe Loader #2
Backhoe Loader #3
Loader #1
Loader #2
Rough Terrain Crane

Due to a technical problem, explained in the sampling strategy section, data from five pieces of equipment was collected more than one time. Also, regarding the manufacturing year of each equipment, the tier standard of its engine was found. Table 7 represents all tested equipment detailed information.

Table 7: Equipment Detailed Information

#	Equipment TYPE	MODEL	MANUFACTURER	YEAR	HP	TIER
1	Scraper #1	621	Caterpillar	1986	330	0
2	Scraper #2	621B	Caterpillar	1986	330	0
3	Excavator #1	EC360CL	Volvo	2001	198	1
4	Excavator #2	PC400LC-8	Komatsu	2008	362	3
5	Excavator #3	PC220LC-8	Komatsu	2010	179	3
6	Excavator #4	FF135DX	John Deere	2011	93	3
7	Backhoe loader	420F	Caterpillar	2010	100	3
8	Loader #1	WA250PT-5	Komatsu	2007	139	3
9	Loader #2	WA250PT-5L	Komatsu	2005	135	2
10	Rough Terrain Crane	RT60	Zoomlion	2013	N/A	4

3.2.3 Sampling Strategy

In order to gain accurate data, the measuring instrument should be as close as possible to the target. The target for any inhalant is the breathing zone or near the mouth and nose. When the target is the equipment operator, the whole cab area can be considered as representative of operator personal exposure area (53). Hence, the EVM-7 was always put inside the equipment cabs, as close as possible to the operator, to collect the needed data. For this project, and specifically for the equipment fleet, workday started at 7:30 a.m. and ended at 4:30 p.m. with a lunch break from 11:30 a.m. to 12:30 p.m. the EVM-7 was put in targeted cab sometime between 7:00 a.m. and 7:30 a.m. and picked up sometime after 5:00 p.m. to cover the entire workday. Based on the type of the equipment cab, and safety of the measuring instrument, the position of EVM-7 was different for each piece of equipment. The following table consists of information regarding the date of each test, the weather condition in test date, and the EVM-7 position in cab.

Table 8: Tests Detailed Information

Test Date	Tested Equipment	EVM-7 position	Weather Condition		
			Wind Speed (mph)	Mean Temperature (F)	Average Humidity (%)
29-Nov-2016	Scraper #1	Behind the seat (at neck height)	8	49	46
29-Nov-2016	Scraper #2	Behind the seat (at neck height)	8	49	46
30-Nov-2016	Backhoe Loader #1	Side compartment (at calf height)	8	42	49
30-Nov-2016	Excavator #1	Behind the seat (at back height)	8	42	49
1-Dec-2016	Loader #1	Corner (at lap height)	4	42	55
1-Dec-2016	Excavator #2	Behind the seat (at back height)	4	42	55
2-Dec-2016	Excavator #3	Behind the seat (at back height)	6	42	58
2-Dec-2016	Loader #2	Corner (at lap height)	6	42	58
13-Dec-2016	Excavator #4	Behind the seat (at feet height)	8	28	66
13-Dec-2016	Rough Terrain Crane	Behind the seat (at head height)	8	28	66
28-Dec-2016	Backhoe Loader #2	Side compartment (at calf height)	9	52	47
30-Dec-2016	Scraper #3	Behind the seat (at feet height)	8	42	39
9-Mar-2017	Scraper #4	Behind the seat (at feet height)	10	70	53
9-Mar-2017	Backhoe Loader #3	Side compartment (at calf height)	10	70	53

The EVM-7 user manual recommends each sensor to be calibrated periodically and to grease and clean the impactor after each ten hours of sampling. Hence, a number of calibrations were performed, with details reported on Table 9, where placed checkmarks indicate dates of calibration. After three days of collecting data, it was observed that one of the EVM-7 sampling devices, consistently recorded tVOC concentration as zero ppm. The VOC sensor was checked and calibrated multiple times, and pieces of equipment, tested using defective EVM-7, were tested again to gain tVOC data, but the problem was still unsolved. Therefore, all tVOC data, collected by the defective EVM-7, were excluded from the final report. However, data collected for other pollutants from the same equipment was analyzed and reported, because the same equipment in another day, with a new job description and ambient air could be treated as a new case for study. For this reason, the results contain fourteen equipment data sets, where Scraper #3 and Scraper #4 are same equipment as Scraper #1, and Backhoe #2 and Backhoe #3 are same equipment as Backhoe #1.

Table 9: Sensors Calibration details

Sensor / date	CO2		CO		VOC		PM	Temp.	RH	Flow rate
	Zero	Span	Zero	Span	Zero	Span	Zero-cal	Thermometer	Whirling	Flow Rate
	N2	CO2	N2	CO	N2	Isobutylene	Filter		Hygrometer	Calibrator
(Factory)	✓		✓		✓		✓	✓	✓	✓
11/22/2016	✓		✓		✓		✓	✓	✓	✓
12/9/2016	✓		✓		✓		✓			
1/18/2017	✓				✓					
1/20/2017	✓		✓		✓		✓			

After placing the instrument, the targeted operator was observed for a small period of time, either in the morning or after work, trying to determine whether the operator smokes, uses the air conditioner, or keeps the equipment doors open during the work. Figure 14 shows the checklist that was used to record the information. It was observed that the operators of Backhoe Loader #1, Scraper #2, Excavator #2, and Excavator #3 were smoking inside the cab.

<table>
<tr><td colspan="2">Area (open, facility, or …)</td><td></td></tr>
<tr><td colspan="2">What does the equipment do?</td><td></td></tr>
<tr><td colspan="2">Idling time (if any)</td><td></td></tr>
<tr><td colspan="2">Cab Doors status</td><td></td></tr>
<tr><td colspan="2">Air Conditioner status</td><td></td></tr>
<tr><td colspan="2">Instrument location in cab</td><td></td></tr>
<tr><td colspan="2">Operator's comments
(Ever felt pollutants or not)</td><td></td></tr>
<tr><td colspan="2">Equipment Location</td><td></td></tr>
<tr><td rowspan="4">Ambient weather condition</td><td>Wind</td><td></td></tr>
<tr><td>Temp</td><td></td></tr>
<tr><td>Relative Humidity</td><td></td></tr>
<tr><td>General</td><td></td></tr>
<tr><td colspan="2">Comments</td><td></td></tr>
</table>

Figure 14: Observation Information sheet

In addition to HDD equipment, data was collected from four different university offices. Instruments were set to automatically start logging at 8:00 a.m. and stop at 5:00 p.m., covering the entire workday. All the data was logged at thirty-second intervals, which generated more than one thousand data points for both the HDD equipment cabs and offices. The advantage of logging at thirty-second intervals, in addition ensuring full collection of the exposure, is having the ability to compare collected data with previously collected data points from baseline research (3).

3.3 Data Analysis

As mentioned on section 2.3, there are a multitude of different types of limits, each comparable with the specific type of data collection method and concentration measurement. Some of the limits are correlated with peak concentrations, some with 8-hour time weighted average (TWA), and some are compatible with 15-minute short term concentrations. Therefore, after completion of data collection, initial instantaneous readings of each pollutant over time moved on separate graphs for all tested equipment. Peak concentrations were determined and overall comparisons implemented. Then, in order to include 8-hr TWA limits, using Equation 1, time weighted concentration average was calculated for all pollutants.

$$TWA = PreviousTWA + \frac{MaxLoggedValue \times period(\text{sec})}{480\left(\frac{min}{8\ hour}\right) \times 60\ (\frac{sec}{\text{min}})} \tag{1}$$

Where the denominator is equivalent to eight hour in seconds. Data was collected at thirty-second intervals, so the period in Equation 1 is thirty.

Some sources have reported short time exposure limits (STEL) for specific pollutants which is based on 15-minute average concentrations. EVM-7 records STEL instantaneously, where after each thirty-second interval it reports a number that is the average concentration of the targeted pollutant over the last fifteen minutes.

In order to generalize the study and have almost all reported standards included, 1-hour TWA was calculated, for CO_2, CO, and $PM_{2.5}$, using Equation 2.

$$TWA = PreviousTWA + \frac{MaxLoggedValue \times period(\text{sec})}{60\left(\frac{min}{1\ hour}\right) \times 60\ (\frac{sec}{\text{min}})} \tag{2}$$

Equation 2 is a modification of Equation 1 with a denominator of 1 hour in seconds.

Based on temperature and humidity, heat and cold stresses evaluated whenever they were applicable.

CHAPTER IV

RESULTS

Data was collected for CO_2, CO, Dust ($P.M_{2.5}$), tVOC, Temperature, and Relative Humidity utilizing EVM-7. To make the results as close as possible to reality, the EVM-7s were left in place for a full eight-hour workday inside the equipment cabs. To facilitate the interpretation of the results, graphs and charts of the pollutants were plotted and were compared to the existing limits and screening values from all surveyed resources. Each pollutant was evaluated separately by calculating STEL, 8-hour TWA, and 1-hour TWA concentrations from the collected instantaneous readings. 1-hour TWA concentration at any point illustrates the average pollutant the operator has been exposed to over a one hour time period up to that point. Likewise, 15-minute STEL identifies the same but over most recent fifteen-minute time period. Full results for all pollutants are reported in Appendix A. It also should be mentioned that at some very rare points, EVM-7 provided numbers that did not add up to other readings. Wherever misreading happened, the outlier was substituted with a number that was matched with before and after readings. All such cases are reported in Appendix B.

4.1 Carbon Dioxide (CO_2)

A total of eleven limits were identified for CO_2. Using Equation 1 and Equation 2, 8-hour TWA and 1-hour TWA concentrations were calculated. STEL levels were also recorded and reported by the EVM-7. Out of all of the standards, 8-hour TWA limits were the most repeated ones. Figure 15, Figure 16, Figure 17, and Figure 18 are illustrating peak CO_2 levels, 8-hour TWA, maximum 1-hour TWA, and maximum 15-minute STEL concentrations respectively for each equipment. Appropriate limits are also shown on the charts. All real time readings, 8-hour TWA, 1-hour TWA, and 15-minute STEL graphs over time and also the table of detailed results are shown in Appendix A.

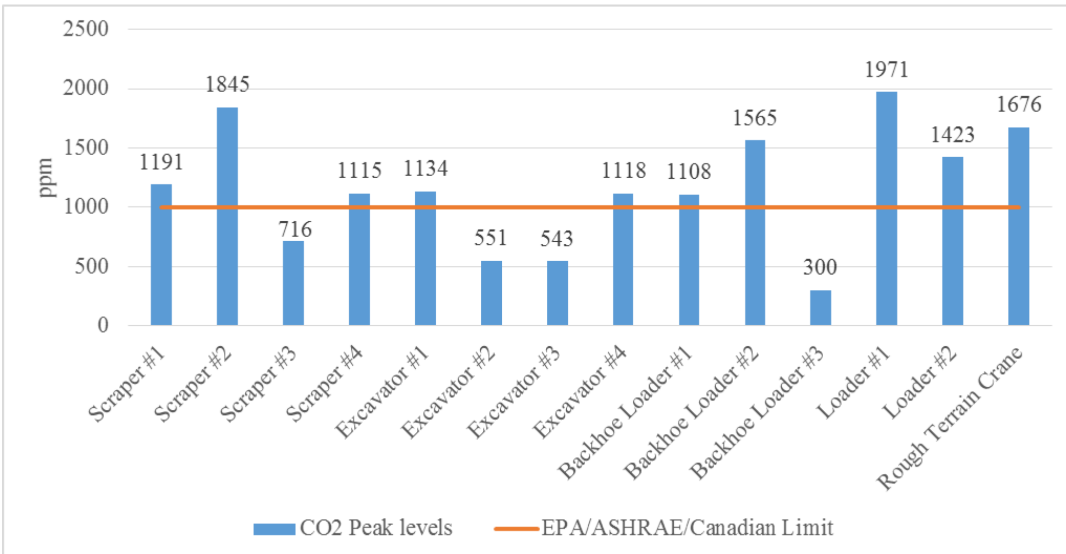

Figure 15: CO2 Peak Levels

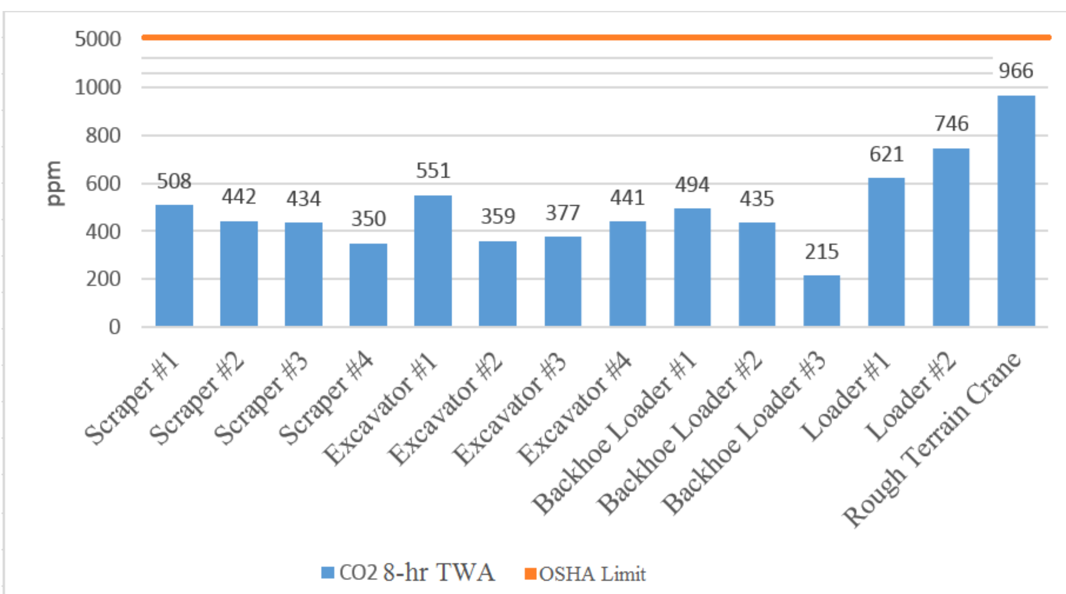

Figure 16: CO2 8-hour TWA

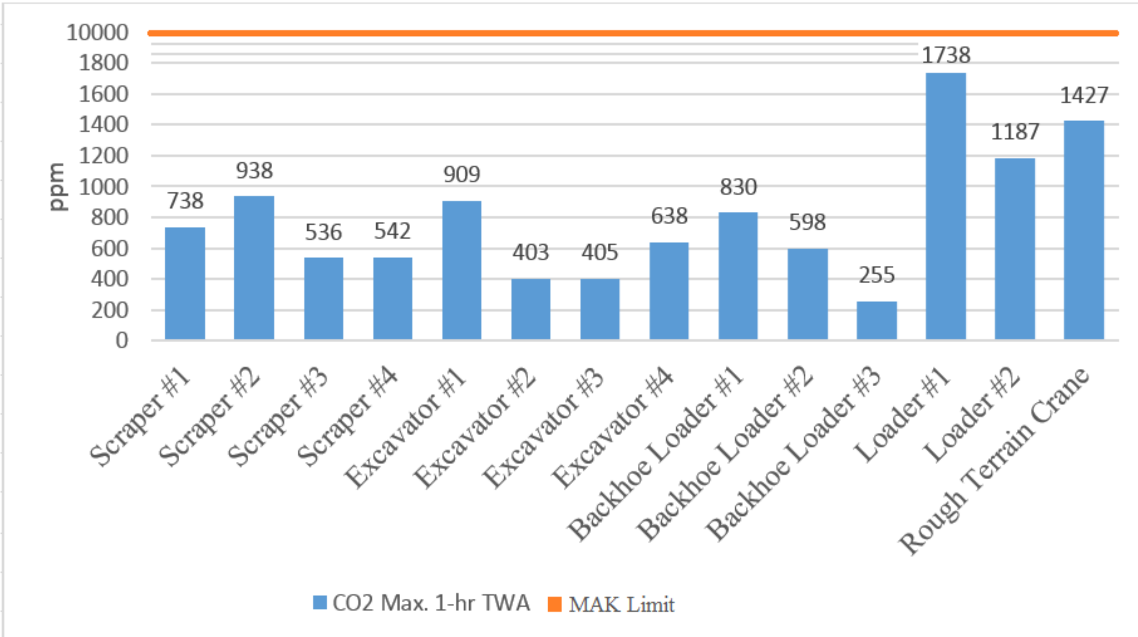

Figure 17: CO2 Maximum 1-hour TWA

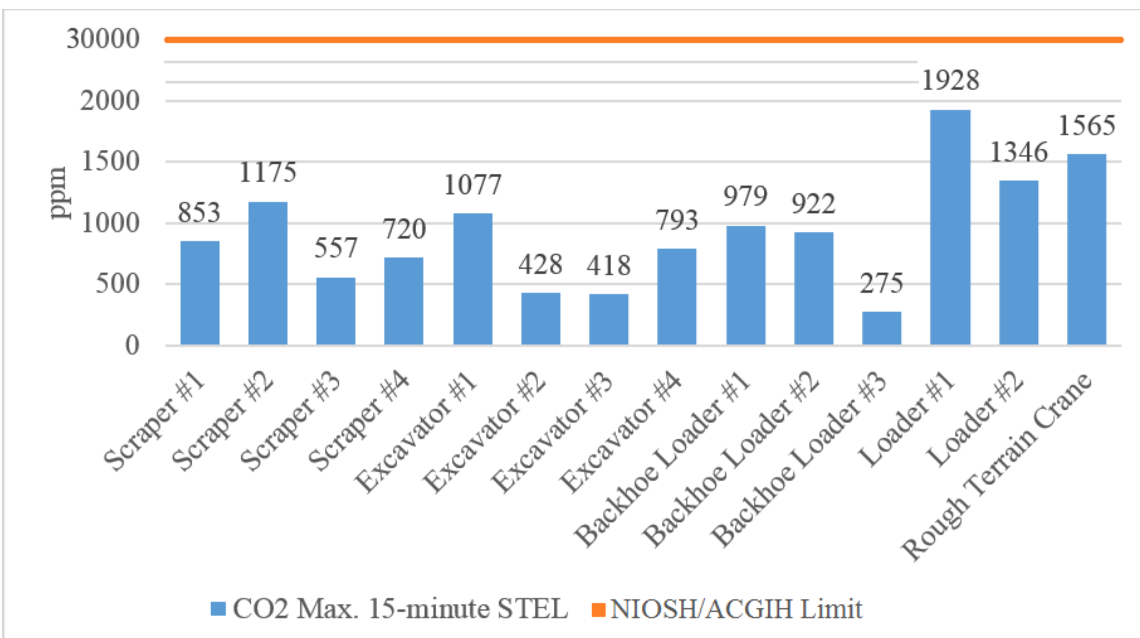

Figure 18: CO2 Maximum 15-minute STEL

A summary of important numbers for CO_2 are shown on Table 10. The last column shows speed of CO_2 accumulation inside the cab over the time. This speed is the slope of the trended line for each equipment on 8-hour TWA graph.

Table 10: Summary of CO_2 Results

Equipment	Peak (ppm)	STEL (ppm)	8-hr TWA (ppm)	1-hr TWA (ppm)	Pollutant Accumulation Speed (ppm/min)
Scraper #1	1191	853	508	738	1.05
Scraper #2	1845	1175	442	938	0.82
Scraper #3	716	557	434	536	0.89
Scraper #4	1115	720	350	542	0.68
Excavator #1	1134	1077	551	909	1.10
Excavator #2	551	428	359	403	0.74
Excavator #3	543	418	377	405	0.79
Excavator #4	1118	793	441	638	0.89
Backhoe Loader #1	1108	979	494	830	1.02
Backhoe Loader #2	1565	922	435	598	0.90
Backhoe Loader #3	300	275	215	255	0.44
Loader #1	1971	1928	621	1738	1.22
Loader #2	1423	1346	746	1187	1.62
Rough Terrain Crane	1676	1565	966	1427	2.17

4.2 Carbon Monoxide (CO)

Total of seventeen limits were identified for CO. Using Equation 1 and Equation 2, 8-hour TWA and 1-hour TWA concentrations were calculated. STEL levels were also recorded and reported by EVM-7. Out of all of the standards, 8-hour TWA limits were the most common. . Figure 19, Figure 20, Figure 21, and Figure 22 are illustrating peak CO levels, 8-hour TWA, maximum 1-hour TWA, and maximum 15-minute STEL concentrations respectively for each equipment. Appropriate limits are also shown on the charts. All real time readings, 8-hour TWA, 1-hour TWA, and 15-minute STEL graphs over time and also table of detailed results are shown in Appendix A.

