Report #25-UI-167

NSTSCE

National Surface Transportation Safety Center for Excellence

Pilot In-Vehicle Carbon Monoxide Detector Study

Aditi Manke • Pat Hicks • Jon Hankey

Submitted: March 28, 2025

Technology
Impairment
Mobility
Infrastructure

Housed at the Virginia Tech Transportation Institute
3500 Transportation Research Plaza • Blacksburg, Virginia 24061

ACKNOWLEDGMENTS

The authors of this report would like to acknowledge the support of the stakeholders of the National Surface Transportation Safety Center for Excellence (NSTSCE): Zac Doerzaph from the Virginia Tech Transportation Institute; John Capp and Yi Glaser from General Motors Corporation; Terri Hallquist and Jonathan Mueller from the Federal Motor Carrier Safety Administration; Mike Fontaine from the Virginia Department of Transportation and the Virginia Transportation Research Council; and Melissa Miles and Elizabeth Pulver from State Farm Insurance.

The NSTSCE stakeholders have jointly funded this research for the purpose of developing and disseminating advanced transportation safety techniques and innovations.

EXECUTIVE SUMMARY

The study addresses the critical issue of carbon monoxide (CO) exposure in truck cabins, particularly in vehicles used for work zones. The research explores the levels of CO within these confined environments, with the objective of identifying factors that could contribute to increased CO levels. Two Truck Mounted Attenuators equipped with CO sensors and data acquisition systems were monitored under real-world operational conditions from July to December 2023.

The study shows that average in-cabin CO levels across the two vehicles were generally low, 1.22 ppm in Truck 1 and 1.61 ppm in Truck 2. There were occasional spikes, with levels reaching 10.05 ppm in Truck 1 and 8.59 ppm in Truck 2. These peaks occur during specific operational scenarios, such as prolonged idling, open windows, and acceleration near traffic congestion. The findings highlight the significance of both environmental factors (e.g., proximity to exhaust sources, ventilation efficiency) and operational behaviors in influencing CO exposure.

The analysis showed some patterns: CO levels were lowest during motion (1.14 ppm in Truck 1, 1.43 ppm in Truck 2), attributed to improved air circulation. But when parked on the road, levels rose to 1.63 ppm and 1.98 ppm, likely from idling and nearby traffic emissions. In controlled environments, such as parking facilities, CO levels stayed consistently low. These findings support prior studies that emphasize the impact of ventilation settings and driver practices on air quality (Dirks et al., 2018; Marinello et al., 2023).

The study highlights the role of vehicle maintenance and design in mitigating CO exposure. Older vehicles with compromised exhaust systems and poor ventilation settings worsen the in-cabin pollution levels. To minimize risks, real-time CO monitoring and regular maintenance are essential. Additionally, educating drivers on best practices, such as limiting idling and optimizing ventilation modes, can significantly reduce exposure.

While the study provides valuable insights, it is limited by its sample size (two vehicles) and duration (39 operational days per truck), which may not capture seasonal variations or represent broader fleet conditions. Future research should include more vehicle types, longer study periods, and additional factors like weather and window positioning to provide a more complete picture.

Overall, the research highlights the need for targeted interventions in truck cabin air quality management. Practical steps include upgrading ventilation systems, integrating CO detection technology, and implementing urban planning measures to cut down on traffic-related exposure. By focusing on these strategies, industry leaders can enhance driver safety and well-being while also contributing to broader public health improvements.

TABLE OF CONTENTS

LIST OF FIGURES

LIST OF TABLES

LIST OF ABBREVIATIONS AND SYMBOLS

CO	carbon monoxide
DAS	data acquisition system
EPA	Environmental Protection Agency
HVAC	heating, ventilation and air-conditioning
NO2	nitrogen dioxide
OSHA	Occupational Safety and Health Administration
PEL	permissible exposure limit
PM	particulate matter
ppm	parts per million
TWA	time weighted average
VDOT	Virginia Department of Transportation
VTTI	Virginia Tech Transportation Institute

CHAPTER 1. INTRODUCTION

The quality of air in transportation vehicles has become a growing area of interest over the past few decades. The enclosed spaces inside these vehicles are vulnerable to pollution from both internal and external sources. Factors like temperature, humidity, and airborne contaminants play a significant role in shaping the air quality within these environments, which can present health risks to passengers and drivers (Cheng et al., 2006). Among these pollutants, carbon monoxide (CO) is particularly concerning. This invisible, odorless gas is highly toxic and poses a serious threat in confined spaces like vehicle cabins.

Exposure to CO can lead to a range of health issues. Even at low to moderate levels, it can cause symptoms such as headaches, dizziness, and fatigue. Higher concentrations or prolonged exposure can result in severe consequences, including impaired vision, reduced cognitive function, and, in extreme cases, death (Davis et al., 2007). CO is dangerous because it binds to hemoglobin in the blood more readily than oxygen, reducing the body's ability to transport oxygen to vital organs.

Studying CO levels in vehicle cabins, particularly in trucks, is essential not just for individual health but also for broader occupational safety. Truck drivers, who spend long hours in their cabins, are especially at risk of CO exposure. Elevated CO levels in these environments can lead to fatigue, reduced alertness, and long-term health issues, which in turn may increase the likelihood of crashes (Harik et al., 2017). Since a truck cabin serves as both a workspace and a microenvironment, its air quality directly impacts a driver's well-being, safety, and productivity (Tan et al., 2006). This makes the study of in-cabin air quality a critical priority for researchers in environmental and occupational health.

This study piloted CO sensor testing under real-world conditions, focusing on truck cabins as representative environments. The objective was to measure CO levels inside truck cabins and identify environmental factors that could contribute to increased concentrations of CO.

CHAPTER 2. LITERATURE REVIEW

Research on air quality in truck cabins has become important due to its impact on both occupational health and road safety. While trucks play a critical role in logistics and transportation, field studies specifically examining air quality inside their cabins remain limited (Cheng et al., 2006). However, several key studies have provided valuable insights into the pollutants that truck drivers encounter. For example, Davis et al. (2006) conducted a large-scale study on U.S. diesel truck drivers and found that in-cab exposure to combustion particles was influenced by factors such as smoking, ambient air quality, truck age, and window positioning. Marinello et al. (2023) further highlighted that inadequate ventilation systems in truck cabins can worsen exposure to traffic-related air pollution.

A major concern in truck cabins is vehicle self-pollution, particularly in older or poorly maintained trucks where exhaust leaks can occur. Harik et al. (2017) found that self-pollution could contribute up to 30% of in-cabin exposure to CO and particulate matter (PM 2.5), often due to leaks in aging exhaust systems. Field studies measuring indoor air quality in truck cabins have reported CO and nitrogen dioxide (NO_2) levels near or exceeding safety thresholds, particularly in urban or congested areas. Portable monitoring systems have revealed that temperature and humidity often fall outside comfort ranges, further impacting air quality. Compared to cars or airplanes, truck cabins consistently show higher pollutant concentrations, underscoring the need for targeted research and mitigation strategies.

