University of Cincinnati

Date: 3/15/2021

I, Mackenzie S Barnwell, hereby submit this original work as part of the requirements for the degree of Master of Science in Industrial Hygiene (Environmental Health).

It is entitled:

Evaluation of Occupational Exposure to In-Bus Traffic Related Air Pollution Concentrations and Noise Levels for Bus Drivers.

Student's name: **Mackenzie S Barnwell**

This work and its defense approved by:

Committee chair: Kermit Davis, Ph.D.

Committee member: Tiina Reponen, Ph.D.

Committee member: Jurate Virkutyte, Ph.D.

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Evaluation of Occupational Exposure to In-Bus Traffic Related Air Pollution

Concentrations and Noise Levels for Bus Drivers.

A thesis submitted to the

Graduate School

of The University of Cincinnati

in partial fulfilment of the

requirements for the degree of

Master of Science

in the Department of Environmental and Public Health Sciences

of the College of Medicine

By

Mackenzie Barnwell

B.S., The University of Findlay 2017

March 2021

Committee Chair: K. Davis, Ph.D.

Abstract

Indoor air quality of buses has been assessed in numerous studies but few have assessed the occupational exposure to the driver to in-cabin pollutants. The purpose of this study was to quantitatively measure common in-cabin pollutants and noise and compare the results to recommended and regulatory limits to determine the risk to the driver. Direct reading instruments were used to measure formaldehyde, total volatile organic compounds, particulate matter of varying diameter, carbon dioxide, temperature, and relative humidity over ten days. A noise dosimeter was used to determine maximum sound level and the peak instantaneous sound pressure level. Daily averages, maximum concentrations, and 8-hour time weighted averages (TWA) were calculated. The 10-hour adjusted threshold limit values (TLVs) were calculated to compare average concentrations to a worst-case scenario. Calculated 8-hour TWAs of formaldehyde was greater than the National Institute for Occupational and Health Recommended Exposure Limits for nine of the ten days. Additionally, average daily concentrations of formaldehyde were greater than the 10-hour adjusted TLV for seven of the ten days if the average exposure were to remain the same for the 10-hour work shift. All other pollutant concentrations and noise were less than recommended and regulatory limits. The results of this study indicate that the occupational exposure of the driver to in-cabin pollutants was low, but further the need for additional investigation into in-cabin exposures to formaldehyde.

Acknowledgements

I would like to thank the National Institute of Occupational Safety and Health for supporting the opportunity to grow my passion for industrial hygiene in an academic setting through the University of Cincinnati Education Research Center (No. T42OH008432).

I would like to thank my advisor and committee chair, Dr. Kermit Davis, for his guidance, encouragement, and knowledge throughout the completion of my thesis. Dr. Davis helped make what seemed like an impossible task, possible. I cannot express enough gratitude to him for his help.

I would also like to thank my committee members, Dr. Tiina Reponen and Dr. Jurate Virkutyte. Dr. Virkutyte helped obtain monitoring instruments that were used in this study and helped guide my research idea into a workable project. Both Dr. Reponen and Dr. Virkutyte provided feedback to help refine my thesis and I am grateful for their help throughout this process.

I would like to thank the professors within the Department of Environmental and Public Health Sciences at the University of Cincinnati who I had the opportunity to be taught by.

I would like to thank my fellow classmates, and specifically Nick Grisso for his encouragement and support throughout our time together at UC and now in the working world.

I would like to thank my parents, fiancé, friends, and co-workers for being supportive throughout this entire process.

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1.0 Introduction

Presently, there is an estimated 179,510 bus drivers employed in the United States, including transit drivers, school bus drivers, and tour bus drivers.[1] A large percentage of the population of bus drivers are moving into retirement and the job field is estimated to increase by nine percent from 2016 to 2026.[2] Poor indoor air quality of a workplace can lead to unwanted exposures to airborne particulates such as dust and fungi, volatile organic chemicals (VOCs) such as formaldehyde, and carbon dioxide.[3] Exposures to these indoor air quality pollutants can cause temporary discomfort until the individual leaves the environment, also known as Sick Building Syndrome (SBS), causing symptoms such as tiredness, headaches, rhinitis, dry throat, and dry skin. Additional factors that can affect SBS include temperature, relative humidity, and ventilation.[4]

Motor vehicles produce roughly 1.5 trillion kilograms of carbon dioxide (CO_2) emissions, while transportation alone contributes to 56% of total carbon monoxide emissions (CO), 38% of total nitrogen oxides (NOx), 2% of particulate matter less than 2.5 micrometers in diameter ($PM_{2.5}$), 23% of VOCs, and 2% of total sulfur dioxide (SO_2).[5] Air quality inside commuter buses are of concern due to the nature of a bus service, where there is a constant influx of outdoor air contaminants into the bus due to the loading and off-loading of passengers. Other factors that can affect air quality inside a bus include traffic patterns, weather conditions, and ventilation. From this point forward, bus drivers will refer to any driver of a commuter, shuttle, or school bus.

Long-term and short-term exposure to $PM_{2.5}$ is directly related to unwanted health effects such as respiratory and cardiovascular diseases. Sources of $PM_{2.5}$ in traffic related air pollution originate from the exhaust pipe of the source, road abrasion, tire wear, brake-wear, and vehicle-induced resuspension of road dusts.[6] A 2009 study of private cars found inside concentrations of particulate matter to exceed outdoor concentrations when compared to sampling stations near the roadside, and levels affected by the number of stops along the traveling route when traveling for twelve to forty-eight minutes.[7] Exposure to $PM_{2.5}$ inside the bus can be affected by the use of air-conditioning, with a study showing a reduction in exposure levels by at least 83%.[8] Other factors influencing $PM_{2.5}$ levels are wind speeds and temperature.

