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Vehicle Cabin Air Quality with Fractional Air Recirculation

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ABSTRACT

A fractional recirculation of cabin air was proposed and studied to improve cabin air quality by reducing cabin particle concentrations. Vehicle tests were run with differing number of passengers (1, 2, 3, and 4), four fan speed settings and at 20, 40, and 70 mph. A manual control was installed for the recirculation flap door so different ratios of fresh air to recirculated air could be used. Full recirculation is the most efficient setting in terms of thermal management and particle concentration reduction, but this causes elevated CO_2 levels in the cabin (see page 2144 of reference [1]). The study demonstrated cabin CO_2 concentrations could be controlled below a target level of 2000ppm at various driving conditions and fan speeds with more than 85% of recirculation. The proposed fractional air recirculation method is a simple yet innovative way of improving cabin air quality. Some energy saving is also expected, especially with the air conditioning system. More recirculation means less energy is required to cool the cabin air, as opposed to cooling 100% outside air under hot weather conditions.

INTRODUCTION

Scientists [1-2] have found that air recirculation can lower in-cabin concentrations of particle pollutants significantly. Particles from roadways are harmful [3-4] to the passengers' health, and therefore are subject to removal. Cabin filter systems capture a portion of particles but there are non-negligible amount of particle penetration into vehicle cabin. There are several other ways to reduce particle concentrations in the cabin than simple air recirculation but most of these options come with difficulties in design and optimization or high cost.

There are other potential benefits by recirculating cabin air. Fuel consumption is currently the biggest concern for automobile manufactures today. One of the biggest drains of the engine power is the AC compressor among auxiliary power devices. Cabin air recirculation can lower compressor power consumption from thermal management point of view.

Prior studies [1-2, 5,6,7] have been conducted on the levels of CO_2 in the cabin. However, they did not take the benefits of air recirculation into consideration because they observed, but could not suppress the increase of CO_2 in the cabin. An additional study done by Mathur [8] did look at CO_2 suppression, by alternating between full and no recirculation on a 2-6 minute interval. This is not a viable option for car manufacturers as it may cause reliability issues. The study was also unable to look into fractional air recirculation.

This study looks at an alternative way to control the vehicle's HVAC system; a way that will increase the efficiency of the car as a whole, while decreasing passengers' exposure to harmful particles. In this study, fractional air recirculation control method was tested as a means to maximize air recirculation while suppressing cabin CO_2 concentrations. This way one can obtain benefits while reducing the side effect of air recirculation.

EXPERIMENTAL

Test Vehicle and Driving Conditions

Real world driving conditions were found to be transient by nature. As vehicle speed changed, so did the leakage between the cabin and the outside environment. This resulted in different cabin CO_2 concentrations making it difficult to analyze data from transient tests. Thus, the tests were conducted at constant vehicle speeds with a standard size SUV provided by Hyundai-Kia motors. Detailed specifications of the vehicle were not necessary to understand this study therefore not provided.

Three different speeds were tested: 15, 40 and 70 mph. The 15 mph test was run around the perimeter of a parking lot that measured 800 ft. by 200 ft. It was manually driven and used to simulate the slow speeds with heavy traffic during rush hour. This test was used to investigate influence of passenger number, ventilation fan speed, and equilibrium CO_2 concentration. The 40 and 70 mph tests were run on the five mile oval at the Hyundai-Kia motor test facility in California City. Cruise control was used on these tests to maintain the constant speeds. The 40 and 70 mph tests were used to study influence of outside winds and vehicle speeds on cabin CO_2 concentrations.

The original test vehicle HVAC system controlled air recirculation; either 0% Recirculated air (fresh, outside air) or 100% recirculated air by changing the opening of the recirculation door. The HVAC control unit was replaced with a re-programmed unit which positioned the recirculation door at a specific angle. This allowed fractional air recirculation at any percentage from 0-100%. The HVAC vent mode was fixed at passenger chest mode as opposed to feet mode to help mixing of CO_2 which is heavier than air. Vehicle HVAC system has an inlet at the floor level and an outlet above the chest level. This can help mixing of CO_2 significantly.

