EPiC Series in Built Environment
Volume 1, 2020, Pages 499–507
Associated Schools of Construction Proceedings of the 56th Annual International Conference

Case Study of In-Cab Pollutants for Nonroad Construction Equipment

Phil Lewis, Ph.D.
Texas A&M University
College Station, TX

Rachel Mosier, Ph.D. and Yongwei Shan, Ph.D.
Oklahoma State University
Stillwater, OK

Like buildings, nonroad construction equipment with enclosed cabs have doors and windows, and heating, ventilating, and air conditioning systems; thus, these machines have their own indoor air quality (IAQ) environment. Understanding the role of thermal comfort and air pollutants can help equipment operators manage in-cab environments to reduce health concerns and increase productivity. The objective of this case study was to collect and analyze IAQ data from the cabs of nonroad equipment as it performed real-world activities. Using state-of-the-art IAQ instrumentation, data were collected for in-cab pollutant concentration levels including carbon monoxide, carbon dioxide, and respirable particulate matter. Concentrations of carbon monoxide did not exceed published exposure limits for IAQ, but they did approach the published limits. Concentrations of CO_2 frequently exceeded IAQ recommended levels for adequate ventilation. Concentrations of respirable particulate matter frequently exceeded IAQ recommended levels. The case study yielded enough information to conclude that studying IAQ in nonroad equipment cabs is necessary to improve human health, safety, and productivity for equipment operators.

Key Words: Indoor air quality, equipment, carbon monoxide, carbon dioxide, particulate matter

Introduction

The United States Environmental Protection Agency (EPA) defines Indoor Air Quality (IAQ) as "air quality within and around buildings and structures, especially as it relates to the health and comfort of building occupants" (USEPA, 2019). Like buildings, nonroad construction equipment with enclosed cabs have doors and windows, as well as heating, ventilating, and air conditioning systems; thus, these machines have their own IAQ environment. Understanding the role of air pollutants can help equipment operators manage in-cab environments to reduce health concerns.

The in-cab environment of heavy equipment is a result of the interaction between the machine, jobsite, climate, and other sources. The machine itself emits high quantities of diesel exhaust

T. Leathem (ed.), ASC 2020 (EPiC Series in Built Environment, vol. 1), pp. 499–507

pollutants including oxides of nitrogen (NO_x), carbon monoxide (CO), carbon dioxide (CO_2), hydrocarbons (HC), and diesel particulate matter (PM). The operator sits within a few feet of the tailpipe that emits these pollutants. Heavy equipment performs on a wide variety of jobsites, oftentimes in dry, dusty conditions that generate large amounts of respirable particulates ($PM_{2.5}$). Other IAQ sources include exhaust from other vehicles and equipment on or near the jobsite, significant pollution point sources near the jobsite, and operator activity such as smoking or opening and closing the doors and windows of the cab.

Potential health effects of poor IAQ may be both short-term and long-term for the equipment operator; they may be experienced shortly after exposure or, possibly, many years later. Short-term effects may show up after a single exposure or many repeated exposures during a short timeframe. 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 and they may also reduce the operator's productivity. Furthermore, these effects often present themselves as symptoms of a cold or other viral infection, so it is often difficult to determine whether they are the result of poor IAQ (USEPA, 2019).

Long-term effects of poor IAQ may manifest themselves as respiratory illness, heart disease, or cancer. These effects may be severely debilitating or fatal. While it is known that pollutants found in diesel exhaust are extremely harmful, there is considerable uncertainty regarding the concentrations or periods of exposure necessary to produce specific health problems (USEPA, 2019). In fact, there are no permissible exposure limits or specific guidance for equipment operator's exposure to diesel exhaust or other harmful pollutants. Research is needed to better understand the in-cab environment of nonroad equipment to provide safer working conditions for the operator.

