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# Development of a Standard Testing Method for Vehicle Cabin Air Quality Index

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## Abstract

Vehicle cabin air quality depends on various parameters such as number of passengers, fan speed, and vehicle speed. In addition to controlling the temperature inside the vehicle, HVAC control system has evolved to improve cabin air quality as well. However, there is no standard test method to ensure reliable and repeatable comparison among different cars. The current study defined Cabin Air Quality Index (CAQI) and proposed a test method to determine CAQI. $\mathrm{CAQI}_{\mathrm{particles}}$ showed dependence on the choice of metrics among particle number (PN), particle surface area (PS), and particle mass (PM). $\mathrm{CAQI}_{\mathrm{particles}}$ is less than 1 while $\mathrm{CAQI}_{\mathrm{CO2}}$ is larger than 1. The proposed test method is promising but needs further improvement for smaller coefficient of variations (COVs).

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## Keywords

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# Introduction

Air pollutants from vehicle emissions have been associated with numerous adverse health effects, such as decrease in respiratory functions, cardiovascular diseases, asthma, and premature death [1, 2, 3, 4]. Commuters using personal vehicles can be exposed to elevated concentrations of air pollutants than background ambient levels while inside the vehicles [5, 6]. Although in-cabin air quality varies from vehicle to vehicle [7], there is no standard test method available to determine the vehicle's ability to maintain clean in-cabin air quality compared to on-road air quality.

A few leading auto manufacturers have introduced cars with active cabin air quality controls. Tesla has implemented a biodefense air control mode with a large HEPA filter [8]. BMW has implemented automatic air recirculation to prevent passengers from high concentration exposure to outside air pollutants [9]. More recently, Toyota has implemented active air recirculation condition to increase fuel economy in their 2017 Prius ECO mode driving [10]. Li et al. [11]showed that cabin air recirculation improve not only cabin air quality but also fuel economy with a caveat that constant recirculation over a long period of time can lead to accumulation of $CO_2$ in the cabin.

United Nations Economic Commission for Europe Vehicles Interior Air Quality Informal Working Group (UNECE VIAQ IWG) was formed in 2015 to establish a standard for volatile organic compounds (VOC) emissions from plastics used in vehicle interior. They are currently working to evaluate vehicle cabin air quality under different experimental conditions. SAE Interior Exhaust Gas Committee has initiated collaboration with UNECE VIAQ IWG in late 2018 to develop test methods for vehicle cabin air quality [12]. Presently, there are no standard test methods for vehicle cabin air quality to the best knowledge of the authors.

In-cabin pollutant concentrations can vary by many parameters, such as ambient air quality outside cabin, cabin volume, fan speed, number of occupants, cabin filter efficiency, and vehicle speed [13]. Cabin air quality deteriorates when there is poor ambient air quality outside the cabin. Cabin filters were originally intended to remove dust and pollens - that is why they were originally called pollen or dust filter - and remove particles depending on their size. Qi et al. [14] reported that the cabin filter removes 66% and 61% of particles by the number and surface area concentration. They also reported that the most penetrating particle size for the cabin filter was ~350 nm with 23% and 17% filtration efficiency at medium and high fan speeds, respectively. As mass median diameter of ambient particles are close to the most penetrating particle size, we expect particles will be removed by cabin filter at low efficiency when they are evaluated on mass basis.

Improvement in vehicle structural and sealing design could reduce in-cabin particle concentrations [15, 16, 17, 18]. The recirculation system inside the vehicle can reduce particle concentrations by controlling the intrusion of external air or ventilation rate also known as air exchange rate (AER). AER is also known as ACH (air changes per hour) when the time scale is hour. It is a measure of the air volume added to or removed from a space divided by the volume of the space [19]. On the other hand, the $CO_2$ exhaled from the passengers can accumulate and reach high concentrations over time [5, 6, 13, 20, 21]. Increasing vehicle speed can affect the pressure difference between in-cabin and external air, which can increase the penetration of particulate and gaseous pollutant concentrations [22].

Most of previous studies, which compared vehicle cabin air quality among different cars, used a variety of conditions to understand vehicle cabin air system. None of the previous studies aimed to establish a standard test method with proper justification for the proposed test conditions. For example, Knibb et al. [16] tested five vehicles through a 4 km road tunnel and used trip average median in-cabin to the outside ambient concentration (I/O ratio) of particle number (PN) concentrations to understand the effect of ventilation setting and ventilation rate on ultrafine particle (UFP) exposure inside automobiles. The I/O ratio of pollutants is an important parameter to evaluate vehicle cabin air quality. A previous study [23] have attempted to use a model to predict the I/O ratio and achieved high correlations for average trip concentrations ($R^2 = 0.97$). The study assumed a constant AER and did not account for the fact that it is a function of vehicle speed and type. Hudda et al. [24] found from their model that AER was the most significant determinant of UFP I/O ratios. Their model could explain greater than 79% of the variability in the measured UFP I/O ratios by accounting for ventilation fan speed, vehicle age or mileage, and driving speed. Regardless, there was still a significant gap between predicted and measured values on real-time basis. Therefore, instantaneous or average I/O ratio is not appropriate to evaluate vehicle cabin air quality. It is also inappropriate to conduct a test without constraining the vehicle speed. High vehicle speed leads to a large pressure difference between in-cabin and outside ambient resulting in large AER regardless of ventilation settings. On the other hand, Fruin et al. [7] conducted a test at constant speeds of 32, 56, and 89 km/h. Constant speed tests cannot capture dynamically changing real-world AER at varying vehicle speeds. In analogy it is like determining a fuel economy at a constant speed.

