Integrating a CPC into a "low cost" air quality monitoring device: challenges & opportunities

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NAQTS

Cambridge Particle Meeting | 15th June 2018

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

Currently funding three PhD projects

1. Energy Efficiency & IAQ
2. Indoor Particulate Matter Mitigation
3. IAQ & Environmental Justice

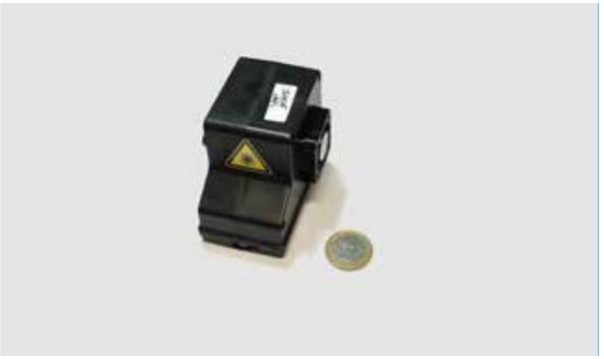
NAQTS

Low Cost Sensor Technologies

Metal oxide sensors
(used to measure NO_2, O_3, CO)

- Low cost: around 10 - 15 € for a sensor.
- Good sensitivity, from mg/m³ to µg/m³.

- Results are affected by temperature and humidity variations.
- Long response time (5 – 50 min).
- Output depends as well on history of past inputs.
- Instability can be observed.



Optical particulate counter
(used to measure PM)

- Moderate cost: 300 € for a sensor to 2000 € for handled device.
- Fast response time (1 s).
- Sensitivity in the range of 1 µg/m³.
- Able to identify the size of the particle (PM10, PM2.5,..).

- Conversion from particle counts to PM mass is based on theoretical model.
- The measured signal depends on a variety of parameters such as particle shape, color and density, humidity, refractive index, ..

Electrochemical sensors
(used to measure NO_2, SO_2, O_3, NO, CO)

- Medium cost: around 50 - 150 € for a sensor.
- Good sensitivity, from mg/m³ to µg/m³.
- Fast response time (30-200s).

- Highly sensitive to temperature and humidity variations (change in meteorology) depending on electrolyte.
- Selectivity: show cross-reactivity with similar molecule types

Photo Ionization Detector
(used to measure VOC)

- Moderate price: 400 € for a sensor to 5000 € for handled device.
- Good sensitivity, down to mg/m³, some down to µg/m³.
- Limited temperature dependence and humidity effects.
- Very fast response time (few seconds).

- Not selective: reacts to all VOCs that can be ionised by the UV lamp.
- Significant signal drift.

