Behavior of carbon monoxide, nitrogen oxides, and ozone in vehicle cabin with a passenger

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Background

- Previous studies focused on passengers' exposure to pollutants under various types of vehicles at different locations and times.
- Previous studies focused on determining and characterizing cabin air quality for fine particles (PM2.5).
- There are other previous studies which focused on air exchange rates.
- There is no study which characterized unique behavior of criterial pollutants in vehicle cabin with a passenger.

Reference for the testing method

INTERNATIONAL

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

Liem Pham, *University of California, Riverside, USA*
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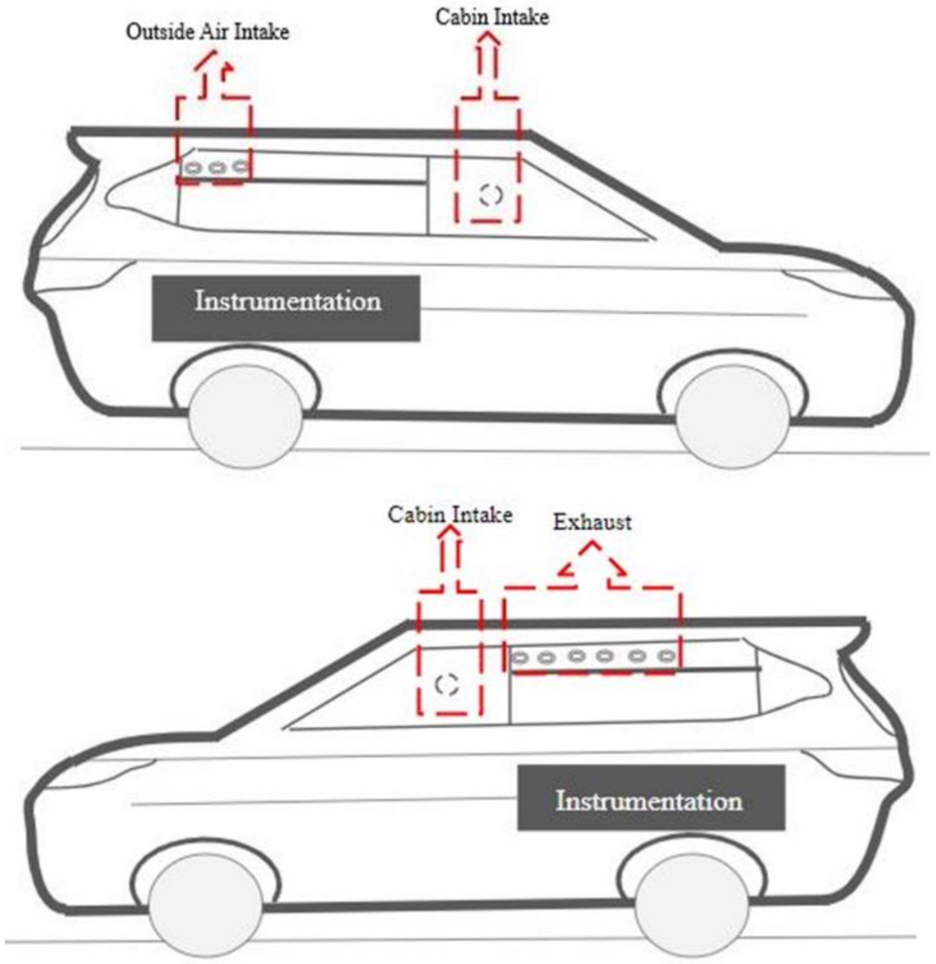
Kent Johnson and Heejung Jung, *University of California, Riverside, USA*

Experimental setup



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. Pseudo-dynamic test

   Vehicle at rest, engine on, vehicle power on, ventilation fan on, in close proximity to a major highway

3. 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 or 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