Previous studies (except the one by Fruin et al. [7]) typically used at most a few vehicles to evaluate the particulate and gaseous pollutant concentrations within a vehicle cabin, which were lacking in vehicle database on ventilation performances. Each study had its own test method to evaluate and analyze in-vehicle occupant exposure, which makes results from different studies incomparable. This study aims to develop a consistent and repeatable test method to create CAQI, which evaluates a vehicle's ability to maintain clean cabin air quality. While particle mass (PM) is the metric of the regulations for source emissions and ambient air quality, most of previous studies used PN concentrations as the metric. The current study evaluates three important metrics, namely, PN, PS, and PM for each test vehicle to understand characteristics and response of different metrics. The long-term goal is to create a large vehicle CAQI database and make it accessible to consumers and developers. Establishing a database of

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cabin air quality measurement for different vehicles can be beneficial to the modelling community. *Emissions Analytics* (UK) is a company based in the United Kingdom, with operations in the United States, Germany, and South Korea, which some co-authors are associated with. They have already established a large database on vehicle fuel economy. We are currently evaluating vehicle cabin air quality for gases and UFPs using National Air Quality Testing Services instrument (NAQTS, www.naqts.com, U.K.), which can measure UFPs, $NO_x$, CO, $CO_2$, and $NH_3$. This work will be published separately.

# Experiment

## Test Vehicles and Cabin Air Settings

Eight light-duty vehicles were obtained from *Motor Trend*® via a partnership with *Emissions Analytics* (UK) for this study. These vehicles were relatively new models from different manufacturers at the time. These vehicles included two 2018 Mercedes-Benz GLA250, a 2018 Mitsubishi Outlander, a 2018 BMW 230i Coupe, a 2018 Hyundai Genesis G80, a 2018 BMW 740i plug-in, a 2017 Chevrolet Bolt, and a 2017 Lexus LS500 AWD. The vehicles were checked for general road worthiness such as tire pressures and oil level. Each vehicle was tested for a static and a dynamic test.

## Static Test

The static tests were conducted outside in the *MOTORTREND*® car park with the engine running at idle to maintain the air-conditioning (AC) unit at a constant power to characterize AERs at different ventilation settings without being affected by aerodynamics (e.g., wind or moving vehicle) around the test vehicle. AER is a function of cabin volume and body leakage flow. First, doors were left open for 2 min to ventilate cabin, and all windows and doors were closed. Next, the test vehicle engine was started and left under idle condition during the test. Ventilation mode was set at chest mode while AC on/off, recirculation, and fan speed were varied. Data was recorded for 5 min after $CO_2$ canister (G2132 Threaded $CO_2$ Cartridge, 20g, Genuine Innovations) was deployed. The $CO_2$ canister released high concentrations of $CO_2$. During this test, decay of $CO_2$ concentrations was measured to determine AER at different ventilation conditions. The test was repeated for different ventilation conditions. The test was done without any occupant except a "dummy" mannequin to represent a front passenger as shown in Figure 1.

## Dynamic Test

The dynamic test is to characterize the vehicle's ability to maintain clean air quality under two representative ventilation settings during a driving condition on the road. Infiltration of on-road air pollutants is a strong function of the vehicle speed. At high vehicle speeds such as during well-flowing highway driving, pressure difference between the inlets and outlets of vehicle cabin increases which lead to higher AERs compared to vehicles at low speeds. People are exposed to high concentrations of air pollutants at low speed driving conditions such as stop-and-go traffic conditions for two reasons: more emissions from frequent acceleration of densely packed cars on the road and absence of passive ventilation by outside aerodynamics due to low vehicle speeds. The test route included arterial roads for low vehicle speeds near southeast of Los Angeles International Airport (LAX) and Hawthorne, CA. The test vehicles were driven to the statutory speed limits relevant to the road sections and prevailing traffic conditions. The timing of the tests was mid-morning (10:30-11:00 am) through to mid-afternoon (1:30-3:00 pm). Generally triplicate tests were conducted back to back to evaluate repeatability with exception for three vehicles due to either malfunction of instruments or test operator's mistake. Chevrolet Bolt data used duplicate test results, BMW230i data used duplicate test result for the AC off/fresh air condition, and Genesis G80 $CO_2$ data is from a single test result. During the first half of each test, the cabin air setting was fresh air mode with AC off while during the second half of the test, the cabin air was in recirculation mode with AC on. There was only a driver for all tests except for the test with one of Mercedes-Benz GLA250 2018 MY (for Figures 2-5) where there were two passengers including the driver. One set of tests lasted for ~40 min, the cabin air temperature was set at 19 °C with the fan speed at mid-level. Detailed step-by-step procedure is provided in the appendix of this article.