Studies of CO exposure in other vehicles provide useful comparisons. For instance, Harrison et al. (2002) observed that average CO exposure inside cars and buses (1.14 and 1.15 ppm, respectively) exceeded that in trains (0.59 ppm). Similarly, Arnold et al. (2004) reported that personal CO exposure was highest in cars (1.4 mg/m^3), followed by taxis (1.2 mg/m^3) and buses (0.8 mg/m^3). These findings suggest that vehicle occupants, particularly in smaller or older vehicles, may face significant exposure risks.

Several factors contribute to elevated CO exposure inside vehicles. The age and maintenance condition of vehicles significantly affect pollutant levels. Older vehicles with worn seals and deteriorating exhaust systems are more prone to in-cabin CO leaks. Duggan (2024) found a significant correlation between vehicle age and CO concentrations, with older cars and trucks frequently exceeding WHO-recommended limits.

Studies have also shown that the ventilation mode plays a critical role. Dirks et al. (2018) highlighted that different ventilation settings can drastically alter in-cabin CO concentrations. Specifically, the “recirculate” setting often resulted in higher CO levels compared to settings that allow fresh air from outside (“new air”) or having the windows open. This was particularly noted during peak traffic times when vehicles are closer to each other, increasing the likelihood of CO infiltration from nearby exhaust.

Studies also highlight the impact of driver behaviors, such as prolonged idling, which significantly increases in-cabin pollutant levels. For instance, a UK study reported CO concentrations peaking during idling periods in older vehicles, with levels occasionally exceeding health-based thresholds. These findings underline the importance of incorporating routine maintenance and educating drivers about practices that minimize exposure risk. The variation in CO concentrations across studies highlights differences in methodology, locations, and vehicle conditions. Duggan (2024) reported mean in-cabin CO levels ranging from negligible to 192 ppm, with the highest exposures in vehicles with internal exhaust leaks. Similarly, Harik et al. (2017) observed that truck cabin CO levels were 2–3 times higher than those in passenger vehicles due to prolonged operational hours and closer proximity to exhaust sources.

REGULATORY CONTEXTS AND ADVANCES

The U.S. has taken significant steps to reduce CO emissions and exposure through regulations like the Clean Air Act, first enacted in 1963. Over time, stricter emission standards have led to major advancements, such as the widespread use of catalytic converters and improved vehicle technologies. Programs like California's Smog Check have further helped cut CO emissions, making the air inside and outside vehicles much cleaner than in previous decades.

Longitudinal studies in the U.S. illustrate the positive impact of regulations on CO exposure. Flachsbart and Ott (2019) reported a decline in mean in-vehicle CO concentrations from 9.7 ppm in 1980 to 0.5 ppm in 2010, driven by stricter emissions standards and improved vehicle technologies. However, these gains are not evenly distributed. Older vehicles and areas with dense traffic continue to pose challenges.

Occupational exposure standards set by the Occupational Safety and Health Administration (OSHA) limit CO exposure to 50 ppm over an 8-hour workday, with short-term exposure limits of 200 ppm. Complementing these workplace guidelines, the Environmental Protection Agency (EPA) established ambient air quality standards to protect the general population. For CO, the EPA's National Ambient Air Quality Standards recommend maintaining 8-hour average concentrations below 9 ppm to minimize health risks. Despite these efforts, gaps in enforcement and the aging vehicle fleet pose ongoing challenges. Advocacy groups like the National Carbon Monoxide Awareness Association have called for lower alarm thresholds on CO detectors to address chronic low-level exposure risks.

Overall, research on air quality in truck cabins highlights an urgent need to address occupational health risks and promote road safety. While there has been progress in understanding pollutant exposure in vehicles, truck cabins remain an understudied environment despite the unique challenges they pose. Truck drivers, who spend long hours in confined spaces, face heightened risks from factors like vehicle self-pollution, poor ventilation, and aging equipment. Studies on in-vehicle air quality emphasize how variables such as vehicle age, maintenance habits, ventilation settings, and driver behaviors can all contribute to elevated CO levels. It's clear that more focused research is needed to better understand CO exposure in truck cabins, create effective strategies to reduce risks, and shape policies that prioritize the health and safety of truck drivers.

CHAPTER 3. METHODS

Researchers at the Virginia Tech Transportation Institute (VTTI) partnered with the Virginia Department of Transportation (VDOT) to conduct a pilot study exploring CO exposure in work zone environments. For this study, CO sensors provided by Crowcon Gas were installed in two Truck Mounted Attenuators located in Northern Virginia. VTTI obtained VDOT's approval to equip these vehicles with both the sensors and data acquisition systems (DASs).

STUDY SETUP AND DATA COLLECTION

The study setup involved multiple steps to ensure comprehensive air quality monitoring inside vehicles, including sensor installation, video recording, and a structured data collection period.

Sensor Installation

The primary sensing unit was the AMG-300 multi-gas detector, which provided real-time CO concentration readings and allowed historical data export via USB. These sensors were configured to log data every 2 minutes and had the capacity to store up to 75 days of readings. To streamline operations and avoid the need for recalibration during each startup, the sensors remained active 24/7, recording continuously regardless of whether the truck was operational.

Video Recording

The DAS included three cameras: one capturing the external environment to assess traffic density and vehicle idling, one positioned at the rear of the cabin to observe whether windows were rolled up or down, and another to observe the heating, ventilation and air-conditioning (HVAC) system.

Study Duration

The data collection phase ran from July 25, 2023, to December 15, 2023. VTTI researchers conducted routine visits to the VDOT locations to maintain the equipment and download sensor data, ensuring that no information was lost due to the DAS's 75-day storage limit.

DATA ANALYSIS

Data analysis utilized summary statistics, including mean, median, line graphs, and box plots, to evaluate CO levels under various conditions. Negative CO readings, which are always expected to be positive, were excluded from the dataset as they likely indicated measurement errors. During the study, DAS video footage failed during 12 trips while the truck was operational, resulting in the loss of approximately 24 hours of video data for analysis. Without video context to determine the truck's operational scenario, these data points were removed from the analysis. The available video data was instrumental in categorizing operational scenarios, such as when the truck was parked at a fleet yard facility, on the road, in a public parking lot, or in motion. This categorization enabled a deeper exploration of CO exposure across different contexts. As a pilot study, the research provided valuable insights into the potential risks of CO exposure in trucking environments and highlighted the environmental and operational factors influencing gas concentrations.

CHAPTER 4. RESULTS

Data on CO levels was gathered from two VDOT trucks which are used in work zones from July 25, 2023, to December 15, 2023. Since the trucks would be in operation based on their work assignments, the trucks were not active during all days in the study period. The data from the two trucks were analyzed separately.

TRUCK 1

During the study period, Truck 1 was operational for 39 days and VTTI's DAS collected around 120 hours of video data. The make and model of Truck 1 is Class 6, 2019 International MV607 SBA 4x2. Table 1 provides a cumulative summary of the in-cabin CO levels for Truck 1 during its operation and over the data collection period. CO levels were recorded at 2-minute intervals and the truck was in use at various times during the day. A total of 3,604 in-cabin CO measurements were recorded during the truck's operation. The results show that the average in-cabin CO level for Truck 1 was relatively low (1.22 ppm), but there was some variation in the readings. The presence of a maximum value of 10.05 ppm indicates some occasional spikes in CO levels. The median value of 1.04, being lower than the mean, further indicates that most readings were concentrated at lower levels, with occasionally higher spikes influencing the average.

