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
Agenda

1. Background
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Define Cabin Air Quality Index (CAQI)

\[ CAQI_{\text{pollutant}} = \frac{\int_0^t c_{\text{pollutant\_inside}} \, dt}{\int_0^t c_{\text{pollutant\_outside}} \, dt} \]

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

- \( CAQI_{\text{particle}} < 1 \) Infiltration ratio

• There are two modes 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 CO₂ 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.
Experimental setup

- In-Cabin Meas.
  - CPC 3022A
  - EAD 3070A
  - microAeth MA300

- Outside Meas.
  - CPC 3022A
  - EAD 3070A
  - microAeth MA300

- Batteries: NAQTS #1, NAQTS #2

- Outside Sampling Port

- 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

<table>
<thead>
<tr>
<th>Test #</th>
<th>Fan Speed</th>
<th>Recir.</th>
<th>AC</th>
<th>AER(h⁻¹)</th>
</tr>
</thead>
<tbody>
<tr>
<td>1</td>
<td>1</td>
<td>Off</td>
<td>Off</td>
<td>30</td>
</tr>
<tr>
<td>2</td>
<td>3</td>
<td>Off</td>
<td>Off</td>
<td>44</td>
</tr>
<tr>
<td>3</td>
<td>5</td>
<td>Off</td>
<td>Off</td>
<td>54</td>
</tr>
<tr>
<td>4</td>
<td>3</td>
<td>On</td>
<td>On</td>
<td>4</td>
</tr>
</tbody>
</table>

The logarithm of the concentration difference ($\ln[C(t) - C_{amb}]$) vs. elapsed time (s) is shown in the graph. The linear regression equations and $R^2$ values for each test are:

- **Test 1**: $y = -0.0011x + 7.5068$, $R^2 = 0.946$
- **Test 2**: $y = -0.0082x + 7.4771$, $R^2 = 0.9991$
- **Test 3**: $y = -0.0121x + 7.231$, $R^2 = 0.9946$
- **Test 4**: $y = -0.0149x + 6.4109$, $R^2 = 0.9964$
Dynamic test

Particle number

AC Off
Fresh Air
Recirc.

AC On

Inside

Outside

Particle number (#/cm³)

0
2.0E+04
4.0E+04
6.0E+04
8.0E+04
1.0E+05
1.2E+05
1.4E+05
1.6E+05

Elapsed Time (s)

0
500
1000
1500
2000
2500

CO₂

AC Off
Fresh Air
Recirc.

AC On

Inside

Outside

CO₂ (ppm)

0
500
1,000
1,500
2,000
2,500
3,000

Elapsed Time (s)

0
500
1000
1500
2000
2500
Cabin air quality index (CAQI)
The effect of particle metric on CAQI

The figure shows the variation of CAQI with different particle metrics (Number, Surface area, Mass) under two conditions: Fresh Air AC OFF and Recir. AC ON. The graph indicates that CAQI values are higher for Fresh Air AC OFF compared to Recir. AC ON, with the highest CAQI values observed for the Surface area metric.
Agenda

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3. Behavior of gaseous pollutants in vehicle cabin
Experimental setup

A 2016 Toyota Highlander with a 7 seat capacity

<table>
<thead>
<tr>
<th>Horiba instruments</th>
<th>Gases</th>
</tr>
</thead>
<tbody>
<tr>
<td>APMA-370</td>
<td>CO</td>
</tr>
<tr>
<td>APNA-370</td>
<td>NO, NO₂, NOₓ</td>
</tr>
<tr>
<td>APOA-370</td>
<td>O₃</td>
</tr>
</tbody>
</table>

<table>
<thead>
<tr>
<th>Instrument/equipment</th>
<th>Brand/model</th>
</tr>
</thead>
<tbody>
<tr>
<td>Data logger</td>
<td>dataTaker, model dt80</td>
</tr>
<tr>
<td>6 V lead acid batteries</td>
<td>US Battery, model 145</td>
</tr>
<tr>
<td>Inverter</td>
<td>Chicago Electric Power Systems, 2000 W AC/DC</td>
</tr>
</tbody>
</table>
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$_2$O$_2$, 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

<table>
<thead>
<tr>
<th>Reaction</th>
</tr>
</thead>
<tbody>
<tr>
<td>( \text{O}_3 + hv \rightarrow \text{O} + \text{O}_2 )</td>
</tr>
<tr>
<td>( \text{O} + \text{O}_2 (+ M) \rightarrow \text{O}_3 (+ M) )</td>
</tr>
<tr>
<td>( \text{NO} + \text{O}_3 \rightarrow \text{NO}_2 + \text{O}_2 )</td>
</tr>
<tr>
<td>( \text{NO}_2 + hv \rightarrow \text{NO} + \text{O} )</td>
</tr>
<tr>
<td>( \text{O}_3 + \text{NO}_2 \rightarrow \text{NO}_3 + \text{O}_2 )</td>
</tr>
<tr>
<td>( \text{NO}_2 + \text{NO}_3 (+ M) \rightarrow \text{N}_2\text{O}_5 (+ M) )</td>
</tr>
<tr>
<td>( \text{N}_2\text{O}_5 (+ M) \rightarrow \text{NO}_2 + \text{NO}_3 (+ M) )</td>
</tr>
<tr>
<td>( \text{N}_2\text{O}_5 + \text{H}_2\text{O} \rightarrow 2\text{HNO}_3 ) (on surfaces)</td>
</tr>
<tr>
<td>( \text{O}_3 ) reaction with gas-phase VOCs or deposition to car surfaces</td>
</tr>
<tr>
<td>( \text{O}_3 + \text{Isoprene} \rightarrow \text{Products} )</td>
</tr>
<tr>
<td>( \text{O}_3 ) reaction with gas-phase VOCs or deposition to car surfaces</td>
</tr>
<tr>
<td>( \text{NO}_2 ) deposition to car surfaces with a certain yield of NO</td>
</tr>
<tr>
<td>( \text{CO} + \text{OH} \rightarrow \text{CO}_2 + \text{H} )</td>
</tr>
<tr>
<td>( \text{H} + \text{O}_2 \rightarrow \text{HO}_2 )</td>
</tr>
<tr>
<td>( \text{HO}_2 + \text{NO} \rightarrow \text{NO}_2 + \text{OH} )</td>
</tr>
<tr>
<td>( \text{OH} + \text{NO}_2 \rightarrow \text{HNO}_3 )</td>
</tr>
<tr>
<td>( \text{HO}_2 + \text{HO}_2 \rightarrow \text{H}_2\text{O}_2 + \text{O}_2 )</td>
</tr>
<tr>
<td>( \text{H}_2\text{O}_2 + hv \rightarrow \text{OH} + \text{OH} )</td>
</tr>
<tr>
<td>( \text{H}_2\text{O}_2 + \text{OH} \rightarrow \text{HO}_2 + \text{H}_2\text{O} )</td>
</tr>
</tbody>
</table>
Static test
Static test
Dynamic test
Cabin Air Quality Index, \( CAQI_i = \frac{\int_0^t c_{i,cabin} \, dt}{\int_0^t c_{i,outside} \, dt} \)
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