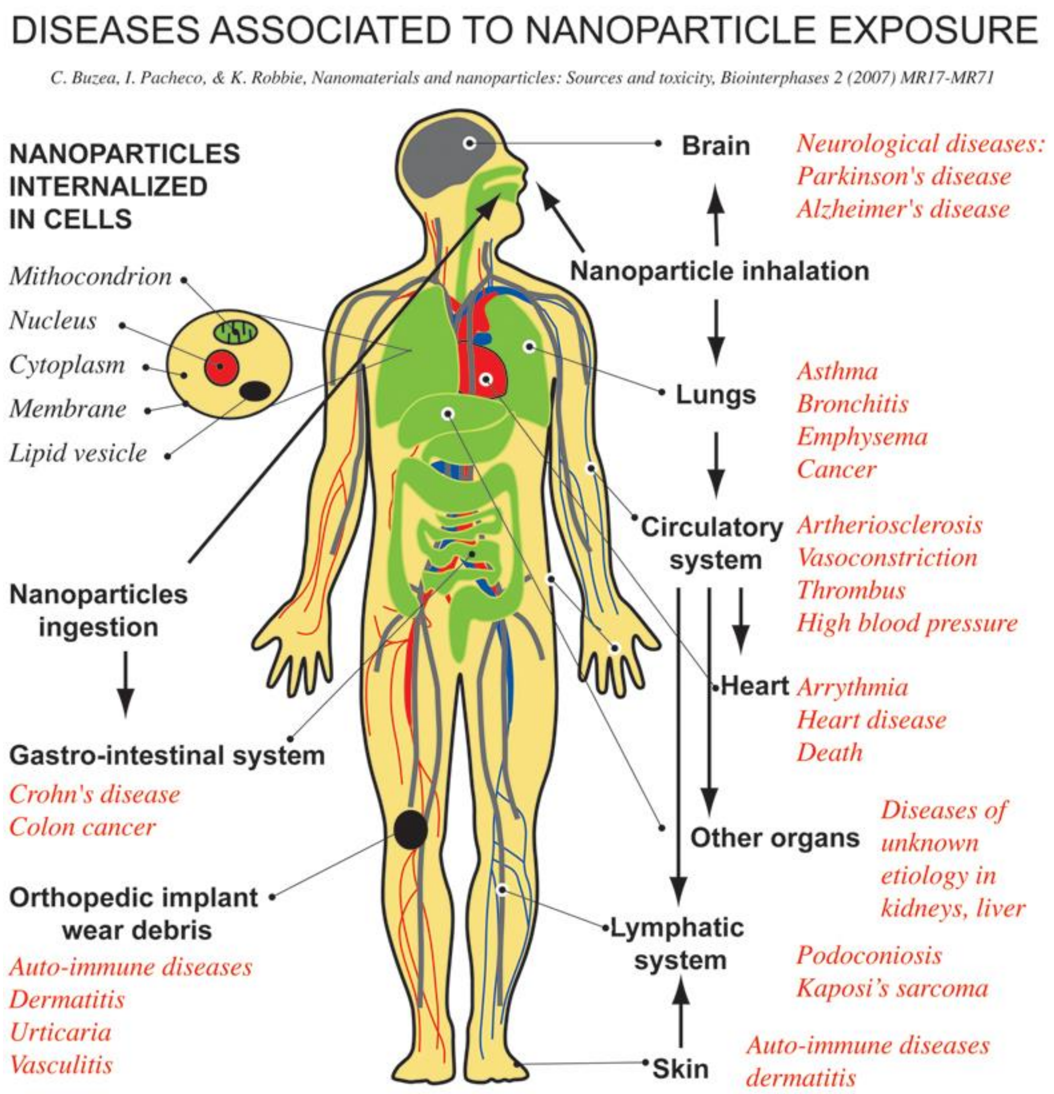
http://ec.europa.eu/environment/air/pdf/Brochure%20lower-cost%20sensors.pdf

What about ultrafine particles?

Dearth of "low-cost" UFP measurement technology

Important as:

- Huge spatial/temporal variability in UFP concentrations
- Limited number of controlled human exposure and toxicological studies that examined UFPs alone or in well-characterized combinations with other pollutants



What about ultrafine particles?

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Important as:

