Carbon Dioxide Monitoring in Refuse Collection Vehicle Cabins to Reduce the Risk of SARS-CoV-2 Airborne Transmission

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SUMMARY

During the COVID-19 pandemic, essential workers such as waste collection crews continued to provide services in the UK, but due to their small size, maintaining social distancing inside waste collection vehicle cabins is impossible. Ventilation in cabins of 11 vehicles operating in London was assessed by measuring air supply flow rates and carbon dioxide (CO_2) in the driver's cabin, a proxy for exhaled breath. The indoor CO_2 indicated that air quality in the cabins was mostly good throughout a working day. However, short episodes of high CO_2 levels above 1500 ppm did occur, mainly at the beginning of a shift when driving towards the start of their collection routes. This data indicated that the ventilation systems on the vehicles were primarily recirculating air and the fresh air supply made up only 10-20 % of the total airflow. Following recommendations to partly open windows during shifts and to maintain ventilation systems, a second monitoring campaign was carried out, finding on average, an improvement in ventilation on board the vehicles.

KEYWORDS

CO_2, COVID-19, SARS-CoV-2 transmission risk mitigation, Indoor ventilation

1 INTRODUCTION

Since the start of the COVID-19 pandemic caused by the rapid spread of the SARS-CoV-2 virus, humanity has confronted extraordinary challenges that shook the pillars of modern society. During the pandemic, waste sector workers in the UK continued working, as essential workers, which raised concerns about COVID-19 transmission between waste collection workers in vehicle cabins. The motivation to research mitigating the risk of SARS-CoV-2 transmission in refuse vehicle cabins arose from several factors, such as creating a safe working environment for key workers in this sector and ensuring vital waste collection services are not interrupted. The main risk identified was due to the inability to maintain social distancing between two to three workers in the vehicle cabin for the duration of a shift. Although the crew commonly wear protective gloves as part of their standard Personal Protective Equipment (PPE), masks were not recommended to the workers who were physically active throughout their shift and are continuously in contact with waste, as they were likely to keep re-adjusting masks during the day and this would be unhygienic and impractical. This study thus aimed to assess the ventilation in cabins of several refuse collection vehicles operating in London during two monitoring campaigns, focusing on attempts to reduce the risk of airborne transmission via inhalation as the most practical mitigation measure for these workers. The assessment comprised measurements of airflows from the mechanical ventilation of several waste collection vehicles at a depot in West London, and monitoring of carbon dioxide (CO_2) on board the vehicles for several days at a time.

SARS-CoV-2 transmission occurs through "spray" (via droplets), "inhalation" (via aerosols) or "touch" (via fomites). Droplets are particles larger than 100μm in diameter, which are heavy enough to settle onto surfaces after a short time, and mask-wearing and social distancing have been advised as mitigation measures for droplet transmission. To mitigate against fomite transmission, frequent and thorough cleaning of surfaces was advised. Aerosols are liquid or solid particles suspended in the air with a diameter of less than 100μm. Due to their small size, aerosols can linger in space for a few hours, moving long distances before evaporating or dispersing (Escandón K et al., 2021). Several case studies, including transmission cases in a restaurant (Buonanno et al., 2020, Li et al., 2020), aircraft (Yang et al., 2020), apartment buildings (Wang & Du, 2020), church choir practice (Miller et al., 2020), cruise ship (Azimi et al.,2021) and in a quarantine hotel (Eichler et al., 2021) indicated that airborne transmission through aerosols was the most likely method of transmission. As social distancing is impossible in the vehicle cabin due to its width of 1.95 m and mask-wearing is not recommended for active workers in contact with the waste, the most useful layer of protection for the crew was providing sufficient ventilation to reduce prolonged exposure to high concentrations of aerosols.