VOCs can contribute to headaches, nausea, dizziness, eye and throat irritation. VOCs are a constituent of vehicle exhaust emission, and harmful pollutants include benzene, toluene, ethylbenzene, and xylene (BTEX). One study completed in the United Kingdom compared passenger exposures of different modes of transportation during a ten to forty-minute commute and found personal vehicles to have the highest VOC concentrations when comparing to buses, cycling, and walking. The high concentration of VOCs was attributed to the fact that personal cars are more likely to be in traffic lanes where other personal vehicles are present and close to car exhausts, while buses were in their own designated bus lane.[9] Not all buses have a designated bus lane to use and must travel in lanes with personal cars and utility vehicles. A 2003 study of commuter exposure to VOCs in different transportation modes in China determined another factor affecting in-cabin VOC concentrations is whether air conditioning is used, where concentrations are higher in non-air-conditioned buses and lower in air-conditioned buses.[10]

Another common exposure for bus drivers is noise. Studies have analyzed sound levels through noise dosimetry on various modes of transportation during short periods of sampling and found significant association between transit noise levels at or above 85 dBA and noise induced hearing loss.[11-12] The authors of a study of Toronto transit systems concluded that although average noise levels on the transit system are within recommended ranges of safe exposure, intermittent impulse noise on buses can be of concern.[12] Bus driver's exposure to noise using the Occupational Safety and Health Administration (OSHA) configuration for dosimeters will be assessed during this study.[13]

While most studies on indoor air quality of buses focus on short-term exposure to the passengers, there is a potential of occupational exposure to elevated levels of unwanted air pollutants over an eight-hour standard working day for the bus driver. To determine the risk of health effects to bus drivers, exposures to concentrations of air pollutants need to be compared to accepted regulatory limits promulgated under the OSHA Permissible Exposure Levels (PELs), or recommended limits from the American Conference of Governmental Industrial Hygienists (ACGIH) Threshold Limit Values (TLVs) and National Institute of Occupational Safety and Health (NIOSH) Recommended Exposure Limits (RELs).[13-15] Regulatory and recommended limits are derived based on evidence of a chemical's properties and effects on workers. Additionally, in-bus temperature and relative humidity were compared to recommended guidelines by the American Society of Heating, Refrigerating, and Air-Conditioning Engineers.[16] This study aimed to observe pollutant concentrations and sound levels inside University of Cincinnati buses during normal operating hours to evaluate potential exposure to the driver and comparing levels to regulatory and recommended limits.

2.0 Methods

2.1 Study Design

Quantitative data was collected inside of a University of Cincinnati Shuttle Bus within the “Bearcat Transportation System” fleet. All parameters were sampled over increments of either two hours, three hours, four hours or six hours, for a total of forty hours over ten days during April and May 2019. Measurements were taken during the day between 8:00 AM to 7:00 PM. The bus was exclusively on the CCM Plaza/1819 Route for the University that operated between East Campus, West Campus, and the 1819 Building. Drivers worked 6-hour shifts, either morning or afternoon. An aerial view of the route can be found in Figure 1. The CCM Plaza/1819 Route bus followed a continuous loop for twenty-five minutes. An aerial diagram of the bus layout and sampling location can be found in Figure 2.

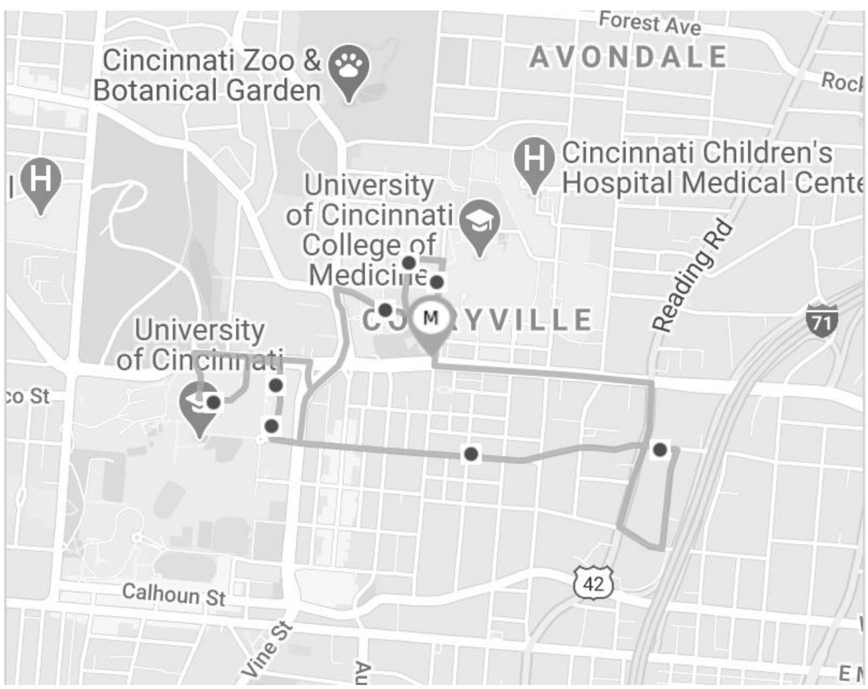

Figure 1. Schematic of the bus route monitored by research team.

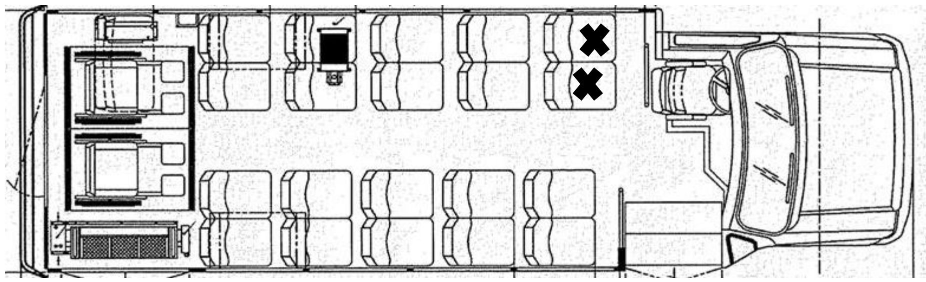

Figure 2. Aerial diagram of the Ford StarTrans 20 passenger bus with sampling location indicated by X.[17]

2.2 Bus Description

The bus on the CCM Plaza/1819 Route was a 2018 Ford StarTrans 20 passenger with two wheel-chair spaces plus the driver (Figure 2). The gas engine was 6.8 liter and 40-gallon capacity. There were two entrances and exits, one to the right of the driver at the front right side of the bus, and one at the back right side of the bus for wheel-chair access. There were twelve total windows around the bus with four windows on the right side and six windows on the left side with the ability to be opened. The passenger and the driver's seat were vinyl covered with non-retractable seat belts. The wheel-chair lift was a Intermotive Gateway 505-F Ford E or 515-F Transit Fast Idle with Lift Interlock. The bus did have heating and air conditioning, but only heat was used on days with cooler temperatures. The driver's side window and all windows on the right and left side of the bus were open during data collection.

