Behavior of particles and gases in vehicle cabin

Micro-environment that can affect our health

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Agenda

1. Background
2. Behavior of particles in vehicle cabin
3. Behavior of gaseous pollutants in vehicle cabin

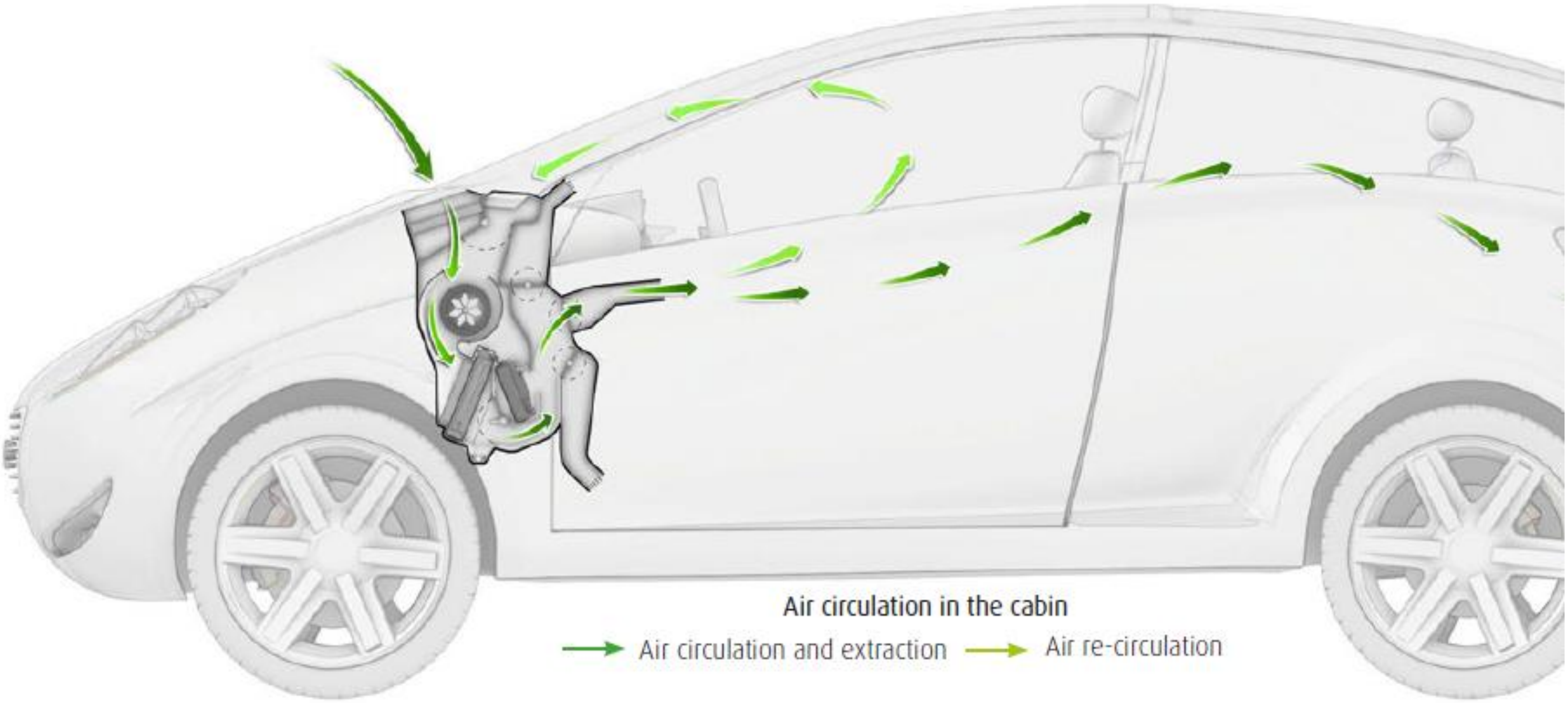
Background

- The in-cabin microenvironment was estimated to contribute 10–50% of people's daily exposure to vehicular emitted UFPs (Zhu et al. 2007)
  - Probably the same for other gaseous pollutants and PM2.5.

- Cleaner vehicle cabin air quality.

  → Less exposure to mobile source air toxics (MSATs) and criteria pollutants.

Cabin air flow and the HVAC unit



From Valeoscope technical handbook

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Define Cabin Air Quality Index (CAQI)

- $\boldsymbol{CAQI_{pollutant} = \frac{\int_0^t C_{pollutant\_inside}\, dt}{\int_0^t C_{pollutant\_outside}\, dt}}$

- $\boldsymbol{CAQI_{CO_2} > 1}$ Stuffiness Ex) 1000ppm/400ppm=2.5

- $\boldsymbol{CAQI_{particle} < 1}$ Infiltration ratio

Standard Vehicle Cabin Air Quality Testing Method (SAE Int. J. Commer. Veh. 12 (2))

- There are two mode of testing: Static and Dynamic
- Static test characterizes auto-manufacturer’s original HVAC design
- Dynamic test characterizes vehicle’s ability to maintain clean cabin air quality on-road real-world condition.
- It enables inter-comparison among different vehicles and researchers

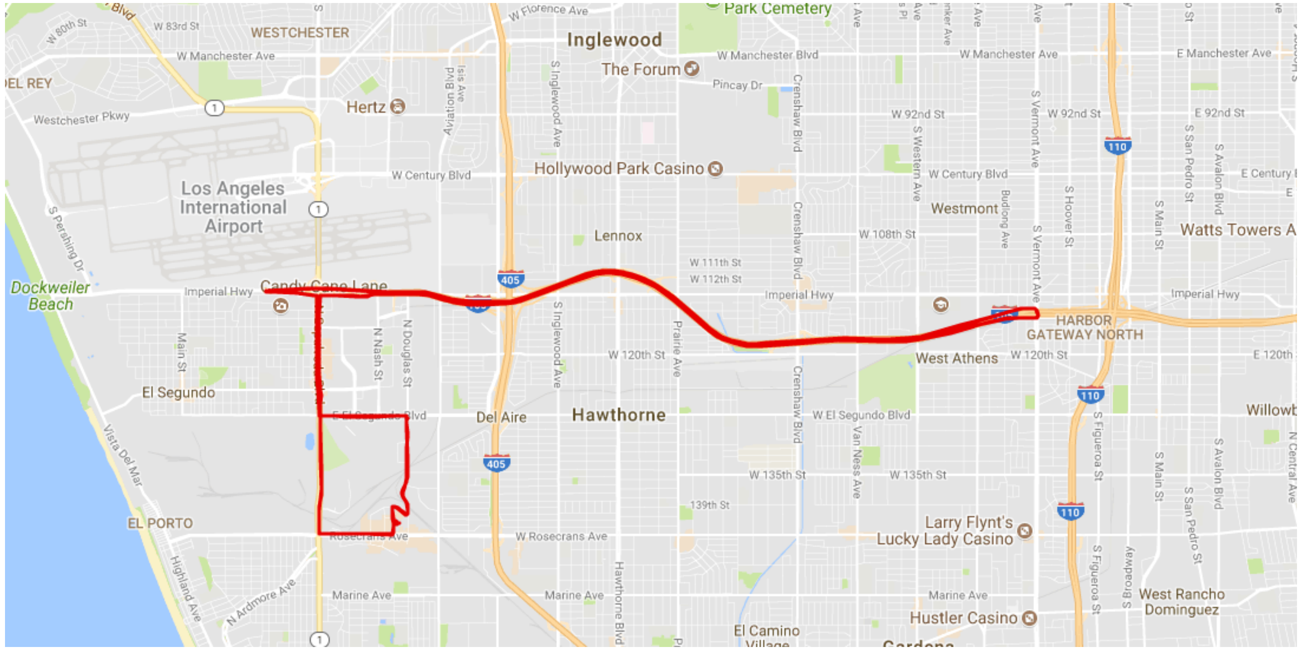
Static test (test vehicle at rest in a workshop)