Monitoring CO_2 levels has been used as a ventilation marker in scenarios before the COVID-19 pandemic. If exhalation can be assumed to be the only source, CO_2 can be used as a proxy to indicate exhaled breath levels in a well-mixed space. Rudnick and Milton (2003) presented a model to estimate the risk of airborne transmission using the Wells-Riley formula linking CO_2 levels to the risk of infection. Exposure time to air with high CO_2 levels, or high concentrations of exhaled breath in a shared space, plays a significant role and should be included when evaluating risk. Providing sufficient fresh air through ventilation strategies with ten l/s or 15 ACH per person of fresh air ingress is recommended (Dai & Zhao, 2020). Current UK guidelines of the Chartered Institute of Building Service Engineers (CIBSE, 2021) for indoor spaces state that CO_2 levels below 800 ppm indicate good ventilation, and levels above 1500 ppm suggest poor space ventilation. SAGE EMG, a scientific advisory group set up to advise the UK government on Environmental factors relevant to the transmission of SARS-CoV-2, have made several reviews of the available literature during the pandemic and have advised that spaces that regularly present CO_2 values above 1500 ppm should be targeted for improvement, although 800 ppm was recommended as a target for enhanced ventilation. These targets may not be sufficient with new highly transmissible variants such as Omicron, however, there is no conclusive evidence that points to any specific targets to date. Moreover, no specific vehicle guidelines exist to this date to our knowledge, hence stated indoor space ventilation guidelines for buildings are adopted in this study.

2 METHODS

Ventilation was assessed in vehicle cabins of vehicles of different models from two different manufacturers during two monitoring campaigns. The dates and vehicle details are outlined in Table 1. The first monitoring campaign took place in October 2020 and the second in March 2021. Except for one older vehicle, most vehicles were of two models that are Euro 6 standard compliant (and thus produce lower pollution emissions than older vehicles). All vehicle cabins had a volume of 7 m^3. The main difference between vehicle models A and B is in the ventilation outlet layout in the cabin, as shown in Figure 1.

Data were collected using two separate methodologies, at the vehicle depot at the end of a shift. Firstly, air flows from vents were measured using Environmental Monitor EVM Series (TSI) with an Air Probe 10 Air flow sensor. It was noted by the research team upon first boarding of the vehicles, that they were in most cases found to be pre-set to "recirculate only" and that variable fan speeds had been selected by the drivers prior to switching off the vehicle engine for the day. The air probe measured air flows from vents in the vehicle cabins when the ventilation system was set to the maximum fan speed. These measurements aimed to demonstrate if the mechanical ventilation systems available in both truck types can deliver enough ACH, and what is the likely fresh air ingress into the vehicle cabin during its operation. The variable measured in this methodology is the average airspeed from each vent, then used to calculate ACH from mechanical ventilation available in vehicle cabins. The resolution of the Air Probe sensor is 0.1 m/s and the range is 0 to 20 m.s, with an accuracy of ± 0.12 m/s.

Table 1: Vehicle and campaign details

Campaign Dates	Vehicle ID	Make
Campaign 1 - 2nd to 9th October 2020	1, 2, 3, 4, 6	A
	5	B
Campaign 2 - 10th to 23rd March 2021	7	B
	8, 9, 10, 11	A

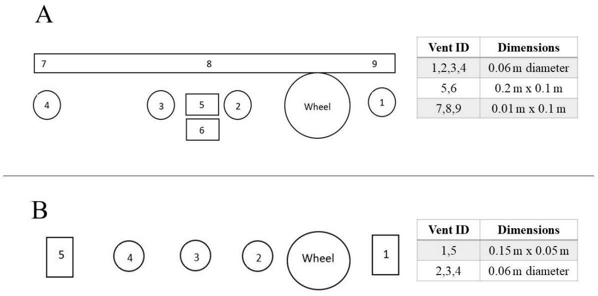

Figure 1: Vent layout and dimensions

Secondly, CO_2 was continuously logged in 11 different vehicles during two monitoring campaigns, with sensors installed at the back of the vehicle cabin seats, just above the passenger's headspace. HOBO MX CO_2 (NDIR) sensors, logging temperature, relative humidity and CO_2 were used. The CO_2 range of these sensors is 0 to 5000 ppm, with an accuracy of ± 50 ppm. Data was logged every minute. The route information and vehicle departure from and arrival back to depot time were provided by the operator. CO_2 data was analysed to identify episodes of poor air quality and their frequency. It was also used to draw conclusions and propose mitigations to improve ventilation and air quality after the 1st monitoring campaign.

