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On-Road Air Quality and the Effect of Partial Recirculation on In-Cabin Air Quality for Vehicles

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On-Road Air Quality and the Effect of Partial Recirculation on In-Cabin Air Quality for Vehicles

A Thesis submitted in partial satisfaction
of the requirements for the degree of

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in

Mechanical Engineering

by

Michael Lee Grady

December 2013

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ABSTRACT OF THE THESIS

On-Road Air Quality and the Effect of Partial Recirculation on In-Cabin Air Quality

by

Michael Lee Grady

Master of Science, Graduate Program in Mechanical Engineering
University of California, Riverside, December 2013
Dr. Heejung Jung, Chairperson

The California Air Resource Board (CARB) recently reported that due to exposure to particle emissions, 9,000 people die annually in California alone [11]. A method for quantifying the exposure during a daily commute as well as reducing the exposure for the passengers has been developed. 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 15, 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 [5]. 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. Additionally, some energy saving is also expected 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 proposed fractional air recirculation method is a simple yet innovative way of improving cabin air quality.

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1. Introduction and Direction

Two motives are currently driving the decisions automotive manufacturers are making about the types of vehicles they manufacture: better energy efficiency and less impact to the environment. To produce cars with higher mileage per gallon, auto manufacturers are using lighter materials and developing more efficient engines and parts. To decrease environmental impact for the life of cars, the government has implemented regulations for gaseous and particulate emissions. When vehicular emissions are reduced, the surrounding living environment – especially air quality on the road, near the road and even background atmospheric air quality – can be improved. Together, these advancements allow the public to spend less money on travel and improve their health due to less exposure to harmful pollutants from their vehicles. These two factors usually go hand in hand. If a car is more efficient, it produces fewer pollutants. This is a proactive response for new cars in production, but does nothing about the cars that are currently on the road.

Energy efficiency is usually indicated by fuel consumption of the car. Fuel consumption has become a huge buzzword for automotive and government officials. Dependence on external sources for fuel and energy has put a strain on America's economy, causing the government to increase their regulation of car sales. For example, the National Highway Traffic Safety Administration (NHTSA) regulates the Corporate Average Fuel Economy (CAFE), which mandates the average fuel consumption of vehicles sold by each individual company. Until recently, companies were held to a harmonic fleet average of 27.5 miles per gallon (mpg). In 2011 that number rose to 30.2 mpg [1]. In 2011, President Obama came to an agreement with the major automakers to greatly increase the average based on the footprint of the vehicle [2]. As shown in figure 1, in the 13 years between 2012 and 2025, vehicles, depending on size, will have to increase their fuel economy between 60-100%. This huge increase has caused companies to prioritize most of their resources into the efficiency of their vehicles.

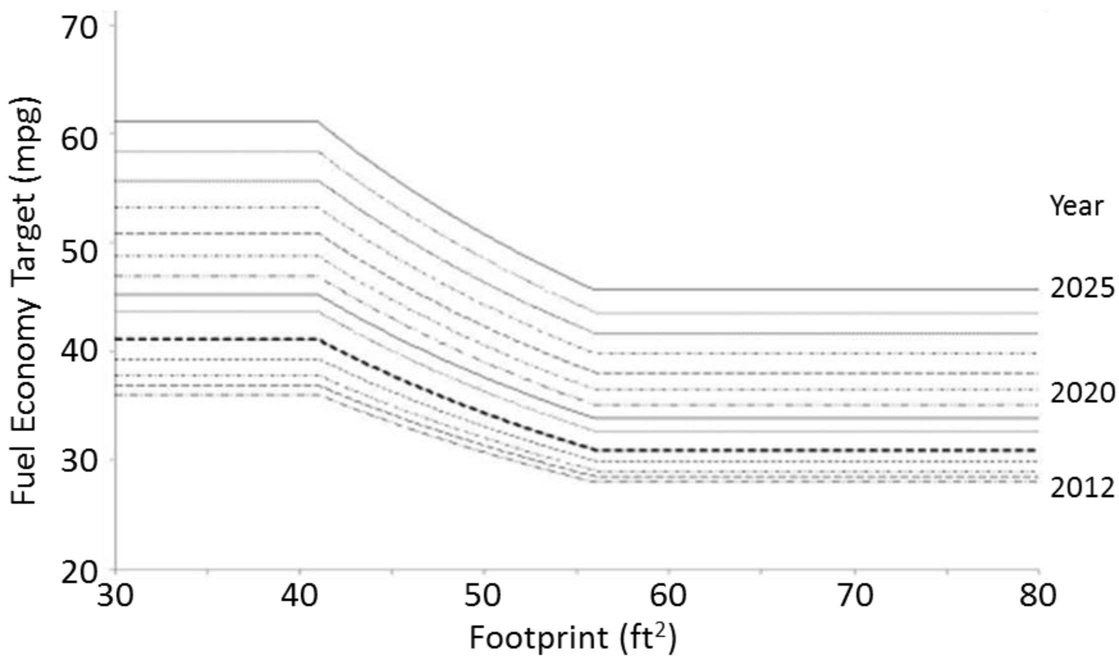

Figure 1 - Fuel economy restrictions for fleets based on year and size of the vehicle [2].

In addition to regulating fuel mileage, exhaust fumes and particulate matter, which are closely tied to fuel mileage, are also being carefully monitored. For example, the California Air Resources Board has mandated that all heavy duty diesel vehicles be retrofit with a Diesel Particulate Filter by 2014 [8]. Figure 2 shows that particulate matter standards are stricter now than ever before, and are approaching minimal particulate matter emissions by the year 2017.

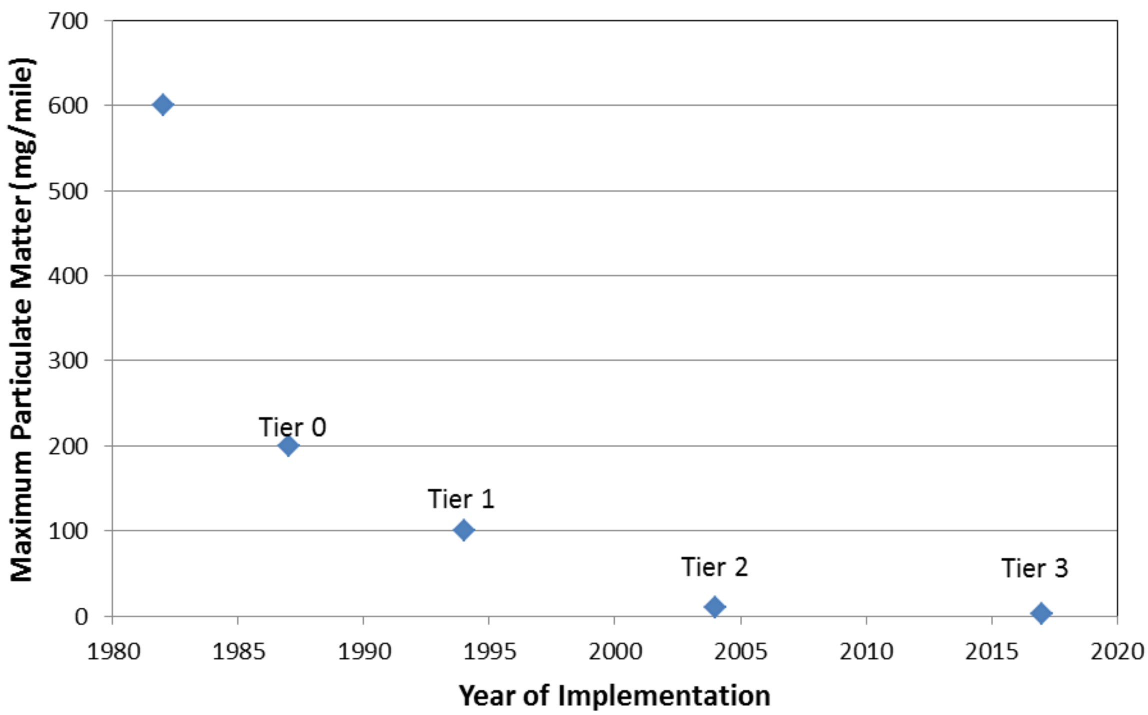

Figure 2 - Particulate matter standards for cars produced after the corresponding year, data is from [7].

Particulate matter created by vehicles has been linked to many diseases, shortening life expectancy over long-term exposure [3-4]. Cities with large networks of highways have particularly bad air quality because they are so close to the source of the particulate matter. The average U.S. driver spends 50 minutes behind the wheel daily. 15% of trips are for commuting; 3.3 million Americans commute at least 50 miles one way daily [10]. Most commuting occurs during a 'rush hour' time period, when drivers are subject to spending large amounts of time among bumper-to-bumper traffic on a daily basis. These drivers experience an extreme concentration of particulate matter.

The ventilation system plays a large role in addressing both of these concerns. The ventilation unit can recirculate the air in the vehicle cabin through a filter multiple times. Cabin air recirculation can improve fuel economy by better thermal management. When the AC (air conditioner) is running, the air temperature in the vehicle becomes cooler than the ambient air temperature outside the vehicle. Recirculating the air means that the AC is conditioning the already cooled air, instead of the hotter outside air. The AC, which draws its power from the engine, thus requires less power because the compressor in the AC does not have to work as hard to condition the air. The AC unit contains a filter that removes particulate matter, which means that recirculating the air decreases the particulate matter concentration in the cabin [5]. This greatly increases the air quality inside the vehicle cabin, especially on the highway during long commutes when drivers are exposed to particulate matter for long periods of time.

The same study also found that recirculating the air causes an increase in carbon dioxide (CO_2) concentrations inside the vehicle's cabin. This is due to passengers continuous exhaling without introduction of any outside air into the vehicle. Increased levels of CO_2 are known to have negative side effects drowsiness and headaches [6]. This is extremely dangerous when operating a vehicle. The simple solution to this problem is to install a CO_2 monitor and allow the vehicle to switch recirculation on and off by a feedback control. Some automotive companies, like BMW [9], have actually implemented an intermittent closed loop control into some of their higher market cars for a similar purpose. Their sensor detects high concentration of gas on the road and starts recirculating cabin air until the roadway gas concentration becomes low enough. This prevents introduction of high concentration gaseous (and probably particle pollutant) into the cabin. However, this approach is expensive and adds another sensor that would require maintenance or replacing. Additionally, their operation is intermittent and did not consider thermal management of cabin air.

Figure 3 – Schematic diagram explaining the concept of partial recirculation combining inside and outside air to filter out particles without increasing CO_2 concentrations to unsafe levels.

This thesis aims to develop a method for controlling the indoor air quality of a vehicle with the use of an open loop system and partial (continuous) recirculation. The open loop will allow the system to govern itself based on time, vehicle speed, fan speed, and number of passengers. This would create a system that is less expensive than a closed loops system, and is able to be implemented on vehicles across all price ranges. The partial recirculation will be used to maximize the benefits of full recirculation, without increasing CO_2 concentrations to unsafe levels. The reduction in particulate matter could result in improved health and well-being for people who endure long-term exposure on highways and in cities.