2.3 Instrumentation

An EGVOC-180 multi-function direct-reading air quality sensor (EG Air, China) measured concentrations of formaldehyde (HCHO), total volatile organic compounds (TVOC), $PM_{1.0}$, $PM_{2.5}$, and PM_{10}. Contaminants were measured by pulling in air through a built-in fan and across a temperature and humidity sensor, electrochemical formaldehyde sensor, TVOC sensor, and a laser sensor to measure particulate matter.

Concentrations were data-logged manually every two minutes along the route for each contaminant. The EGVOC-180 was calibrated for 300 seconds in zero air before each use according to the manufacturer’s requirements. The EGVOC-180 was held by the user sitting in the left seat closest to the window behind the driver.

A Hydrofarm AutoPilot APCEMDL Monitor w Removable Data Card Desktop CO_2 (Hydrofarm, Petaluma, CA) was used to measured concentrations of CO_2, and temperature and relative humidity. Data was measured through the use of a 2-channel low drift non-dispersive infrared gas sensor. Data for all three factors were data-logged every five seconds and saved onto a MicroSD card. Data was downloaded using a multifunction card reader and saved into an excel file. The autopilot APCEMDL was placed on the bus seat, approximately six feet away from the driver and three feet upwards from the bus floor.

The Quest Technologies the Edge-4 personal noise dosimeter (TSI, Shoreview, MN) was used to evaluate noise exposure while utilizing OSHA PEL Parameters (90 dBA Criteria Level, 5 dBA Exchange Rate, 90 dBA Threshold) and the OSHA Hearing Conservation (HC) Parameters (90 dBA Criteria Level, 5 dBA Exchange Rate, 80 dBA Threshold). The Quest Technologies the Edge-4 noise dosimeter was positioned approximately six feet behind the driver and five feet high on the shoulder of the user. The noise dosimeter was calibrated with the Quest QC-20 calibrator at 114 dB at 1000 Hertz calibration standard. The same calibrator was used to verify the dosimeter’s response after sampling to ensure accuracy.

2.4 Data Collection Procedures

Concentrations of HCHO, TVOC, $PM_{1.0}$, $PM_{2.5}$, and PM_{10} data were recorded every two minutes by manually typing the EGVOC-180 direct-reading air monitor sensor readings into a Microsoft Excel spreadsheet. The EGVOC-180 was plugged into a PowerADD ChargerCenter II power station (PowerADD, Pasadena, CA) to ensure battery life throughout the sampling period.

All concentrations, temperature, relative humidity, and sound levels were collected approximately six feet behind the driver in the first row of seats located on the left side of the bus. CO_2 concentrations, relative humidity, and temperature were data logged digitally onto a MicroSD card every five seconds housed in the Hydrofarm AutoPilot APCEMDL. The Hydrofarm AutoPilot APCEMDL was plugged into the PowerADD ChargerCenter II power station to ensure battery life and for the monitor to function. The monitor automatically turns on and begins data logging as soon as it is plugged in. The data for carbon dioxide, relative humidity, and temperature were retrieved by using a multifunction card reader and downloading the data into a Microsoft Excel file.

Noise measurements were data logged every sixty seconds throughout the sampling period and data was retrieved through the TSI Detection Management Software. The dosimeter was configured to OSHA Noise Standard criteria of an exchange rate of 5 decibels (dB), frequency weighting set to A, response time on slow, criterion level of 90 dBA, and two different thresholds of both 80 dBA and 90 dBA. The Edge-4 dosimeter was pre-calibrated, post calibrated, and data retrieval was performed in accordance with the user instruction manual before and after data collection.

2.5 Data analysis

Averages over each day for HCHO, TVOC, $PM_{1.0}$, $PM_{2.5}$, and PM_{10}, CO_2, temperature, and relative humidity were calculated. Additionally, maximum concentrations over each day were determined for HCHO, TVOC, $PM_{1.0}$, $PM_{2.5}$, and PM_{10}, and CO_2. Time-weighted averages (TWA) for an eight-hour workday were calculated for HCHO, TVOC, $PM_{1.0}$, $PM_{2.5}$, and PM_{10}, and CO_2 by multiplying the calculated average concentration by the sampling time performed in minutes and dividing the product by 480 minutes to simulate a best-case scenario if the exposure was zero for the remainder of the unsampled time and the work-shift was 8 hours. Additionally, a worst-case scenario was calculated if the drivers were to switch to a 10-hour shift, as it represents the longest shift length a driver can operate a passenger carrying vehicle in a single day[28]. Assuming the average exposure would remain the same for the whole 10-hour work shift, i.e., represented the 10-hour TWAs. The 10-hour TWA values were compared with adjusted ACGIH TLVs that were calculated (Appendix A) using the Brief and Scala Method[27]. Noise data was analyzed by determining the maximum sound level, or highest sound level recorded during a measurement interval (Lasmx) and the peak instantaneous sound pressure level recorded during a measurement interval (Lcpk). Calculated TWAs, maximum sound level and peak instantaneous sound pressure levels, and averages of temperature and relative humidity were compared to applicable regulatory and recommended values.