## Instrumentation

The test vehicle had pairs of instruments that can measure PN concentrations, active PS, and black carbon (BC) mass. The condensation particle counters (CPC 3022A, TSI) can detect particles down to 7 nm and up to 3 μm in diameter. They have both single-count and photometric detection modes, which can provide accurate measurements for concentrations up to $10^7$ particles/$cm^3$. The electrical aerosol detectors (EAD 3070A, TSI) provide measurements for particle active surface area with diameter in the range from 10 nm to 1 μm. The EADs had a 1 μm cyclone installed at the inlet to remove large particles. BC mass concentration was measured using microAeth MA300 (Aethlabs, San Francisco, USA). The microAeth MA300 is a portable instrument powered by a battery, and it measures mass concentrations of light-absorbing carbonaceous particles in the sampled aerosol. The instrument has five analytical channels that operate at different wavelengths (375, 470, 528, 625, and 880 nm). The time base was set to 60 s because it will provide optimum performance in response to high transient sampling environment and the impact of contamination and vibration. The sampling flows for both inside and outside microAeth were set to 50 mL/min for the first Mercedes GLA250 and Chevrolet Bolt tests. The sampling flows were set to 150 mL/min and 100 mL/min for subsequent

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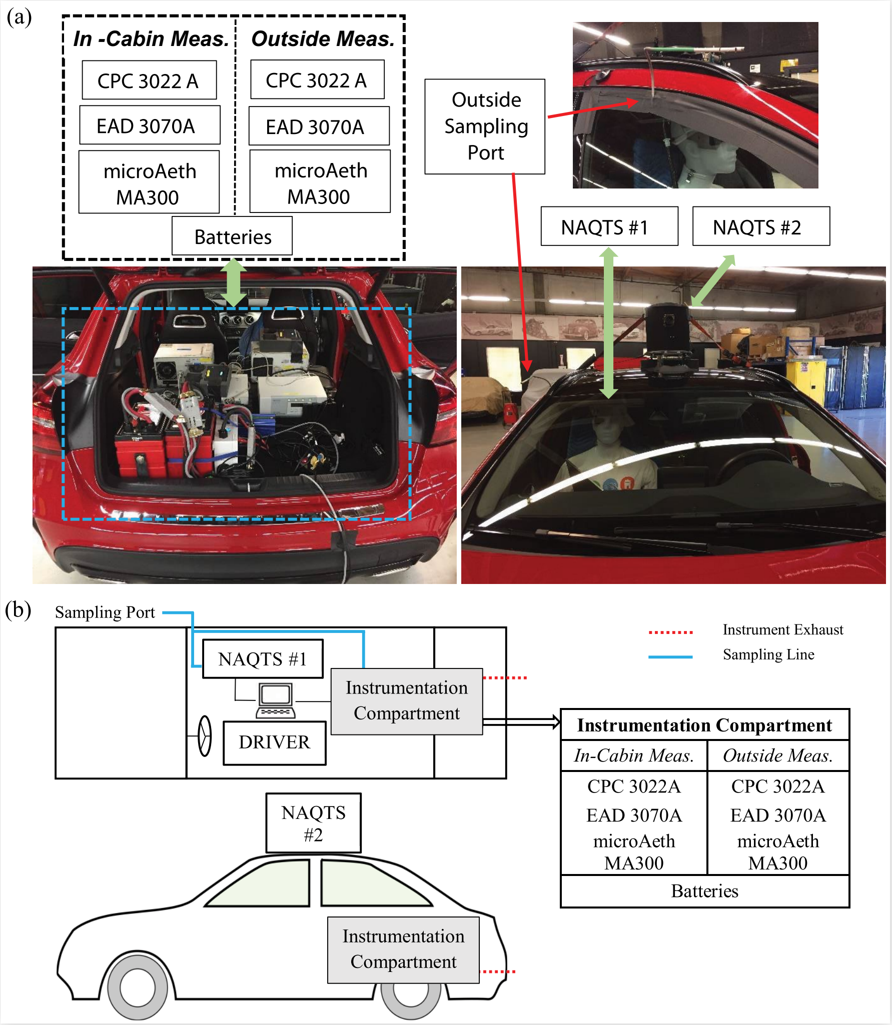
**FIGURE 1** Experimental setup: (a) pictures and (b) schematic.



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tests for inside and outside microAeth, respectively. The purpose of increasing the flow was to increase the signal-to-noise ratio for the BC measurements. The microAeth located inside the cabin pulled at higher sample flow due to lower BC concentrations inside the cabin. BC concentrations obtained from 880 nm at a single spot mode were used for this study. The outside microAeth had a microCyclone installed to remove particles that were larger than 1.6 μm diameter from the road and to prevent large particles from clogging the filter cartridge. All instruments were set to sample at 1 Hz except for microAeth.

The National Air Quality Testing Services (NAQTS) V1000 was installed inside a "dummy" to represent a front passenger and measure inside cabin air. NAQTS V1000 measures UFPs (with lower cutoff diameter of 15 nm) and gas concentrations including carbon dioxide ($CO_2$), carbon monoxide (CO), nitrogen dioxide ($NO_2$), and volatile organic compounds (VOCs) using both metal oxide and electrochemical sensors. The second NAQTS was mounted to the top of the vehicle to measure outside ambient air. $CO_2$ data measured by the two NAQTS V1000 was used for this article.

All instruments were set up into two groups and dedicated to measuring cabin air and outside ambient. Each group of instruments consisted of one CPC, EAD, microAeth, and NAQTS. The size of the sampling port was 1/4″ outside diameter port. 1/4″ and 3/8″ conductive flexible tubing was used for inside flow distribution to the instruments. Hard plastic tubing was used as exhaust line for CPCs, EADs, and a NAQTS. These exhaust lines were routed to the outside of the vehicle by squeezing between the rear passenger door or the back trunk soft sealing grommets. Figure 1 illustrated the setup and arrangement of the instruments.