2. Literature Review

2.1 Particulate Matter and Outdoor Measurement Techniques

The California Air Resource Board (CARB) recently reported that due to exposure to particle emissions, 9,000 people die annually in California alone [11]. One of the biggest sources of the particle emissions is vehicles on major highways. Prior Studies have looked at the concentration of particulate matter as a function of the distance from the highway [12]. This study shows that drivers on the highway see about three times the concentration as do people located 100m from the highway.

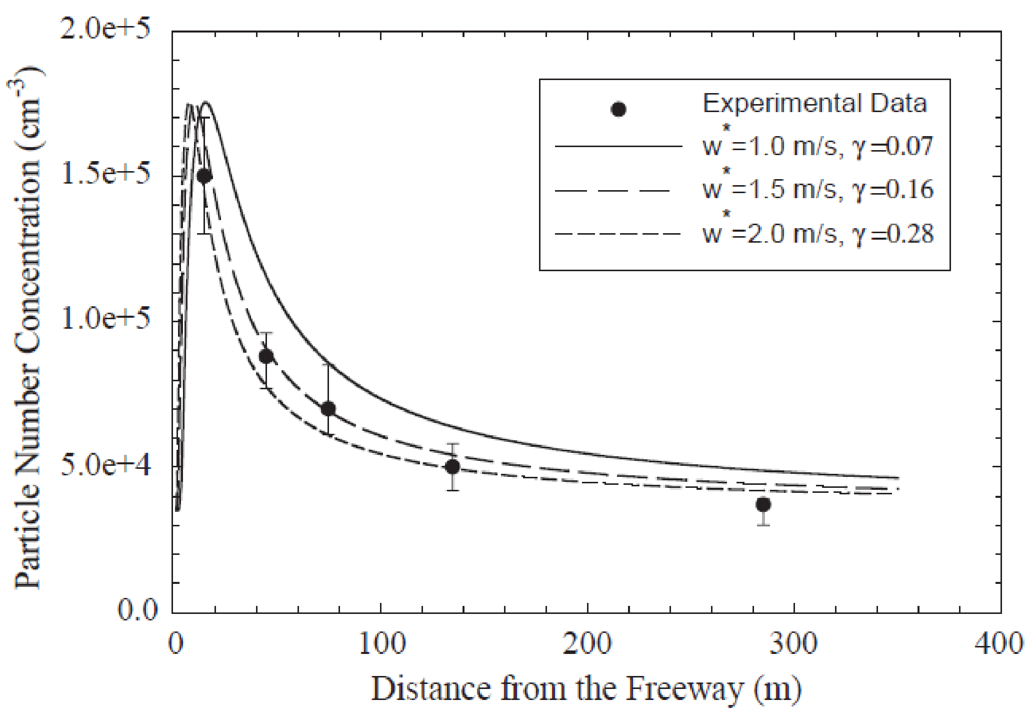

Figure 4 - Comparison of a model of predicted total particle number concentration with experimental data from the California 405 freeway. [12]

Data from this study was not collected during rush hour, where the concentration is bound to be higher. On the highway, exposure to in-cabin, ultrafine particles have been shown to be 10 times higher than ambient levels. This exposure contributes to approximately 50% of total daily ultrafine particle exposure for Los Angeles commuters [5]. Ultrafine particles (<100nm) are of great interest because it is much easier for them to diffuse into the alveoli and deposit on lung walls [13-15]. Understanding the magnitude of the exposure will aid in preventing more deaths from the exposure.

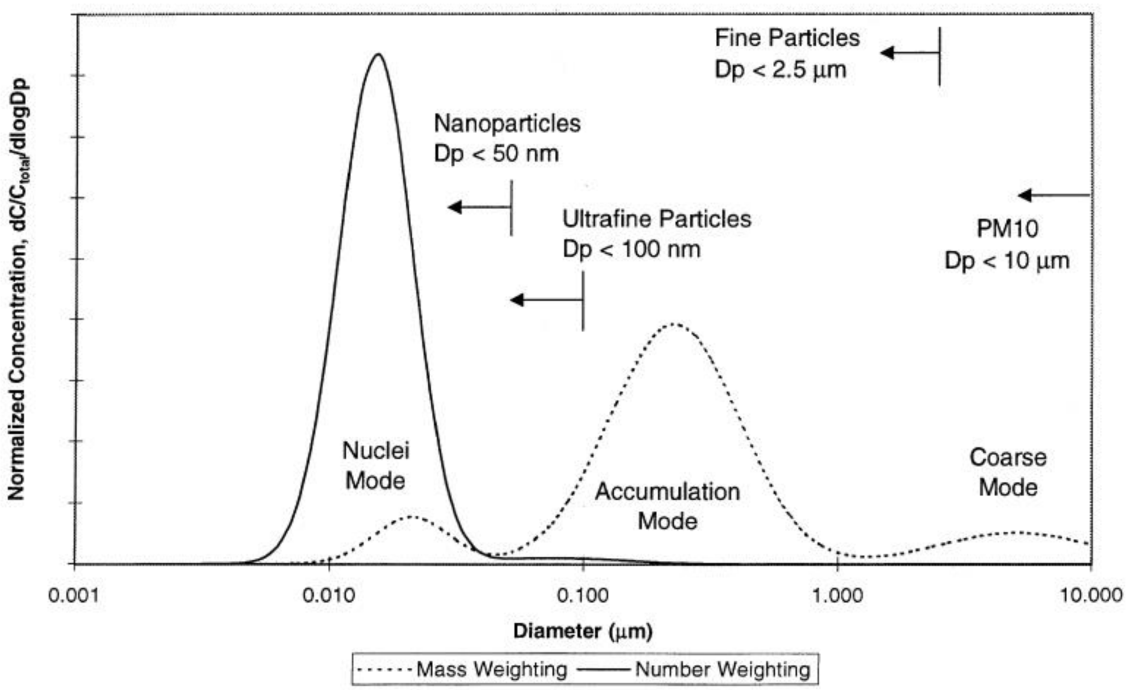

Figure 5 - Typical engine exhaust particle size distribution. Both number and mass weighted distributions are shown. Image from [16]

Ultrafine particles are extremely prevalent on the highway because they are typically found in high concentrations in engine exhaust [16]. More recent research has stated that even with low sulfur diesel, nuclei mode particles make up 40-50% of diesel exhaust [17]. Previous studies have tried to expand on the ways in which scientists can quantify the exposure of particle emissions to the public from this source. Stationary monitoring stations are plentiful throughout the country [34], but do not report an accurate picture as to the levels of exposure for commuters on the road, because they are located near, but not on the highway. Scientists have said that there is a large discrepancy between these monitoring sites and actual exposure [18]. Other studies have implemented mobile platforms that profile the source temporally and spatially. This gives a great profile of what any car sees on any given day because there is a lot of fluctuation in particle concentration. The fluctuation stems from the short lifespan of ultrafine particles [19]. This fluctuation would not be seen by the stationary devices, and the mobile platforms would allow the profiles to be more accurate so automobile companies know what they had to do in order to protect their passengers.

These prior studies believed that an electric vehicle would be better for this use, as to not add any of their particulate matter to the study [20]. Researchers Nguyen and Jung [21] used computational fluid dynamics to illustrate that this was not the case. They found that the chance that a conventional gasoline PFI (port fuel injection) engine has an effect on measurements is extremely low. It can even be avoided entirely by proper placement of the sampling inlet. The use of gasoline powered vehicles insures that measurement periods are a longer duration since they do not have to worry about the driving range limit associated with electric vehicles. Studies that used this mobile emission lab technique tended to have many expensive instruments in order to get the best profile [21-22]. While this does give extremely detailed measurement of the on-road air quality, it is not necessary. Scientists Ranjan and Dhaniyala showed that total number concentration is sufficient to quantify the particle level exposure [23]. Since the instrumentation in this instance is cheaper, more mobile stations can exist, covering more highways and providing more information. This is the approach that this thesis will take to measure outdoor particulate matter exposure.

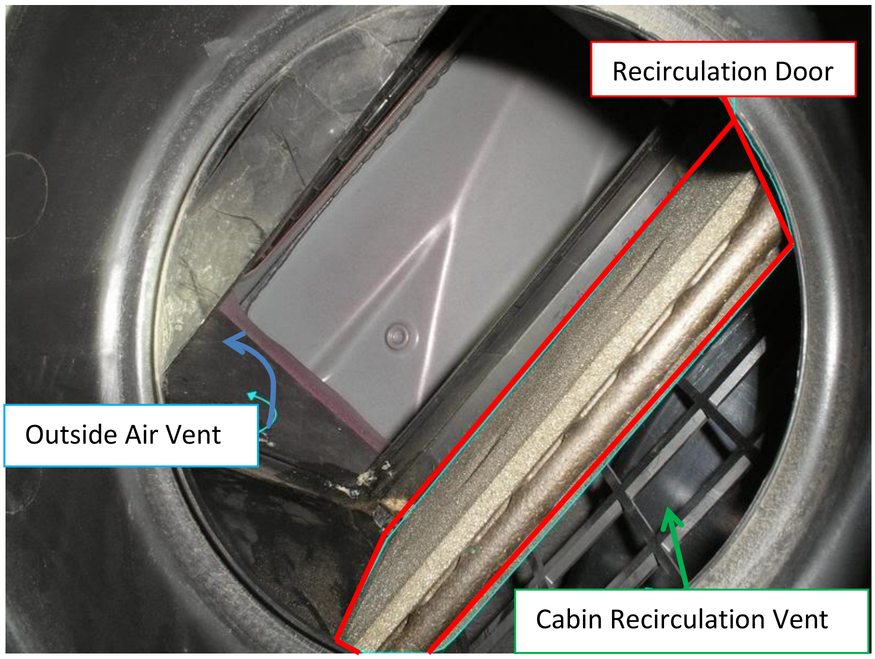

Figure 6 - Diagram of a typical recirculation door. Adapted from [30].

One approach to a healthier commute for the driver is to isolate the driver from the outside air. The air conditioning unit is an already implemented system that provides this. When the air is not being recirculated, it is being drawn from the “fresh” air outside. As seen in Figure 7, this causes the indoor particle concentration to mimic the outside. Recirculating the air is known decrease the particle concentration inside of the vehicle [7,24]. Recirculating the air causes it to run through the in-cabin air filter multiple times removing additional particles each time.

