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Accumulation of metabolic carbon dioxide (CO₂) in a vehicle cabin

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Abstract. In traffic congestions, the typical reaction of the drivers is to switch-on the recirculation mode of the vehicle's air conditioning system. In the summertime, in many cities with high air humidity and temperatures, people typically drive their cars in recirculation mode as well, to ensure the best cooling. However, the recirculation mode of the air in the cabin prevents O₂ from entering and leads to an increase in CO₂. In confined spaces (e.g., a vehicle cabin), the raised CO₂ concentration due to human exhalation and metabolism is associated with increased health symptoms, decreased concentration, and impaired performance. The paper presents an experimental study on the accumulation of carbon dioxide in a vehicle cabin from occupants breathing and metabolism. The concentration of CO₂ and O₂ were measured in terms of the number of occupants (1-4) in the car. The change in the indoor environmental parameters in the car cabin was also monitored. The results obtained show the increment of the CO₂ concentration at the expense of oxygen availability, together with the apparent impact of the number of people in the vehicle.

1. Introduction

The outdoor concentration of carbon dioxide (CO₂) is considered to be around 380 parts per million (ppm) [1], though the global average CO₂ concentration level of May 2019, measured at Mauna Loa Observatory, Hawaii is 414.66 ppm (NOAA, 2019) [2].

Perisly [3] reported that CO₂ levels in the outdoor air in an urban area could reach up to 500 ppm. According to [4], the annual CO₂ concentration in Beijing for the period 2013-2016 was 374.4, 382.7, 389.0, and 392.8 ppm for the respective year, being highest in winter months and lowest in summer. Beijing is not, however, among the most congested cities in the world. The first place is occupied by Moscow, followed by Istanbul, Bogota, Mexico City, Sao Paulo, London, Rio de Janeiro, Boston, Saints Petersburg, and Rome [5].

There is an undoubted relationship between the traffic congestions in a city and the CO₂ in the cars (vehicles). In traffic congestions, the typical reaction of the drivers is to switch-on the recirculation mode of the vehicle's air conditioning system. In the summertime, in many cities with high air humidity and temperatures, people typically drive their cars in recirculation mode as well, to ensure the best cooling. However, the recirculation mode of the air in the cabin prevents O₂ from entering and leads to an increment of the CO₂. In confined spaces (e.g., a vehicle cabin), the CO₂ concentration rises fast due to human exhalation and metabolism. The high CO₂ concentration is associated with increased health symptoms, decreased concentration, and impaired performance.



The research in [6] investigated the hypothesis that higher concentrations of CO₂ in confined spaces, without changes in ventilation rate, have a harmful influence on the decision-making performance of the occupants. The hypothesis was based on the findings in [7, 8] that concentrations of CO₂ in the range 2000-5000 ppm in a controlled indoor environment negatively affected the proofreading of text. These conclusions contradicted to previous findings that CO₂ concentration up to 5000 ppm in enclosures did not affect occupants' perception, work performance, or health [9]. The authors of [1] investigated nine primary factors and combinations that demonstrate the level of performance in a controlled indoor environment with three different levels of CO₂ concentration: 600, 1000, and 2500 ppm. They have found that seven of the factors (basic activity, task orientation, applied activity, initiative, flexibility in approach to the task, information usage, and basic strategy) were significantly reduced at 2500 ppm and the results were statistically proven. Only the information search and the focused activity were not affected by the CO₂ in the studied concentrations.

In the case of recirculation mode of the ventilation system, the CO₂ concentration in the vehicle cabin can rise fast due to the human metabolism and exhalation and at the expense of the oxygen (O₂) concentration [10]. The increment is steepest in small volume of the vehicle cabin [6]. However, there are no limits for the CO₂ levels in cars, though the ASHRAE standard 62-2001 [11] suggests a permissible level of 1200-1300 ppm for the cabin interior.

