REAL WORLD DATA MEASUREMENT OF FACTORS AFFECTING AIR QUALITY FOR NONROAD DIESEL EQUIPMENT OPERATORS

December 2023

Center for Advancing Research in
Transportation Emissions, Energy, and Health
A USDOT University Transportation Center

Texas A&M Transportation Institute
Georgia Tech College of Engineering
Johns Hopkins Bloomberg School of Public Health
College of Engineering, The University of Texas at El Paso
UC Riverside CE-CERT

Disclaimer

The contents of this report reflect the views of the authors, who are responsible for the facts and the accuracy of the information presented herein. This document is disseminated in the interest of information exchange. The report is funded, partially or entirely, by a grant from the U.S. Department of Transportation's University Transportation Centers Program. However, the U.S. Government assumes no liability for the contents or use thereof.

TECHNICAL REPORT DOCUMENTATION PAGE

<table>
<tr><td>1. Report No.</td><td>2. Government Accession No.</td><td colspan="2">3. Recipient's Catalog No.</td></tr>
<tr><td colspan="2" rowspan="2">4. Title and Subtitle
Real World Data Measurement of Factors Affecting Air Quality for Nonroad Diesel Equipment Operators</td><td colspan="2">5. Report Date
December 2023</td></tr>
<tr><td colspan="2">6. Performing Organization Code</td></tr>
<tr><td colspan="2">7. Author(s)
Phil Lewis
Jeremy Johnson
Adam Mayer
Hardick Kaser</td><td colspan="2">8. Performing Organization Report No.
03-24-TTI</td></tr>
<tr><td colspan="2" rowspan="2">9. Performing Organization Name and Address:
CARTEEH UTC
Texas A&M Transportation Institute
3135 TAMU, College Station Texas 77843</td><td colspan="2">10. Work Unit No.</td></tr>
<tr><td colspan="2">11. Contract or Grant No.
69A3551747128</td></tr>
<tr><td colspan="2" rowspan="2">12. Sponsoring Agency Name and Address
Office of the Secretary of Transportation (OST)
U.S. Department of Transportation (USDOT)</td><td colspan="2">13. Type of Report and Period
Final
9/1/2020–8/31/2023</td></tr>
<tr><td colspan="2">14. Sponsoring Agency Code</td></tr>
<tr><td colspan="4">15. Supplementary Notes
This project was funded by the Center for Advancing Research in Transportation Emissions, Energy, and Health University Transportation Center, a grant from the U.S. Department of Transportation Office of the Assistant Secretary for Research and Technology, University Transportation Centers Program.</td></tr>
<tr><td colspan="4">16. Abstract
This project focused on creating a methodology to measure the in-cab air quality for diesel powered construction equipment. The research team focused on currently available technologies, used for measuring personal and ambient air quality, and created a methodology that future projects can implement in order to better understand the in-cab air quality that workers are exposed to as they operate this equipment. The researchers implemented the methodology in a controlled environment using equipment owned and operated by the Texas A&M Transportation Institute. They collected data using the technologies to ensure that they were able to capture the changes in the in-cab air quality as the operator was using the construction equipment. The research found that the methodology could be used in future studies to accurately capture the in-cab air quality for construction equipment operators. The study found that while the gases measured in the cab were minimal, PM data indicated there is a potential impact to the drivers health with elevated PM levels during operation. This methodology could help develop and test ways to reduce the impact of in-cab air quality to the operators health.</td></tr>
<tr><td colspan="2">17. Key Words
In-Cab, Air Quality, Emissions, Diesel, Construction Equipment, PM, Exposure</td><td colspan="2">18. Distribution Statement
No restrictions. This document is available to the public through the CARTEEH UTC website.
http://carteeh.org</td></tr>
<tr><td>19. Security Classif. (of this report)
Unclassified</td><td>20. Security Classif. (of this page)
Unclassified</td><td>21. No. of Pages
17</td><td>22. Price
$0.00</td></tr>
</table>

