# Transient $CO_2$ Diffusion from Vehicle Cabin Micro-environment in Hot and Humid Climates

Poonyapat Stitnimankarn, Thaisiri Siripoorikan, Napat Thanomkul, Prabhath De Silva, Porpin Pungetmongkol, and Joshua Staubs

***Abstract*—It is well known that, in the absence of any fresh air, the $CO_2$ concentration in a vehicle interior can increase above the ambient level due to the occupants' exhalation. When the vehicle HVAC (heating ventilating and air conditioning) system is operating in recirculation (REC) mode, very little to no fresh air is ingested into the cabin interior. At the end of a commute, when the vehicle is turned off and parked, the accumulated $CO_2$ that escapes from the vehicle interior is of importance because it is the initial conditions during the subsequent commute. During the time the vehicle is parked, $CO_2$ diffuses from the interior to the outside through small holes and leaks in the vehicle envelope. This study considers this phenomenon under various influencing parameters, which include the wind speed outside the vehicle cabin, the air temperature inside the vehicle cabin, and the dimensions of the diffusing holes. The results indicate that the wind speed has the highest impact on the diffusion rate for a given hole size.**

***Index Terms*—$CO_2$ diffusion, Vehicle cabin air quality, Vehicle occupant safety.**

## I. Introduction

During the last few decades, the air quality of the vehicle cabin microenvironment has received as much attention as the indoor air quality of built environment. The volume of a vehicle cabin ranges from about 2 $m^3$ for a small car to about 5 $m^3$ for a full size SUV or a minivan. Thus, the amount of air available for breathing by each occupant in a fully loaded vehicle is less than that of a residence, hence the air quality of cabin environment is of significant importance. The air change rate in a residential home ranges from about (5-20) $h^{-1}$, whereas that for a passenger vehicle is about (3-6) $h^{-1}$, when fan in recirculation mode. A recent review on vehicle cabin air quality summarizing the influence of particulate matter, VOC, hydrocarbons and other chemical compounds is given in [1]. The present study focuses on the transient behavior and the persistent presence of $CO_2$ inside a vehicle cabin originated from exhalation by the occupant(s).

The main purposes of the vehicle HVAC system are to maintain vehicle cabin comfort and to provide air ventilation to the occupants. The HVAC system operates in two distinct modes: recirculation (REC) and outside (OSA) air modes. In the REC mode, the HVAC system circulates air within the cabin, while in the OSA mode, fresh air from outside is ingested into the cabin. As a result, there is an increase in $CO_2$ concentration in the vehicle cabin due to occupants' exhalation. The $CO_2$ concentration rises rapidly above ambient concentration of about 400-600 ppm as shown by a number of studies [2]-[8]. American Society of Heating Refrigerating and Air-Conditioning Engineers (ASHRAE) standard 62-2001 suggests that the acceptable $CO_2$ concentration is 1200-1300 ppm. A concentration in excess of 30,000 ppm can affect health adversely and may cause decision-making impairment.

This study is particularly important in hot and humid Asian countries. The traffic congestion in Asian countries is notoriously bad. Typically, in hot and humid environments, the commuters keep the vehicle HVAC system operating in REC mode to improve fuel economy and to keep unwanted odors from entering the vehicle cabin. After a commute, the vehicle is parked overnight and what happens to the accumulated $CO_2$ is of importance, as it affects the $CO_2$ concentration for the following commute. Previous work [8] suggests that the $CO_2$ concentration declines during parking. Their work showed that parking for a period of about 10 hours brings the concentration level to near ambient level. This happens because $CO_2$ diffuses out from the vehicle cabin through small leakages and imperfect sealing found in the vehicle envelope. With that background, this study is formulated to understand the $CO_2$ diffusion process across a vehicle envelope. The leakage area in an actual vehicle is difficult to quantify, and since vehicles are subjected to varying environmental conditions, this study simulates the diffusion under controlled laboratory conditions. The effects of leakage area, ambient exterior wind speed, and interior air temperature are considered.

The study also has applications in the agriculture industry where one of the biggest concerns for grain storage is the $O_2$ and $CO_2$ concentrations inside the grain bin. The $O_2$ depletion and $CO_2$ accumulation are required to suppress the pest and microorganism survival rate [9], [10]. Studies on $CO_2$ diffusion through the grain storage have been done both theoretically and numerically [11], [12]. More recent studies on food packaging investigated the diffusion of gas through micro-perforated films [13]-[15]. The diffusion of $O_2$ and $CO_2$ in food packages is crucial to determine the quality of food preservation and logistics.