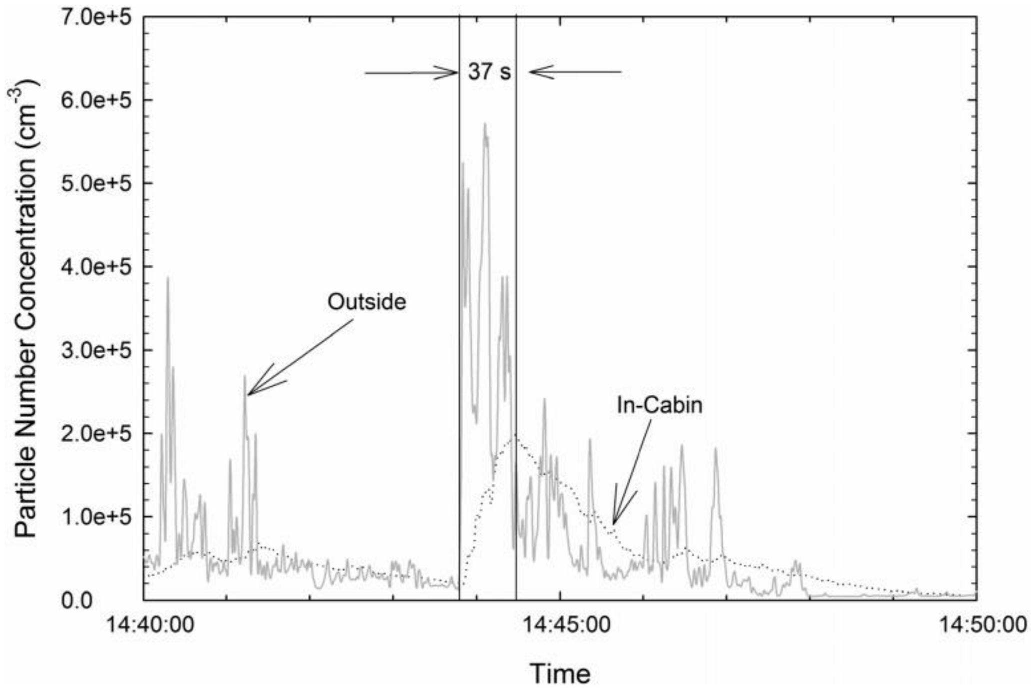

Figure 7 - In-cabin and outside particle concentrations as seen on the PCH1 highway. Recirculation is off. Figure from [5]

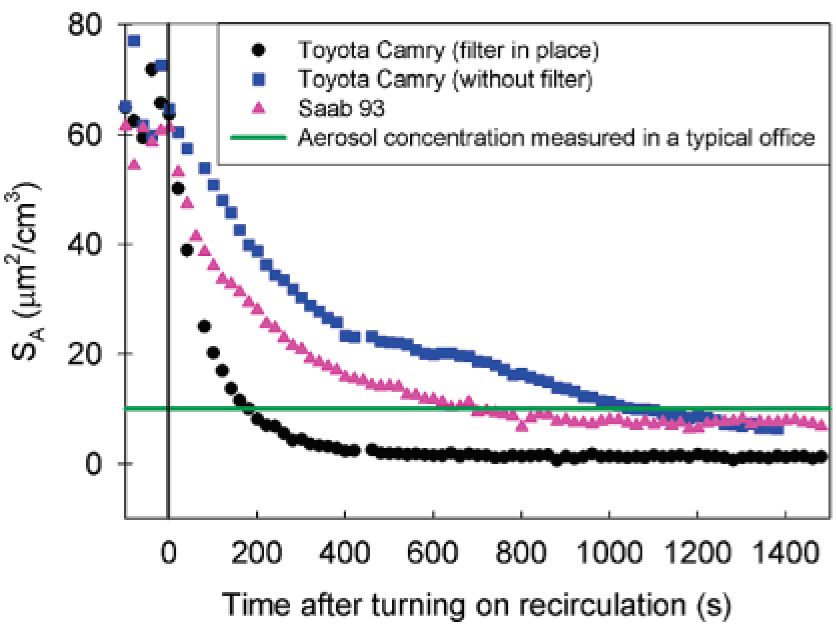

Figure 8 - Measured in-cabin particle lung deposited surface area as a function of time. Air recirculation is tuned. Figure from [24]

Figure 8 shows how quickly the particles are able to be filtered out after running through the AC filtration for an extended period of time. Within 200 seconds, the newer newer model car (the Camry), was able to reduce the concentration to typical indoor levels. This provides and environment that is much healthier for the vehicles passengers.

2.2 Carbon Dioxide

One disadvantage to recirculating air is that it causes the carbon dioxide levels to increase inside the cabin since passengers exhale into the same batch of air. Initially this does not cause any harm, but over time, and with increased passengers, the carbon dioxide concentration can reach unsafe levels. The same studies that looked at recirculation's effect on in-cabin particle concentration also looked at the carbon dioxide concentration. Figure 9 shows that once the recirculation is turned on, the particle concentration decreases as the CO_2 levels increase.

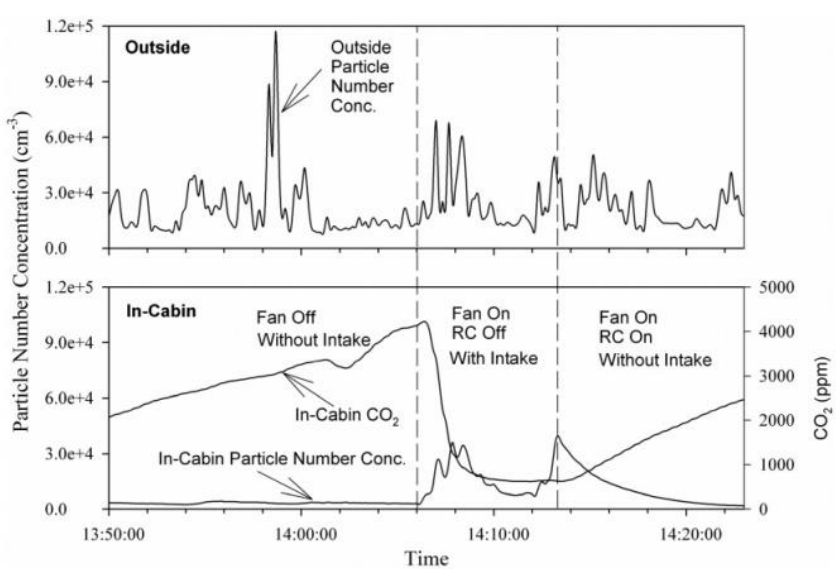

Figure 9 - Effect of ventilation settings on in-cabin particle and carbon dioxide concentrations. Test was conducted on the PCH1 highway with 3 passengers. Figure is from [5].

Scientist G. Mathur has published many articles on the subject of carbon dioxide levels with respect to air recirculation [25-27]. In one of his studies Mathur looks at the effect that number of passengers and vehicle speed have on the CO_2 concentration. Figure 10 shows the carbon dioxide levels as a function of time with four passengers, in city traffic.

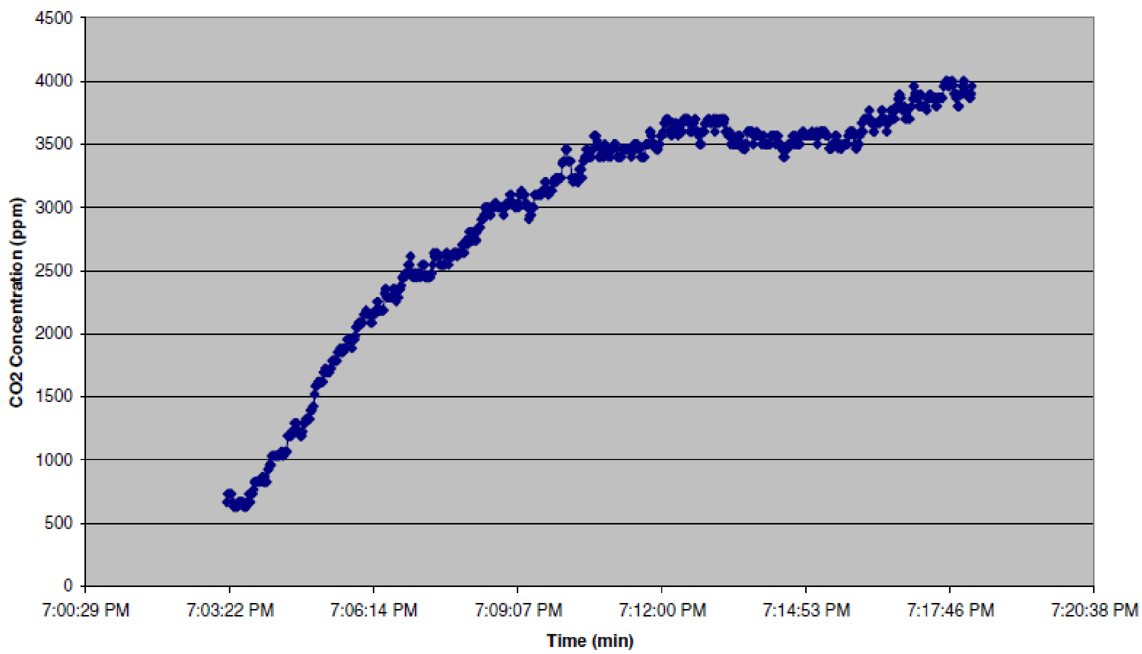

Figure 10 - Cabin concentration of carbon dioxide as a function of time. Four occupants in city traffic. Figure from [25].

In Figure 10 the concentration reaches 4000 ppm within the first fifteen minutes. This is far above the 400 ppm concentration that is in normal air [28]. ASHRAE standard 62 states that the concentration of carbon dioxide in the air should not be more than 700 ppm above nominal levels [29]. This level however, is quickly eclipsed in a closed space such as the in vehicle cabin environment. Mathur tried to control the level of carbon dioxide by alternating between full recirculation and no recirculation as shown in Figure 11.

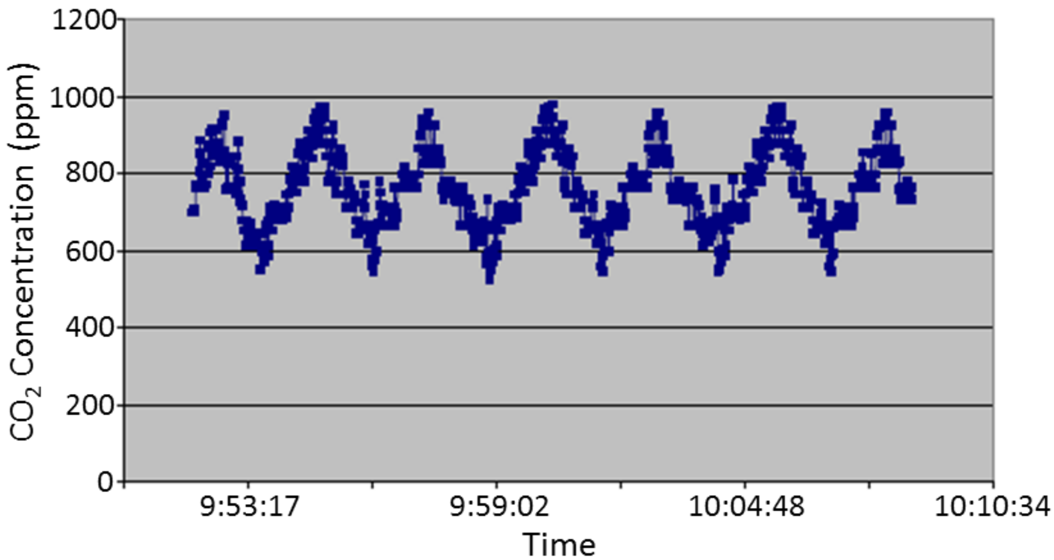

Figure 11 - Cabin concentration levels for carbon dioxide as a function of time. Recirculation alternates between on and off, with four passengers. Figure from [25]

This study repeatedly alternates the recirculation door (shown in Figure 6.) Full recirculation drives the concentration up while no recirculation drives it back down. Mathur's goal was to keep the concentration below 1000 ppm to keep with the ASHRAE standard.