3 RESULTS

3.1. Air Supply & Fresh Air

Airflow in terms of ACH was calculated from airspeed measurements using Equation 1 below. The summary of total ACH for each vehicle monitored is given in Table 2.

$$ACH = \frac{\Sigma Q}{V} = \frac{\Sigma vA}{V} \qquad (1)$$

Table 2: Total air supplied by the vents per vehicle

Vehicle	ACH
1	10.1
2	9.4
3	18.0
4	14.8
5	39.4
6	15.1
7	34.1
8	27.2
9	27.8
10	11.4

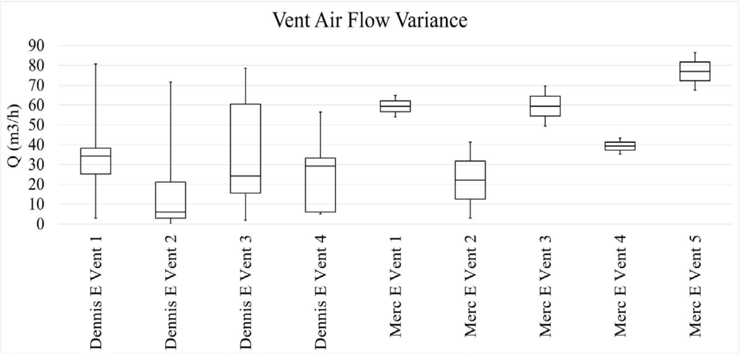

Figure 2: Vent Air Flow Variance

Where Q is the volumetric airflow rate from each vent in m^3/h and V is the cabin volume in m^3. Volumetric flow rate Q can be calculated from airspeed (v) measured in m/h multiplied by the cross-sectional area of the vent A in m^2.

Although ACH calculated for some vehicles monitored are high, a large variance in measurements was found and highlighted in Figure 2. Same area and location vents in different vehicles were compared to highlight that air flows vary significantly. In Model B (vehicles 5 & 7), measured airflows were much higher with smaller interquartile ranges compared to Model A vehicles. There is reasonable evidence that only a small portion of air flows measured from vents is fresh air and the air supplied is mostly re-circulated. From airflow measurements, it was noted that the ventilation system alone cannot guarantee enough if any, fresh air ingress in all vehicles consistently.

Therefore, CO_2 data were analysed in terms of how many episodes of poor air quality of a given duration were recorded in actual daily operations. Episodes of high CO_2 are defined as continuous periods of a minimum of three minutes in which CO_2 is above a given threshold. The monitoring campaigns were carried out in the winter and it was estimated that most crews had their windows closed as a matter of routine during their shifts, and fresh air ingress mainly occurred at their delivery stops as they opened the doors to leave the vehicle and again to board the vehicle, a repetitive pattern during a typical collection shift in the busy streets of London, both in ultra-urban and in suburban areas. Figure 3 indicates clearly that the ventilation system does not supply enough fresh air into the cabin. The data also indicates there could be risks of viral infection via inhalation as these episodes last up to 45 minutes in the worst cases: the length and daily frequency of the episodes can be used to estimate the risk of infection but further research would be needed to establish quantitively the parameters of viral loads and infectious doses in case of an infector being present.