## Results

Test results from one test vehicle (more specifically one of the two 2018 Mercedes-Benz GLA250 with two passengers) are selected to show general trends of the result in Figures 1-4, while comparison for all of the test vehicles are shown in Figure 5.

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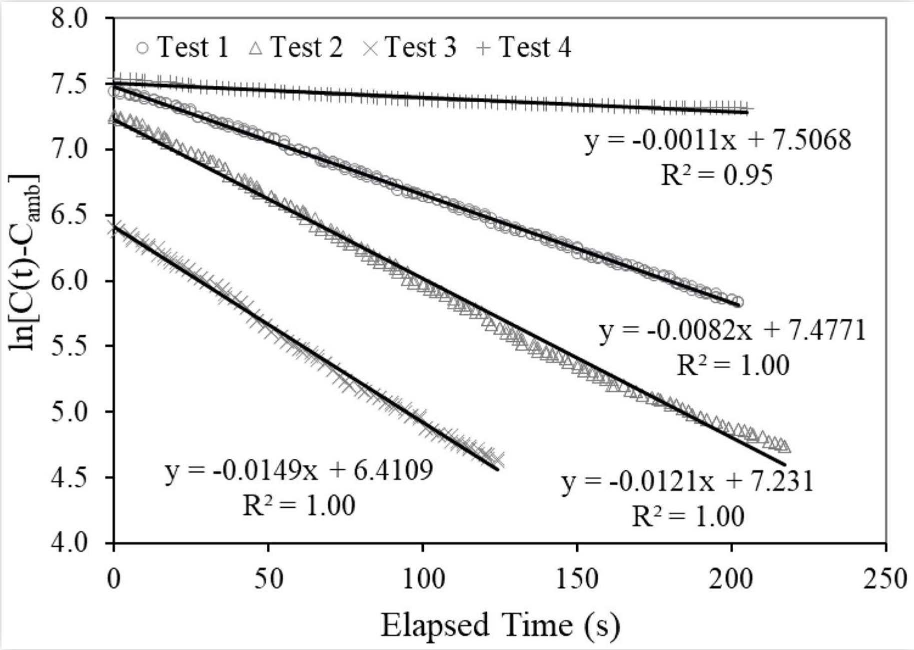
**FIGURE 2** AER determined from the static test, $C_{amb}$ was assumed as 400 ppm. Test vehicle was Mercedes-Benz GLA250 2018 MY.



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## Static Test Result

Decay of $CO_2$ concentrations in the cabin is plotted in Figure 2. Outside background concentration was assumed as 400 ppm. When natural logarithm is taken for the general solution given by Jung [6], it is a linear function of the elapsed time as shown below:

$$\ln\left(C(t)-C_0\right)=At+B \qquad \text{Eq. (1)}$$

where $C(t)$ is cabin $CO_2$ concentration at time $t$, $C_0$ is ambient $CO_2$ concentration, $A$ is slope, and $B$ is $y$-intercept. The slope is equal to -$Q_l/V_c$, where $Q_l$ is the body leakage flow and $V_c$ is the cabin volume. In addition, Jung et al. [20] showed

$$\text{AER}=\frac{1}{\tau}=\frac{Q_l}{V_c} \qquad \text{Eq. (2)}$$

where $\tau$ is the time constant which is inverse of AER. Slopes in Figure 2 are in the unit of $\text{second}^{-1}$. When the slopes are multiplied by 3600, they result in AER in the unit of $\text{hour}^{-1}$ as shown in Table 1.

The $CO_2$ decay data fitted to the equation showed correlation coefficient, $R^2$ ranging from 0.95 to 1. At fresh air mode with AC off, the lowest fan speed resulted in AER 30 $h^{-1}$, suggesting the cabin air was exchanged 30 times per hour assuming a well-mixed condition in the cabin. At the maximum fan speed the AER was 54, indicating the cabin air was exchanged almost every minute. During air recirculation condition with AC on, AER was at much lower value of 4 $h^{-1}$. This suggests a long operation of recirculation mode can lead to poor ventilation. Similar results were found by Jung et al. [20]. They determined AER as a function of recirculation door opening percentage.

Simultaneously measured particle and $CO_2$ concentrations within and outside the vehicle cabin during the dynamic test are shown in Figure 3. Red color means outside and blue color means inside cabin measurement. Outside particle concentrations showed random fluctuation indicating the dynamic nature of particle emissions on the road. Outside $CO_2$ concentration on the road remained at ~500 ppm which was slightly higher than the atmospheric background $CO_2$ concentration of ~400 ppm. When AC was off with fresh air mode, PN and active PS concentrations inside the cabin were lower than those outside. Small particles such as UFPs ($D_p$< 100 nm) were more effectively filtered by cabin air filter due to high particle diffusivity, and that is why outside high particle concentration events were shown at much reduced and damped concentrations inside the cabin. PM concentrations, in terms of BC mass, inside vehicle cabin crossed over with outside concentrations. We primarily attribute this to slow time response of the microAeth and a little to higher weighting on large particles for mass metric. Large particles have a longer lifetime in cabin compared to smaller particles, and mass mean diameter of on-road particles are near 350nm where filtration efficiency of the cabin filter is the lowest. Cabin $CO_2$ concentration remained 700-800 ppm which was 200-300 ppm higher than the outside concentration due to exhalation of the passenger.

Particle and $CO_2$ concentration trends changed dramatically when air recirculation mode was selected at ~1004 s.