Figure 11 shows the concentration as a function time with four passengers. In order to keep the carbon dioxide below 1000 ppm, the recirculation has to be turned off every two minutes. This frequency decreases with the number passengers. With only one passenger this frequency is reduced to every six minutes. This is a great way to control the carbon dioxide concentration levels, but it is not feasible. If a vehicle has a recirculation door that moves this often, it is only a matter of time before the recirculation door motor fails. To this author's knowledge, no one has attempted to use partial recirculation, keeping the recirculation door partially open continuously. Partial recirculation would allow the automobile to keep the benefits of recirculation (gas mileage and particle filtration,) without driving the carbon dioxide levels up to unsafe levels.

3. Outdoor Air Quality Measurement During Rush Hour

3.1 Mobile Platform and Sampling System

A PFI (port fuel injection) conventional gasoline vehicle (Ford Focus) served as the mobile platform for this study. A wooden insert 1.5" height was inserted at the top of front passenger seat window and a sampling inlet was installed at the wooden insert using a bulk head Swagelok fitting. Sample probe was 52 inches (1.32 meter) high from the ground. Two inch length 3/8" copper tubing has served as a sampling inlet connected to the bulk head Swagelok fitting. The direction of sampling probe is chosen to ensure sample flows not to impose dynamic pressure change due to the vehicle's motion to monitoring aerosol instruments. Figure 12 shows detailed schematic diagram of sample probe and layout of the sampling system. The sample flow was routed from the inlet to the trunk of the vehicle via 3 meters of conductive silicon tubing (TSI, model 3001788). In the trunk were four instruments, each sampling from this air supply. Isopropanol vapor from a particle counter was vented out through the rear passenger window on the other side. The window was at a minimal opening and the remaining gap was sealed using plastic tapes. The instruments described in the following section were operated using a deep cycle marine battery (U.S. Battery, model US 2200 XC2) carried at the truck of the mobile platform. The battery pack weighed a total of 57.7 kg adding the most weight of the entire instrument cluster. As far as the weights of the other instruments, the CPC weighed 1.8 kg, the EAD weighed 6.8 kg, the nanoscan SMPS weighed 9.1 kg and the optical particle sizer weighed 1.6 kg.

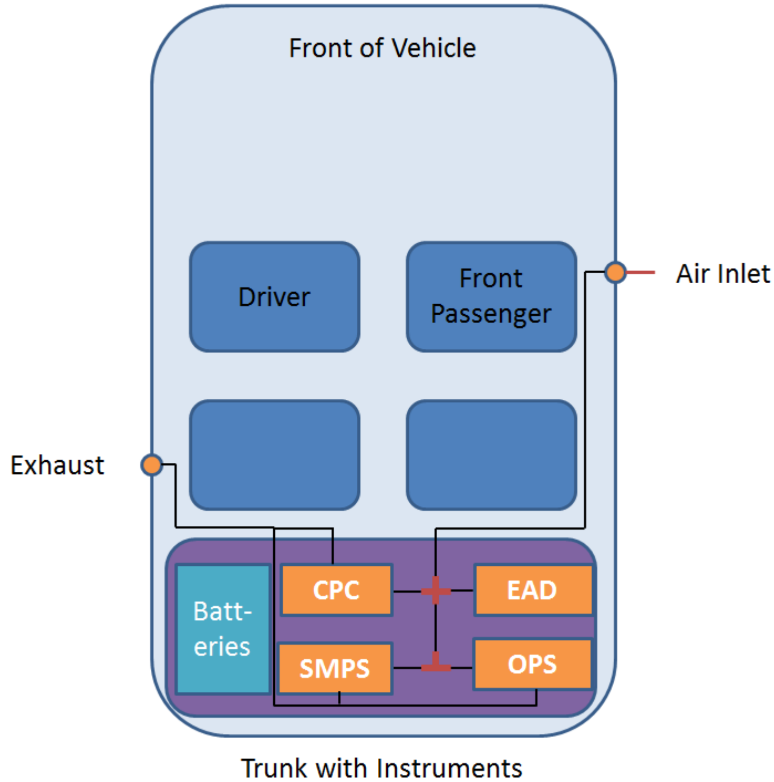

Figure 12 - Top: experimental layout of the vehicle, including instrument and sampling locations. Bottom: Picture of sampling probes used in the test.

The aerosol sampling instruments include a portable condensational particle counter (CPC) (TSI, model 3007) which has a cutoff diameter of 10nm and concentration range of 10^5 particles/cm^3 and an electrical aerosol detector (EAD) (TSI, model 3070A) which measures total particle surface area. An impactor inlet of the EAD was not used intentionally not to have an upper limit of the particle size. This is to be consistent with inlet condition for the CPC. As a supplementary measurement to confirm the measurement of the CPC and EAD, a portable scanning mobility particle sizer (TSI NanoScan SMPS model 3910) was used. The NanoScan SMPS is composed of soft x-ray unipolar particle charger, radial differential mobility analyzer, and an isopropanol based particle counter. It measures a particle size distribution in one minute with 16 channel resolution. It also has its own battery for power and memory for data logging. In addition to above aerosol instruments location and vehicle speed were recorded using a GPS logger (model FV-M8, San Jose Navigation) at 1 Hz. This is to take the traffic condition into account for the data analysis.

3.2 Driving Route and Test Protocol

Two distinctive drive routes were chosen to prove feasibility of the monitoring concept this study proposes. The traffic condition at highway 91 near Yorba Linda, CA is called Yorba Linda creep during commute times. It shows typical stop and go traffic conditions which consists of approximately 92-98 % of light duty vehicles and 2-8 % of heavy duty vehicles such as container trucks [31]. This route was selected because it shows traffic conditions on roads dominated by light duty vehicles. The congestion occurs for the west bound traffic during morning commute time. This is due to the commuters from Inland Empire to Orange County and LA. The congestion occurs again during afternoon commute time for the east bound. The mobile platform was driven east bound from 6:56 am to 8:10 am and returned in west bound from 8:10 am to 8:38 am. The route is shown in Figure 13.

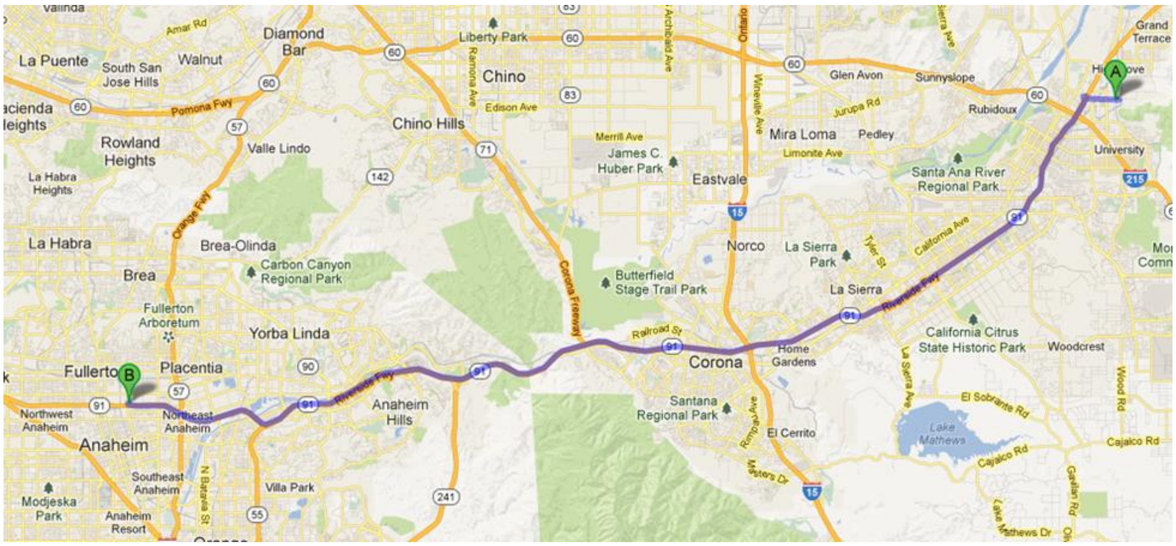

Figure 13 - Highway 91 route taken on Oct. 1 2012. Point A starts at CE-CERTS location in Riverside, CA and point B ends at Raymond Ave. in Fullerton, CA. Image courtesy of google maps.

The second test route is highway 710. A second route was designed during afternoon rush hour on the 710. This route was chosen due to its distinctive composition of traffic, which has a larger composition of heavy duty trucks going to Long Beach port. Highway 710 shows a 3-30 % heavy duty vehicle composition which is much higher compared to Highway 91 [31]. The trucks are mainly diesel engine powered therefore it is expected to show distinctive signature particle size distributions from diesel engines. The mobile platform was driven to south bound from the highway 60 and 710 interchange to Navy Way during 4:18 pm – 4:46 pm and returned using north bound during 4:47-5:16 pm. Each of these runs began and ended at CE-CERT as to not endanger the driver with instrument monitoring while driving. The 710 was entered and left at the highway 60 interchange. This is shown in Figure 14

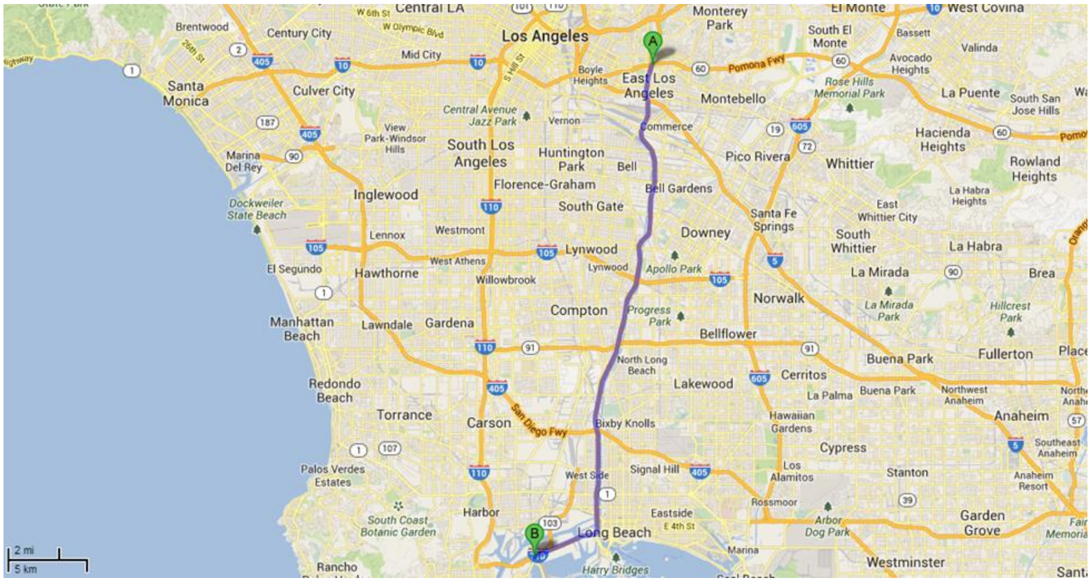

Figure 14 - Highway 710 route taken on Sept. 28 2012. Point A starts at the highway 60 and 710 interchange in Los Angeles, CA and point B ends at Navy Way in Long Beach, CA. Image courtesy of google maps.