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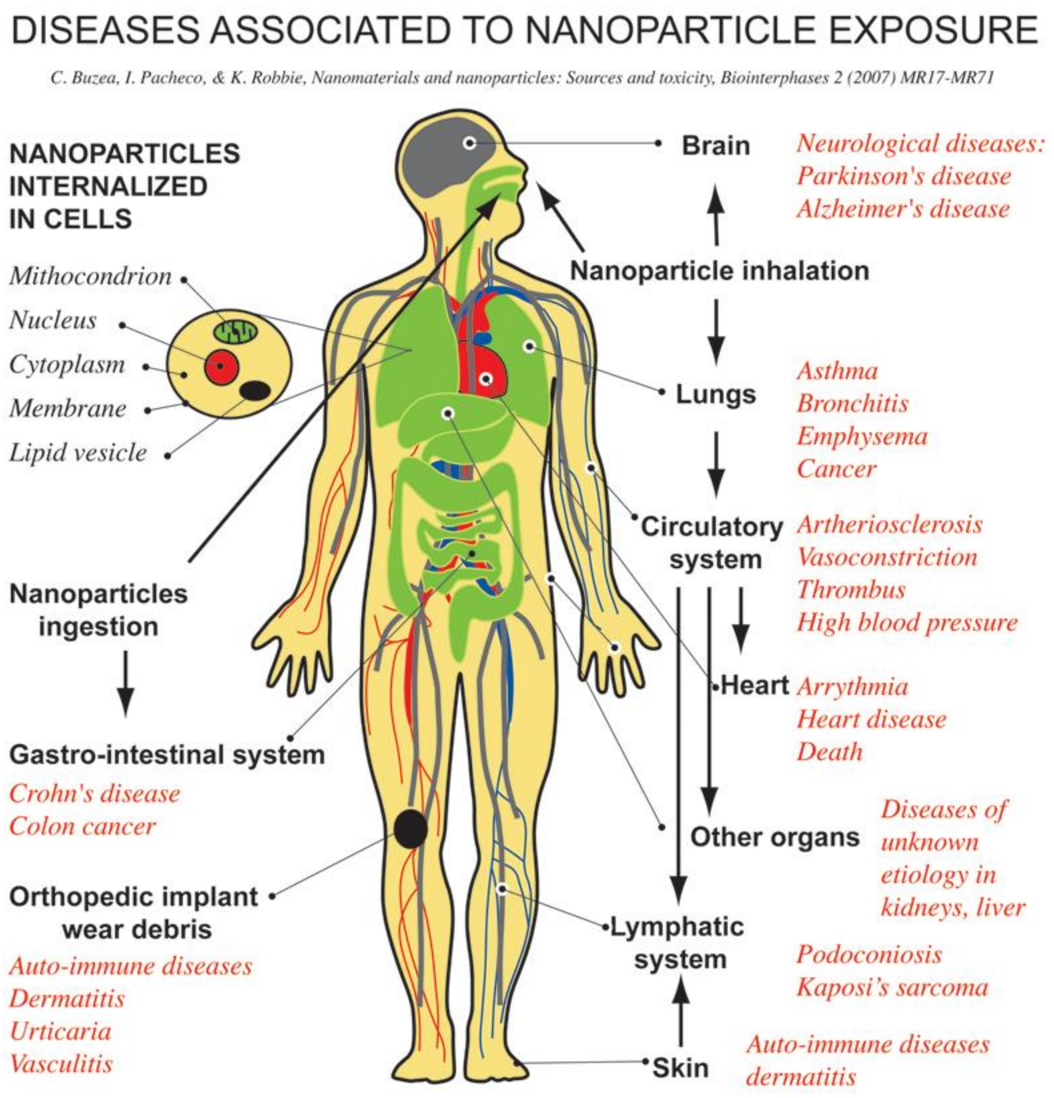
Can we measure UFP in a low-cost, accurate device? YES.



NAQTS Air Quality Bench

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

CO, NO_2, NO – Electrochemical

CO, NO_2, VOCs – Metal Oxide

VOCs – Metal Oxide

CO_2 – NDIR

T, P, RH – BME280

Vibration – 3D accelerometer and 3D Gyro

Suitable for OEM applications

Condensation Particle Counter (CPC)

NAQTS

Regulatory grade PN: ISO 27891

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

CERTIFICATE OF CALIBRATION

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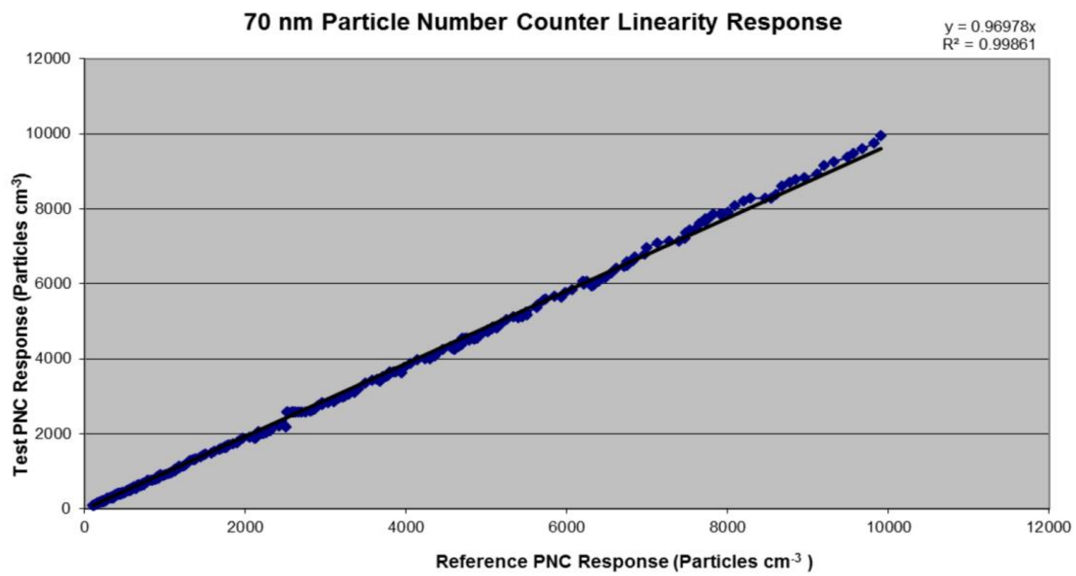
EXAMPLE ONLY