The objective of this case study was to collect and analyze real-world data from inside the cabs of nonroad equipment as it performed typical duty cycles on a jobsite. The scope of the case study was limited to a few items of equipment that were operating on a single jobsite. The primary output of the case study is a database of real-time information related to pollutant concentrations of CO, CO_2, and $PM_{2.5}$. The primary outcome is a better understanding of in-cab environments for nonroad equipment operators which helps focus the direction of future research in this area.

Literature Review

Although diesel construction equipment has been in use for over a century, equipment operators were not identified as at-risk health groups until the 1970s. Decoufle et al. (1977) performed a study that revealed an unusually high frequency of lung cancer and intestinal cancer in 2,190 deceased construction workers. As seen in other studies, there was a link between diesel exhaust exposure and liver cancer, prostate cancer, and heart disease (Seidler et al, 1998; Finkelstein et al, 2004). These studies highlighted the adverse human health impacts of diesel exhaust over time, but they did not specifically address the in-cab environment of heavy-duty diesel equipment.

Lewis and Karimi (2018) conducted a case study on tailpipe diesel exhaust concentrations of NO_x, CO, CO_2, and PM for five wheeled loaders. They observed that the tailpipe concentrations were many times higher than the exposure limits for these pollutants published by the Occupational Safety and Health Administration (OSHA) (USDOL, 2019). Although the operator does not breathe exhaust directly from the tailpipe, the operator does sit near the tailpipe, oftentimes for long durations.

Furthermore, they referenced a previous school bus study by the California Environmental Protection Agency that concluded it is possible for vehicles to self-pollute themselves with diesel exhaust (CEPA, 2003). The case study by Lewis and Karimi yielded another research project on this topic funded by the Center for Advancing Research in Transportation, Energy, and Environmental Health.

To begin characterizing IAQ in heavy equipment cabs, Mosier et al (2017) conducted a case study for six items of heavy-duty diesel equipment. In this case study, concentration levels of CO, CO_2, NO_2, and total volatile organic compounds (tVOC) were measured as the equipment idled for 20-minute periods. Although no specific exposure limits for these pollutants exist for construction equipment, the measurements were compared to general industrial permissible exposure limits and other screening values. Results revealed that the expected 8-hour time weighted averages for tVOC approached or exceeded some of the published limits. Considering that the case study equipment was idling only, and not fully active, the research team concluded that additional data were needed while the equipment was performing routine work to achieve more representative results. That case study served as motivation for the case study presented here.

Methodology

The basic approach to the case study was to gather data related to thermal comfort and pollutant concentrations inside nonroad equipment cabs over the course of a normal workday. This was accomplished using state-of-the-art IAQ instrumentation. After the data were collected, descriptive statistics were computed to characterize the in-cab environment of the equipment. When possible, the results were compared to permissible exposure limits, threshold values, and screening limits found in published literature, although there are no specific limits or values for equipment operators.

The EVM-7 Advanced Particulate and Air Quality Monitor manufactured by 3M Solutions, as shown in Figure 1, was used for in-cab air sampling (3M, 2019). The EVM-7 measured pollutant concentrations of CO, CO_2, and $PM_{2.5}$. With all dimensions less than 20 centimeters and weighing less than 1.5 kilograms, the unit was compact and light enough to be easily placed and secured inside the cabs of the equipment without interfering with the operator's activity. Battery life of the monitors was at least eight hours in running mode; however, throughout the data collection process, up to 12 hours of battery life was possible without another power source, making it possible to measure pollutants for a complete eight-hour workday.

Figure 1. EVM-7 advanced particulate and air quality monitor

The EVM-7 sensor had specific calibration requirements. The particulate sampling filter was calibrated using a factory provided zero-calibration filter. The pump flow rate was calibrated by a standard flowmeter calibrator. The flow rate was adjusted to 1.67 liters per minute per the manufacturer. For CO and CO_2, two limits were needed for calibration: zero (minimum) and span (maximum). For setting the zero limit, a nitrogen (N_2) calibration gas cylinder, which contained zero parts per million (ppm) of CO and CO_2, was used. For identifying the maximum limit, a CO sensor calibrated by a 100 ppm CO gas cylinder and a CO_2 sensor calibrated by a 100 ppm CO_2 gas cylinder were used. During the data collection process, each sensor was calibrated on a regular basis as prescribed by the manufacturer. Table 1 shows the standards regarding the accuracy, precision, and display range for the EVM-7 (3M, 2019).