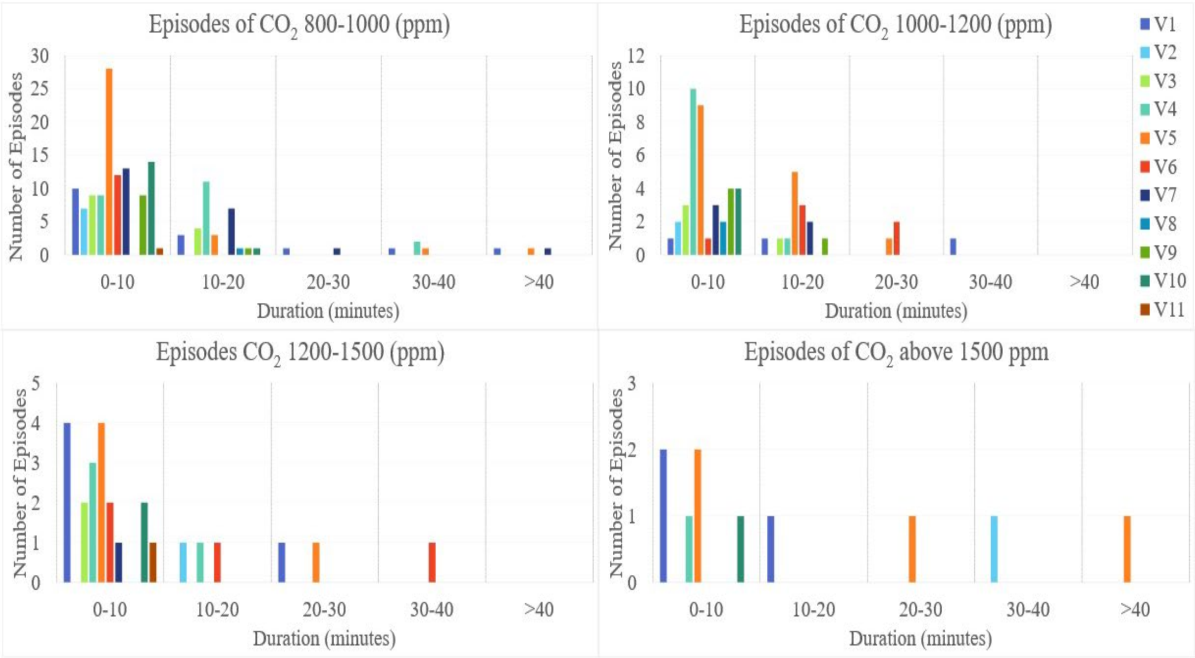

Figure 3: Episodes of high CO_2; Vehicles 1 to 6 (V1-V6) were measured in October 2020 and V7 to V11 were monitored in March 2021 after air quality recommendations were made.

To gain further understanding of ventilation in vehicles, instances when the CO_2 increase rate was the highest per day, were selected and air change rates inside the cabin during the increases of CO_2 were calculated, following equation 2 below. Only vehicles monitored in the first campaign (V1-V6) were considered as in the second monitoring campaign staff had already been encouraged to keep windows open during their shifts and this data cannot be used with confidence to quantify fresh air ingress from ventilation alone. The fresh air ingress presented in Table 3 was calculated using equation (2) and it is a six-day average.

Table 3: Fresh air ingress from CO_2 decay

Vehicle	Average ACH (hr^{-1})
V1	1.1
V2	2.8
V3	1.9
V4	1.6
V5	2.6
V6	3.3

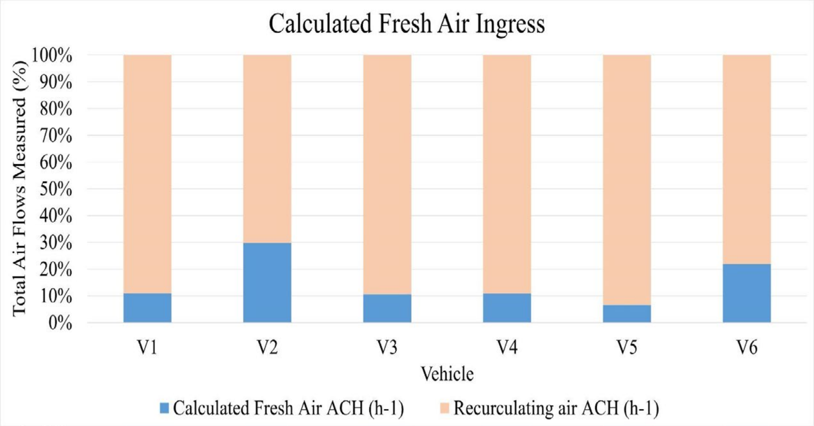

Figure 4: Fresh air ingress percentage estimate

$$CO_2(t) = CO_{2(ext)} + \frac{q_{CO_2} x\ 10^6}{Q} - (CO_{2(ext)} - CO_{2(initial)} + \frac{q_{CO_2} x\ 10^6}{Q}) exp\ (\frac{-Qt}{V}) \qquad (2)$$

Where $CO_2(t)$ is the concentration at time t in (ppmv), t is time in s, $CO_{2(ext)}$ is the external air concentration (ppmv), q_{CO2} is the volumetric emission rate of CO_2 (m^3/s), Q is the volume flow rate of air entering the space (m^3/s), $CO_{2(initial)}$ is the concentration at time 0 (ppmv) and V is the volume of space in m^3.