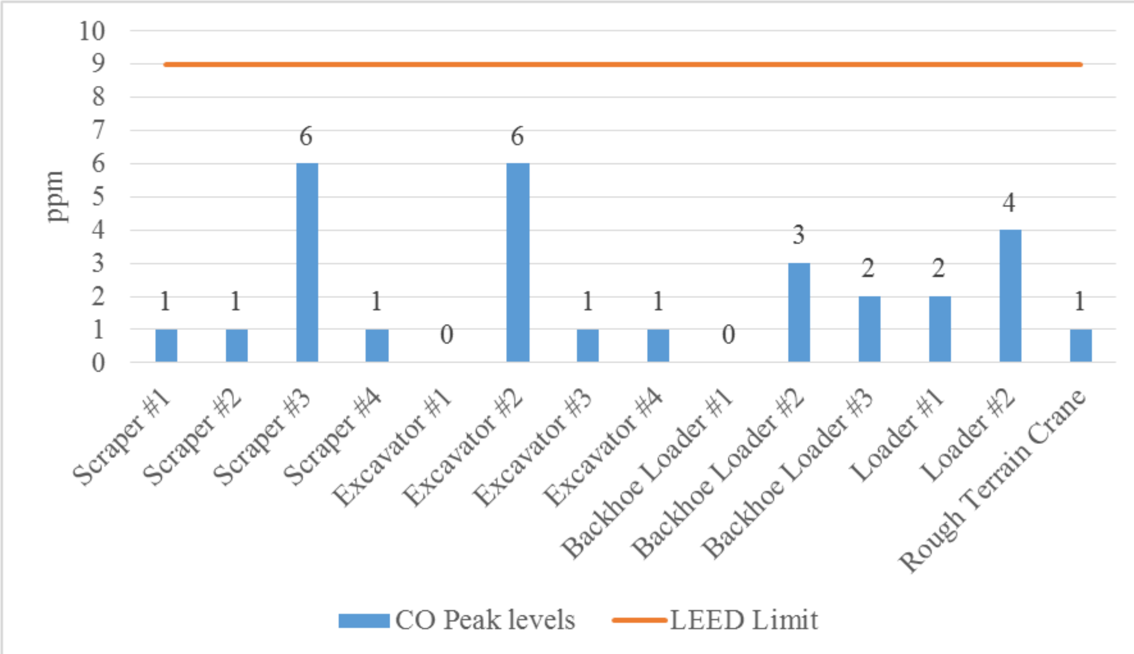

Figure 19: CO Peak Levels

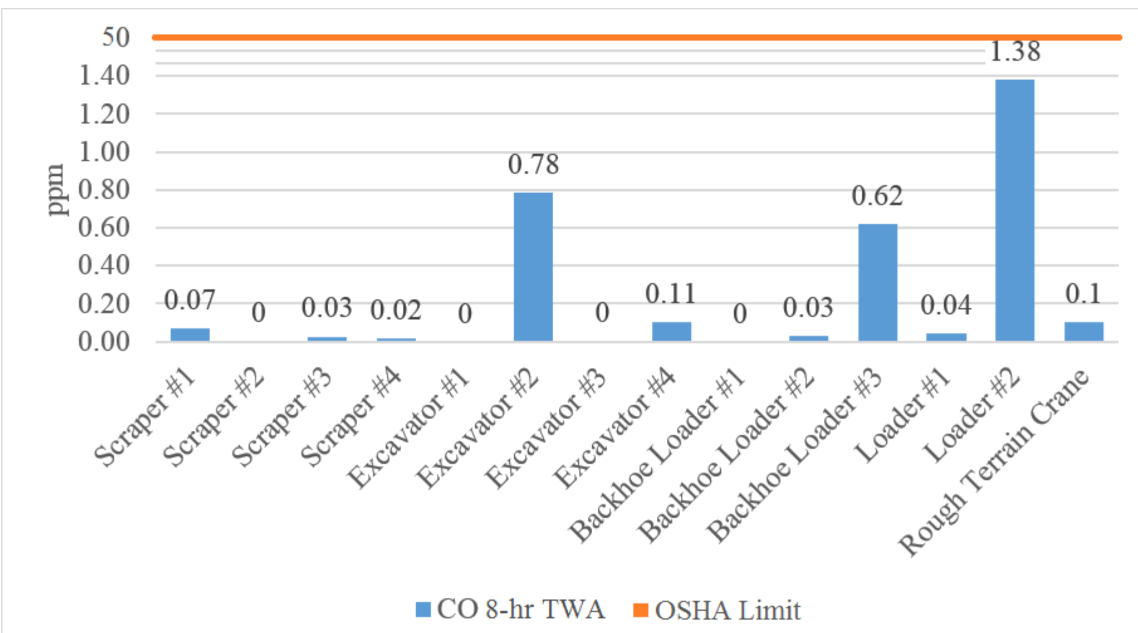

Figure 20: CO 8-hout TWA

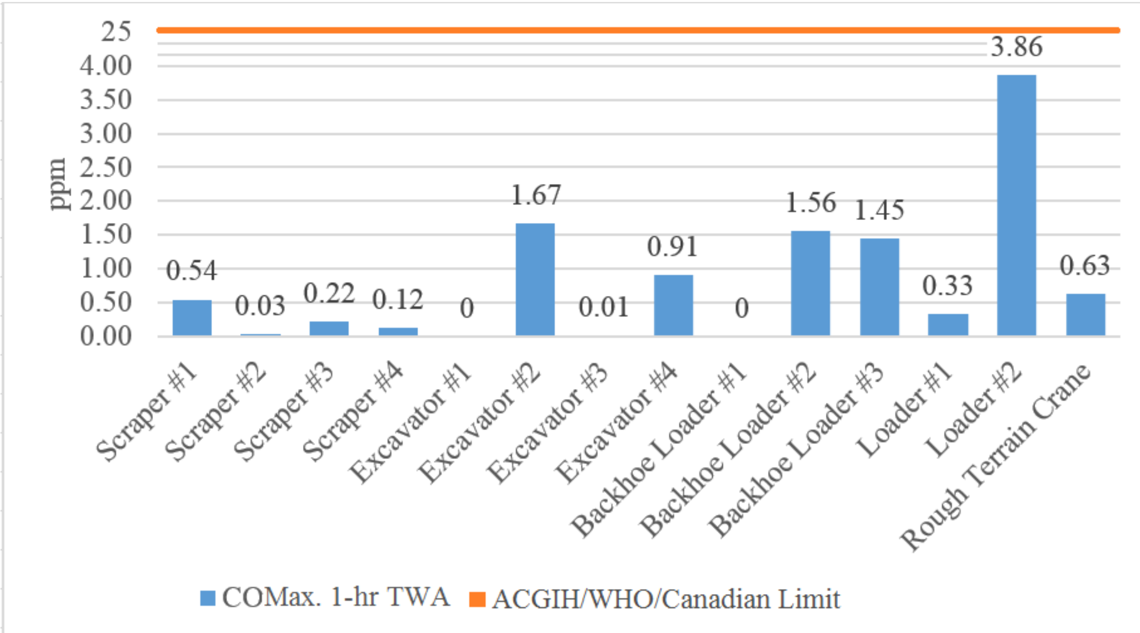

Figure 21: CO Maximum 1-hour TWA

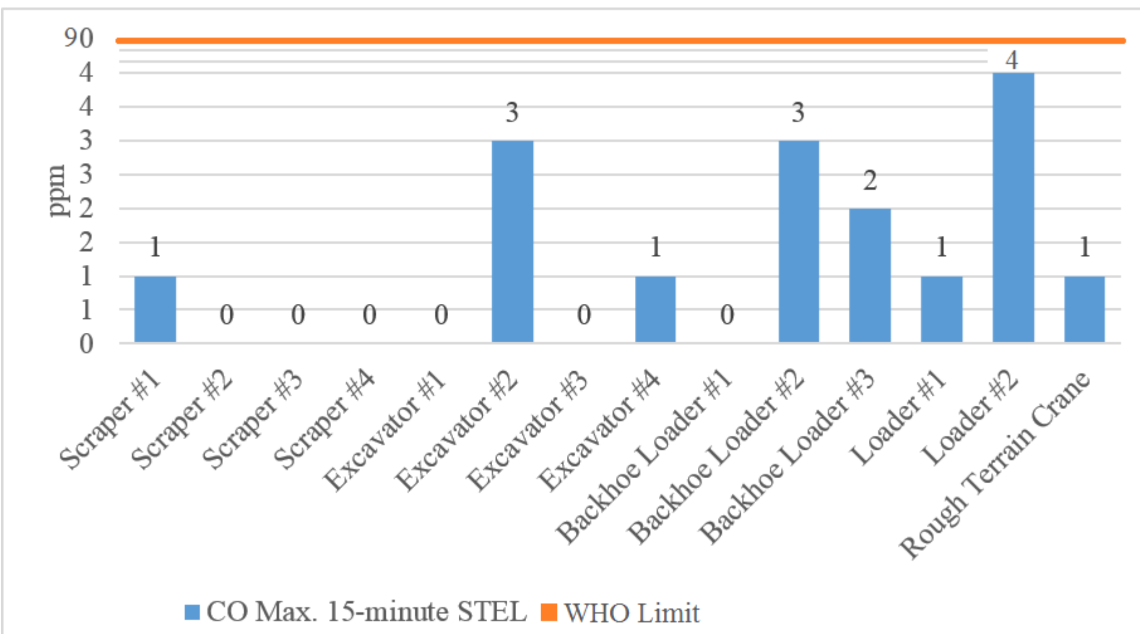

Figure 22: CO Maximum 15-minute STEL

Summary of important results for CO is mentioned in Table 11. Since numbers for a toxic gas like CO are too small, it was not very informative to calculate speed of gas accumulation over the 8-hour time period.

Table 11: Summary of CO Results

Equipment	Peak (ppm)	STEL (ppm)	8-hr TWA (ppm)	1-hr TWA (ppm)
Scraper #1	1	1	0.07	0.54
Scraper #2	1	0	0	0.03
Scraper #3	6	0	0.03	0.22
Scraper #4	1	0	0.02	0.12
Excavator #1	0	0	0	0
Excavator #2	6	3	0.78	1.67
Excavator #3	1	0	0	0.01
Excavator #4	1	1	0.11	0.91
Backhoe Loader #1	0	0	0	0
Backhoe Loader #2	3	3	0.03	1.56
Backhoe Loader #3	2	2	0.62	1.45
Loader #1	2	1	0.04	0.33
Loader #2	4	4	1.38	3.86
Rough Terrain Crane	1	1	0.1	0.63

4.3 Fine Particles ($PM_{2.5}$)

A total of eight limits were identified for $PM_{2.5}$. Unlike CO_2 and CO, $PM_{2.5}$ is not a gas and time weighted average concentrations are not as important as instantaneous readings. Dust could be a carcinogen and has chronic health effects which happen when particles accumulate in the lungs. If someone exposed to high levels of dust at once or lower levels over a long period of time, depending on particle size and duration of exposure, there could be some sort of health effects. Reported limits are concentrated on either instantaneous readings or very long-term measurements. However, one standard has been reported for each 8-hour TWA and 1-hour TWA levels. Figure 23, Figure 24, and Figure 25 represent peak $PM_{2.5}$ levels, 8-hour TWA, and maximum 1-hour TWA concentrations respectively for each equipment. Appropriate limits are also shown on the charts. 15-minute STEL concentrations are not calculated for $PM_{2.5}$ as there is no limit based on them. All real time readings, 8-hour TWA, and 1-hour TWA graphs over time and also the table of detailed results are shown in Appendix A.

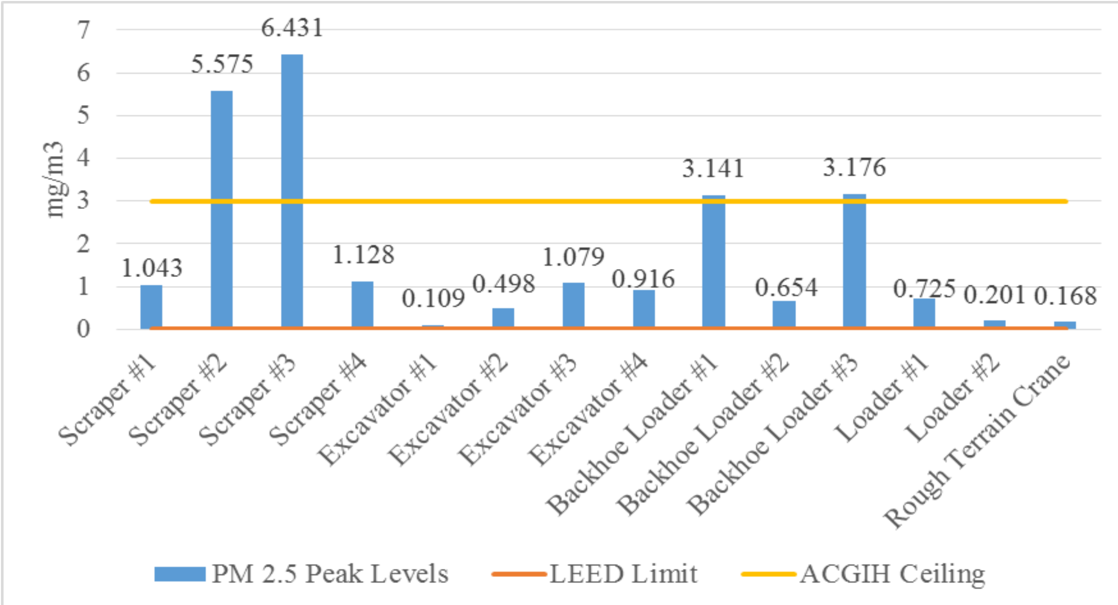

Figure 23: PM 2.5 Peak Levels

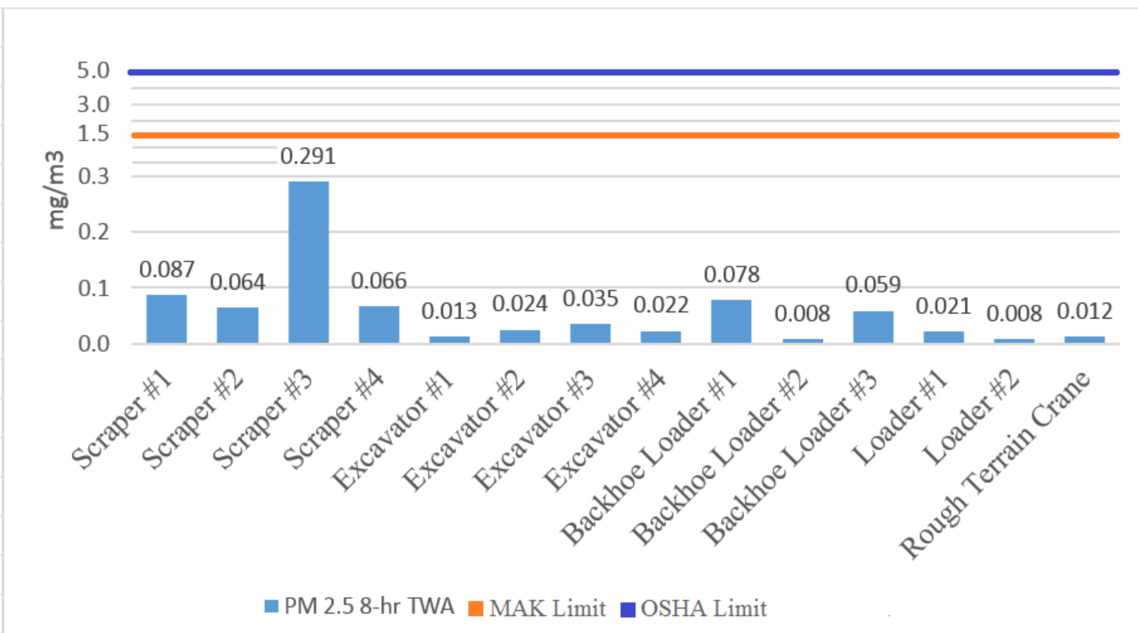

Figure 24: PM 2.5 8-hour TWA

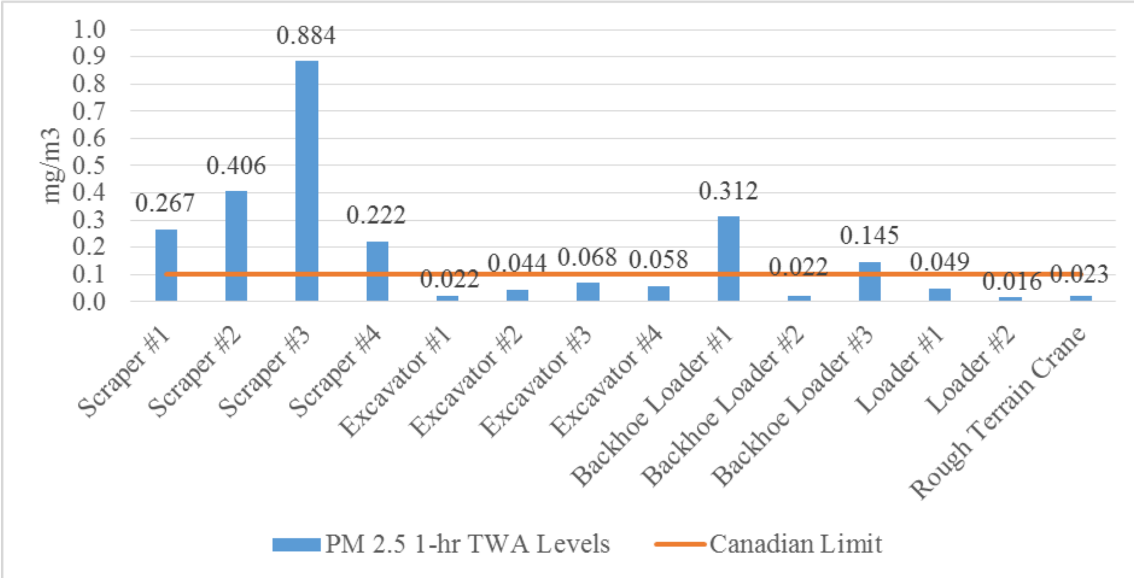

Figure 25: PM 2.5 Maximum 1-hour TWA

Important numbers for $PM_{2.5}$ are summarized in Table 12.

Table 12: Summary of Fine Particles ($PM_{2.5}$) Results

Equipment	Peak (mg/m3)	8-hr TWA (mg/m3)	1-hr TWA (mg/m3)
Scraper #1	1.043	0.087	0.267
Scraper #2	5.575	0.064	0.406
Scraper #3	6.431	0.291	0.884
Scraper #4	1.128	0.066	0.222
Excavator #1	0.109	0.013	0.022
Excavator #2	0.498	0.024	0.044
Excavator #3	1.079	0.035	0.068
Excavator #4	0.916	0.022	0.058
Backhoe Loader #1	3.141	0.078	0.312
Backhoe Loader #2	0.654	0.008	0.022
Backhoe Loader #3	3.176	0.059	0.145
Loader #1	0.725	0.021	0.049
Loader #2	0.201	0.008	0.016
Rough Terrain Crane	0.168	0.012	0.023

4.4 Total Volatile Organic Compound (tVOC)

In terms of standard and limits, tVOC is the most complicated surveyed pollutant in this research. As mentioned, tVOC is a broad name that refers to the multiple numbers of substances.