Instruments and Sampling Conditions

CIRAS-2 SC (PP-Systems) was used for the measurement of cabin CO_2 and H_2O. It measured both gases at high precision using NDIR (Non-Dispersive Infrared) technique. The linearity is better than 1% throughout the range, and the precision is 3μm/mol for the range used for this study. It had a built-in auto-zero calibration capability which ensured stable measurement. Two condensational particle counters (CPC), model 3776 (TSI), were used to measure particle concentrations of cabin air and outside air simultaneously.

The outside air was sampled through the right front passenger window, perpendicular to the flow of the air around the car. A wood insert with a height of 2 inches was fabricated to allow the sampling of outside air without compromising the weathering of the vehicle. Additionally, the insert was used to create a tight seal between the outside and inside of the vehicle. A ¼ inch tube was held tight perpendicular to the wood insert with a bulkhead Swagelok fitting. The tube stuck out to the window by 2 inches not to be affected by boundary layer during driving conditions. CPC exhaust was ventilated out through this insert with a separate hole as not to pollute the cabin of the vehicle with butanol vapor from the CPC exhaust.

The inside air was sampled at the shoulder level of a driver above the center console, facing towards the rear. All machines were powered by two deep cycle 6V batteries wired in series with a 1000W inverter. The batteries, CPCs and CIRAS-2 SC were placed in the trunk of the test vehicle. The laptops that recorded the data were placed in the back seat.

RESULTS

Feasibility Test: Proof of Concept

Figure 1 shows simultaneous measurement of particle concentrations inside and outside of the cabin using two CPCs. The measurements are conducted continuously, starting at 18:02 (hh:mm) and ending 18:45. The model 3776 CPCs are able to measure particles above 2.5 nm.

The upper curve in the graph shows outside particle concentration while the lower curve shows particle concentrations in the vehicle cabin. The curve for the outside particle concentration shows occasional spikes reflecting some air parcels which contain a higher concentration of particles. At the same time, these spikes are not mirrored in the lower curve. This occurs mainly because of two reasons: the cabin filter captures those particles and the particles are diffused and lost to the HVAC duct system. From time 18:02 to 18:16, with 0% recirculation, the cabin air shows particle concentration reduction by ~30% compared to that of outside air. Full (100%) recirculation begins at 18:16. There is an immediate drop in the particle concentration in the cabin, which levels out at about 2000 particles/cm3. This is a significant improvement and greatly diminishes the health risks that commuters may experience in their cars during rush hour. It is notable that major spikes in the upper curve are also seen in the lower curve. These spikes occur at a much lower concentration and with some time delay when there is no air recirculation.

This data is taken in the parking lot where outside concentration is not as dense as that of the highway. Greater difference in particle concentration is expected between cabin air and outside air on the highway. Full recirculation allows the cabin air to pass through the air filtration system multiple times. This is true for most of commercial cars including the one used in this study and results in more efficient filtration. Some energy saving is also expected, especially with the air conditioning system. More recirculation means less energy is required to cool the cabin air, as opposed to cooling 100% outside air under hot weather conditions.

The main problem with having full recirculation is that it drives up other gas concentrations in the vehicle. Passengers' breathing generates CO_2 and H_2O, and it does not take long for these concentrations to become problematic (more so the CO_2). A higher CO_2 concentration has been known to cause

