Integrated air quality monitoring technology for high-volume, low-cost measurements of indoor air quality

Douglas Booker
NAQTS
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Background

National Air Quality Testing Services (NAQTS) is a social business that is passionate about improving the quality of life. We seek to improve awareness of indoor air quality through widespread public and commercial monitoring using our holistic, high-quality, air pollution monitoring technology.

Our technology incorporates the latest developments in low-cost sensor technologies, alongside a regulatory grade Condensation Particle Counter, Thermal Desorption tubes, and other environmental measurements, the NAQTS V1000 is a portable air quality monitoring station designed to be easy-to-use for high-volume, lower-cost air quality measurements.

Based in UK (Lancaster University Environment Centre and Cardiff), and in Ann Arbor, Michigan, USA.
Lancaster University

Co-located with Lancaster Environment Centre (LEC) one of the largest multi-disciplinary environment centres in the world

It combines an academic university department with a number of businesses

PhD Projects
1. Energy Efficiency & IAQ
2. Particulate Matter Mitigation
3. IAQ & Environmental Justice
Technology

**PN** - CPC with 20:1 pre-dilution (IPA, $d_{50}$ 15nm)

**CO, NO$_2$** - Multiple Electrochemical and Metal Oxide sensors

**VOCs** - Electrochemical, Metal Oxide and Thermal desorption tubes for GC-MS Analysis.

**CO$_2$** - NDIR

**T, P, RH** – BME280

**Noise** – dBA

**Location** – GPS

**Vibration** – 3D accelerometer and 3D Gyro

**Web GUI** with SQL Database
Metrology

PN Calibration in accordance with ISO 27891

Gas calibration (Zero/span linearity)
Applications

INSIDE:OUTSIDE SCHOOLS IN THE BRUSSELS AREA
Capturing real-time pollution levels during school drop off/pick up times, as well as levels of student exposure in the classroom

VOC SPECIATION
Real – time VOCS / thermal desorption results

V1000 accommodates 4 Active TD tubes that can be configured to sample on events, or on a timer basis

BENCHMARKING VEHICLES “COMFORT”
Air Quality, Noise, and Vibration

Data on in-cabin comfort from 100s of vehicles
Applications

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BENCHMARKING VEHICLES “COMFORT”
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Data on in-cabin comfort from 100s of vehicles
Vehicle Interior Air Quality

101 minutes per day in vehicles (Dong et al. 2004)

Immediate proximity to significant pollutant sources (other vehicles), plus in urban areas, high outdoor concentrations

The challenges for Vehicle Interior Air Quality (VIAQ) are similar to IAQ

Studies are done jointly with Emissions Analytics.

Q1: How much ambient air pollution is coming into the vehicle?

Simultaneous measurements of inside and outside the vehicle

Immediate proximity to significant pollutant sources (other vehicles), plus in urban areas, high outdoor concentrations
German Sedan

### PN

<table>
<thead>
<tr>
<th>Recirculation</th>
<th>Inside</th>
<th>Outside</th>
</tr>
</thead>
<tbody>
<tr>
<td>Off</td>
<td>3924</td>
<td>16153</td>
</tr>
<tr>
<td>On</td>
<td>851</td>
<td>17946</td>
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</table>

### CO2

<table>
<thead>
<tr>
<th>Recirculation</th>
<th>Inside</th>
<th>Outside</th>
</tr>
</thead>
<tbody>
<tr>
<td>Off</td>
<td>672</td>
<td>465</td>
</tr>
<tr>
<td>On</td>
<td>1653</td>
<td>464</td>
</tr>
</tbody>
</table>

#### Ingress Ratio

- Recirculation Off: 24%
- Recirculation On: 5%

#### Stiffness Factor

- Recirculation Off: 1.4
- Recirculation On: 3.6
American Hatchback

<table>
<thead>
<tr>
<th></th>
<th>INGRESS RATIO</th>
<th>STUFFINESS FACTOR</th>
</tr>
</thead>
<tbody>
<tr>
<td>Recirculation Off</td>
<td>60%</td>
<td>1.2</td>
</tr>
<tr>
<td>Recirculation On</td>
<td>13%</td>
<td>3.3</td>
</tr>
</tbody>
</table>
Japanese Crossover