The tVOC screening value is for typical VOCs and based on instantaneous readings. Additionally, according to field experiences a screening value was identified based on isobutylene units and for 8-hour TWA levels (70). Due to the mentioned technical problem for VOC sensor, only six data sets were available. Table 13 represents peak readings and 8-hour TWA levels for each equipment.

Table 13: Summary of tVOC Results

Equipment	Peak (ppm)	8-hr TWA (ppm)
Scraper #2	14.5	5.984
Scraper #3	1.4	0.007
Excavator #2	2.9	1.819
Backhoe Loader #2	4.5	0.136
Loader #2	3.7	0.479
Rough Terrain Crane	2.5	0.174

Figure 26 and Figure 27 are showing tVOC peak levels and calculated 8-hour TWA levels for each equipment respectively. Appropriate limits are added to the charts. All real time readings, and 8-hour TWA graphs over time and also table of detailed results are shown in Appendix A.

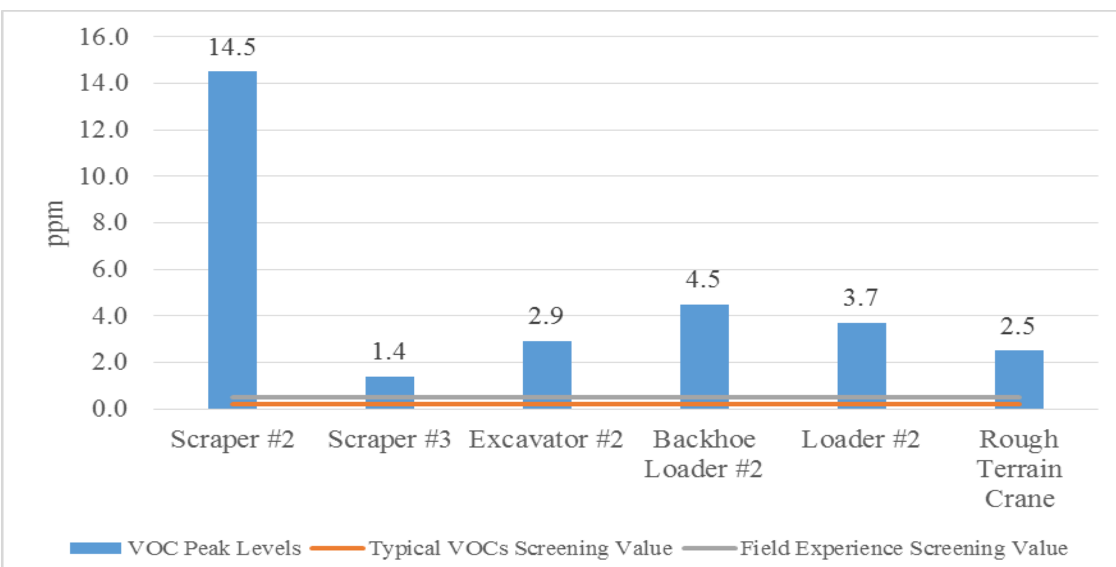

Figure 26: tVOC Peak Levels

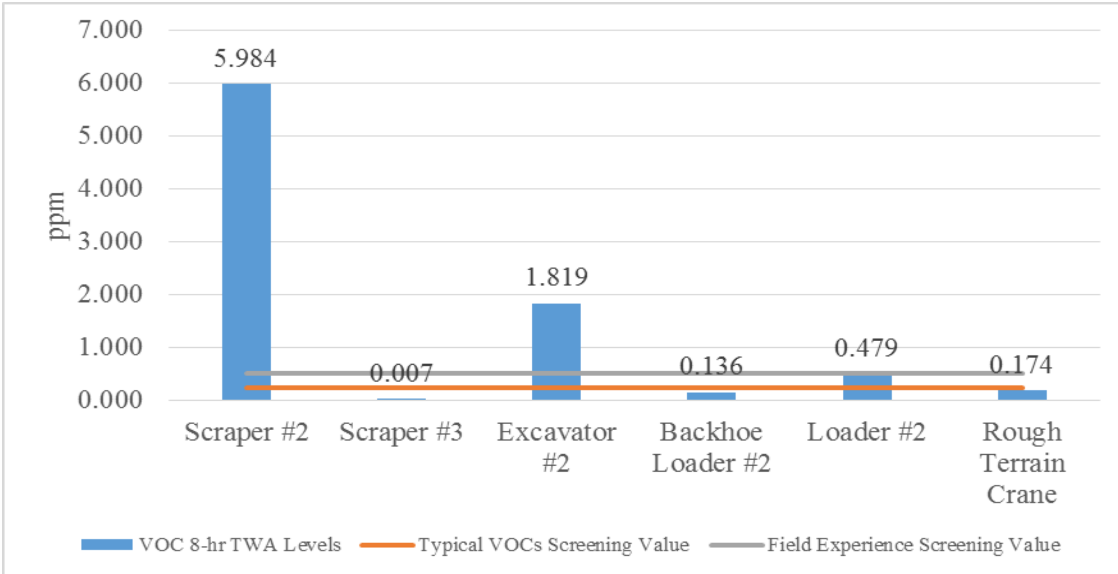

Figure 27: tVOC 8-hour TWA

4.5 Temperature and Relative Humidity

When the temperature is below 32 ^{0}F, based on the wind speed, cold stress could be determined to show whether the operator is at risk. Conversely, when the temperature is above 80 ^{0}F and RH is more than 40%, calculating heat index is the best way to determine heat stress. There is no concern for heat or cold stresses between these values. Scraper #3 was the only equipment that the operator experienced a temperature below 32 ^{0}F, and it lasted for one hour and four minutes. Heat index requirements were met in three of the equipment cabs; Loader #2, Scraper #4, and Backhoe loader #3 for different periods of time. Heat indexes graph is shown in Appendix A along with all collected data for temperature and relative humidity.

4.6 University Offices

In university offices, sources of indoor pollutants are believed to be limited. Examples are people breathing, or scan and copying machines. However, due to ventilation, if done adequately, IAQ should be observed satisfyingly. For this reason, three faculty offices with and without printers, and one room with seven 3D printers were selected in Oklahoma State

University to collect data from. At the data collecting time, three of the 3D printers were running. Later, this data was compared to data from equipment cabs to determine the difference. Since CO and tVOC were below sensitivity of the EVM-7s for all offices, Table 14 only summarizes the results of CO_2 and $PM_{2.5}$. Temperature and relative humidity, with an average of 71.42 ^{o}F and 56.1% respectively, are not subjects of interest for offices, since they are adjusted automatically.

Table 14: Summary of Office Results

Location	CO2 (ppm)		PM 2.5 (mg/m3)	
	PEAK	8-hour TWA	PEAK	8-hour TWA
Office 1	503	212	0.069	0.031
Office 2	1597	1077	0.023	0.002
Office 3	638	423	0.016	0.001
3D Printers room	1243	870	0.008	0

4.7 Construction Site Ambient Air

In order to determine the enclosed cabs efficiency to protect operators, and observe the difference inside the tested equipment cabs IAQ and air quality of outside air, EVM-7s were put in the north east side of the construction site to measure pollutants in equipment ambient air. The results are shown in table 15. For CO and tVOC, levels were below the sensitivity of the instrument, so it was recorded as zero for the whole time.

Table 15: Construction Site Ambient Air Results

Substance	Peak	8-hr TWA
CO2 (ppm)	287	267.1
PM 2.5 (mg/m3)	0.023	0.009

4.8 Outdoor Air

For some of measured pollutants there are limits based on outdoor air concentrations. For instance, LEED determines CO_2 limit as 700 ppm above outdoor air levels. In order to add this type of limits to the evaluation, outdoor air pollutants were measured for 8 hours, using the EVM-7. The results are shown in Table 16. Again, levels were below sensitivity of the EVM-7s for CO and tVOC.

Table 16: Outdoor Air Results

Substance	Peak	8-hr TWA
CO_2 (ppm)	358	316
PM 2.5 (mg/m3)	0.394	0.064

One graph that contains all of the results together along with ambient air peak level and outdoor air peak level is shown for each pollutant in Appendix A.

CHAPTER V

DISCUSSION

To fulfill the goal of this research, which is determining whether HDD equipment operators are at health risk, collected data was compared with all identified limits for each pollutant. Using the results of the previous study (3), the potential compatibility between those results and the results of the current study was evaluated. Additionally, measurements from equipment cabs were compared with results of university offices to determine the severity of operator's exposure to pollutants, regardless of limits and screening values. The difference between the results of construction site ambient air and equipment cabs was also considered to determine how effective the enclosed cab is protecting the operator. Finally, according to obtained maintenance records, existence of any potential correlation between cab IAQ and maintenance status of the equipment, which was suggested by the previous study (3), was examined. At the end, based on 8-hour TWA concentrations, equipment ranking was determined, identifying the best and worst equipment in terms of protecting the operator. Engine tier information is also provided on the last column.

5.1 Carbon Dioxide (CO_2)

The Canadian guideline (64) says when CO_2 level is above 1,000 ppm, there is an insufficient supply of fresh air. The New Jersey Department of Labor requires employers to check the HVAC system when CO_2 exceeds 1,000 ppm (71). With the exception of Excavator #2, Excavator #3, Scraper #3, and Backhoe loader #3, all other cabs have experienced CO_2 levels above 1,000 ppm (Table 10). LEED v.3 (60) defines CO_2 limit as 700 ppm above ambient outdoor air. According to the outdoor air data (section 4.8), CO_2 has a peak level of 317 ppm which converts the LEED limit to about 1,000 ppm, same as the Canadian/ASHRAE/EPA limit, which means the same equipment are exceeding this limit. This 1,000 ppm limit is set for indoor areas and to keep building occupants from minor discomforts, so exceeding this limit in an industrial environment is not raising serious concerns. The 15-minute STEL standard is 30,000 ppm which is much greater than the largest calculated STEL, found to be 1,565 ppm in the Crane cab. The maximum 1-hour TWA level was observed in Loader #1 with 1,738 ppm, which is well below the 10,000 ppm limit. For the 8-hour TWA, regulations consider 5,000 ppm as the limit while maximum logged level, 966 ppm, observed in the Crane cab, is not approaching this limit.

Construction site ambient air measurement (section 4.7) shows CO_2 level way lower than what was observed in equipment cabs. Backhoe Loader #3 is the only equipment with a lower 8-hour TWA CO_2 concentration than ambient air. The reason as mentioned before is the operator breathing in the enclosed cab.

5.2 Carbon Monoxide (CO)

NIOSH (58) reports 200 ppm as the ceiling exposure limit for CO, which should not be violated at any time. Table 11 shows Excavator #2 and Scraper #3 have 6 ppm as the maximum logged CO in their cabs, which is well below the ceiling. LEED v.4 (68) has the CO limit as 2 ppm above outdoor air. According to measured outdoor levels, CO is below sensitivity of the EVM-7s and considered as zero ppm, which sets the LEED v.4 limit as 2 ppm. Excavator #2, Backhoe Loader #2, and Scraper #3 are exceeding this limit. STEL standard is 50 ppm which is much greater than the largest calculated STEL, 4 ppm in Loader #2. The maximum 1-hour TWA level happens in Loader #2 with 3.86 ppm, which is well below the 35 ppm limit. For the 8-hour

TWA, the lowest amount regulations consider as the limit is 9 ppm while the maximum logged level, 1.38 ppm, which belongs to Loader #2, is not approaching the limit.

For CO, it was mentioned in section 4.7 that the EVM-7 did not record any CO in the construction site ambient air. It was expected to observe CO as zero inside the equipment cab, which is supposed to protect the operator from hazards like toxic gasses. Data showed six equipment cabs did not experience any CO, but eight of them had 8-hour TWA CO concentrations more than zero. Although there was no CO in the construction ambient air the data can be anecdotally interpreted to determine that the equipment most likely is the source of the logged CO. The CO could be result of leaking tailpipe emissions into the cab.

5.3 Fine Particles ($PM_{2.5}$)

The LEED V3 limit for the instantaneous reading of $PM_{2.5}$ is 0.015 mg/m^3 (60), which was exceeded by all tested equipment, with peaks between 0.109 mg/m^3 for Excavator #1 and 6.431 mg/m^3 for Scraper #3. However, only Scraper #2 and #3, and Backhoe loader #1 and #3 exceeded the ACGIH 3 mg/m^3 ceiling limit (72). All four tested scrapers, Backhoe loader#1, and Backhoe loader #3 are violating 0.1 mg/m3 1-hour TWA limit (64). The maximum calculated 8-hour TWA concentration is 0.291 mg/m^3 for Scraper #3 which is well below the OSHA 5 mg/m^3 limit. In general, if a remarkable portion of the measured $PM_{2.5}$ was silica, surveyed operators were in serious danger. So, specific silica test could help to assess the situation better.

Comparing $PM_{2.5}$ levels inside the equipment with what has measured in the construction site ambient air can be quite determinative of how protective the tested equipment cabs were. Results from this research showed that $PM_{2.5}$ levels in the job site ambient air was way below what was observed inside the cabs, where other than Loader #2, and Backhoe Loader #2, all tested equipment experienced more particulates than what was measured in ambient air.

5.4 Total Volatile Organic Compounds (tVOC)

Defining an exposure limit for tVOC is a very complicated and case sensitive process. It can be more accurate to define a specific limit for each targeted group, as this research approach does. However, maximum exposure limit for typical VOCs is 500 µg/m^3. Since the EVM-7 logged tVOC in ppm, the standard should be converted to ppm using Equation 3.

$$ppm = \frac{\text{Limit in } \mu g/m^3 \times 24.45}{1000 \times \text{MW}} \tag{3}$$

Where the limit is 500 µg/m^3, 24.45 liter is the standard volume of the air, and MW is molecular weight of the gas. In this case, Isobutylene molecular weight, 56.106 gr/mole, was used as a basis since the EVM-7 was calibrated using it as a medium. The converted standard would be 0.22 ppm. Among six valid data collection for tVOC, all of them, with peak amounts between 1.4 ppm and 14.5 ppm, are exceeding this limit. However, considering 500 ppb or 0.5 ppm units of isobutylene screening value which was concluded from field experiences, Scraper #2 and Excavator #2 are exceeding while Loader #2 is approaching it, means they have potential air quality contaminant. Results comply with expectations since second hand tobacco smoke is included in tVOC and, based on records, operators have smoked in Scraper #2 and Excavator #2.

As mentioned before, tVOC screening values have been reported for indoor environments and not for occupational areas. Hence, exceeding these values could cause the operator to feel disturbed sporadically but it does not necessarily mean that the operator’s health is at risk. For instance, Heptane and Benzene are both between diesel exhaust constituents while exposure limit is 400 ppm for latter and 0.5 ppm for former one. So, if all of the measured VOCs in this research were Benzene, the operator was at a remarkable risk, and conversely, if all of the VOCs were Heptane, there was no concern at all. Therefore, since the composition of measured tVOC is not clear, specific tests based on the potential existing VOCs could help.

5.5 Temperature and Relative Humidity

In terms of heat index, as showed in Figure 28, Loader #2, Backhoe loader #3, and Scraper #4 operators have experienced heat stresses between 80.2 ^{o}F and 91.6 ^{o}F for time periods of three minutes, six hours and ten minutes, and four hours and thirty minutes respectively. Except for the Backhoe loader #3 operator who experiences heat stress in “extreme caution” status for ten minutes, all other calculated heat stresses were in “caution” status. As long as heat indexes stay below the “danger” level, no specific protection is needed to be taken, however, extreme caution is not a safe zone for the operator.

Cold stress was just applicable to Scraper #3, where the temperature was below 32 ^{0}F for about one hour. Since the EVM-7 minimum logging limit for temperature is 32 ^{0}F, the exact temperature during that one hour is unknown, however, records from city ambient air in that day (73) show that minimum temperature was 23 ^{0}F, and maximum wind speed was 36 mph. These the minimum temperature and the maximum wind speed cause a cold stress in the “caution” area (Figure 1).

5.6 Overall Comparison

The concentration of one pollutant can be more than normal in one cab, while other IAQ factors are perfectly in normal range, or, conversely, data may show very low levels of a toxic gas when the overall status of IAQ in that cab is critical. For this reason, and in order to determine an overall comparison between tested equipment cabs, equipment cabs were graded regarding levels of each pollutant in them. In order to make this grading applicable to other studies, all 8-hour TWA concentrations were divided by the relevant limit, then summed up for each piece of equipment. The OSHA limits were considered for CO_2, CO, and Particulates, as 5,000 ppm, 50 ppm, and 5 mg/m^3 respectively. For tVOC, the suggested 0.5 ppm screening value was used. Table 17 shows the result. These numbers can be representatives of the overall IAQ of the equipment. The smaller this number is, the better IAQ that equipment has. As it can be seen, Scraper #2 has the highest number and can be considered to have the worst IAQ among tested equipment. Conversely, Backhoe Loader #3 has the lowest average, which means its operator experienced the best IAQ. Last column shows the corresponding tier standard that each equipment engine has. However, since tVOC levels were really high compared to the limit, it has a determinative role in sum. By removing tVOC from the calculations, the results would be different, where the Crane with sum of 0.2 would be the highest and worst case, and Backhoe Loader #3 would stay be the best one with sum of 0.07. Comparison charts based on this table are shown at the end of the Appendix A.

Table 17: Tested Equipment Ranking

Equipment	CO2	CO	Particulate	tVOC[a]	SUM	Tier
Scraper #1	0.102	0.0014	0.017	N/A	0.120	0
Scraper #2	0.088	0.0001	0.013	11.969	12.070	0
Scraper #3	0.087	0.0005	0.058	0.014	0.160	0
Scraper #4	0.07	0.0003	0.013	N/A	0.084	0
Excavator #1	0.11	0.0	0.003	N/A	0.113	1
Excavator #2	0.072	0.0157	0.005	3.639	3.731	3
Excavator #3	0.075	0.0	0.007	N/A	0.082	3
Excavator #4	0.088	0.0021	0.004	N/A	0.095	3
Backhoe Loader #1	0.099	0.0	0.016	N/A	0.114	3
Backhoe Loader #2	0.087	0.0006	0.002	0.271	0.360	3
Backhoe Loader #3	0.043	0.0123	0.012	N/A	0.067	3
Loader #1	0.124	0.0008	0.004	N/A	0.129	3
Loader #2	0.149	0.0276	0.002	0.959	1.137	2
Rough Terrain Crane	0.193	0.002	0.002	0.348	0.545	4

[a] *For VOC, only six series of data were valid*

The previous study (3) had CO_2, CO, and tVOC in common with this research. Table 18 shows minimum and maximum 8-hour TWA levels calculated for each pollutant in either of the studies. The differences are remarkable for all three substances. In the previous study, conducted at an open air maintenance yard rather than a construction site, tested equipment were idle during the measurement, and much higher CO_2 levels were recorded. On the other hand, more CO and tVOCs were measured in the current research which is consistent with the test circumstances. The previous study only measured equipment for 20-minute idle times which may be cause of some of the differences.

Table 18: Previous Study VS. Current Study Results

Pollutant	Study	Minimum Logged	Maximum Logged
CO2 (ppm)	Previous Study	645	2950
	Current Study	215	966
CO (ppm)	Previous Study	0.1	0.75
	Current Study	0	1.38
VOC (ppm)	Previous Study	0.09	0.275
	Current Study	0.007	5.98

5.7 University Offices

In order to obtain a better understanding about HDD equipment operator work environment, this research compared operator ambient air data to the data collected from four university offices. CO and tVOC were below sensitivity of EVM-7s in university offices, while only four equipment cabs had same situation for CO and none of them for tVOC. For CO_2, the university offices experienced higher levels than the equipment cabs. The reason can be that fresh air was introduced to equipment cabs more frequently than building offices. Conversely, for $PM_{2.5}$ equipment cabs showed much greater amounts of particulate than what was measured in university offices. Figure 29 represents a comparison between university offices and tested equipment cabs for CO_2 and Particulates based on 8-hour TWA exposures. Each line shows the range of the pollutant based on minimum and maximum calculated levels. Compatible limits are also shown in the figure. CO_2 was the only pollutant that equipment operators experienced less than office occupants and the reason can be opening and closing the cab door and windows, which introduces fresh air to the cab. Other pollutants were observed in much greater levels in equipment cabs. So, it can be concluded that the HDD equipment operators experienced worse IAQ compared to the office occupants.