The paper presents an experimental study on the accumulation of carbon dioxide in a vehicle cabin from occupants breathing and metabolism. The concentration of CO₂ and O₂ were measured in terms of the number of occupants (1-4) in the car. The change in the indoor environmental parameters in the car cabin was also monitored. The results obtained show the increment of the CO₂ concentration at the expense of oxygen availability, together with the apparent impact of the number of people in the vehicle.

2. Experimental methodology

The experiments were performed in a vehicle (car) cabin with switched on recirculation (REC) mode: the fresh air intake was prohibited, and only cabin air was recirculated. The passengers (subjects) were sitting inside the cabin without physical activity. Thus, minimum concentration levels of CO₂ were measured, due to regular metabolic activity and respiration rate at about 6 l/min [6].

Two carbon-dioxide sensors were used for the study: one in the front, and one in the back side of the cabin (figure 1). One sensor for monitoring of the O₂ concentration, together with the air temperature, and relative humidity was placed in front of the cabin. The used software allowed direct monitoring of the changes in the measured indoor air parameters (figure 2). The accuracy of the O₂ and CO₂ concentrations were $\pm 10\%$ of the measured value. The measuring frequency was 0.1 Hz.

The study was performed in 4 stages: each stage involved a different number of subjects (4 at the beginning and 1 at the end of the measurements). The measurement aimed to reach CO₂ concentration of 2500 ppm, and this goal limited each stage in terms of time. The car cabin was ventilated (open doors) after each stage.

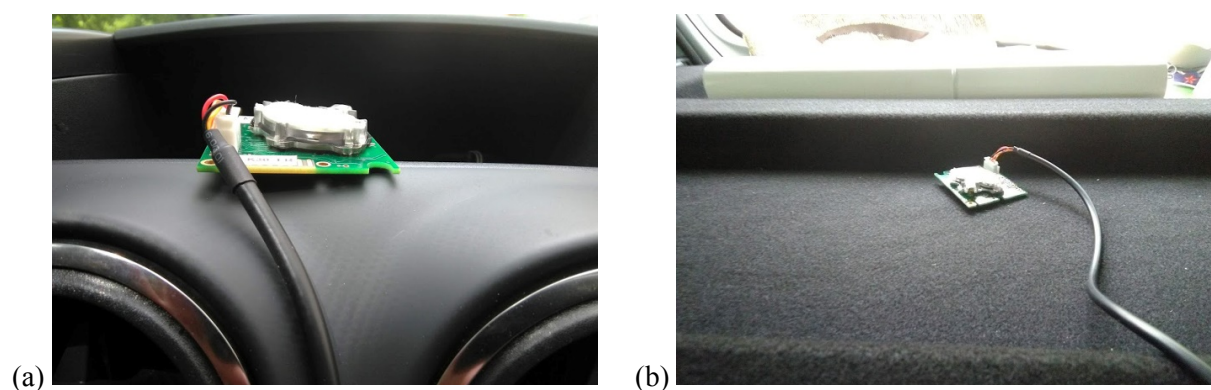


Figure 1. Tests sensors: (a) front CO₂ sensor; (b) back CO₂ sensor.