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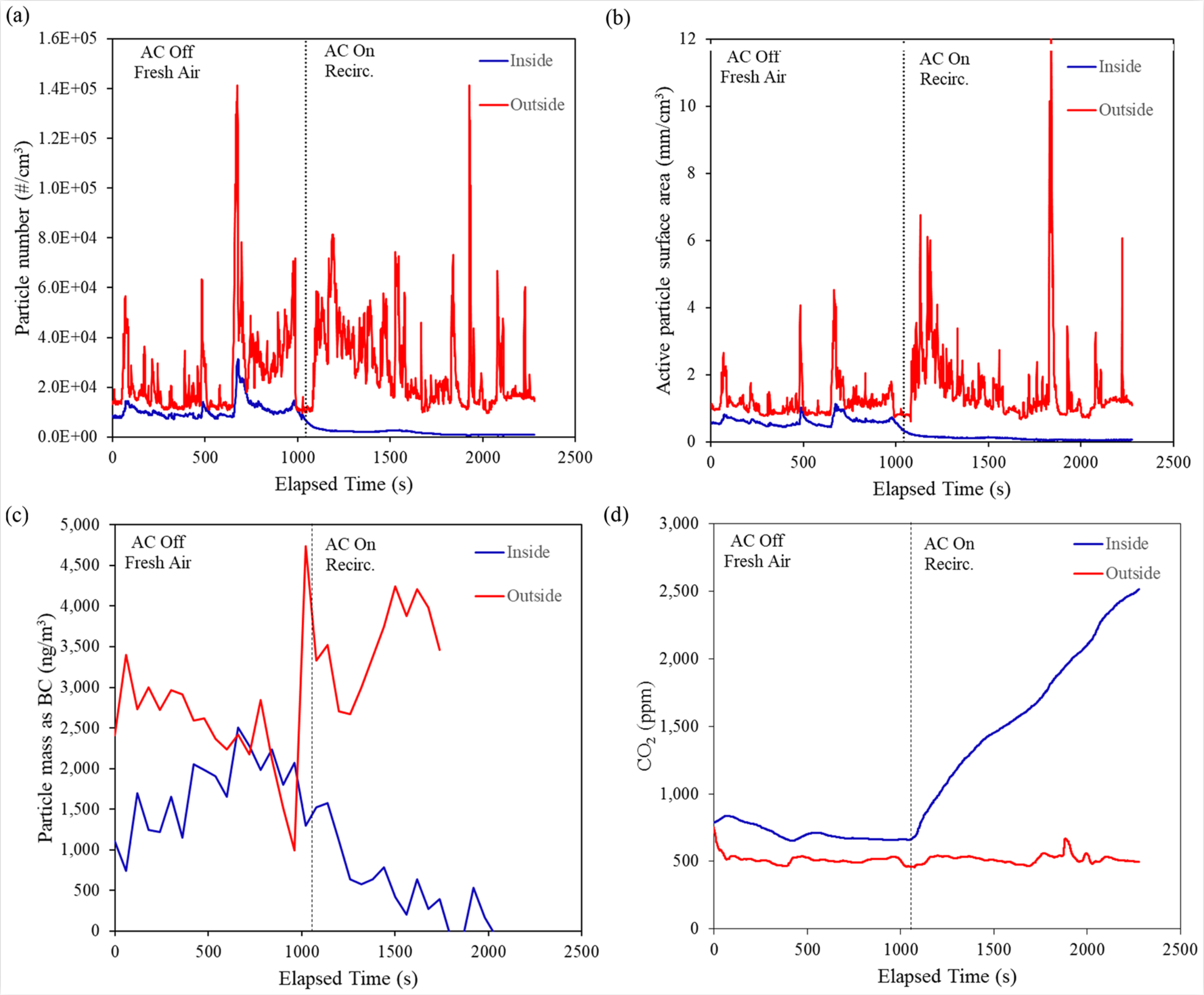
**FIGURE 3** Real-time particle concentrations during the dynamic test (a) PN concentrations, (b) active PS concentrations, (c) BC concentrations, and (d) $CO_2$ concentrations.



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Particle concentrations decreased rapidly while $CO_2$ concentration increased. PN and PS concentrations appeared to decrease faster than PM concentrations. We attribute this primarily to slow time resolution of microAeth which measured BC mass. Hudda et al. [21] characterized the factors (ventilation setting, vehicle age, speed, cabin volume, trip duration, and number of occupants) that lead to $CO_2$ accumulation in the vehicle cabin. They concluded under recirculation mode, a 2500 ppm threshold - the threshold consistently linked to detrimental cognitive effects - would not be exceeded for most one- or even two-occupant average for the duration of daily commutes (26 min in the USA). This contrasts to our finding (Figure 3d). In the current study, the threshold limit (2500 ppm) was reached in 20 min with two occupants. As low speed driving conditions are very common in urban areas, and emissions and infiltration are most significant, future studies need to pay attention to these conditions.

