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Modeling CO_2 Concentrations in Vehicle Cabin

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ABSTRACT

Passengers are exposed to roadway pollutants due to entrainment of outside air into the vehicle cabin. Previous works found cabin air-recirculation can reduce pollutant particle concentrations significantly. However simultaneous increase of CO_2 concentrations in the cabin prevented wide use of recirculation mode for such purpose. A mathematical model was developed to predict CO_2 concentrations in vehicle cabin air during air-recirculation mode. The model predicts temporal CO_2 concentration changes as a function of cabin volume, vehicle body leakage, and number of passengers. This model can be used to design and control air-recirculation mode for a variety of vehicle conditions.

INTRODUCTION

A vehicle cabin provides a unique environment in which passengers are confined during their ride. Current vehicle HVAC (Heating, Ventilation, and Air Conditioning) systems are optimized to reduce the dust concentration and noise coming from roadway while maintaining comfortable temperature and humidity for passengers.

In 2010 CARB (California Air Resources Board) reported 9,000 people in California die prematurely each year as a result of exposure to fine particle pollution (PM2.5) [1]. On roadways, in-cabin exposures to ultrafine particles have been shown to be 10 times higher than ambient levels and contribute to approximately 50% of total daily ultrafine particle exposure among Los Angeles commuters [2, 3]. These results can apply to most of urban areas where high traffic volume exists. The high exposure at the above studies is because air on the roadway is entrained into the vehicle cabin. On roadway vehicles with internal combustion engines emit particulate emissions. CARB [4] and WHO [5] declared diesel exhaust (including particulate) as a carcinogen based on numerous health effect studies. The vehicle emissions including PM (particulate matter) emissions are strictly regulated to protect public health. However, roadways pose serious threat to the health of passengers due to a high concentration of pollutants including particle emissions.

Scientists found cabin air-recirculation can reduce particle concentrations in the vehicle cabin significantly and effectively. Zhu et al. [2] found up to 85% reduction in particle concentrations with cabin air-recirculation. Qi et al. [6] reported similar improvement in cabin air quality under freeway driving conditions with air-recirculation. However, their findings could not be applied to the cars in the market. One important problem should be resolved to implement air-recirculation algorithm into the vehicle HVAC system for reduction of particle concentrations. Zhu et al. [2] showed that CO_2 concentrations rise to 4500ppm in 10 min for a passenger car with 3 passengers during air-recirculation mode. Occupational Safety and Health Administration (OSHA) has established 5000 ppm as the Permissible Exposure Limit (PEL) of CO_2 for 8 hour [7]. As the occupancy of a home or office space is very different from that of a vehicle, researchers have also referenced other standard. Mathur [8] cited ASHRAE standard 62 which specifies the safety level of CO_2 in conditioned space. The ASHRAE standard is 700 ppm over ambient conditions on a continuous basis. Therefore development of an air-recirculation system to reduce PM level is not possible without controlling or suppressing increase of CO_2 concentrations in the cabin. Grady et al. [9] suggested such a system which recirculates a fraction of cabin air (as opposed to 100% recirculation) to reduce PM concentrations while suppressing CO_2 increase is possible.

This paper will provide mathematical model with which temporal change of CO_2 concentrations can be predicted under various cabin air-recirculation conditions. This model can be used to design and control air-recirculation mode for production cars.

MODELING CO$_2$ CONCENTRATION

The cabin of a modern vehicle is a relatively well sealed space except a distinctive inlet and outlet. Most of passenger cars draw air from outside through a duct system which has an inlet placed near the bottom of the windshield and the engine hood. This duct system is connected to the vehicle HVAC system. The outlet is called body vent which is usually hidden at rear bottom space of the cabin. The size and position of the body vent is critical to maintain pressure balance of the cabin and to reduce noise from outside. Although vehicle body leakage (i.e. flow in and flow out through gaps and crevice) can take place in any location other than the distinctive inlet and outlet, it is assumed that most of the leakage flow will be through the distinctive inlet and outlet for properly maintained modern vehicles.