3.0 Results

3.1 Comparison of Air Quality Results to Recommended Limits

The maximum of HCHO over ten days of sampling ranged from 0.105 to 0.223 mg/m^3, which is less than the OSHA ceiling of 2.46 mg/m^3 and the ACGIH ceiling of 0.37 mg/m^3. The average ranged from 0.033 to 0.114 mg/m^3. The calculated TWA of HCHO ranged across the 10 days from 0.024 to 0.074 mg/m^3, which is less than the ACGIH TLV TWA of 0.12 mg/m^3, and less than the OSHA PEL of 0.92 mg/m^3. All ten days of calculated TWAs of HCHO were greater than the NIOSH REL of 0.0197 mg/m^3 (Figure 3). If the average exposure were to remain the same for a 10-hour work-shift, seven of the ten days were above the 10-hour adjusted ACGIH TLV of 0.084 mg/m^3 (Figure 4).

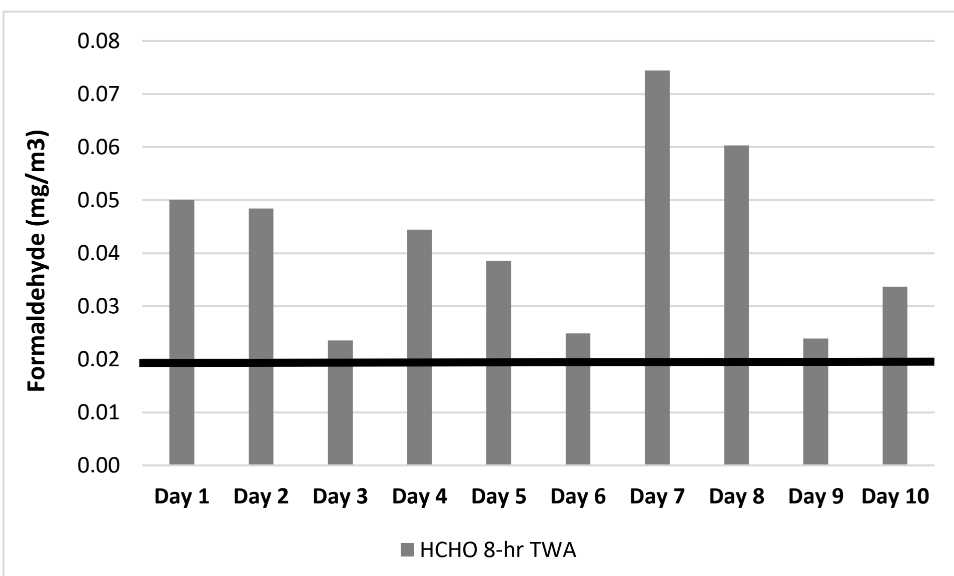

Figure 3. Calculated 8-hour Time Weighted Averages (TWAs) of Formaldehyde (HCHO) Compared to Recommended Value (NIOSH-REL of 0.0197 mg/m^3 as indicated by horizontal line).

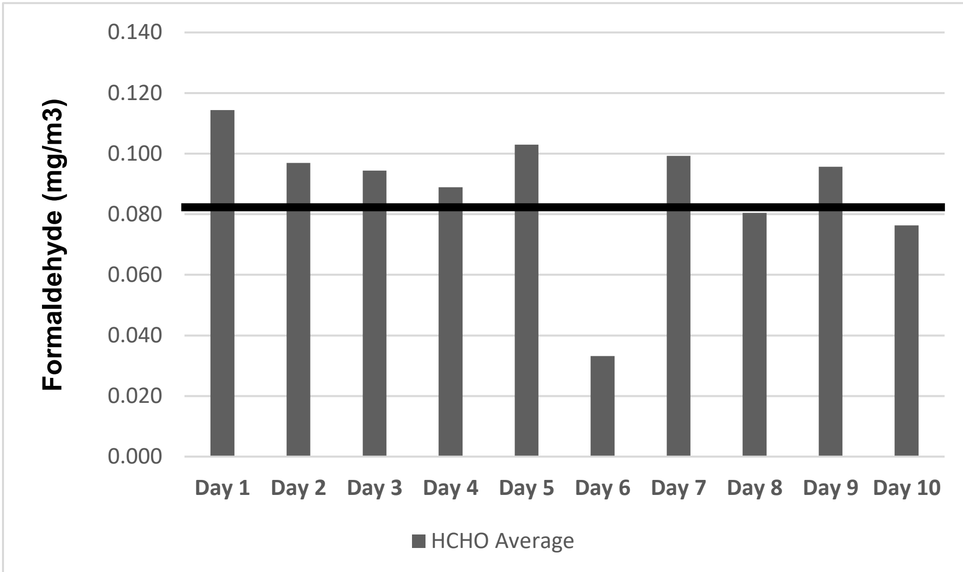

Figure 4. Average HCHO Exposure of Formaldehyde (HCHO) (10-hour TWA) Compared to 10-Hour adjusted ACGIH TLV (0.084 mg/m^3 as indicated by horizontal line) for Worst Case Scenario Depiction.

The maximum of TVOCs ranged across the 10 days from 0.445 to 1.041 mg/m^3, and the average ranged (across the 10 days) from 0.141 to 0.428 mg/m^3. The calculated TWAs of TVOCs ranged across the 10 days from 0.098 to 0.321 mg/m^3 (Figure 5). There are no regulatory or recommended limits to compare to for the results of the TVOCs because it can only be speculated the content and percentage of each VOC. The percentage of HCHO of the TVOCs monitored over ten days ranged from 23.18% to 28.78%.