## II. Experimental Procedure

The experimental set up is shown in Fig. (1). It consists of

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The authors are with the International School of Engineering, Faculty of Engineering, Chulalongkorn University, Bangkok 10330, Thailand (e-mail: meenoi_smn@windowslive.com, thaisiri6@gmail.com, napattnk@gmail.com, prabhath.d@chula.ac.th, porpin.r@chula.ac.th, joshua.s@chula.ac.th).

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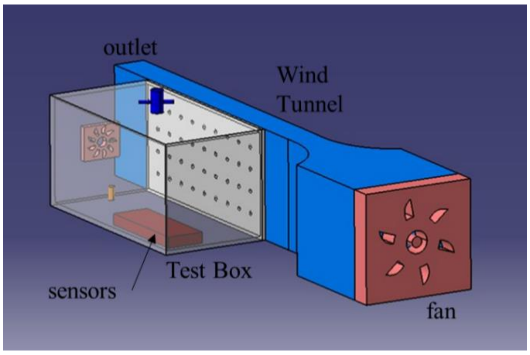
the following three main parts:

### A. Test Box

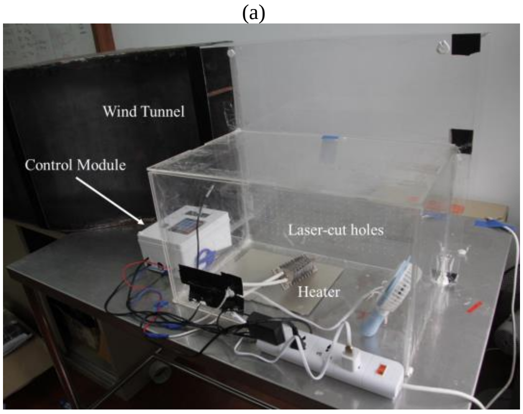
The 0.3m×0.3m×0.5m Test Box representing the vehicle cabin is made out of 4.76mm thick acrylic plates. The swappable test plate it shares with the wind tunnel contains 96 small, laser-cut holes representing the small gaps/holes in a vehicle cabin. Two different hole diameters, 1.5 mm and 3.0 mm, were used in the experiment. A 900W coil heater is included in the Test Box to set the air temperature at the desired level. A small USB fan is installed in the test box to ensure that the temperature and $CO_2$ concentration inside the test box are fairly uniform.

### B. Wind Tunnel

The Wind Tunnel is used to provide a uniform air flow alongside the test plate to simulate the scenario of wind flowing around a parked vehicle. The tunnel has a large cross-sectional area (0.54m × 0.51m) at the inlet, which converges to the smaller cross-sectional area (0.13m × 0.51m) at the outlet. A flow straightener consisting of straws packed tightly together, is located downstream of the three-speed fan and provides a parallel air stream alongside the perforated plate.




(a)




(b)

Fig. 1. (a) Schematic of the experimental set up, and (b) Test box showing the sensors.

### C. Controlling/Monitoring Module

The Controlling and Monitoring Module controls the temperature inside the Test Box and records $CO_2$ concentration in the Test Box with time. The concentration of $CO_2$ is measured continuously at 5 sec intervals using the sensor AQ-9901SD.

The experiments are performed by placing dry ice in the Test Box to achieve the desired $CO_2$ concentration as the initial conditions simulating the $CO_2$ accumulation from the prior commute. When the concentration reaches a suitable level (approximately 10,000 ppm), the dry ice is removed to allow the $CO_2$ to diffuse. The concentration of $CO_2$ is then measured continuously at 5 sec intervals for the remainder of the experiment. Table I, shows the descriptions of the test run.

In addition to the experiment at laboratory conditions, tests were also conducted on two vehicles, a 2018 Mercedes Benz CLA 250 AMG and a 2012 Lexus RX270. These two vehicles were chosen to represent a newer and an older vehicle, as the dimensions of the leakage paths of a vehicle depends on the age of the vehicle. As vehicles age, the gaps and seals tend to deteriorate, and consequently the leakage increases. These tests were conducted in a semi-open garage by parking the car overnight. The $CO_2$ sensor was placed in the center of the vehicle and the concentration was recorded at 5 sec intervals.