Table 1

Display range, precision, and accuracy of EVM-7

Pollutant	Display Range	Precision	Accuracy
CO_2	0 to 5,000 ppm	1 ppm	±100 ppm
CO	0 to 1,000 ppm	1 ppm	±5%
$PM_{2.5}$	0 to 200 mg/m^3	0.001 mg/m^3	±15%

To gain the most accurate data, the monitor was placed as close as possible to the breathing zone of the operator (near the nose and mouth). For the purposes of the case study, the entire in-cab area of the equipment was considered the representative operator personal exposure area. The monitor was secured 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 monitor was never concealed in a manner such that it did not have access to the breathing zone of the operator. The typical equipment operator workday started at 7:30 am and ended at 4:30 pm, with a lunch break from 11:30 am to 12:30 pm. The monitor was placed in the targeted equipment cab between 7:00 am and 7:30 am and removed after 5:00 pm to collect data over the entire workday. Data were collected and logged in 30 second increments over the course of the workday.

A residential development project, including a retirement center and future home lots, was identified in Stillwater, Oklahoma and selected to be the case study jobsite. The project included earthwork, roadwork, and building construction. Nonroad construction equipment was used for mass excavation, rough grading, and fine grading. The case study jobsite had a variety of equipment types and it was near the research team's laboratory, which facilitated the data collection process. Furthermore, the research team was granted unlimited access to the site and the equipment to collect data. The case study equipment included one backhoe loader, four excavators, two scrapers, one rough terrain crane, and two wheeled loaders. Table 2 presents a summary of the case study equipment. Overall, 15 tests were conducted on these 10 items of equipment.

After the data were collected, summary statistics were calculated including minimum, maximum, and mean values. The data parameters that were summarized included temperature, relative humidity, Heat Index, CO, CO_2, and $PM_{2.5}$. The summary statistics were used to interpret the results and provide an overall characterization of the in-cab environment of the tested equipment.

Table 2

Summary of tested equipment

Equipment Type	Model	Manufacturer	Model Year	Engine HP	EPA Tier
Backhoe Loader (BHL)	420F	Caterpillar	2010	100	3
Excavator 1 (EXC 1)	EC360CL	Volvo	2001	198	1
Excavator 2 (EXC 2)	PC400LC-8	Komatsu	2008	362	3
Excavator 3 (EXC 3)	PC220LC-8	Komatsu	2010	179	3
Excavator 4 (EXC 4)	FF135DX	John Deere	2011	93	3
Rough Terrain Crane (RTC)	RT60	Zoomlion	2013	215	4
Scraper 1 (SCR 1)	621	Caterpillar	1986	330	0
Scraper 2 (SCR 2)	621B	Caterpillar	1986	330	0
Wheel Loader 1 (WLL 1)	WA250PT-5	Komatsu	2007	139	3
Wheel Loader 2 (WLL 2)	WA250PT-5L	Komatsu	2005	135	2

Results and Discussion

Table 3 summarizes the minimum, maximum, and mean concentration values for CO, CO_2, and $PM_{2.5}$. Although these pollutants rarely reach sustained levels that pose a severe human health threat in ambient conditions, it is important to know whether they are even present in equipment cabs to determine their potential of a health threat to the operator. Moreover, the presence of CO, CO_2, and $PM_{2.5}$ reduces overall IAQ in equipment cabs.

