

Field Tests to Monitor Build-up of Carbon Dioxide in Vehicle Cabin with AC System Operating in Recirculation Mode for Improving Cabin IAQ and Safety

Gursaran D. Mathur
CalsonicKansei North America

Copyright © 2008 SAE International

ABSTRACT

The vehicle's AC system should not be operated in recirculation mode for extended periods of time due to build up of CO₂ inside the vehicle cabin. This is the CO₂ that is exhaled by the occupants of the vehicle. This CO₂ is then inhaled by the occupants that goes into their blood streams which results in a negative impact on health. This becomes critical when a number of people are sitting inside the vehicle. Field tests were conducted on a MY 2003 vehicle in recirculation mode to monitor the build-up of the CO₂ concentration inside the cabin as a function of number of occupants, vehicle speed and ambient temperatures. The vehicle was driven in Detroit Metro area in city and highway traffic conditions. Based on this investigation it is determined that the cabin concentration levels reaches ASHRAE (Standard 62-1999) specified magnitudes in first 5 minutes of driving with only one occupant in the vehicle. Hence, operation of the vehicle beyond 5 minutes will result in much higher levels of cabin carbon dioxide concentration then specified by ASHRAE standard. This situation would be much severe if a number of people are sitting inside the vehicle and are going on a long drive. Additional tests were conducted by imposing ASHRAE standard 62 limits (700 ppm over the background limit on a continuous basis) that resulted in cycling of blower unit's mode door between recirculation and OSA and vice versa. Details of the investigation are presented in this paper.

INTRODUCTION

Indoor Air Quality (IAQ) is becoming an important issue for vehicles in the United States, Europe and Asia. This is due to the fact that the number of vehicles is increasing at an exponential rate resulting in traffic congestions with very high levels of tailpipe emissions (NO_x, CO, HC, and VOC gases). Due to these congestions, we are spending more time each day in our vehicles and are more likely to be exposed to the exhaust gases from automobiles. In this case, if the quality of the outside air is poor then the

position of the blower unit's mode door can be changed from outside air mode to recirculation mode. Once the vehicle is out of the traffic jam, the mode door could be switched back to outside air mode. This has been recently investigated by the author (Mathur, 2006, 2007a).

Another aspect of IAQ is the build-up of carbon-dioxide inside the cabin in recirculation mode. The carbon dioxide that is exhaled by humans remains in the cabin during operation in recirculation mode. Typically, in southern states (e.g., Arizona) people drive their vehicles in summer by running vehicle's air conditioning systems in recirculation modes only. Carbon dioxide that is exhaled by humans remains in the cabin during operation in recirculation mode. The concentration of carbon dioxide then increases in the cabin. The CO₂ that is inhaled by the occupants goes into their blood streams and results in a negative impact on their health. Carbon dioxide reacts in the blood to form carbonic acid and bicarbonate and, if it were allowed to accumulate, would cause acidosis. This condition is particularly harmful to the cells of the brain (Oxford University Press, 2007). ASHRAE (1999) have conducted studies and have determined guidelines to address this issue. The vehicle's AC system should not be operated in recirculation mode for extended periods of time due to build up of CO₂ inside the vehicle. This becomes critical when a number of occupants are sitting inside the vehicle. Hence, it is recommended that a timed strategy be used for recirculation (say 10 minutes) - after this time, the mode will automatically change to OSA mode to reduce the levels of CO₂ inside the cabin. A carbon dioxide sensor could be used inside the cabin to monitor the cabin carbon dioxide levels. If the level goes beyond a pre-determined level, the blower unit's intake door will go to OSA mode.

LITERATURE REVIEW

ASHRAE standard 62 (ASHRAE, 1999) specifies the safe levels of carbon dioxide in conditioned space for humans. The CO₂ concentration limit by ASHRAE is 700 ppm (on a

continuous basis) over the ambient conditions on a continuous basis. Typical ambient concentration level of CO₂ is approximately 220 ppm. Hence, if the CO₂ concentration exceeds approximately 900 ppm inside of a home or in a vehicle cabin, then we must introduce outside air into the home or vehicle cabin to reduce the CO₂ concentration. There is a lot of information available (ASHRAE Handbook, 2005) on the concentration levels of CO₂ for homes, aircraft and space craft cabins and its influence on humans. For the automotive sector, some information is available in the public domain due to the development of alternative refrigerant air conditioning systems (Amin et. al., 2004; RACE, 1997; Pearson, 2001; Arndt, 2007) with CO₂ as the working fluid. Table 1 shows the physiological effects of carbon dioxide on humans (Amin et. al., 2004; RACE, 1997). SAE (2007) is developing a standard (J2772) for measurement of passenger compartment refrigerant concentration under system refrigerant leakage conditions. Based on their simulated results (for a given charge, airflow, refrigerant leakage rate, cabin volume and vehicle speed), the maximum concentrations in the cabin reaches approx 2~8% (or 20,000 to 80,000 ppm). The concentrations initially increase and then peaks after a certain time, and then fall off gradually. In a recent investigation the author (Mathur, 2007b) had investigated this issue – the details are given in the next section.