Table 1. Summary statistics of CO levels in Truck 1.

Vehicles	N	Mean	Std. Dev.	Median	Min	Max
Truck 1	3,604	1.22	0.91	1.04	0	10.05

Figure 1 illustrates the distribution of in-cabin CO levels during operation. The CO levels were categorized into five ranges: 0 ppm, up to 1 ppm, 1–3 ppm, 3–4 ppm, and above 4 ppm. The data reveals that 1,700 measurements recorded CO levels at or below 1 ppm, while another 1,740 measurements fell between 1 and 3 ppm. Combined, these categories represent approximately 95% of all measurements, indicating that CO levels were predominantly low. This aligns with a mean value of 1.22 ppm and a standard deviation of 0.91 ppm. Occurrences of zero CO levels were infrequent, with just 16 measurements, reflecting periods when the truck was stationary or well-ventilated (i.e., windows were rolled down). Elevated CO levels between 3 and 4 ppm were recorded in 62 instances, while levels exceeding 4 ppm appeared in 86 measurements. The highest recorded CO level was 10.05 ppm. These occasional spikes indicate specific conditions, such as increased engine activity or environmental factors, that momentarily raised CO levels.

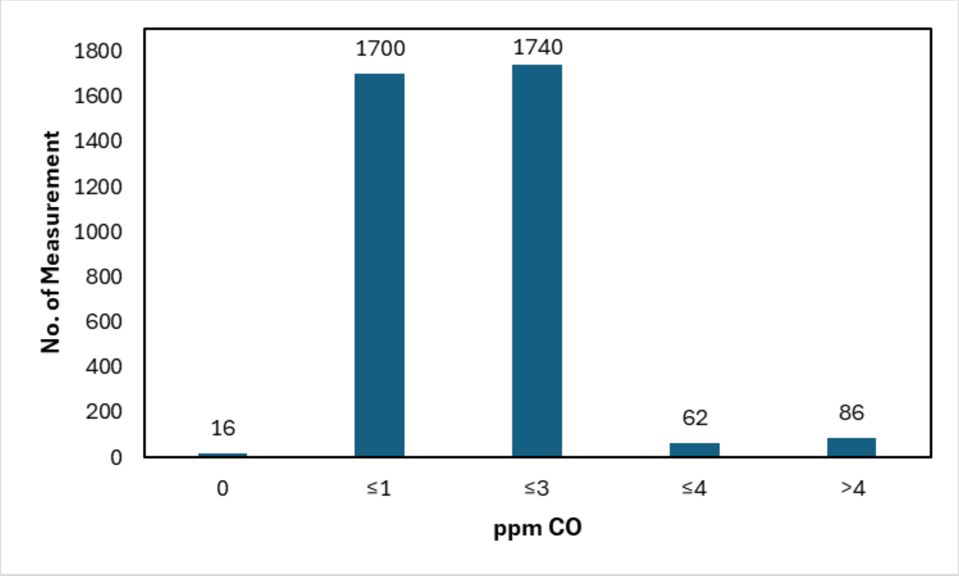

Figure 1. Chart. Number of measurements corresponding to CO levels.

Figure 2 shows the average in-cabin CO levels for Truck 1 during various operational scenarios over a 39-day period, highlighting how CO levels varied depending on the truck's activity. The lowest average CO level, 0.7 ppm, was recorded when the truck was at the fleet yard facility, likely due to controlled and well-ventilated conditions. When the truck was in motion, the average CO level rose slightly to 1.14 ppm, indicating that CO levels while driving were generally low and well-managed within the cabin. Higher averages were observed when the truck was stationary: 1.63 ppm when parked on the road, likely due to engine idling or environmental exposure, and 1.45 ppm when parked in a public lot, reflecting similar factors but at slightly reduced levels compared to being parked on the road.

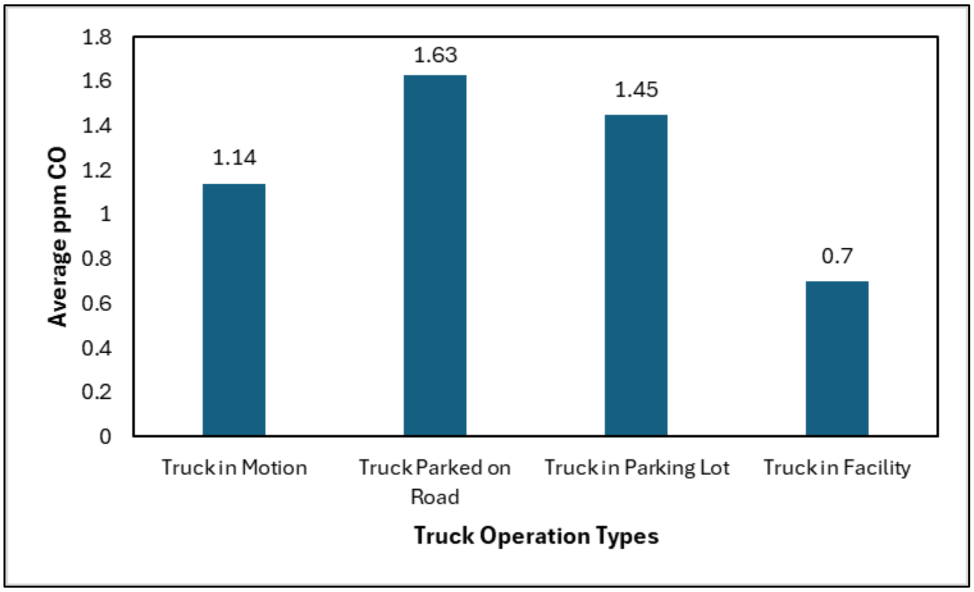

Figure 2. Chart. Average ppm CO by truck operation types.

Figure 3 shows how in-cabin CO levels changed throughout the day on September 5, 2023, comparing the recorded exposure to OSHA's 8-hour permissible exposure limit (PEL) of 50 ppm. The blue line represents the measured CO levels, which stayed consistently low with only minor fluctuations and a small peak later in the shift. The red dashed line represents the time-weighted average (TWA) CO exposure, which remained well below the OSHA limit. This suggests that even if the shift had extended to a full 8 hours, the overall CO exposure would still have been within safe limits. The black dashed line marks the OSHA exposure threshold, showing that CO levels never approached a concerning level at any point. This analysis focuses on one full workday rather than multiple days. The data was only recorded while the truck was in use, so there are breaks and gaps both between days and sometimes even within a day, making it difficult to track cumulative CO exposure over extended periods. By examining a continuous 7.5-hour shift, this approach provides a clearer picture of the driver's exposure without misrepresenting long-term trends. The results indicate that CO exposure inside the truck cabin was well within safety limits, and even the short-term peaks did not pose a significant risk to the driver's health.

