CHARACTERIZING IN-CAB AIR QUALITY IN HEAVY-DUTY DIESEL CONSTRUCTION EQUIPMENT

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16. Abstract

Previous research indicates that air quality in the cabs of heavy-duty diesel equipment may exceed recommended exposure limits for certain pollutants. The objective of this case study was to collect and analyze air pollutant data near the cabs of heavy-duty diesel equipment while performing real-world activities. Using state-of-the-art instrumentation, the research team conducted 24 tests on nine different items of heavy-duty equipment. The team collected data related to pollutant concentrations of carbon monoxide, carbon dioxide, nitric oxide, nitrogen dioxide, particulate matter, and black carbon. Average concentrations of carbon monoxide and nitric oxide did not exceed published exposure limits on a consistent basis, but their maximum values occasionally exceeded the limits. Carbon dioxide concentrations frequently exceeded recommended levels for adequate ventilation. The most concerning results belonged to particulate matter and black carbon. Concentrations of respirable particulates often exceeded recommended levels on a sustained basis. Overall, the case study yielded enough information to conclude that studying in-cab air quality in heavy-duty equipment cabs is necessary to reduce hazards related to human health, safety, and productivity for equipment operators.

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Executive Summary

The in-cab environment of heavy-duty diesel (HDD) equipment is a result of the interaction between the machine, jobsite, climate, and other sources. The equipment itself emits diesel exhaust with pollutants including oxides of nitrogen, carbon monoxide (CO), carbon dioxide (CO_2), hydrocarbons, and diesel particulate matter (PM). The operator sits in close proximity to the tailpipe that emits these pollutants. Heavy-duty equipment operates on a wide variety of jobsites under a wide variety of conditions. Other air quality sources include exhaust from other vehicles and equipment, significant point or area sources of pollution near the jobsite, and operator activities such as smoking or eating in the cab.

The potential health effects of poor air quality may be both short term and long term for the equipment operator and other employees working nearby. While pollutants found in diesel exhaust are extremely harmful, there is uncertainty regarding the concentrations or periods of exposure necessary to produce specific health problems. In fact, there are no permissible exposure limits or specific guidance for equipment operators' exposure to diesel exhaust or other harmful pollutants. A better understanding of the in-cab environment of heavy-duty equipment is necessary to provide safer and more productive working conditions for equipment operators.

This research addresses an important problem because the current number of HDD equipment operators will grow by 19 percent (faster than the national average for other occupations) to approximately 500,000 operators in 2022. Those that can operate various types of equipment will have the best career opportunities but may also have the greatest exposure to poor indoor air quality (IAQ); therefore, HDD equipment operators may have a disproportionate risk of poor IAQ compared to other workers.

This research is significant because the U.S. Environmental Protection Agency (EPA) identifies IAQ as one of the five most urgent risks to public health. Given that equipment operators spend most of their day inside the equipment cab, IAQ is a significant issue. Furthermore, HDD equipment operates in a harsh environment including temperature and humidity extremes and dusty conditions, and in close proximity to a high-pollution source—the tailpipe of the equipment. For a typical IAQ scenario inside a building, opening a door or window introduces fresh air that helps dilute pollutants; however, opening the door to the equipment cab may worsen the problem by allowing in even more diesel exhaust and PM. Research must characterize IAQ in HDD equipment cabs in order to determine the severity of the problem.

This research is also significant because exposure to diesel exhaust is an important human health concern. EPA assessed the possible health hazards associated with its exposure and concluded that there are effects from short-term and/or acute exposures, as well as long-term chronic exposures, including repeated occupational exposures. EPA states there is enough evidence to indicate that inhalation of diesel causes acute and chronic health effects. Acute exposure may cause irritation to the eyes, nose, throat, and lungs, as well as neurological effects such as lightheadedness. Acute exposure also may elicit coughs or nausea and exacerbate asthma. These effects may lead to lost workdays for equipment operators, which decreases construction productivity. Characterizing IAQ for equipment operators is an important first step toward mitigating these effects.

This research aligns with three of the five Center for Advancing Research in Transportation, Energy, and Environmental Health (CARTEEH) focus areas:

- **Emissions and energy estimation** by using measurement and modeling HDD equipment emissions resulting from diesel fuel consumption, and by identifying the implications for air pollution and the health of the equipment operator.
- **Exposure assessment and health impacts** by promoting a better understanding of how exposure to diesel emissions and PM affects the health of equipment operators and of how to mitigate these impacts.

- **Data integration** by exploring existing construction equipment activity and emissions datasets, and by developing new methods for collecting IAQ data in order to analyze the relationships between construction equipment emissions and the health of equipment operators.

The main goal of the research was to collect and analyze real-world data from the cabs of active HDD equipment in order to determine the hazard exposure of the operator. The scope of the study included various items of heavy-duty equipment operating on various jobsites. The primary output of the study was a database of real-time information related to pollutant concentrations of CO, CO_2, nitric oxide (NO), nitrogen dioxide (NO_2), black carbon (BC), and $PM_{2.5}$. The primary outcome of the study is a better understanding of in-cab environments for heavy-duty equipment operators, which may lead to the mitigation of a potential health hazard.