CURRENT INVESTIGATION

In a recent study, the author (Mathur, 2007b) had monitored the build-up of carbon dioxide in a vehicle cabin as a function of number of occupants (1 to 4), vehicle speed (idle to 100kph), and ambient conditions (30 and 40°C). These tests were conducted in Calsonic's wind tunnel, i.e., in a controlled environment. The tests were conducted on a 2003 MY production vehicle by installing two carbon dioxide sensors. One sensor was installed at blower unit's intake door to monitor the carbon dioxide levels for the outside air and one installed inside of the cabin to monitor the concentration level of carbon dioxide inside the cabin. The influence of the number of occupants inside the vehicle was investigated by having one, two, three, and four occupants inside the vehicle at a given time.

The objective of this study is to experimentally determine the time it takes to increase the CO₂ concentration levels inside of the vehicle cabin 700 ppm on a continuous basis over the ambient CO₂ levels (ASHRAE Standard 62-1999) as a function of number of occupants, vehicle speed, and ambient temperature.

This is a follow-up investigation on the build-up on carbon dioxide in the cabin. In this investigation, field tests were conducted and cabin carbon dioxide levels were monitored and recorded by driving the vehicle in the Detroit metro area. The number of occupants, vehicle speed, and type of driving (typical local traffic and highway conditions) are the major variables for this study. The tests were conducted during mild to hot ambient temperatures (15 to 40°C). Detailed results have been presented in the paper.

CARBON DIOXIDE SENSOR AND ITS LOCATION

A commercially available carbon-dioxide sensor (Bosch, 2006) was used for the study – see Figure 1. This sensor utilizes the principle of photometric gas measurement. The gas concentration is measured via a wavelength specific reduction of electromagnetic radiation within the infrared range. This sensor outputs a voltage (0~5V) based on the concentration of carbon-dioxide. The accuracy of the carbon-dioxide concentration measurement is $\pm 10\%$ of the measured value and the measuring frequency is 1 Hz. Two such sensors were used for this study. A 2003 MY production vehicle was used for this investigation. This vehicles' HVAC system is designed to use 100% recirculated air when the intake door is in recirc mode. One of the sensors was installed at the blower unit's intake door (Figure 2) to monitor the concentration of carbon dioxide in the air that is coming into the cabin through the cowl. This is valid as long as the blower unit's intake door position stays in outside air (OSA) mode. Once the door position moves to recirculation mode then this sensor measures the concentration of the carbon dioxide within the cabin. Figure 1 shows the location of the other sensor near the parcel shelf area. In recirculation mode, the concentration readings of both the sensors were close indicating good mixing of the air within the cabin.

EXPERIMENTAL TESTS

Tests were conducted by driving the test car in the Detroit metro area on local city roads and on all major highways. During the tests, the test vehicle was driven at the posted speeds and cabin carbon dioxide concentration (ppm) was monitored on a real time basis. The tests were conducted by first driving on a specific route with one occupant (i.e., only driver) in the car. The vehicle was then returned back to the originating point. At this time, the data file on the laptop was closed and the file was saved. The doors and windows of the vehicle were opened and the blower unit's mode door was switched to OSA mode. This was done to help in bringing the cabin concentration level of carbon dioxide to ambient conditions. Once the cabin carbon dioxide concentration levels were back to the ambient levels, the windows and doors were closed and the blower unit's mode door was switched back to recirculation mode. At this time a second person sat in the car along with the driver. The data collection was restarted and the vehicle was again driven on the same route. The same route for testing was used to reduce the variations in the traffic pattern for each test. The above procedure was also used for third and the fourth passenger. The above testing was conducted for the following two control strategies for the mode door of the blower unit:

- i. Always remained in recirculation mode during the tests: This was required to determine the peak cabin concentration levels in typical driving conditions.

- ii. The mode door was switched from recirculation to OSA mode and vice versa based on the following strategy: Cabin Carbon dioxide ppm ≥ 900 ppm; Door switched from recirculation to OSA mode. Now when the cabin carbon dioxide concentration ppm falls to 450 ppm the mode door goes back to recirculation mode. This testing was necessary to determine the frequency of the cabin carbon dioxide magnitudes reaching the levels defined by ASHRAE as a function of 1, 2, 3, and 4 people sitting inside the vehicle.