1. Set data marker
2. Open doors for two minutes to ventilate cabin
3. Close doors and windows
4. Air recirculation on or off
5. Set fan speed
6. Switch on AC at manual setting, 50% of maximum fan speed
7. Deploy CO_2 canister
8. Wait for five minutes
9. Set data marker

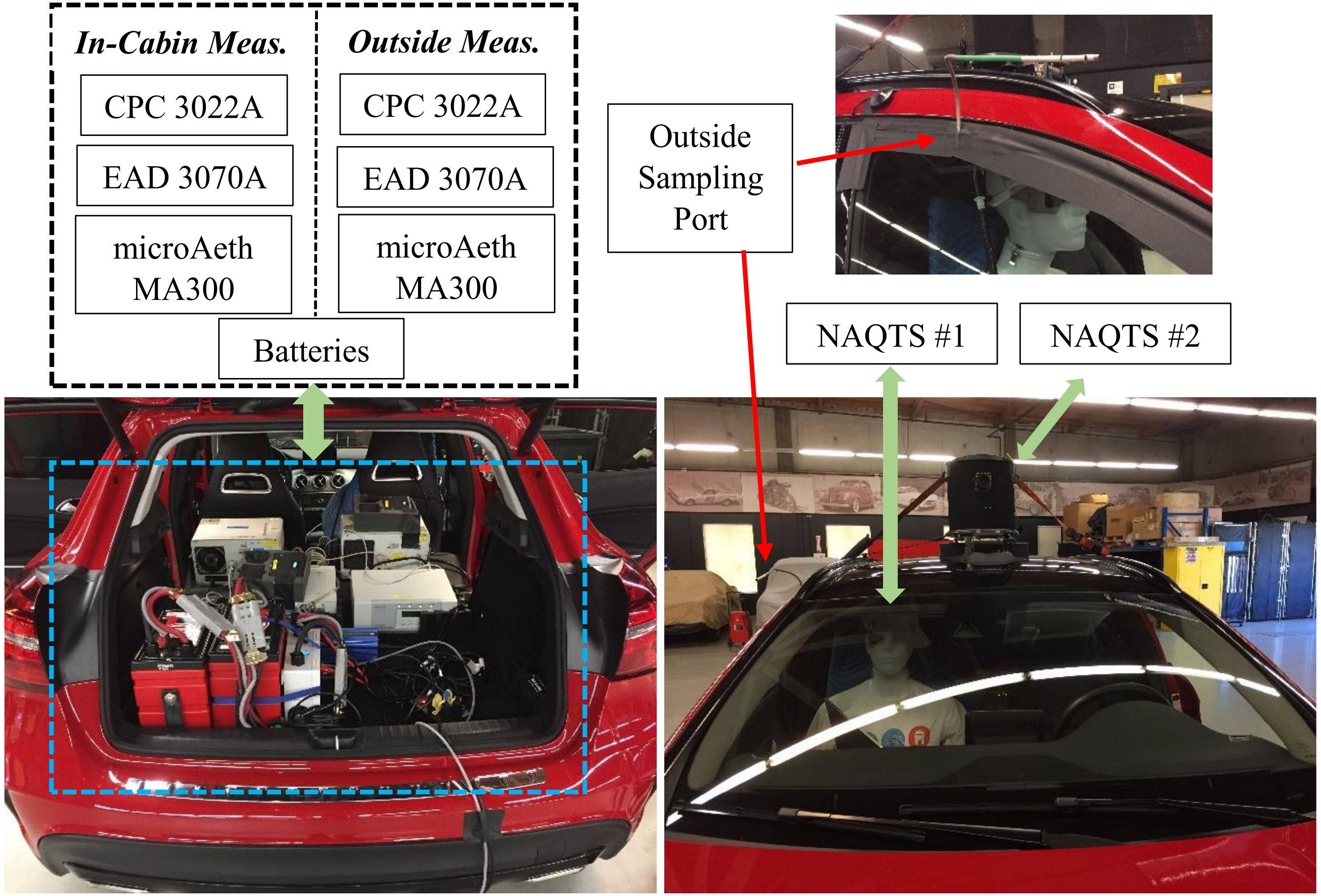
Dynamic test

- 30 min drive of urban polluted route
- Low speed range (i.e <40 mph for 90% of time)
- Recirculation ON/OFF
- Two passengers, AC ON, fan speed at mid speed, and chest vent mode.
- Integrated IO ratio over the driving route.