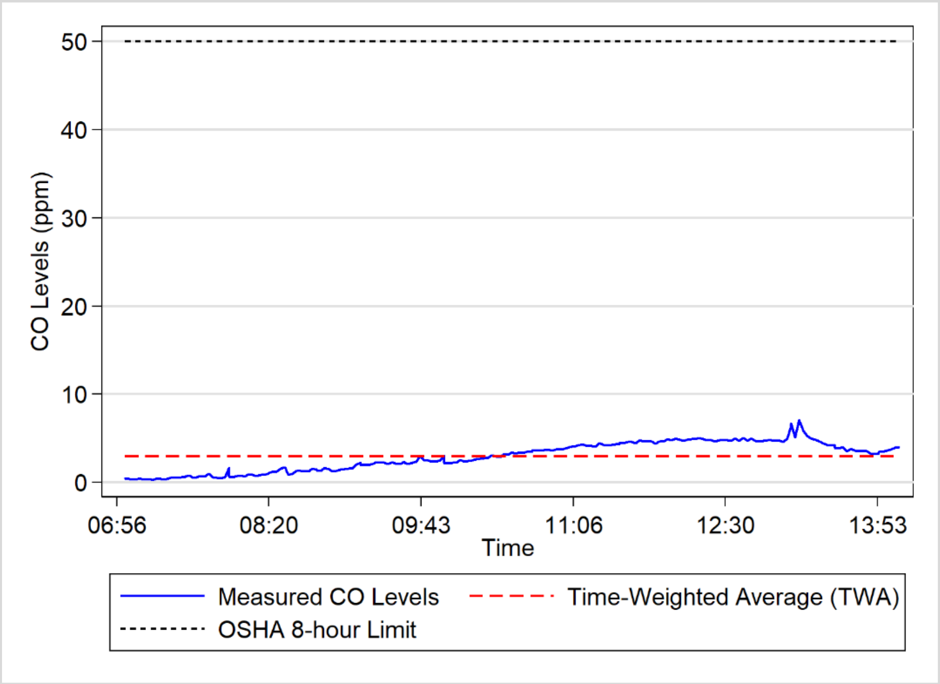

Figure 3. Graph. CO distribution on September 5, 2023.

To better understand how driving scenarios might influence CO levels inside the truck cabin, the team analyzed data from two specific days, focusing on variability based on driving environment and acceleration. Figure 4 highlights the distribution of in-cabin CO levels recorded on September 29, 2023, over time, with the mean CO level marked by a dotted line at 1.65 ppm.

The data reveals fluctuating CO levels throughout the morning, with notable spikes at specific times. The minimum CO level, 1.04 ppm, reflects relatively low concentrations during several periods, particularly between 7:13 a.m. and 8:20 a.m., when levels remained stable and below the mean. However, a sharp spike occurred at 8:59 a.m., with CO levels surging to around 7 ppm.

After this, levels briefly returned closer to the mean before another significant peak was recorded at 11:03 a.m., reaching the day's maximum value of 10.05 ppm. These spikes occurred during specific events or conditions that temporarily elevated CO concentrations.

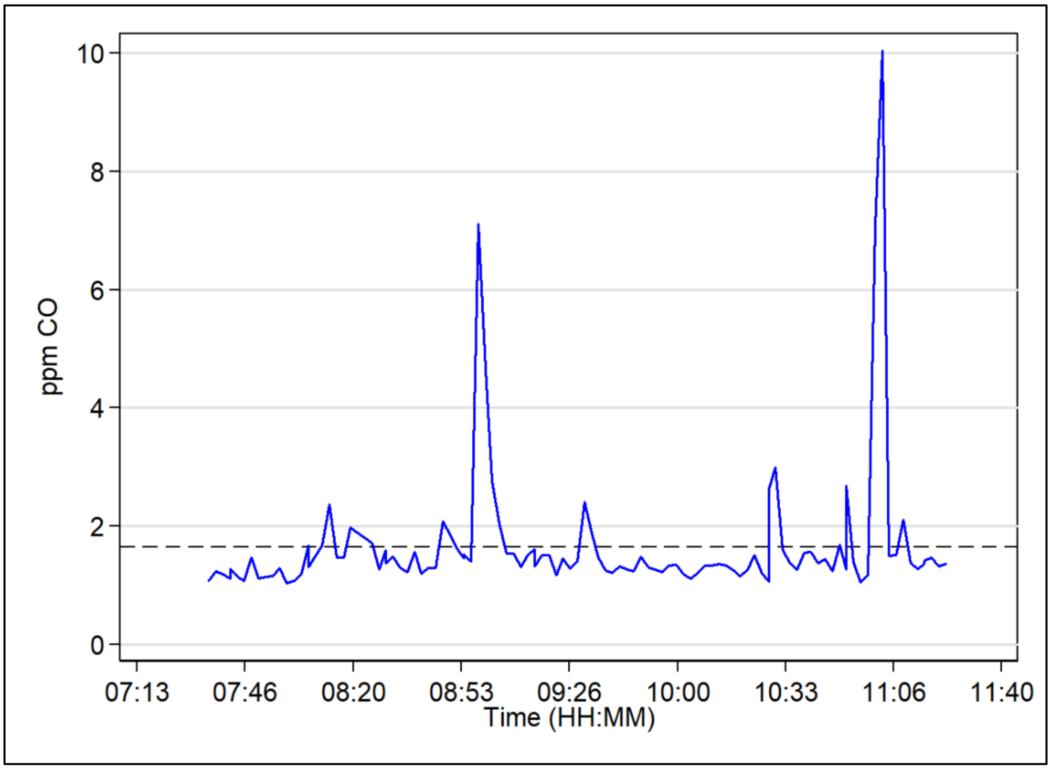

Figure 4. Graph. CO distribution on September 29, 2023.

Table 2 summarizes the in-cabin CO levels recorded during different operational scenarios for Truck 1 on September 29, 2023, revealing how CO levels varied based on the type of activity. While the truck was in motion, the average CO level was 1.2 ppm, with the widest variability, reflected in a standard deviation of 1.71 ppm. This scenario also recorded the highest CO level of 10.05 ppm, likely due to specific conditions causing sharp spikes in concentration. When parked on the road, the average CO level increased to 1.64 ppm, with a maximum of 7.12 ppm and a standard deviation of 0.94 ppm. This suggests consistently higher but somewhat less variable CO levels compared to when the truck was moving. In contrast, when parked and idling in a public lot, the average CO level was 1.45 ppm, with much lower variability (a standard deviation of 0.18 ppm) and a maximum value of 1.71 ppm, reflecting relatively stable conditions. The lowest CO levels were observed when the truck was idling at the fleet yard facility, with an average of 1.17 ppm, minimal variability (standard deviation of 0.12 ppm), and a range of 1.04 to 1.47 ppm.

Table 2. Summary statistics of CO levels by truck operation types.

Truck Operation Types	N	Mean	Std. Dev.	Min	Max
Truck in Motion	36	1.2	1.71	1.05	10.05
Truck Parked on Road	57	1.64	0.94	1.06	7.12
Truck Parked in a Lot	6	1.45	0.18	1.26	1.71
Truck in Facility	14	1.17	0.12	1.04	1.47

Figure 5 provides insight into the driving environment during the first peak in CO levels, which occurred between 8:50 a.m. and 9:00 a.m. on September 29, 2023. At this time, the truck was parked near the median, with light traffic visible on the road. A review of the over-the-shoulder video revealed that the driver had rolled down the window, which may have allowed outside air and exhaust fumes to enter the cabin. Additionally, the truck's velocity increased from 0.05 m/s at 8:57 a.m. to 2.12 m/s at 8:59 a.m. as the driver started the engine and moved forward slightly before stopping again. This brief engine activity, combined with the open window, likely contributed to the spike in CO levels. The interaction of factors such as engine operation, slight movement, and the rolled-down window offers a likely explanation for the sudden rise in in-cabin CO concentrations during this period.

