Empirical Studies Assessing the CO2 Levels in Indoor Spaces

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Abstract. The COVID-19 pandemic forced everyone to isolate themselves and confine their lives to enclosed spaces to protect themselves from the outbreak and spread of the virus. Contrary to this, recent studies have shown that restricting ventilation in a space can lead to health risks resulting from CO_2 build-up from exhaled breath. There have also been a substantial number of multidisciplinary research studies that have established CO_2 exhalation in an enclosed room as a proxy for COVID-19 and other similar variants of viruses. We conducted experiments to understand the spatio-temporal spread of CO_2 inside a car in the hot and dry climate of Jodhpur and a bedroom in the composite climate of New Delhi during the winter season. The experiments were carried out using reference-grade sensors and custom-built devices for indoor use, which measured the ambient temperature, relative humidity, and CO_2 levels. On analyzing the findings from our studies, we observed that even seemingly harmless situations, such as an enclosed vehicle and a non-ventilated bedroom space, could lead to harmful levels of CO_2 built-up of over nine times and three times over the acceptable threshold of 1000 ppm for a car and a bedroom respectively. Reassessment of the design guidelines underlying environmental ergonomics is advised for automobiles and residential spaces.
Keywords: Carbon dioxide (CO_2), COVID-19, Environmental ergonomics, ventilation.

1 Introduction

Human factors in the ambient environment, often known as "Environmental Ergonomics," is a design specialization that refers to the improvement of indoor environments in terms of thermal comfort, illumination, sound, and indoor air quality (IAQ) [1]. Out of these parameters, IAQ highlights the necessity of improving the ambient ergonomics of indoor spaces in the context of reducing airborne transmission of diseases. With the recent SARS-Cov-2 (COVID-19) pandemic, it has come to light that sharing confined areas with restricted ventilation may have implications to the health of the occupants [2].

When CO_2 gas accumulates in an enclosed space, the same gas may be inhaled by the same inhabitants, increasing the risk of airborne infections such as COVID-19, tuberculosis, and even the common cold. Therefore, CO_2 gas has been viewed as a proxy for several airborne illnesses [2, 3]. As a response, monitoring and controlling CO_2 levels in enclosed spaces is vital from the perspective of environmental ergonomics. Monitoring CO_2 levels and understanding its trends can help human factors professionals improve ventilation guidelines for indoor occupants' better health.

The number of studies that employ CO_2 concentrations as a consideration in IAQ-related decision-making has increased in recent times. For example, Q. Huang et al. examined CO_2 levels in dental clinics to evaluate doctors' occupational health and human factors. According to the authors' conclusion, "ventilation" contributed to CO_2 build-up by measuring CO_2 emissions in these rooms [4]. Natalie Bain-Reguis et al. evaluate the human factors of students in 20 Scottish schools during the COVID-19 pandemic by monitoring CO_2 levels with different ventilation systems. This study concluded that mechanically ventilated classrooms performed better than naturally ventilated classrooms, indicating that opening the windows is contingent upon conventions and habits [5].

Similarly, many researchers have assessed the IAQ in the context of airborne diseases in a wide range of indoor spaces, such as classrooms, hospital wards, airline cabins, multi-story structures, and others, using sensor monitoring and computational fluid dynamics [6]–[11]. It has been observed that residential rooms and automobiles are spaces where individuals spend the most time and have environmental control. People in a city drive with the air conditioner on and close the windows for optimal thermal comfort. This stops O_2 in the fresh air from entering the car and causes a rise in CO_2 levels. In addition, some studies indicate that rising CO_2 concentrations in indoor spaces, without corresponding changes in ventilation rate, are detrimental to the decision-making performance of occupants [12, 13]. Another study analyzed nine critical parameters and combinations that indicate the level of performance in a controlled indoor environment at three distinct CO_2 levels: 600, 1000, and 2500 PPM. At 2500 PPM, fundamental activity, conscientiousness, applied activity, initiative, flexibility in work approach, information utilization, and fundamental strategy were substantially diminished [14]. A similar situation is also observed in confined bedrooms.

People tend to restrict natural ventilation and use heating devices throughout the winter to feel thermally comfortable while sleeping. According to research conducted by the Occupational Safety and Health Administration (OSHA), even though this may seem thermally comfortable, it causes roughly 90 deaths yearly [15]. Due to the recirculation of CO_2 within the bedroom, the risk of airborne illnesses increases in bedrooms where individuals are in closer proximity.