Figure 1 shows a schematic diagram of the vehicle cabin system. Q_i is a flow through the inlet duct system and this should balance with Q_o which is a flow through the body vent. Passengers are the source of CO$_2$ within the cabin. The normal human breath exhales CO$_2$ at levels ranging from 38,000 ppm to 56,000 ppm with rates ranging from 220 ml/min at rest to 1650 ml/min during moderate exercise [10]. This high concentration exhale can lead to high levels of the CO$_2$ concentration in enclosed spaces like the vehicle cabin unless it is well ventilated. The outside CO$_2$ concentration is fixed at the ambient CO$_2$ level which is around 385 to 395 ppm [11]− 390 ppm was used for all fits- while the in-cabin CO$_2$ concentration can vary as a function of the strength of the source term (i.e. number of passengers), cabin volume (V_c) and body leakage flow (Q_l=Q_i=Q_o). Q_l can vary as a function of other parameters such as ventilation fan speed, vehicle speed, geometry of the HVAC duct system etc.

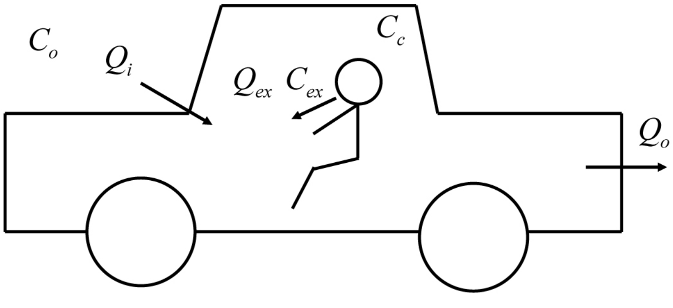

Figure 1. Schematic diagram of vehicle cabin air system

The CO$_2$ mass balance equation for the vehicle cabin can be expressed as equation 1 using schematics in Figure 1.

$$\frac{dm_c}{dt} = n \cdot C_{ex} \cdot Q_{ex} + C_o \cdot Q_l - C_c \cdot Q_l \tag{1}$$

Where m_c is the mass of CO$_2$ in cabin, t is the time, n is the number of passengers, C_{ex} is the concentration of CO$_2$ in exhale and Q_{ex} is the flow rate of exhale, C_o is the CO$_2$ concentration outside, Q_l is the body leakage flow, and C_c is the CO$_2$ concentration in cabin. Left side of the equation 1 shows the time derivative of CO$_2$ mass in the control volume (i.e. vehicle cabin). The first, second and third term on the right side show CO$_2$ mass change due to exhale, inflow of outside air and outflow of the cabin air. Equation 2 shows relationship between the cabin volume, CO$_2$ mass and CO$_2$ concentration.

$$C_c = \frac{m_c}{V_c} \quad \text{then} \quad dC_c = \frac{dm_c}{V_c} \tag{2}$$

, where V_c is the cabin volume. After substituting equation 2 into equation 1, the governing equation which determines CO$_2$ concentrations in the vehicle cabin can be expressed by:

$$V_c \cdot \frac{dC_c}{dt} = n \cdot C_{ex} \cdot Q_{ex} + C_o \cdot Q_l - C_c \cdot Q_l \tag{3}$$

, which is the first order ordinary differential equation. The solution of the equation 3 should predict CO$_2$ concentrations of the cabin air under various conditions. It is worth to note that the body leakage (Q_l) should be determined to solve the equation 3. When the vehicle is motionless and ventilation fan is off, the body leakage (Q_l) becomes nearly zero. Under this condition there is a special solution:

$$C_c(t) = \frac{n \cdot C_{ex} \cdot Q_{ex}}{V_c} t + C_{c_0} \tag{4}$$

, where C_{c0} is the in-cabin CO$_2$ concentration at t=0. Equation 4 shows a linear increase of the CO$_2$ concentration as a function of time. The body leakage (Q_l) will have non-zero value under all other conditions such as when vehicle is in motion and/or the ventilation fan is on. Under these conditions the equation 3 has a general solution as shown below:

$$C_c(t) = \left(C_{c_0} - \left(C_o + nC_{ex} \cdot \frac{Q_{ex}}{Q_l} \right) \right) \cdot \exp\left(-\frac{Q_l}{V_c} t \right) + \left(C_o + nC_{ex} \cdot \frac{Q_{ex}}{Q_l} \right) \tag{5}$$

The coefficient of the exponential function can become positive or negative depending on whether the initial in-cabin CO$_2$ concentration is greater than the equilibrium CO$_2$

concentration or not. This will result in exponential decrease or increase of the cabin CO_2 concentration.