Figure 5. Photo. Driving environment during first peak on September 29, 2023.

Figure 6 highlights the driving environment during the second CO level peak, which occurred between 10:55 a.m. and 11:05 a.m. At this time, the truck was in motion, making stops at a traffic light with moderate traffic surrounding the vehicle. A review of the over-the-shoulder video showed that the driver had rolled down the window. The video also revealed that the truck idled for about 2 minutes while waiting at the traffic light before accelerating when the light turned green. The spike in CO levels during this period is likely due to a combination of engine emissions while idling, exhaust from nearby vehicles in traffic, and the open window, which allowed fumes to enter the cabin.

Figure 6. Photo. driving environment during second peak on September 29, 2023.

The team also looked at the variability of CO levels during nighttime when the truck was in operation. The box plot in Figure 7 illustrates the distribution of in-cabin CO levels between 8 p.m. on October 15 and 4 a.m. on October 16, based on 89 observations. The average CO level during this period was 0.181 ppm, with a standard deviation of 0.211 ppm, indicating generally low and consistent CO levels. The minimum recorded level was 0 ppm, reflecting instances of negligible CO exposure, while the maximum reached 1.17 ppm, appearing as an outlier above the whiskers. The interquartile range spanned approximately from 0.1 to 0.3 ppm. The median, slightly below 0.2 ppm, shows that most readings were clustered at the lower end of the range. Overall, the data indicates that in-cabin CO levels were consistently low during this timeframe, with a few sporadic spikes.

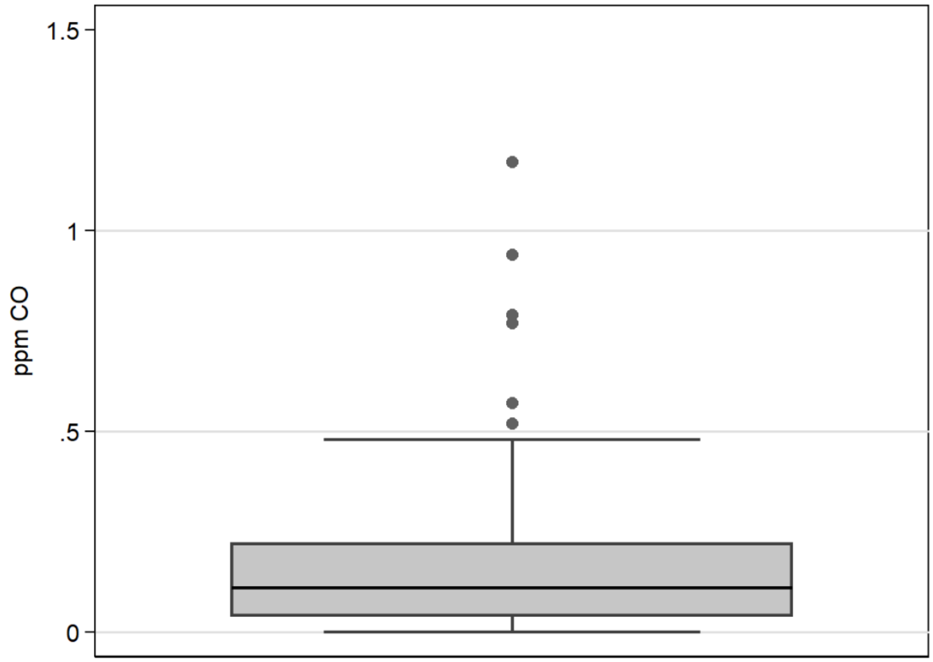

Figure 7. Illustration. Box plot of distribution of CO levels on October 16, 2023.

TRUCK 2

During the study period, Truck 2 was operational for 39 days, with VTTI's DAS system capturing approximately 105 hours of video data. The make and model of Truck 2 is a Class 6 1995 International 4700 4x2. Table 3 provides a summary of the CO levels measured inside the cabin during this time, when the truck operated intermittently at various intervals. A total of 3,155 measurements were collected, with an average CO level of 1.61 ppm and a median of 1.23 ppm. This indicates that most CO levels tended to cluster near the lower end, although the mean was slightly influenced by higher readings. The standard deviation of 1.07 ppm reflects moderate variability, with CO levels ranging from a low of 0.12 ppm to a high of 8.59 ppm. These occasional spikes in CO concentrations likely stem from specific operational or environmental factors.

Table 3. Summary statistics of CO levels in Truck 2.

Vehicles	N	Mean	Std. Dev.	Median	Min	Max
Truck 2	3,155	1.61	1.07	1.23	0.12	8.59

Figure 8 depicts the distribution of in-cabin CO levels during operation, categorized into four ranges: up to 1 ppm, 1–3 ppm, 3–5 ppm, and above 5 ppm. The majority of the measurements (1,273) recorded CO levels at or below 1 ppm, with an even greater number (1,563) falling between 1 and 3 ppm—closely aligning with the average CO level of 1.61 ppm. Fewer measurements (284) were in the range of 3 to 5 ppm, and only 35 readings exceeded 5 ppm. This distribution highlights that most CO levels were relatively low, with higher concentrations occurring rarely.

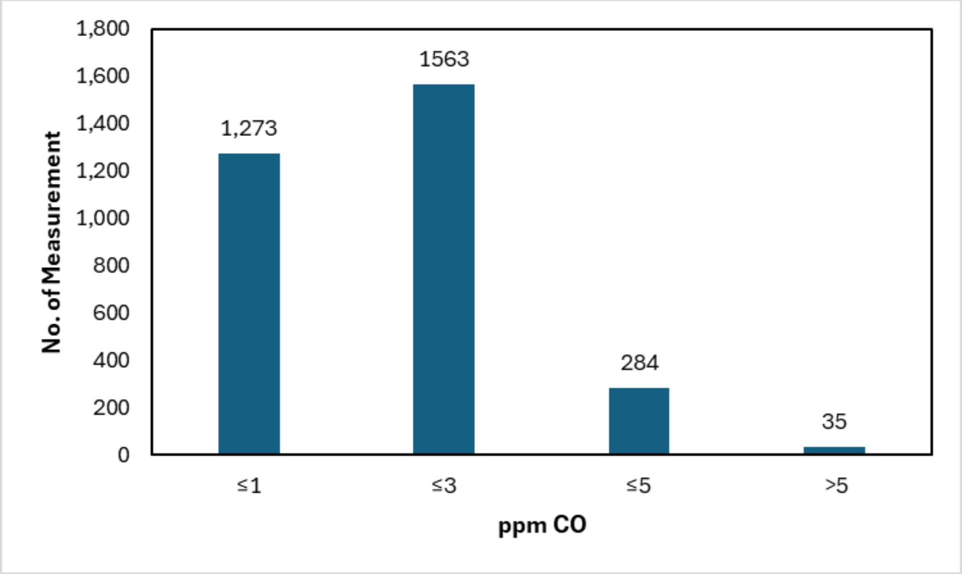

Figure 8. Chart. Number of measurements corresponding to CO levels.