TABLE I: THE TEST RUNS

| Run Number | Hole diameter (mm) | Temperature (Deg. C) | Wind Speed (m/s) |
|---|---|---|---|
| 1 | 3.0 | 27 | no wind |
| 2 | 3.0 | 45 | no wind |
| 3 | 1.5 | 27 | no wind |
| 4 | 1.5 | 27 | 2.4 |
| 5 | 3.0 | 27 | 2.4 |
| 6 | 3.0 | 27 | 3.3 |
| 7 | 1.5 | 27 | 3.3 |
| 8 | 3.0 | 27 | 3.9 |
| 9 | 3.0 | 45 | 3.9 |
| 10 | 1.5 | 27 | 3.9 |
| 11 | 1.5 | 45 | 3.9 |

## III. RESULTS

Fig. 2 shows the sample transient behavior of the $CO_2$ concentration measured in ppm for Run 2 (see Table I for experimental conditions). The recording of the data started when the concentration was 10000 ppm. The data clearly show the continuous decrease in the concentration that is a common feature observed in all tests.

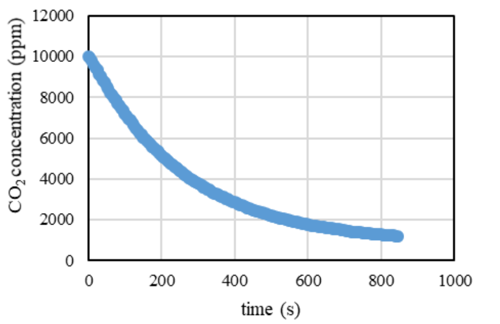



Fig. 2. Measured $CO_2$ concentration time series in Run 2. Table I shows the experimental conditions.

In the absence of any $CO_2$ generation, the reduction in the amount of $CO_2$ is due to the diffusion across the leakage holes. An equation for the transient behavior of the $CO_2$ concentration can be obtained using control volume mass conservation for the Test Box as outlined in [8]. Assuming Fickian diffusion behavior, the time rate of the change of the mass of $CO_2$ in the vehicle can be written as,

$$\frac{d}{dt}(Vc) = \frac{DA}{\delta k}(c - c_o) \cdot \quad (1)$$

The left hand side of (1) indicates the time rate of change in mass of $CO_2$, while the right hand side represents the mass diffused from the box. Here, $V$ is the volume of the test box, $D$ is the diffusivity of the $CO_2$ in air at the testing temperature, $A$ is the total area of the holes, $\delta$ is the thickness of the test plate, $c$ is the $CO_2$ concentration in the test box at time $t$, and $c_o$ is the outside $CO_2$ concentration. The non-dimensional coefficient $k$ is used to recognize the fact that diffusion length may not be exactly equal to the thickness of the plate [13]. It also accounts for any unintended leaks in the Test Box. Denoting the initial concentration as $c_i$, (1) yields,

$$\ln\left(\frac{c - c_o}{c_i - c_o}\right) = -\frac{DA}{V\delta k}t \quad \cdot \quad (2)$$

Fig. 3(a, b, c, d) shows the experimental results for all test runs, based on the air speed of the air vent. The reason for this is that the diffusion behavior is affected by the thickness of the boundary layer [13]. The vertical and horizontal axes in all graphs are the non-dimensional $CO_2$ concentration and the non-dimensional time, respectively. All plots are drawn to the same scale so that comparison between them can be clearly shown. When there is no wind velocity, (Fig. 3a) the rate of decay of concentration is the lowest. As the wind speed increases, the rate of decay of concentration increases as evident from the gradient of plots seen in the Fig. 3(b, c, d). The cabin air temperature of a parked vehicle under the sun can reach as high as 60°C. The diffusivity of $CO_2$ in air is temperature dependent; and this is the reason why the tests were conducted at two different temperatures. However, comparison of tests conducted at two different temperatures indicates that this temperature difference is not significant enough to cause much effect in the diffusion rate.

From Fig. (3) the average gradient corresponding to each wind speed can be estimated by approximating an exponential fit. These can be used to estimate the coefficient $k$, with the calculated values shown in Table II. The value of $k$ decreases with the increase in wind speed.