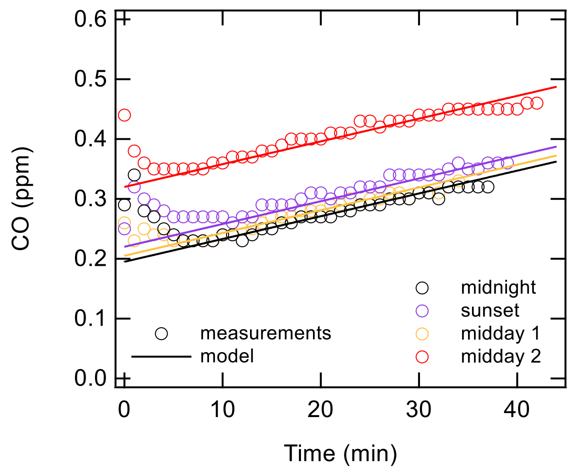
20 Reaction equations

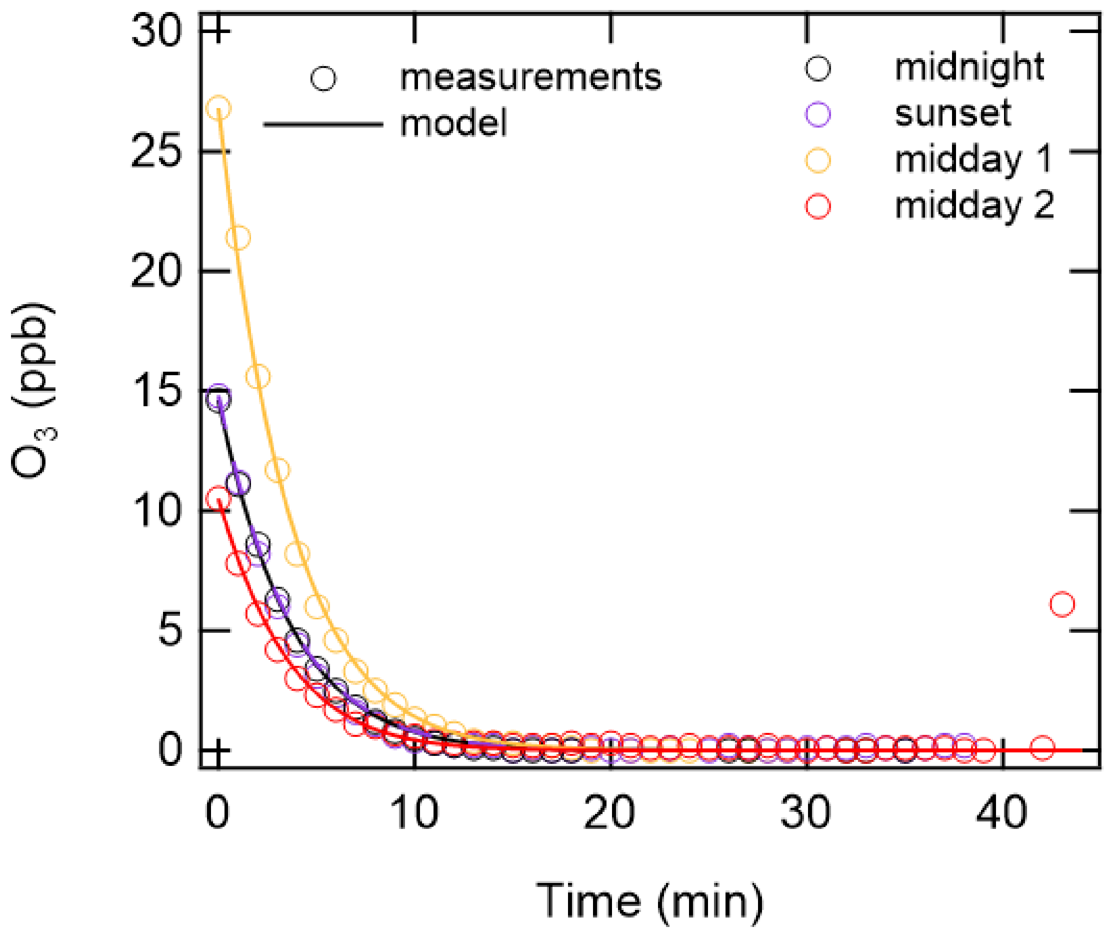
Reaction
$O_3 + h\nu \rightarrow O + O_2$
$O + O_2\ (+ M) \rightarrow O_3\ (+ M)$
$NO + O_3 \rightarrow NO_2 + O_2$
$NO_2 + h\nu \rightarrow NO + O$
$O_3 + NO_2 \rightarrow NO_3 + O_2$
$NO_2 + NO_3\ (+ M) \rightarrow N_2O_5\ (+ M)$
$N_2O_5\ (+ M) \rightarrow NO_2 + NO_3\ (+ M)$
$N_2O_5 + H_2O \rightarrow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