Figure 9 shows the average CO levels inside the cabin of Truck 2 during various operational scenarios over 39 days. The highest average CO level, 1.98 ppm, was observed when the truck was parked on the road. This elevated level is likely due to environmental factors such as proximity to traffic or exhaust from idling. When parked in a public parking lot, the average CO level was slightly lower at 1.52 ppm, reflecting similar influences but with less intensity compared to being parked on the road. During motion, the average CO level decreased to 1.43 ppm, likely because of improved air circulation and reduced idling. The lowest average CO level, 1.14 ppm, occurred when the truck was inside a fleet yard facility, where controlled conditions likely contributed to the reduced levels.

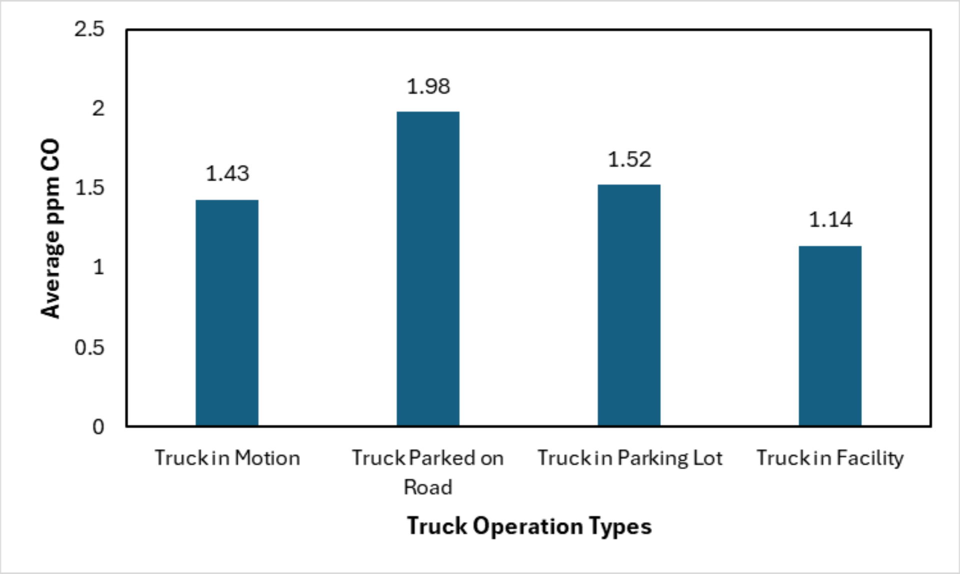

Figure 9. Chart. Average ppm CO by truck operation types.

Figure 10 shows how CO levels fluctuated inside the truck cabin throughout the day on October 6, 2023, with a focus on comparing exposure to OSHA's 8-hour PEL. The blue line represents the actual CO levels recorded, while the red dashed line shows the TWA, and the black dashed line marks OSHA's exposure limit of 50 ppm. Throughout the day, CO levels stayed relatively low, with occasional small spikes depending on the truck's operation. Importantly, the TWA remained well below OSHA's threshold, suggesting that even with some fluctuations, overall exposure was within safe limits. This particular day was analyzed because the dataset had gaps in time and wasn't continuous, making it impossible to track cumulative exposure across multiple days. The results indicate that, under normal driving and idling conditions, CO levels inside the truck cabin do not pose a significant health risk based on OSHA's guidelines.

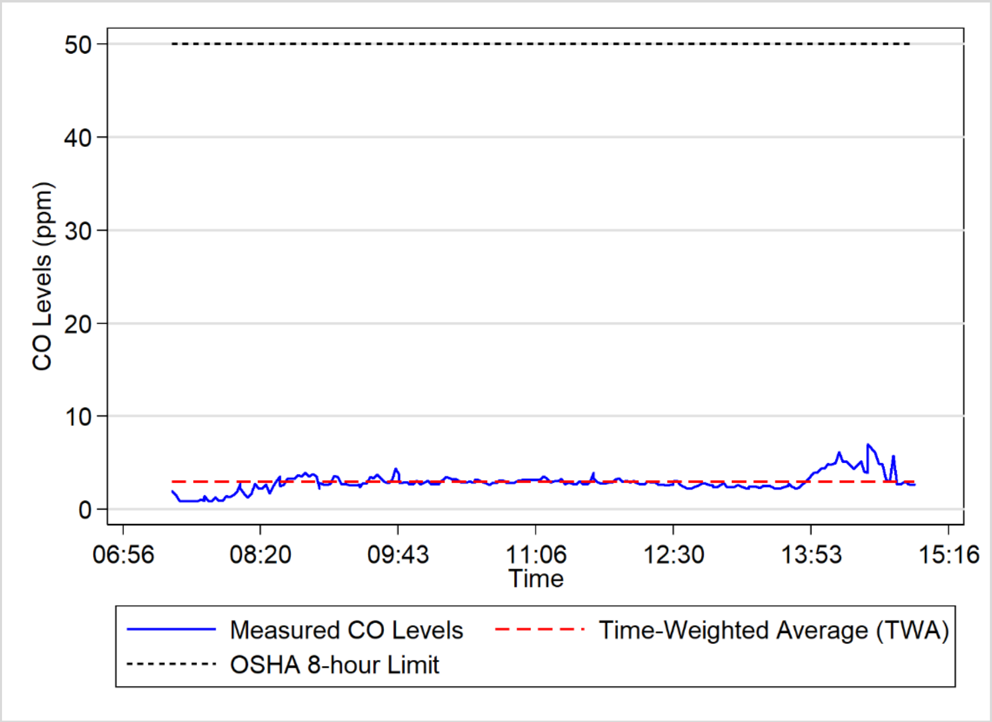

Figure 10. Graph. CO distribution on October 6, 2023.

For Truck 2, the team also focused on one case scenario to better understand how the driving environment might influence CO levels inside the truck cabin. Figure 11 shows the distribution of CO levels inside the cabin of Truck 2 on October 4, 2023, with the mean CO level represented by a dotted line at 2.14 ppm. Throughout the day, CO levels ranged from a minimum of 1.12 ppm to a maximum of 8.59 ppm, with a standard deviation of 0.74 ppm, indicating moderate variability around the mean. In the early hours of the day, CO levels remained relatively stable, hovering below or near the mean. However, after 8:00 a.m., fluctuations began to increase, culminating in a significant spike at approximately 9:10 a.m., when CO levels reached the day's maximum of 8.59 ppm. Following this peak, levels gradually declined and stabilized around the mean until about 1:00 p.m. In the afternoon, particularly after 1:30 p.m., CO levels started to rise again, displaying increased variability and several smaller peaks.