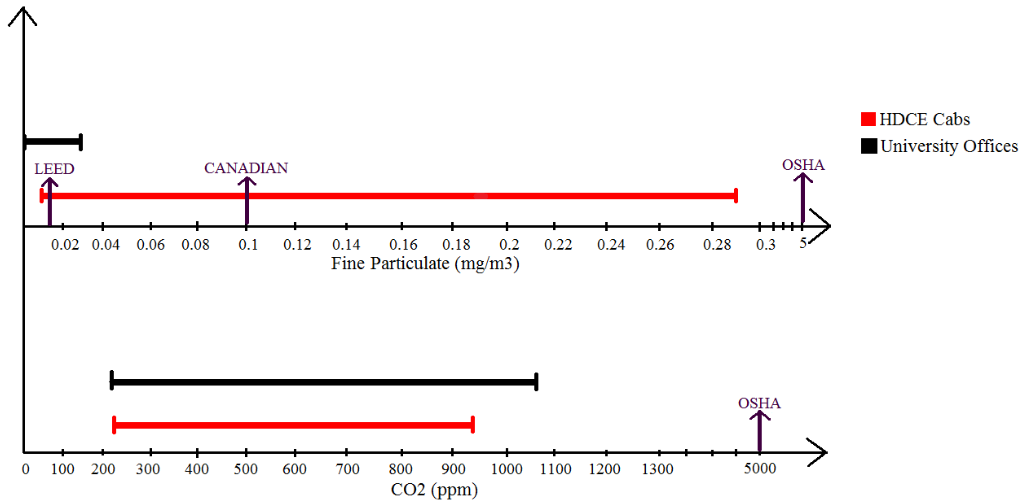

Figure 28: HDD equipment Cabs VS. University Offices (CO2 & PM 2.5)

CHAPTER VI

CONCLUSION

Indoor Air Quality (IAQ) has been the center of attention of researchers for a long period of time, but little has been known about IAQ in HDD equipment cabs. Factors such as being close to diesel exhaust as well as typical existing pollutants in construction sites, increase the probability of having risky IAQ in HDD equipment cabs. This research focused on collecting data from HDD construction equipment cabs and assessing their IAQ.

Data was collected using two EVM-7 instruments manufactured by 3M, capable of measuring CO_2, CO, $PM_{2.5}$, tVOC, Temperature, and Relative Humidity. The EVM-7 was put inside each equipment cab for the whole eight hour work-day time period. In total, fourteen data sets were provided from ten pieces of equipment. To evaluate IAQ, a comprehensive research was performed to achieve reported standards and limits. Although there is no specific IAQ standard for equipment operators, different organizations have reported different limits and screening values for measured pollutants. All reported limits are not comparable with instantaneous readings. So, 15-minute STEL, 1-hour TWA, and 8-hour TWA concentrations were calculated out of the EVM-7 results, then compliance with limits and screening values was determined. Later, to better understand the state of IAQ in the equipment cabs, data was compared to the data collected from three university offices and one room with some running 3D-printers. With adequate ventilation, it is believed that university offices should have acceptable IAQ.

Results showed that from legal perspective, none of the measured pollutants are exceeding OSHA limits, which are enforceable in the United States. However, the literature review revealed that OSHA limits are usually much greater than other allowable reported ones. So comparing to other limits, including indoor area limits, some values were exceeded by measured pollutants. Table 19 shows comparison between measured pollutants and surveyed standards based on calculated 8-hour TWA concentrations, where "below" means not exceeding and "above" means at least one equipment cab exceeded that limit.

Table 19: Comparison to Established Values

Canadian	Measured Pollutant			
	CO2	CO	PM 2.5	VOC[a]
OSHA	Below	Below	Below	N/A
NAAQS	N/A	Below	Above	N/A
NIOSH	Below	Below	N/A	N/A
ACGIH	Below	Below	Above	N/A
LEED	Below	Below	Above	Above
MAK	Below	Below	Above	N/A
Canadian	Above	Below	Above	N/A

[a] *VOC also exceeds the limit that was suggested based on field experiences*

In summary, CO_2 and CO did not approach the limits. Although CO_2 exceeded Canadian/ASHRAE/EPA 1,000 ppm limit, this does not raise a remarkable concern since the exceeded limit is a screening value for indoor environments rather than occupational exposure limits and set for occupants comfort.

$PM_{2.5}$ exceeded almost all of the limits except for the OSHA. Given the fact that types of equipment that were tested almost always are dealing with dirt, $PM_{2.5}$ results may be observed in similar measurements. Also, considering the high probability of silica to be a portion of measured $PM_{2.5}$, results of this research are high enough to raise concerns about the silica exposure. For tVOC, two limits were introduced and both of them were exceeded by the results. Since proportions of different VOC substances in reported tVOC numbers is not clear, no solid conclusion could be drawn for tVOC exposure. However, numbers are high enough to raise need of specie tests.

Considering results from university offices, almost all pollutants were at greater levels in the equipment cabs. This difference was more obvious for CO and tVOC where concentrations in university offices were as low as zero. Even for Particulates, numbers were close to zero in university offices while in equipment cabs particulates were more than what was expected. Also comparison between construction site ambient air data and equipment cabs data revealed that all of the pollutants were at higher levels inside the cab.

CHAPTER VII

LIMITATIONS AND RECOMMENDATIONS

One limitation for this study was sample size, where only five types of HDD construction equipment were tested and there was one sample for some of them like the crane. Due to the mentioned technical problem, sample size for tVOC was even more limited. Expanding equipment types and collecting samples from five to six of each type can strengthen the results.

Based on the results from the previous study (3), NO_x was not a great risk for surveyed operators, so in this research CO was observed a toxic gas. Due to a very limited sample size of the previous study, it is recommended to use the NO_x sensor again and evaluate it with a greater sample size. The NO_x sensor can easily be substituted with the CO sensor in EVM-7s.

Also, the equipment selection process did not take into account equipment manufacturing year or maintenance record. According to previous research, there might be a relationship between equipment maintenance status and severity of pollution inside the cab. The results from that research showed the oldest maintained piece of equipment although had the highest tier standard, experienced the worst IAQ (3). For this research, maintenance records were not available. It will be helpful to test specific number of equipment, with engines from all tier standards, and also observing results from irregular and regular maintained equipment and their differences.

Results revealed that Particulate levels were high enough to raise serious concerns. Even if twenty percent of the measured $PM_{2.5}$ was silica, the OSHA silica limit, which is 0.05 mg/m^3, would be violated. So, it is highly recommended to perform a silica testing in HDD construction equipment cabs. Since it could be cheaper for employers and owners to measure $PM_{2.5}$ rather than silica, it would be helpful to investigate the correlation between $PM_{2.5}$ and silica by collecting more data and doing appropriate analysis.

As mentioned in this study, there is no specific standard for IAQ in equipment cabs. Instead, each organization has multiple numbers as exposure limits for different pollutants. Some of these limits are not in compliance. For instance, both 9 ppm and 50 ppm have been reported as the 8-hour TWA limit for CO. For tVOC, assumptions and conversions have made existing limits very inaccurate. Future research could focus on sampling and separating the possible existing pollutants in HDD construction equipment cabs and their individual limits and how to interpret or even improve them.

Future study could also focus on solutions to improve IAQ in the equipment cab. As revealed in this research, the level of pollutants inside the equipment cab was much worse than construction site ambient air. IAQ difference between cabs with and without filtration systems, as one way to prevent pollutants from entering, could be observed to see how efficient the filters are. Fuel additives may reduce diesel exhaust pollutants, as one potential source of pollutants inside the equipment cab. Research has shown that adding Nano sized Ceria (CeO_2) additives to fuel, could reduce particulate emission to almost half, along with cutting 11.3% of CO and CO_2 emissions, but it will increase Nitrogen oxides by 27.8% (74). Running one piece of equipment with and without using fuel additives and assessing the IAQ in the cab can show the effect of fuel additives.

Historically CO_2 represents overall quality of air in indoor areas, where measuring CO_2 can be used as a marker for IAQ. However, some studies showed that tVOC is not in correlation with CO_2 (23). Future studies can examine both of the claims based on collected data in this research.

Moreover, as certain activities were observed, but not quantified in this study, a next step could focus on the effect of season and weather, or operator activities such as smoking and eating on the cab IAQ.

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APPENDICES

Appendix A. Detailed Results

Appendix A contains tables of detailed results, graphs of all collected data over time, heat index graph, and total result charts.
Following tables are detailed results for all measured pollutants for each piece of the equipment. For each pollutant, instantaneous readings, reported STEL levels, calculated 8-hr TWA levels, and 1-hr TWA levels with corresponding statistics are reported.

CO_2

Equipment	Type	Average	Maximum	Minimum	Variance	Standard Deviation
Scraper #1	Instantanous	490	1191	305	18255	135.1
	STEL	492	853	318	13321	115.4
	8hr-TWA		508			
	1hr-TWA	467	738	3	18229	135
Scraper #2	Instantanous	431	1845	312	50527	224.8
	STEL	432	1175	324	44543	211.1
	8hr-TWA		442			
	1hr-TWA	411	938	325	29301	171.2
Backhoe Loader #1	Instantanous	497	1108	320	40628	201.6
	STEL	494	979	335	31266	176.8
	8hr-TWA		494			
	1hr-TWA	494	830	345	15569	124.8
Excavator #1	Instantanous	528	1134	321	60190	245.3
	STEL	523	1077	333	53813	232
	8hr-TWA		551			
	1hr-TWA	513	909	335	43995	209.7
Loader #1	Instantanous	609	1971	327	215291	464
	STEL	616	1928	338	199851	447
	8hr-TWA		621			
	1hr-TWA	614	1738	352	162056	402.6

CO_2 (Continues):

Equipment	Type	Average	Maximum	Minimum	Variance	Standard Deviation
Excavator #2	Instantanous	359	551	325	490	22.1
	STEL	358	428	342	304	17.4
	8hr-TWA		359			
	1hr-TWA	356	403	344	174	13.2
Excavator #3	Instantanous	379	543	332	650	25.5
	STEL	379	418	346	399	20
	8hr-TWA		377			
	1hr-TWA	380	405	348	291	17.1
Loader #2	Instantanous	763	1423	327	107344	327.6
	STEL	770	1346	336	90354	300.6
	8hr-TWA		746			
	1hr-TWA	792	1187	344	66388	257.7
Excavator #4	Instantanous	434	1118	340	17377	131.8
	STEL	431	793	352	13068	114.3
	8hr-TWA		441			
	1hr-TWA	418	638	348	8387	91.6
Rough Terrain Crane	Instantanous	1016	1676	331	137014	370.2
	STEL	1027	1565	341	104631	323.5
	8hr-TWA		966			
	1hr-TWA	1067	1427	422	47563	218.1
Backhoe Loader #2	Instantanous	428	1565	312	23309	152.7
	STEL	425	922	325	12713	112.8
	8hr-TWA		435			
	1hr-TWA	425	598	353	4024	63.4
Scraper #3	Instantanous	424	716	312	7476	86.5
	STEL	422	557	329	4992	70.7
	8hr-TWA		434			
	1hr-TWA	419	536	330	4244	65.1
Scraper #4	Instantanous	345	1115	269	14314	119.6
	STEL	340	720	286	8913	94.4
	8hr-TWA		350			
	1hr-TWA	329	542	290	2561	50.6
Backhoe Loader #3	Instantanous	215	300	172	528	23
	STEL	214	275	193	345	18.6
	8hr-TWA		215			
	1hr-TWA	212	255	197	214	14.6

CO:

Equipment	Type	Average	Maximum	Minimum	Variance	Standard Deviation
Scraper #1	Instantanous	0.061	1	0	0.06	0.24
	STEL	0.074	1	0	0.07	0.26
	8hr-TWA		0			
	1hr-TWA	0.069	0.542	0	0.02	0.15
Scraper #2	Instantanous	0.004	1	0	0	0.06
	STEL	0	0	0	0	0
	8hr-TWA		0			
	1hr-TWA	0.004	0.033	0	0	0.01
Backhoe Loader #1	Instantanous	0	0	0	0	0
	STEL	0	0	0	0	0
	8hr-TWA		0			
	1hr-TWA	0	0	0	0	0
Excavator #1	Instantanous	0	0	0	0	0
	STEL	0	0	0	0	0
	8hr-TWA		0			
	1hr-TWA	0	0	0	0	0
Loader #1	Instantanous	0.036	2	0	0.04	0.20
	STEL	0.032	1	0	0.03	0.18
	8hr-TWA		0			
	1hr-TWA	0.041	0.325	0	0.01	0.10
Excavator #2	Instantanous	0.756	6	0	0.48	0.69
	STEL	0.730	3	0	0.42	0.65
	8hr-TWA		1			
	1hr-TWA	0.736	1.667	0	0.19	0.43
Excavator #3	Instantanous	0.001	1	0	0	0.03
	STEL	0	0	0	0	0
	8hr-TWA		0			
	1hr-TWA	0.001	0.008	0	0	0
Loader #2	Instantanous	1.365	4	0	1.55	1.25
	STEL	1.406	4	0	1.49	1.22
	8hr-TWA		1			
	1hr-TWA	1.543	3.858	0	1.16	1.08
Excavator #4	Instantanous	0.104	1	0	0.09	0.31
	STEL	0.108	1	0	0.10	0.31
	8hr-TWA		0			
	1hr-TWA	0.118	0.908	0	0.06	0.25

CO (Continues):

Equipment	Data Type	Average	Maximum	Minimum	Variance	Standard Deviation
Rough Terrain Crane	Instantanous	0.091	1	0	0.08	0.29
	STEL	0.078	1	0	0.07	0.27
	8hr-TWA		0			
	1hr-TWA	0.085	0.633	0	0.03	0.18
Backhoe Loader #2	Instantanous	0.186	3	0	0.31	0.56
	STEL	0.219	3	0	0.35	0.59
	8hr-TWA		0			
	1hr-TWA	0.201	1.558	0	0.18	0.43
Scraper #3	Instantanous	0.024	6	0	0.11	0.33
	STEL	0	0	0	0	0
	8hr-TWA		0			
	1hr-TWA	0.018	0.217	0	0	0.06
Scraper #4	Instantanous	0.014	1	0	0.01	0.12
	STEL	0	0	0	0	0
	8hr-TWA		0			
	1hr-TWA	0.006	0.117	0	0	0.02
Backhoe Loader #3	Instantanous	0.647	2	0	0.33	0.58
	STEL	0.641	2	0	0.31	0.56
	8hr-TWA		1			
	1hr-TWA	0.675	1.450	0	0.28	0.53

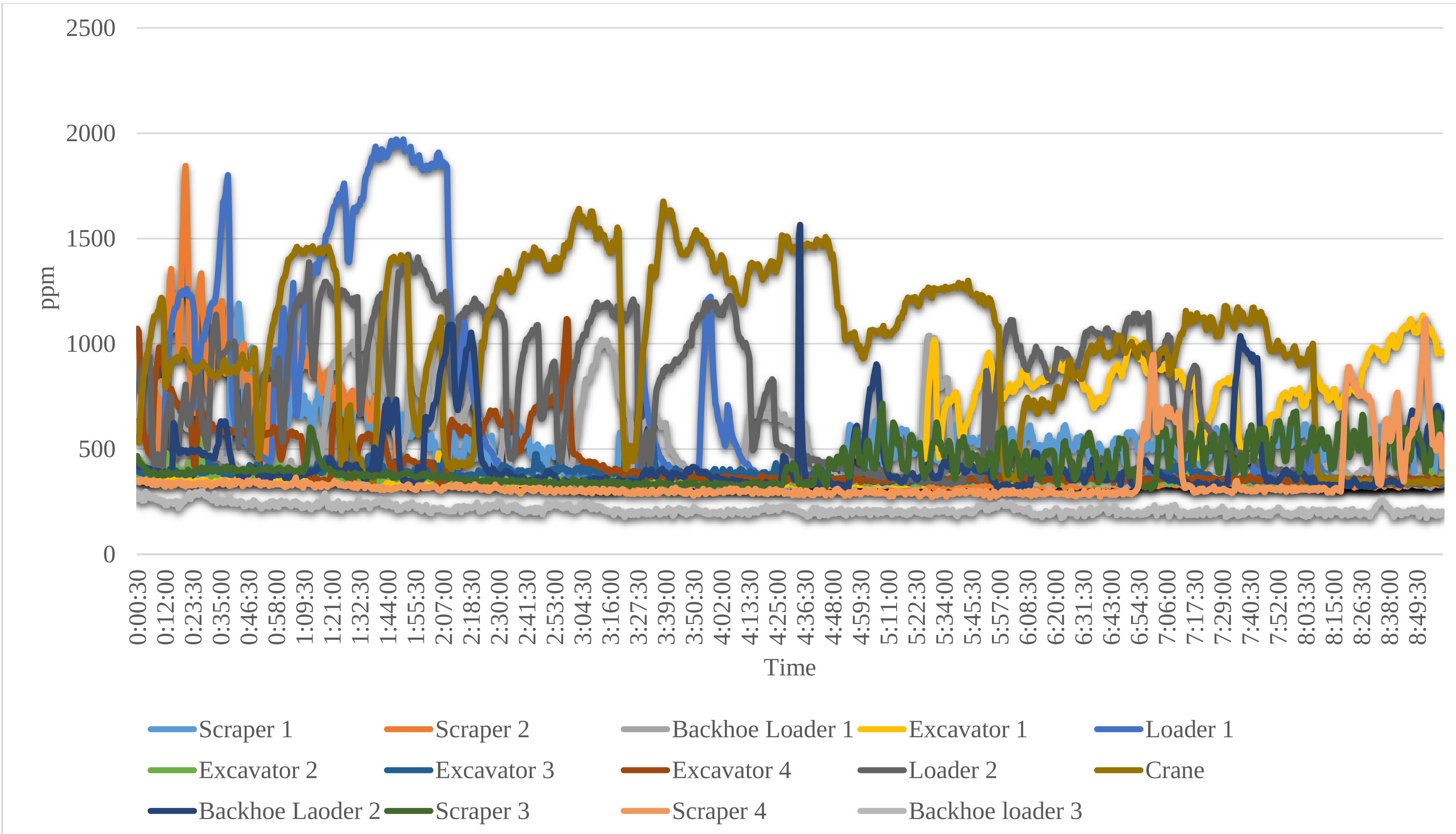
$PM_{2.5}$:

Equipment	Type	Average	Maximum	Minimum	Variance	Standard Deviation
Scraper #1	Instantanous	0.079	1.043	0	0.01	0.1
	8-hr TWA		0.087			
	1-hr TWA	0.083	0.267	0.002	0	0.07
Scraper #2	Instantanous	0.058	5.575	0	0.09	0.31
	8-hr TWA		0.064			
	1-hr TWA	0.054	0.406	0.003	0.01	0.12
Backhoe Loader #1	Instantanous	0.070	3.141	0	0.05	0.23
	8-hr TWA		0.078			
	1-hr TWA	0.075	0.312	0.004	0.01	0.08
Excavator #1	Instantanous	0.013	0.109	0	0	0.01
	8-hr TWA		0.013			
	1-hr TWA	0.013	0.022	0.002	0	0.01
Loader #1	Instantanous	0.021	0.725	0.003	0	0.04
	8-hr TWA		0.021			
	1-hr TWA	0.021	0.049	0.005	0	0.01
Excavator #2	Instantanous	0.024	0.498	0	0	0.03
	8-hr TWA		0.024			
	1-hr TWA	0.023	0.044	0.009	0	0.01
Excavator #3	Instantanous	0.037	1.079	0.003	0	0.05
	8-hr TWA		0.035			
	1-hr TWA	0.039	0.068	0.006	0	0.02
Loader #2	Instantanous	0.009	0.201	0	0	0.01
	8-hr TWA		0.008			
	1-hr TWA	0.008	0.016	0.001	0	0.00
Excavator #4	Instantanous	0.020	0.916	0	0	0.04
	8-hr TWA		0.022			
	1-hr TWA	0.018	0.058	0.005	0	0.01
Rough Terrain Crane	Instantanous	0.012	0.168	0	0	0.01
	8-hr TWA		0.012			
	1-hr TWA	0.011	0.023	0.007	0	0
Backhoe Loader #2	Instantanous	0.008	0.654	0	0	0.02
	8-hr TWA		0.008			
	1-hr TWA	0.008	0.022	0.001	0	0.01
Scraper #3	Instantanous	0.261	6.431	0	0.38	0.61
	8-hr TWA		0.291			
	1-hr TWA	0.208	0.884	0.005	0.05	0.22
Scraper #4	Instantanous	0.061	1.128	0.007	0.01	0.09
	8-hr TWA		0.066			
	1-hr TWA	0.055	0.222	0.018	0	0.06
Backhoe Loader #3	Instantanous	0.055	3.176	0.005	0.02	0.15
	8-hr TWA		0.059			
	1-hr TWA	0.057	0.145	0.011	0	0.03