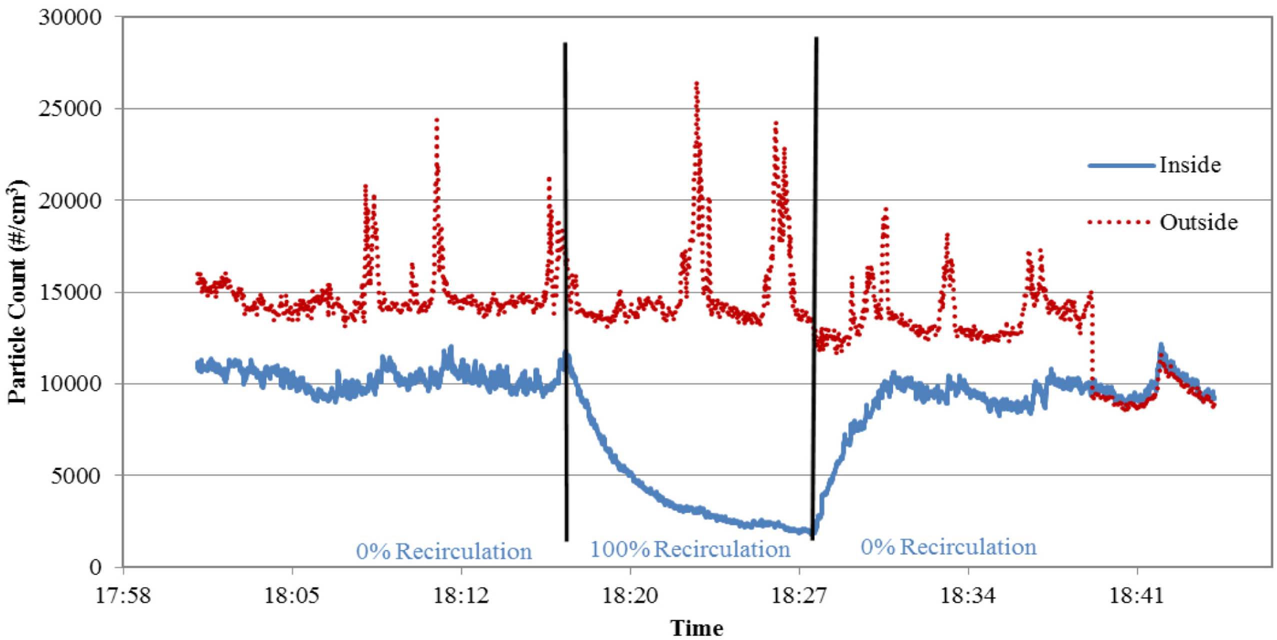

Figure 1. Effect of full air recirculation on particle concentration in cabin: comparison with outside air

drowsiness [9] and elevated H_2O concentrations requires more frequent dehumidification of the windshield.

Figure 2 shows rise and fall of H_2O and CO_2 concentrations under 100 and 0% recirculation conditions for one passenger. The first full recirculation starts at 13:41 where the CO_2 and H_2O concentrations show steep increase until 13:56. Here the recirculation was changed to 0% (i.e. 100% fresh outside air). The second full recirculation started at 14:04, showing similar increase of both CO_2 and H_2O concentrations until it ends at 14:18. It is worth to note that both CO_2 and H_2O show similar patterns. Their concentrations are subject to change depending on the strength of sources (i.e. number of passengers, adult vs. child) and cabin volume.

OSHA (Occupational Safety and Health Administration) enforces a standard CO_2 concentration of 5,000 ppm for the work place [10]. This limit is chosen because at this amount of exposure, no negative side effects have been noticed. OSHA also suggests that a CO_2 level of 1000ppm indicates inadequate ventilation for indoors [11]. As the occupancy of a home or office space is very different from that of a vehicle, researchers have also referenced a second standard. Mathur [5] cited ASHRAE standard 62 [12] which specifies the safety level of CO_2 in a conditioned space. The ASHRAE standard is 700 ppm over ambient conditions on a continuous basis.

This study proposes a partially recirculated HVAC system (or fractional air recirculation) as opposed to binary nature of current systems. The fractional air recirculation could have the efficiency and health benefits of full recirculation, while minimizing CO_2 and H_2O levels.

Characterization of Vehicle HVAC System

The vehicle cabin is relatively well-sealed closed system except a distinctive inlet (HVAC inlet to draw outside air) and outlet (so-called body ventilation valve). The majority of air flow between cabin and outside is through this distinctive inlet and outlet for ordinarily maintained vehicles. When full or 100% recirculation is chosen almost all cabin air should recirculate as the recirculate door will block the passage from outside. (Note that it is possible some auto manufacturers may choose to recirculate less than 100% at full recirculation condition for various reasons with a bypass line. Authors are not investigating this aspect, nor are they surveying cars from various auto manufacturers.)