<table>
<thead>
<tr>
<th></th>
<th>Ingress Ratio</th>
<th>Stuffiness Factor</th>
</tr>
</thead>
<tbody>
<tr>
<td>Recirculation Off</td>
<td>99%</td>
<td>1.3</td>
</tr>
<tr>
<td>Recirculation On</td>
<td>18%</td>
<td>3.4</td>
</tr>
</tbody>
</table>
# German MPV

## PN

<table>
<thead>
<tr>
<th>Condition</th>
<th>PN (10^3)</th>
<th>Inside</th>
<th>Outside</th>
</tr>
</thead>
<tbody>
<tr>
<td>Recirculation Off</td>
<td>30529</td>
<td>12426</td>
<td></td>
</tr>
<tr>
<td>Recirculation On</td>
<td>11583</td>
<td>1975</td>
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</table>

## CO2

<table>
<thead>
<tr>
<th>Condition</th>
<th>CO2 (PPM)</th>
<th>Inside</th>
<th>Outside</th>
</tr>
</thead>
<tbody>
<tr>
<td>Recirculation Off</td>
<td>177</td>
<td>677</td>
<td>2235</td>
</tr>
<tr>
<td>Recirculation On</td>
<td>477</td>
<td></td>
<td>459</td>
</tr>
</tbody>
</table>

## Ingress Ratio and Stuffiness Factor

<table>
<thead>
<tr>
<th>Condition</th>
<th>Ingress Ratio</th>
<th>Stuffiness Factor</th>
</tr>
</thead>
<tbody>
<tr>
<td>Recirculation Off</td>
<td>41%</td>
<td>1.4</td>
</tr>
<tr>
<td>Recirculation On</td>
<td>17%</td>
<td>4.97</td>
</tr>
</tbody>
</table>
Ultrafine Particles – Ingress Ratio

Ingress Ratio

- German Sedan
- American Hatchback
- Japanese Crossover
- German MPV

Recirc Off  Recirc On
Ultrafine Particles – Ingress Ratio

The data from these four vehicles shows the heterogeneity of Ingress Ratios.

24-99% with recirculation mode off

5-17% with recirculation mode on
CO2 – Stuffiness Factor
An inherent tradeoff between protecting passengers from ambient ingress, and adequate ventilation.

Huge influence of passenger habit on dose. By driver education, and automation of HVAC controls, exposure to PN can be reduced significantly.
Q2: What are the in-vehicle sources of air pollution?

Volatile Organic Compounds (VOCs), responsible for the “new car smell”, can be emitted from an array of interior parts and components: the dashboard, interior panels, flooring materials, and many others.

Within the confined space of a vehicle, VOCs emitted from these components may reach levels that are potentially harmful to human occupants, causing symptoms such as nausea, allergies, fatigue, stinging eyes, and headaches.

Beyond affecting drivers’ and passengers’ well-being and comfort, such symptoms may have also consequences on safe driving.
Experimental Set-Up (Static Baseline)

Hydrophobic TnxTA/Cg1

Integrated into NAQTS V1000

Tested inside Emissions Analytics’ Stokenchurch Emissions Lab

Top 20 peaks, Semi-quantitative (spiked with d8-Toluene, d6-benzene and d4-dichlorobenzene)

1. Ethanol
2. n-Heptane
3. 2-Butanone (MeK)
4. 4-Methylacetanilide
5. Hexamethyldisiloxane
6. Methyl
7. Toluene
8. Hexamethylcyclotrisiloxane
9. Diphenylamine
10. Isopropylbenzene
11. 2-Octyltertbutanol
12. α-Xylene
13. 1-Phenyl-2-propanol
14. Octamethylcyclotetrasiloxane
15. Decane
16. Undecane
17. Dodecane
18. Tridecane
19. 1,2,4,5,6,7-Hexamethyldi-1,1,2,2-tetrafluoroethane
20. Tetradecane