O_3 + Geranyl acetone $\rightarrow$ 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
$CO + OH \rightarrow CO_2 + H$
$H + O_2 \rightarrow HO_2$
$HO_2 + NO \rightarrow NO_2 + OH$
$OH + NO_2 \rightarrow HNO_3$
$HO_2 + HO_2 \rightarrow H_2O_2 + O_2$
$H_2O_2 + h\nu \rightarrow OH + OH$
$H_2O_2 + OH \rightarrow HO_2 + H_2O$

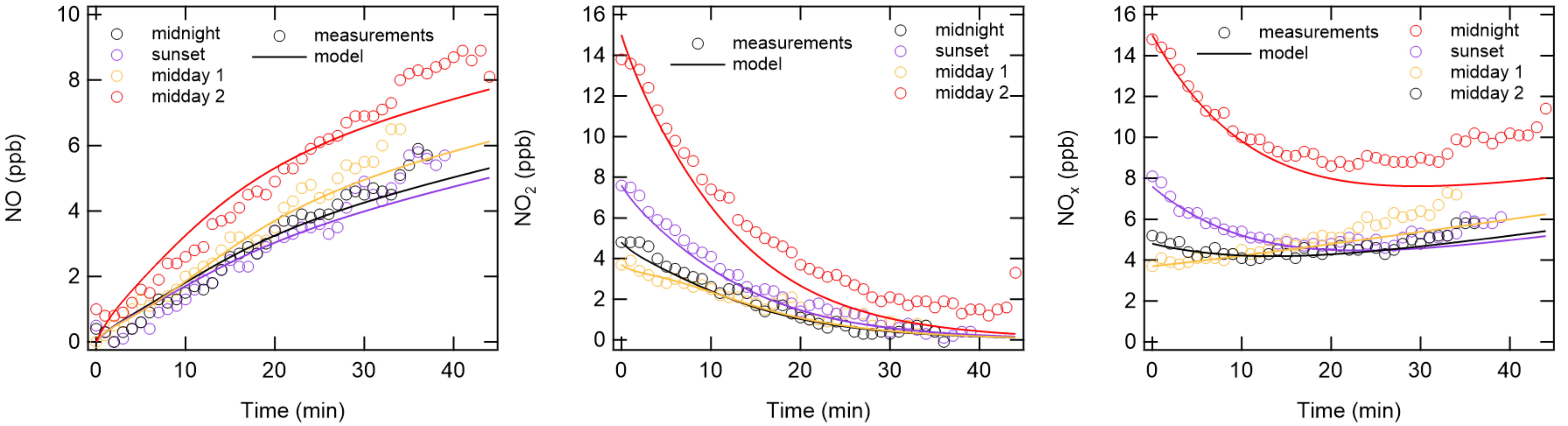
Results