The volume flow rate was used to calculate fresh ACH (CIBSE, 2014). The volumetric emission rate was calculated based on a CO_2 emission rate of 20 l/hr per person for three occupants. Current guidelines recommend achieving ten l/s per person of fresh air or 15 ACH for three people. Figure 4 estimates that only 10-20% of air supplied through the ventilation system is fresh air.

3.2. Poor Air-Quality Periods

A rising trend was noticed in CO_2 values on most days while the vehicles are on the way to the refuse collection points from depots. CO_2 data shown in Figure 4 from the first monitoring campaign on the 8th of October 2020 highlights this. Similar trends were noted on other days in all vehicles. Overall, the peak CO_2 values are most likely to occur when all 3 workers are inside the cabin, driving in between collection points for prolonged periods with windows closed. The collection routes were always outdoors, and no waste was collected in underground places. Collection routes are different for each vehicle, but they are similar in duration and are in the same area.

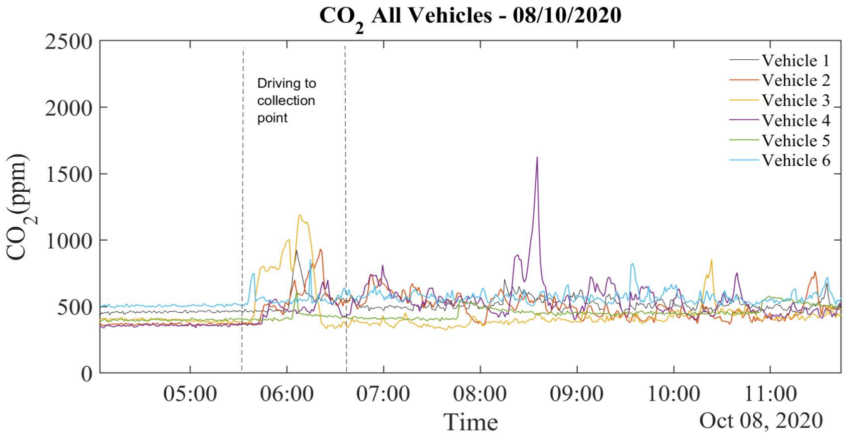

Figure 4: CO_2 Time-series, all vehicles - 8th of October

3.3. Comparison of two monitoring campaigns

Campaign two (March 2021) involving vehicles seven to eleven, shows improvement over campaign 1 (October 2020) involving vehicles one to six. The data for the second monitoring campaigns shows shorter and fewer episodes of high CO_2 in all four ranges considered, compared to the first monitoring campaign. Most of the routes in the second campaign were the same as the routes in the first campaign. The duration of all routes was similar.