The general research methodology was to gather data related to pollutant concentrations from the in-cab environment of HDD equipment over the course of a normal workday. The research team used state-of-the-art air quality instrumentation to collect the air quality data. After collecting the data, the research team computed descriptive statistics in order to characterize the in-cab air quality environment of the equipment.

None of the average values in the tests exceeded CO exposure limits; however, some test results approached these limits. Because CO was present in the cabs for most of the tests, and in some cases had maximum values that exceeded recommended concentrations, CO is a potential health, safety, and productivity hazard for equipment operators. The results of this research revealed that CO_2 concentrations frequently exceeded recommended levels for adequate ventilation but not for human health. Although this is primarily a comfort issue for the equipment operator, it still has the potential to serve as a distraction that may reduce productivity and pose a safety threat.

Based on this research, results indicated that NO has the potential to be a health hazard for equipment operators; however, NO_2 scarcely appeared in the results and likely does not pose as much of a threat as NO.

$PM_{2.5}$ and BC exhibited the greatest potential to be a health threat to equipment operators. Numerous tests yielded results that far exceeded both short-term and long-term exposure limits. Equipment operator exposure to PM largely depends on jobsite conditions; thus, earthmoving activities that stir up large amounts of dust may be especially problematic. This topic requires more research to characterize the problem more accurately and to identify appropriate mitigation strategies.

The results of the research presented here, as well as previous research, prove that in-cab air quality is a topic worth investigating. Work to date has begun to answer questions related to the *who*, *what*, and *where* of equipment cab air quality; however, researchers need to learn more about *how* and *why* pollutants impact air quality for equipment operators. Future research must address the primary factors that contribute to air quality for heavy-duty equipment operators. These factors include tailpipe pollutant emissions, in-cab air quality parameters, equipment duty cycles, diesel engine performance, operator behavior, and jobsite and environmental conditions.

The primary output of the research is the dataset of in-cab air quality data. Data related to air quality in construction equipment cabs are scarce. This dataset is among the first developed in this area. The 24 datasets include minute-by-minute instantaneous measurements of in-cab air quality data for nine different types of heavy-duty equipment while performing real-world construction duty cycles. The measurements include CO, CO_2, NO, NO_2, $PM_{2.5}$, and BC. All of the data are available in easy-to-use spreadsheets. The research team uploaded all datasets to the CARTEEH Data Hub.

A secondary output of the research is a new process for collecting in-cab air quality data for construction equipment. Since this was a first-of-its-kind study, no protocols existed for collecting this type of data. With the appropriate instrumentation, other researchers may replicate the methodology for future studies.

Since this research is still in its fundamental stage, outcomes have not yet affected the regulatory or policy framework of the transportation system; however, there is potential to do so. The results of this research may provide a basis for developing new IAQ standards or regulations for HDD equipment since none currently exists. This research must expand to include all diesel vehicles used in the mining and agriculture industries, as well as on-road HDD vehicles such as trucks and buses.

The impact of this research may potentially shift paradigms concerning IAQ for HDD equipment operators. Since older models of equipment did not have enclosed cabs, a common misconception is that today's operators are protected and safe in an enclosed cab that reduces their exposure to heat, cold, humidity, wind, dust, and diesel exhaust; however, until now, no empirical evidence existed to support that claim. It is possible that enclosed cabs actually create an IAQ problem for equipment operators. This research determined that IAQ pollutants are present in cabs of HDD equipment and helped provide a better understanding of the working conditions for equipment operators. A logical next step is to consider new mitigation plans for the future.

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Introduction

The in-cab environment of heavy-duty diesel (HDD) equipment is a result of the interaction between the machine, jobsite, climate, and other sources. The equipment itself emits diesel exhaust with pollutants including oxides of nitrogen (NO_x), carbon monoxide (CO), carbon dioxide (CO_2), hydrocarbons, and diesel particulate matter (PM). The operator sits in close proximity to the tailpipe that emits these pollutants. Heavy-duty equipment operates on a wide variety of jobsites under a wide variety of conditions. Other air quality sources include exhaust from other vehicles and equipment, significant point or area sources of pollution near the jobsite, and operator activities such as smoking or eating in the cab.

The potential health effects of poor air quality may be both short term and long term for the equipment operator and other employees working nearby. Symptoms may develop shortly after exposure or, possibly, many years later. Short-term effects may occur after the first exposure or may take many repeated exposures during a short period. Typical short-term effects include irritation of the eyes, nose, and throat, as well as dizziness, headaches, and fatigue. Although these symptoms are temporary and are easily treatable, they may interfere with the operator's ability to operate the machine in a safe manner or possibly reduce the operator's productivity. Furthermore, these effects often present themselves as symptoms of cold or flu, so it may be difficult to determine whether they are the result of poor air quality (*1*).