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

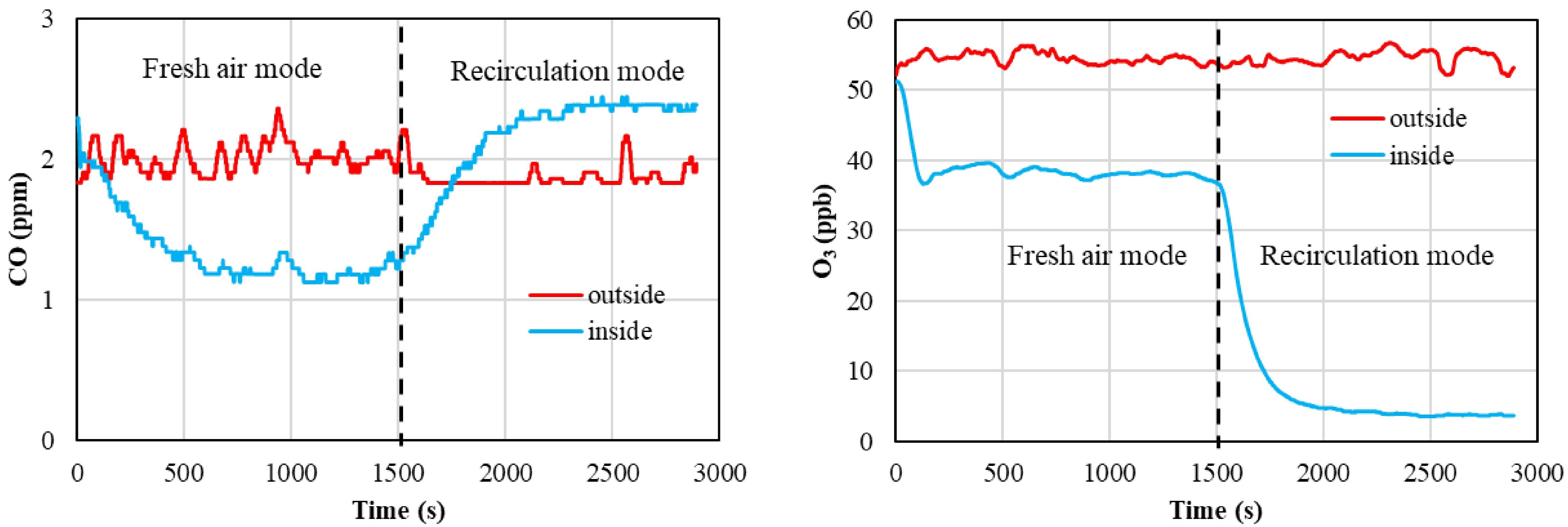

O_3 (ppb)
30
25
20
15
10
5
0
0
10
20
30
40
Time (min)
measurements
model
midnight
sunset
midday 1
midday 2

Static test

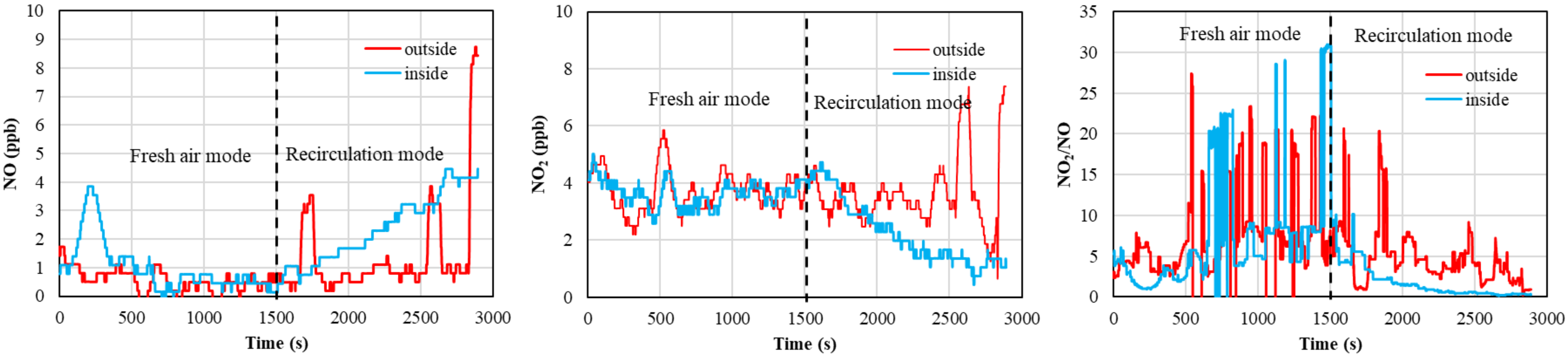


midnight
sunset
midday 1
midday 2
measurements
model
NO (ppb)
Time (min)
NO_2 (ppb)
Time (min)
NO_x (ppb)
Time (min)