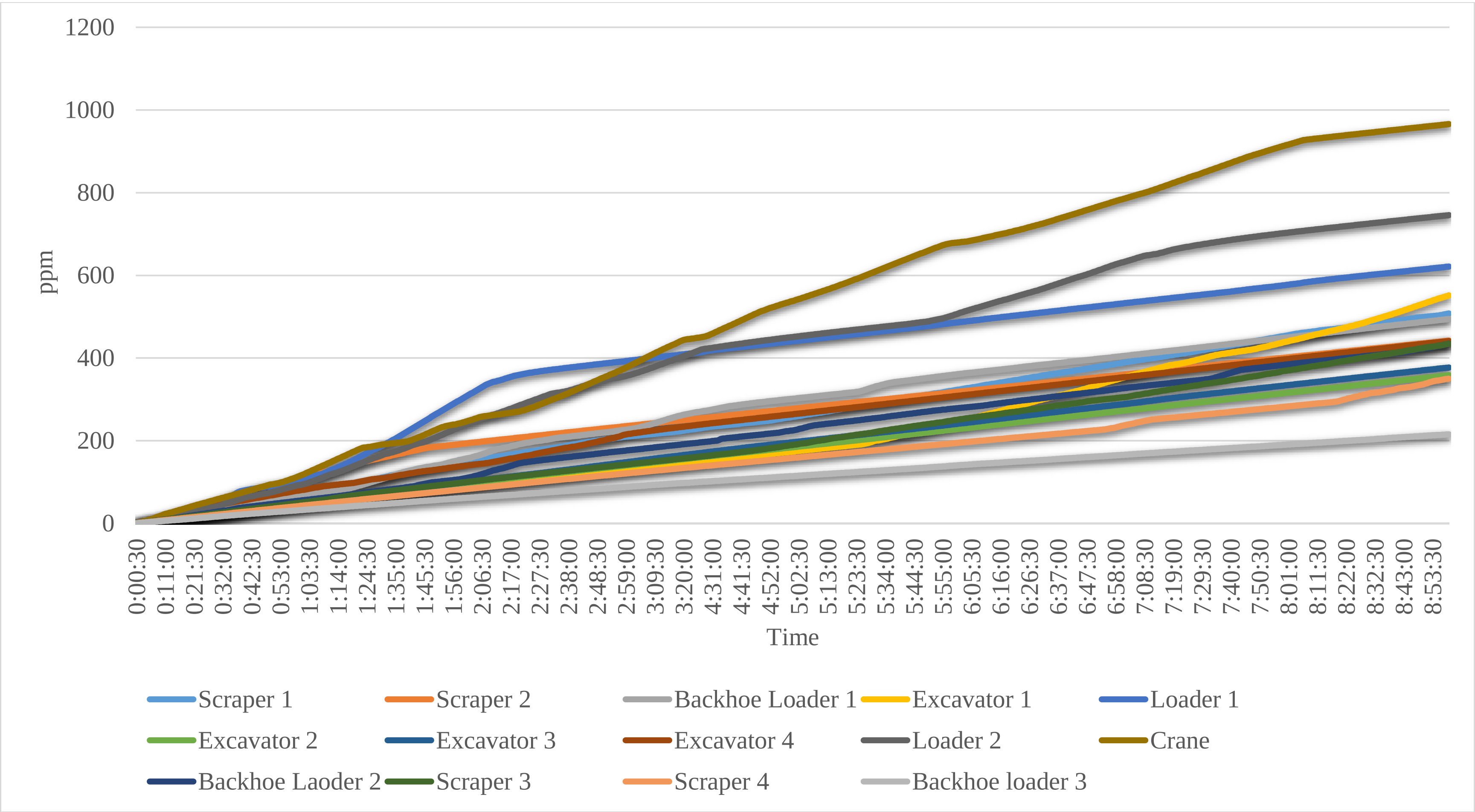
tVOC:

Equipment	Type	Average	Maximum	Minimum	Variance	Standard Deviation
Scraper #2	Instantanous	6.6	14.5	0	19.52	4.42
	8-hr TWA		6.0			
Excavator #2	Instantanous	1.8	2.9	0.9	0.08	0.28
	8-hr TWA		1.8			
Loader #2	Instantanous	0.5	3.7	0	0.47	0.68
	8-hr TWA		0.5			
Rough Terrain Crane	Instantanous	0.2	2.5	0	0.14	0.38
	8-hr TWA		0.2			
Backhoe Loader #2	Instantanous	0.4	4.5	0	0.63	0.80
	8-hr TWA		0.1			
Scraper #3	Instantanous	0.0	1.4	0	0.00	0.07
	8-hr TWA		0.0			

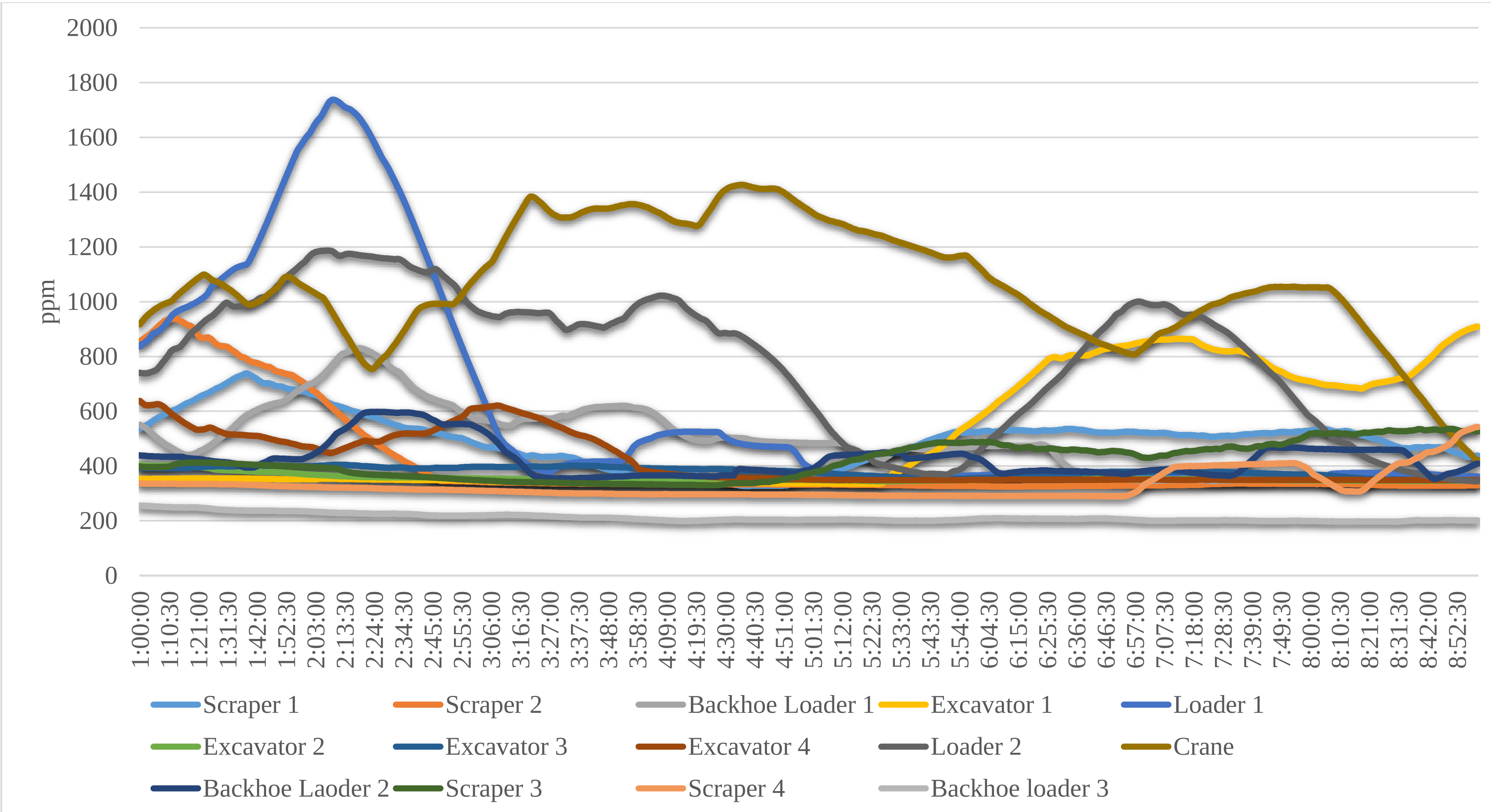
Following graphs are Instantaneous readings, calculated 8-hour TWA, 1-hour TWA, and 15-minute STEL levels over the time for all measured pollutants. The description of each graph is indicated on its caption. Last two graphs are instantaneous readings of the temperature (in ^{0}C) and relative humidity. For 8-hour TWA graphs, slope of the line for each equipment at any time, shows the accumulation speed of the pollutant in equipment cab at that time.