The long-term effects of poor air quality may manifest themselves as respiratory illness, heart disease, or cancer, which may be severely debilitating or fatal. While pollutants found in diesel exhaust are extremely harmful, there is uncertainty regarding the concentrations or periods of exposure necessary to produce specific health problems (*1*). In fact, there are no permissible exposure limits or specific guidance for equipment operators' exposure to diesel exhaust or other harmful pollutants. A better understanding of the in-cab environment of heavy-duty equipment is necessary to provide safer and more productive working conditions for equipment operators.

Background

Carbon Monoxide

CO is a highly toxic gas that may result in death in cases of acute exposure. Less severe health effects include headache, dizziness, fatigue, nausea, and rapid heartbeat. Heavy-duty equipment operators must avoid these symptoms in order to ensure a safe work zone. CO is hard to detect by equipment operators because it is colorless, odorless, and tasteless; thus, operators may begin experiencing symptoms of CO exposure without knowing that they were exposed. Although health-related publications report a wide range of exposure limits, a typical short-term exposure limit for CO is 11 ppm for an eight-hour average concentration (*2*).

Carbon Dioxide

Burning fossil fuels is one of the major sources of CO_2 emissions. Furthermore, CO_2 concentrations in exhaled air from humans is higher than typical ambient conditions (*3*); therefore, there may be elevated concentrations of CO_2 in equipment cabs due to diesel exhaust and operator respiratory activity. CO_2 is a simple asphyxiate and potential inhalation toxicant but is not harmful for chronic exposures (*4*). In the case of acute exposure, corresponding symptoms may include shortness of breath, deep breathing, headache, dizziness, restlessness, increased heart rate and blood pressure, visual distortion, impaired hearing, nausea, vomiting, and loss of consciousness.

CO_2 also serves as a general indicator of air quality. When exposed to high levels of CO_2, humans perceive air quality as unpleasant and unacceptable (*5*). Since measuring all potential pollutants in indoor areas is expensive, time consuming, and often impractical, measuring CO_2 helps determine whether ventilation is adequate. The U.S. Environmental Protection Agency's (EPA's) *Building Air Quality Guide* mentions that CO_2 levels above 1,000 ppm indicate inadequate ventilation (*6*). For construction equipment operators, personal discomfort due to elevated

CO_2 concentrations may serve as a distraction and inhibit the operator's performance, which may lead to safety risks and reduced productivity on the jobsite.

Nitric Oxide

Nitric oxide (NO) is a colorless gas with a distinct smell. It converts readily into nitrogen dioxide (NO_2) in air. Inhalation of NO leads to irritation of the nose, throat, and lungs. Constant high-dose exposure leads to medical emergencies including headache, dizziness, unconsciousness, and even death (*7, 8*). Most regulations related to NO exposure establish permissible long-term exposure limits at 25 ppm averaged over 8–10 hours (*9*).

Nitrogen Dioxide

NO_2, along with NO, is a gas in the group of oxides of nitrogen. Adverse effects from inhalation of NO_2 are airway irritation, recurrent infection, and exacerbation of existing lung diseases such as asthma. A particular environmental hazard linked to NO_2 is reaction with atmospheric oxygen and vapor to form acid rain, which has subsequent deleterious effects on various ecosystems, such as forests and lakes. NO_2 also reacts with volatile compounds in the atmosphere to form ozone. The National Emissions Inventory (*10*) tracks emissions of NO_2. Long-term and short-term exposure limits for NO_2 range from 1 to 5 ppm.

Particulate Matter

Both indoor and outdoor air contains airborne PM, which is mostly comprised of sulfates, nitrates, ammonium, elemental carbon, organic mass, and inorganic material. In terms of size, PM contains coarse and fine particles, where *fine* refers to particles smaller than 2.5 µm in diameter (*11*). EPA evaluated a number of studies on the short-term and long-term exposure health effects of $PM_{2.5}$ and concluded that there is a relationship between short-term exposure to $PM_{2.5}$ and cardiovascular disorders, such as heart disease and congestive heart failure (*12*). Furthermore, a relationship between $PM_{2.5}$ and respiratory infections like chronic obstructive pulmonary disease and asthma likely exists. Mortality due to short-term exposure to $PM_{2.5}$ is often the result of the previously mentioned diseases, whereas mortality for long-term exposures is associated with lung cancer. Equipment operators are susceptible to both short- and long-term effects of $PM_{2.5}$.

Black Carbon

Black carbon (BC) is a major component of PM, both fine and coarse; however, it is more associated with $PM_{2.5}$ due to its smaller molecular size. BC originates from the incomplete combustion of fossil fuels and biomass. Its main characteristic is its ability to absorb light energy with great efficacy. BC absorbs light energy and later emits it as heat, and is a major factor influencing both indoor and outdoor air quality. Approximately 25 percent of BC emissions derive from diesel sources (*13*). Health impacts include cardiovascular effects such as blood pressure and heart rate variability, arrhythmias, and ischemia. Other effects are respiratory infection, distress, and difficulties, as well as depression and anxiety (*14*).