Agilent GC-MS, samples run on full scan mode

Thermal Desorption
Experimental Set-Up (Real World Driving)

- Hydrophobic TnxTA/Cg1
- Integrated into NAQTS V1000
- Tested dynamically on RDE-type route (Geofencing – Urban, Rural, Highway etc.) at same time as indoor-outdoor research to see VOCs ingress

Top 20 peaks, Semi-quantitative (spiked with d8-Toluene, d6-benzene and d4-dichlorobenzene)

Agilent GC-MS, samples run on full scan mode

Thermal Desorption
VW Golf (2011)
Renault Clio (2016)
Mercedes C220 (2005)
Ford Focus (2009)

VOC Concentration (µg.m⁻³)

- Benzene
- Dodecane
- Ethylbenzene
- Hexamethyldisiloxane
- Limonene
- M-p-Xylene
- Octamethyldisiloxane
- O-xylene
- Tetradecane
- Toluene
- Tridecane
- Undecane

<table>
<thead>
<tr>
<th>Abundance</th>
<th>TIC: 06051422_Ddata.js</th>
<th>Time (min)</th>
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</thead>
<tbody>
<tr>
<td>1. Hexane</td>
<td>4.5e+07</td>
<td>5.00</td>
</tr>
<tr>
<td>2. Benzene</td>
<td>4.0e+07</td>
<td>5.00</td>
</tr>
<tr>
<td>3. Methylcyclohexane</td>
<td>3.5e+07</td>
<td>5.00</td>
</tr>
<tr>
<td>4. Methyl isobutyl ketone</td>
<td>3.0e+07</td>
<td>5.00</td>
</tr>
<tr>
<td>5. Toluene</td>
<td>2.5e+07</td>
<td>5.00</td>
</tr>
<tr>
<td>6. Hexamethyldisiloxane</td>
<td>2.0e+07</td>
<td>5.00</td>
</tr>
<tr>
<td>7. Butyl acetate</td>
<td>1.5e+07</td>
<td>5.00</td>
</tr>
<tr>
<td>8. Ethylbenzene</td>
<td>1.0e+07</td>
<td>5.00</td>
</tr>
<tr>
<td>9. m/p-Xylene</td>
<td>5.0e+07</td>
<td>5.00</td>
</tr>
<tr>
<td>10. Heptan-1-ol</td>
<td>1.0e+07</td>
<td>5.00</td>
</tr>
<tr>
<td>11. O-xylene</td>
<td>5.0e+07</td>
<td>5.00</td>
</tr>
<tr>
<td>12. Octamethyldisiloxane</td>
<td>5.0e+07</td>
<td>5.00</td>
</tr>
<tr>
<td>13. Propylenzene</td>
<td>4.5e+07</td>
<td>5.00</td>
</tr>
<tr>
<td>14. D-Limonene</td>
<td>4.0e+07</td>
<td>5.00</td>
</tr>
<tr>
<td>15. Undecane</td>
<td>3.5e+07</td>
<td>5.00</td>
</tr>
<tr>
<td>16. Benzyl acetate</td>
<td>3.0e+07</td>
<td>5.00</td>
</tr>
<tr>
<td>17. Dodecane</td>
<td>2.5e+07</td>
<td>5.00</td>
</tr>
<tr>
<td>18. Naphthalene</td>
<td>2.0e+07</td>
<td>5.00</td>
</tr>
<tr>
<td>19. Benzo[b]thiophene</td>
<td>1.5e+07</td>
<td>5.00</td>
</tr>
<tr>
<td>20. Tetradecane</td>
<td>1.0e+07</td>
<td>5.00</td>
</tr>
</tbody>
</table>
Ford Focus (2015)

VOC Concentration (µg.m⁻³)

- Benzene
- Dodecane
- Ethylbenzene
- Hexamethyldisiloxane
- Limonene
- M/xylene
- Octamethylcyclotrisiloxane
- O-xylene
- Tetradecane
- Toluene
- Tridecane
- Undecane