Driving route



Experimental setup



PN: CPC, NAQTS
PS: EAD
BC: µAeth
Gases: NAQTS

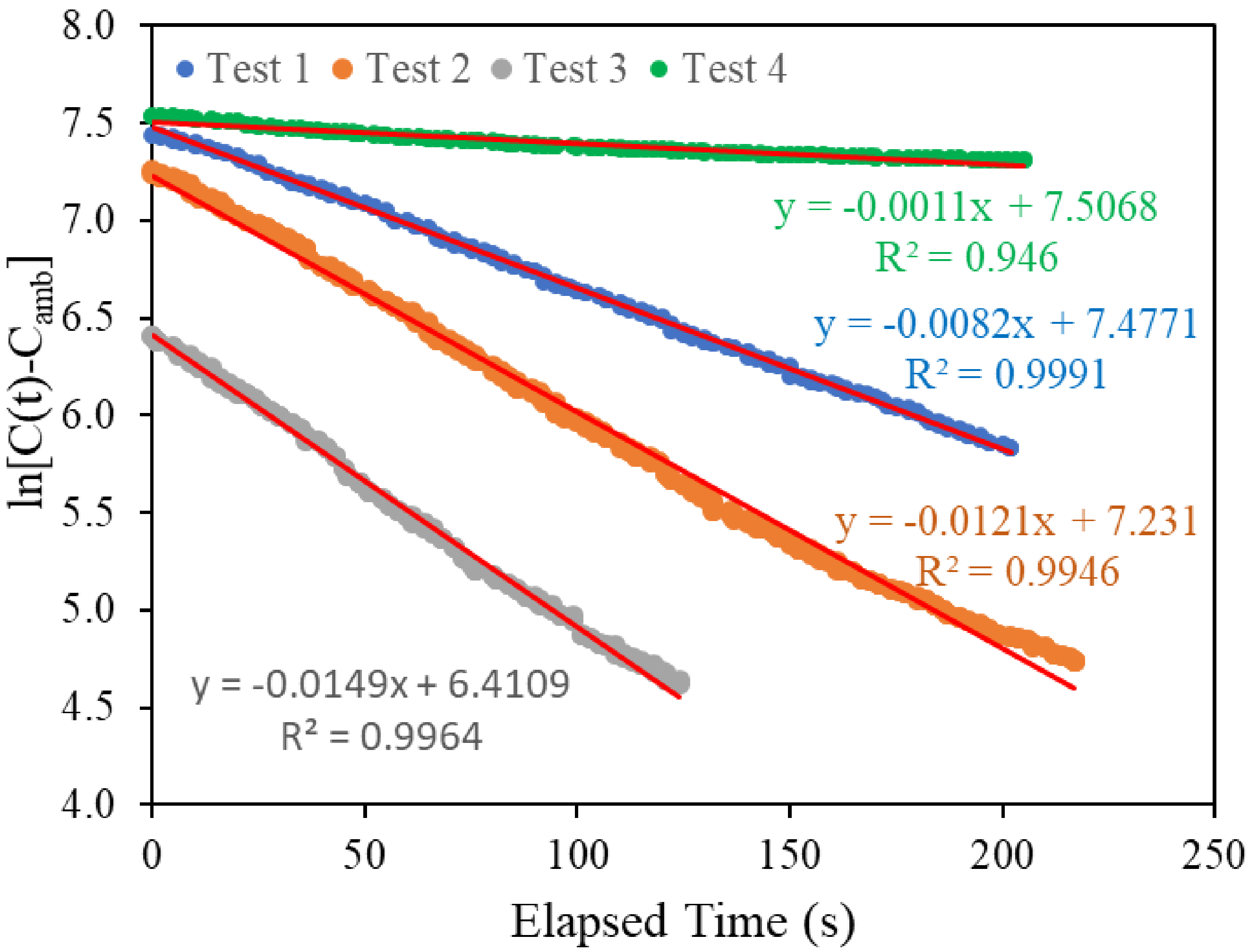
Experimental setup

Pairs of instruments

- TSI CPC 3022 (d50=7nm) => d^0
- TSI Electrical Aerosol Detector (d50=10nm) =>$d^{1.13}$
- MicroAeth MA300=>d^3 or BC mass
- NAQTS (CO_2, and particle count)

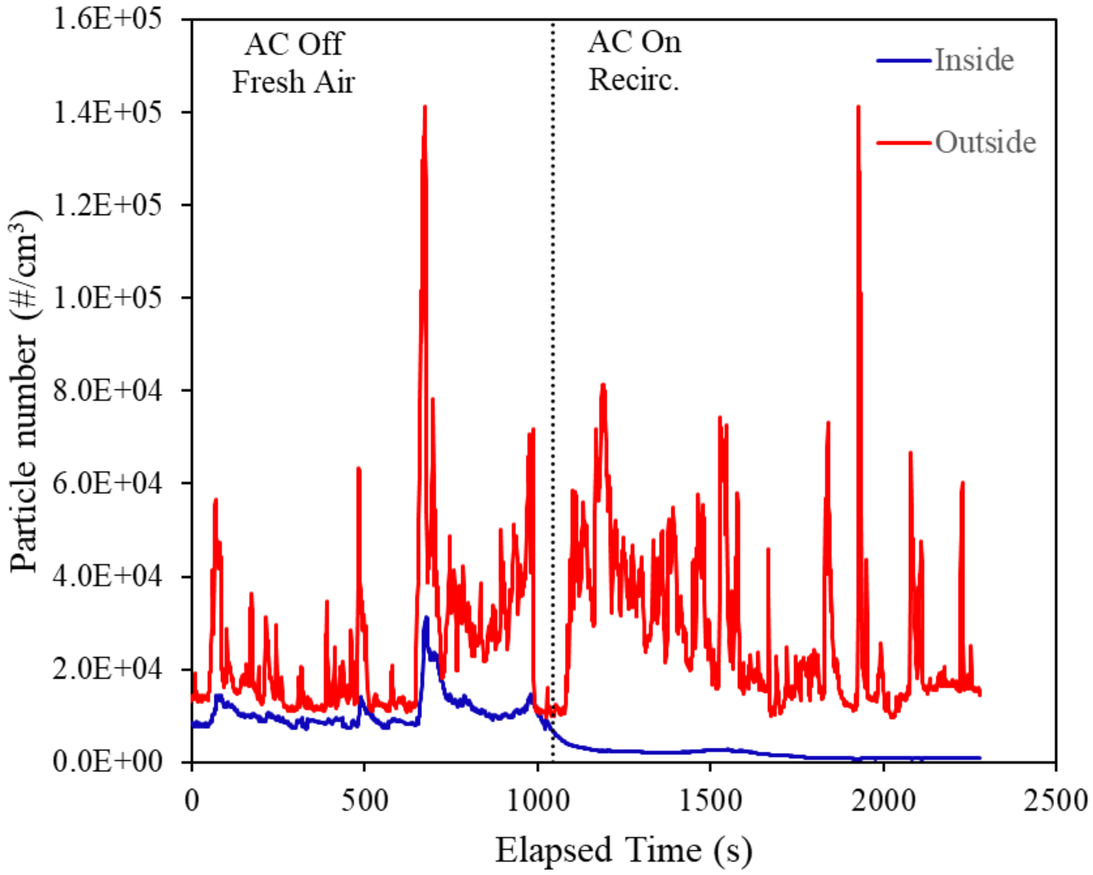
Static test

Test #	Fan Speed	Recir.	AC	AER(h^{-1})
1	1	Off	Off	30
2	3	Off	Off	44
3	5	Off	Off	54
4	3	On	On	4