Literature Review

Diesel equipment operators became at-risk health groups during the 1970s. Decoufle et al. (*15*) completed a study that identified high frequencies of lung and intestinal cancer in 2,190 deceased construction workers. Likewise, other studies showed a relationship between diesel exhaust exposure and liver and prostate cancer, and heart disease (*16, 17, 18*). Although these studies recognized the negative human health effects of diesel exhaust over time, they did not focus on the in-cab environment of HDD equipment.

Pronk et al. (*19*) compiled a comprehensive literature review that revealed that from over 10,000 measurements collected to assess occupational exposure to diesel exhaust, none of them specifically related to equipment operators. In 2013, Hansen (*20*) measured CO, NO_2, and PM in 13 different equipment cabs and concluded that none of the measured pollutants served as an indicator to predict other pollutants. Furthermore, Hansen correlated CO and NO_2 in-cab concentrations with the American Conference of Governmental Industrial Hygienists Threshold Limit Values. He found them to be within acceptable limits; however, these limits were not specifically for equipment operators (*20*).

Organiscak et al. (*21*) targeted agricultural and mining activities. The researchers measured dust and diesel particulates in four equipment cabs in two different underground silicosis mines to assess cab filtration system performance. The researchers found that three of four cabs had adequate protection, and the high level of dust in the fourth was due to a damaged filtration system. In another case study, Moyer et al. (*22*) tested cab filtration systems for tractors used in orchards to determine if they protected operators from regularly used pesticides; however, no conclusive result was determined. These studies focused on dust and particulates but did not address gaseous pollutants such as NO_x or CO.

Lewis and Karimi (*23*) conducted a case study on diesel exhaust concentrations of NO_x, CO, CO_2, and PM for five wheel loaders. The researchers concluded that the tailpipe concentrations were many times higher than the exposure limits for these pollutants published by the Occupational Safety and Health Administration (*24*). Although the operator does not breathe exhaust directly from the tailpipe, the operator sits close to the tailpipe, usually for a long time. Furthermore, the researchers referenced a previous school bus study by the California Environmental Protection Agency (*25*) that concluded it is possible for vehicles to self-pollute themselves with diesel exhaust. The case study by Lewis and Karimi helped secure another research project on this topic funded by the Center for Advancing Research in Transportation, Energy, and Environmental Health (CARTEEH), which is the basis for the research presented here (*26*).

In an effort to begin characterizing in-cab air quality, Mosier et al. (*27*) conducted a case study for six pieces of HDD equipment. In this study, researchers measured concentration levels of CO, CO_2, NO_2, and total volatile organic compounds (tVOC) as the equipment idled for 20-minute periods. Although no specific exposure limits for these pollutants exist for construction equipment, the researchers compared measurements to general industrial permissible exposure limits and other screening values. Results revealed that the expected eight-hour time weighted averages for tVOC approached or exceeded some of the published limits. Considering the equipment was idling only and not fully active, the research team decided to collect additional data while the equipment was performing routine work in order to achieve results that are more representative of real-world activity.

The preliminary work by Mosier et al. led to a case study analysis by Lewis et al. (*28*). The objective of this case study was to collect and analyze air quality data from the cabs of HDD equipment while it performed real-world activities. Using state-of-the-art instrumentation, the research team collected data for in-cab temperature and humidity and calculated the in-cab heat index. The team measured concentration levels of CO, CO_2, and $PM_{2.5}$. Results indicated that, in some cases, the heat index exceeded cautionary levels, even in winter months. Concentrations of CO did not exceed published exposure limits but did approach the limits. Concentrations of CO_2 frequently exceeded recommended levels for adequate ventilation in buildings. Concentrations of $PM_{2.5}$ frequently exceeded recommended levels. In general, the case study yielded enough information to conclude that studying air quality in heavy-duty equipment cabs is necessary from a worker health perspective, which served as motivation for the new research presented here.

Significance of the Problem

This research addresses an important problem because the current number of HDD equipment operators will grow by 19 percent (faster than the national average for other occupations) to approximately 500,000 operators in 2022. Those that can operate various types of equipment will have the best career opportunities but may also have the greatest exposure to poor indoor air quality (IAQ); therefore, HDD equipment operators may have a disproportionate risk of poor IAQ compared to other workers.

This research is significant because EPA identifies IAQ as one of the five most urgent risks to public health. Given that equipment operators spend most of their day inside the equipment cab, IAQ is a significant issue. Furthermore, HDD equipment operates in a harsh environment including temperature and humidity extremes and dusty conditions, and in close proximity to a high pollution source—the tailpipe of the equipment. For a typical IAQ scenario inside a building, opening a door or window introduces fresh air that helps dilute pollutants; however, opening the door to the equipment cab may worsen the problem by allowing in even more diesel exhaust and PM. Research must characterize IAQ in HDD equipment cabs to determine the severity of the problem.

This research is also significant because exposure to diesel exhaust is an important human health concern. EPA assessed the possible health hazards associated with its exposure and concluded effects occur from short-term and/or acute exposures, as well as long-term chronic exposures, including repeated occupational exposures. EPA states there is enough evidence to indicate that inhalation of diesel causes acute and chronic health effects. Acute exposure may cause irritation to the eyes, nose, throat, and lungs, as well as neurological effects such as lightheadedness. Acute exposure may also elicit coughs or nausea and may exacerbate asthma. These effects may lead to lost workdays for equipment operators, which decreases construction productivity. Characterizing IAQ for equipment operators is an important first step toward mitigating these effects.

