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Experimental Study on Cabin Carbon Dioxide Concentration in Light Passenger Vehicles †

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Abstract: This paper discusses the initial experimental results of monitoring carbon dioxide (CO_2) and total volatile organic compounds (TVOC) inside automobiles with different cabin sizes and with different number of occupants. The initial study shows the CO_2 and TVOC concentrations are inversely proportional to cabin volume and proportional to passenger numbers and time when the metabolic activities were maintained at the same level. This study aimed at short distance travel on normal road and further studies are to be carried out for long distance running on highways to make sound decision on automatic air inflow control to maintain the in-cabin air within permissible levels of CO_2. The study shows that a CO_2 concentration of 1500ppm is reached by all three light passenger vehicle types used within 20 minutes with single person and reached nearly 3000ppm of CO_2 level within the same time with two passengers in cabin.

Keywords: carbon dioxide; vehicle cabin air quality; vehicle occupant safety; human metabolism

1. Introduction

Automobiles have become an essential part of hardware in the modern human society where all services and businesses are highly depend upon. Since its development in the last century occupant safety and comfortability has become a main focal point in automobile industry. Since the air conditioning has been introduced to automobiles there is a generic trend among users to close the external airflow into the cabin to increase the cooling efficiency. This leads to a situation of increasing Carbon Dioxide (CO_2) concentration in the cabin. This paper discusses an experimental investigation using three different light passenger vehicles to study the actual in-cabin CO_2 and concentration of Total Volatile Organic Compounds (TVOC) in cabin during operation.

Vehicle cabin air quality has been investigate by different research groups under various conditions in different parts of the world [1,2]. Carbon Dioxide level in the cabin can be assumed to be equal to the CO_2 levels in outside air and that also vary by location. The atmospheric CO_2 concentration measured by Global Monitoring Laboratory of US National Oceanic and Atmospheric Administration (NOAA) for the month of September 2020 is 411.29ppm [3]. This value is on increase at an alarming rate since the industrial revolution mainly due to human activities [4]. Studies show that the atmospheric CO_2 levels were comparatively lower than that of today, but still varying in the range of 170ppm ~ 260ppm due to natural events during the period of 650,000 to 800,000 years before today [5]. Current rate of rice is nearly 2.5ppm per year and the air we inhale becoming polluted continuously [4]. Therefore monitoring and controlling the in-cabin air of automobile becomes an interesting topic in the industry to avoid possible health and safety risks due to hi CO_2 concentrations for long time periods.

There are various standards developed by respective authorities regarding the recommended levels of CO_2 concentrations in enclosed environments [6–8]. Allen et al. shows in their study that the level of CO_2 in an environment has direct impact on cognitive abilities of people. In their experiments they have tested the same individuals at two different CO_2 concentrations of 945ppm and 1400ppm and observed a 21% decrease in cognitive ability with an increase of CO_2 concentration by 0.044%. this itself reveals how crucial the in-cabin CO_2 concentration on the decisions made by drivers while driving and how important to monitor and control the CO_2 concentration inside the cabin.

ASHRAE standard 62 of 1981 recommends the allowable CO_2 levels linked to minimum area per person in an indoor environment [9]. In an indoor environment it relates the required airflow rate Q_0 as

$$Q_0 = \frac{G}{C_{in,ss} - C_{out}} \quad (1)$$

where G is the CO_2 generation rate per person, $C_{in,ss}$ is the steady state indoor CO_2 concentration, and C_{out} is the outdoor CO_2 concentration.

When it comes to in-cabin air quality, we can calculate the required flow rate of fresh air. However due to various reasons such as carbon monoxide smoke in outside air in urban environments passengers in vehicles prefer to put the switch the air circulation to inside mode preventing fresh air into the cabin.