Particle counting efficiency against d_{50}=10 nm transfer standard

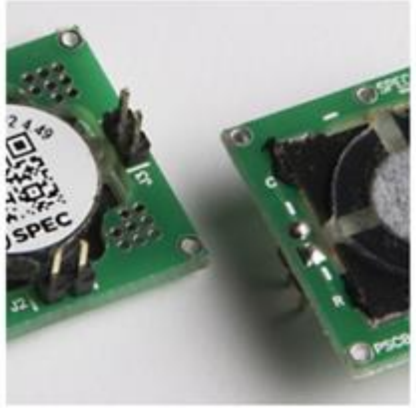
Diameter (nm)	Efficiency	$\lvert x_{min.}(a_1-1)+a_0 \rvert$ ≤5% max	Standard Error of Estimate (SEE) ≤10% max	Correlation coefficient
200	107.0%	-	-	0.999
100	104.0%	-	-	0.999
70	97.0%	0.67%	0.90%	0.999
55	104.0%	-	-	0.997
30	98.9%	-	-	0.998
23	104.0%	-	-	0.998



Electrochemical

Using state-of-the-art transimpedance amplifier (LMP9100) for flexibility for set-up and calibration

Electrochemical sensors used in conjunction with metal oxide sensors to address cross-interferences (orthogonal calibration methodology)



TEXAS INSTRUMENTS

LMP91000

SNAS506I – JANUARY 2011 – REVISED DECEMBER 2014

LMP91000 Sensor AFE System: Configurable AFE Potentiostat for Low-Power Chemical-Sensing Applications

1 Features

- Typical Values, T_A = 25°C
- Supply Voltage 2.7 V to 5.25 V
- Supply Current (Average Over Time) <10 µA
- Cell Conditioning Current Up to 10 mA
- Reference Electrode Bias Current (85°C) 900pA (max)
- Output Drive Current 750 µA
- Complete Potentiostat Circuit-to-Interface to Most Chemical Cells
- Programmable Cell Bias Voltage
- Low-Bias Voltage Drift
- Programmable TIA gain 2.75 kΩ to 350 kΩ
- Sink and Source Capability
- I^2C Compatible Digital Interface
- Ambient Operating Temperature –40°C to 85°C
- Package 14-Pin WSON
- Supported by WEBENCH® Sensor AFE Designer

3 Description

The LMP91000 is a programmable analog front-end (AFE) for use in micro-power electrochemical sensing applications. It provides a complete signal path solution between a sensor and a microcontroller that generates an output voltage proportional to the cell current. The LMP91000's programmability enables it to support multiple electrochemical sensors such as 3-lead toxic gas sensors and 2-lead galvanic cell sensors with a single design as opposed to the multiple discrete solutions. The LMP91000 supports gas sensitivities over a range of 0.5 nA/ppm to 9500 nA/ppm. It also allows for an easy conversion of current ranges from 5 µA to 750 µA full scale.

The LMP91000's adjustable cell bias and transimpedance amplifier (TIA) gain are programmable through the I^2C interface. The I^2C interface can also be used for sensor diagnostics. An integrated temperature sensor can be read by the user through the VOUT pin and used to provide additional signal correction in the µC or monitored to verify temperature conditions at the sensor.