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- **Emissions and energy estimation** by using measurement and modeling of HDD equipment emissions resulting from diesel fuel consumption, and by identifying the implications for air pollution and the health of the equipment operator.
- **Exposure assessment and health impacts** by promoting a better understanding of how exposure to diesel emissions and PM affects the health of equipment operators and of how to mitigate these impacts.
- **Data integration** by exploring existing construction equipment activity and emissions datasets, and by developing new methods for collecting IAQ data in order to analyze the relationships between construction equipment emissions and the health of equipment operators.

Approach

The main goal of the research was to collect and analyze real-world data from cabs of active HDD equipment in order to determine the hazard exposure of the operator. The scope of the study included various pieces of heavy-duty equipment operating on various jobsites. The primary output of the study was a database of real-time information related to pollutant concentrations of CO, CO_2, NO, NO_2, $PM_{2.5}$, and BC. The primary outcome of the study is a better understanding of in-cab environments for heavy-duty equipment operators, which may lead to the mitigation of a potential health hazard.

Methodology

The general research methodology was to gather data related to pollutant concentrations from the in-cab environment of HDD equipment over the course of a normal workday. The research team used state-of-the-art air quality instrumentation to collect the air quality data. After collecting the data, the research team computed descriptive statistics to characterize the in-cab air quality environment of the equipment.

The MX6 iBrid by Industrial Scientific collected data for gaseous pollutants including CO, CO_2, NO, and NO_2. The Thermo Scientific Personal DataRAM (pDR-1000AN) gathered data for $PM_{2.5}$. The AethLabs microAeth AE51 recorded BC data. All of the instruments were tested, calibrated, installed, and maintained according to the manufacturer's specifications. Table 1, Table 2, and Table 3 present the technical specifications for each instrument.

Table 1. Technical Specifications for MX6 iBrid for Gaseous Pollutants

Gas	Sensor Type	Measurement Range	Temperature Range (°C)	Humidity Range (Percent)
CO	Electrochemical	0–1,500 ppm	−20 to 50	15–90
CO_2	Infrared	0–5% volume	−20 to 50	0–95
NO	Electrochemical	0–1,000 ppm	−20 to 50	15–90
NO_2	Electrochemical	0–150 ppm	−20 to 50	15–90

Table 2. Technical Specifications for Personal DataRAM pDR-1000AN for $PM_{2.5}$

Specification	Range
Concentration measurement	0.001 to 400 mg/m^3
Scattered coefficient	1.5×10^{-6} to 0.6 m^{-1}
Accuracy	−5 to +5% of reading
Particle size	0.1 to 10 µm

Table 3. Technical Specifications for microAeth AE51 for BC

Specification	Range
Concentration measurement	0.1 mg/m^3
Precision	±0.1 $\mu g/m^3$ for 1-minute average
Resolution	0.001 $\mu g/m^3$

Although all of the equipment cabs were fully enclosed, the in-cab area of the equipment included both indoor and outdoor air. The research team placed the monitors in the cabs as close as possible to the breathing zone of the operator. The team secured the monitors inside the equipment cab in locations near the operator, such as behind the operator's seat, the rear corner of the cab, or an open side storage compartment. The team placed the monitors in the targeted equipment cab before 7:00 a.m. and removed them after 5:00 p.m. in order to collect data over the entire workday. The monitors collected and logged data in one-minute increments.

The case study equipment included two bulldozers, three excavators, one rolling compactor, one rotary mixer, one agricultural-type tractor, and one wheel loader. The equipment performed various construction and maintenance tasks in various locations in College Station, Texas. Table 4 summarizes the case study equipment. Overall, 24 tests were conducted on these nine pieces of equipment.

Table 4. Summary of Tested Equipment

Equipment Type	Manufacturer	Model	Engine HP	EPA Tier	Tests
Bulldozer 1 (BD 1))	John Deere	700J XLT	115	3	2
Bulldozer 2 (BD 2)	John Deere	700K XLT	125	4	2
Excavator 1 (EX 1)	John Deere	450D	348	3	5
Excavator 2 (EX 2)	Volvo	EC250E	215	4	1
Excavator 3 (EX 3)	John Deere	200D	159	3	4
Rolling compactor (RC 1)	Caterpillar	CP-563C	147	3	1
Rotary mixer (RM 1)	Caterpillar	RM300	260	3	2
Tractor 1 (TR 1)	John Deere	8400	225	4	2
Wheel loader 1 (WL 1)	John Deere	644K	173	2	5

After collecting the pollutant concentration data, the team computed summary statistics including minimum, maximum, and mean values. The summarized pollutant data included CO, CO_2, NO, NO_2, $PM_{2.5}$, and BC. The minimum values for all pollutants were zero, except CO_2; ambient concentrations of CO_2 are approximately 300–500 ppm. The maximum and minimum values helped interpret the results to provide a characterization of the in-cab environment of the equipment.