- Ethanol
- 2-Butanone (MEK)
- 1-Methoxy-2-propanol
- Propylene glycol
- Toluene
- Hexamethyldisiloxane
- Butyl acetate
- Ethylbenzene
- m/p-Xylene
- 2-Butoxyethanol
- o-Xylene
- 1-Butoxy-2-propanol
- Octamethylcyclotrisiloxane
- Benzaldehyde
- 2-Ethyl-1-hexanol
- D-Limonene
- 1-Ethyl-2-pyrrolidinone
- alpha-Terpineol
- Undecyl acetate
- Tetradecane
Fiat Punto (2008)

VOC Concentration ($\mu$g.m$^{-3}$)

- Benzene
- Dodecane
- Ethylbenzene
- Hexamethyldisiloxane
- Limonene
- M/p-xylene
- Octamethylcyclotrisiloxane
- Oxyene
- Tetradecane
- Toluene
- Tridecane
- Undecane

Graph showing VOC concentrations.
Mini Cooper (2006)

VOC Concentration (μg.m⁻³)

- Benzene
- Dodecane
- Ethylbenzene
- Hexamethyldisiloxane
- Limonene
- M/p-Xylene
- Octamethylcyclotrisiloxane
- O-Xylene
- Tetradecane
- Toluene
- Tridecane
- Undecane

Chart showing the concentration of various volatile organic compounds (VOCs) in a Mini Cooper (2006) vehicle.
Comparisons - TVOCs

Total VOCs (µg.m⁻³)

- Fiat Punto
- Ford Focus (2009)
- Ford Focus (2015)
- German Saloon
- Mercedes C220
- Mini Cooper
- Renault Clio
- VW Golf
Comparisons - TVOCs

Health Effects
- $<200 \, \mu g/m^3$ - No irritation or discomfort
- $200-3000 \, \mu g/m^3$ - Irritation and discomfort possible
- $3000-25000 \, \mu g/m^3$ - Discomfort expected and headache possible
- $>25000 \, \mu g/m^3$ - Toxic
Comparisons II - Speciation

- **VW Golf**
- **Renault Clio**
- **Mini Cooper**
- **Mercedes C220**
- **Ford Focus (2015)**
- **Ford Focus (2009)**
- **Fiat Punto**
- **German Saloon**

**VOC Concentration (μg/m³)**

- Benzene
- Dodecane
- Ethylbenzene
- Hexamethyldisiloxane
- Limonene
- M/p-xylene
- Octamethyldisiloxane
- O-xylene
- Tetradecane
- Toluene
- Tridecane
- Undecane
Comparisons II - Speciation

3 µg/m³ Carcinogen (Group 1)
Comparisons II - Speciation

VW Golf: 8.4 µg/m³
Renault Clio: 23 µg/m³
Mini-Cooper: 5.5 µg/m³
Mercedes C220: 5.5 µg/m³
Ford Focus (2015): 15 µg/m³
Ford Focus (2009): 15 µg/m³
Fiat Punto: 8.4 µg/m³
German Saloon: 15 µg/m³
Comparisons II - Speciation

Carcinogen (Group 2A)

14 µg/m³

20 µg/m³

19 µg/m³
How do you communicate these results to the general public?

Vehicle manufacturers beginning to differentiate themselves based on VIAQ, we need more independent research to inform the consumer.

“You can literally survive a military grade bio attack by sitting in your car” - TESLA

Complicated subject matter + general public aversion to analytical chemistry
Conclusions

This case study represents a small data set, however, Emissions Analytics are using NAQTS’ air quality monitoring technology to gather data on Ingress & Stuffiness for 100s of vehicles per year. Moreover, this will be extended to include other pollutants (NO2, CO, VOCs).

The NAQTS V1000 is a holistic, portable air quality monitoring station designed to be easy-to-use for high-volume, lower-cost air quality measurements.
Any questions?