	Sensor>>	CO	H2S	O3; -200mV	O3; 0mV	NO2	SO2	EtOH	NO	TOX	Tred
Gas	**ppm tested**	ppm Measured									
Carbon Monoxide	**400**	**400.0**	1.1	<0.05	<0.05	<0.1	7.3	251.4	4.0	400.0	-2.8
Hydrogen Sulfide	**25**	**<1**	**25.0**	-5.8	-12.5	-5.8	142.3	63.2	78.6	92.1	-67.6
Ozone	**5**	<1	-0.9	**5.0**	**5.0**	5.0	-3.3	<5	-1.8	-3.6	3.8
Nitrogen Dioxide	**10**	<1	-2.0	10.0	5.0	**10.0**	1.4	<5	0.8	-5.5	10.0
Sulfur Dioxide	**20**	<1	1.7	0.1	tbd	<0.1	**20.0**	11.6	11.0	14.7	-13.9
Ethanol	**200**	5.4	-1.9	2.3	tbd	2.3	-1.8	**200.0**	-1.0	285.3	12.7
NO	**50**	26.1	1.2	0.2	tbd	0.2	90.5	54.5	**50.0**	40.8	0.1
Chlorine	10	<1	-2.2	9.4	10.0	9.4	-2.8	-14.3	-1.6	-5.5	6.5
n-Heptane	500	<1	<0.05	-0.2	-0.2	-0.2	-0.7	-12.6	-0.4	<0.1	-0.3
Ammonia	100	<1	0.1	<0.05	tbd	<0.1	<0.2	<5	<0.1	0.3	-0.3
Methane	500	<1	0.1	<0.05	<0.05	<0.1	0.7	<5	0.4	<0.1	0.4
Hydrogen	100	17.0	---	---	---	---	---	---	---	---	---
Carbon Dioxide	5000	<1	---	---	---	---	---	---	---	---	---

Metal Oxide

e2v

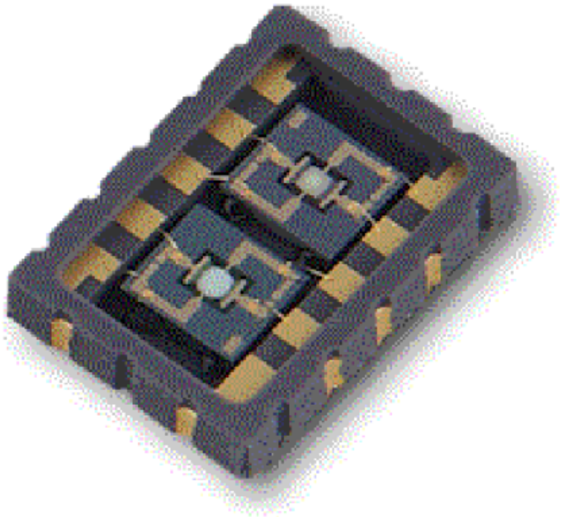
MiCS-4514
Combined CO and NO_2 Sensor

This datasheet describes the use of the MiCS-4514. This is commonly, but not exclusively, used in automobile applications. The package and the mode of operation described in this document describe the detection of reducing gases such as CO and hydrocarbons, and oxidising gases such as NO_2.

A typical application for this type of sensor is in areas that are subject to emissions from automobile exhausts.

FEATURES

- Low heater current
- Wide detection range
- Wide temperature range
- High sensitivity
- Short pre-heating time
- Two sensors in one SMD package with miniature dimensions
- High resistance to shocks and vibrations
- Compliant with automotive test requirements