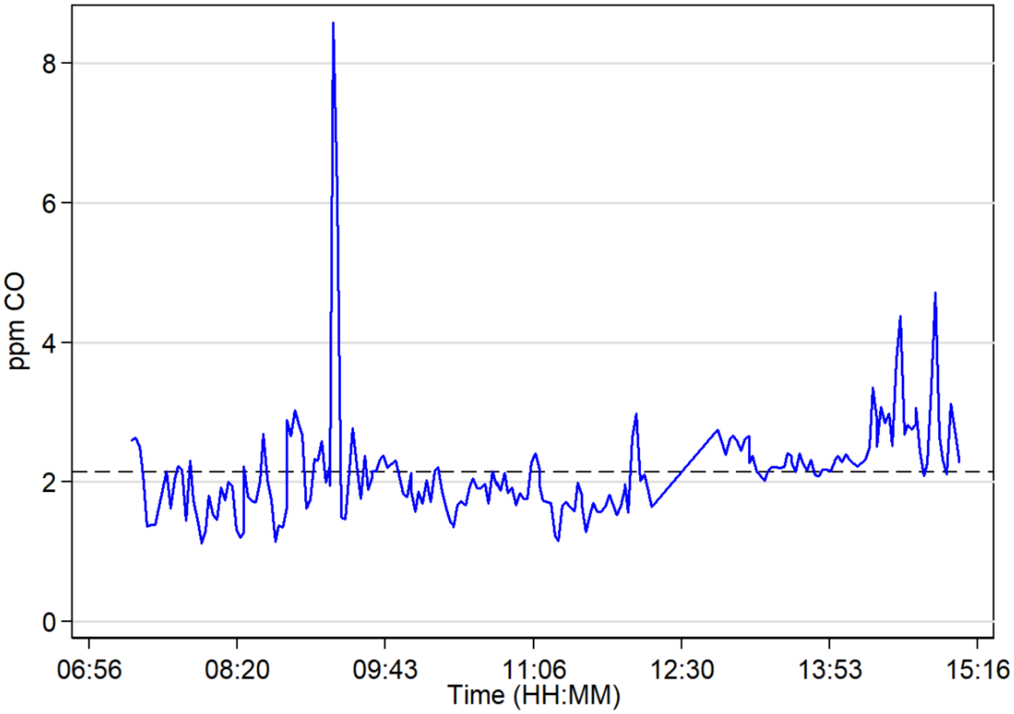

Figure 11. Graph. CO distribution on October 4, 2023.

Figure 12 highlights the driving environment surrounding the truck during the first significant CO level peak around 9:10 a.m. Video footage reveals that the truck was frequently starting and stopping in light traffic conditions. The driver had rolled down the window, which allowed exhaust fumes from the truck or nearby vehicles to enter the cabin. The truck's velocity increased from 0.06 m/s at 9:08 a.m. to 5.22 m/s by 9:10 a.m., indicating a sudden acceleration after a period of near idling. The spike in CO levels during this time is likely due to exhaust emissions being released as the engine transitioned from an idling state to acceleration, coupled with the open window, which allowed these emissions to seep in the cabin.

Figure 12. Photo. Driving environment during the first peak on October 4, 2023.

The graph in Figure 13 illustrates the distribution of CO levels inside the cabin of Truck 2 during a 2.5-hour period on October 4, while the truck was parked roadside with light to medium traffic passing by. During this time, the truck remained mostly stationary, with an average velocity of just 0.018 m/s, and the driver was not inside the vehicle. CO levels fluctuated between roughly 1 ppm and just under 3 ppm, showing noticeable variability throughout the period. The intermittent movement of traffic and occasional forward adjustments of the truck likely contributed to these fluctuations, as exhaust emissions from nearby vehicles, or the truck itself, entered the cabin. Toward the end of the period, CO levels rose consistently, possibly reflecting increased traffic density or increase in acceleration or both. This data underscores how external factors, such as nearby traffic, can significantly influence in-cabin CO levels even when the vehicle is parked.

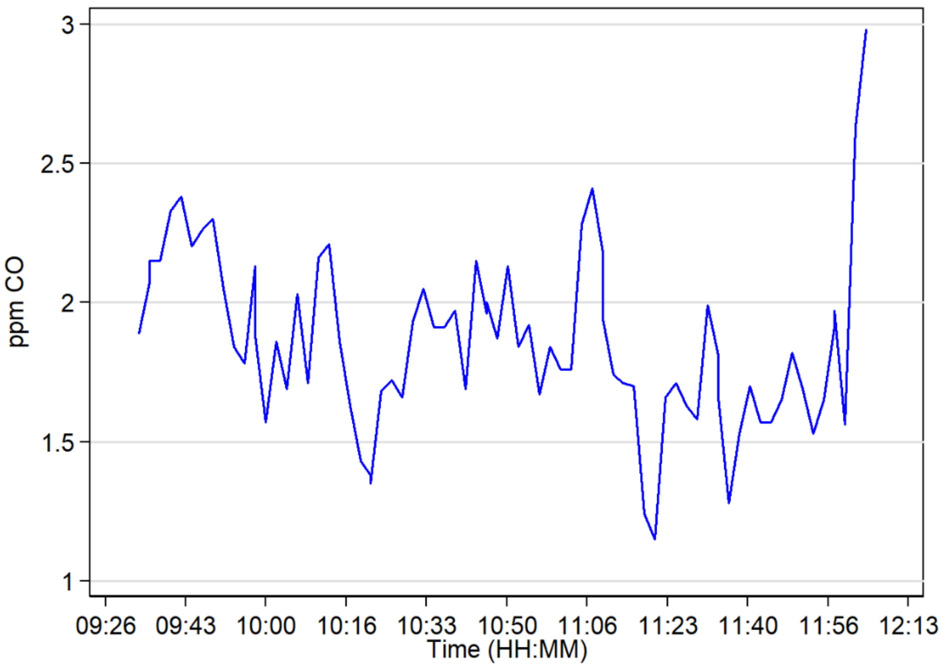

Figure 13. Graph. CO distribution during truck parked on road.

CHAPTER 5. DISCUSSION

The results of this study provide valuable insights into the in-cabin CO levels of two VDOT trucks operating in work zones. These findings align with existing literature on vehicle cabin air quality while offering fresh perspectives on CO exposure in work trucks.

Truck 1 showed an average CO level of 1.22 ppm, while Truck 2 had an average of 1.61 ppm. Both trucks generally maintained low CO concentrations, but occasional spikes were observed, reaching 10.05 ppm in Truck 1 and 8.59 ppm in Truck 2. These peaks seem to occur during specific activities such as idling, using window ventilation, and accelerating in traffic, supporting findings from Harik et al. (2017), which highlighted idling and proximity to exhaust as major factors in CO exposure.

In Truck 1, the highest CO levels occurred while parked on the road (average 1.63 ppm), likely due to idling near traffic. Controlled conditions in a fleet yard facility showed significantly lower levels (0.7–1.17 ppm). Similarly, Truck 2 saw its highest levels (1.98 ppm) while parked, with levels dropping to 1.43 ppm during motion, likely due to better ventilation. This pattern supports research like Dirks et al. (2018), which found that fresh air reduces in-cabin CO levels. Other studies, such as Koushki et al. (1992) and El-Fadel and Abi-Esber (2009), also highlight how external factors like traffic and ventilation efficiency affect air quality in vehicle cabins.