Real-time I/O ratio can lead to misinterpretation of the result. Assume a vehicle just left a tunnel where outside and therefore infiltrated inside cabin pollutant concentrations were much higher than ambient or typical on-road conditions. In-cabin pollutant concentrations will remain higher than outside for a while after leaving the tunnel environment due to finite AER. The current study proposes to use a time-integrated I/O ratio as CAQI to overcome such an issue. It is defined as

$$\mathrm{CAQI}_i = \frac{\int_0^t C_{i,\mathrm{cabin}}\,\mathrm{d}t}{\int_0^t C_{i,\mathrm{outside}}\,\mathrm{d}t} \qquad \text{Eq. (3)}$$

where *i* means specific pollutant. We propose all criteria pollutants (except lead), ammonia and VOCs to be measured for the standard testing in the future, while other specific

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**FIGURE 4** (a) CAQI as a function of elapsed time. (b) Residue as a function of elapsed time. Note the integration reset when the mode is switched from AC off/fresh air mode to AC on recirculation mode.

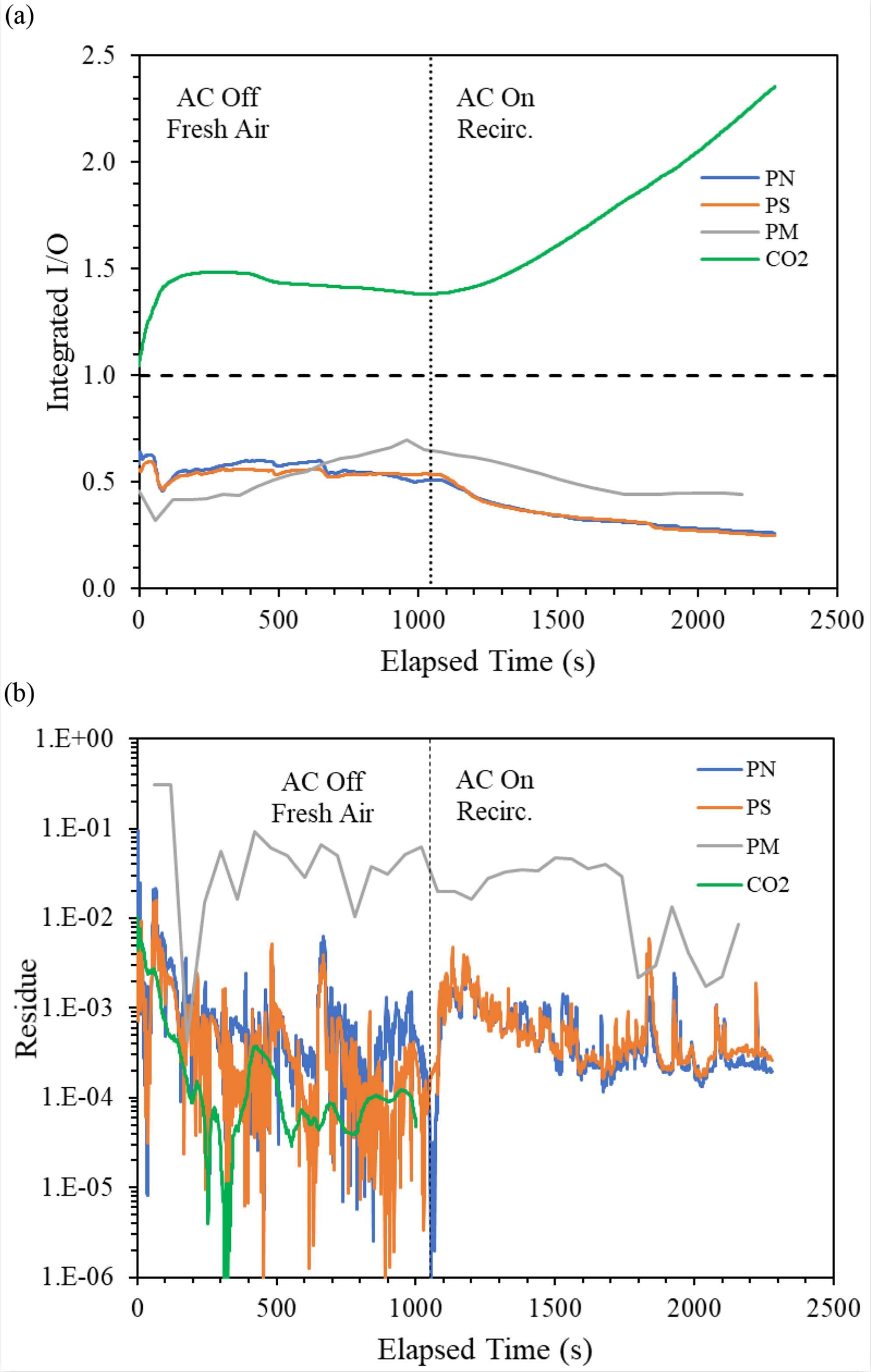

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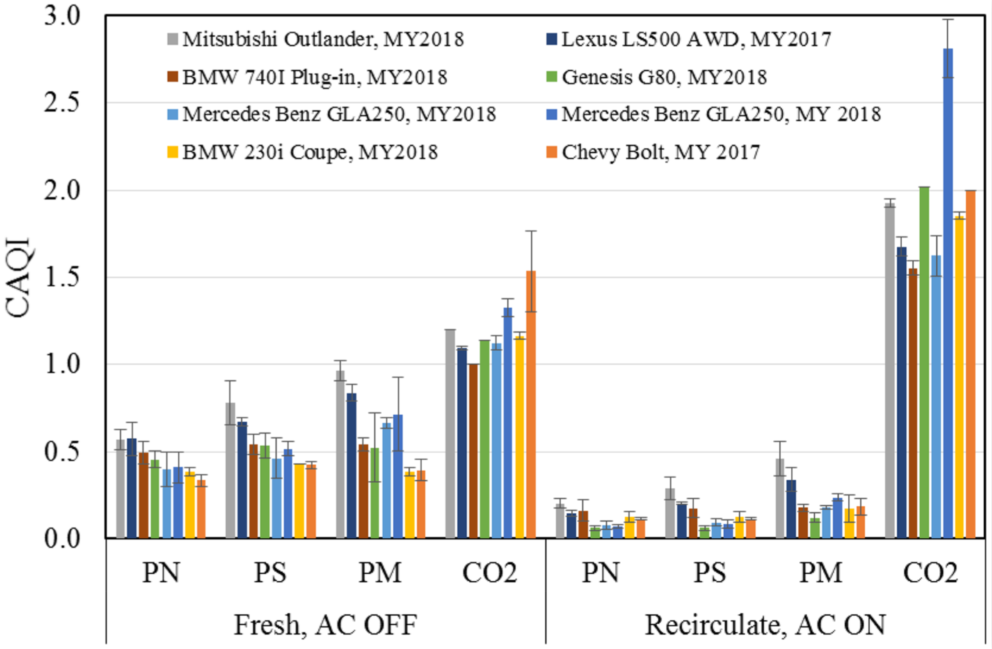
**FIGURE 5** CAQI of eight test vehicles for PM, PS, PN, and $CO_2$.



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pollutant from MSAT (mobile source air toxics) can be added. Suarez-Bertoa et al. [25] suggested the need to regulate ammonia emissions. $CAQI_{particles}$ is smaller than 1 as particles are removed in the cabin, while $CAQI_{CO2}$ is larger than 1 as passengers exhale $CO_2$. $CAQI_{particles}$ represents infiltration ratio while $CAQI_{CO2}$ represents stuffiness. It is now well understood how well the charcoal sprayed filter or adsorbing type filter perform for other gaseous pollutants. CAQI for other gases ($SO_x$, ozone, CO, NO, $NO_2$, and $NH_3$) are an important subject for future studies. It is also important to understand the behavior of VOCs in a vehicle cabin. Rudell et al. [26] reported reduced adverse health effects when both VOCs and diesel particles were removed, while filtration of diesel particles itself did not show reduced adverse health effects. Their study suggests reduction of VOCs and diesel particles using an adsorbing type filter along with a cabin filter can reduce adverse health effects of roadway pollutants to passengers.

CAQI is plotted as a function of time during the dynamic test in Figure 4 using the data in Figure 3. $CAQI_{CO2}$ increased initially during the first part of the test with fresh air and AC off and converged to the dynamic equilibrium value of 1.4 suggesting 700 ppm $CO_2$ concentration inside the cabin which is 40% higher than the outside concentration of 500 ppm.