Form DOT F 1700.7 (8-72) Reproduction of completed page authorized

Executive Summary

This research project addressed six primary factors that contribute to air quality for nonroad diesel equipment operators. These factors included: (a) tailpipe pollutant emissions, (b) in-cab air quality data, (c) equipment duty cycles, (d) diesel engine performance, (e) operator behavior, and (f) jobsite/environmental conditions. The pollutants assessed included particulate matter (PM), black carbon (BC), oxides of nitrogen (NO_x), carbon monoxide (CO), and carbon dioxide (CO_2). Duty cycles, such as idling and non-idling, of the work being performed by the equipment were recorded. Diesel engine performance variables such as engine load percentage, revolutions per minute, and manifold absolute pressure were measured. Operator behavior such as smoking in the equipment cab, opening/closing the door to the cab, and using the air conditioner/heater in the cab were recorded. Jobsite and environmental conditions including temperature, humidity, and wind speed were measured both inside the equipment cab and on the jobsite. These datasets were synchronized to a common timescale. Analysis included identifying patterns, trends, and correlations among the many variables. The main purpose of the analysis was to identify potential factors that may be controlled to reduce the equipment operator's exposure to harmful conditions and improve worker health.

The research addressed an important problem because the current number of nonroad diesel equipment operators is expected to grow by 12 percent (faster than the national average for other occupations) by 2026. This research is significant because the Environmental Protection Agency (EPA) identifies indoor air quality as one of the five most urgent risks to public health. Given that equipment operators spend most of their day inside the equipment cab, air quality is a significant issue. This research is also significant because exposure to diesel exhaust is an important human health concern. EPA assessed the possible health hazards associated with diesel exhaust 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. Furthermore, nonroad equipment operates in a harsh environment including temperature and humidity extremes, dusty conditions, and in close proximity to a high pollution source—the tailpipe of the equipment.

This research is complementary to the previous CARTEEH project Characterizing In-Cab Air Quality in Heavy Duty Diesel Construction Equipment (TTI-01-11); however, this research is more than a continuation of the previous project. Results from CARTEEH Project TTI-01-11 revealed that nonroad equipment operators are almost always exposed to varying concentrations of PM, BC, NO_x, CO, and CO_2. In a related study by researchers at Oklahoma State University, findings showed that PM, NO_x, CO, and CO_2 were nearly always present in the equipment cab during operation. Furthermore, temperature and humidity conditions frequently created cautionary heat index levels inside the equipment cab, sometimes even during cooler winter months [1]. The gap in knowledge is an understanding of which factors contribute significantly to air quality for nonroad equipment operators. This research helps fill that gap by developing a methodology to identify, measure, and characterize how the equipment, operator, and environment work together to create air quality conditions for equipment operators.

This research is directly related to the CARTEEH priority area of Data and Empirical Measurements by collecting real-world measurements that generate data to fill existing gaps in understanding the full-chain effects of transportation emissions to health. The data collected and analyzed from the proposed research also support the other CARTEEH priority areas of Data Integration, Impact Assessment, and Modeling Studies.

The primary objective of the research was to develop a methodology to collect and analyze real-world data related to air quality for nonroad equipment operators. The collected data included: (a) tailpipe emissions, (b) in-cab air quality, (c) nonroad equipment engine activity, (d) nonroad equipment duty cycles, (e) nonroad equipment operator behavior, and (f) jobsite/environmental conditions. The nonroad equipment tested was owned and operated by partner stakeholders in the Crash Test Unit at the Texas A&M Transportation Institute. All testing occurred at the Texas A&M-RELLIS campus in Bryan, TX.

In conclusion, the research developed a methodology to collect in-cab air quality data for heavy duty diesel construction equipment. The methodology can be used by future research projects that include data collection in the cab of diesel-powered construction equipment. Due to the limited amount of variation in the collected data there was no in-depth analysis included in this report. Much more data collection is needed to gain an understanding of how each factor impacts in-cab air quality. For the data that were collected, the values were very low (often zero) for the gaseous pollutants; however, PM data indicated that there is a compelling reason to continue research in particle pollution inside of heavy equipment cabs. The activity data collected, and that may be collected in future studies that rely on the methodology developed under this project, may also be useful in helping equipment managers develop productivity and safety plans for their operators. This could further reduce the level of pollutants that operators are exposed to as they make their operations more efficient.