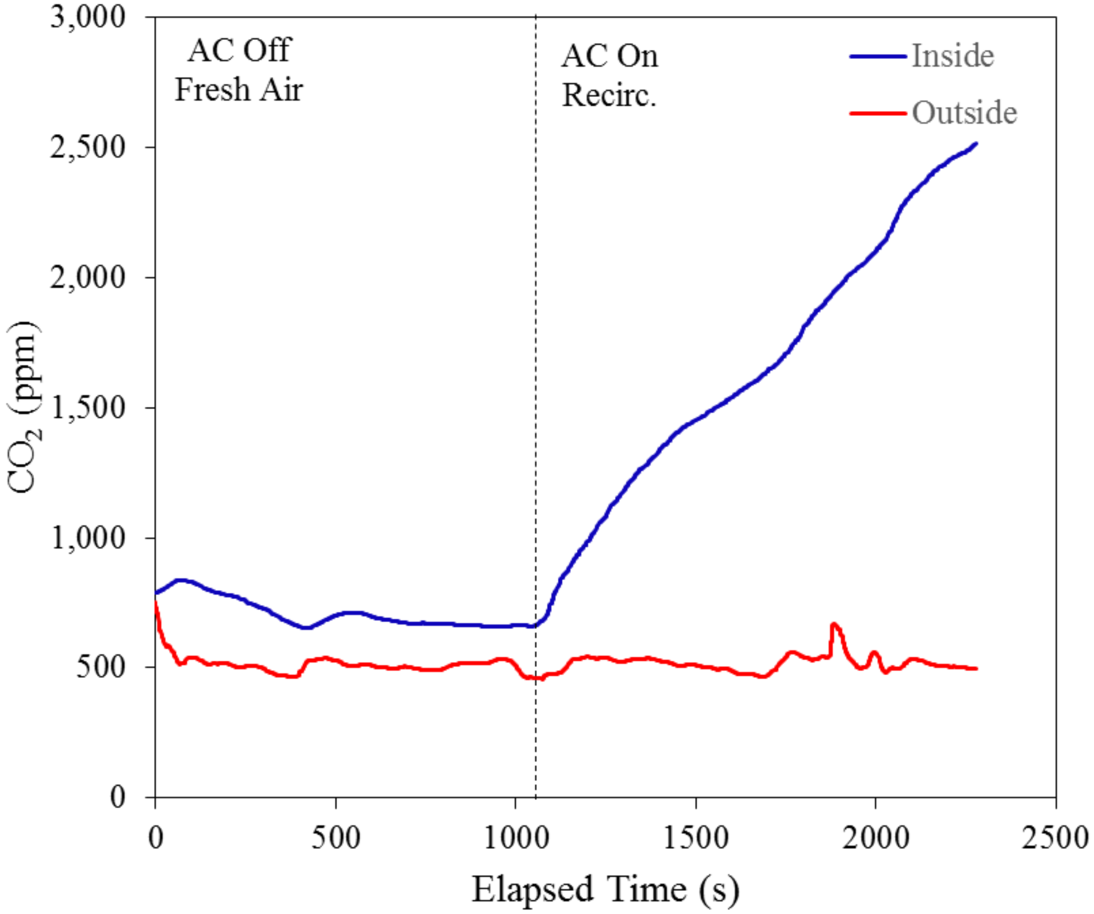


Dynamic test

Particle number

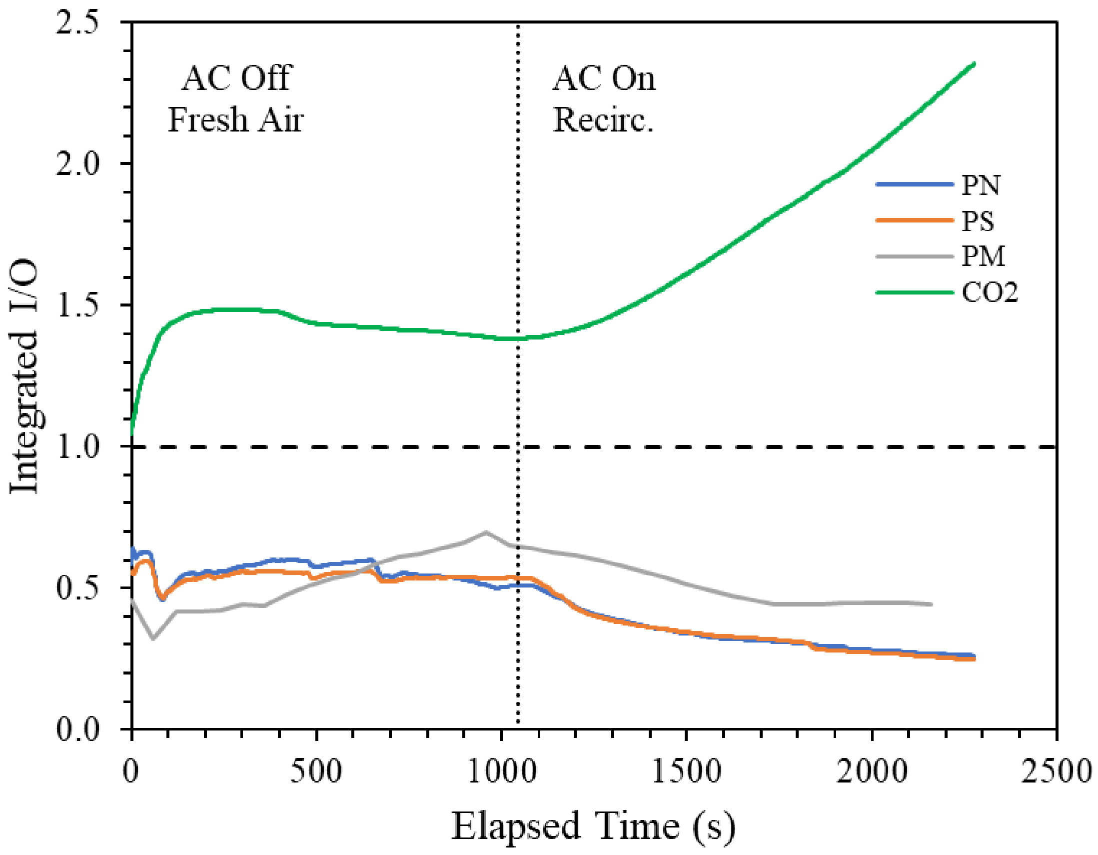


CO_2

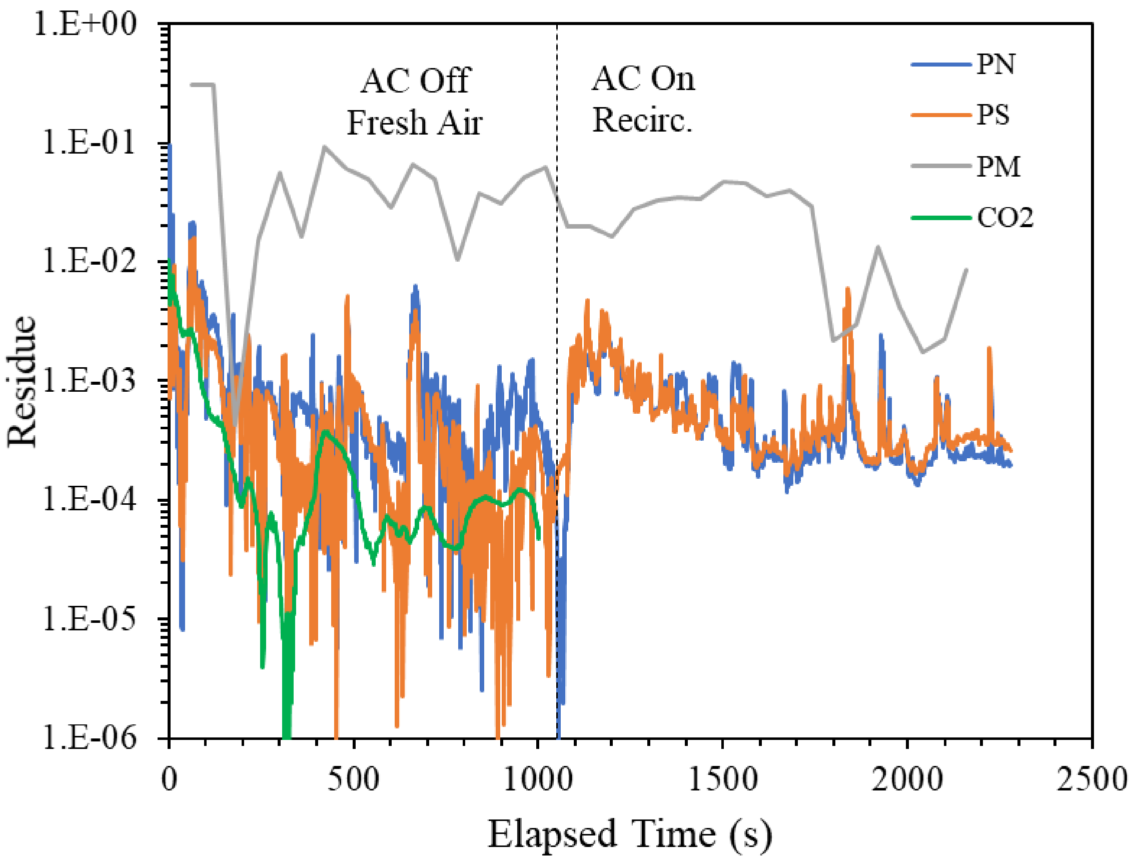


Cabin air quality index (CAQI)