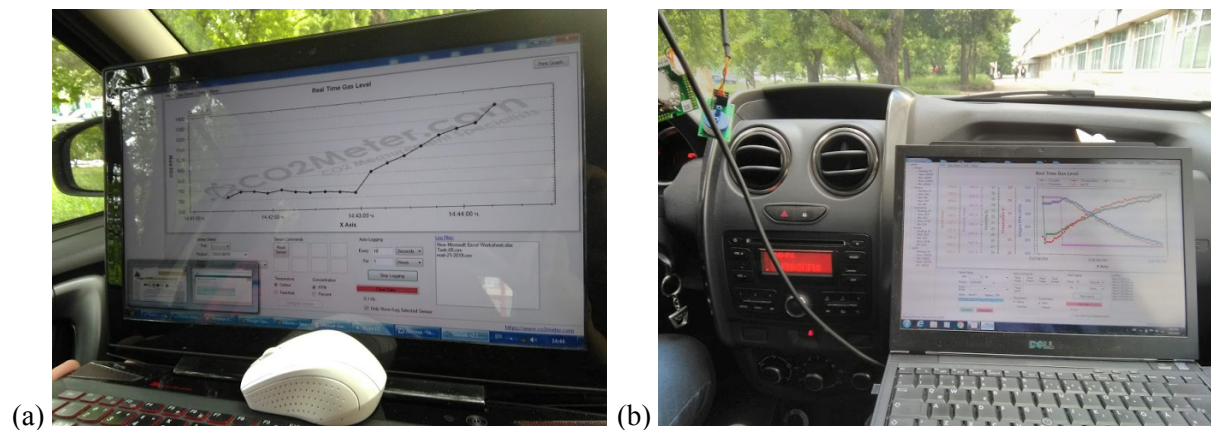


Figure 2. Online monitoring of the parameters in the car cabin: (a) CO₂ concentration (front); (b) O₂ concentration and indoor environmental parameters.

3. Results and discussions

Figure 3 presents a comparison between the front and rear sensor for CO₂ concentration measurement when 3 subjects occupied the car cabin. The performed statistical analysis of the results (two-tailed t-test) showed that there was no difference between the two sets of data (confidence level 95%). Therefore, the results for the CO₂ concentration from the front sensor only are further discussed.

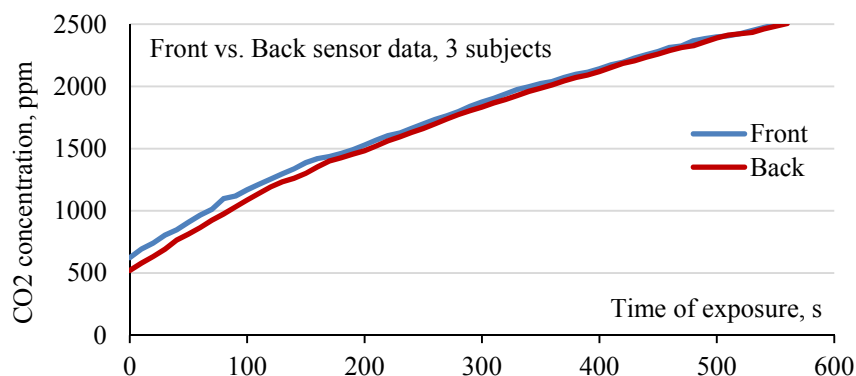


Figure 3. Comparison between front and back sensor data for CO₂ concentration (3 subjects in the car cabin).

The effect of the number of occupants on the CO₂ concentration in the cabin is summarized in figure 4. The results showed that reaching the set limit of 2500 ppm was fastest in the largest number of passengers in the car (4 subjects, REC mode). The reason is the natural exhalation process: for 340 s all passengers in the car, including the driver, were exposed to the increased carbon dioxide (2517 ppm). Therefore, for approx. 5 minutes in a congestion or recirculation mode for other reasons, a family with two children going on holiday could be subjected to the negative effect of CO₂. This is especially dangerous for the driver, who can be expected to have a reduced performance [1], being at the same time the only one, responsible for the safety of the passengers.

The increment of the CO₂ concentration in the cabin was at the expense of oxygen availability. Figure 5 presents the results for the O₂ concentration, measured for each of the stages. Though CO₂ concentration in the cabin air reached 2500 ppm in the case of 4 passengers, the oxygen decrement was lowest, due to the short time of the exposure. On the contrary, the regular breathing of a single person in the car cabin in REC mode led to 1.7% decrement in the O₂ concentration, because of the very long time of the exposure (37 min and 20 s) and the gradual oxygen depletion.