The main output of this project was the methodology developed for collecting in-cab air quality data for diesel powered construction equipment. This is an important step in the health of the equipment operators, and as the methodology is implemented it can help identify potential health hazards for equipment operators. This can lead to the development and implementation of mitigation strategies that can improve the long-term health of operators by reducing their exposure to harmful pollutants released by the diesel-powered machines. Additionally, the research was used as the basis for theses by two students at Texas A&M University. Both students were Master of Science in Construction Management candidates. The theses were: (1) *Analyzing Factors Affecting In-Cab Air Quality in Heavy-Duty Diesel Construction Equipment*, by Hardick Kasar; and (2) *Development of a Data Collection Methodology for Examining Construction Equipment Emissions and In-Cab Air Quality*, by Adam Mayer.

Table of Contents

List of Figures ..... **vii**

List of Tables ..... **vii**

Background **1**

Approach **1**

Tailpipe Emissions 2

Duty Cycle and Engine Performance 3

Operator Behavior 4

Environmental Conditions 4

In-Cab Air Quality 4

Data Collection Procedure **6**

Results **7**

Conclusions **8**

Outputs, Outcomes, and Impacts **9**

Research Outputs, Outcomes, and Impacts **9**

References **9**

List of Figures

Figure 1: parSYNC Mini PEMS 2
Figure 2: parSYNC Installed on Motor Grader 3
Figure 3: HEM Data Mini Logger 3
Figure 4: Vantage Pro2 from Davis Instruments 4
Figure 5: MX6-iBrid (Top Left), AE51 (Top Right), and pDR-1000AN (Bottom) 5
Figure 6: iBrid and AE51 Devices in Container for Sampling 5
Figure 7: Sensor Container (Right with two ports) 6
Figure 8: iBrid Calibration Station 6
Figure 9: Wheel Loader 8
Figure 10: Motor Grader 8

List of Tables

Table 1: Construction Equipment Tested 7
Table i: General Specification for parSYNC iPEMS from 3DATX 11
Table ii: Specifications for parSYNC iPEMS from 3DATX 11
Table iii. Specifications for MX6 iBrid 11
Table iv. Specifications for DataRAM™ pDR-1000AN 11

Background

As technologies continue to improve and additional infrastructure is added, the number of electric vehicles operating in the United States continues to grow. The overall sales of electric vehicles in the United States were only 0.2 percent in 2011 but increased to 4.6 percent in 2021 [2]. Estimates vary on what that percentage will look like in the future, but the consensus is that number will continue to grow.

While there is also a push to move away from diesel-powered construction equipment to alternatives such as electric options, that change has been slower in implementation, and operators today are still operating a fleet of mostly diesel-operated equipment. Additionally, the number of nonroad diesel equipment operators in the United States continues to grow, an estimated a 3 percent by the year 2032 [3]. These operators often spend a large portion of their daily routine inside the cabin of these pieces of equipment, exposed to air quality inside the cab itself, which can be a significant issue. The United States Environmental Protection Agency (EPA) assessed the possible health hazards associated with diesel exhaust 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 [4]. Furthermore, nonroad equipment operates in a harsh environment including temperature and humidity extremes, dusty conditions, and near a high pollution source—the tailpipe of the equipment. Since the move to the electric options in the construction fleet is slow, it is important to understand what the operators are exposed to while operating the diesel-powered equipment, since they are still going to be operated in large quantities in the construction field for the foreseeable future.

The goal of this project was to develop a methodology to measure the in-cab air quality of non-road construction equipment during operations, as well as the other factors that could contribute to lower in-cab air quality for non-road equipment. The framework that was developed will guide future research into the impacts that these factors have on in-cab air quality. The remainder of this report details the methodology developed as well as the equipment and procedures that were used to test the methodology.