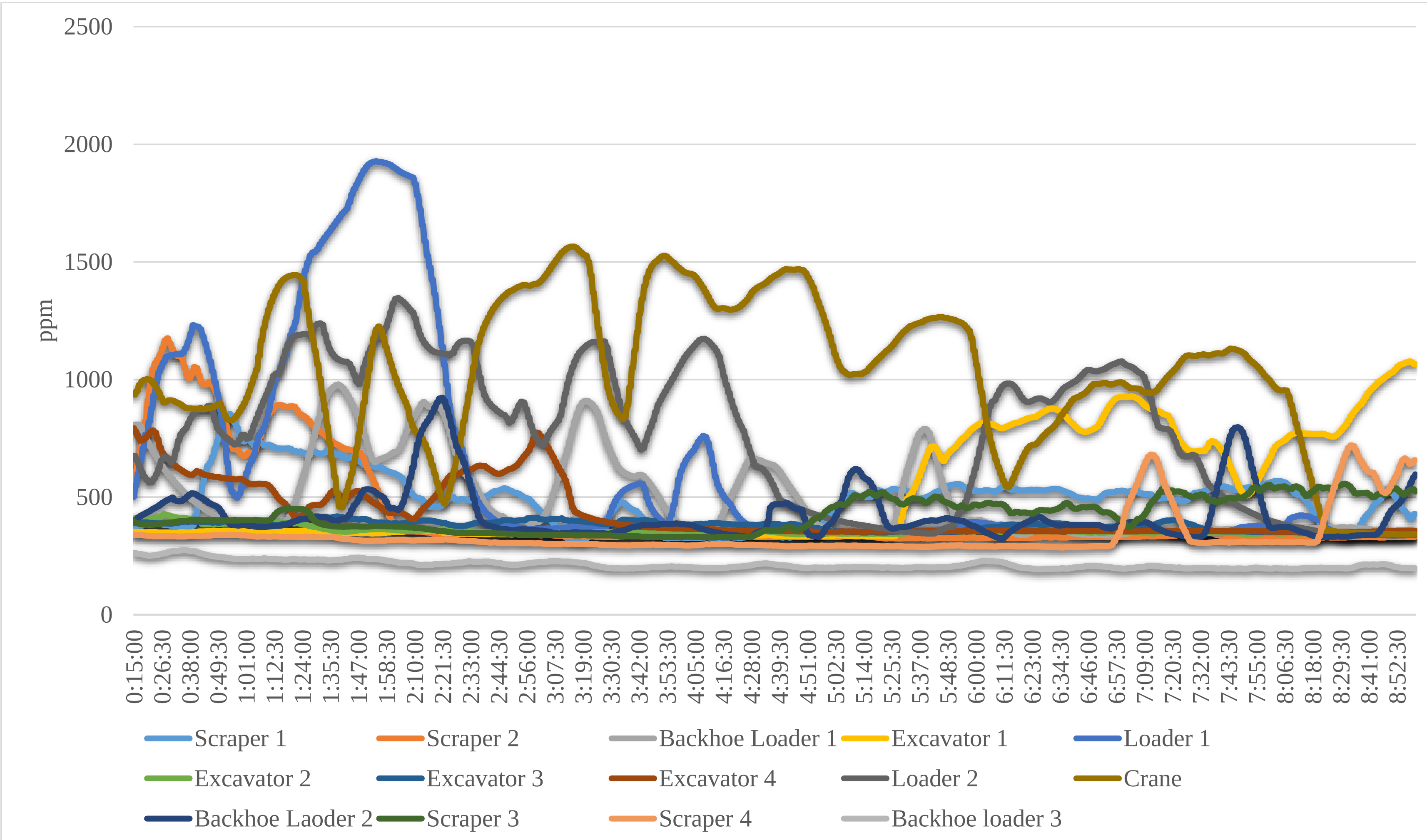
CO_2 Instantaneous Readings



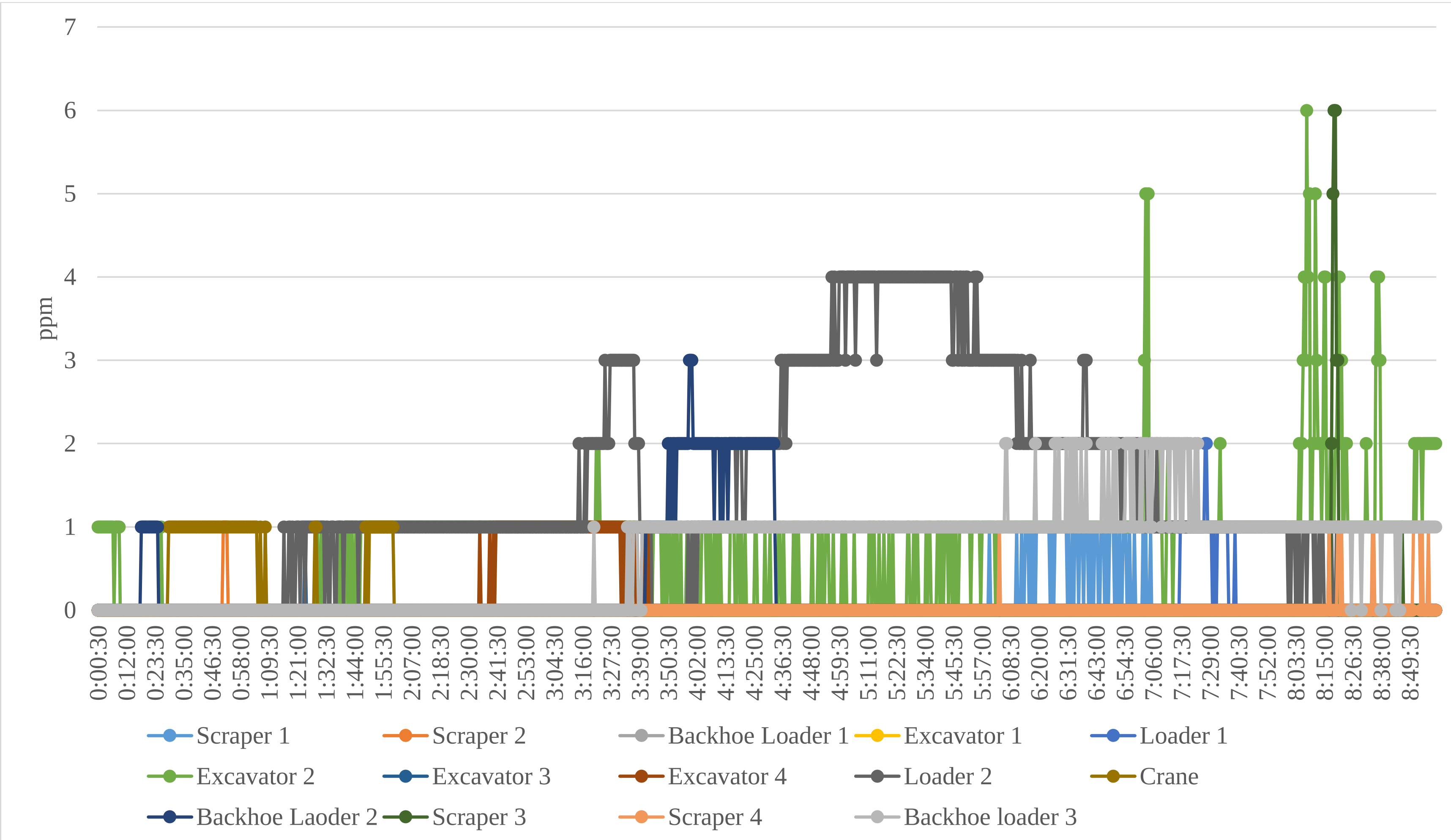
CO_2 8-hour TWA Level



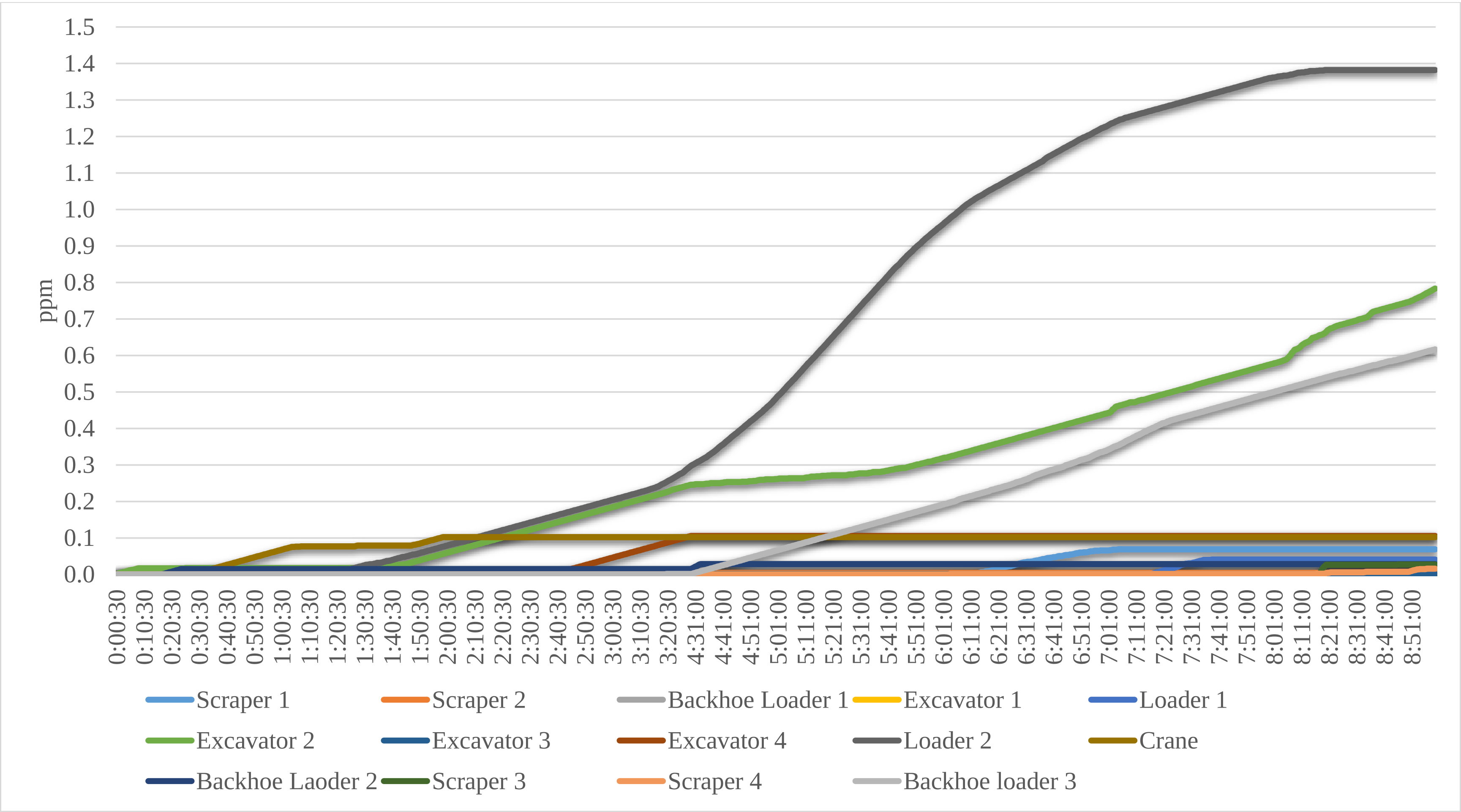
CO_2 1-hour TWA Levels



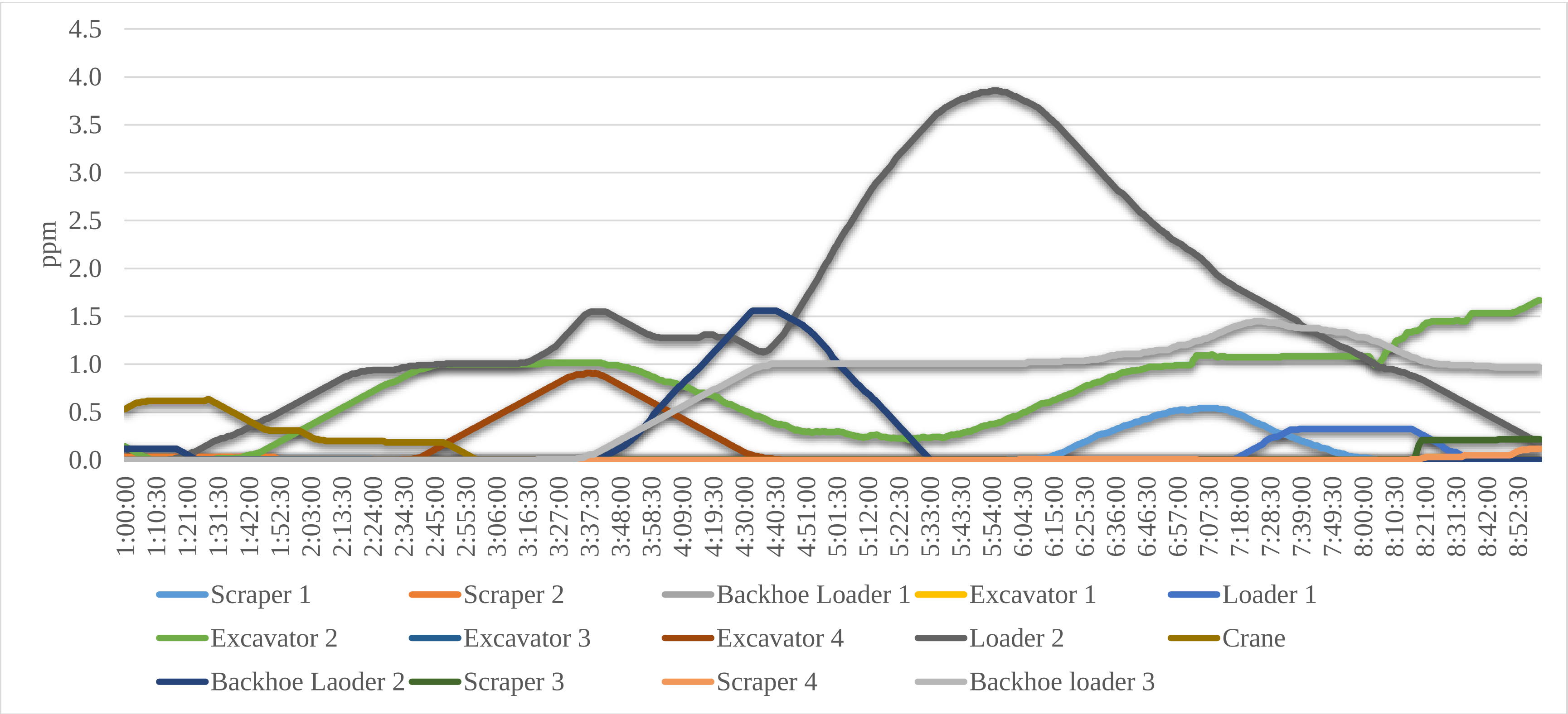
CO_2 15-minute STEL Levels



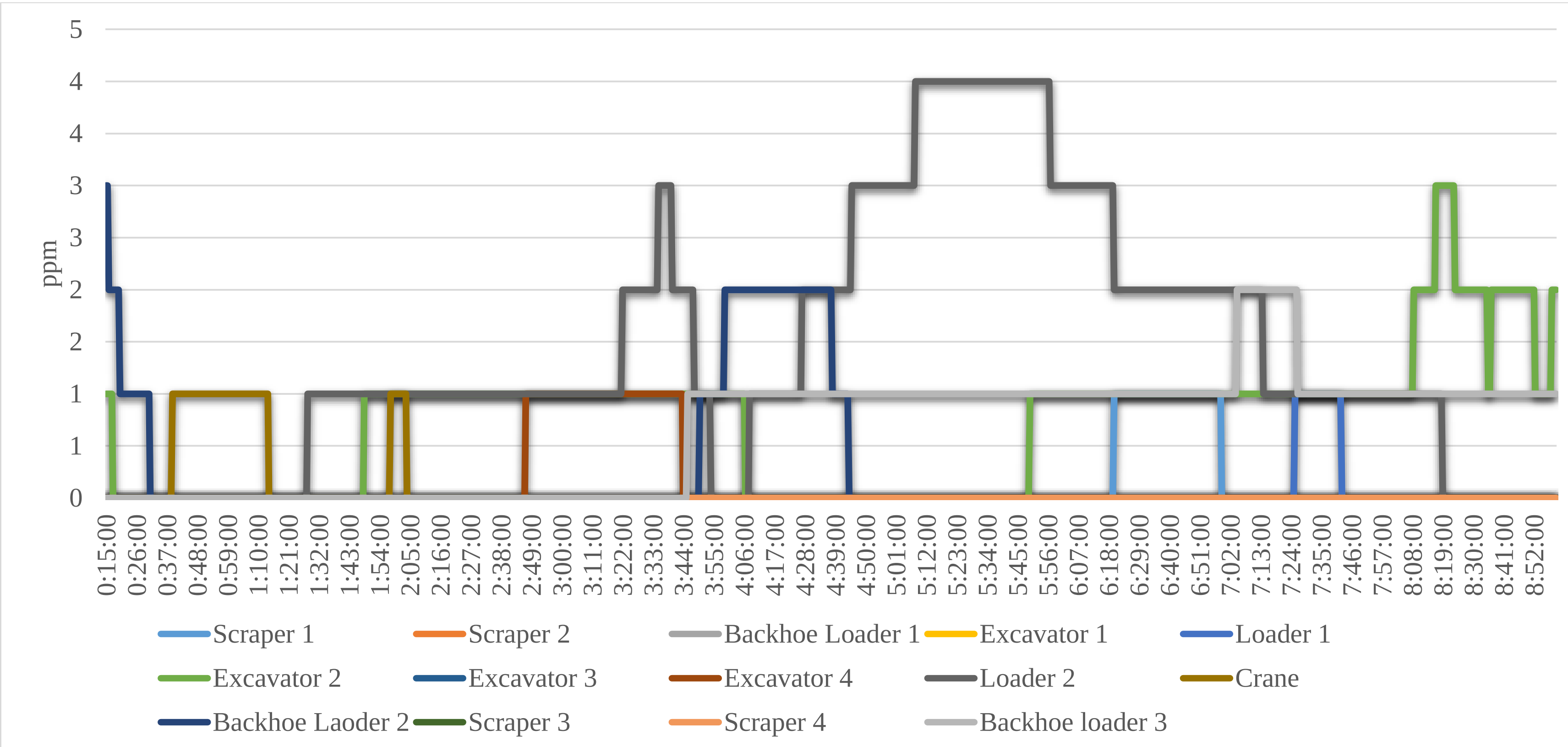
CO Instantaneous Readings



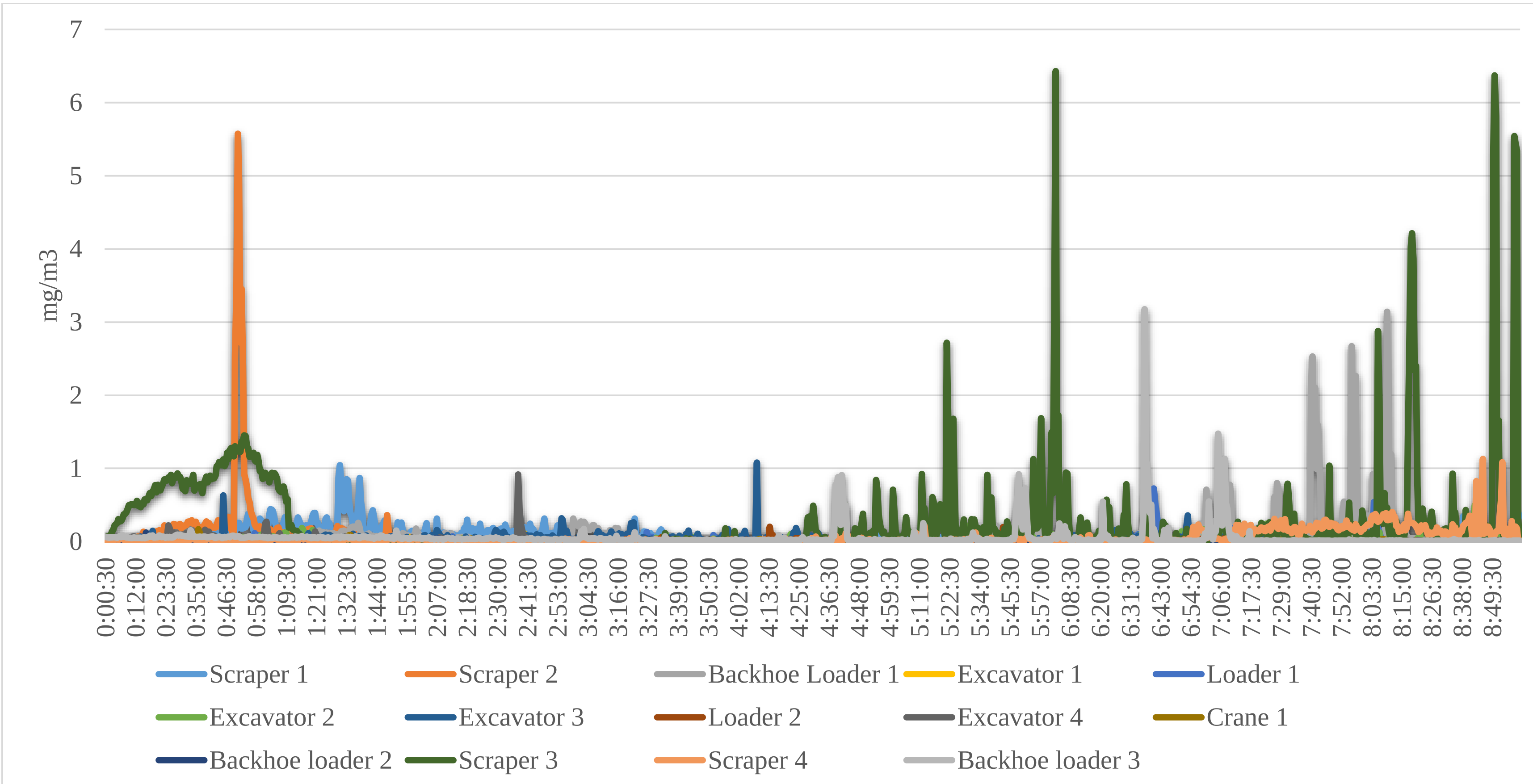
CO 8-hour TWA Level



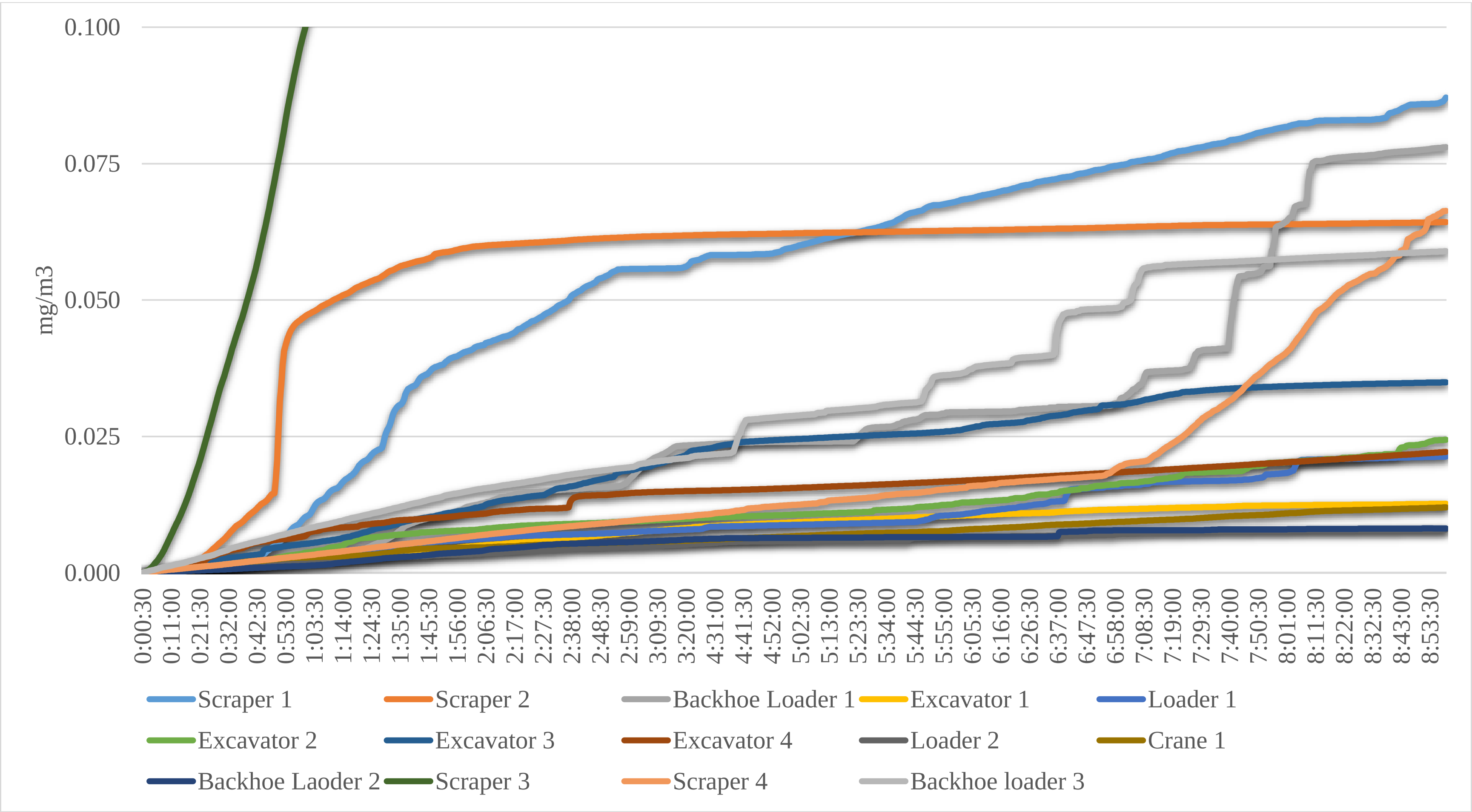
CO 1-hour TWA Levels



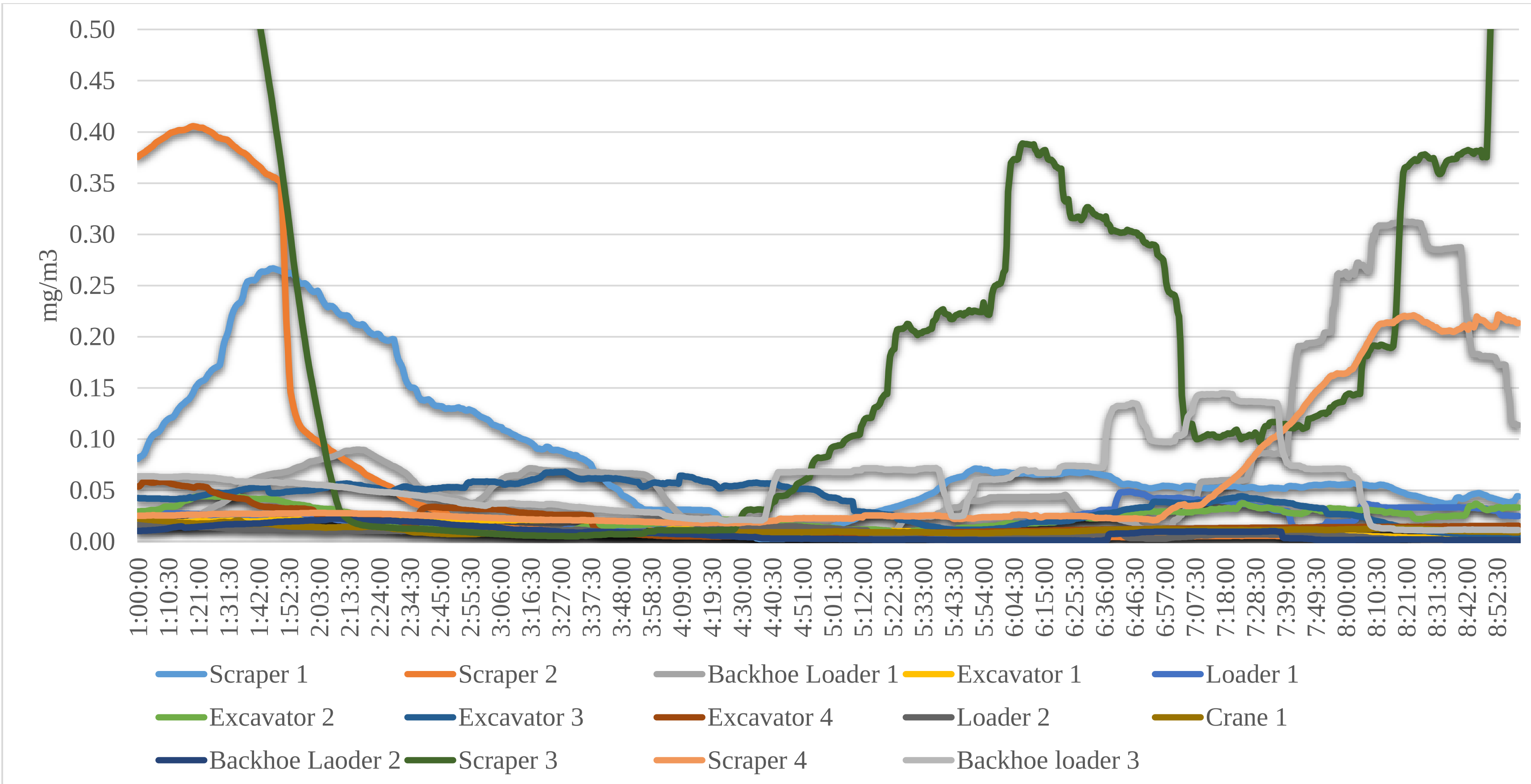
CO 15-minute STEL Levels



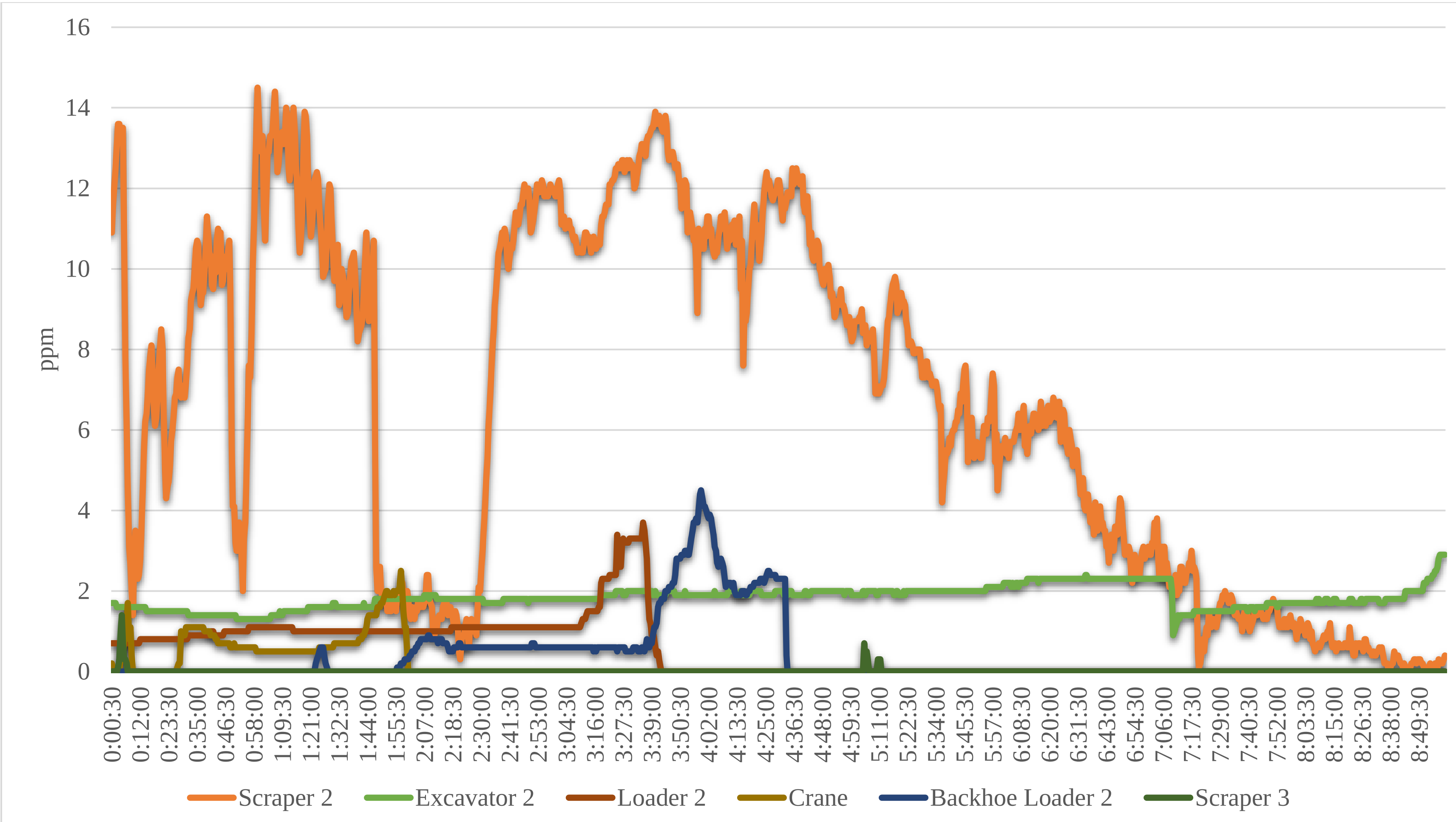
$PM_{2.5}$ Instantaneous Readings



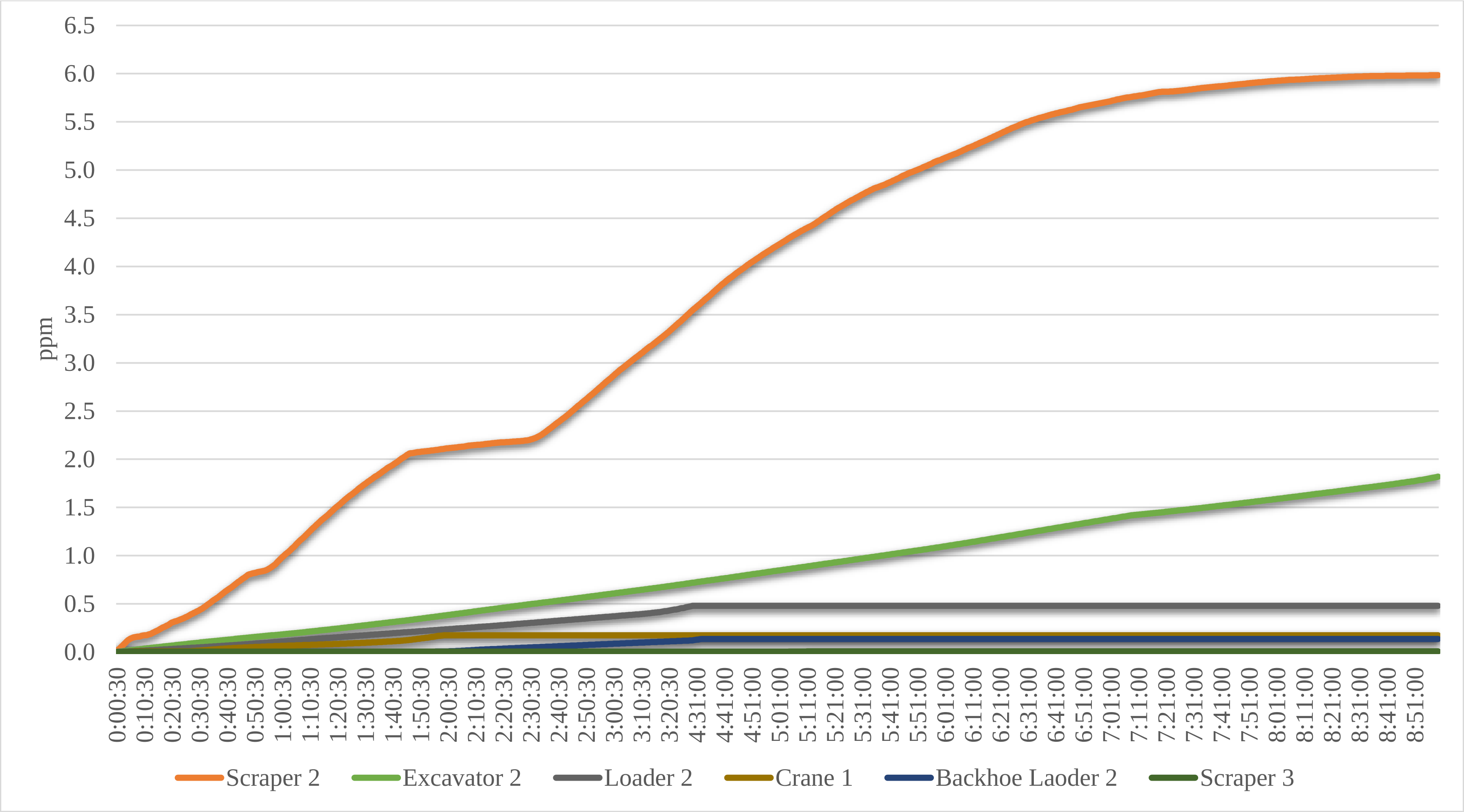
$PM_{2.5}$ 8-hour TWA Level



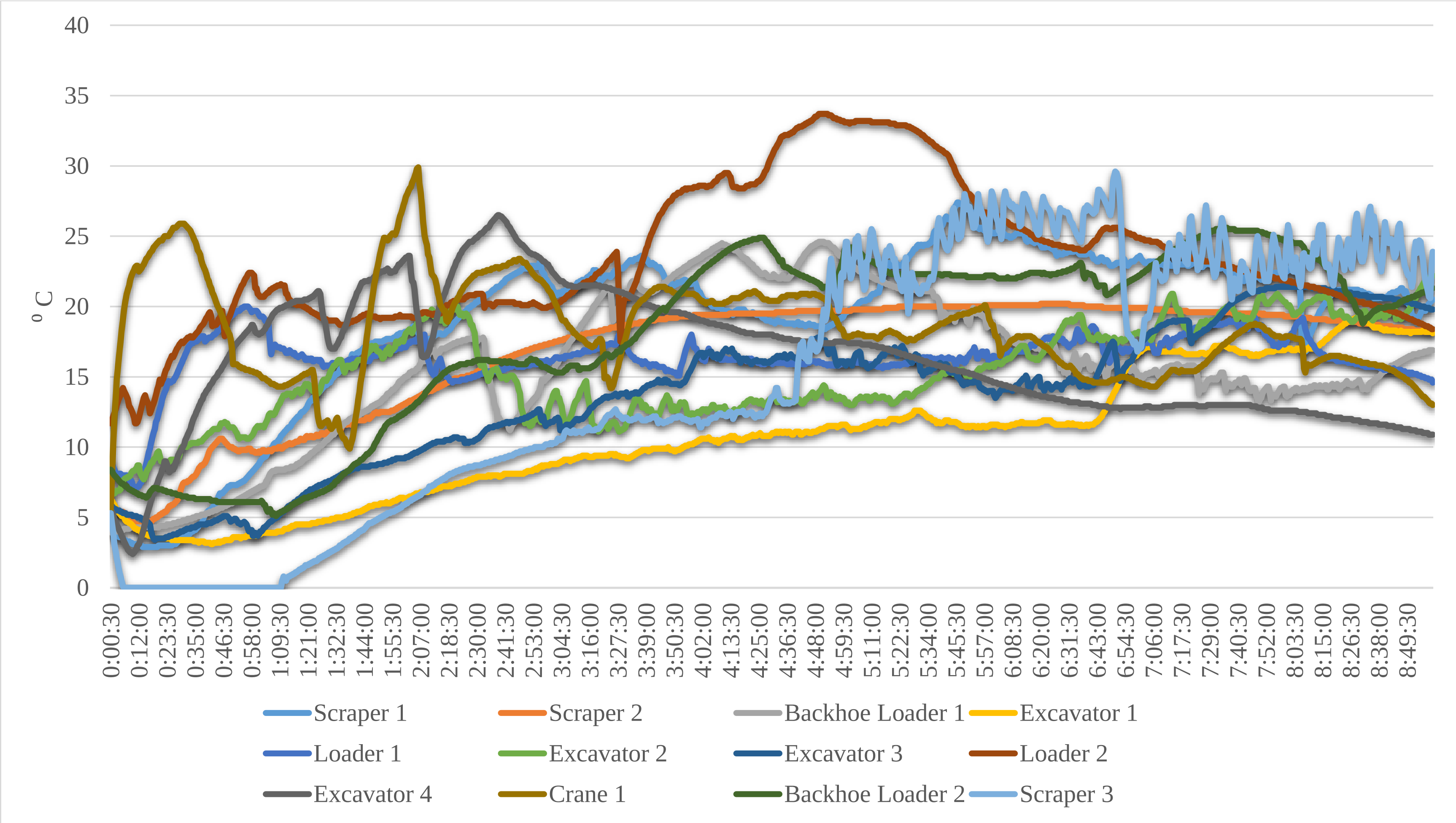
$PM_{2.5}$ 1-hour TWA Levels



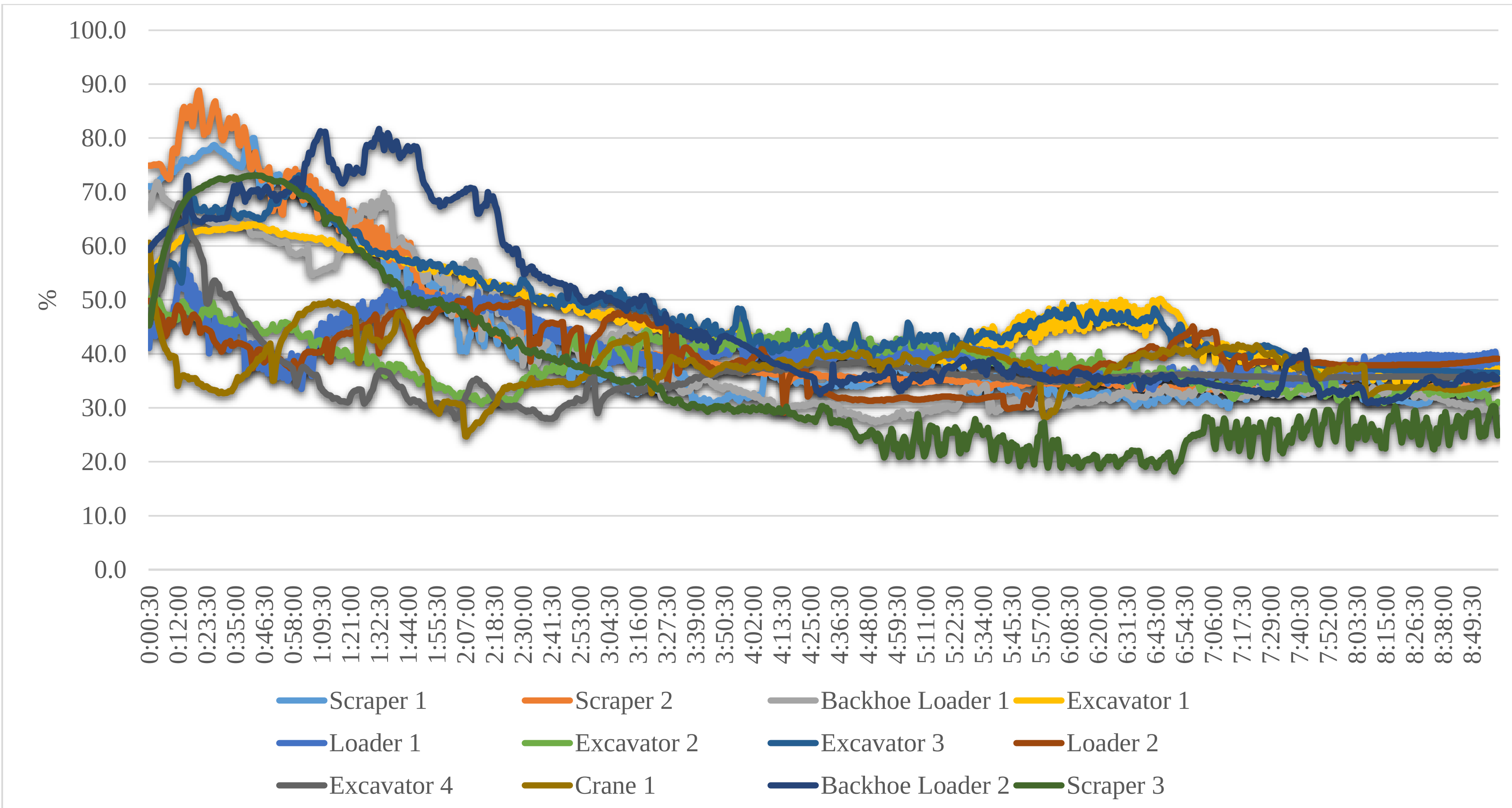
tVOC Instantaneous Readings



tVOC 8-hour TWA Level

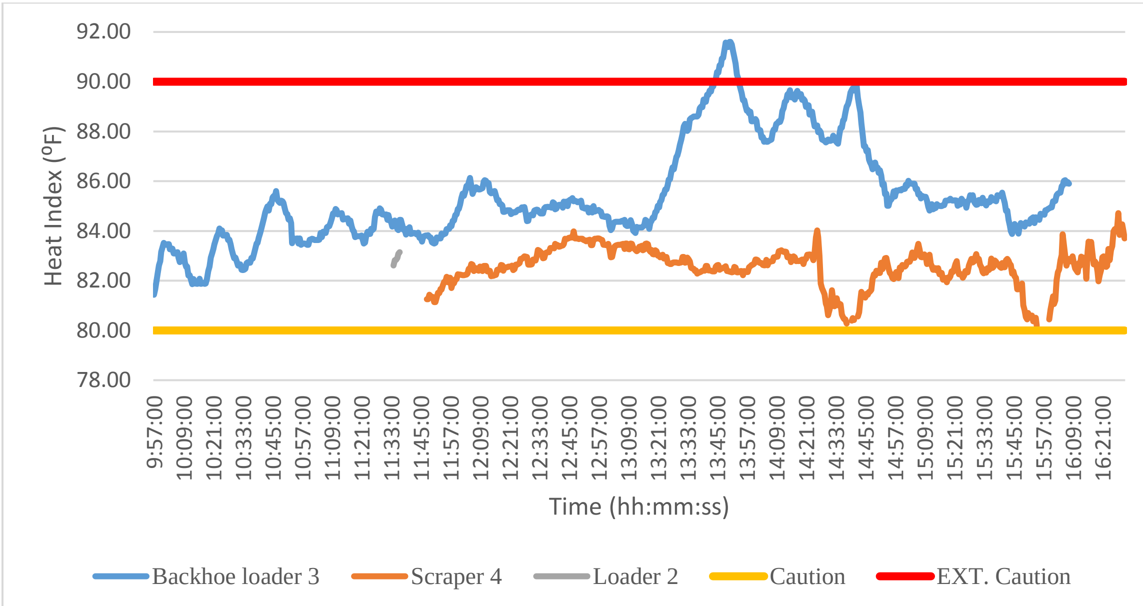


Temperature over the Time

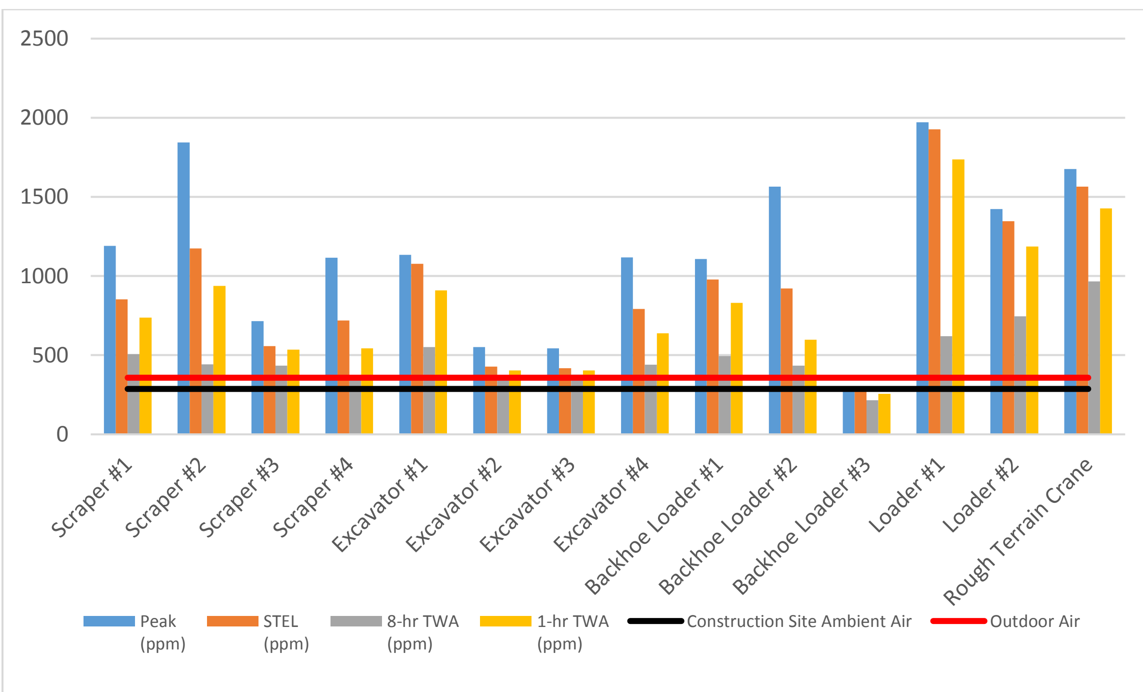


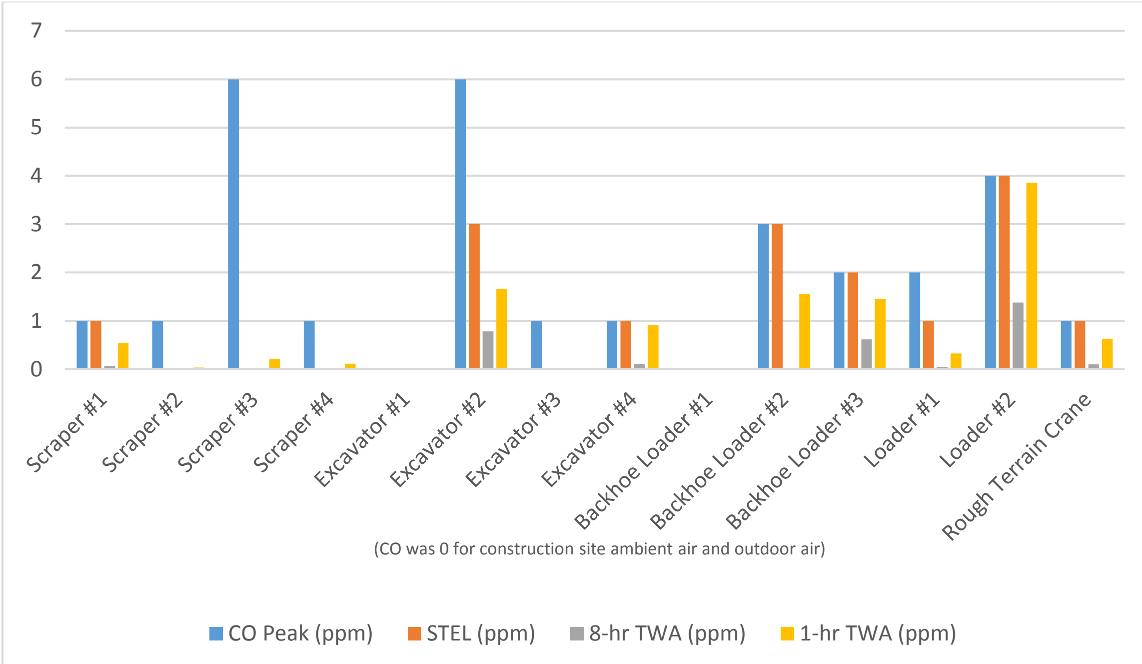
Relative Humidity over the Time

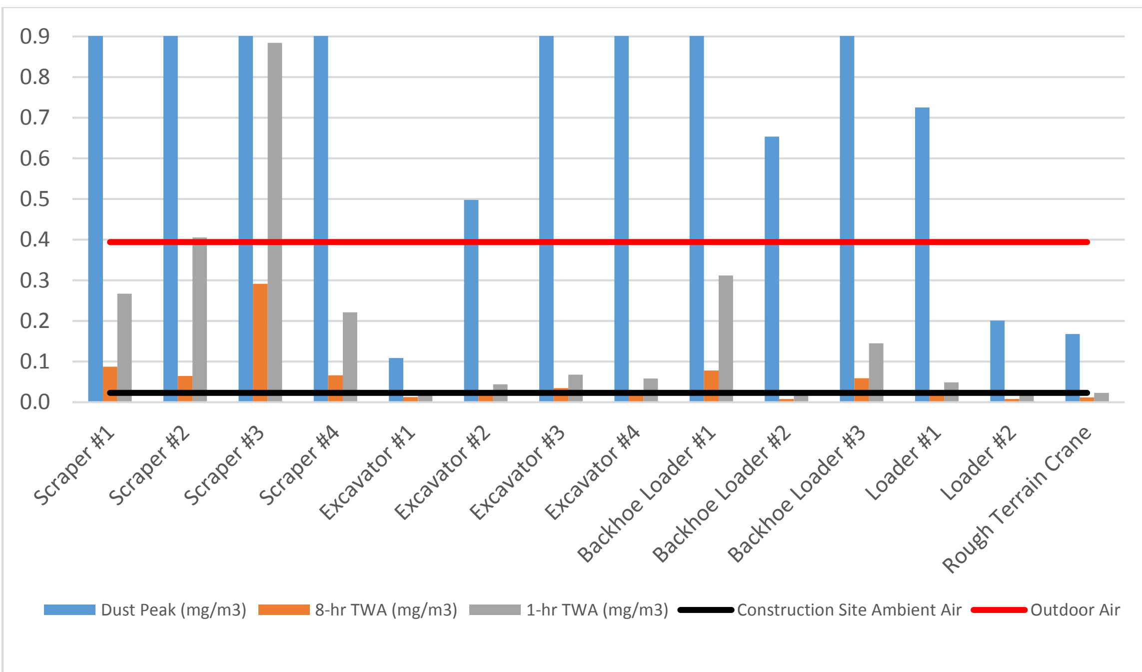
Following figure shows calculated heat indexes (whenever requirements were met) over time and appropriate limits that should be taken into consideration.



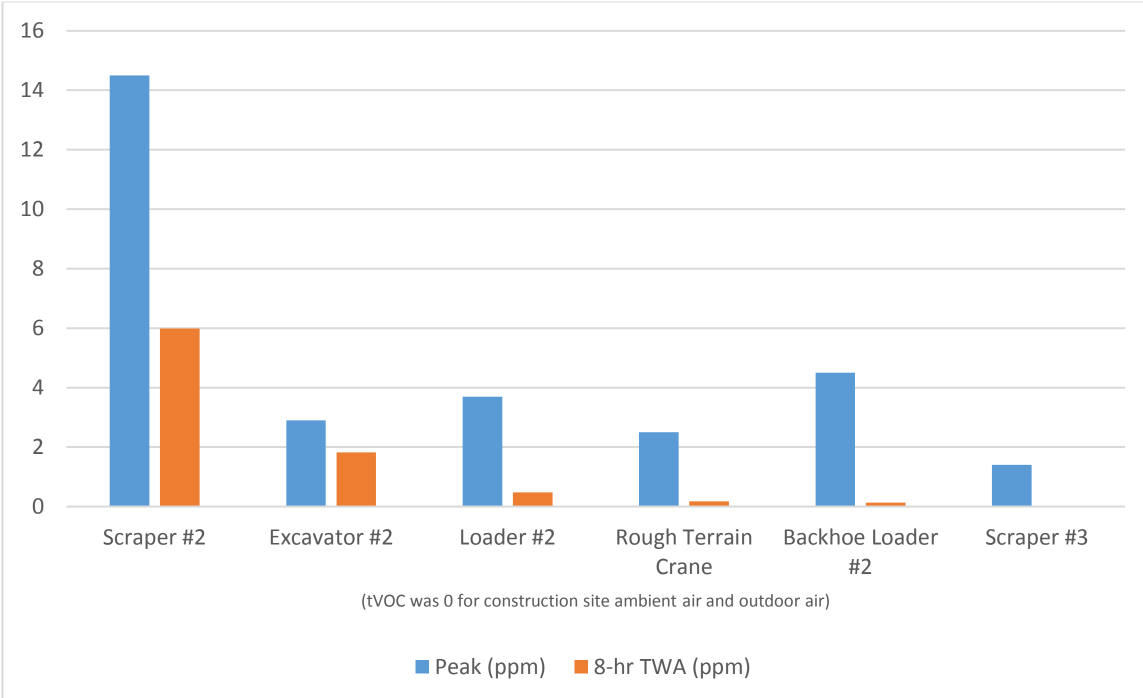
Following graphs are depicting all results together along with recorded construction site ambient air peak level and outdoor air peak level for CO_2, CO, $PM_{2.5}$, and tVOC respectively.







(Vertical axis just shows levels from 0 to 0.9 mg/m3, in order to make the chart readable, while the maximum peak level was 6.43 mg/m3)


16
14
12
10
8
6
4
2
0
Scraper #2
Excavator #2
Loader #2
Rough Terrain Crane
Backhoe Loader #2
Scraper #3
(tVOC was 0 for construction site ambient air and outdoor air)
Peak (ppm)
8-hr TWA (ppm)

Appendix B. Outliers

EVM-7 manual mentions that sensors usually need some time to warm up, which may take up to one hour. The day Backhoe Loader #2 was tested, it is believed that sensors did not have enough time to warm up, so for CO and tVOC, early recordings do not add up with rest of the data. Decreasing trend in recordings makes it more clear that as the sensor warms up, numbers are getting closer to real pollutant levels. All numbers were substituted with zero. Also, for Scraper #3, and Scraper #4, for specific periods of time, EVM-7 recorded numbers that were much greater than what it recorded before and after that time period. These numbers were substituted with average of before and after recordings to keep the trend. All details are presented in following table.

Pollutant	Equipment	Equivalent Time	Changed from	Changed to	Pollutant	Equipment	Equivalent Time	Changed from	Changed to
CO	Backhoe Loader #2	0:00:30	6	0	VOC	Backhoe Loader #2	0:07:30	4.7	0.0
		0:01:00	6	0			0:08:00	4.4	0.0
		0:01:30	5	0			0:08:30	3.9	0.0
		0:02:00	5	0			0:09:00	3.6	0.0
		0:02:30	4	0			0:09:30	3.0	0.0
		0:03:00	4	0			0:10:00	2.8	0.0
		0:03:30	4	0			0:10:30	2.7	0.0
		0:04:00	3	0			0:11:00	2.7	0.0
		0:04:30	3	0			0:11:30	2.8	0.0
		0:05:00	3	0			0:12:00	2.9	0.0