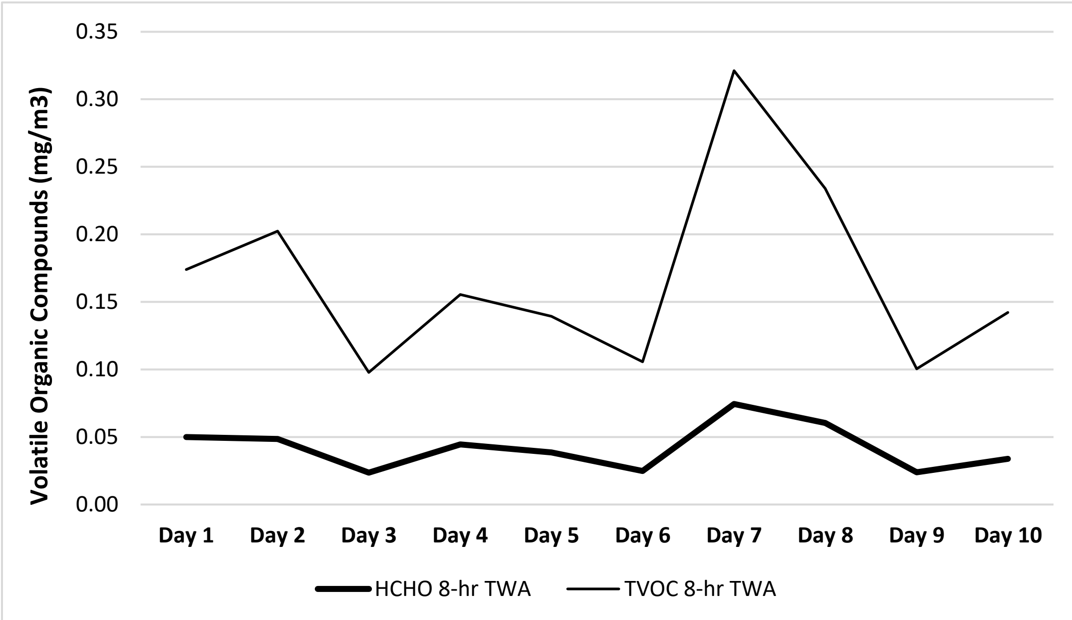

Figure 5. Calculated 8-hour Time Weighted Averages (TWAs) of Formaldehyde (HCHO) and Total Volatile Organic Compounds (TVOCs) for the Ten Days of Observation.

3.2 Particulate Matter and Carbon Dioxide

The maximum of $PM_{1.0}$ ranged from 1 to 12 μg/m^3, the average ranged from 1.000 to 3.750 μg/m^3, and the calculated TWAs ranged from 0.438 to 2.813 μg/m^3. The maximum of $PM_{2.5}$ ranged across the ten days from 3 to 17 μg/m^3, the average ranged from 1.552 to 5.750 μg/m^3, and the calculated TWA ranged from 0.679 to 4.313 μg/m^3. The maximum of PM_{10} ranged from 2 to 19 μg/m^3, the average ranged from 1.619 to 5.750 μg/m^3, and the calculated TWAs ranged from 0.708 to 4.313 μg/m^3. Daily averages of $PM_{2.5}$ and PM_{10} were similar compared to the daily average of $PM_{1.0}$ (Figure 6). All Calculated TWAs of $PM_{1.0}$, $PM_{2.5}$, and PM_{10} were less than the converted ACGIH recommended TLV of 3000 μg/m^3 and OSHA PEL of 5000 μg/m^3 for respirable dust. Additionally, all 10-hour TWAs were less than the 10-hour adjusted ACGIH TLV of 2100 μg/m^3.

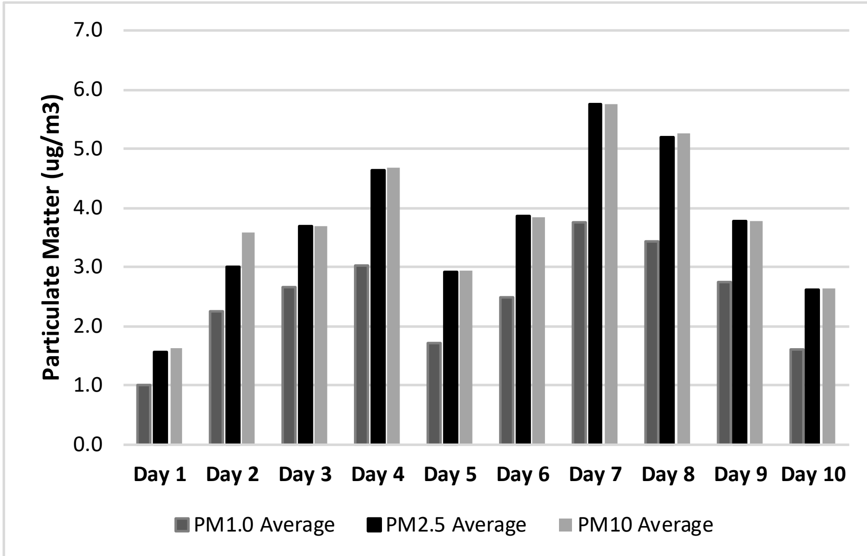

Figure 6.Daily Averages of Particulate Matter ($PM_{1.0}$, $PM_{2.5}$, and PM_{10}) for the Ten Days of Observation.

The maximum of CO_2 ranged from 572 to 1530 parts per million (ppm), which is less than the ACGIH TLV and NIOSH REL Ceiling of 54,000 ppm. The average ranged from 430 to 637 ppm (Figure 7). The calculated TWAs ranged from 138 to 448 ppm, which is less than the ACGIH TLV, NIOSH REL, and OSHA PEL of 5000 ppm. The 10-hour TWAs for all ten days were less than the 10-hour adjusted ACGIH TLV of 3500 ppm for CO_2 when comparing the daily average exposure for worst-case scenario.