Approach

To develop the methodology for measuring the in-cab air quality, the researchers first looked at the factors that could be contributors to poor in-cab air quality. The five primary factors that were identified were:

Tailpipe Emissions: The tailpipe emissions coming from the equipment would be one of the closest sources of pollutants that could be infiltrating the cabin. Equipment that is a high-emitter is putting more pollutants in the air in and around the cabin, and therefore could have a major impact on the in-cab air quality.

Duty Cycle: The duty cycle of the equipment is referring to how the unit is being operated. Is a large percentage of the time being spent idling, is it moving around and potentially kicking up dust as is often the case on a construction site, how many hours a day is it operating, etc.

Engine Performance: The engine performance, while perhaps highly dependent on the duty cycle, can also impact the in-cab air quality. Is the engine running at high loads for long periods of time (moving heavy loads around a site), or is it doing lighter work (driving from location to location with no real load on the engine)?

Operator Behavior: Perhaps one of the biggest factors in air quality is the behavior of the operator. Are they smoking in the cab; are they operating the unit with the doors open, potentially letting in the dirt being kicked up from the equipment; are they running the air conditioner (if equipped), which could potentially filter out some of the pollution in the cab?

Job Site/Environment Conditions: What are the environmental conditions at the jobsite? Is it operating on a dirt road versus a paved road, and what are the weather conditions that could impact the behavior of the driver (need for air conditioning)?

After identifying the factors that could impact the in-cab air quality, the researchers developed a methodology to measure and/or document each of the factors. The following sections describe the equipment and methodology used to measure each of the factors as well as measure the in-cab air quality. Specifications for the equipment used can be found in Appendix A.

Tailpipe Emissions

Tailpipe emissions are generally measured using a portable emissions measurement system (PEMS). PEMS is a term used by EPA and others to describe state-of-the-art technologies designed to be small enough, yet accurate enough, to install on vehicles for in-use emissions testing. There are several manufactures of PEMS units that are capable of measuring both gaseous pollutants as well as particulate matter (PM), both of which can have potential health impacts to those exposed to high levels of pollution. PEMS units are recognized by EPA and approved for in-use testing and are included within the U.S. Code of Federal Regulations [4].

For this study, the research team focused on a subcategory of PEMS, called Mini-PEMS. Mini-PEMS, as the name implies, are smaller PEMS units designed to be used in non-regulatory work. Their design makes them smaller, and therefore easier to install for short duration testing. They are also generally quicker to calibrate and prepare for testing than a full PEMS, making them ideal for this type of study that is looking at correlation between the tailpipe emissions and in-cab air quality. For this study the research team deployed a parSYNC mini PEMS from 3-DATX [1]. The parSYNC, shown below in Figure 1, can measure carbon monoxide (CO), carbon dioxide (CO_2), nitrogen oxide (NO), nitrogen dioxide (NO_2), and PM. The device is installed by inserting a probe into the tailpipe of the equipment being tested, as seen in Figure 2.

Figure 1: parSYNC Mini PEMS

[1] https://3datx.com/parsync/

Figure 2: parSYNC Installed on Motor Grader

Prior to each use the parSYNC is calibrated using a documented calibration procedure provided by the manufacture using calibrated gasses with known concentrations of the different pollutants.

Duty Cycle and Engine Performance

The duty cycle and engine performance are measured using an OBD Mini Logger from HEM Data[2], shown in Figure 3. The data logger, which is plugged into the J1939/1708 port on the construction equipment, records all the data that the vehicle broadcasts on the port, which include all the engine information (revolutions per minute, load, pedal position, etc.) needed for the engine performance analysis. The device also includes a GPS chip, which reports the GPS location and speed alongside the engine information. By combining these two data sets, the duty cycle and engine performance can be analyzed to determine the impact they have on the in-cab air quality.