The vehicle was driven to this location, where all of instruments were turned on and measurement started. Efficient use of time was necessary in order to get the most out of a full charge of the batteries. Once all of the instruments were recording, the vehicle began moving and entered the highway. The vehicle was consistently in the second most left lane of the highway except when exiting was necessary. All instruments, computers and GPS were time synced with one another.

3.3 Results and Discussion

The SMPS and corresponding speed is displayed in Figure 15. Figures 15A and 15B are both east bound data measured as a function of distance, while figures 15C and 15D are both westbound data. Identical routes were taken both ways, the only difference being the side of the highway. The graphs are aligned so that points on the x-axis of A and B vertically correspond with points on the x-axis of C and D. This indicates that they are at the same point on the highway.

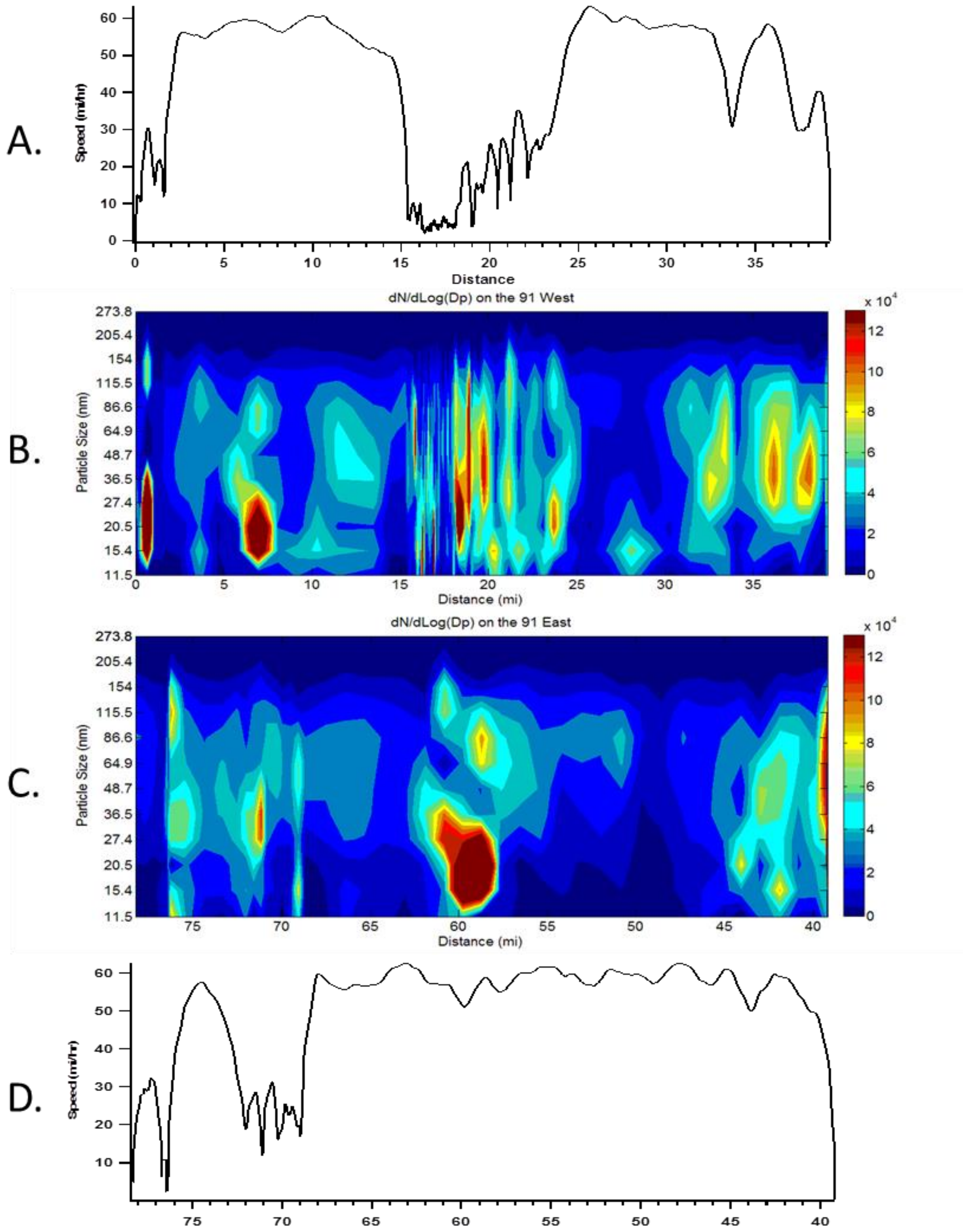

Figure 15 - Highway 91 Data from : A. Westbound speed (mph) as a function of distance (miles). B. Westbound particulate concentration (dN/dLog(Dp)) as a function of size (nm) and distance (miles). C. Eastbound particulate concentration as a function of size and distance. D. Eastbound speed as a function of distance. Speed graphs were created by Liem Pham.

Increased traffic was seen approximately from mile 15 to mile 25. This is shown by the decrease in speed and the higher peaks in the particulate concentration. The peaks are associated with the quick acceleration and deceleration seen on the speed graph. The greatest peaks occur between 10 and 60 nm which is indicative of the nucleation mode particles from a typical internal combustion engine. With the stop and go associated with this bumper-to-bumper traffic, this makes sense. When vehicles need to accelerate quickly, they tend to burn fuel rich; this causes more particles to be emitted since the fuel is not being burned at a high efficiency.

Similar peaks are seen around mile 17 westbound and 59 eastbound and these occur at the same point on the highway. Westbound traffic is stop-and-go at this point (10-30 mph) while eastbound is free flowing (50-60 mph). Even with differing speeds, the peaks were still seen Traffic data (Figure 16) shows that traffic did increase at that time, but not by an extreme amount. Occupancy is defined as the amount of time the traffic measurement instruments were in use divided by the total time. It is essentially the ratio of the amount of space taken up by vehicles to the total space available on that stretch of the highway.

	Westbound			Eastbound		
	Vehicles per 5 min.	Occupancy	Avg. Speed	Vehicles per 5 min.	Occupancy	Avg. Speed
7:25 (mile 15)	325	0.1329	29.8 mph	390	0.07	68.4 mph
8:30 (mile 59)	344	0.2313	23.9 mph	392	0.0697	71 mph

Figure 16 - Traffic data for highway 91 on October 1 2012. Data from Caltrans PeMS

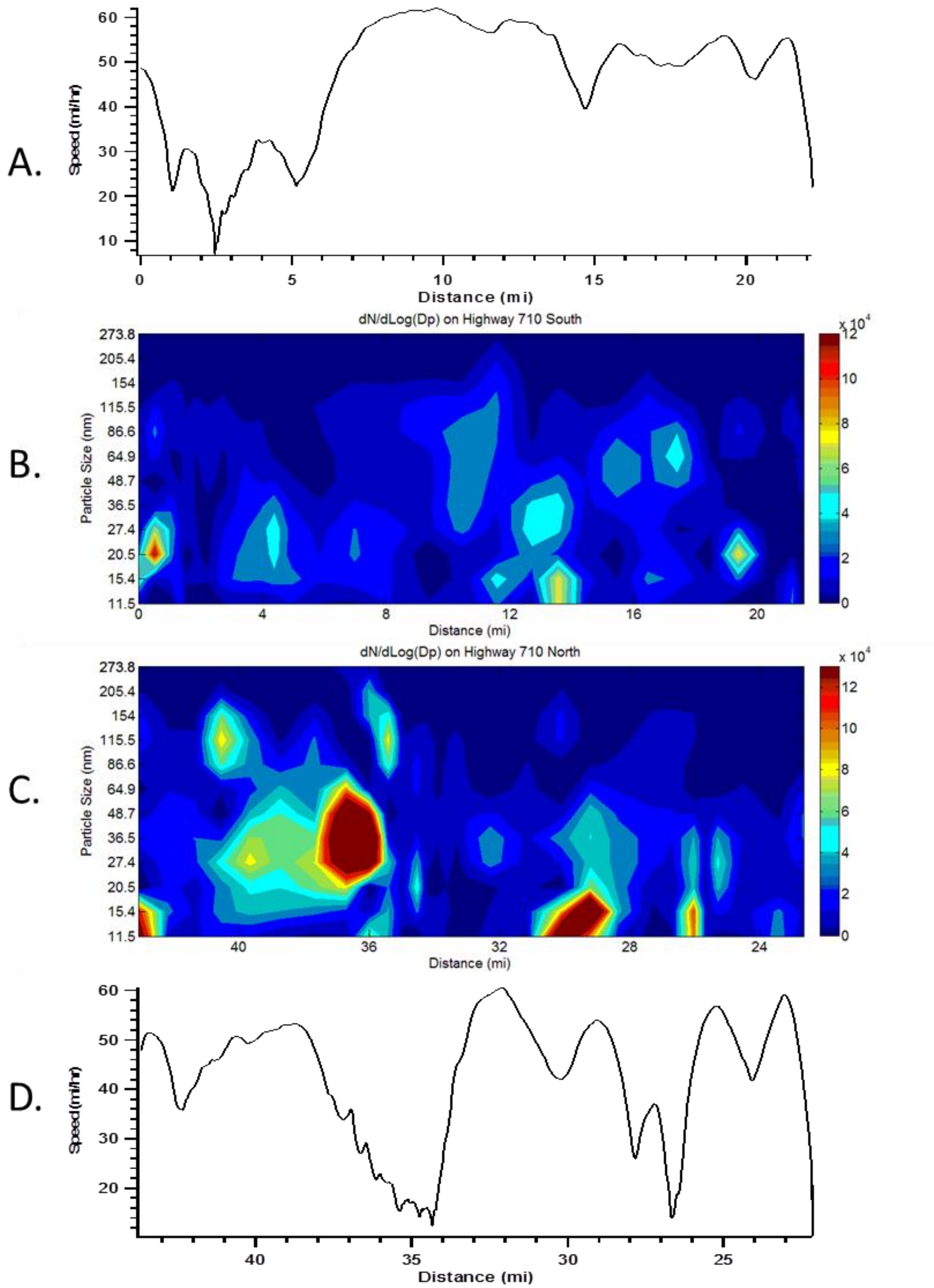

Figure 17 - Highway 710 data from September 28, 2012: A. Southbound speed (mph) as a function of distance (miles). B. Southbound particulate concentration (dN/dLog(Dp)) as a function of size (nm) and distance (miles). C. Northbound particulate concentration as a function of size and distance. D. Northbound speed as a function of distance. Speed graphs were created by Liem Pham.

The same test was run on highway 710 with results shown in Figure 17. In the same manor, peaks are seen around times of hard acceleration and deceleration. However, this time the southbound route did not mimic the results of the northbound route. The peaks are at similar locations but south bound magnitude of particulate matter concentration is considerably smaller. The reason for this is due to weather and wind gusts.