Results

Table 5 summarizes the maximum and mean concentration values for CO, CO_2, NO, NO_2, $PM_{2.5}$, and BC. Many regulations monitor these pollutants for their ambient concentrations; however, it is important to know if they are present in heavy-duty equipment cabs even if no specific regulations exist for such conditions. Moreover, the presence of these pollutants reduces overall air quality in the cabs and may pose a threat to worker health.

Carbon Monoxide

According to the maximum values in Table 5, the monitors detected CO in the equipment cabs in 19 of 24 tests. The maximum concentrations ranged from 4 to 15 ppm. Even though the mean values (which were approximately eight-hour averages) did not approach the short-term exposure limit of 11 ppm, five tests had maximum concentrations that met or exceeded this level. This implies that it is possible for the CO concentration level to increase to the point that it exceeds the eight-hour average exposure limit.

Carbon Dioxide

Ambient concentrations of CO_2 are approximately 300 ppm; elevated levels of CO_2 higher than 1,000 ppm indicate poor ventilation and lead to human discomfort. Based on Table 5, three of 24 tests had a sustained average CO_2 concentration over 1,000 ppm; however, 11 tests had maximum values that exceeded 1,000 ppm. This implies that ventilation in equipment cabs may be generally unacceptable with regard to air quality.

Nitric Oxide

Diesel exhaust infiltration is the most likely source of NO in equipment cabs. According to Table 5, 15 of 24 tests recorded the presence of NO. The maximum concentrations ranged from 1 to 28 ppm. Although none of the mean values approached the long-term exposure limit of 25 ppm, two tests had maximum values of 28 ppm. This implies, however, that it is possible for equipment cabs to achieve sustained levels of NO that could exceed long-term exposure limits.

Table 5. Summary of Maximum and Mean Values for Pollutant Concentrations

Item	CO (ppm)		CO_2 (ppm)		NO (ppm)		NO_2 (ppm)		$PM_{2.5}$ (mg/m^3)		BC (mg/m^3)	
	Max.	Mean	Max.	Mean	Max.	Mean	Max.	Mean	Max.	Mean	Max.	Mean
BD1	0	0.0	600	315	0	0	0	0	0.95	0.04	0.05	0.002
BD1	0	0.0	900	390	1	0.0	0.2	0.001	1.6	0.06	0.24	0.007
BD2	13	3.5	1,400	557	28	10	0	0	0.38	0.04	0.00	0.000
BD2	15	6.2	600	322	17	6.3	0	0	0.19	0.04	0.10	0.004
EX1	11	0.5	1,000	497	4	0.1	0	0	NA	NA	0.02	0.004
EX1	4	0.7	0	0	1	0.0	0	0	NA	NA	0.01	0.002
EX1	8	0.2	3,200	1,336	0	0	0	0	0.91	0.03	0.07	0.001
EX1	4	0.1	2,400	1,283	0	0	0	0	0.04	0.00	0.00	0.001
EX1	0	0.0	4,600	1,656	0	0	0.3	0.001	0.09	0.01	0.03	0.001
EX2	4	1.7	1,400	432	1	0.0	0.3	0.001	0.42	0.02	0.00	0.000
EX3	8	2.3	1,600	657	11	3.3	0	0	1.6	0.14	0.31	0.002
EX3	6	3.4	900	302	7	3.2	0	0	1.4	0.21	0.06	0.033
EX3	5	2.0	800	304	7	2.8	0	0	1.3	0.19	0.00	0.000
EX3	13	3.5	1,400	557	28	10	0	0	0.38	0.04	0.00	0.001
RC1	4	0.5	500	300	0	0	0	0	0.30	0.11	0.02	0.001
RM1	7	3.9	400	300	2	0.3	0	0	7.0	2.7	1.86	0.016
RM1	6	1.8	500	300	3	0.3	0	0	18	0.20	0.07	0.002
TR1	11	2.1	1,500	372	13	2.3	0	0	NA	NA	0.00	0.000
TR1	8	2.7	500	407	11	3.4	0	0	0.37	0.03	0.05	0.003
WL1	5	3.6	1,500	672	0	0	0.4	0.238	0.29	0.03	0.01	0.001
WL1	0	0.0	0	0	0	0	0	0	NA	NA	NA	NA
WL1	10	0.3	1,900	551	0	0	0	0	2.7	0.04	0.36	0.002
WL1	5	2.1	800	527	1	0.0	0	0	2.5	0.06	0.01	0.001
WL1	0	0.0	800	619	0	0	0.2	0.001	0.24	0.03	0.00	0.001

NA = Data not available

Nitrogen Dioxide

Similar to NO, the most likely source of NO_2 concentrations in equipment cabs is diesel exhaust from the tailpipe; however, only five of 24 tests detected any level of NO_2. Maximum values for NO_2 ranged from 0.2 to 0.4 ppm, which were well below the published long-term and short-term exposure limits of 1–5 ppm. Furthermore, approximately 80 percent of the tests did not detect any level of NO_2 at all in the equipment cabs.