The percent measurement uncertainty in vehicle speed and the ambient temperature are ± 2 kph and $\pm 1^\circ\text{C}$, respectively. The measurement uncertainty in the carbon dioxide is $\pm 10\%$. The laptop computer for the data acquisition system outputs the measured data on a real time basis. The magnitude of the outside CO_2 concentration in Farmington Hills was measured (am) from 180~220 ppm. Note that based on UNEP's (2007) global atmospheric data, the average global concentration for 2007 is 365 ppm. Obviously, the difference is due to concentration gradients between different parts of the cities, geographical area. For data collection, the people first sat inside of car and then the doors were closed and the data acquisition was turned on. By this time the cabin concentrations were already around 400 to 500 ppm range. Figures 3 and 4 show the equipment that was used for this study.

RESULTS AND DISCUSSIONS

Figures 5 to 8 show the build-up in cabin CO_2 concentration as a function of time with the blower unit's mode door in recirculation mode. The test vehicle was driven in Farmington Hills in city traffic. The average vehicle speed for this trip was approximately 20~25mph. This specific route has a number of stop lights with maximum posted speeds between 40 to 45 mph. The ambient temperature during these tests was 27°C . Figure 5 shows data for 1 occupant in the car. At the end of the test, the peak cabin concentration reached just over 1200 ppm. The test was repeated by adding another occupant inside the cabin and by following the test procedures as described in the test methodology. The peak cabin concentration levels with two, three and four occupants resulted in 2000, 3150, and 4025 ppm, respectively. These concentrations are well above the concentration specified by ASHRAE standard 62. However, the total time for this trip was close to 18 to 20 minutes. Figure 8 shows a slight drop in the cabin concentration at about 7.13 pm for next 2 minutes. This was due to the fact that during the test we got green lights on two intersections that resulted in higher vehicle speeds for few extra minutes. This caused more body leakage (i.e., exchange of airflow between the cabin and outside) resulting in a drop of the concentration levels of carbon dioxide inside the cabin. Note that even though the vehicle is operated in recirculation mode, there is air exchange between the outside and the cabin due to the pressure gradients over and under the vehicle.

Figures 9 and 10 show the build-up of cabin carbon dioxide for highway driving with one and four occupants. The vehicle was driven from Farmington Hills on I-696 and on I-275. For this part of the highway, the average vehicle speed was between 65 to 70 mph. The ambient temperature for this test was approximately 30°C . Data for two and three occupants have been eliminated as this data falls within the boundaries of one and four occupants. With one occupant inside the vehicle (Figure 9), the peak carbon dioxide concentration within the cabin is approx 930 ppm. This magnitude is slightly lower than the city traffic driving (1200 ppm) due to the difference in the body leakage at an average speed of 25 and 65 mph. The body leakage is more at higher speeds resulting in air exchange between cabin and outside. This helps in reducing the levels of cabin carbon dioxide concentration. Figure 10 shows the data with four occupants sitting inside the vehicle. During the first 6 minutes of the testing, the vehicle was driven on local roads to access highway. During these 6 minutes the average vehicle speed was approx 35 mph. Hence during these first 6 minutes, the peak concentration level reaches around 3780. Once the vehicle is driven on highways (i.e., after 6 minutes of driving), the cabin peak concentration starts to decrease and levels off at approx 3100 ppm. This is significantly lower than at city traffic conditions (4025 ppm).

Figures 11 to 14 show the test results for cabin carbon dioxide concentrations when ASHRAE-62 standard was imposed as a boundary condition for the blower unit's mode door. The mode door was switched from recirculation to OSA mode and vice versa based on the following strategy: Cabin Carbon dioxide ppm ≥ 900 ppm; Door switched from recirculation to OSA mode. Now when the cabin carbon dioxide concentration ppm falls to 450 ppm the mode door goes back to recirculation mode. This testing was necessary to determine the frequency of the cabin carbon dioxide magnitudes reaching the levels defined by ASHRAE as a function of 1, 2, 3, and 4 people sitting inside the vehicle.

Figures 11 and 12 show the test results for city traffic for one and four occupants with the above described imposed boundary condition for intake unit's mode door. The test vehicle was driven in Farmington Hills in city traffic. The average vehicle speed for this trip was approximately 20~25mph. This specific route has a number of stop lights with maximum posted speeds between 40 to 45 mph. The ambient temperature during these tests was 27°C . As the vehicle is driven, the cabin concentration starts to increase. Once it reaches 900 ppm (700 ppm over the ambient on a continuous basis), the microprocessor sends a signal to change the position of the blower unit's mode door from recirculation to OSA mode. Once this is done, the cabin concentration level of carbon dioxide starts to decrease with time. Once it reaches close to the lower concentration level (including sensor tolerance), the microprocessor sends a signal to change the door back to recirculation mode. One cycle takes about 6 minutes. Figure 12 shows the same data with four occupants inside the vehicle. With

four occupants sitting inside the vehicle, the cabin concentration reached the upper limit very quickly. Based on this data, one cycle takes about 2 minutes, i.e., to change the blower unit's mode intake door to go from recirculation mode to OSA mode and vice versa.