As a response, through our study, we are monitoring CO_2 levels in a car cabin and a bedroom for a specified time to assess the environmental ergonomics in these spaces and create a knowledge base for designers and policymakers to develop suitable designs necessary for maintaining a healthy indoor environment for the occupants. The main objectives of our study are:

- To determine the scope of low-cost IAQ monitoring devices in personal indoor spaces
- To verify whether the CO_2 concentrations within these personal spaces (Car and bedroom) are under the recommended threshold
- To assess the thermal comfort performance of indoor spaces with respect to CO_2 concentrations

2 Methodology

We conducted two experiments as follows:

i) Inside a mid-sized car with four occupants
ii) Inside a residential bedroom with two occupants

The methodologies of these experiments are shown in Sections 2.1 and 2.2, respectively.

2.1 Experimentation inside a car

The studies were conducted in a closed vehicle with four participants, including one of the authors, with all doors and windows shut on 17th December 2021 in Jodhpur's hot and dry climate. The passengers were seated without engaging in any physical activity within the cabin and were aware of the experiment but not about the expected outcomes in terms of desirable CO_2 range. This investigation employs five IAQ sensors (mainly monitoring CO_2, Temperature, and Relative Humidity). These IAQ sensors include one reference-grade sensor from Testo 400 and four low-cost sensors from Aerogram [16]. The study was conducted in two phases sequentially: (1) When all five sensors were placed in the same location for calibration, and (2) When all five sensors were placed in multiple locations to understand the spatio-temporal distribution of CO_2 levels. After installing and activating all monitoring devices in the vehicle, the data was analyzed. At 4:20 pm, all sensors were installed and the data was recorded every 6 seconds. At 4:20 pm, the average CO_2 sensor reading was 2168 ppm, indicating data logging began at that concentration. From 4:20 pm to 4:24 pm is an experiment with a single occupant. From 4:24 pm to 4:34 pm, there are two individuals inside; after that, there are four.

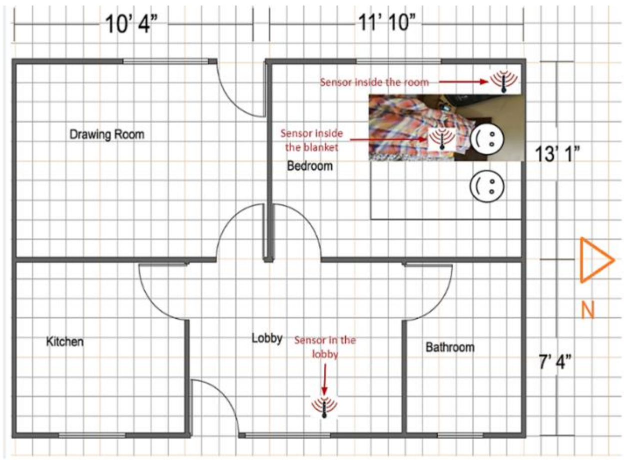
2.2 Experimentation in a bedroom

The experiment was conducted in the bedroom of a 1BHK apartment (Figure 1) in the composite climate of New Delhi in December 2021 with two participants (one of the authors is one of the participants). The bedroom has a size of 20ft x 20ft with no heating system. For conducting the experiment, three Testo CO_2 sensors were used in the following locations:

i) In the lobby
ii) In the bedroom, on the bedside table
iii) In the bedroom, inside the blanket

The experiment was conducted from 10 pm on 25th December till 9 am on 26th December. The data was collected for CO_2 levels from 10 pm to 6:36 am every 6 seconds keeping the door closed and from 6:36 am to 9 am keeping the door open. Various CO_2 level differences were recorded by keeping the head inside and outside the blanket.

Fig. 1. The layout of the residential apartment with the location of sensors



3 Results and discussions

3.1 For the car experiment

3.1.1 Calibrating the sensors

As stated in the methodology section, we measured CO_2 levels using four low-cost sensors and the data was recorded every 6 seconds. Accordingly, these four sensors have been designated as sensor-1, sensor-2, sensor-3, and sensor-4. The calibration experiment was conducted from 4:20 pm to 4:57 pm. Python workbench was used to compute Pearson's correlation coefficient [17]. Figure 2 shows the correlation between Sensor-1,2,3,4 and the benchmark device to be 96%, 93%, 90%, and 92%, respectively. It indicates that all the sensors in the study have a significant correlation with the reference-grade sensor.