Product shown without cap

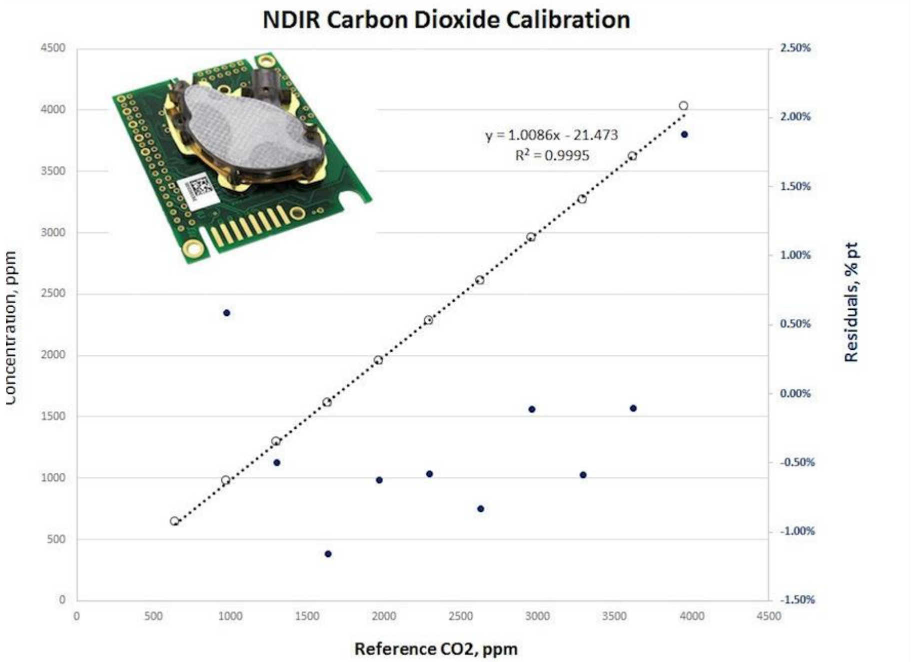
SENSOR CONFIGURATION

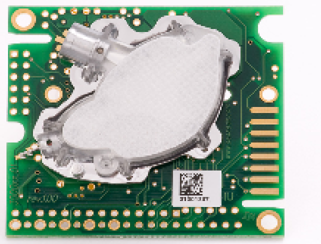
The silicon gas sensor structure consists of an accurately micro machined diaphragm with an embedded heating resistor and the sensing layer on top.

NDIR

Auto Baseline algorithm used for long-term sampling (400ppm CO_2)

Can be fitted with sampling manifold adapter





CO_2 Engine®K30

CO_2 Engine K30 can be customized for a variety of sensing and control applications. This platform is designed to be an OEM module for built-in applications in a host apparatus. K30 is a flexible product with 2 analog outputs and 2 digital outputs that can be configured with SADK or other custom software to meet your requirement.

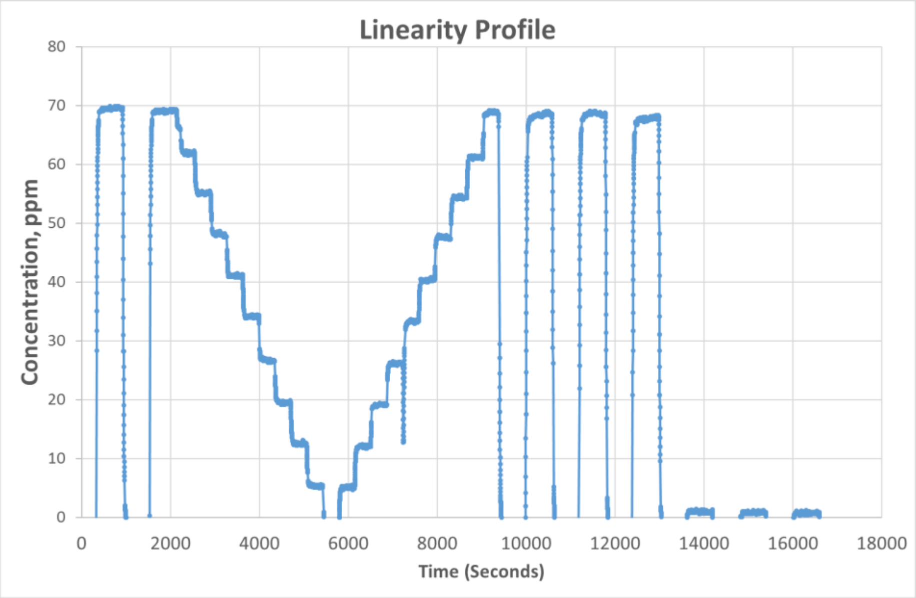
Key Benefits | Applications | **Specifications** | Art.no. | Download