Particulate Matter

A typical short-term exposure range for $PM_{2.5}$ is 0.1 mg/m^3 for a one-hour concentration. A typical long-term exposure range is 0.04 mg/m^3 for an eight-hour average (*29*). According to Table 5, 13 of 19 tests that successfully acquired data had sustained mean values over the eight-hour period greater than the acceptable long-term exposure range. All but two of the tests had maximum values that were greater than the acceptable short-term exposure range, with values up to 17 mg/m^3. Although it is not possible to distinguish diesel exhaust particulates from dust or other particles, these results indicate that $PM_{2.5}$ has the potential to have both short-term and long-term health effects for equipment operators.

Black Carbon

As a constituent of $PM_{2.5}$, BC concentrations are lower than those of $PM_{2.5}$. Even though there are no published exposure limits for BC, what was significant here was that five tests had maximum values that equaled or exceeded the 0.1 mg/m^3 short-term exposure limit. Likewise, 10 tests had maximum values that equaled or exceeded the

0.04 mg/m^3 long-term exposure limit. Accordingly, BC has high potential to be a health hazard for diesel equipment operators.

Conclusions and Recommendations

In high concentrations, CO is a toxic gas and may even be fatal. In lower concentrations, symptoms of CO exposure include dizziness, fatigue, and decreased manual dexterity—all of which may impair the operator's ability to control the equipment. Because CO is colorless, odorless, and tasteless, operators may not even be aware of their exposure. None of the average values in the tests exceeded CO exposure limits; however, some test results approached these limits. Because CO was present in the cabs for most of the tests, and in some cases had maximum values that exceeded recommended concentrations, CO is a potential health, safety, and productivity hazard for equipment operators.

Although CO_2 is widely known as a greenhouse gas, the scientific community often overlooks it from an air quality and health standpoint. From a human health perspective, CO_2 may be fatal in extremely high concentrations although it is extremely rare for that to occur. From an air quality perspective, CO_2 is a general indicator of ventilation conditions. The results of this research revealed that CO_2 concentrations frequently exceeded recommended levels for adequate ventilation but not for human health. Although this is primarily a comfort issue for the equipment operator, it still has the potential to serve as a distraction that may reduce productivity and pose a safety threat.

Nitrogen oxides, including NO and NO_2, are major components of diesel exhaust. Many regulations exist to limit tailpipe emissions of these pollutants; however, the heavy-duty equipment community knows little about their impact on air quality, especially in equipment cabs. Based on this research, results indicated that NO has potential to be a health hazard for equipment operators; however, NO_2 scarcely appeared in the results and likely does not pose as much of a threat as NO.

$PM_{2.5}$ and BC exhibited the greatest potential to be a health threat to equipment operators. Numerous tests yielded results that far exceeded both short-term and long-term exposure limits. Equipment operator exposure to PM largely depends on jobsite conditions; thus, earthmoving activities that stir up large amounts of dust may be especially problematic. This topic requires more research to characterize the problem more accurately and to identify appropriate mitigation strategies.

The results of the research presented here, as well as previous research, prove that in-cab air quality is a topic worth investigating. Work to date has begun to answer questions related to the *who*, *what*, and *where* of equipment cab air quality; however, researchers need to learn more about *how* and *why* pollutants impact air quality for equipment operators. Future research must address the primary factors that contribute to air quality for heavy-duty equipment operators. These factors include tailpipe pollutant emissions, in-cab air quality parameters, equipment duty cycles, diesel engine performance, operator behavior, and jobsite and environmental conditions.

Researchers must examine the duty cycles of the equipment, such as idling and non-idling, to determine if equipment activity affects pollutant emissions and ultimately in-cab air quality. Likewise, diesel engine performance variables, such as engine load percentage, revolutions per minute, and manifold absolute pressure, may affect pollutant emissions. Investigators must evaluate if operator behavior, such as smoking in the equipment cab, opening the door to the cab, and using the air conditioner or heater in the cab, contributes to in-cab air quality. Jobsite and environmental conditions, including temperature, humidity, and wind speed, may contribute significantly to in-cab air quality. Researchers should synchronize these datasets and identify the relationships among the many variables, as well as identify patterns, trends, and correlations. The main purpose of future research is to identify controllable factors in order to reduce the equipment operator's exposure to harmful conditions and improve worker health.

Outputs, Outcomes, and Impacts

The primary ***output*** of the research is the dataset of in-cab air quality data. Data related to air quality in construction equipment cabs are scarce. This dataset is among the first developed in this area. The 24 datasets include minute-by-minute instantaneous measurements of in-cab air quality data for nine different types of heavy-duty equipment while performing real-world construction duty cycles. The measurements include CO, CO_2, NO, NO_2, $PM_{2.5}$, and BC. All of the data are available in easy-to-use spreadsheets. The research team uploaded all datasets to the CARTEEH Data Hub.