The inverse of the coefficient in the exponential function defines the time constant of the system as:

$$\tau = \frac{V_c}{Q_l} \tag{6}$$

, where τ is the time constant. Time response of the CO_2 concentration becomes slow as the cabin volume increases and body leakage decreases.

An equilibrium CO_2 concentration can also be obtained from the equation 3 by assuming zero value for the time derivative term.

$$C_{c\_equil} = \frac{n \cdot C_{ex} Q_{ex}}{Q_l} + C_o \tag{7}$$

This expression was already included in equation 5 to determine the coefficient of the exponential term.

DETERMINATION OF UNKNOWNS

This section explains how to determine unknowns in the analytic solutions by comparing with experimental data. First, a test was conducted using a light duty passenger vehicle. Specifications of the vehicle are not important for understanding therefore not provided. The cabin air was sampled at the shoulder level of a driver above the center console, facing away from the front vehicle HVAC system. The CO_2 concentration was quantified using CIRAS-2 SC (PP-Systems) using NDIR method. The vehicle was at rest and the ventilation fan was off. Two passengers were in the vehicle and the CO_2 concentration was measured as a function of time. This experimental condition is for the special solution (equation 4). The data was fitted to a linear line and coefficients of the fitted lines are shown in Figure 2. By comparing coefficients of the fitted line and equation 4, the unknown, $n \cdot C_{ex} \cdot Q_{ex}$ could be determined. For example, $C_{ex} \cdot Q_{ex} = 2.69 \cdot V_c$. Then $C_{ex} \cdot Q_{ex} = 2.69 \cdot V_c =$ 9,713 V_c assuming is 3600 liter. It should be noted that was forced to be 390 ppm for all data fittings. Predicted trend lines were also drawn using equation 4 for 3 and 4 passengers in Figure 2.

Second, tests were conducted while a vehicle was in motion at a constant speed with two passengers. For this test, cabin air was recirculated and the ventilation fan was on at speed 2 and 8 out of 8. The experimental data was fitted to an equation which has a form of the general solution (equation 5), $C_{cabin}(t) = (A - B) \exp(-Ct) + B$. The fit showed excellent agreement with the data in terms of R^2 values as in Figure 3 and coefficients (A, B and C) could be obtained as (390, 7219, 0.00042) and (390, 5293, 0.00061) for fan speed 2 and 8, respectively.

Coefficient A's were determined by forcing them to 390 ppm as mentioned previously to match with the ambient CO_2 concentration. Body leakage flow rate is $Q_l = C \cdot V_c$ by comparing coefficient C and equation 5. Body leakage flow rates were 92 and 131 lpm for fan speed 2 and 8 conditions, respectively. More leakage flows occurred at a higher fan speed leading to the lower equilibrium in-cabin CO_2 concentration. CQ product, $C_{ex} \cdot Q_{ex}$, could be obtained by comparing coefficient B with equation 5:

$$C_{ex} \cdot Q_{ex} = \frac{(B - A) Q_l}{n} \tag{8}$$

The CQ products were determined as 10423 and 10707. From this study three CQ product values (9713, 10423 and 10707) obtained. Average and standard deviation of the CQ product is 10,280±510 ppm. With the values of CQ product and body leakage flow rate, Q_l, one can predict in-cabin CO_2 concentration under various conditions.

The evolution of CO_2 concentrations can significantly change at different breathing rate or number of passengers. Figure 2 shows prediction of CO_2 increase as a function of passenger number when fan is off and vehicle is at rest. Figure 4 shows influence of number of passengers when cabin air is recirculated while the vehicle is in motion.