Fig. 2. Calibrating the sensors with respect to reference-grade sensors

	BENCHMARK	SENSOR-1	SENSOR-2	SENSOR-3	SENSOR-4
BENCHMARK	1				
SENSOR-1	0.955441457	1			
SENSOR-2	0.932074846	0.990548537	1		
SENSOR-3	0.90321297	0.979702524	0.994778586	1	
SENSOR-4	0.920856792	0.983810203	0.997032221	0.995090163	1

3.1.2 CO_2 levels in a car

We also visualized the CO_2 trends with time (calibration & spatial observations) and illustrated them as shown in figures 3a and 3b.

Fig. 3a. CO2 levels vs. time plot in a car

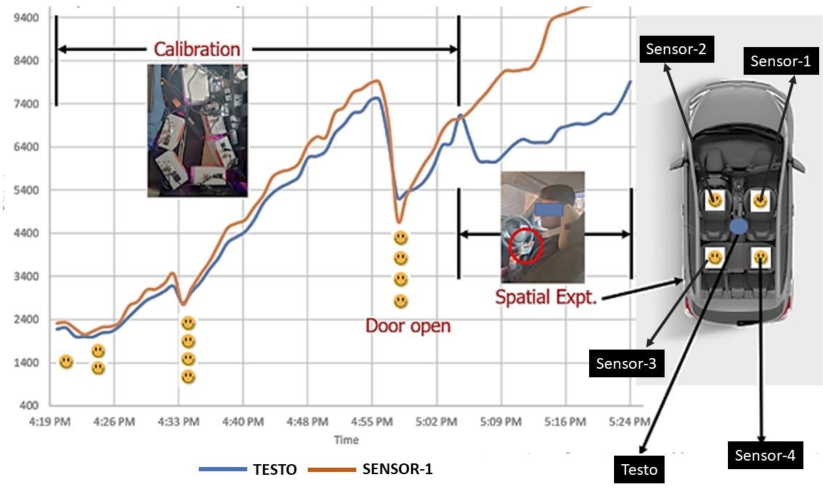


Fig. 3b. Spatio-temporal distribution of CO_2 levels in the car

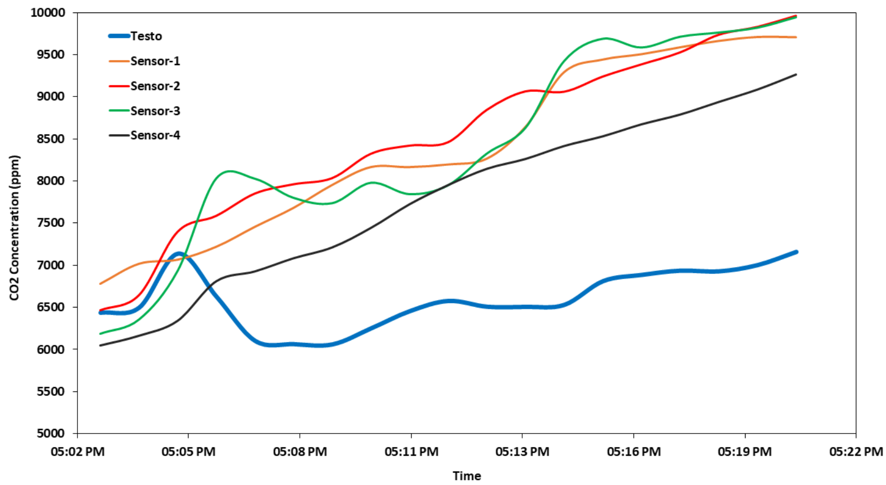


Figure 3a shows the calibration and spatial experiment results for the Testo 400 reference sensor and low-cost sensor Sensor-1. It was observed that a negative spike in the CO2 levels between 4:55 pm and 5:02 pm resulted from the drop of CO2 levels from 7,000 to 4,000 ppm (43% reduction) because of the opening of the door. From 5:03 pm to 5:25 pm, the spatio-temporal spread of CO_2 levels was visualized (as shown in figures 3a and 3b), where each sensor was placed in a different location inside a car. During this phase of the experiment, each of the four low-cost sensors (sensor-1,2,3 and 4) were held by four occupants seated at four locations in the car, as shown in figure 3a. The testo probe was placed at the centre of the car where there was no occupant. From figure 3b, it was observed that all low-cost sensors exhibited similar trends and the Testo probe had an offset in the downward direction. This may have been because there was no occupant around the Testo probe, resulting in lesser CO_2 values than the other sensors. Since the occupants held the low-cost sensors, their respective breathing zones exhibited higher CO_2 levels than the reference sensor placed (Testo's location) where there were no occupants. This shows that there is higher CO_2 spatial distribution around an occupant's breathing zone. It means that when more than two people are seated at the back, this would result in poor indoor air quality with respect to CO_2 levels compared to the people sitting on the front side. However, more experiments are needed for conclusive evidence of such spatio-temporal distribution of CO2 levels. CO_2 level stratification with height should also be observed. The CO_2 coming out of exhaled breath may rise as the temperature of the exhaled breath is higher than the ambient temperatures and after it reaches the ambient temperature, it may settle down at a lower height as it is a denser gas than air.