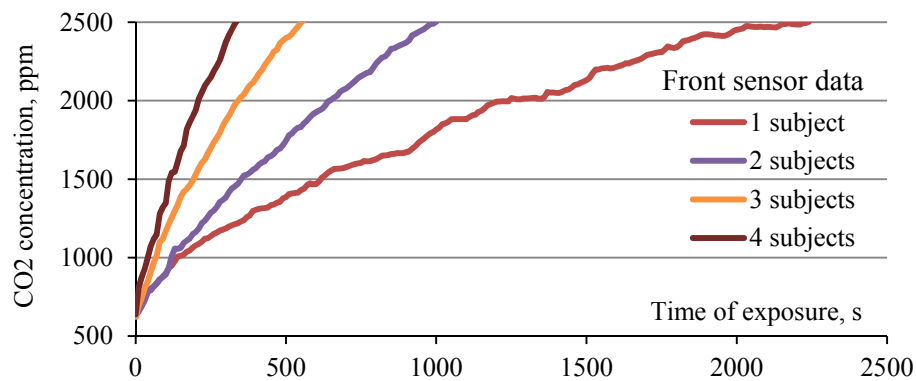


Figure 4. CO₂ concentration in the car cabin: effect of the number of passengers.

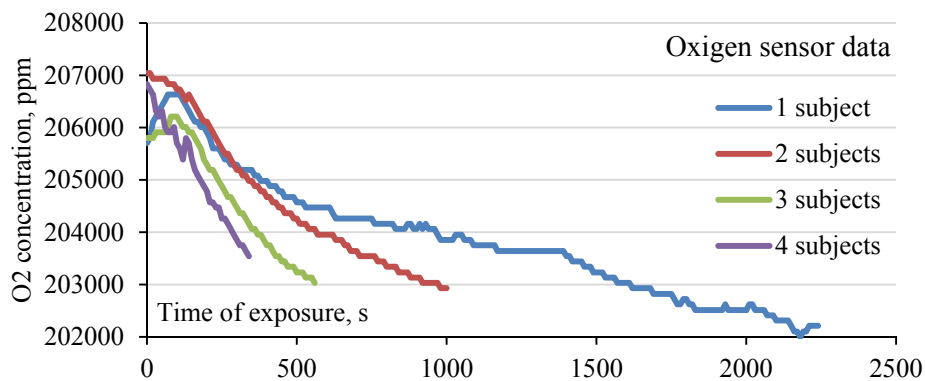


Figure 5. O₂ concentration in the car cabin: effect of the number of passengers.

Figure 6 illustrates the rate of CO₂ concentration increment for each of the tested stages. The presence of 4 passengers in the car led to an increase of the carbon dioxide in the air with 5.53 ppm/s. When only the driver was in the car, the CO₂ concentration in the cabin air (REC mode) increased with 0.84 ppm/s.

A trendline was added in figure 6 to search for a regression equation that describes the influence of the number of the occupants in the cabin and the CO₂ concentration change rate. The proposed regression model (regression coefficient $R = 0.99$) is:

$$CR_{CO_2} = 0.4881e^{0.6244N}, \quad (1)$$

where CR_{CO_2} is the rate of increment of the CO₂ concentration, ppm/s; N is the number of the occupants.

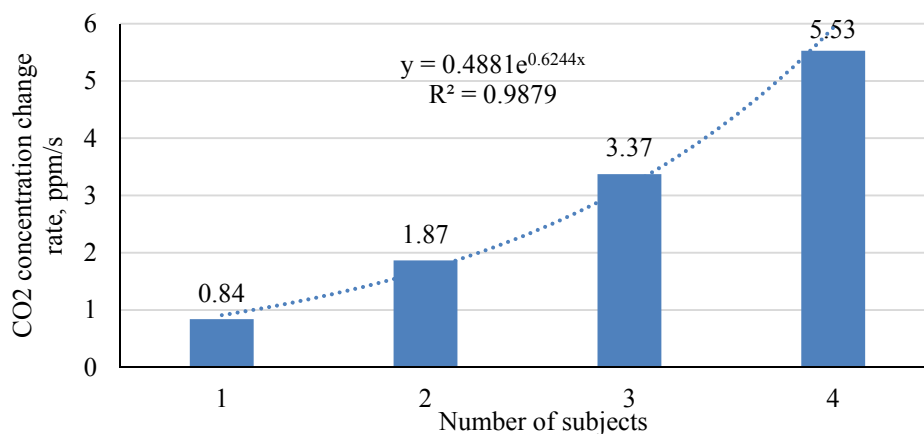


Figure 6. CO₂ concentration change rate: effect of the number of passengers.