		0:05:30	3	0			0:12:30	2.8	0.0
		0:06:00	3	0			0:13:00	2.6	0.0
		0:06:30	3	0			0:13:30	2.6	0.0
		0:07:00	3	0			0:14:00	2.4	0.0
		0:07:30	3	0			0:14:30	2.2	0.0
		0:08:00	3	0			0:15:00	2.3	0.0
		0:08:30	2	0			0:15:30	2.9	0.0
		0:09:00	2	0			0:16:00	2.2	0.0
		0:09:30	1	0			0:16:30	2.1	0.0
		0:10:00	1	0			0:17:00	2.1	0.0
		0:10:30	1	0			0:17:30	2.1	0.0
		0:11:00	1	0			0:18:00	2.1	0.0
		0:11:30	1	0			0:18:30	2.1	0.0
		0:12:00	1	0			0:19:00	2.1	0.0
		0:12:30	1	0			0:19:30	2.3	0.0
		0:13:00	1	0			0:20:00	2.3	0.0
		0:13:30	1	0			0:20:30	2.5	0.0
		0:14:00	1	0			0:21:00	2.6	0.0
		0:14:30	1	0			0:21:30	2.5	0.0
		0:15:00	1	0			0:22:00	2.5	0.0
		0:15:30	1	0			0:22:30	2.8	0.0
		0:16:00	1	0			0:23:00	2.9	0.0
		0:16:30	1	0			0:23:30	2.6	0.0
		0:17:00	1	0			0:24:00	2.3	0.0
PM 2.5	Scraper #3	8:51:00	7.421	5.812			0:24:30	2.2	0.0
		8:51:30	9.174	1.022			0:25:00	2.1	0.0
		8:58:30	11.944	5.442			0:25:30	2.0	0.0
	Scraper #4	8:45:00	8.486	0.098			0:26:00	1.9	0.0
		8:45:30	12.213	0.617			0:26:30	1.9	0.0
		8:52:00	87.072	0.141			0:27:00	1.9	0.0
		8:52:30	98.850	0.370			0:27:30	1.9	0.0
		8:53:00	22.577	0.599			0:28:00	1.8	0.0
VOC	Backhoe Loader #2	0:00:30	9.0	0.0			0:28:30	1.7	0.0
		0:01:00	8.8	0.0			0:29:00	1.6	0.0
		0:01:30	7.6	0.0			0:29:30	1.5	0.0
		0:02:00	6.9	0.0			0:30:00	1.5	0.0
		0:02:30	6.6	0.0			0:30:30	1.5	0.0
		0:03:00	6.2	0.0			0:31:00	1.4	0.0
		0:03:30	5.8	0.0			0:31:30	1.3	0.0
		0:04:00	5.2	0.0			0:32:00	1.3	0.0
		0:04:30	5.0	0.0			0:32:30	1.3	0.0
		0:05:00	4.9	0.0			0:33:00	1.3	0.0
		0:05:30	5.1	0.0			0:33:30	1.3	0.0
		0:06:00	5.2	0.0			0:34:00	1.3	0.0
		0:06:30	4.9	0.0			0:34:30	0.8	0.0
		0:07:00	5.0	0.0			0:35:00	0.1	0.0

Appendix C. Possible VOC Substances in HDD construction equipment Operator's Ambient Air and Corresponding Limits

Following table summarizes the most likely VOCs that are expected to be found in HDD construction equipment operator ambient air and corresponding limits. There are two main sources for these VOCs, diesel exhaust and general VOCs which are produced in typical construction sites. VOCs that are belong to paint products are not included, because usually when HDD equipment are working on job site, painting related activities have not started yet.

#	Substance	CAS #	Limit	unit	type	Limit Source	Substance Source
1	Acetylene	74-80-2	2500	ppm	Ceiling	NIOSH	Diesel Exhaust
2	Benzene	71-43-2	0.1	ppm	8-hr TWA	NIOSH	Diesel Exhaust
			1	ppm	STEL (15-mins)	NIOSH	
			1	ppm	8-hr TWA	OSHA	
			5	ppm	STEL (15-mins)	OSHA	
			0.0009 (3)	ppm (µg/m3)	Instantaneous	LEED v3 (2009), for pilot testing (pilot credit 68)	
3	Naphthalene	91-20-3	10	ppm	8-hr TWA	NIOSH	Diesel Exhaust
			10	ppm	8-hr TWA	OSHA	
			15	ppm	STEL (15-mins)	OSHA	
			0.002 (9)	ppm (µg/m3)	Instantaneous	LEED v3 (2009), for pilot testing (pilot credit 68)	
4	Crotonaldehyde	4170-30-3	2	ppm	8-hr TWA	OSHA	Diesel Exhaust
			2	ppm	8-hr TWA	NIOSH	
5	Chloroaldehyde	167-20-0	1	ppm	Ceiling	OSHA	Diesel Exhaust
			1	ppm	Ceiling	NIOSH	
6	Formaldehyde	50-00-0	0.016	ppm	8-hr TWA	NIOSH	Diesel Exhaust
			0.027	ppm	Instantaneous	LEED v4	
			0.05	ppm	Long term	Canadian	
			0.081	ppm	30-min	WHO/Europe	