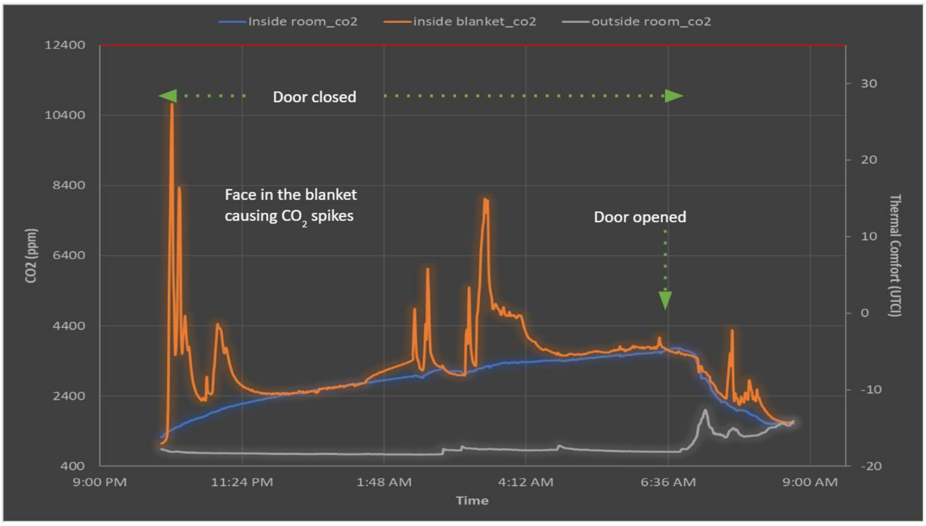
With more elaborate experiments, it is also possible to devise the relationship of variation of CO_2 levels with time with occupancy and weather variables such as temperature and humidity. This would help with car design guidelines without the need for a sensor setup. Therefore, it is advised that alternatives for fan speed, ventilation mode, and cabin air recirculation be investigated and modeled to assist in safeguarding the passengers' respiratory health. The algorithms from these kinds of more in-depth research may be used to develop the HVAC control unit for maintaining the CO_2 at a tolerable level based on the study's findings.

3.2 Result and discussions for the bedroom experiment

3.2.1 CO_2 level in the bedroom

From the graph depicted in Figure 4, it can be seen that the CO_2 concentration in the room increased to a maximum of 3770 ppm between 10 pm and 6:43 am. The room's door was opened at 6:43 am and the CO_2 level decreased to 1,670 ppm by 8:43 am. When the occupant placed their head inside the blanket, the CO_2 concentration spiked to a maximum of 10,642 ppm. After the room's door was opened at 6:43 am, the ventilation caused the CO_2 level to decline by 2100 ppm over the course of two hours. On the contrary, when the bedroom door was opened in the morning, CO_2 concentrations surged in the lobby, which was empty. In two hours, the CO_2 level rose by 872 ppm.