Persily and Jonge suggested the rate of CO_2 generation per person V_{CO_2} is given by [10]

$$V_{CO_2} = \frac{0.00276 A_D\, M\, RQ}{(0.23\, RQ + 0.77)} \quad (2)$$

where, A_D is the DuBois surface area (m^2), M is the metabolic rate (met), and RQ is the respiratory quotient (dimensionless). A_D is calculated using the following equation where H is height in meters and W is weight in kilograms.

$$A_D = 0.202 H^{0.725} W^{0.425} \quad (3)$$

As per the ASHRAE standards the recommendations are 1200–1300 ppm of CO_2 while the maximum of 8 hours exposure at 5000ppm [6,7,9]. Therefore the experiments were designed to be run on the bottom end of the allowable range for safety reasons.

2. Materials and Methodology

In this study three different vehicle types were subjected to tests with two different passenger numbers. CO_2 concentrations and TVOC concentrations were measured in every 10 seconds using a CCS881 environmental air quality measurement sensor. The vehicles used were:

(a) Toyota Corolla (Petrol) (2005)
(b) Toyota Kluger (Petrol) (2015)
(c) Toyota RAV4 (Hybrid) (2019)

The cabin size of the corolla is the smallest while Kluger is the largest among the three vehicle used.

Figure 1 shows the experimental setup used for the measurements and before every measurement cycle all windows were opened to get fresh air into the cabin for a reasonable time. Then the passengers get in and windows were closed before starting the measurements. The route used was the same for all the measurements. The air circulator was put on inside recirculation mode where no fresh air comes in to the cabin. Fan was set to low flow rate with flow direction on *head and foot* mode and temperature was set to 22 °C. The sensor was placed towards front of the glovebox in each vehicle.

Previous research have shown that the in cabin temperature, metabolic activity, and various other factors have influence on cabin CO_2 concentration and therefore in this experiment they were set to constant levels in all three vehicles the same as much as possible. However there are clear differences in interior setup is different from vehicle to vehicle and the sensor placement has differences due to physical setup of different vehicles. In future experiments it is expected to employ multiple sensors in different places and map the air quality with respect to their physical locations.

In all the experiments carried out the metabolic rate s were kept constant by limiting the activities to the same during each test and respiratory quotient can be assumed the same throughout all experiments as per equation (2).

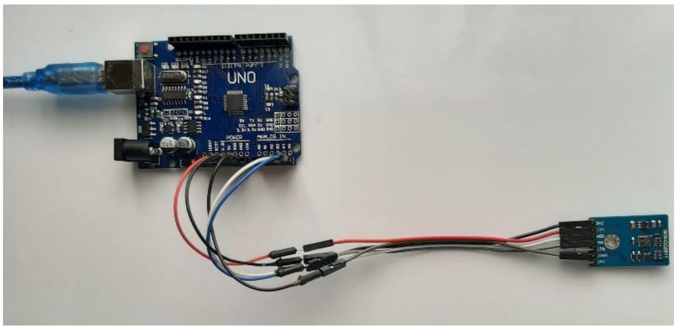
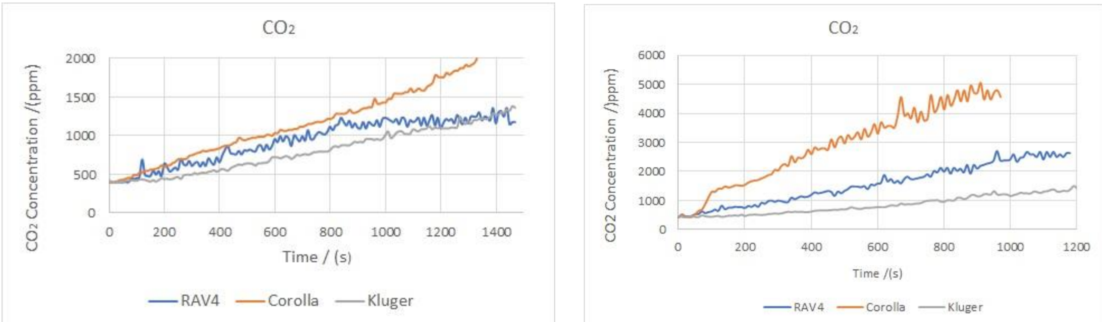


Figure 1. Indoor air quality measurement sensor and data acquisition hardware.