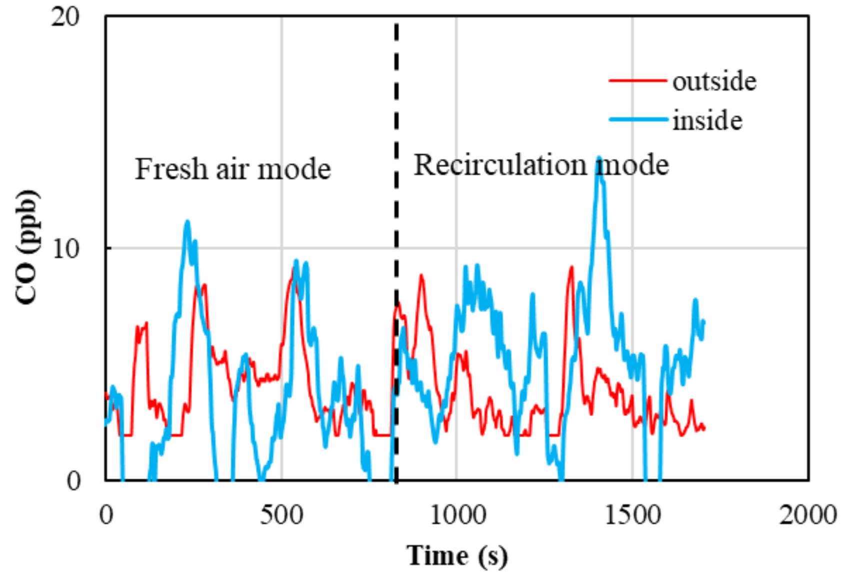
Pseudo-dynamic test

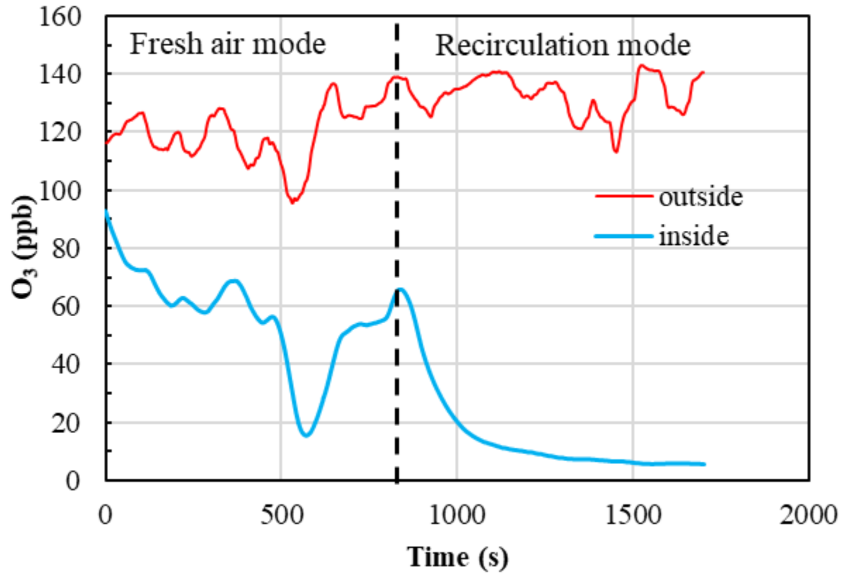


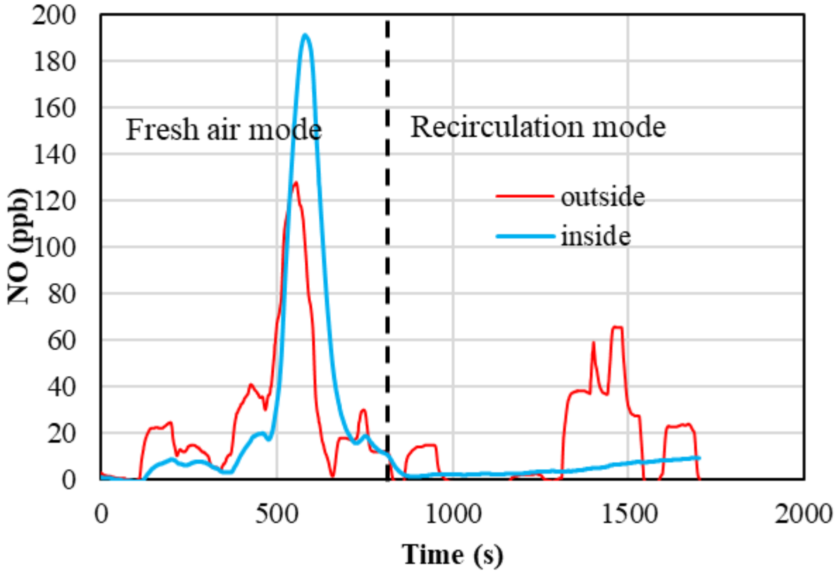
Pseudo-dynamic test

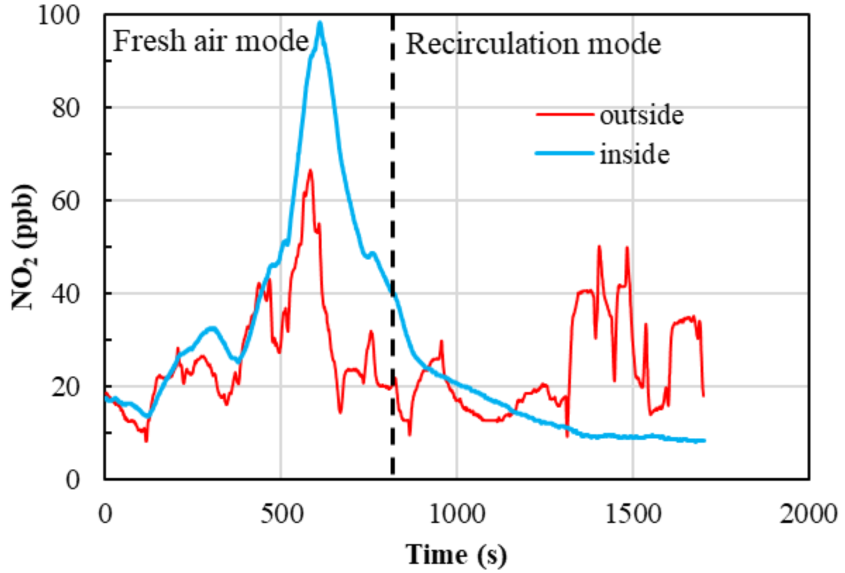


Dynamic test

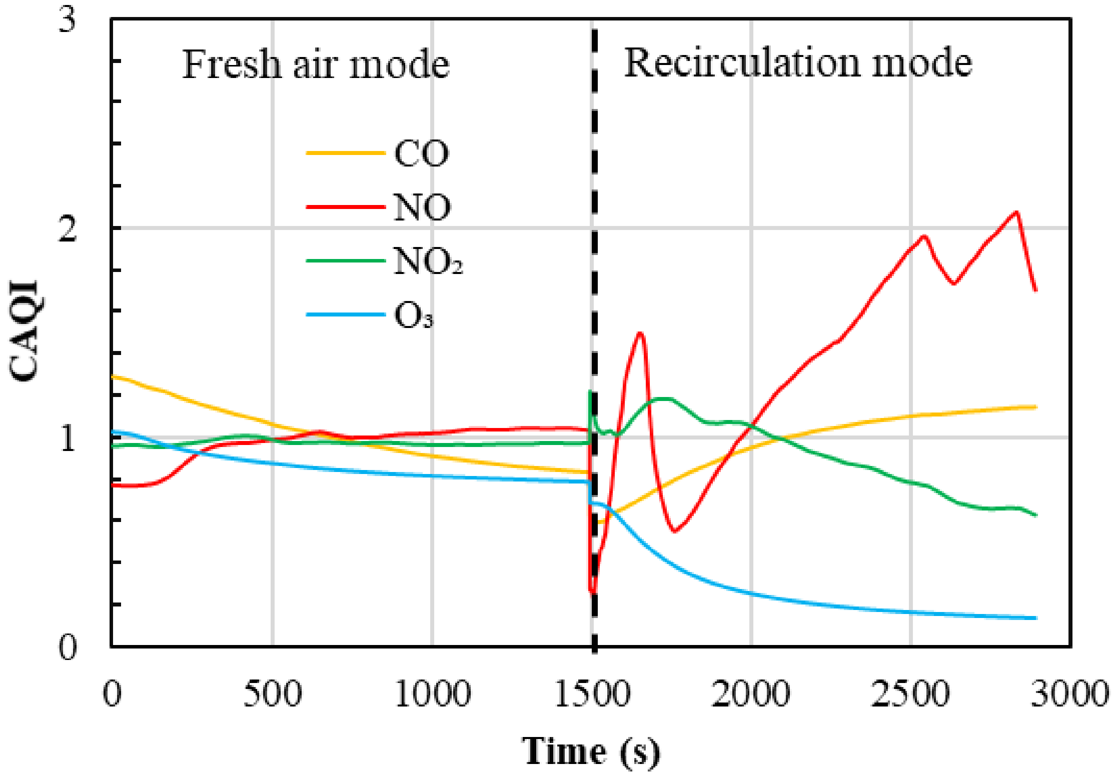


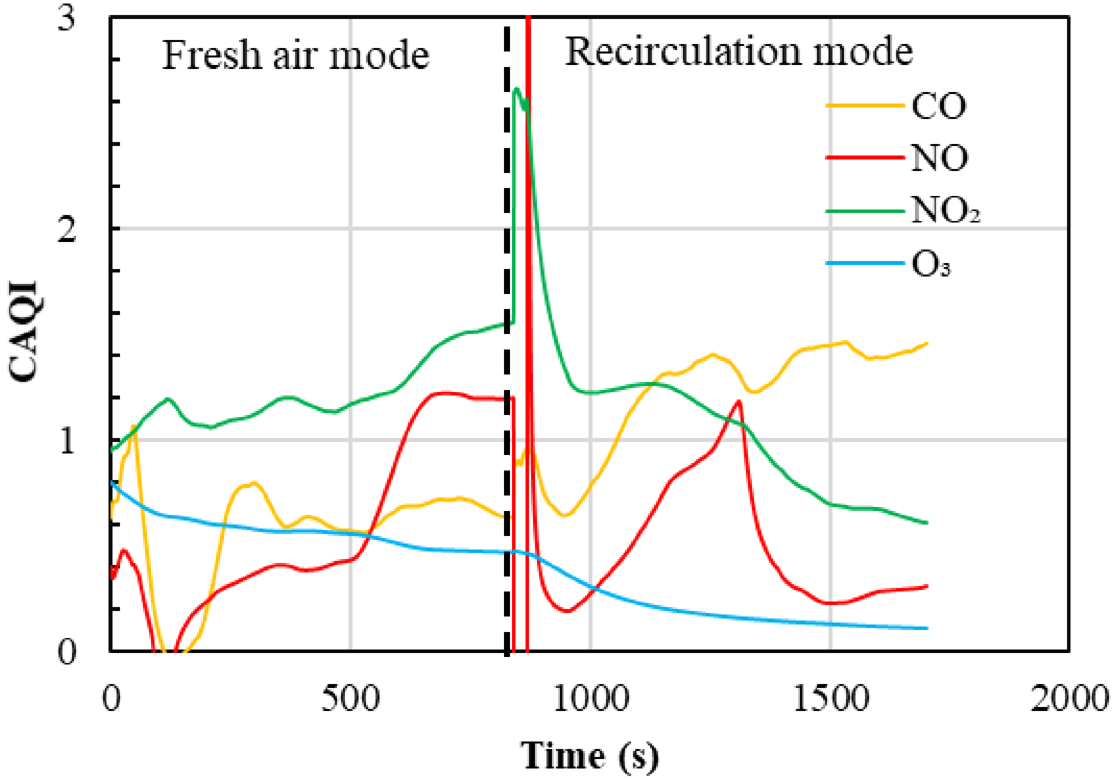






Cabin Air Quality Index, $\mathrm{CAQI}_i = \dfrac{\int_0^t C_{i,cabin}\ dt}{\int_0^t C_{i,outside}\ dt}$





Conclusion from static test

- CO and NO accumulate in the vehicle cabin due to exhalation from the driver and in the case of NO due to conversion of NO_2 to NO on surfaces.
- Ozone decreased faster compared to NO_2 because of faster losses to surfaces and reactions with VOCs. The model assumed a 40 – 100 % NO yield upon deposition of NO_2 in order to achieve agreement with the experimental results

Conclusion from pseudo-dynamic and dynamic test for fresh mode.