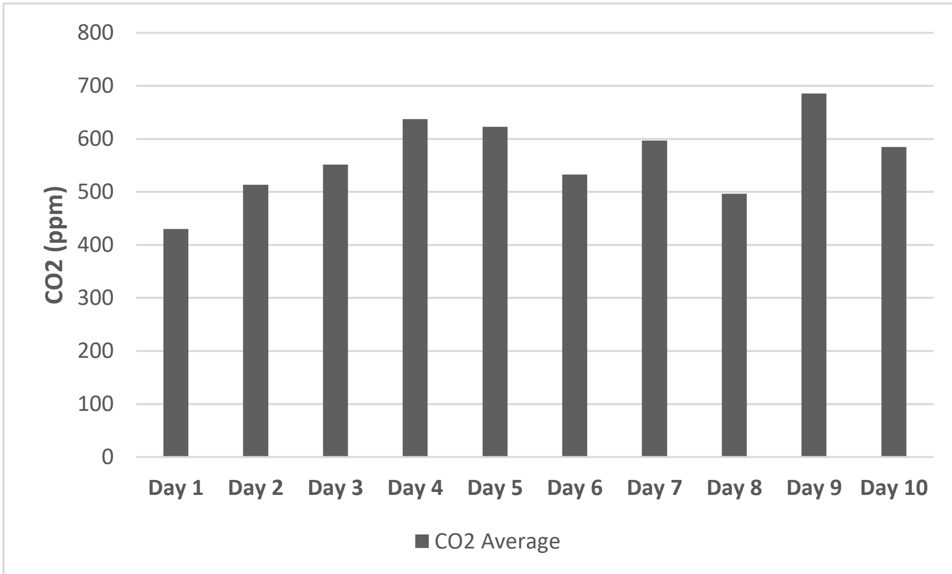

Figure 7. Daily Averages of Carbon Dioxide (CO_2) for the Ten Days of Observation.

Calculated TWAs of all sizes of monitored particulate matter and CO_2 were shown to have a direct relationship over the ten days of monitoring (Figure 8).

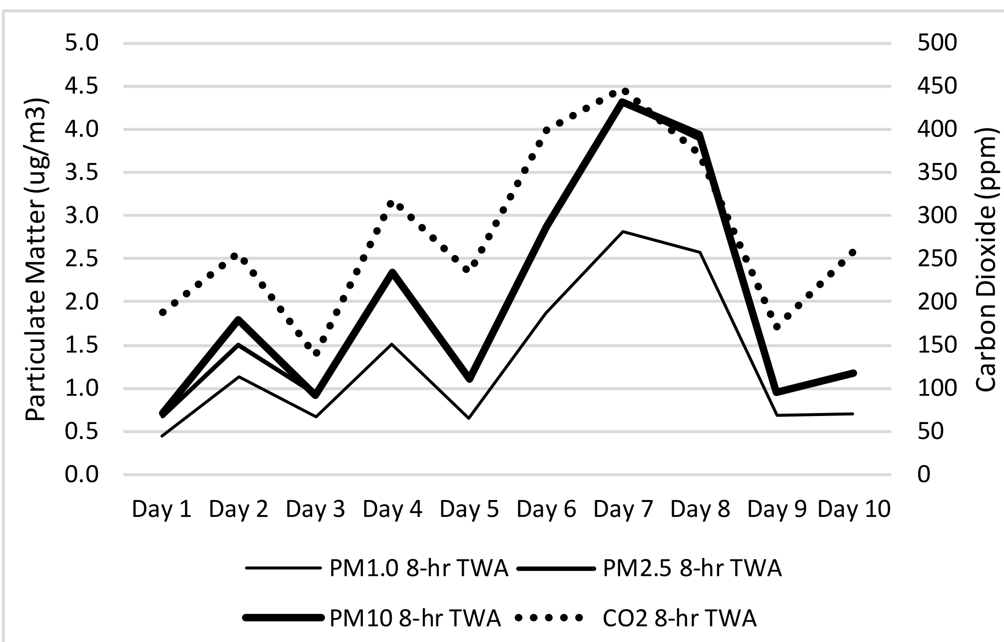

Figure 8. Calculated 8-hour TWAs of Carbon Dioxide (CO_2) and Particulate Matter ($PM_{1.0}$, $PM_{2.5}$, and PM_{10}) for the Ten Days of Observation.

3.3 Noise Levels

The maximum noise level ranged from 92.6 to 100.8 dBA, which is less than the 115 dBA short-term exposure limit (STEL) set by OSHA. The peak instantaneous noise level ranged from 118.9 to 127.5 dB, which is less than OSHA's instantaneous ceiling limit of 140 dB for impact noise. Results for both the maximum sound level and peak instantaneous noise level can be found in Table 1.

Table 1. Highest Recorded Maximum Noise Level and Peak Instantaneous Noise Level during Sampling Period for Each Day.

	Maximum Sound Level (Lasmx)[a]	**Peak Instantaneous Sound Level (Lcpk)[b]**
Day 1	100.5 dBA	122.6 dB
Day 2	98.7 dBA	121.2 dB
Day 3	94.2 dBA	123.0 dB
Day 4	97.7 dBA	127.5 dB
Day 5	83.2 dBA	122.3 dB
Day 6	92.6 dBA	127.1 dB
Day 7	98.3 dBA	123.9 dB
Day 8	95.7 dBA	119.9 dB
Day 9	97.6 dBA	126.0 dB
Day 10	100.8 dBA	118.9 dB

[a]*Lasmx* = highest sound level recorded during a measurement interval in dBA
[b]*Lcpk* = peak instantaneous sound pressure level

3.4 Temperature and Relative Humidity

Temperature measured in Fahrenheit ranged from 72.7 to 89.6 ^{o}F and relative humidity ranged from 23.6 to 45.7%. All average results over the day of monitoring can be found in Table 2. Temperature and relative humidity averages were compared to ASHRAE Standard 55-2017, Thermal Environmental Conditions for Human Occupancy[16], and recommended ranges of temperature for summer months ranged from 30% relative humidity for 76.0 to 82.0ºF, 40% relative humidity for 75.5 to 81.0 ºF, 50% relative humidity for 75.0 to 80.5 ºF, and 65% relative humidity for 74.5 to 80.0 ºF. Based on these recommendations, all ten days were not within the recommended ranges of temperature and relative humidity for thermal comfort for summer.