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. These are all symptoms that need to be avoided by heavy equipment operators. CO is hard to detect by equipment operators because it is colorless, odorless, and tasteless; thus, operators may begin experiencing symptoms before they are aware that they are exposed to CO. Although a wide range of exposure limits may be found in health-related publications, a typical short-term exposure limit for CO is 11 ppm for an eight-hour average concentration (Health Canada, 1989).

As shown by the minimum values of zero in Table 3, CO is typically not found in ambient air. For it to be present in equipment cabs, it must be produced by some activity such as the combustion of diesel fuel or smoking by the operator. Based on the maximum values in Table 3, CO was detected in all tests except Backhoe Loader 1 and Excavator 1. Even though the mean values (which were approximately eight-hour averages) did not approach the short-term exposure limit of 11 ppm, two tests (Excavator 2 and Scraper 3) had maximum concentrations of 6 ppm. This implies that it may be possible for CO concentration levels to increase to the point that the eight-hour average exposure limit may be exceeded.

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 (Willem et al, 2006); 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 it is not considered harmful for chronic exposures (CCOHS, 2019). In 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. These symptoms need to be avoided by equipment operators.

Table 3

Summary of air pollutant data

		CO (ppm)			CO_2 (ppm)			$PM_{2.5}$ (mg/m^3)		
Test Date	Equip.	Min	Mean	Max	Min	Mean	Max	Min	Mean	Max
11/29/16	SCR 1	0	0.1	1	305	490	1191	0.00	0.08	1.04
11/29/16	SCR 2	0	0.0	1	312	431	1845	0.00	0.06	5.58
11/30/16	BHL 1	0	0.0	0	320	497	1108	0.00	0.07	3.14
11/30/16	EXC 1	0	0.0	0	321	528	1134	0.00	0.01	0.11
12/01/16	EXC 2	0	0.8	6	325	359	551	0.00	0.02	0.50
12/01/16	WLL 1	0	0.0	2	327	609	1971	0.00	0.02	0.73
12/02/16	EXC 3	0	0.0	1	332	379	543	0.00	0.04	1.08
12/02/16	WLL 2	0	1.4	4	327	763	1423	0.00	0.01	0.20
12/13/16	EXC 4	0	0.1	1	340	434	1118	0.00	0.02	0.92
12/13/16	RTC 1	0	0.1	1	331	1016	1676	0.00	0.01	0.17
12/28/16	BHL 2	0	0.2	3	312	428	1565	0.00	0.01	0.65
12/30/16	SCR 3	0	0.0	6	312	424	716	0.00	0.26	6.43
03/09/17	BHL 3	0	0.6	2	172	215	300	0.01	0.05	3.18
03/09/17	SCR 4	0	0.0	1	269	345	1115	0.01	0.06	1.13

CO_2 also serves as a general indicator of IAQ. When humans are exposed to high levels of CO_2, they perceive air quality as unpleasant and unacceptable (Martoft et al, 2016). 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 EPA Building Air Quality Guide mentions that CO_2 levels above 1,000 ppm indicate inadequate ventilation (USEPA, 1991). 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.

Unlike CO, CO_2 is found in ambient air, typically in concentrations of approximately 300 ppm. This fact is verified by the minimum values in Table 3, except for Backhoe Loader 3 and Scraper 4 which had minimum values below 300 ppm. Only one test, Rough Terrain Crane 1, sustained an average CO_2 concentration over 1000 ppm, which indicates inadequate ventilation; however, 11 of 15 tests had maximum values that exceeded 1000 ppm. This implies that ventilation in equipment cabs may be generally unacceptable in terms of IAQ.

Airborne particulate matter (PM) is found in both indoor and outdoor air. It is mostly comprised of sulfates, nitrates, ammonium, elemental carbon, organic mass, and inorganic material. In terms of size, PM is commonly characterized as coarse and fine particles, where fine refers to particles smaller than 2.5 μm in diameter. EPA evaluated several studies on 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 (USEPA, 2009). Furthermore, a relationship between $PM_{2.5}$ and respiratory infections like Chronic Obstructive Pulmonary Disease (COPD) 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 the short-term effects of $PM_{2.5}$ and they are potentially susceptible to the long-term effects.