- During the fresh air mode, outside and inside cabin concentrations of NO and NO_2 followed similar trends for the pseudo dynamic test.
- In cabin NO and NO_2 concentrations were slightly higher than outside when compared cumulatively with CAQI larger than 1 during the dynamic test at fresh air mode.

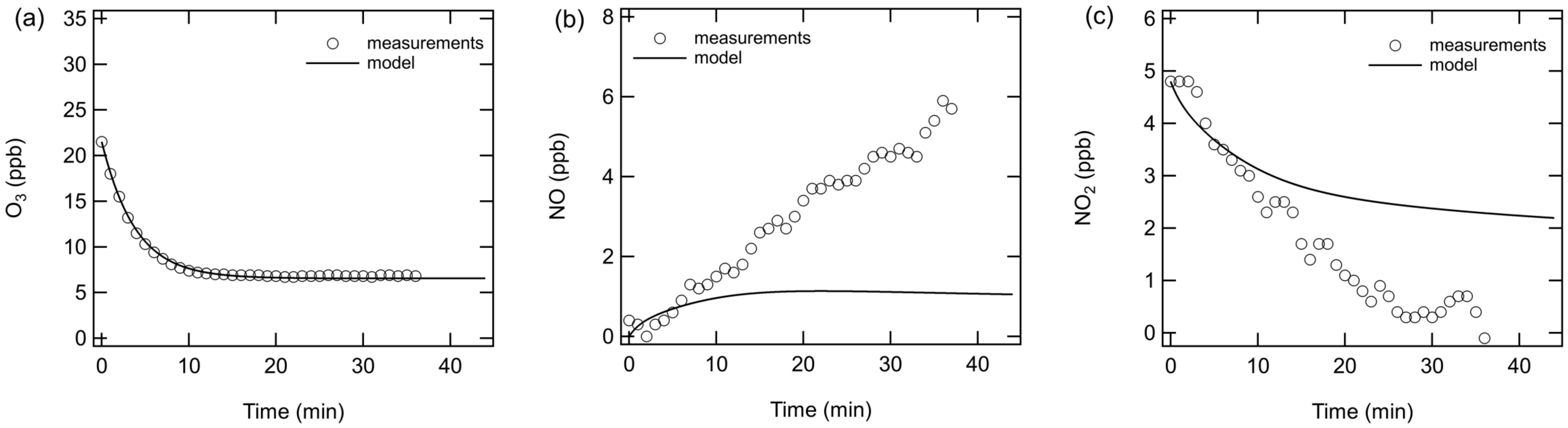
- Future studies should perform calibrations of measurement instruments daily and place the outside air sampling position at the intake of the cabin air to answer the reason of CAQI of NO and NO_2 being larger than 1 during the fresh air mode.
- Outside and inside cabin CO concentrations followed similar trends during the dynamic test at fresh air mode.

Conclusion from pseudo-dynamic and dynamic test for air recirculation mode.

- O_3 and NO_2 reduced while CO increased. The reason of CO increase during recirculation needs further investigation.
- NO accumulation was not obvious as the magnitude of variation of outside NO outweighed the small increase of NO in vehicle cabin.
- Optimizing the extent of recirculation (e.g. partial recirculation) as a function of control parameters such as number of passengers, fan speed, and vehicle speed can reduce concentrations of multiple pollutants (O_3, NO_2, and particles) while suppressing accumulation of other pollutants (CO_2, NO, and CO).
- We encourage auto manufacturers to develop in-cabin multipollutant control devices to improve cabin air quality and reduce passenger’s exposure to harmful air pollutants.

Backup slide

When ozone generation in cabin was assumed.



- Figure S1: Concentrations of (a) O_3, (b) NO and (c) NO_2 predicted by the model at midnight when an ozone production rate of 8.1×10^8 molecule cm^{-3} s^{-1} was included in the model in order to match ozone concentrations. All other parameters were kept consistent with those found in Table S1.