Figure 3: HEM Data Mini Logger

[2] https://hemdata.com/products/dawn/obd-mini-logger/

Operator Behavior

Measuring and recording the operator behavior is a combination of data from the mini logger as well as survey with the driver. The driver behavior, such as smoking in the cab, cannot be measured using electronics. However, some driver behavior data, such as the use of the air conditioner, or the opening and closing of doors, is reported via the port that the mini logger records. For vehicles that do report these data, the mini logger will save that information, which can then be combined with the user survey information, to analyze the impact of operator behavior.

Environmental Conditions

The environmental conditions during the testing was monitored using a weather station located at the job site. The weather station used for this project was a Vantage Pro2 from Davis instruments, shown in Figure 4. The device measures the local temperature, humidity, wind speed and direction, and precipitation. These datapoints are used to determine the impact of the environmental conditions on the in-cab air quality.

Figure 4: Vantage Pro2 from Davis Instruments

In-Cab Air Quality

The most important data that are required to determine the impacts the discussed factors have on the in-cab air quality is the actual air quality data. There are many different components to air quality, including both gaseous and PM emissions. For this project a set of three different air quality monitors were used to measure in-cab air quality during data collection. All the instruments used for this study were considered portable, or wearable, devices. The use of the portable type devices was due to their low operations requirements. Since they are small and can run from batteries, no additional hardware is required to run them in the cab of the test equipment. One instrument, the MX6-iBrid[3] from Industrial Scientific, is a gas monitor that measures NO, NO_2, CO, and CO_2. The MicroAeth AE51[4], from Aethlabs, measures black carbon, and the final instrument, the pDR-1000AN from Thermo Scientific, measures PM. All three devices are shown in Figure 5.

[3] https://www.indsci.com/en/gas-detectors/multi/mx6-ibrid

[4] https://aethlabs.com/microaeth/ae51/overview

Figure 5: MX6-iBrid (Top Left), AE51 (Top Right), and pDR-1000AN (Bottom)

Both the MX6 and AE51 devices used have a sample inlet port where the air is pulled into the device for measurement. The pDR-1000AN samples from the top of the device but has larger area where the sample comes into the device. To ensure that the devices were able to monitor the air freely, a container was designed with both inlet and outlet ports for the AE51 and Mx6 devices. This ensured that the devices were monitoring from the same location, but also allowed the team to support them easily when installed in the test equipment. The pDR-1000AN designed allowed for it to be used without the need for a separate container. Figure 6 shows the iBrid and QE51 inside the container, and Figure 7 shows the container with both ports as it was placed next to the lunchbox of the equipment operator inside the cab.

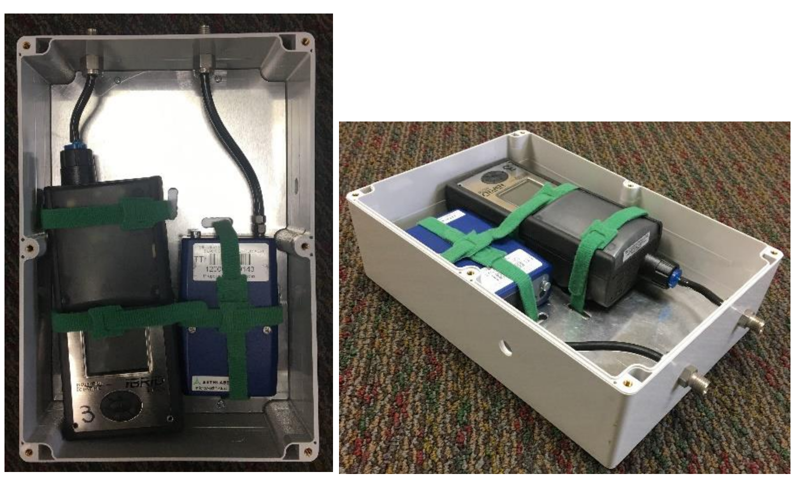

Figure 6: iBrid and AE51 Devices in Container for Sampling

Figure 7: Sensor Container (Right with two ports)

Data Collection Procedure

After determining the equipment that would be used, a data collection procedure was developed to ensure that each time data were collected it was conducted in a similar manner. This ensured that the quality of the data would be the same, independent of who was collecting the data or what equipment the data were being logged by that day. The data collection procedure developed for this study was a five-step process.