Table 2. Average Measurements of Temperature and Relative Humidity for the Ten Days of Observation.

	Average Temperature (ºF)	**Average Relative Humidity (%)**
Day 1	72.7	34.2
Day 2	89.3	28.8
Day 3	84.3	23.6
Day 4	83.1	45.0
Day 5	72.9	44.5
Day 6	82.8	29.1
Day 7	83.6	36.0
Day 8	89.6	31.6
Day 9	87.6	38.7
Day 10	83.3	45.7

4.0 Discussion

4.1 Comparison of Air quality results

This study evaluated the in-cabin concentrations of various air contaminants for a gasoline powered bus. Further, unlike many of the previous studies, the current study compared measured values to applicable regulatory and recommended limits. Previous studies have observed various couplings of in-cabin concentrations of HCHO, CO_2, CO, NO_x, SO_x, $PM_{1.0}$, $PM_{2.5}$, PM_{10}, and TVOC from gasoline powered cars, or diesel, biodiesel, compressed natural gas, or ultra-low sulfur diesel buses.[5-10,18-20]

When compared to recommended and regulatory limits, HCHO TWA exceeded the NIOSH REL over all ten days, but was less than other reported recommended and regulatory limits. The NIOSH REL is much lower than the enforceable PEL, the NIOSH REL for formaldehyde was set to be the lowest feasible concentration based on the analytical limit of quantification, as set forth in NIOSH's carcinogen policy.[23] Additionally, this value was derived with sensitive populations with pre-existing respiratory diseases who may experience symptoms at exposures between 0.05 to 0.1 ppm.[23] Bus drivers who have a history of allergies or have pre-existing respiratory diseases should be considered in this instance and their exposure should be evaluated if they begin to experience symptoms. The average results of HCHO were also considerably higher than results obtained from other researchers who have measured air pollutants that school children are exposed to in diesel and compressed natural gas buses, which ranged from 0.0003 to 0.0021 mg/m^3 with the windows open.[18] When compared to the 10-hour TWA of HCHO to the 10-hour adjusted ACGIH TLV of 0.084 mg/m^3 to simulate a worst-case scenario, seven out of ten days were greater than the adjusted TLV. The observed simulated results further prove that full-shift exposure monitoring for HCHO in buses should be considered in future studies.

The results of TVOC averages compared to HCHO averages were shown to have a direct relationship with maximum daily results for both variables being elevated at the same sampling instance. While HCHO is a VOC, it only accounted for up to 28% of the TVOCs measured, making the rest of the distribution of the in-cabin TVOCs to be from combustion by-products and off-gas of interior materials. Two studies observed TVOC concentrations inside newer vehicles found interior materials of cars less than three years of age to be the main contributor[20,21], while infiltration of combustion by-products was the next. The results from the Faber and Brodzik[20] study indicated a combined in-cabin TVOC level ranging from 0.136 to 14.8 mg/m^3. One study[10] in Hong Kong observed commuter exposure to aromatic VOCs in public transportation modes, and found BTEX concentrations to be higher in air-conditioned buses compared to non-air conditioned buses. The authors equated the higher concentrations in the air-conditioned bus to new interior. Additionally, multiple other studies[5,9,19] observed individual VOCs in cabin, however those results were not directly comparable to the current results since no characterization of individual VOC compounds were available in this study. Some notable differences from their results compared to our study included showing higher in-cabin VOC concentrations in the winter due to limited air exchange.[5,9] Overall, the values of TVOC in the current study were lower than previous research, may have been due to concentration levels in more densely populated areas, in-cabin difference due to heat and air conditioning, and methods to quantify the TVOCs.

4.2 Particulate matter and Carbon Dioxide

Compared to other studies within Ohio, the current results for various diameters of particulate matter were significantly lower. A study[5] of in-cabin pollutant concentration between two different buses powered by either biodiesel or ultra-low sulfur diesel in the City of Toledo observed results (in a similar time frame: April 2008) of $PM_{1.0}$ range from 11.24 to 11.87 µg/m^3, $PM_{2.5}$ range from 13.86 to 14.32 µg/m^3, and PM_{10} range from 23.0 to 24.28 µg/m^3. Another similar study[19] completed by the aforementioned authors calculated an 8-hour TWA for $PM_{2.5}$, which ranged from 9.51 to 17.99 µg/m^3 for ultra-low sulfur diesel and 7.84 to 18.82 µg/m^3 for biodiesel. Factors potentially affecting the differences between these two studies[5,9] and the current study include engine age, bus idling behavior, ambient particle concentrations, and vehicle density in the sampled area. The bus age was unknown in both of the studies completed in Toledo. However, a study[7] of in-cabin concentrations of particulate matter of 18 used private cars of varying age in Northern Italy found in-cabin levels directly depended on the ambient air concentrations and choice of ventilation in the vehicles. The bus that was used for this study had windows open and no air conditioning used, allowing for ambient particle concentration to heavily influence in-cabin concentrations, as shown by trends of average particulate concentrations in-cabin being slightly elevated on days with a moderate rating on the Air Quality Index[26] (days 4-8), compared to those with a good rating (days 1-3, 9-10).

A factor influencing ambient concentrations is the location of the monitoring instrumentation. Studies[7-10] of various in-cabin particulate matter concentrations done in China, Italy, and Ireland have shown much higher concentrations compared to our study. Additionally, weather conditions of the road surface can affect particulate matter with dry roads adding to ambient concentrations more than wet roads.[6] This was also observed in the current study with lower average concentrations on days where rain was involved (days 5 and 10).