Figure 3 shows increase of cabin CO_2 concentration at various ventilation fan speeds. For this test, two passengers are in the vehicle that is being driven at 15 mph cruise condition. For differing fan speeds, CO_2 concentrations plateau at differing values (equilibrium concentrations).

Jung [13] describes that the CO_2 concentration reaches equilibrium due to the balance between CO_2 source (exhale of passengers), and the leakage in and out of the vehicle cabin. The higher the ventilation speed, the lower the equilibrium CO_2 concentration as shown in Figure 3. This is because higher ventilation speed creates bigger pressure difference across recirculation door and closing surface region. This results in larger leakage into the cabin. Jung [13]

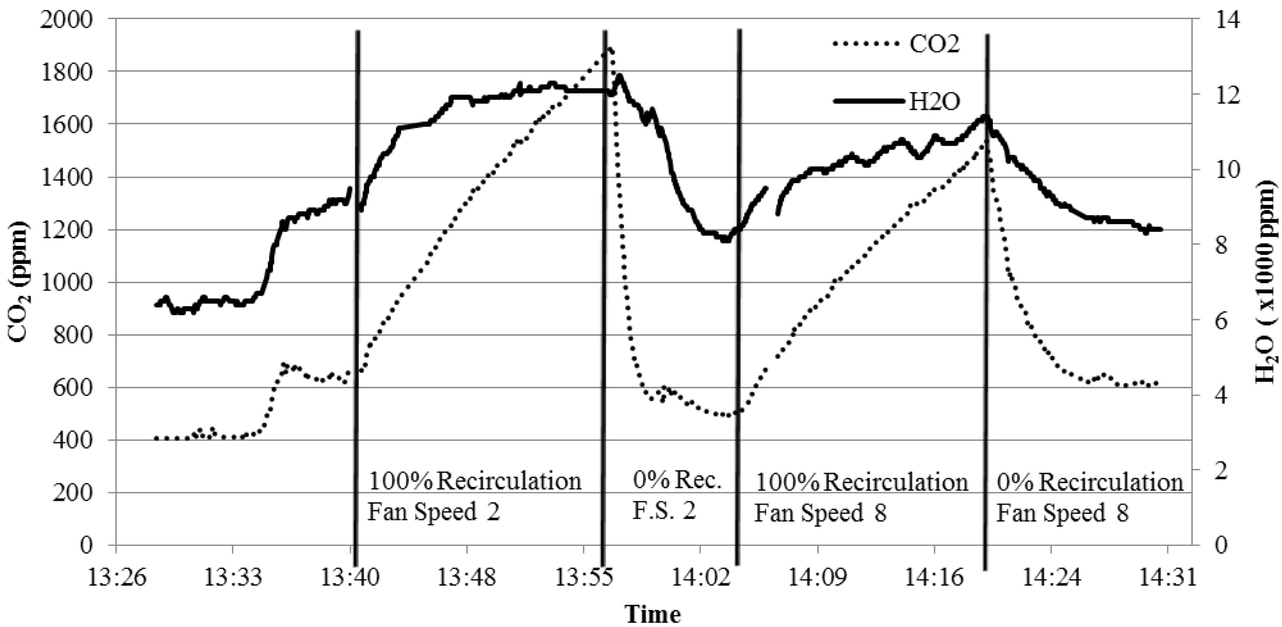

Figure 2. Effect of full air recirculation on water vapor and CO_2 concentration in cabin with one passenger