CCS881 sensor module was interfaced to an Arduino Uno microcontroller development kit on I²C bus and it was programmed to take measurements in every 10 seconds period and write the data directly to laptop via USART protocol. CCS881 has the measurement ranges of 400ppm to 29,206ppm of eCO_2 and 0ppb to 32,768ppb of eTVOC where 'e' stands for equivalent.

3. Results and Discussion

Figure 2 shows the equivalent CO_2 measurement results using three different vehicles with one and two passengers in cabin. The rate of change of CO_2 concentration can be said to be inversely proportional to the cabin size as well as the number of occupants in the cabin.

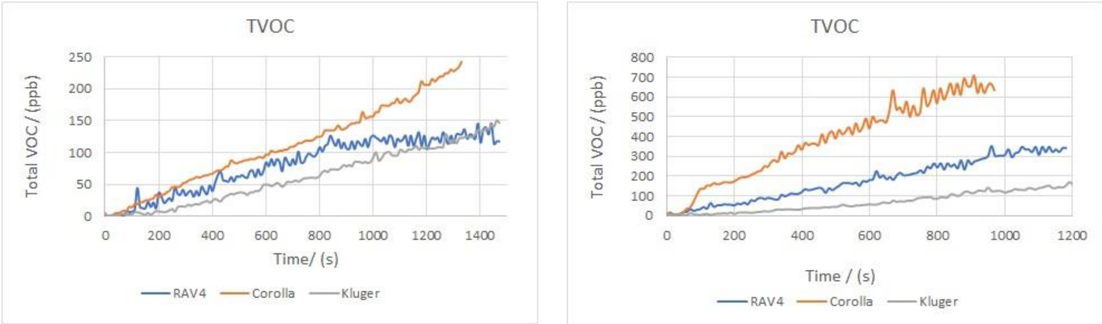


(**a**) (**b**)

Figure 2. eCO_2 concentration variation with time (**a**) single person in cabin (**b**) two persons in cabin.

It can be clearly seen from these results that the cabin size of the vehicle play a great role in the CO_2 concentration where Toyota Corolla has the highest rate of CO_2 concentration and the Toyota Kluger has the lowest, where Corolla has the smallest cabin size while Kluger has the highest.in some trials the initial part looks little bit different from what is expected and that may be the initial heating time needed for the sensor is not received properly.

Figure 3 shows the equivalent TVOC measurement results and the outcome is very similar to the eCO_2 measurement results. This may be due to the fact that the sensor outputs are eCO_2 and eTVOC which are being calculated from the same measurement by the sensor and converted into two parameters logically within inside the sensor hardware. Therefore in subsequent experiments it is decided to employ different types of CO_2 and TVOC sensors to have more realistic measurements.



(**a**) (**b**)

Figure 3. eTVOC concentration variation with time (**a**) single person in cabin (**b**) two persons in cabin.

The total volatile organic compounds measured are well inline with the expected profile over time with respect to occupant number and volume of the cabin. However to ensure the accuracy of measurements different types of TVOC sensors and CO_2 sensors need to be employed simultaneously.

4. Conclusion

This experimental study was carried out to understand the actual pattern of in-cabin CO_2 concentrations during travel in light passenger vehicles. In the initial experiments carried out it can be concluded that the eCO_2 and eTVOC concentrations are inversely proportional to the cabin volume and proportional to the time. However, it is necessary to employ multiple types of CO_2 and TVOC sensors and have multi location within the cabin measurement system with temperature, humidity and oxygen sensors to make a more accurate decision on when to open the external airflow into the cabin and how long it should be kept open. Once all those parameters were measured a more informed decision can be made and that can be integrated into the vehicle heating ventilation and air conditioning system control program.

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