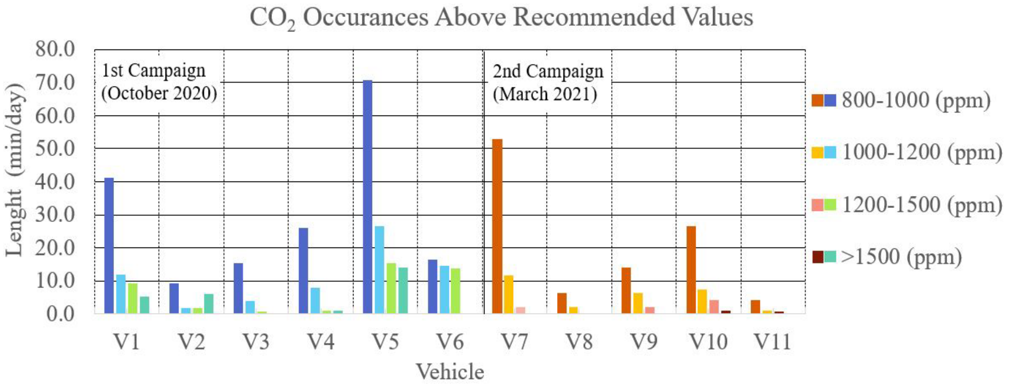

Figure 5: High CO_2 occurrences over the 2 campaigns

4 DISCUSSION

The study was based on the assumption that a vehicle cabin is a well-mixed space and that the only source of CO_2 levels above ambient levels of ~400 ppm is human exhalation. It was also assumed that if windows and cabin doors are closed, the leakage is negligible and therefore this was not considered. The lack of leakage of fresh air into the vehicles was also evident to the research team when carrying out airflow measurements at the depot inside the vehicles; as CO2 values would rise very quickly during the ~10 minutes it took to collect data on each vehicle. The CO_2 sensors were placed just behind seats, and the concentration measured there is assumed to be the same as at the breathing height due to the small cabin volume.

Mechanical ventilation was assessed by measuring air flows from vents. The air coming from the vents is assumed to be a mixture of recirculating air and fresh air. A large variance was found in air flows in different vehicles and vents, even if the same vehicle model is compared. Although airspeeds measured from vents indicated enough ACH can be supplied through the mechanical ventilation, CO_2 data indicated that a large portion of this air is recirculating air. Furthermore, the CO_2 data was used to quantify the amount of fresh air supplied through the ventilation system if three people are present in the cabin. This analysis confirmed that fresh air ingress makes up for 10-20% of the air supplied, depending on the vehicle. Due to the method used to quantify the fresh air ingress being to an extent subjective, the percentage values should be looked at as estimates.

From the journey data provided in this study, it was noted that instances of CO_2 most frequently occur while the vehicle is driving between collection points in different neighborhoods or streets. It is assumed that at this point all three workers are in the cabin together. Once the collection points or streets are reached, the CO_2 levels drop as two workers leave the cabin repeatedly and the duration of drives between collection points is very short. One of the limitations of this study is that it isn't possible to ensure the exact number of occupants at any time during monitoring periods.

These results were communicated to the organization after the first monitoring campaign in October 2020. Following the first monitoring campaign and it becoming clear that further ventilation would be beneficial, the importance of fresh air was stressed to the organization and they embarked on a campaign to encourage staff to open the windows at least 10 cm in the vehicles for the duration of their shifts. Results indicate that the second monitoring campaign shows improvement in ventilation rates across all vehicles monitored. This is likely due to the initiative to introduce as much as possible fresh air into the cabins. Regular maintenance of the ventilation systems was also recommended after the first set of results was analysed. Although the vehicles in the second campaign were different, the same models of vehicles were used in both campaigns so the results from the two campaigns are comparable. The frequency and length of episodes across all ranges of elevated CO_2 were reduced in the March 2021 monitoring campaign. A limitation of this study is that not all routes are the same in the first and the second monitoring campaign. However, they are comparable because all routes have a very similar duration and are operated in the same area of London; in any case, vehicles are assigned different routes every day and the pattern of opening doors on the vehicle for collections was found to be the main source of fresh air into the vehicles, other than opening windows, rather than the vehicle ventilation systems themselves.

5 CONCLUSIONS

In marked contrast to building well-developed ventilation guidelines, there are almost no air quality guidelines for vehicles. This has posed a challenge during the COVID-19 pandemic as it became clear that it will be difficult to ensure that vehicle cabins for waste collection crews or other delivery trucks are well ventilated. Due to the inability to impose social distancing in refuse collection vehicles and the no-mask policy, providing sufficient fresh air into truck cabins is crucial to limit the spread of infectious diseases amongst the crew. This study highlighted that even if high airspeeds are measured at the vents, only a small fraction of the air supplied may be fresh air. Therefore, the only reliable source of fresh air into refuse vehicle cabins considered in this study is through open windows and doors. Ventilation was according to guidelines of below 800 ppm for the majority of the vehicles monitored with some instances of high CO_2 episodes during the first monitoring campaign, with major improvements in the second monitoring campaign. Further work such as numerical modelling or experimental studies of the cabin is recommended; this could provide answers such as for how long can the staff be in the vehicle cabin safely if windows and doors are closed and fresh air ingress comes from mechanical ventilation only and set new standards for the supply of fresh air to such cabins for safer operations in future.

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