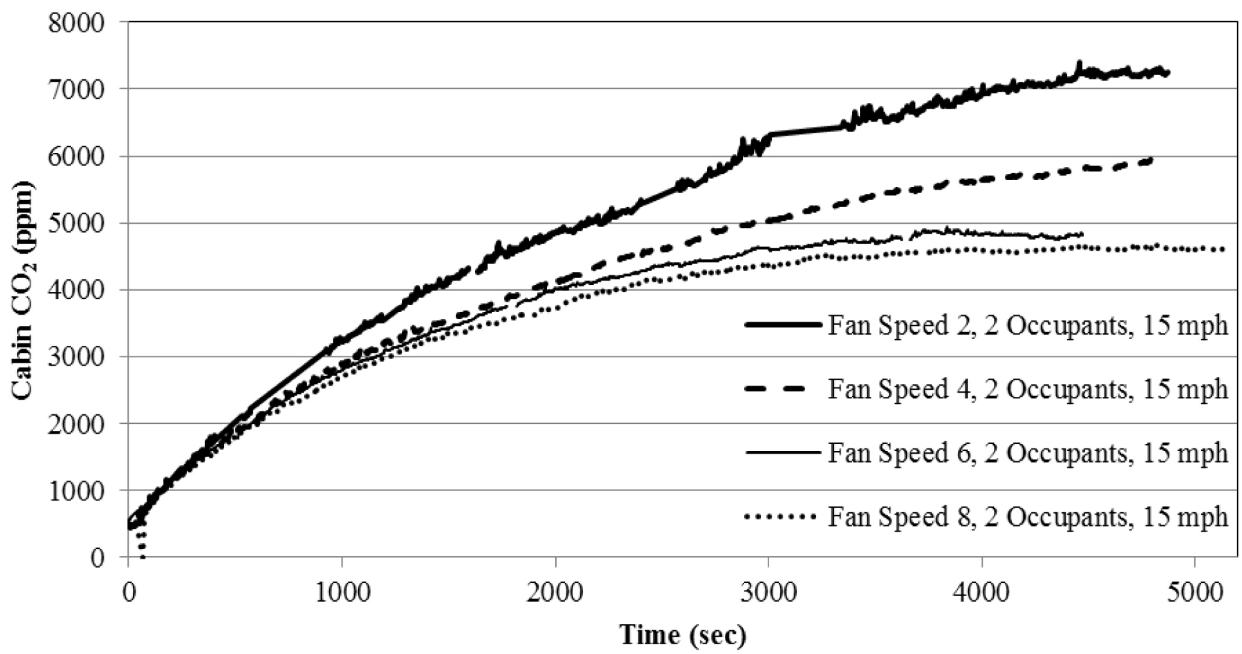

Figure 3. Evolution of cabin CO_2 concentration as a function of time and fan speed. Test conducted at full recirculation condition with two passengers

models vehicle cabin CO_2 concentration with mathematical equations applies those to experimental data such as Figure 3 and predicts evolution of CO_2 concentrations. The data in Figure 3 along with a mathematical model provides characteristic parameters of the vehicle cabin HVAC system to control cabin CO_2 concentration at certain level.

Feasibility Test: Manual Control (Pre-Step to Auto Control)

Full or 100% recirculation corresponds to the HVAC recirculation door being closed, allowing no outside air into the cabin. Likewise, 0% recirculation corresponds to this door being completely open, drawing fresh air from the outside. As a preface to implementing CO_2 concentration control logic to the vehicle HVAC system, manual control tests are conducted.

A CO_2 control cycle for feasibility test begins with full recirculation and then opens the recirculation door partially to maintain the upslope at slightly positive value. The test then cycles with a second recirculation door angle which exhibits the slight downslope. This is to maintain the CO_2 concentration at a target range of concentrations. Different ventilation speeds create varying amounts of body leakage. This results in the need for the fraction of air recirculation, which is determined by the recirculation door angle, to be adjusted to a different level. For example a faster ventilation fan speed results in more body leakage flow. Therefore the fraction of outside air needs to be less compared to that of a slower ventilation fan speed.

Figure 4 shows cabin CO_2 concentrations that are maintained within a target range of concentrations for different ventilation fan speeds. The process described above is used to achieve the same level of CO_2 concentration. The recirculation door control was done manually by providing DC power to the actuator which controls the position of the recirculation door.