Regarding IAQ, an acceptable short-term exposure range for $PM_{2.5}$ is 0.1 mg/m^3 for a one-hour concentration. An acceptable long-term exposure range is 0.04 mg/m^3 (Health Canada, 1989). According to Table 3, seven of the 15 tests had sustained mean values (eight-hour average) greater than the acceptable long-term exposure range. All the tests had maximum values that were greater than the acceptable short-term exposure range, with values up to 6 mg/m^3. Note that zero values do not necessarily mean that no $PM_{2.5}$ was detected but that the value was lower than 0.005 mg/m^3. These results indicate that $PM_{2.5}$ has potential to have both short-term and long-term health effects for equipment operators.

Conclusions

CO is a highly toxic and potentially fatal gas. In lower levels, CO exposure may result in dizziness, fatigue, and loss of manual dexterity – all of which have the potential to impair the equipment operator's performance. Because CO is colorless, odorless, and tasteless, it is difficult for equipment operators to know when they are exposed to it. Although the results of this case study did not reveal any instances of recommended CO exposure limits being exceeded, there were cases in which these limits were approached. Due to the potential health, safety, and productivity consequences of CO exposure for equipment operators, additional research in this area is warranted.

CO_2 is commonly thought of as a greenhouse gas that impacts the atmosphere and climate, with little attention given to it as factor in IAQ. From a human health perspective, CO_2 may be fatal in extremely high concentrations, although that rarely occurs. From an IAQ perspective, CO_2 is a general indicator of whether adequate ventilation is present, which impacts comfort levels. The results of this case study revealed that recommended exposure limits of CO_2 were frequently exceeded. Although this is primarily a comfort issue for the equipment operator, it still has the potential to serve as a distraction which may reduce productivity and pose a safety threat.

Based on this case study, $PM_{2.5}$ exhibited the greatest potential to be a health threat to equipment operators. Although there are a wide range of published exposure limits for particulate matter based on specific conditions, one set of these standards aimed at IAQ were frequently exceeded for both short-term and long-term exposure. Equipment operator exposure to particulate matter is largely based on jobsite conditions; thus, earthmoving activities that stir up large quantities of dust may be especially concerning. More research is needed on this topic.

Limitations and Recommendations

The primary limitation for this case study was the sample size of heavy equipment that was tested. There were only 15 tests in total, so additional tests must be conducted to improve the statistical power of the analysis. Furthermore, only five types of equipment were tested, and in some cases, only one item of that type was tested. Including different types of equipment in future studies will help characterize IAQ in heavy equipment and provide a better understanding of potential health hazards for equipment operators.

The case study did not consider specific activities performed by the equipment during the testing period. The IAQ instrumentation was placed in the equipment cab at the beginning of the workday and then removed at the end of the workday. Although the research team was assured that the equipment was used during the testing period, there were no data collected for the hours of use or the type of activity performed. Future research should include efforts to monitor the duration and type of activities performed by the equipment. Also, operator activities that may affect IAQ, such as smoking and opening doors and windows, should be monitored to enhance interpretation of the results.

Another limitation is that the equipment selection process did not consider equipment metadata, such as manufacturer, model type, model year, and engine size. All these factors have the potential to affect tailpipe pollutant emissions, which in turn have the potential to affect IAQ in the equipment cab. Furthermore, different fuel types, such as biofuels, must be evaluated since different fuel types have different emissions rates. Maintenance history of the equipment should also be considered. According to previous research, there may be a relationship between equipment maintenance and the presence of diesel pollutants inside the cab (Mosier et al, 2017). The results from that research showed that the oldest maintained item of equipment tested, although it had the most stringent EPA engine tier standard, experienced the worst IAQ. For the case study presented here, maintenance records were not available for the equipment that was tested. Reviewing maintenance records of the tested equipment (when available) will provide additional insight regarding IAQ in equipment cabs.