			0.1	ppm	Long term	Canadian	
			0.1	ppm	STEL (15-mins)	NIOSH	
			0.3	ppm	8-hr TWA	MAK	
			0.75	ppm	8-hr TWA	OSHA	
			1	ppm	Ceiling	MAK	
			2	ppm	STEL (15-mins)	OSHA	
			0.027 (33)	ppm (µg/m3)	Instantaneous	LEED v3 (2009), for pilot testing (pilot credit 68)	
7	Glutaraldehyde	111-30-8	0.05	ppm	8-hr TWA	MAK	Diesel Exhaust
			0.2	ppm	Ceiling	NIOSH	

#	Substance	CAS #	Limit	unit	type	Limit Source	Substance Source
8	Acetaldehyde	75-07-0	25	ppm	Ceiling	ACGIH	Diesel Exhaust
			50	ppm	Instantaneous	MAK	
			200	ppm	8-hr TWA	OSHA	
			0.034 (140)	ppm (µg/m3)	Instantaneous	LEED v3 (2009), for pilot testing (pilot credit 68)	
9	Acrolein	(07-02-8)	0.1	ppm	8-hr TWA	NIOSH	Diesel Exhaust
			0.1	ppm	8-hr TWA	OSHA	
			0.3	ppm	STEL (15-mins)	NIOSH	
10	Ammonia	7664-41-7	25	ppm	8-hr TWA	OSHA	Diesel Exhaust
			50	ppm	8-hr TWA	NIOSH	
			0.287 (200)	ppm (µg/m3)	Instantaneous	LEED v3 (2009), for pilot testing (pilot credit 68)	
11	Methane	74-82-8	1000	ppm	8-hr TWA	ACGIH	Diesel Exhaust
12	Ethylene	74-85-1	200	ppm	8-hr TWA	ACGIH	Diesel Exhaust
13	Hexadecane (Kerosene)	8008-20-6	14.38 (100)	ppm (mg/m3)	8-hr TWA	NIOSH	Diesel Exhaust
			28.76 (200)	ppm (mg/m3)	8-hr TWA	ACGIH	
14	ᾱ-olefines C3-C15	C3 (Propane)	1000	ppm	8-hr TWA	OSHA, NIOSH	Diesel Exhaust
		C4 (Butane)	800	ppm	8-hr TWA	NIOSH	
		C5 (Pentane)	508.32 (1500)	ppm (mg/m3)	8-hr TWA	ACGIH	
		C6 (Hexane)	426.45 (1500)	ppm (mg/m3)	8-hr TWA	ACGIH	
		C7 (Heptane)	366.75 (1500)	ppm (mg/m3)	8-hr TWA	ACGIH	
		C8 (Octane)	321.71 (1500)	ppm (mg/m3)	8-hr TWA	ACGIH	
		C9 (Nonane)	229.22 (1200)	ppm (mg/m3)	8-hr TWA	ACGIH	
		C10 (Decane)	206.62 (1200)	ppm (mg/m3)	8-hr TWA	ACGIH	
		C11 (Undecane)	187.7 (1200)	ppm (mg/m3)	8-hr TWA	ACGIH	
		C12 (Dodecane)	172.24 (1200)	ppm (mg/m3)	8-hr TWA	ACGIH	
		C13 (Tridecane)	159.14 (1200)	ppm (mg/m3)	8-hr TWA	ACGIH	
		C14 (Tetradecane)	147.89 (1200)	ppm (mg/m3)	8-hr TWA	ACGIH	
		C15 (Pentadecane)	138.12 (1200)	ppm (mg/m3)	8-hr TWA	ACGIH	
15	Aldehydes C3-C15	C3 (Propanal)	20	ppm	8-hr TWA	ACGIH	Diesel Exhaust
		C4 (Butanal)	N/A		N/A	N/A	
		C5 (Pentanal)	50	ppm	8-hr TWA	ACGIH, NIOSH	
		C6 (Hexanal)	500	ppm	8-hr TWA	OSHA	
		C7 (Heptanal)	N/A		N/A	N/A	
		C8 (Octanal)	N/A		N/A	N/A	
		C15 (Pentadecanal)	N/A		N/A	N/A	

#	Substance	CAS #	Limit	unit	type	Limit Source	Substance Source
16	Carbon disulfide	75-15-0	1	ppm	8-hr TWA	NIOSH	Construction site
			5	ppm	8-hr TWA	MAK	
			10	ppm	STEL (15-mins)	NIOSH	
			20	ppm	8-hr TWA	OSHA	
			30	ppm	Ceiling	OSHA	
			100	ppm	30-min	OSHA	
			0.257 (800)	ppm (µg/m3)	Instantaneous	LEED v3 (2009), for pilot testing (pilot credit 68)	
17	Turpentine		100	ppm	8-hr TWA	OSHA	Construction site
			100	ppm	8-hr TWA	NIOSH	
18	Butadiene	106-90-0	1	ppm	8-hr TWA	OSHA	Construction site
			5	ppm	STEL (15-mins)	OSHA	
			0.009 (20)	ppm (µg/m3)	Long term	ASHRAE	
19	Carbon tetrachloride	56-23-5	0.5	ppm	8-hr TWA	MAK	Construction site
			2	ppm	STEL (15-mins)	NIOSH	
			10	ppm	8-hr TWA	OSHA	
			25	ppm	Ceiling	OSHA	
			200	ppm	4-hr	OSHA	
			0.006 (40)	ppm (µg/m3)	Instantaneous	LEED v3 (2009), for pilot testing (pilot credit 68)	

VITA

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