Fig. 4. CO2 levels in the bedroom with no heating device

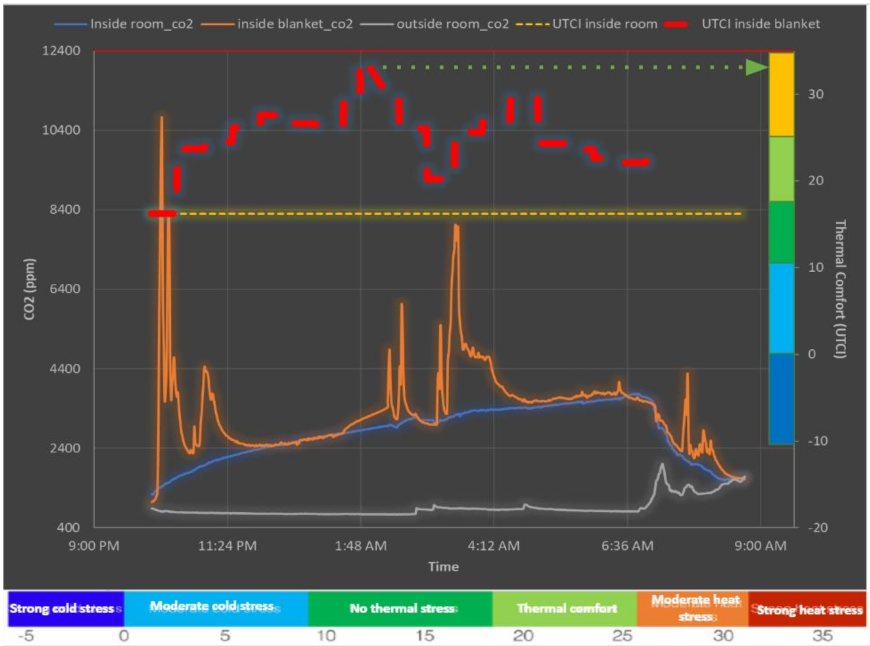


As seen from the results of this experiment, CO_2 levels rise to more than three times the acceptable range of 1000 ppm [3] when the occupants sleep in a non-ventilated room. Given that the participants in this study spent most of the winter season (60 to 90 days) in a room with CO_2 levels ranging from 1000 ppm to 3400 ppm, they are susceptible to health problems like CO_2 retention, inflammation, and cognitive impairment [18].

3.2.2 Thermal comfort in the bedroom

Figure 5 demonstrates that the Universal Thermal Climate Index (UTCI) inside the room and the lobby stayed constant at approximately 16°C. UTCI is an indicator of thermal comfort in a space. However, due to the CO_2 accumulated within the blanket each time the occupant kept their head inside, the temperature reached 34 °C, which is on the warmer side for UTCI. It is seen that even though the CO_2 build-up achieved by keeping their head inside the blanket can help in reaching a warmer comfort level, it can quickly reach a hot thermal stress state and also create a condition with CO_2 levels over ten times the acceptable range. Hence it is recommended that people should not cover their heads while sleeping. Ventilation devices with small openings are advised to maintain a thermally comfortable climate in naturally ventilated indoor areas. These ventilators allow for air mixing while limiting significant heat exchange.

Fig. 5. CO_2 levels vs. thermal comfort with respect to time



4 Conclusion

India's permitted range for CO_2 levels is up to 1000 parts per million [2]. Our findings show that the CO_2 levels rise to more than three times the acceptable range when the occupants sleep in a non-ventilated room and nine times the acceptable range in an enclosed car. As humans spend one-third of their lives sleeping and Indian commuters travel approximately 35 kilometers per day [19], exposure to such high levels of CO_2 can be detrimental to their health and may result in sick-building syndrome [18]. CO_2 levels above 800 ppm in enclosed spaces can also be responsible for transmitting airborne infections such as COVID-19 and similar viruses [20]. Therefore, it is recommended that people spend their time in well-ventilated areas and sleep without blankets on their heads. Although sick-building syndrome has been studied extensively in other areas of the world, it has not been explored much in India due to the high cost of monitoring devices. For achieving more reliable results in defining environmental ergonomics standards for the Indian setting, these experiments must be conducted in multiple climatic locations and weather conditions across India.

The calibration tests in this research establish the relevance and applicability of low-cost CO_2 sensors. Indoor air quality (IAQ) indicators should be examined regularly in the light of growing concerns about airborne diseases and cognitive performance. Establishing several indoor monitors for the study is costly. Thus, designers should focus on developing low-cost equipment. Future Indian marketplaces should have the availability of affordable CO_2 monitoring devices such as wearables, wall mounts and standalone sensors.

The results of the current study highlight the necessity to evaluate the ergonomics of the environment with regard to ventilation and CO_2 concentrations when building living spaces and automobiles. There are still many research gaps to be filled before making firm recommendations about environmental and product design for today's ventilation-restricted environmental settings, despite the fact that the effects of CO_2 build-up in enclosed spaces have recently become relatively important research. The issues of upgrading our personal spaces for the challenges of the twenty-first century will be easier to tackle with continued research's assistance in creating new knowledge, promoting better standards, and more informed solutions.

The results of this study should guide further empirical research into the significance of ventilation and air-flow design in enclosed spaces in order to address the issues of occupant health, well-being, and productivity that are impacted by CO_2 build-up in their environment. These findings may also be applied to future design projects.

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