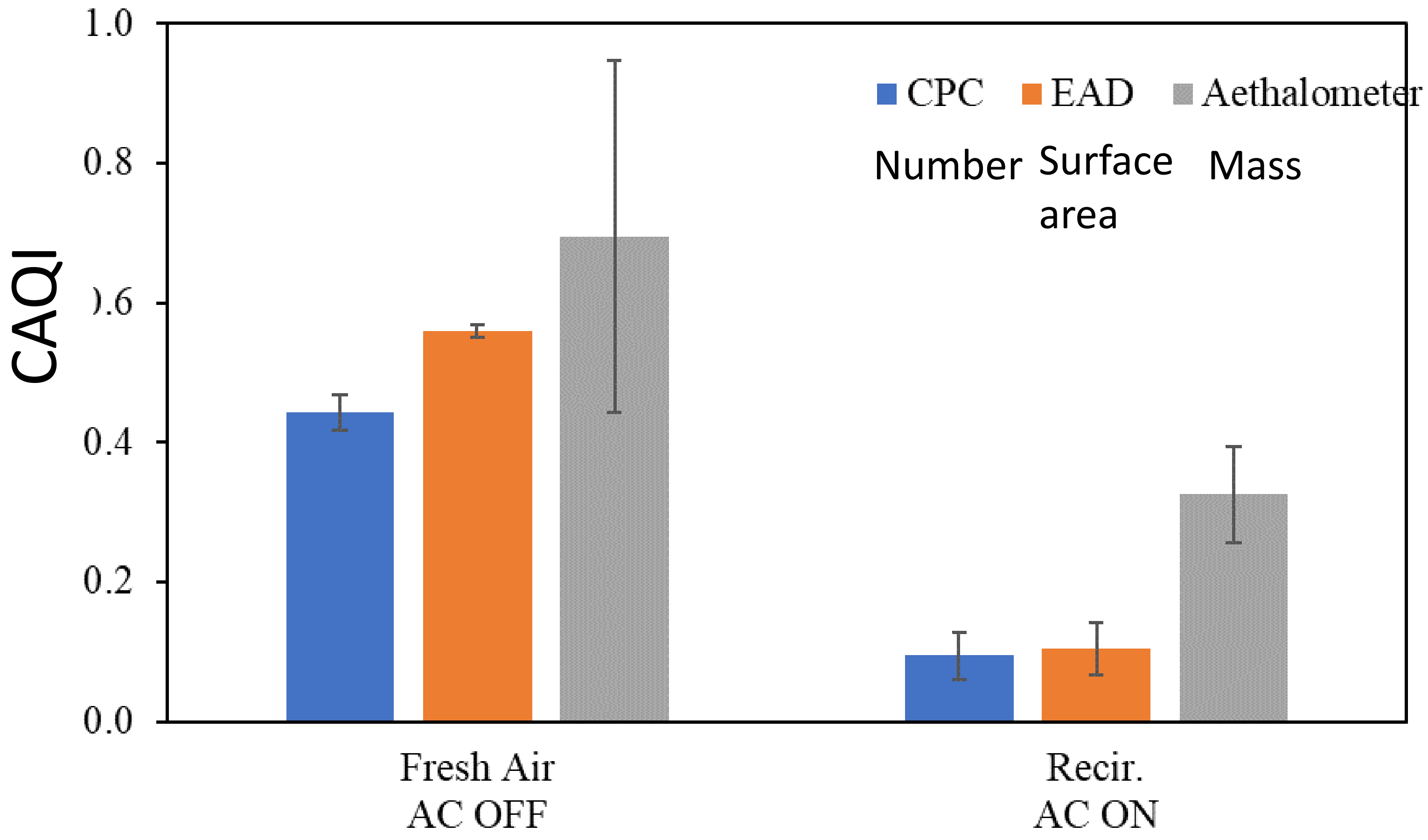
CAQI



Residue



The effect of particle metric on CAQI



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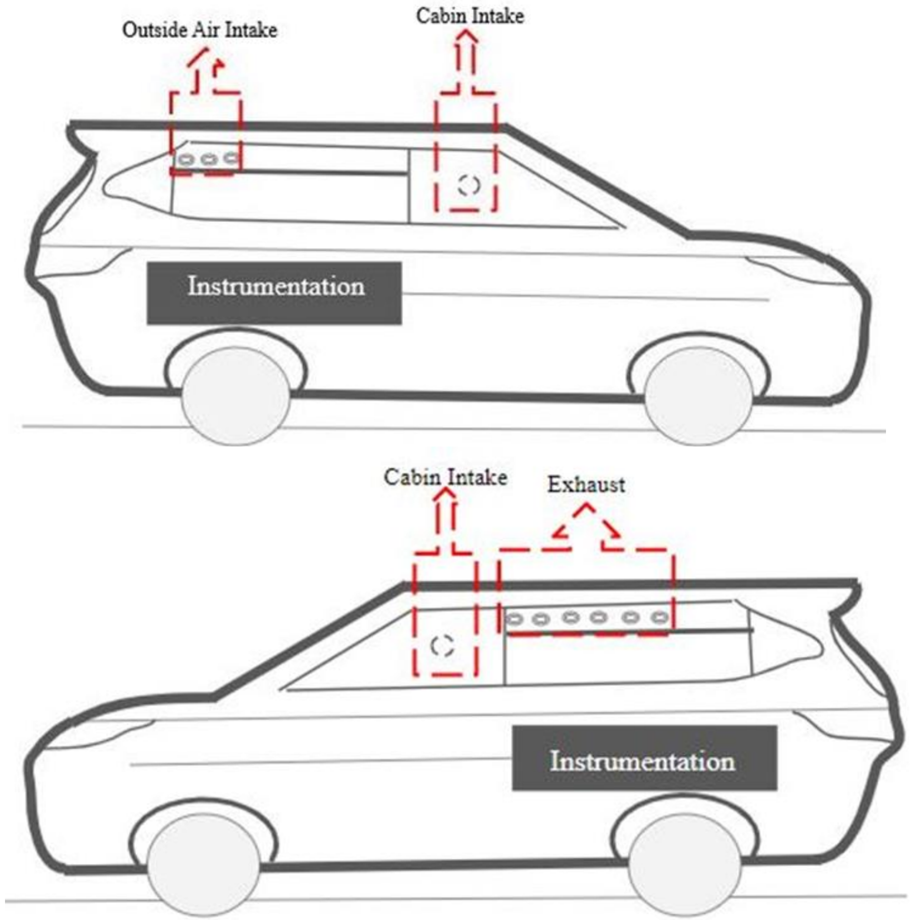


A 2016 Toyota Highlander with a 7 seat capacity

Horiba instruments	Gases
APMA-370	CO
APNA-370	NO, NO_2, NO_x
APOA-370	O_3

Instrument/equipment	Brand/model
Data logger	dataTaker, model dt80
6 V lead acid batteries	US Battery, model 145
Inverter	Chicago Electric Power Systems, 2000 W AC/DC

Test types

1. Static test

Vehicle at rest, engine off, vehicle power off, ventilation fan off, in a background location.