A secondary output of the research is a new process for collecting in-cab air quality data for construction equipment. Since this was a first-of-its-kind study, no protocols existed for collecting this type of data. With the appropriate instrumentation, other researchers may replicate the methodology for future studies.

Since this research is still in its fundamental stage, ***outcomes*** have not yet affected the regulatory or policy framework of the transportation system; however, there is potential to do so. The results of this research may provide a basis for developing new IAQ standards or regulations for HDD equipment since none currently exist. This research must expand to include all diesel vehicles used in the mining and agriculture industries, as well as on-road HDD vehicles such as trucks and buses.

The ***impact*** of this research may potentially shift paradigms concerning IAQ for HDD equipment operators. Since older models of equipment did not have enclosed cabs, a common misconception is that today's operators are protected and safe in an enclosed cab that reduces their exposure to heat, cold, humidity, wind, dust, and diesel exhaust; however, until now, no empirical evidence existed to support that claim. It is possible that enclosed cabs actually create an IAQ problem for equipment operators. This research determined that IAQ pollutants are present in cabs of HDD equipment. A logical next step is to consider new mitigation plans for the future. This research helped provide a better understanding of the working conditions for equipment operators.

Research Outputs, Outcomes, and Impacts

As of November 2019, the following research outputs have been developed:

- Lewis, P., and El Khouly, S., *Evaluation of Air Pollutants in Nonroad Diesel Construction Equipment Cabs*, 2020 Construction Research Congress, American Society of Civil Engineers, Tempe, AZ, 2020 (conference paper).
- Lewis, P., and El Khouly, S., *Evaluation of Air Pollutants in Nonroad Diesel Construction Equipment Cabs,* 2020 Construction Research Congress, American Society of Civil Engineers, Tempe, AZ, 2020 (conference presentation).
- Lewis, P., and El Khouly, S., *Assessment of Near-Cab Air Quality for Nonroad Diesel Equipment*, 99th Annual Meeting of the Transportation Research Board, Washington, DC, 2020 (conference paper).
- Lewis, P., and El Khouly, S., *Assessment of Near-Cab Air Quality for Nonroad Diesel Equipment*, 99th Annual Meeting of the Transportation Research Board, Washington, DC, 2020 (conference presentation).
- Lewis, P., *Assessing In-Cab/Near-Cab Air Quality for Heavy Duty Diesel Equipment,* 29th CRC Real World Emissions Workshop, Long Beach, CA, 2019 (poster presentation).
- El Khouly, S., *Assessing In-Cab/Near-Cab Air Quality for Heavy Duty Diesel Equipment,* CARTEEH Transportation, Air Quality, and Health Symposium, Austin, TX, 2019 (poster presentation).
- Lewis, P., *Assessing In-Cab Air Quality for Construction Equipment,* CARTEEH Transportation, Air Quality, and Health Symposium, Austin, TX, 2019 (invited presentation).

- El Khouly, S., *Characterizing Near-Cab Air Quality In Construction Equipment,* Texas A&M University, 2020 (final thesis).

The research team expects to produce additional research outputs based on this research.

Technology Transfer Outputs, Outcomes, and Impacts

The primary technology transfer ***output*** is 24 datasets available in spreadsheet format. Each dataset includes minute-by-minute real-time measurements of CO, CO_2, NO, NO_2, $PM_{2.5}$, and BC inside HDD equipment cabs. All 24 datasets are available on the CARTEEH Data Hub.

Another technology transfer output is strategic partnerships with organizations that are capable of informing decision-making. These organizations include the EPA Office of Transportation Air Quality, American Association of State Highway and Transportation Officials, Transportation Research Board Standing Committee on Maintenance Equipment (AHD 60), American Society of Civil Engineers Construction Research Congress, and Coordinating Research Council. All of these organizations have expressed an interest in this research and have the potential to influence public fleet owners including state departments of transportation and municipalities.

Education and Workforce Development Outputs, Outcomes, and Impacts

Students involved in this project included Mr. Sherif El Khouly and Mr. Adam Mayer, both of whom are master of science in construction management students in the Department of Construction Science at Texas A&M University. This research served as the basis for Mr. El Khouly's thesis. Based on his outstanding work on the project, Mr. El Khouly received the Outstanding Graduate Student–Research Award from the Department of Construction Science. Mr. El Khouly successfully defended his thesis and graduated in spring 2019.

This project also provided important preliminary data and knowledge for Mr. Mayer's thesis proposal. Mr. Mayer will be collecting additional data and identifying the relationships between in-cab air quality and operator, equipment, and environmental factors. That work has received additional funding from CARTEEH; however, data collection was delayed due to the COVID-19 pandemic but it has resumed. Mr. Mayer plans to defend his thesis and graduate in spring 2021.

The data collected through this research have excellent potential to add educational value to the Department of Construction Science. For example, the project may serve as a case study for teaching research methods in the COSC 690 Theory of Research course. The datasets are available to students in COSC 693 Professional Study as a case study on data collection and analysis for non-thesis students. Ultimately, a COSC 689 Special Topics course on the environmental impacts of heavy-duty equipment used in construction is possible.

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