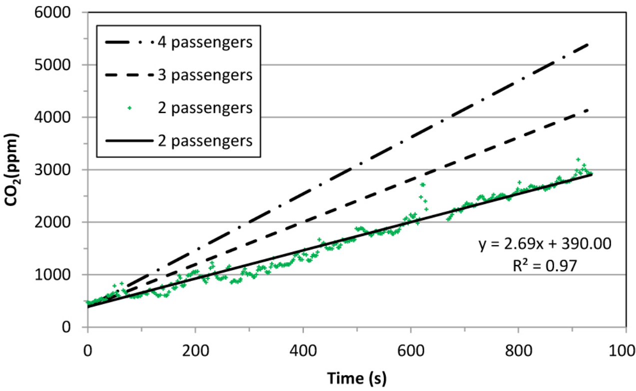

Figure 2. Evolution of cabin CO_2 concentrations when the ventilation fan is off and the vehicle is at rest. Green markers show experimental data and black solid line shows fitted line.

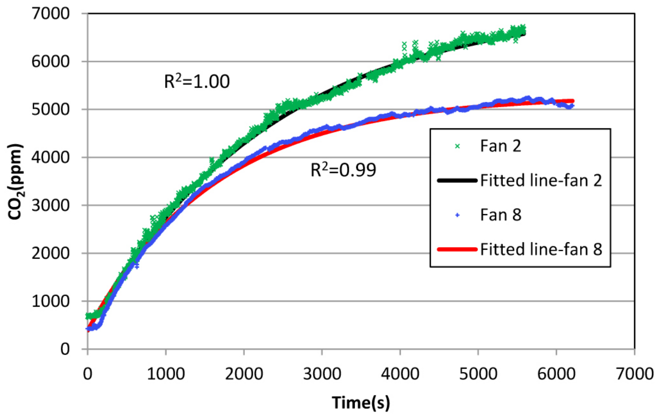

Figure 3. Evolution of cabin CO_2 concentration during full recirculation mode. The vehicle was at constant speed of 21 km/h. Green and blue markers show experimental data and black and red solid lines show fitted lines for fan speed 2 and 8, respectively.

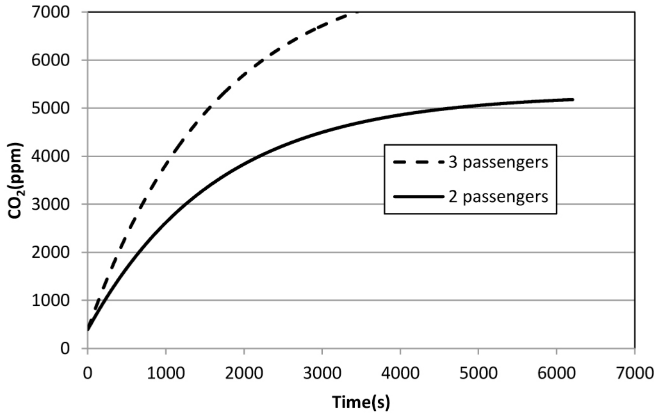

Figure 4. Evolution of cabin CO_2 concentration during full recirculation mode for different number of passengers i.e. breathing rate. The conditions are vehicle at constant speed of 21 km/h and fan speed 8.

DISCUSSION

Passengers can choose either full air-recirculation or outside air for ventilation. Full air-recirculation is chosen when lower air temperature is desired with a limited power of the vehicle air conditioning system. Full recirculation is also chosen by passengers to prevent some visible smoke or dust from entering the cabin. For example one can choose full recirculation when a vehicle passes through a dusty environment such as a long tunnel. On the other hand outside air is chosen for ventilation when passengers want to have fresh air as opposed to recirculated air. It is irony that the fresh outside air brings air with lower CO_2 concentrations at the price of fresh therefore high concentrations of air pollutants into the vehicle cabin. Fresh air pollutants deposit to the walls of the HVAC system, inner surface of the passengers' lung, cabin air filter and vehicle cabin interior walls. As mentioned earlier in the introduction, air borne particle pollutants are most efficiently removed by air-recirculation in the cabin to the above mentioned sinks especially to the cabin air filter due to multiple passes, while concentrations of other gaseous pollutants will remain unchanged unless they are soluble to the human lung fluid (meaning lung can be a sink for soluble gases). Therefore it is beneficial to recirculate vehicle cabin air to lower particle concentrations. However one needs to suppress increase of the cabin CO_2 concentration due to exhale of the passengers.