2. Dynamic test

Vehicle driven at city driving condition at the speed less than 40 mph. Ventilation fan on.

Kinetic model

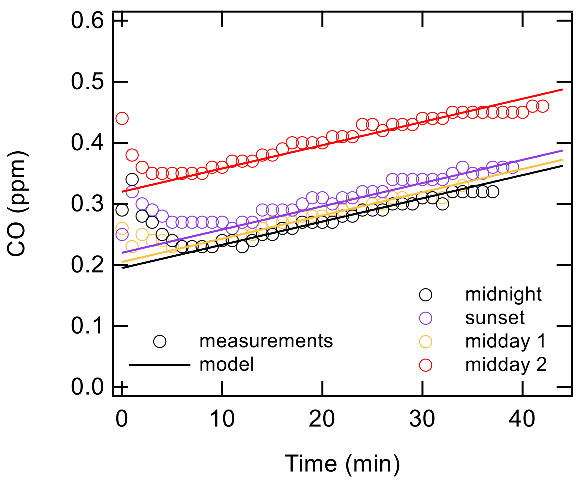
- A box model with 20 reaction equations/deposition rates to vehicle surfaces
- Although simplified, major reactions for HO_x and NO_x chemistry, photolysis of O_3, H_2O_2, and NO_2, O_3 reactions with VOCs and skin oxidation products, and surface deposition of O_3 and NO_2 were included.
- Passenger's breathing rate, volume of vehicle, air exchange rate due to instruments consuming cabin air, endogenous emissions of CO, NO, and isoprene were assumed.
- Isoprene was included in the model as it is a major VOC emitted from breath and contains two double bonds making it reactive with ozone.
- Ozone deposition velocity and skin area of the passenger were taken into account.

Kinetic model

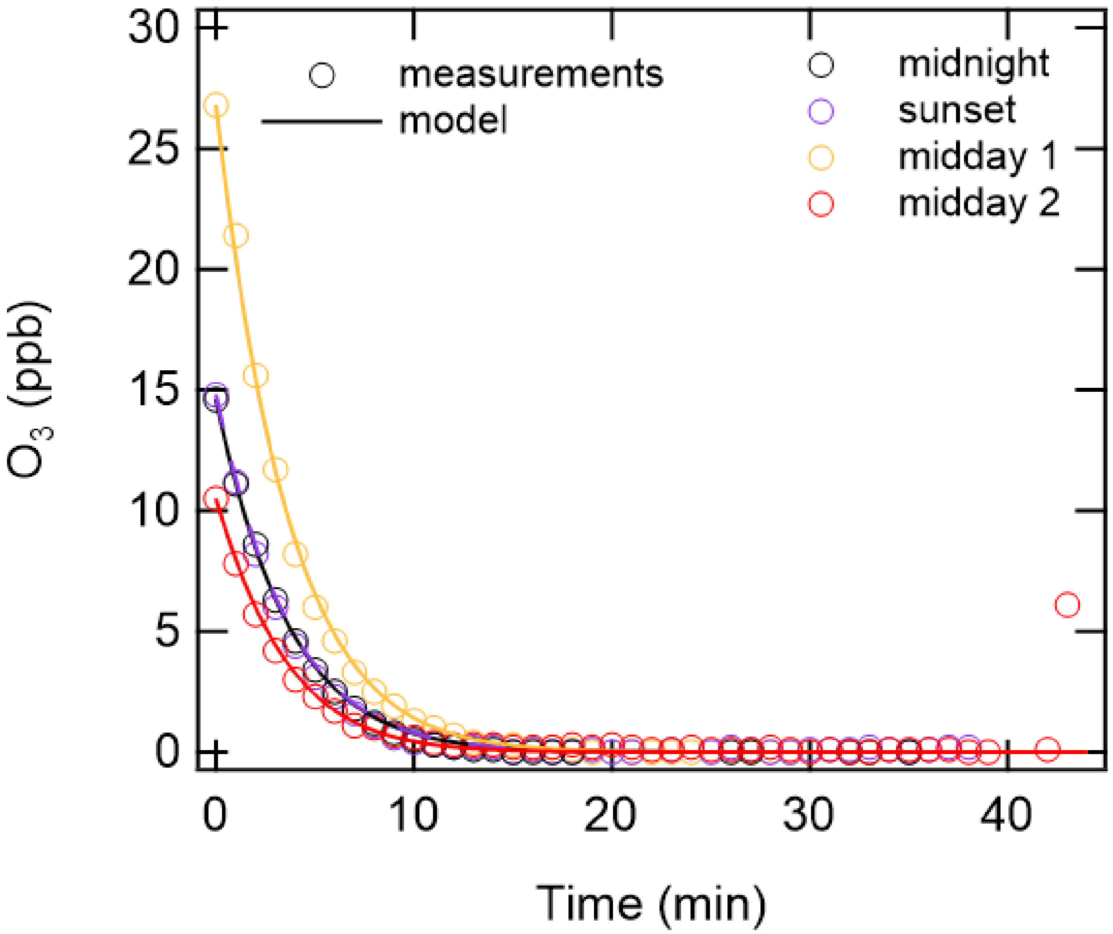
Reaction
$O_3 + hv \rightarrow O + O_2$
$O + O_2$ (+ M) $\rightarrow O_3$ (+ M)
$NO + O_3 \rightarrow NO_2 + O_2$
$NO_2 + hv \rightarrow NO + O$
$O_3 + NO_2 \rightarrow NO_3 + O_2$
$NO_2 + NO_3$ (+ M) $\rightarrow N_2O_5$ (+ M)
N_2O_5 (+ M) $\rightarrow NO_2 + NO_3$ (+ M)
$N_2O_5 + H_2O \rightarrow 2HNO_3$ (on surfaces)
O_3 + 6-MHO $\rightarrow$ Products

O_3 + Isoprene $\rightarrow$ Products
O_3 reaction with gas-phase VOCs or deposition to car surfaces
NO_2 deposition to car surfaces with a certain yield of NO
$CO + OH \rightarrow CO_2 + H$
$H + O_2 \rightarrow HO_2$
$HO_2 + NO \rightarrow NO_2 + OH$
$OH + NO_2 \rightarrow HNO_3$
$HO_2 + HO_2 \rightarrow H_2O_2 + O_2$
$H_2O_2 + hv \rightarrow OH + OH$
$H_2O_2 + OH \rightarrow HO_2 + H_2O$