Figure 7 summarizes the in-cabin environmental conditions during the measurements. The most significant change in the air temperature (figure 7 a) and relative humidity (figure 7 b) were for the stage with only one subject in the car. The main reason is the prolonged exposure. The thermophysiological comfort of the passengers in the cabin will be of particular interest in the next experiments within this research study.

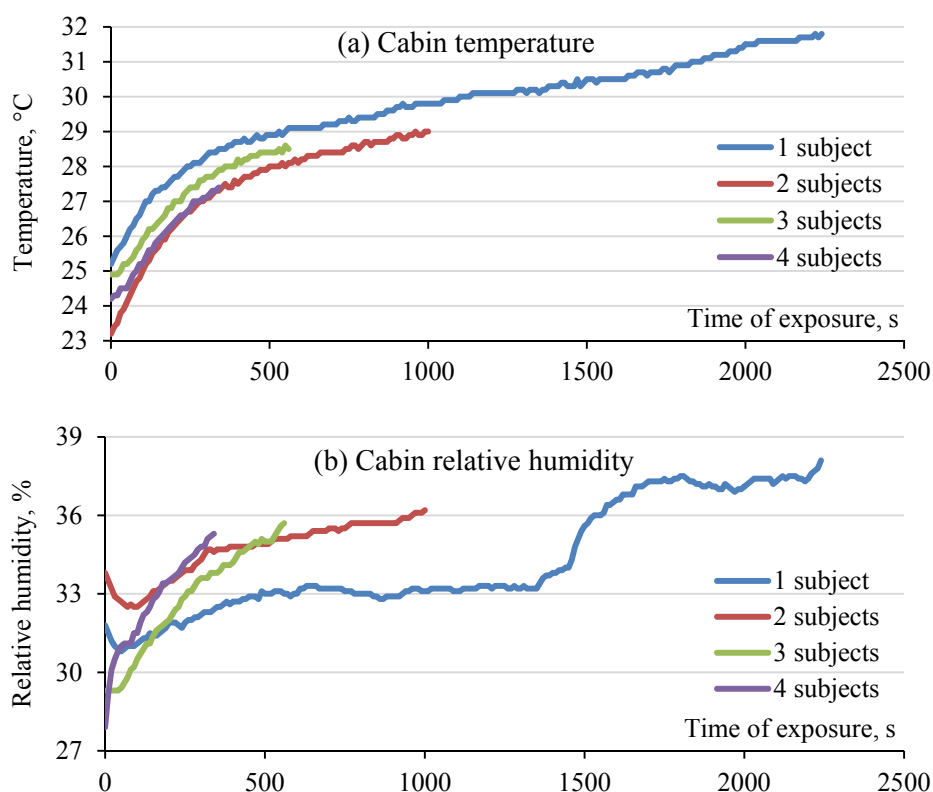


Figure 7. Cabin environmental parameters: (a) air temperature; (b) relative humidity.

4. Conclusion

The results obtained clearly show potential safety problems, related to both the increment of the CO₂ concentration and the depletion of oxygen in the vehicle cabin. The comparison between the results from the front and back sensors showed that the driver is affected by the CO₂ concentration to the same level, like the passengers in the car, due to the effective air mixing. In REC mode, when three, four or five occupants are in the car, the CO₂ concentration may reach dangerous for the driver's performance levels even for several minutes (e.g., in a city traffic congestion). The same is valid for family trips during the summer when the outside air in the passenger compartment is discontinued (REC mode) to assure the desired cooling. A solution of the problem is the regular or automatic switched-off of REC mode after several minutes of internal air recirculation.

Acknowledgments

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