There are two interesting examples. First, BMW invented the automatic air recirculation (AAC) system [12]. The AAC system relies on a fast responding gas sensor to detect high concentrations of gaseous pollutants on roadways. Then the AAC system quickly and automatically closes off air intake from outside and temporarily recirculates the air in the cabin. It reduces passengers' exposure to high concentrations of air pollutants. It does it in a way cabin air temperature is not changed and fog is not formed in the windshield. This is an on/off recirculation control triggered by a gas sensor. The effectiveness of their system relies on the fast response of the detecting sensor and the actuator. Second, Grady et al. [9] proposed fractional continuous recirculation as opposed to full recirculation. This is to suppress increase of the CO_2 concentration while lowering particle pollutant concentrations in cabin air. They showed a small change of the recirculation door angle can effectively suppress increase of the cabin CO_2 concentration. By controlling the amount of fresh air under different ventilation conditions they could demonstrate that benefits of air recirculation could be utilized while suppressing the increase of CO_2 concentrations.

For both of the above examples it is critical to assess how quickly the cabin CO_2 concentration changes during recirculation to determine either the on/off interval or the fraction of recirculation. The analytic solutions in this paper provide an important tool to predict cabin CO_2 concentrations for these purposes. It is worth to note that there is one important parameter which needs to be determined. That is the vehicle body leakage flow (Q_l). Vehicle body leakage flow changes as a function of the vehicle speed, ventilation fan speed and geometry of the HVAC system. Ventilation fan speed is more important at low vehicle speeds while the vehicle speed drives body leakage at high speed. The body leakage can be determined directly by measuring flow at the distinctive inlet or outlet but access to those locations as well as possible obstruction of the flow by flow meters pose technical difficulties. On the other hand measurements of CO_2 concentrations can be used as an indirect alternative. Using the analytical solutions (equation 4 and 5) the body leakage can be determined from CO_2 measurements. In this case finding sources of uncertainties can be a challenge but it may be possible technically. The author plans to determine vehicle body leakage at a variety of conditions in the following study.

CONCLUSIONS

The main objective of this study was to derive theoretical equations which can predict cabin CO_2 concentrations under various conditions. This was done by applying CO_2 mass balance on the vehicle cabin system. A secondary objective was to validate the theoretical equations by comparing with experimental data. This was done by fitting experimental data using the theoretical equations.

The model equations were validated against experimental data. The coefficients of the special solution (equation 4) were determined by comparing with experimental data obtained while the fan was off and the vehicle was at rest. The coefficients of the general solution (equation 5) were determined by comparing with experimental data obtained while the fan is at 2 and 8 out of 8 and the vehicle was at 21 km/h constant speed. The R squared values of the two fits were 1.00 and 0.99 respectively. This reflects the theoretical solution predicts the change of CO_2 concentrations extremely well.

To take full advantage of the theoretical equations derived in this paper, vehicle body leakage needs to be determined experimentally at all conditions of interest. Then, cabin CO_2 concentrations can be predicted with no further experiment. The uncertainty in measuring body leakage will propagate to predicted CO_2 concentrations. Comprehensive characterization of vehicle body leakage and uncertainties determining CO_2 concentrations are subjects which require further study.

In conclusion, analytic solutions were derived to model time evolution of cabin air during recirculation. This mathematical model can be used to design on/off or a fractional recirculation system which can reduce passengers' exposure to airborne pollutants, especially particle pollutants, entrained from outside.

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DEFINITIONS/ABBREVIATIONS

CARB - California Air Resource Board

PM2.5 - particles below 2.5 μm

WHO - World Health Organization

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