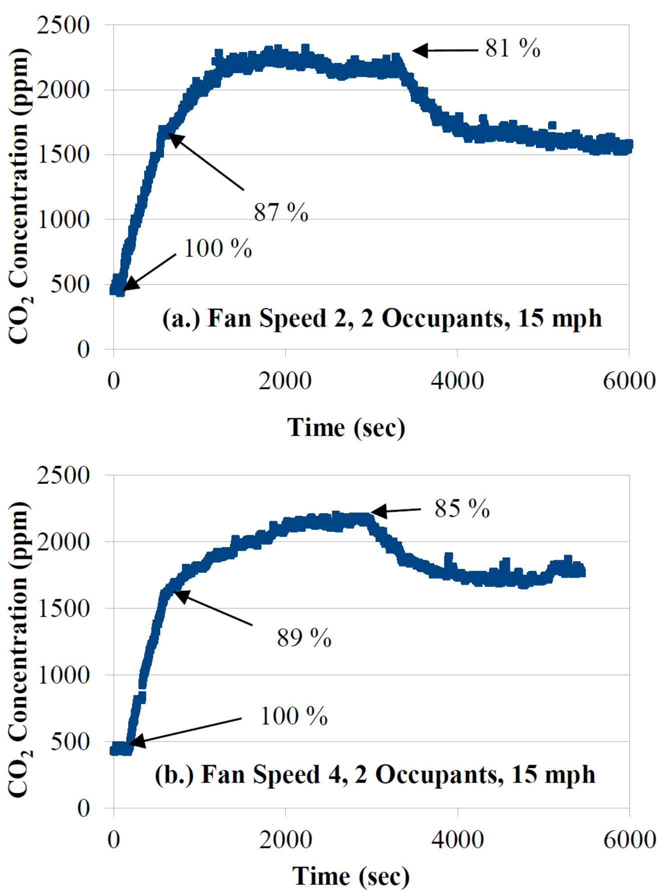

Figure 4.

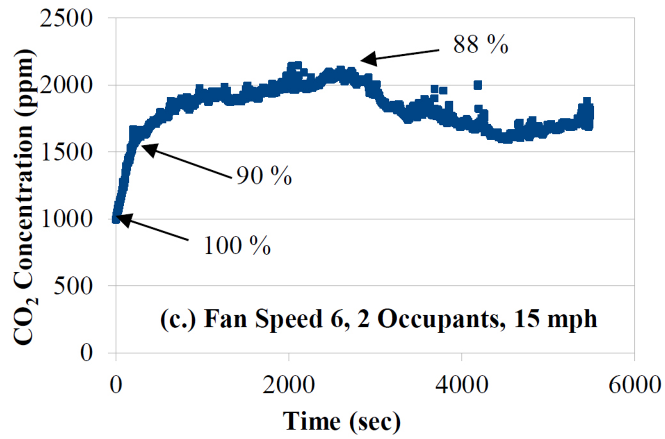

Figure 4. (cont.) Feasibility test to control cabin CO_2 concentration at a target level of 2000 ppm, at 15 mph with two passengers. Different fan speeds were tested: (a.) Fan Speed 2 is slow; (b.) Fan Speed 4 is medium and (c.)Fan Speed 6 is fast. Percentage indicates degree of recirculation

Influence of Vehicle Speed

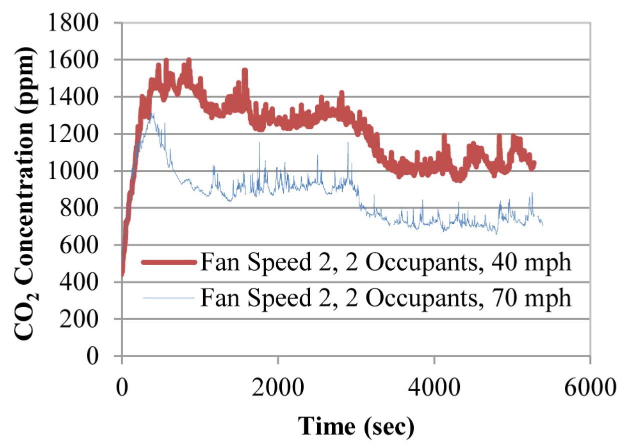

Figure 5. Influence of vehicle speed on cabin CO_2 concentration control. Both tests had two passengers and used Fan Speed 2 with the vehicle driven at 40 mph (top line) and 70 mph (bottom line)

The final variable that is tested is vehicle speed. This has a big effect on vehicle leakage due to the higher pressure outside of the vehicles at high speeds. Tests for speeds of 40 and 70 mph, Figure 5, are recorded with the same algorithm for voltages as the 15 mph test shown in Figure 4. The fan speed is fixed at level 2 and the number of passengers is also fixed at two people. Higher speeds cause more leakage which cause variable recirculation to have less of an impact on CO_2 concentrations. In other words CO_2 concentrations are maintained below target concentrations due to strong body leakage from outside of the vehicle. It should be noted that the vehicle was driven the oval track at Hyundai's test track. Any possible effect of wind direction is not noted therefore it is assumed the wind effect is canceled out due to the circular driving pattern of the vehicle.