Static test

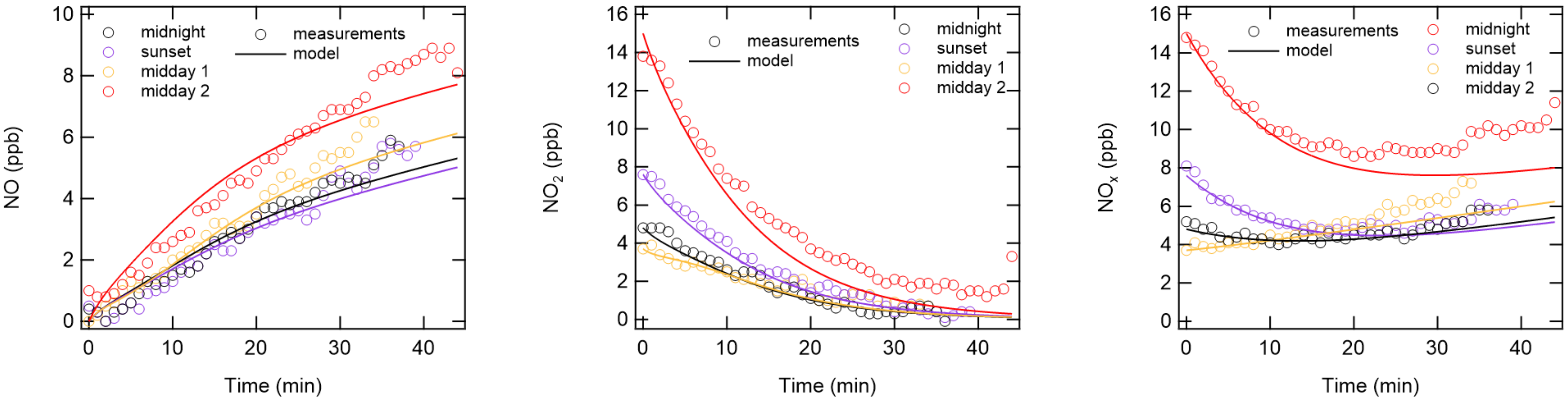


CO (ppm)
0.6
0.5
0.4
0.3
0.2
0.1
0.0
0
10
20
30
40
Time (min)
measurements
model
midnight
sunset
midday 1
midday 2



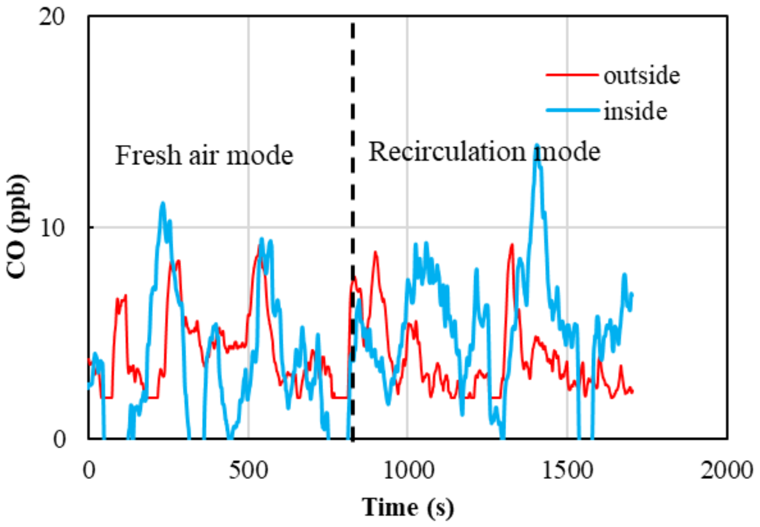
O_3 (ppb)
30
25
20
15
10
5
0
0
10
20
30
40
Time (min)
measurements
model
midnight
sunset
midday 1
midday 2

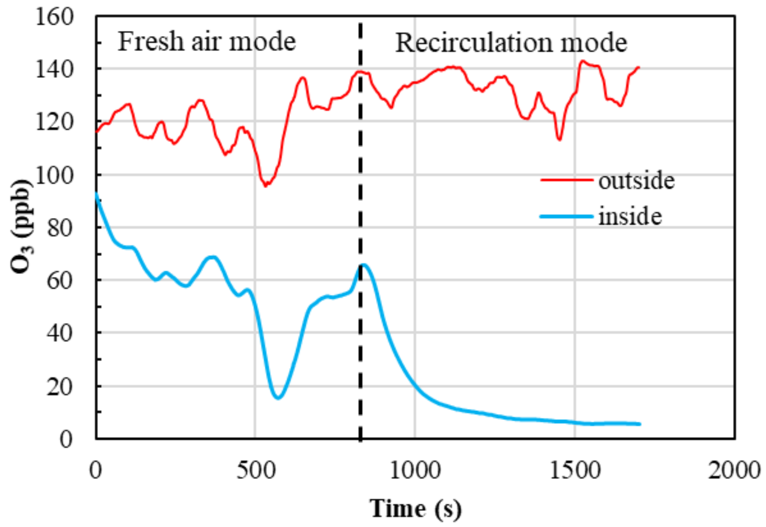
Static test

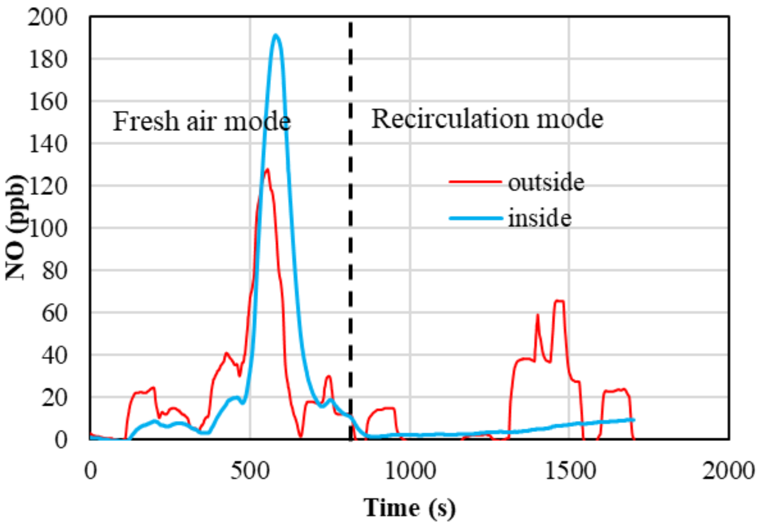


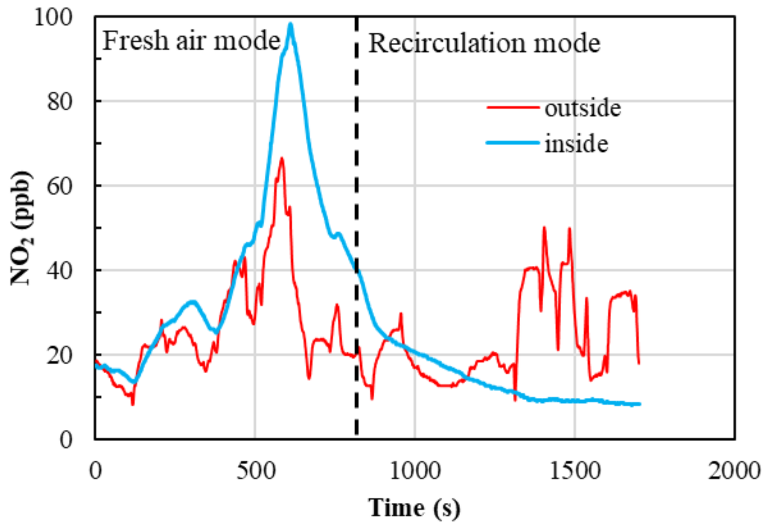
midnight
sunset
midday 1
midday 2
measurements
model
NO (ppb)
Time (min)
measurements
model
midnight
sunset
midday 1
midday 2
NO2 (ppb)
Time (min)
measurements
model
midnight
sunset
midday 1
midday 2
NOx (ppb)
Time (min)