Figures 13 and 14 shows the test results for highway driving for one and four occupants with the above described imposed boundary condition for blower unit's mode door. The vehicle was driven from Farmington Hills on I-696 and on I-275. On highway the average vehicle speed was between 65 to 70 mph. The ambient temperature for this test was approximately 30°C. Figure 13 shows that one cycle for blower units intake door takes about 9 minutes to change position from recirculation to OSA and vice versa. With four occupants sitting inside the vehicle, the cycle rate decreases due to the fact that we have more carbon dioxide being exhaled by the occupants. The cycle rate is about 3 minutes with 4 occupants at highway speeds.

DISCUSSIONS ON SAFETY ISSUES

Typically, during summer season, people operate their vehicle's HVAC system in recirculation mode for maximum cooling performance. Customers normally run in this mode for extended periods of time. This could become a potentially severe situation for families with children who are going on vacations during the summer season. A typical minivan or SUV has a gas tank with capacities ranging from 15 to 20 gallons. Assuming gas mileage of 25 mpg, this vehicle has a potential to go 375 to 500 miles without refueling. Assuming an average highway speed of 70 mph, this vehicle could be driven continuously for 5 to 7 hours! For vehicles that are operated in recirculation mode for extended periods, this could become a potential safety hazard. In this current investigation, we see that the cabin concentrations of carbon dioxide reaches ASHRAE standard-62 specified ppm levels in less than 5 minutes! Hence, we must either install a carbon dioxide sensor in the cabin to monitor the ppm levels or have a timed recirculation (say max 10 minutes).

CONCLUSIONS

A 2003 MY production vehicle was equipped with two sensors to record the concentration levels of CO₂. One of the sensors was installed at the blower unit intake door to monitor the concentration of carbon dioxide in the air that is coming into the cabin through the cowl. The second sensor was located near the parcel shelf area to monitor the cabin CO₂ concentration. Field tests were conducted by driving the vehicle in the Detroit metro area. The following are the major conclusions based on the current study:

- a) At low vehicle speeds (average 20~25 mph), the magnitudes of the peak cabin concentration for carbon dioxide are higher in comparison to higher average vehicle speeds (65 mph). This is due to

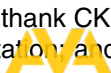
the fact that at lower vehicle speed we have less body leakage.

- b) For city traffic, the peak cabin concentrations of 1200, 2000, 3150 and 4025 ppm were recorded for one, two, three and four occupants. These magnitudes are well above the recommended levels specified by ASHRAE standard 62.
- c) At highway speeds (65~70 mph), the peak cabin concentrations of 1020 and 2800 ppm were recorded for one and four occupants.
- d) For tests conducted in city traffic by imposing ASHRAE standard 62 limits (700 ppm over the background limit on a continuous basis) resulted in cycling of blower unit's mode door in approx 6 minutes for one occupant. This frequency increased to approximately 2 minutes with four people sitting inside of the vehicle.
- e) For tests conducted on highways by imposing the ASHRAE standard 62 limits resulted in cycling of the mode door in approximately 9 minutes for one occupant. The cycle rate increased to 3 minutes with four occupants sitting inside of the vehicle.
- f) Based on the above data, it is clear that the cabin concentration levels reaches ASHRAE standard 62 specified magnitudes in first 5 minutes of driving with only one occupant in the vehicle. Hence, operation of the vehicle beyond 5 minutes will result in much higher levels of cabin carbon dioxide concentration than specified by ASHRAE standard. This situation would be much severe if a number of people are sitting inside the vehicle and are going on a long drive.

FUTURE WORK

Based on the information from this study, control strategy will be developed to control the cabin CO₂ concentration below the safe limits. This could be accomplished by continuously sensing the level of cabin carbon dioxide and then comparing it against a pre-determined threshold level. If the cabin carbon dioxide level exceeds the threshold value the sensor will give signal to the blower unit via control head/CPU to change the intake door position from recirculation to OSA mode. In vehicles that have automatic windows, the windows could be rolled down automatically (signal via CPU) to allow OSA into the cabin. When safe levels of CO₂ concentration are reached within the cabin, the intake door position can be switched back to recirculation mode for maximum cooling.

ACKNOWLEDGMENTS

The author would like to thank CKN Instruments for helping in the instrumentation and the management (Mr.  ).