1. Calibration: Each day, prior to installing the devices on the non-road equipment, each device was calibrated according to the manufacturer recommended procedures. The parSync, pDR-1000AN, AE51, and iBrid were each calibrated daily, while the mini-logger used for the GPS and onboard data collection did not require calibration. Figure 8 shows the calibration station used for calibrating the iBrid gas monitor.

Figure 8: iBrid Calibration Station

2. Installation: Arrangements were made with the equipment owner to allow the instruments to be installed in the equipment daily before general operations began. In most instances this included having the instruments calibrated and installed before 6:00 a.m. After the devices were installed, they were powered on and allowed to operate for the duration of the test day. Pictures were taken at each installation in order to ensure that the data were analyzed correctly and to document the test equipment being monitored. The mini-PEMS and the mini-logger were installed in the same location for each test, since they can only be placed in a single location (the probe in the tailpipe and the OBD-J1939 data port, respectively). However, the location of the in-cab measurements varies based on the equipment being tested. Many of the different construction equipment identified for this project had different interior designs due to their operational characteristics. The exact location of the in-cab monitors, therefore, must vary due to the need to measure the in-cab air quality but also the requirement that they do not interfere with operations. Therefore, the researchers must use their judgement on a case-by-case basis as to the exact location of the monitors.
3. Removal: The devices were removed at the end of each day, typically after 4:00 p.m., when the operator's shift was over. The instruments would be powered down, removed from the test equipment, and taken back to the lab.
4. Data Download: At the conclusion of each day the data from each instrument would be downloaded, named, and saved to a location that would identify the date, equipment that was tested, and type of data in the file. Identifying the data is a very important step to ensure that the correct data are used during the analysis process. The naming convention should be well documented for a project to ensure that everyone who may interact with the data understands where they came from.
5. Cleaning: Since the instruments were used in real-world construction activities, they were often dirty at the end of each test period. The researchers would clean the devices daily and verify that they were still operational prior to the next use. This was also verified in step 1 when the devices were calibrated.

Results

Upon designing the methodology of the data collection, the research team conducted testing on two pieces of construction equipment. The two pieces tested were part of the Texas A&M Transportation Institute Roadside Safety & Physical Security Division, and testing was conducted on the proving grounds at the Texas A&M-RELLIS campus of the Texas A&M University System[5]. The two pieces of equipment tested are detailed in Table 1 and shown in Figure 9 and Figure 10.

Table 1: Construction Equipment Tested

Equipment Type	Manufacturer	Model	Year
Wheel Loader	Caterpillar	950K	2013
Motor Grader	Caterpillar	12M3	2018

[5] https://rellis.tamus.edu/

Figure 9: Wheel Loader

Figure 10: Motor Grader

The primary goal of this initial testing was to gather a set of data that could be used to determine any deficiencies on the data collection process; however, the opportunities for collecting data under various conditions were limited. For example,

- All testing was conducted in October and November with little variation in ambient temperature data;
- The same operator was used for all testing, and therefore variation in the operator behavior was not observed during the data collection; and
- All testing was conducted at the RELLIS campus, which is largely paved, therefore there was not direct impact from the work on the ambient air quality conditions (such as dust being kicked up on dirt road construction).

Conclusions

The following section outlines the conclusions from the data collected during the study.

- The project was able to develop a methodology to collect in-cab air quality data for heavy duty diesel construction equipment. The methodology can be used by future research projects that include data collection on the cab on diesel-powered construction equipment.
- Due to the limited amount of variation in the collected data, there was no in-depth analysis included in this report. Much more data collection is needed to get an understanding of how each factor impacts the in-cab air quality.
- For the data that were collected, the values were very low (often zero) for the gaseous pollutants; however, PM data indicated that there is a compelling reason to continue research in particle pollution inside of heavy equipment cabs.