The study also reinforces previous findings on the impact of vehicle age and maintenance on in-cabin CO levels (Duggan, 2024). The trucks in this study varied significantly in age, with Truck 1 being 4 years old and Truck 2 being 28 years old at the time of the study. The observed CO spikes during specific operational activities such as idling and acceleration highlight the importance of engine performance and maintenance, which may be more critical for older vehicles. Additionally, ventilation settings and driver behaviors, such as rolling down windows, emerged as significant factors influencing exposure. These observations align with Marinello et al. (2023), who emphasized the critical role of ventilation in managing in-cabin air quality.

Moreover, the study showed that CO levels in both trucks were generally within OSHA's safe occupational exposure limits of 50 ppm over an 8-hour period. On the specific days analyzed, September 5, 2023, for Truck 1 and October 6, 2023, for Truck 2, CO exposure was consistently low, with only minor fluctuations and occasional small peaks. The TWA for both trucks remained well below OSHA's threshold, indicating that even if shifts had extended to a full 8-hour period, the overall exposure would have remained within safe limits. Notably, CO levels never approached concerning levels at any point, reinforcing that under normal driving and idling conditions, in-cabin CO exposure does not pose a significant health risk according to OSHA guidelines. While intermittent spikes were observed, they did not reach levels that would trigger immediate concern. This observation aligns with Davis et al. (2006), who noted that localized spikes in pollutant levels pose significant risks, even when average concentrations remain low. The study also highlights minimal CO levels in Truck 1 during nighttime operations, averaging 0.181 ppm, with infrequent peaks. This contrasts with daytime operational spikes and suggests the impact of environmental factors, such as reduced traffic density, on in-cabin air quality. By focusing on work-zone trucks, this study expands existing research, emphasizing the importance of driver health and safety in occupational settings.

These findings highlight the need for targeted solutions to improve air quality in truck cabins. Studies like Tan et al. (2006) show that truck cabins often have higher CO and NO_2 levels than other transportation environments, strengthening the need for action. Simple but effective strategies such as improving ventilation systems, enforcing regular maintenance, and educating drivers on how to minimize exposure can make a significant difference. Beyond individual trucks, urban planning efforts, like easing congestion near high-traffic work zones, could help protect both drivers and the surrounding community from prolonged exposure to harmful pollutants.

STUDY LIMITATIONS

Despite its contributions, the study has notable limitations:

1. **Limited Sample Size**: With data collected from only two trucks, the findings may not fully represent the variability across different truck types, designs, and ages. Expanding the sample size could provide a more comprehensive understanding of influencing factors.

2. **Short-Term Monitoring**: While data collection spanned multiple months, only 39 days of operational data were recorded for Truck 1. This temporal scope may not account for seasonal variations in air quality or HVAC usage.

3. **Unmeasured Variables**: Key factors, such as real-time weather conditions, ventilation settings, and cabin window positions, were not explicitly tracked. These variables likely play a significant role in determining in-cabin pollutant levels, as highlighted by Koushki et al. (1992) and Harik et al. (2017).

CONCLUSION

This study highlights the importance of maintaining in-cabin air quality for truck drivers, who spend extended periods in enclosed spaces. While average CO levels were within safe limits, periodic spikes pose risks influenced by external conditions like traffic and operational activities, as well as internal factors such as cabin design and ventilation.

Future research should address current limitations by studying a larger and more diverse sample of vehicles, tracking seasonal variations, and monitoring real-time variables like weather and ventilation settings. Innovations such as real-time CO monitoring systems could alert drivers to hazardous conditions and help mitigate risks immediately. Coupled with stricter maintenance standards and improved vehicle cabin designs, these advancements can create safer work environments for drivers.

By exploring these dynamics, this study develops our understanding of vehicle microenvironments and their impact on public health.

REFERENCES

Arnold, S. J., ApSimon, H., Barlow, J., Belcher, S., Bell, M., Boddy, J. W., Britter, R., Cheng, H., Clark, R., Colvile, R. N., Dimitroulopoulou, S., Dobre, A., Greally, B., Kaur, S., Knights, A., Lawton, T., Makepeace, A., Martin, D., Neophytou, M., ... Robins, A. (2004). Introduction to the DAPPLE Air Pollution Project. *Science of The Total Environment, 332*(1-3), 139-153. https://doi.org/10.1016/j.scitotenv.2004.04.020

Cheng, X., Tan, Z., Tay, R., & Yuan, W. (2006). Air quality in transportation cabins--Part I: how much do we know about it?. *ASHRAE Transactions, 112*(2).

Davis, M. E., Smith, T. J., Laden, F., Hart, J. E., Blicharz, A. P., Reaser, P., & Garshick, E. (2007). Driver exposure to combustion particles in the U.S. Trucking industry. *Journal of Occupational and Environmental Hygiene, 4*(11), 848–854. https://doi.org/10.1080/15459620701643347

Dirks, K. N., Talbot, N., Salmond, J. A., & Costello, S. B. (2018). In-cabin vehicle carbon monoxide concentrations under different ventilation settings. *Atmosphere, 9*(9), 338. https://doi.org/10.3390/atmos9090338

Duggan, S. (2024). Carbon monoxide exposure inside UK road vehicles: A pilot study. *Environment International, 194*, 109070. https://doi.org/10.1016/j.envint.2024.109070

El-Fadel, M., & Abi-Esber, L. (2009). In-vehicle exposure to carbon monoxide emissions from vehicular exhaust: A critical review. *Critical Reviews in Environmental Science and Technology, 39*(8), 585–621. https://doi.org/10.1080/10643380701798264

Flachsbart, P., & Ott, W. (2019). Trends in passenger exposure to carbon monoxide inside a vehicle on an arterial highway of the San Francisco Peninsula over 30 years: A longitudinal study. *Journal of the Air & Waste Management Association, 69*(4), 459–477. https://doi.org/10.1080/10962247.2018.1548387

Harik, G., El-Fadel, M., Shihadeh, A., Alameddine, I., & Hatzopoulou, M. (2017). Is in-cabin exposure to carbon monoxide and fine particulate matter amplified by the vehicle's self-pollution potential? Quantifying the rate of exhaust intrusion. *Transportation Research Part D: Transport and Environment, 54*, 225-238

Harrison, R. M., Thornton, C. A., Lawrence, R. G., Mark, D., Kinnersley, R. P., & Ayres, J. G. (2002). Personal exposure monitoring of particulate matter, nitrogen dioxide, and carbon monoxide, including susceptible groups. *Occupational and Environmental Medicine, 59*(10), 671-679. https://dx.doi.org/10.1136/oem.59.10.671

Koushki, P. A., al-Dhowalia, K. H., & Niaizi, S. A. (1992). Vehicle occupant exposure to carbon monoxide. *Journal of the Air & Waste Management Association, 42*(12), 1603–1608. https://doi.org/10.1080/10473289.1992.10467104

Marinello, S., Lolli, F., Coruzzolo, A. M., & Gamberini, R. (2023). Exposure to air pollution in transport microenvironments. *Sustainability, 15*(15), 11958. https://doi.org/10.3390/su151511958

Tan, Z., Cheng, X., & Tay, R. (2006). Air quality in transportation cabins- Part II, Air quality in a truck-cabin. *ASHRAE Transactions, 112*(2), 518-525.