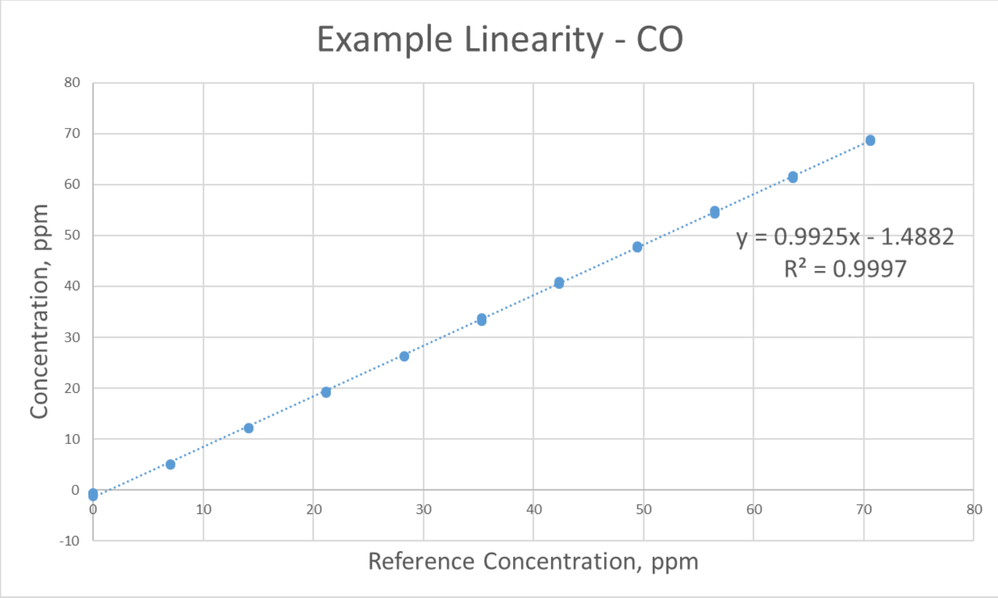
Operating Principle	Non-dispersive infrared (NDIR)
Measured gas	Carbon dioxide (CO_2)
Measurement range CO_2	0 to 5000 ppm / 0 to 3%vol
Accuracy	±30 ppm ±3% of reading
Dimensions	57 mm x 51 mm x 14 mm
Maintenance	Maintenance-free*
Life Expectancy	> 15 years
Operation temperature range	0 to 50 °C
Operation humidity range	0 to 95% RH (non-condensing)
Power supply	4.5 to 14.0 V DC
Response time$_{(T1/e)}$	20 sec diffusion time
Warm-up time	1 min
Communication	Uart (Modbus)
Outputs	
OUT $_1$ linear output	0 to 4 V DC = 0 to 2000 ppm
OUT $_2$ linear output	1 to 5 V DC = 0 to 2000 ppm
OUT $_3$ digital output	700/800 ppm
OUT $_4$ digital output	900/1000 ppm

*Maintenance-free with using SenseAir ABC Self calibration using for normal indoor applications.

Gas Metrology

Easy, low cost calibration using typical automotive gas bottles, e.g. 16% CO_2 Quad Blend (CO, HC, NO), and NO_2 through the integrated diluter





NAQTS V1000: Integration for holistic monitoring

NAQTS Air Quality Bench integrated into **NAQTS V1000**

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

CO, NO_2, NO – Electrochemical

CO, NO_2, VOCs – Metal Oxide

VOCs – Real-time and **thermal desorption tubes for GC-MS Analysis**

CO_2 – NDIR

T, P, RH – BME280

Vibration – 3D accelerometer and 3D Gyro

Noise – dBA

Location – GPS

OBD – Bluetooth

Vibration – 3D accelerometer and 3D Gyro

Web GUI with SQL Database

Challenges

- Low-cost sensor ≠ low cost device
- How to “de-skill” the operation and use
- Want –near– regulatory grade data
- How to keep it low cost?
  - Delivery
  - Calibration
  - Maintenance
  - Data analysis / reporting
- **Funding!**