**TABLE 1** Static test results.

| Test # | Fan speed | Recirc. | AC | AER($h^{-1}$) |
|---|---|---|---|---|
| 1 | 1 | Off | Off | 30 |
| 2 | 3 | Off | Off | 44 |
| 3 | 5 | Off | Off | 54 |
| 4 | 3 | On | On | 4 |

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Upon the change of ventilation setting to air recirculation, $CAQI_{CO2}$ showed steady increase and did not reach a converged value (or equilibrium) within ~20 min. Time integration has been reset upon the start of new ventilation mode or recirculation mode. $CAQI_{particles}$ by PN and PS converged to ~0.5 during the AC off and fresh air mode condition. $CAQI_{particles}$ by PM appeared to require more time to converge which is attributable to a much lower time resolution of the PM measurement instrument compared to PN and PS measurement instruments (1 min vs 1 s). Upon change of the ventilation condition to recirculation, $CAQI_{particles}$ showed steady decrease. By the end of the recirculation condition (~20 min after) $CAQI_{particles}$ reached to 0.25.

As outside pollutant concentrations cannot be controlled for the test, it is important to run the test until CAQI converges. Constraining a range of allowable on-road pollutant concentrations for the test can improve repeatability therefore resulting in less test time and cost for the future study. Residue is defined as a slope determined by the absolute difference of two consecutive data divided by the time step. Residue became smaller than $10^{-3}$ within 1000 s for both AC off/fresh air mode and AC on recirculation mode. As such, the 1000-second point was used as the critical time to determine CAQI for both gas and particles for this study.

Figure 5 shows $CAQI_{particles}$ by three different metrics, namely, PN, PS, and PM at two different ventilation conditions and $CAQI_{CO2}$. As discussed in the introduction, most of previous studies used PN I/O ratio as a sole metric to evaluate cabin air quality, while source and ambient emission standards are mass based. $CAQI_{particles}$ showed increasing trend at the same ventilation condition in the order of PN, PS, and PM. This result has important indication. For example, assume

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a study found $\text{CAQI}_{\text{particles}}$ of 0.4 by PN a 60% reduction in PN. However, that may mean much higher $\text{CAQI}_{\text{particles}}$ of 0.75 by regulatory metric of mass suggesting only 25% of reduction by mass. Figure 5 suggests that the choice of metric is important in assessing cabin air quality (and its index) for particles. We propose to use mass metric to be consistent with other source and ambient regulatory metrics.