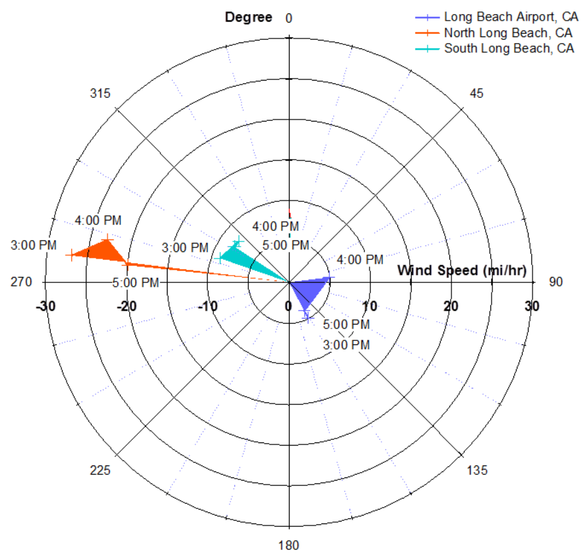

Figure 18 - Wind trajectory and magnitude for areas surrounding highway 710 on September 28, 2012. Graph created by Liem Pham

Wind gusts upwards of 30 mph in the West direction were seen at the time of this test. The sampling probe for the vehicle was located on the right side and faced outwards. In this scenario the probe was facing the west on the southbound trip and east on the northbound trip. The decrease in the peaks on the southbound trip was due to the wind blowing the particulate matter away from the probe. Conversely on the return trip the particulate matter was blow towards the probe. Even though the probe was not affected by perpendicular flow on the 91, it seems to be greatly affected by the parallel flow on the 710. Wind for the 91 test never got above 4 mph.

4. Indoor Air Quality Control with Fraction Recirculation

4.1 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.

4.2 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.

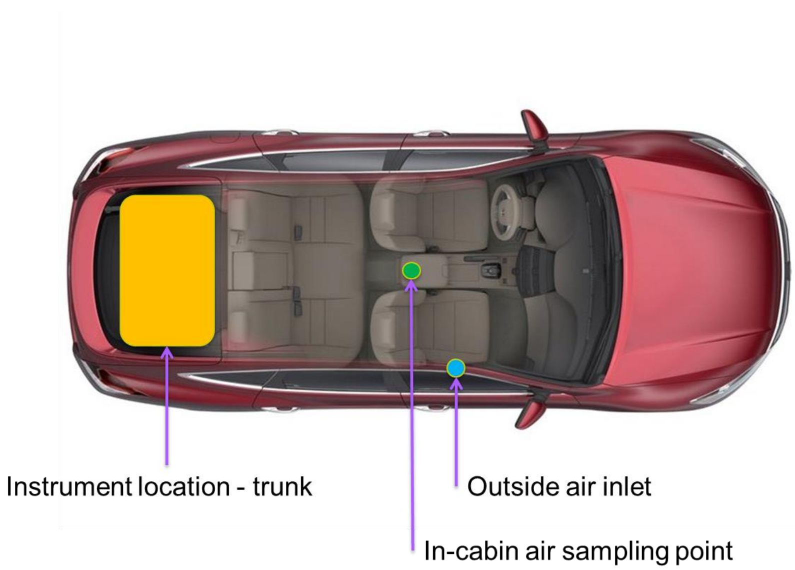

Figure 19 - Sampling and instrument locations

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 (pictured in Figure 19,) facing towards the rear. This allowed the indoor measurements to be taken without direct influence of the ventilation system. 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.

4.3 Results and Discussion

4.3.1 Feasibility Test: Proof of Concept

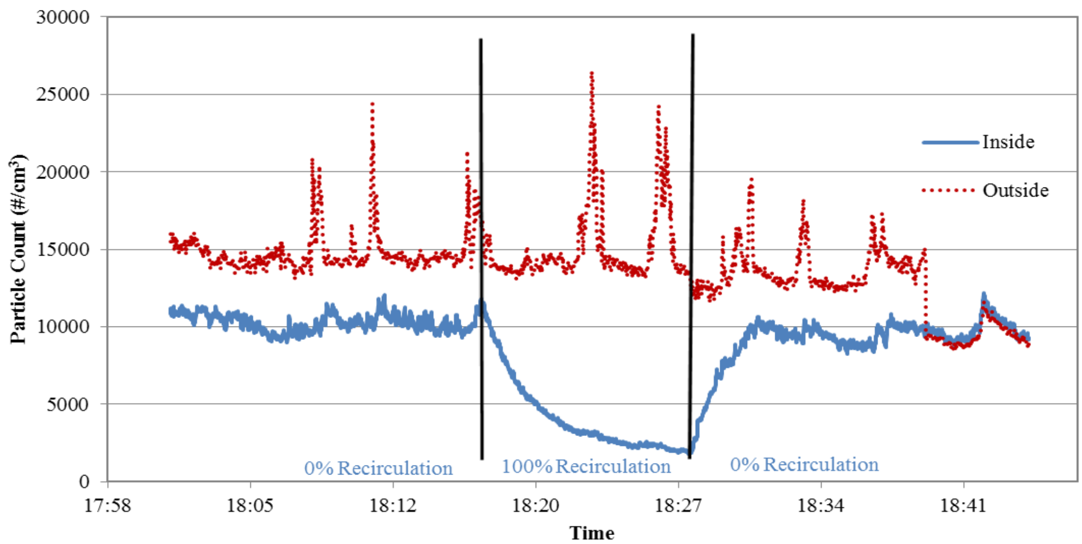

Figure 20 - Effect of full air recirculation on particle concentration in cabin: comparison with outside air

Figure 20 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/cm^3. 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, shown in Figure 21. 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. 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.

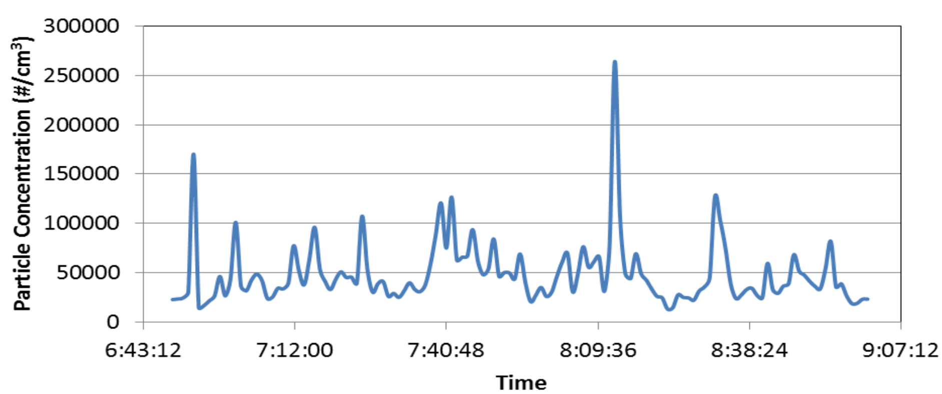

Figure 21 - Typical outdoor particle concentration during a commute. Data is from Highway 91 test.

The main problem with 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 drowsiness [6] and elevated H_2O concentrations requires more frequent dehumidification of the windshield.

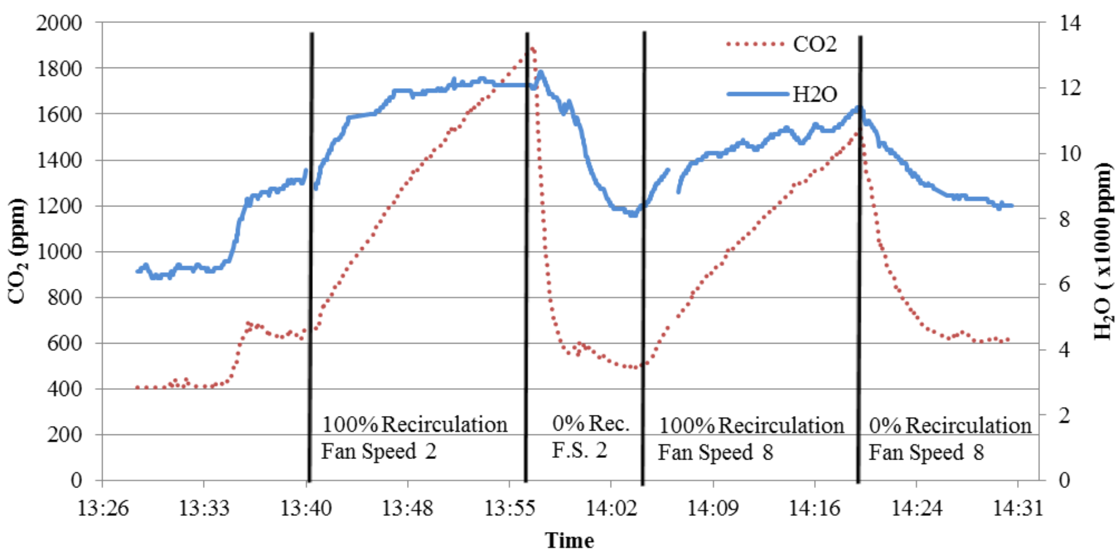

Figure 22 - Effect of full air recirculation on water vapor and CO_2 concentration in cabin with one passenger

Figure 22 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 [28]. 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 [32]. 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 [25] cited ASHRAE standard 62 [29] 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. It is necessary to develop a new standard for a short time exposure to CO_2 in a micro environmental such as vehicle cabin.

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.

4.3.2 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 23 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).

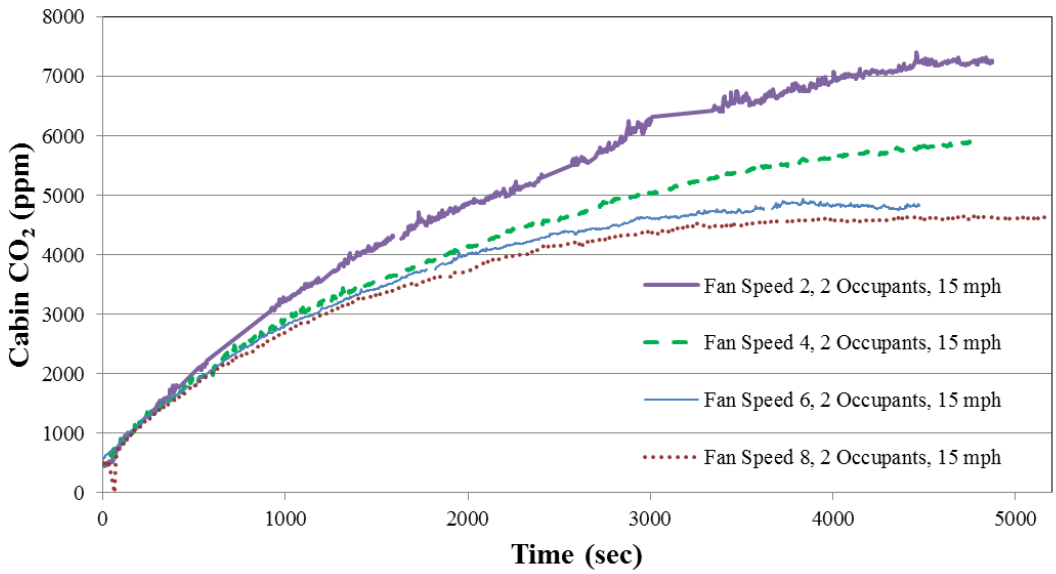

Figure 23 - Evolution of cabin CO_2 concentration as a function of time and fan speed. Test conducted at full recirculation condition with two passengers.