TABLE II: THE COEFFICIENT *K*

| Wind Speed (m/s) | *k* |
|---|---|
| 0.0 | 0.064 |
| 2.4 | 0.030 |
| 3.3 | 0.020 |
| 3.9 | 0.013 |

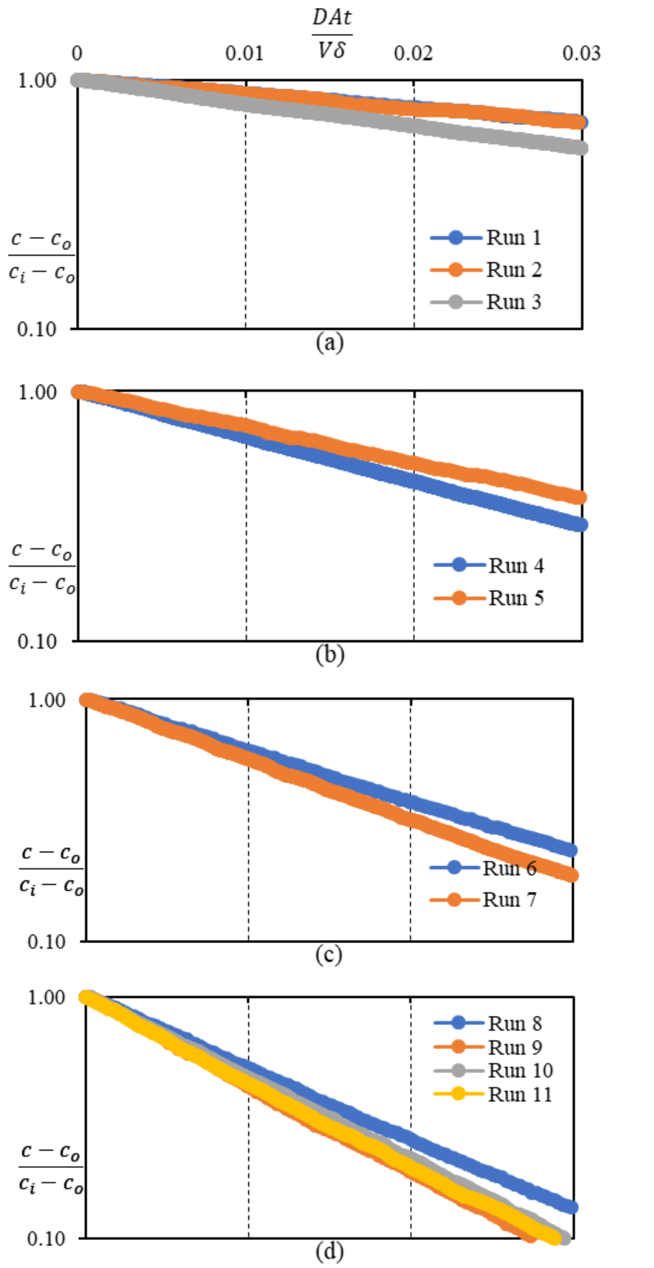



Fig. 3. The time series of measured $CO_2$ concentration plotted according to (2) on log-linear scale. (a) no wind, (b) wind speed = 2.4 m/s, (c) wind speed = 3.3 m/s, and (d) wind speed = 3.9 m/s.

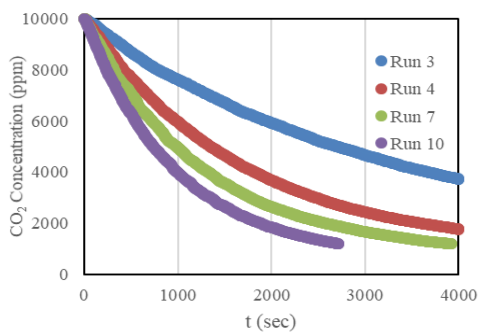



Fig. 4. The time series of measured $CO_2$ concentration plotted against time at different wind speeds. The runs are with the same hole diameter (1.5 mm) and at air temperature of 27°C.

Fig. 4 shows the raw $CO_2$ concentration data measured in test runs with the plate with 1.5 mm diameter and at the temperature 27°C. The four different curves show the results at different wind speeds. This figure also clearly shows how the diffusion rate increases with the wind speed for a given hole size at a given temperature.