$\text{CAQI}_{\text{particles}}$ showed a decrease in all metrics during the recirculation condition while $\text{CAQI}_{\text{CO2}}$ showed an increase during the recirculation condition compared to fresh air mode as expected. Recall, one of Mercedes-Benz GLA250 vehicles had two passengers while all other vehicles had a single passenger. $\text{CAQI}_{\text{CO2}}$ did not show any difference between one and two passengers during AC off/fresh air condition while $\text{CAQI}_{\text{CO2}}$ reported a substantially higher value with two passengers during the AC on recirculation condition. It appears none of the test vehicles adopted either passive or active recirculation air control technology such as the one suggested by Grady et al. [13] and Jung et al. [20]. Cabin air recirculation condition should be used only intermittently with discretion to prevent adverse health effects from increased cabin $CO_2$ concentrations. Figure 5 illustrates that CAQI varies from vehicle to vehicle, and not every vehicle is designed or optimized the same way to control cabin air quality. Coefficient of variations (COVs) ranged from 6 to 37% for $\text{CAQI}_{\text{PN}}$, from 0 to 31% for $\text{CAQI}_{\text{PS}}$, and from 5 to 44% for $\text{CAQI}_{\text{PM}}$. COV for $\text{CAQI}_{\text{CO2}}$ ranged least from 0 to 15%. The COVs obtained in this study show a promise that the test method can work with more improvement, considering the test vehicles were exposed to randomly changing on-road air pollutant concentrations. Future study should consider additional criteria such as defining range of pollutant concentrations allowed for the test, test duration, and number of repeats to reduce COV.

## Conclusion

People often suffer the highest exposure to air pollutants while riding in a car. Infiltration of outside air pollutants into the vehicle cabin poses a threat to the passengers' health. This study developed static and dynamic tests to evaluate and quantify vehicle cabin air quality in more repeatable, comparable, and reliable manners. The static test successfully characterized AERs at different ventilation conditions by measuring decreasing $CO_2$ concentrations after its release using a $CO_2$ canister. The dynamic test was conducted at low vehicle speed conditions considering dense air pollutant concentrations and low air exchange by vehicle's slow motion. $\text{CAQI}_{\text{particles}}$ defined as the ratio of integrated sum of pollutant concentrations inside and outside of cabin converged well within 1000 s during the dynamic test. $\text{CAQI}_{\text{CO2}}$ converged during AC off/fresh air mode, but it showed steady increase during AC on recirculation mode. CAQI evaluated with critical time of 1000 s showed promise for establishment of a repeatable test method to evaluate vehicle cabin air quality. We recommend to determine CAQI for CO, NO, $NO_2$, $SO_x$, $O_3$, $NH_3$, VOCs, and particulates. We recommend to use mass metric for particulates and to constrain a range of allowable on-road pollutant concentrations to improve repeatability of the test. Emissions Analytics plans to build a database of CAQI and disseminate to promote development of vehicles with better cabin air quality control systems.

## Contact Information

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# Appendix

## Standard Operating Procedure for Conducting Cabin Air Quality Tests

### Test 0. Instrument Calibration Test - On Road, Windows Open

1. Ensure both units are sampling inside the cabin, without any sample lines attached.
2. Name the test files for both units and try to start recording on both at the same time.
3. Complete 10 min of driving a short city driving route to gauge the level to which the two units compare.

### Test 1. Dynamic, (On-Road) Medium Fan, No AC

1. Close doors and windows.
2. Switch off air recirculation.
3. Set fan speed to medium.
4. Switch off AC.
5. Drive inbound on-road route.

### Ambient Acclimatization - On-Road or Static, Medium Fan, Windows Open, No AC

1. Following test, open windows/doors until $CO_2$ returns to normal ambient levels (around 400-500 ppm).

### Test 2. Dynamic, (On-Road) Medium Fan, with AC

1. Close doors and windows.
2. Switch on air recirculation.
3. Set fan speed to medium.
4. Switch on AC at manual setting, 50% of maximum (around 19 degrees Celsius).
5. Drive outbound on-road route.

### Test 3. Static, Low Fan, No Recirculation

1. Close doors and windows.
2. Switch off air recirculation.
3. Set fan speed to low.
4. Switch off AC.
5. Deploy $CO_2$ canister.
6. Wait for 4 min (use a stopwatch).
7. Open doors for 2 min to ventilate cabin.

### Test 4. Static, Medium Fan, No Recirculation

1. Close doors and windows.
2. Switch off air recirculation.
3. Set fan speed to medium.
4. Switch off AC.

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5. Deploy $CO_2$ canister.
6. Wait for 4 min (use a stopwatch).
7. Open doors for 2 min to ventilate cabin.

### Test 5. Static, High Fan, No Recirculation

1. Switch off air recirculation.
2. Set fan speed to high.
3. Switch off AC.
4. Deploy $CO_2$ canister.
5. Close doors and windows.
6. Wait for 4 min (use a stopwatch).
7. Open doors for 2 min to ventilate cabin.

### Test 6. Static, Medium Fan, with Recirculation and AC

1. Turn engine on.
2. Switch on air recirculation.
3. Set fan speed to medium.
4. Switch on AC at manual setting, 50% of maximum (around 19 degrees Celsius).
5. Deploy $CO_2$ canister.
6. Close doors and windows.
7. Wait for 5 min (use a stopwatch).

### Completion

1. Stop recording.
2. Download data from analyzers.
3. Upload data to RDE database and Dropbox.
4. Input markers onto PIMS Analysis on RDE.
5. Derig, if testing is complete for the day, you can power down the units to remove them. Remember to connect them back up to the batteries when in the office ready for the next day.

The test is now complete.

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