Jung [33] 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 23. 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 [33] 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 23 along with a mathematical model provides characteristic parameters of the vehicle cabin HVAC system to control cabin CO_2 concentration at a specific level.

4.3.3 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 24 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. The door angle cycles every 6000 seconds compared to Mathur's 600 seconds, creating a more robust operation.

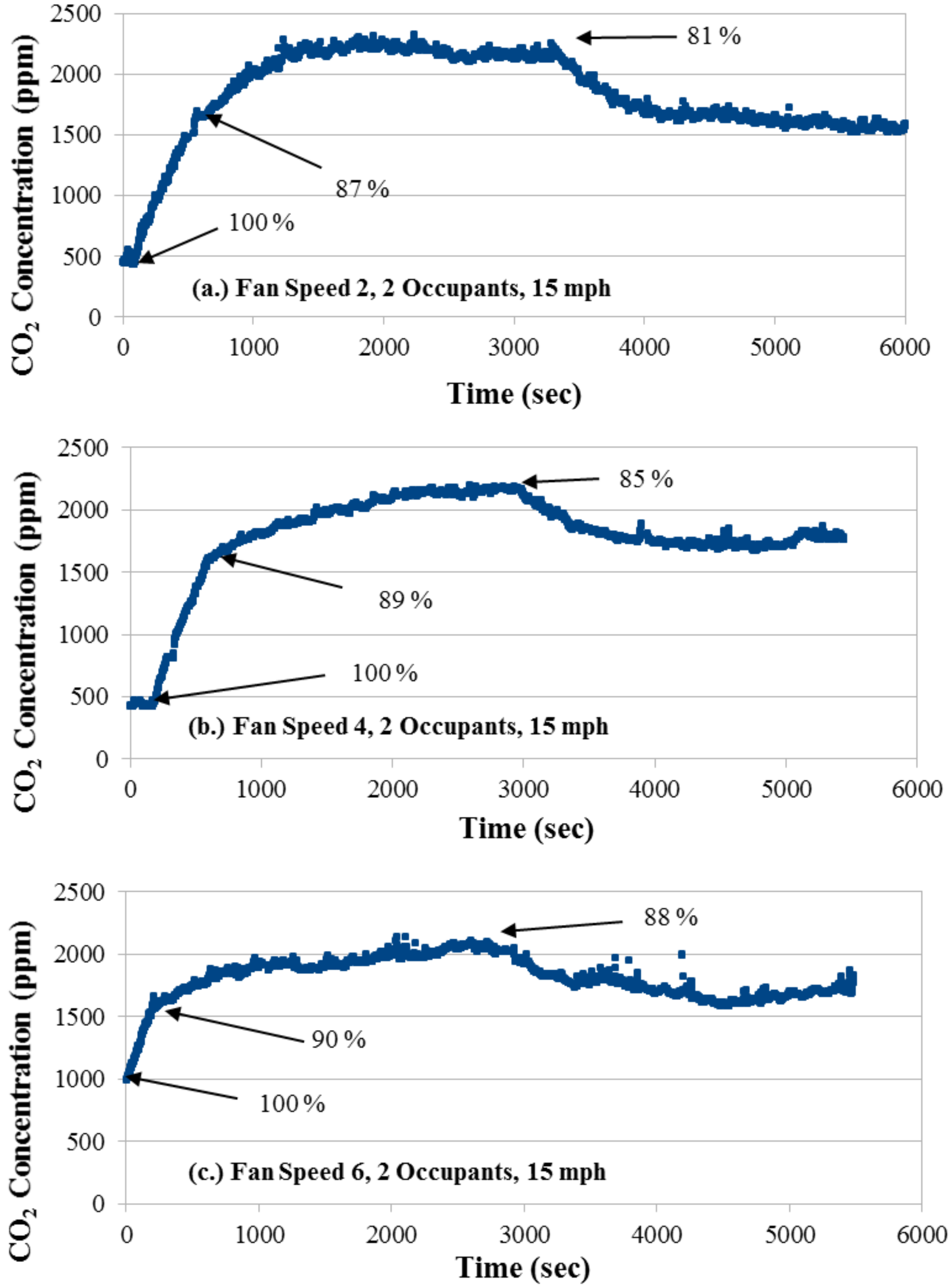

Figure 24 - Feasibility test to control cabin CO_2 concentration at a target level of 2000 ppm, at 15 mph with two passengers. Different fan speeds were tested: (a.) Fan Speed 2 is slow; (b.) Fan Speed 4 is medium and (c.)Fan Speed 6 is fast. Percentage indicates degree of recirculation

4.3.4 Influence of Vehicle Speed

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 25, are recorded with the same algorithm for voltages as the 15 mph test shown in Figure 24a. 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. Neither speed allowed concentration hit 2000 ppm, and both seemed as they would eventually plateau before it.

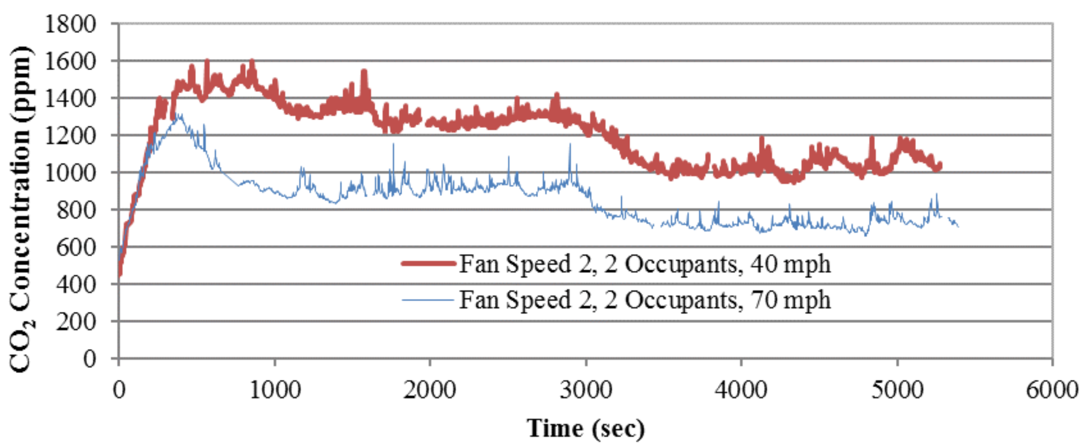

Figure 25 - Influence of vehicle speed on cabin CO_2 concentration control. Both tests had two passengers and used Fan Speed 2 with the vehicle driven at 40 mph (top line) and 70 mph (bottom line)

4.3.5 Effect of Partial Recirculation on Particle Count

Particles found on the roadway during a commute are harmful to a passenger's health [3-4]. Recirculating air has the benefit of filtering out most of these harmful particles. Partial recirculation shares some of these benefits without increasing the concentration of CO_2 above acceptable limits. Some of the original tests were repeated to compare the effect of full versus partial recirculation on particle count. Inside and outside particle concentrations were recorded to show the influence of the outside concentration on the inside concentration. CO_2 concentration was also recorded to replicate the original test. For these tests two mobile CPC machines were used. Both were TSI CPC 3007 which has a limit of 10 nm.

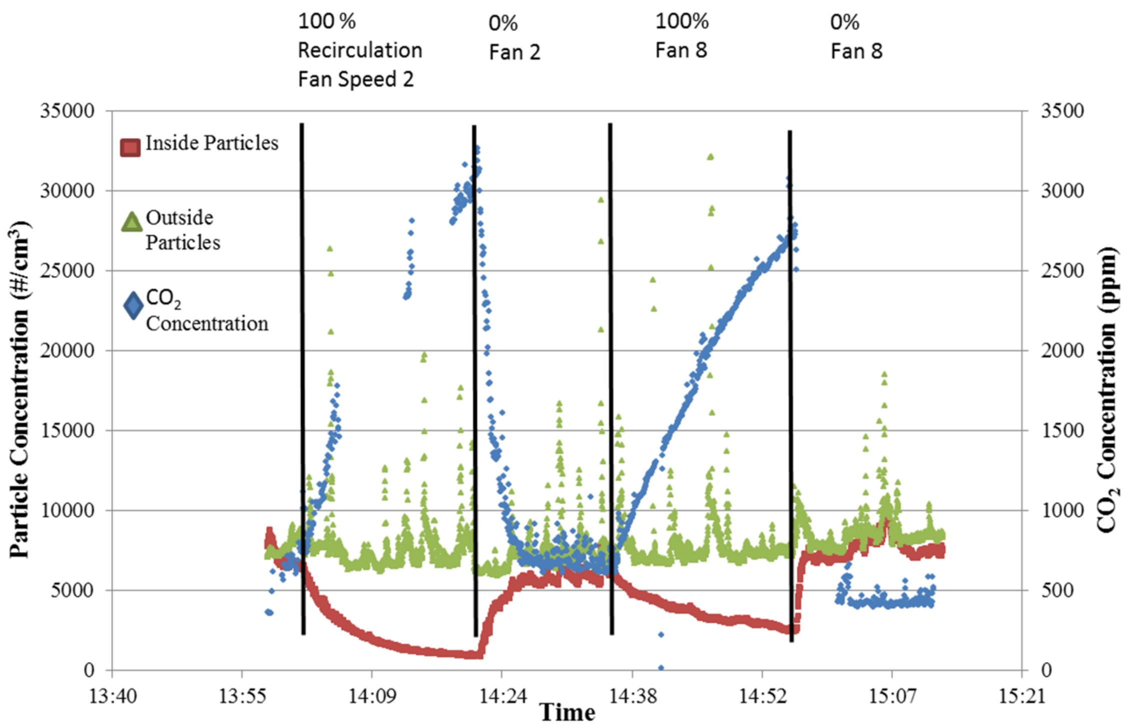

Figure 26 - Effect of full recirculation on particle count and carbon dioxide levels in-cabin. Test used two passengers and 15 mph driving conditions.

The test completed in Figure 26 was the same that was completed in Figure 22, with the addition of monitoring inside and outside particle counts. The effect of full recirculation was tested at fan speeds 2 and 8 with two passengers in the vehicle. The same parking lot was used as the course in these tests. This parking lot loop took two to three minutes to complete. Each completion of the loop is noted by a spike in the outside concentration, which was caused by a nearby intersection where there was more traffic and a higher concentration of exhaust fumes. When looked at very closely, the inside concentration mimics the jumps shown in in the outside concentration, but not nearly of the same magnitude.

At 14:02 the recirculation was switched to 100% with a fan speed of 2. The same increase in CO_2 as seen in the original test was, and it was accompanied by a decrease in the particle concentration inside the cabin. The concentration decreased from about 7,000 to 1,000 particles/cm^3, showing that recirculated air reduces the exposure to these harmful particles. The test was repeated at fan speed 8. The results were similar to fan speed 2 except that the changes in concentrations were less drastic. The faster the fan speed, the more leakage occurred. This lessened the impact that the recirculation of the air had on the quality of the air in the cabin. Since a parking lot was used to simulate the speed of rush hour, instead of an actual highway, the concentrations were lower. If this test were repeated on an actual highway, the difference between outdoor and indoor particle count would be more pronounced. A preliminary test was done to see if particle concentration reduction was feasible with the partial circulation. All tests were completed in the parking lot with two passengers at 15 mph.