In comparison to other studies, the current results of CO_2 averages were similar to the study[5] done in Toledo that had averages range from 498.91 to 508.22 ppm, however did not compare to the second study[19] that calculated an 8-hour TWA of 514.66 to 734.9 ppm, which was much higher than the current TWA results. The authors of the studies done in Toledo equate elevated CO_2 levels to passenger ridership, with maximum levels ranging from 1200 to 2100 ppm.[5] During the current study, passenger ridership throughout the study was relatively low (about two to four at a time, most of the time), with maximum CO_2 levels being during short instances (usually for only about ten to fifteen minutes) when more than seven passengers were on the bus. Due to low ridership, open windows, and no air conditioning, 8-hour TWAs of CO_2, $PM_{1.0}$, $PM_{2.5}$, and PM_{10} were shown to have a direct relationship over the ten days of sampling. All of the 8-hour TWAs for CO_2 and $PM_{1.0}$, $PM_{2.5}$, and PM_{10} were less than regulatory and recommended exposure limits. Additionally, all 10-hour TWAs for CO_2, $PM_{1.0}$, $PM_{2.5}$, and PM_{10} were less than the 10-hour adjusted TLV of 3500 ppm and 2100 $\mu g/m^3$, respectively.

4.3 Noise

Over ten days, the highest recorded maximum sound levels and peak instantaneous noise levels were less than the OSHA STEL for noise and less than the OSHA limit set for impact noise, respectively. It is important to differentiate between both the maximum sound level and peak instantaneous sound level. Maximum sound level (Lmax) is the highest average root means squared sound level with A-weighted frequency and slow response measured in a sampling instance. Peak instantaneous sound level (Lcpk) is the highest instantaneous level recorded during a measurement interval and is independent of dosimeter settings such as weighting and response. Due to this, maximum sound levels are typically always lower than instantaneous peak measures. Exposure to maximum sound levels equal to the 115 dBA STEL set by OSHA can lead to temporary threshold shifts in hearing, and exposure to impact or peak instantaneous sound levels at or above 140 dB can cause possible permanent damage to hearing.[22]

Main sources of noise during the sampling included passing sirens from ambulances, which ranged from a maximum sound level of 78.3 to 97.6 dBA and a peak level of 113.1 to 118.7 dB. There was one instance of a helicopter fly over, which produced a maximum sound level or 70.5 dBA and a peak level of 113.0 dB. Surprisingly, the most frequent cause of higher levels of maximum and peak sound levels was from the wheelchair lift at the back of the bus, which would rattle and shake when going over bumps and intensity of the levels increased as speed increased. The maximum sound level ranged from 75.9 to 98.7 dBA and peak levels ranged from 118.9 to 126 dB. Peak instantaneous measurements have not been measured in bus before (at least based on the literature search that was conducted at the time of publication). When comparing the results of maximum sound level, one study[11] observed noise levels in different types of transportation in New York City's transit systems and found in-bus levels ranged from 85.6 to 96.8 dBA. Additionally, another study[12] completed in Toronto observed maximum sound levels for in-bus ranged from 89.4 to 114.4 dBA. While the results of these studies have a range similar to the results of our study, these studies recorded measurements with dosimeters set up with a 3 dB exchange rate while our results were measured using a 5 dB exchange rate, which may account for some of the differences.

4.4 Temperature and Relative Humidity

Temperature and relative humidity averages were compared to ASHRAE Standard 55-2017, Thermal Environmental Conditions for Human Occupancy.[16] Based on these recommendations, all ten days were not within the recommended ranges of temperature and relative humidity for thermal comfort for summer. Previous studies[24,25] have shown material VOC emission rates to increase as temperature and relative humidity rise but decrease as air exchange rate increases. Due to the constant natural ventilation in-cabin during the current study, temperature and relative humidity were not observed to significantly influence TVOC or HCHO results.

4.5 Limitations

There are many variables that can affect driver exposure to in-cabin air pollutants, such as seasonal variations, bus age, ambient concentrations, ventilation, and route location. Limitations include only observing one season, use of one bus and route, and use of one type of ventilation, which hindered the ability to compare differences of all these factors. Additionally, the sampling time was another limitation of the study, as sampling time varied between two to six hours a day. Lastly, the specific time of day was not consistent to compare morning to night values. While these factors do not take away from the results observed in this study, it would have provided additional opportunities for comparison within the current study, and ultimately, comparisons to other studies.

5.0 Conclusions

Multiple consecutive days of sampling were carried out to measure the pollutant concentrations and sound levels inside a gasoline-powered bus. The measured values of potential exposures to the driver were compared to regulatory and recommended limits. In general, the results of particulate matter ($PM_{1.0}$, $PM_{2.5}$, and PM_{10}), carbon dioxide, maximum sound level, and peak instantaneous sound level were less than applicable recommended and regulatory limits. The only variable of concern was formaldehyde (HCHO) that was found to be greater than the 8-hour NIOSH REL over all ten days, and greater than the 10-hour adjusted ACGIH TLV for seven of the ten days in a worst-case scenario. Thus, it appears the driver of campus commuter buses may have limited exposure to air pollutants and noise levels. Future research is needed to investigate potential seasonal influences, variation between different buses (e.g., age and HVAC practices), and different engine types.

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APPENDIX A
Brief and Scala Method and Calculations for Longer Shifts

The Brief and Scala Method[27] for unusual work schedules is recommended by ACGIH to account for work shifts that are longer than the 8-hour, 40-hour work week to which the TLVs apply. This method adjusts the TLV to account for increased exposure time and decreased recovery time.

$$Adjusted\ TLV\ = Reduction\ Factor\ \times TLV$$

$$Reduction\ Factor = \frac{8}{daily\ hours\ worked} \times \frac{24 - daily\ hours\ worked}{16}$$

$$Daily\ Reduction\ Factor = \frac{8}{10} \times \frac{24 - 10}{16} = 0.7$$

$$Formaldehyde\ 12 - Hour\ Adjusted\ TLV = 0.12\frac{mg}{m3} \times 0.7 = 0.084\frac{mg}{m3}$$

$$Respirable\ Dust\ 12 - Hour\ Adjusted\ TLV = 3000\frac{ug}{m3} \times 0.7 = 2100\frac{ug}{m3}$$

$$Carbon\ Dioxide\ 12 - Hour\ Adjusted\ TLV = 5000\ ppm\ \times 0.7 = 3500\ ppm$$