- The activity data collected, and that may be collected in future studies that rely on the methodology developed under this project, may also be useful in helping equipment managers develop productivity and safety plans for their operators. This could further reduce the amount of pollutants that operators are exposed to as they make their operations more efficient.

Outputs, Outcomes, and Impacts

As previously discussed, the main output of this project was the methodology developed for collecting in-cab air quality data for diesel-powered construction equipment. This is an important step in the health of the equipment operators, and as the methodology is implemented, it can help identify potential health hazards for equipment operators. This can lead to the development and implementation of mitigation strategies that can improve the long-term health of operators by reducing their exposure to harmful pollutants released by the diesel-powered machines.

Research Outputs, Outcomes, and Impacts

In addition to this report the research was also used as the basis for theses by two students at Texas A&M University. Both students were Master of Science in Construction Management candidates. The two theses included:

1) *Analyzing Factors Affecting In-Cab Air Quality in Heavy-Duty Diesel Construction Equipment*, by Hardick Kasar.
2) *Development of a Data Collection Methodology for Examining Construction Equipment Emissions and In-Cab Air Quality*, by Adam Mayer.

References

[1] U.S. EPA, "Code of Fedral Regulations: Field Testing and Portable EMission Measurement Systems," 24 January 2023. [Online]. Available: https://www.ecfr.gov/current/title-40/chapter-I/subchapter-U/part-1065/subpart-J. [Accessed 13 September 2023].

[2] U.S. Department of Labor , "Charging into the Future: The Transition to Electric Vehicles," February 2023. [Online]. Available: https://www.bls.gov/opub/btn/volume-12/charging-into-the-future-the-transition-to-electric-vehicles.htm. [Accessed 13 September 2023].

[3] U.S. Department of Labor, "Construction Equipment Operators," 6 September 2023. [Online]. Available: www.bls.gov/ooh/construction-and-extraction/construction-equipment-operators.htm. [Accessed 13 September 2023].

[4] U.S. EPA, "Health Assessment Document for Diesel Engine Exhaust," National Center for Environmental Assessment, Washington DC, 2002.

[5] U.S. Environmental Protection Agency , "Indoor Air Quality. The Inside Story: A Guide to Indoor Air Quality," [Online].

Appendix A: Instrumentation Details

Table i: General Specification for parSYNC iPEMS from 3DATX

Dimensions	12cm X 22cm X 13cm
Weight	9lb
Battery Life	8-10 hours

Table ii: Specifications for parSYNC iPEMS from 3DATX

Gas	Sensor Technology	Measurement Range	Temperature Range	Repeatability
Nitrogen Oxide	Electro-Chemical	0–5000 ppm	−20° to 50° C	2% of signal
Nitrogen Dioxide	Electro-Chemical	0–300 ppm	−20° to 50° C	2% of signal
Carbon Monoxide	Non-Dispersive Infrared Spectrometer (NDIR)	0–15%	−20° to 50° C	± 0.02% absolute or ± 3% relative
Carbon Dioxide	Non-Dispersive Infrared Spectrometer (NDIR)	0–20%	−20° to 50° C	± 0.1% absolute or ± 2% relative

Table iii. Specifications for MX6 iBrid

Gas	Sensor Technology	Measurement Range	Temperature Range	Humidity Range
Nitrogen Oxide	Electro-Chemical	0–1000 ppm	−20° to 50° C	15–90%
Nitrogen Dioxide	Electro-Chemical	0–150 ppm	−20° to 50° C	15–90%
Carbon Monoxide	Electro-Chemical	0–1500 ppm	−20° to 50° C	15–90%
Carbon Dioxide	Infrared	0-5%	−20° to 50° C	0–95%

Table iv. Specifications for DataRAM™ pDR-1000AN

Accuracy	± 5% of reading ± precision
Precision	± 0.5% of reading ± 0.015 mg/m^3
Data Logging Averaging Periods	1 second to 1 hour
Size	6 inch X 3.6 inch X 2.5 inch
Technology	Single Beam Nephelometry
Data Points	13391