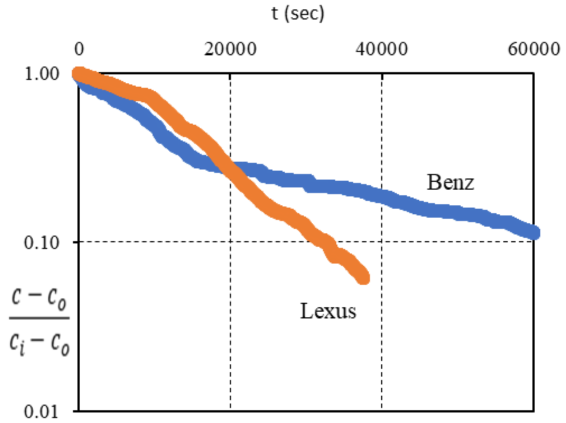



Fig. 5. The time series of measured $CO_2$ concentration on real vehicles plotted on log-linear scale.

The test conducted on the car is shown in Fig. (5). The decay of $CO_2$ concentration in these runs is also plotted in log-linear scale. The decay did not strictly show a straight line behavior as for the laboratory test runs. The reason for this behavior was perhaps due to the fact that the semi-open space where the vehicle was parked overnight had variable wind conditions. Therefore, a straight-line behavior in log-linear scale would not be expected.

## IV. Conclusion

The study aimed at understanding the escape of accumulated $CO_2$ in a vehicle subjected to environmental variables such as the surrounding wind speed, the cabin air temperature, and the dimensions of the leakage holes. It is clear that larger the hole size higher the $CO_2$ transfer across the vehicle envelope. Interestingly, the results also indicate that surrounding wind speed has the significant impact on the rate of diffusion, for a given hole size. The variation in temperature encountered in a car is not large enough to cause much change in the diffusion rate.

Furthermore, from the result of the experiment performed on two real cars, it can be seen that it took about 10-20 hours for the $CO_2$ to diffuse out from 10,000 ppm to 1,200 ppm. As a result, if drivers have to use their cars daily, the $CO_2$ may not be able to diffuse overnight. Commuters can overcome this situation in the car cabin air by running HVAC system in OSA mode at the beginning of the commute.

The study reported here are only preliminary. The authors plan to conduct more carefully controlled tests, including holes of different shapes, in future.

## Conflict of Interest

The authors declare no conflict of interest.

## Author Contributions

Poonyapat Stitnimankarn, Thaisiri Siripoorikan and Napat Thanomkul designed and constructed the experimental setup and conducted the test runs as their senior design project to fulfil the bachelor degree program. They also conducted the test on the vehicle. Porpin Pungetmongkol and Joshua Staubs served as the committee members, and Prabhath De Silva was the project advisor. All authors have approved the final version.

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**Poonyapat Stitnimankarn** is a graduating student in the automotive design and manufacturing engineering undergraduate program at the International School of Engineering at Chulalongkorn University. This work was carried out as a partial fulfilment of the course requirement. He is expected to graduate in October 2019.

**Thaisiri Siripoorikan** is a graduating student in the automotive design and manufacturing engineering undergraduate program at the International School of Engineering at Chulalongkorn University. This work was carried out as a partial fulfilment of the course requirement. He is expected to graduate in October 2019. Currently, he is employed at the PTT Public Company Limited, Thailand.

**Napat Thanomkul** is a graduating student in the automotive design and manufacturing engineering undergraduate program at the International School of Engineering at Chulalongkorn University. This work was carried out as a partial fulfilment of the course requirement. He is expected to graduate in October 2019. He is currently employed at SINPAT International Company Limited, Thailand.

**Prabhath De Silva** received PhD in mechanical engineering from Arizona State University in 1992. His area of expertise is in Fluid and thermal systems. Dr. Prabhath is currently a lecturer at the International School of Engineering at Chulalongkorn University in the Automotive Design and Manufacturing Engineering program.

**Porpin Pungetmongkol** received her PhD in mechanical and control engineering from Tokyo Institute of Technology in 2015. Her area of expertise is in Nano-Microfluidic devices and sensors. Dr. Porpin is currently a lecturer at the International School of Engineering at Chulalongkorn University in the Nano Engineering program.

**Joshua Staubs** received his PhD in aerospace engineering from Virginia Polytechnic Institute and State University in 2008. His area of expertise is in acoustics, UAV and drone aerodynamics. Dr. Joshua is currently a lecturer at the International School of Engineering at Chulalongkorn University in the Aerospace Engineering Program.