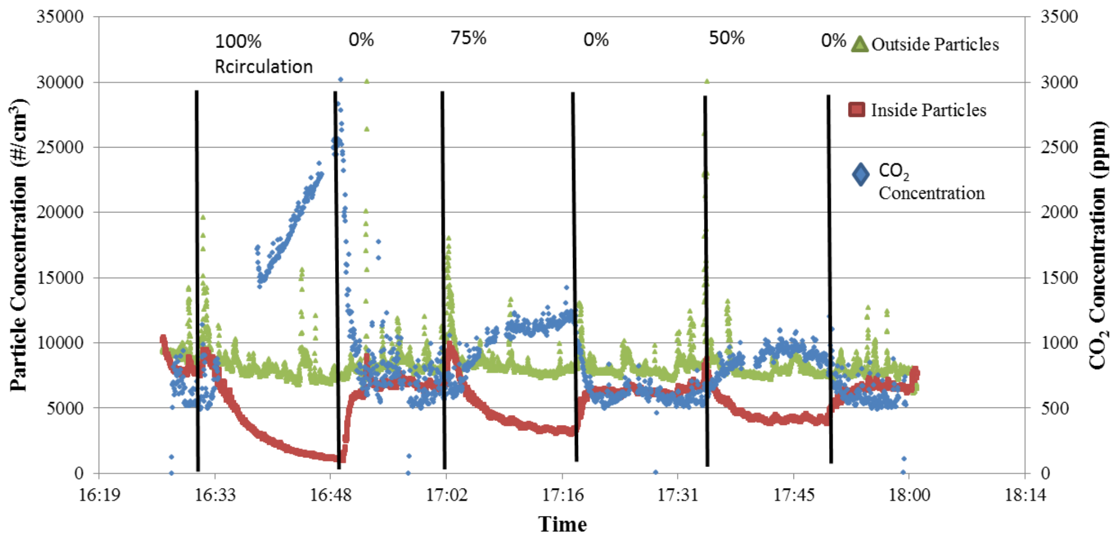

Figure 27 - Effect of partial recirculation on particle count and carbon dioxide levels in-cabin. Test used two passengers and 15 mph driving conditions.

The test in Figure 27 began with 100% recirculation to measure baseline impact, and then switched to 0% recirculation in order to reset the indoor particle concentration. After that, the recirculation was set to 75% and 50% with intervals of 0% recirculation in between to reset the particle count. When the recirculation door was set to these lower percentages, patterns similar to full recirculation were observed. Once partial recirculation was turned on, there was an increase in CO_2 and a decrease in particle count, but to a lesser degree than with full recirculation. In the case of 75% recirculation, the particle concentration decreased from about 7,000 to 3,500 particles/cm^3. While this was a smaller decrease in particle concentration compared to 100% recirculation, it was also accompanied by a decrease in CO_2 concentration. This illustrates a tradeoff between particle concentration and CO_2 concentration with regards to the cabin air quality.

Finally, the test from Figure 24a was repeated. This test aimed for a CO_2 concentration around 2000ppm. Initially recirculation was set to 100% to receive the full benefits recirculation; it was then switched to 87% once the CO_2 concentration was at about 1500 ppm. Like in Figure 24A, the recirculation was switched to 81% after 30 minutes.

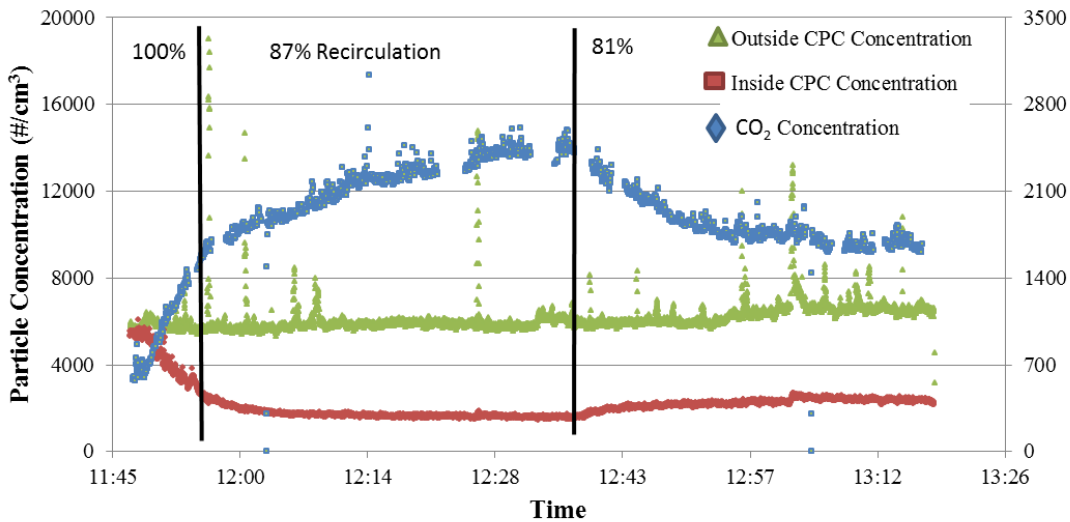

Figure 28 - Effect of an algorithm on particle count and carbon dioxide levels in-cabin. The vehicle was driven at 15 mph, with two passengers and a fan speed of 2.

Figure 28 illustrates the ability to control the CO_2 concentration, and the reduction of particles in the cabin as a result. The Particle Concentration was reduced from about 6,000 to 2,000 particles/cm^3. The recirculation door algorithm allowed the vehicle to receive the benefit of recirculation (reduced particle count) without driving the CO_2 concentration to unsafe levels.

4.4 CO_2 Concentration Modeling from Input Parameters

Using the collected data, Jung [33] was able to create a governing equation that predicts the amount of CO_2 in the cabin based on parameters that are shown in Figure 29. With this logic, vehicles are able to predict their CO_2 level (without a sensor,) and adjust the recirculation accordingly. The parameters are specific to the passengers, the vehicle, and the personal driving style of the driver.

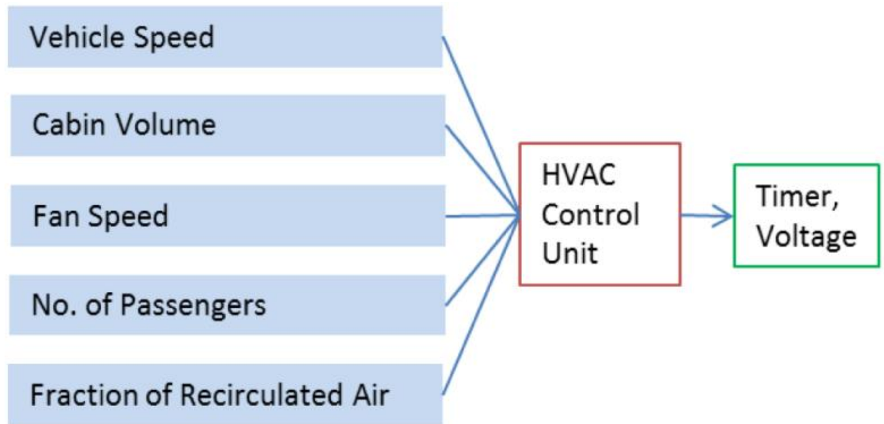

Figure 29 - Schematic of control logic

Vehicles and people vary so much that this prediction is difficult to make. No matter how luxurious a car is, it will never be 100% sealed from its environment. Additionally, no two cars are alike, so the cabin volume and the amount of leakage into and out of the cabin differ from model to model. Similarly, no two people are alike. This alters how fast they drive, what fan speed they choose, and how many people are in their car on a daily basis. Knowing this, Jung created a general equation with which most situations could apply.

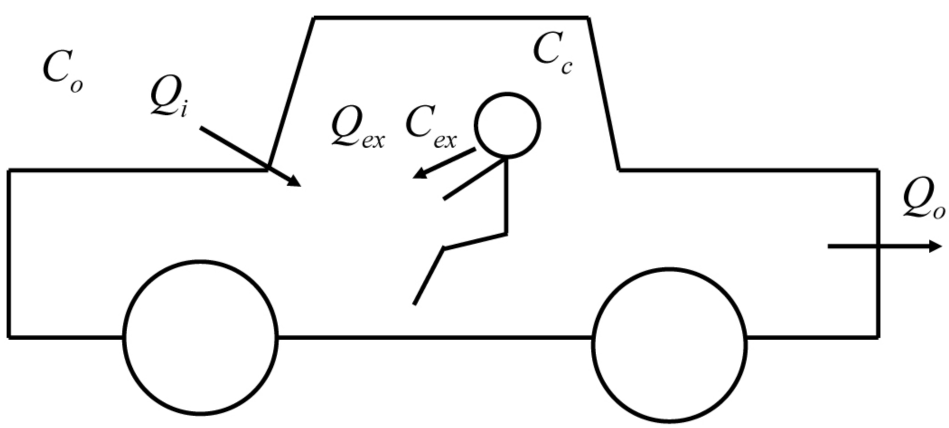

Figure 30 - Jung's model for CO_2 levels in-cabin [33].

Figure 30 depicts the basic aspects of Jung's Model as a differential equation. Q_i is the amount of air flow into the vehicle, Q_o is the amount of air flow out of the vehicle, and Q_{ex} is the amount of air being exhaled by the passengers. Q_{ex} is a function of the number of people, and the state of health of those people. C_o is the concentration of CO_2 outside of the vehicle, C_c is the concentration of CO_2 inside the vehicle, and C_{ex} is the concentration of CO_2 in each exhale. Based on this general idea, Jung was able to create the differential equation based on the change of mass of CO_2.

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

Figure 31 - Carbon dioxide mass balance equation for a vehicle [33].

The term on the left shows the change in mass of CO_2 with respect to time. The first term on the right hand side is a generation term. It shows the amount of CO_2 created by the passengers. The second and third terms on the right hand side are based on the amount of leakage of the vehicle. They essentially show the balance that occurs between the inside and the outside of the vehicle based on the amount of air that is exchanged. From this, Jung goes on to explain that the concentration of CO_2 in the cabin is based on the following equation.

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

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

Figure 32 - First order differential equation that predicts the amount of carbon dioxide in the vehicle cabin [33].

In the equation in Figure 32, V_c is the cabin volume. Solving for the concentration of CO_2 in the cabin, Jung was about to produce the following equation:

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

Figure 33 - Final predicted carbon dioxide concentration based on schematic parameters and time [33].

This final equation uses the inputs named in the schematic in Figure 29 to predict the amount of CO_2. If the above parameters can be quantified, then every car should be able to protect their passengers from the harms of particulate matter on the highway.

5. 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. While driving at 20 mph, with two passengers and fan speed 2, air recirculation was switched from 0% to 100%. Cabin particle concentrations were reduced to 20% of the original concentration, 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 for the test car this study chose. We believe this method is a simple and robust way of maintaining clean air quality of the cabin and can be applicable to new cars, at a minimal cost.

The study showed the highest highway particle concentrations occurred when traffic was congested during rush hour. This was due to the stop-and-go traffic that accelerates and decelerates quickly. At speeds around 20mph, partial recirculation has the greatest impact in filtering out particles without driving up the CO_2 concentration to unsafe levels. At higher speeds, the effect of partial recirculation is diminished due to vehicle body leakage.

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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