Input Parameters to Control Cabin CO2 Concentrations.

It is always possible to do a feedback control of cabin air recirculation by means of CO_2 sensor. This study, along with Jung's [13] modeling result, suggests an open loop control is possible if characteristics of vehicle cabin air system are determined, allowing the car manufacturer to save the CO_2 sensor cost without hampering the cabin occupants health. There are four important parameters which determine vehicle cabin CO_2 concentration as shown in Figure 6. Sensitivity and relative importance of each parameter varies depending on vehicle conditions. These can be determined by combination of well-designed experiments and model equations. More specific and detailed applications (such as full characterization of a specific vehicle cabin air system and/or determining sensitivity and relative importance of each input parameter for control purpose) of the fractional recirculation are possible but it is a subject for future study. This study achieved its goal demonstrating feasibility and benefits of fractional air recirculation system.

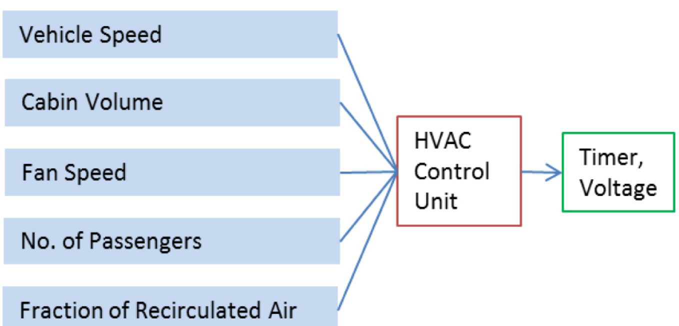

Figure 6. Schematic of control logic

CONCLUSION

Passengers currently can choose either full air-recirculation or outside air for ventilation. This study suggests fractional air recirculation can keep the benefits of full recirculation (reduction of particle pollutant concentrations in cabin and reduction in AC power consumption), while suppressing side effects (increase of cabin CO_2 and H_2O level).

The study demonstrated the effects of air recirculation on cabin particle concentrations, water vapor and CO_2. Cabin particle concentrations were reduced to 20% of 0% recirculation air with 100% air recirculation, while CO_2 and water vapor concentrations increased steeply.

The study proposed a fractional air recirculation to suppress the increase of the cabin CO_2 concentration. It showed cabin CO_2 concentration is determined by the balance between source strength (or number of passengers) and body leakage rate (flow rates in and out of the vehicle). This balance is influenced by multiple parameters: vehicle speed, cabin volume, recirculation, fan speed and number of passengers. Body leakage rates are vehicle specific and need to be fully characterized for the vehicle of interest.

The study aimed to control cabin CO_2 concentrations at certain levels by adjusting the opening of the recirculation door angle. For example, with more than 85% of recirculation, cabin CO_2 concentration of 2000ppm could be obtained for two passengers at various driving conditions and fan speeds. We believe this method is a cost effective way of maintaining clean air quality of the cabin and can be applicable to new cars.

It is known that people get highest exposure to particle pollutants on roadways during their commute. The proposed fractional air recirculation system can contribute to reducing health risks of vehicle passengers by particle pollutants on roadways. The suggested fractional air recirculation method is a simple yet innovative, and easily implementable way of improving cabin air quality.

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DEFINITIONS/ABBREVIATIONS

HVAC - heating ventilation and air conditioning

NDIR - nondispersive infrared sensor

CPC - condensation particle counter

DC - direct current

AC - air condistioning

NIOSH - national institute for occupational safety and health

OSHA - occumational safety and health administration

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