Dynamic test



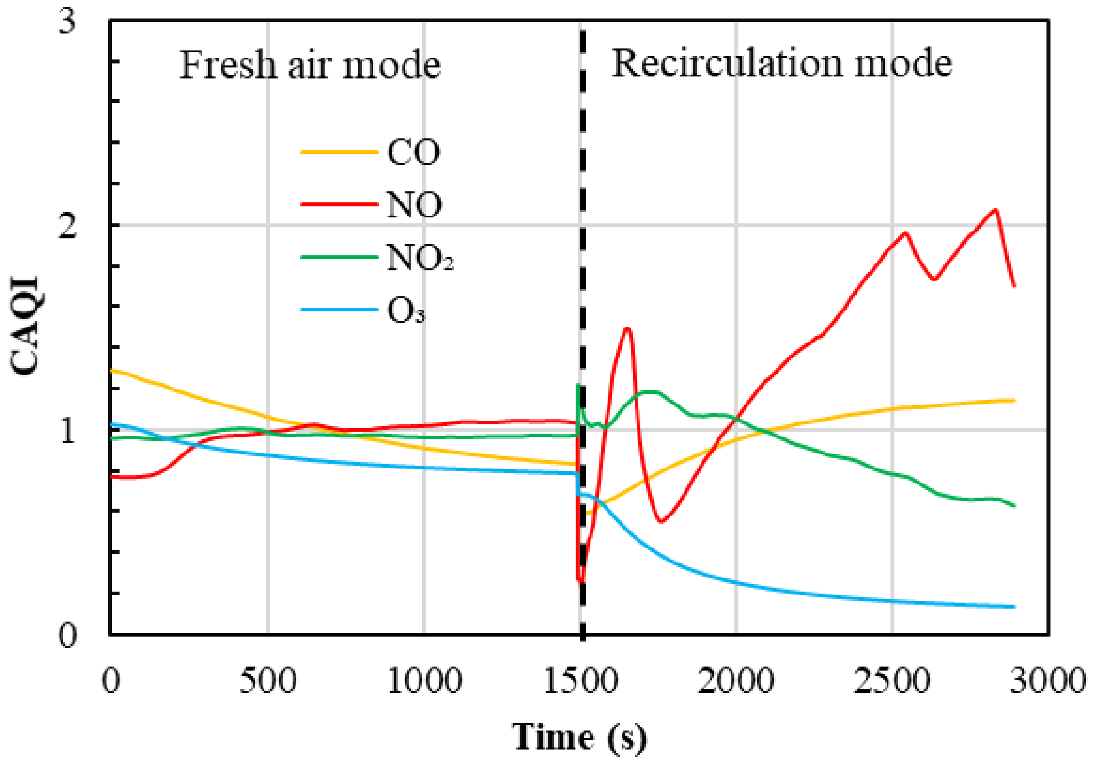


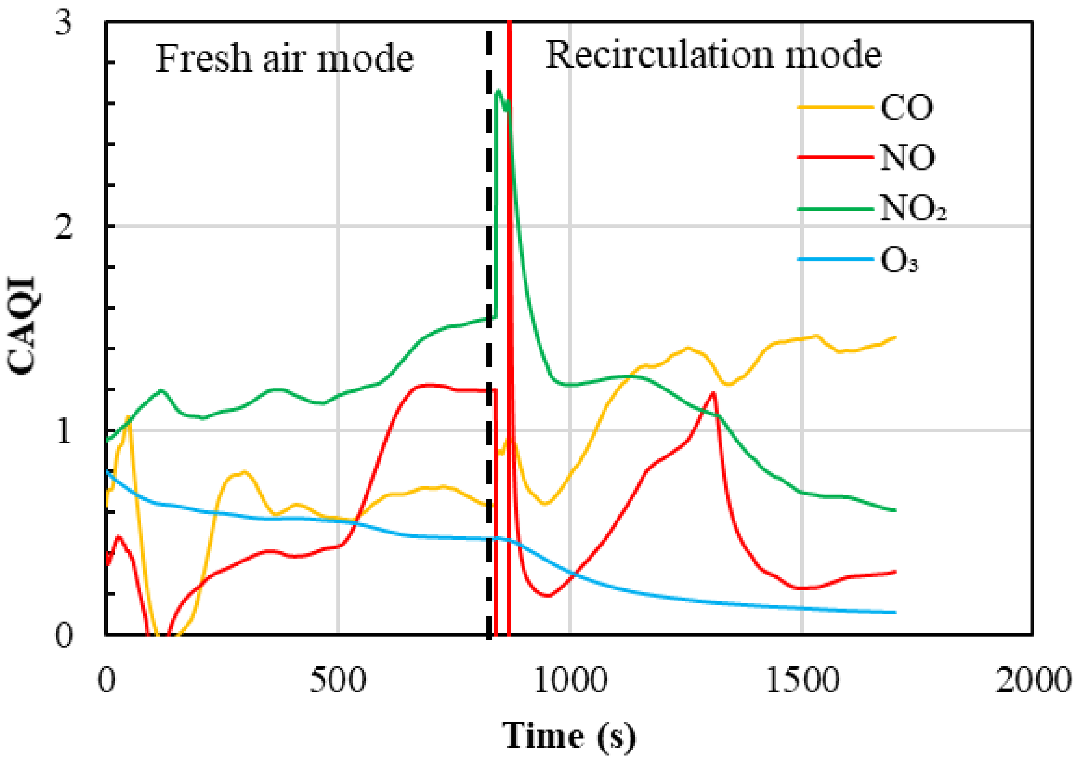




Cabin Air Quality Index,

$$\mathrm{CAQI}_i = \frac{\int_0^t C_{i,cabin}\ dt}{\int_0^t C_{i,outside}\ dt}$$





Conclusion / Take home message

- Vehicle cabin air should be controlled to protect passengers' health
  - Current control method is a baby step.
- Better control devices should be developed and adopted for particulate and gaseous pollutants.

- Industry needs motivation to do the above.
  - Pressure from customers
  - Advanced research results from academia
    - Faster adoption of new technologies

If interested, join the committees.

- SAE Interior Exhaust Gas Committee
- SAE VOC Committee
- UNECE, Vehicle Indoor Air Quality Committee
- CEN WS/103 Real drive test method for collecting vehicle in-cabin pollutant data