Although this study was limited in scope, the results provided compelling evidence for continuing this work for the benefit of worker health. To that end, the research team acquired additional funding to continue the investigation to test more items of equipment and to refine the study design. This future research will be funded by a grant from the Center for Advancing Research in Transportation Emissions, Energy, and Health. The new data will be combined with the existing data collected in this study to provide a robust dataset of real-world information that can be used to thoroughly assess IAQ in heavy equipment.

References

3M Personal Safety Division (2018). “Simultaneous Particulate and Gas Concentration Measurement User Manual.” https://multimedia.3m.com/mws/media/778991O/evm-7-environmental-monitor-series-user-manual.pdf, Information viewed on August 1, 2018.

California Environmental Protection Agency. (2003). Fact sheet: children’s school bus exposure study. Air Resources Board, Sacramento, CA.

Canadian Centre for Occupational Health and Safety (2019) “Carbon Monoxide: OSH Answers.” http://www.ccohs.ca/oshanswers/chemicals/chem_profiles/carbon_monoxide.html. Information viewed on August 1, 2019.

Decoufle, P., Lloyd, J. W., & Salvin, L. G., (1977). "Causes of death among construction machinery operators." Journal of Occupational and Environmental Medicine, 19(2), 123–128.

Finkelstein, M. M., Verma, D. K., Sahai, D., & Stefov, E. (2004). "Ischemic heart disease mortality among heavy equipment operators." American Journal of Industrial Medicine, 46(1), 16–22.

Health Canada: Health Protection Branch. (1989). “Exposure guidelines for residential indoor air quality.” Ottawa, Ontario.

Lewis, P. and Karimi, B., (2018). “Preliminary investigation of diesel exhaust and indoor air quality in heavy equipment cabs,” ASC 54th Annual International Conference, Associated Schools of Construction, Minneapolis, MN.

Martoft, L., Stødkilde-Jørgensen, H., Forslid, A., Pedersen, H. D., & Jørgensen, P. F. (2016). “CO_2 induced acute respiratory acidosis and brain tissue intracellular pH: a 31P NMR study in swine,” Laboratory Animals, 37(3), 241–248.

Mosier, R. D., Reyes, M. D., Aghaeipoor, M., & Lewis, P. (2017). “Indoor air quality in construction equipment cabs.” 96th Annual Meeting of the Transportation Research Board, Washington D.C.

Occupational Safety and Health Administration (2017). “Control of Silica Dust in Construction, Heavy Equipment and Utility Vehicles Used for Grading and Excavating Tasks.” www.osha.gov/Publications/OSHA3937.pdf. Information viewed August 1, 2019.

Seidler, A., Heiskel, H., Bickeböller, R., & Elsner, G. (1998). "Association between diesel exposure at work and prostate cancer." Scandinavian Journal of Work, Environment & Health, 24(6), 486–494.

United States Department of Labor (2019). “OSHA Occupational Chemical Database,” https://www.osha.gov/chemicaldata/, Information viewed on August 1, 2019.

United States Environmental Protection Agency (1991). “Building Air Quality: A Guide for Building Owners and Facility Managers.” Washington, D.C.

United States Environmental Protection Agency (2009). “2009 Final Report: Integrated Science Assessment for Particulate Matter.” Washington, D.C.

United States Environmental Protection Agency (2019). “Introduction to Indoor Air Quality” https://www.epa.gov/indoor-air-quality-iaq/introduction-indoor-air-quality, Information viewed on August 1, 2019.

Willem, H. C., Tham, K. W., Wargocki, P., Wyon, D. P., & Fanger, P. O. (2006). “Effects of outdoor air supply rates on subjective factors in three call centers in the Tropics: a principal component analysis approach.” Proc., Healthy Buildings.