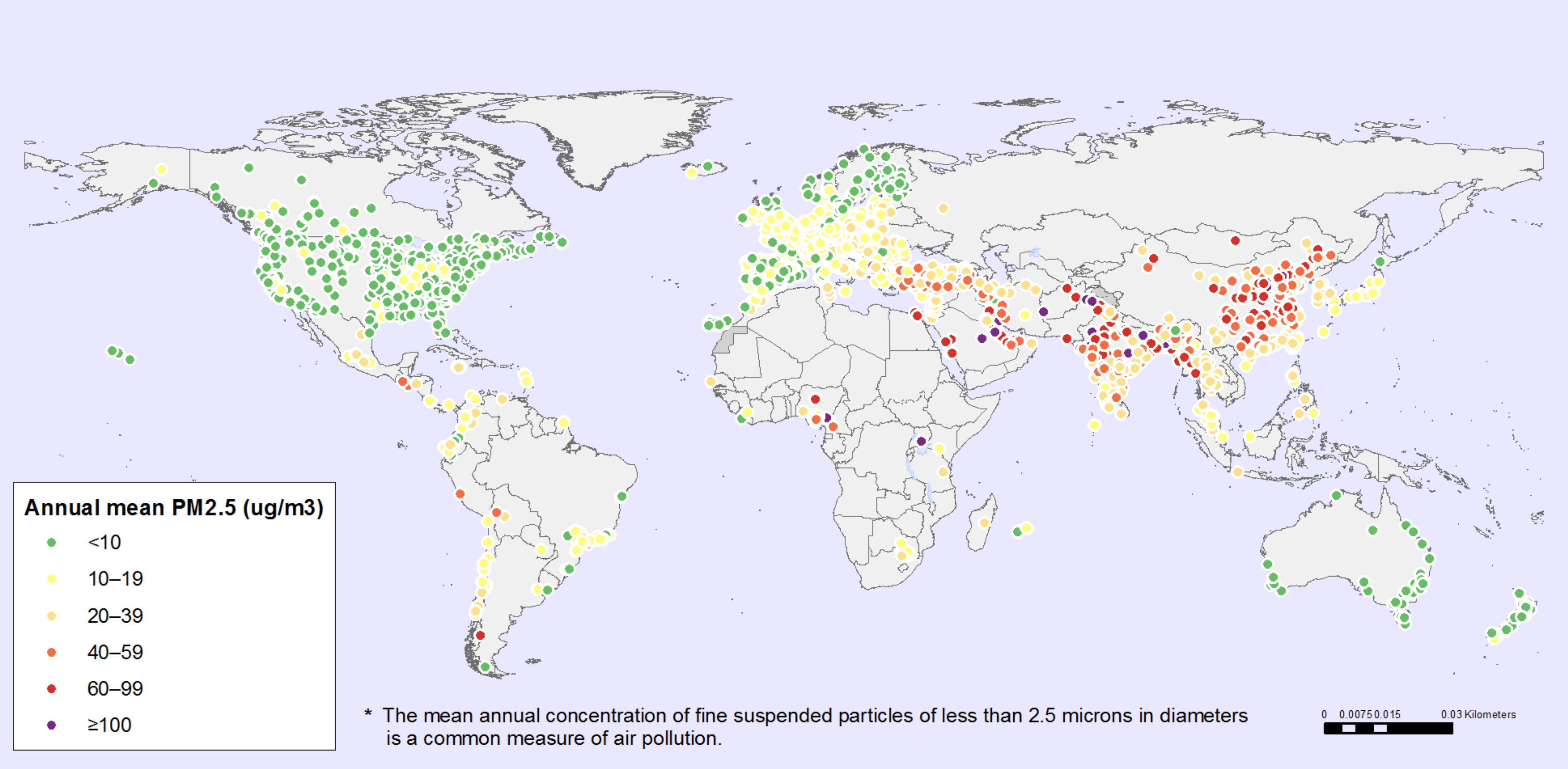
Opportunities

1. **Sparse monitoring networks –** fill data gaps
2. **Monitor new environments –** indoors, in-vehicle etc.
3. **Citizen science –** inspire behavioural change and empower citizens through active participation in the scientific process

Sparse monitoring networks

NAQTS

Concentration of particulate matter with an aerodynamic diameter of 2.5 µm or less (PM2.5) in nearly 3000 urban areas*, 2008–2015



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Data Source: World Health Organization
Map Production: Information Evidence and Research (IER)
World Health Organization

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Sparse monitoring networks

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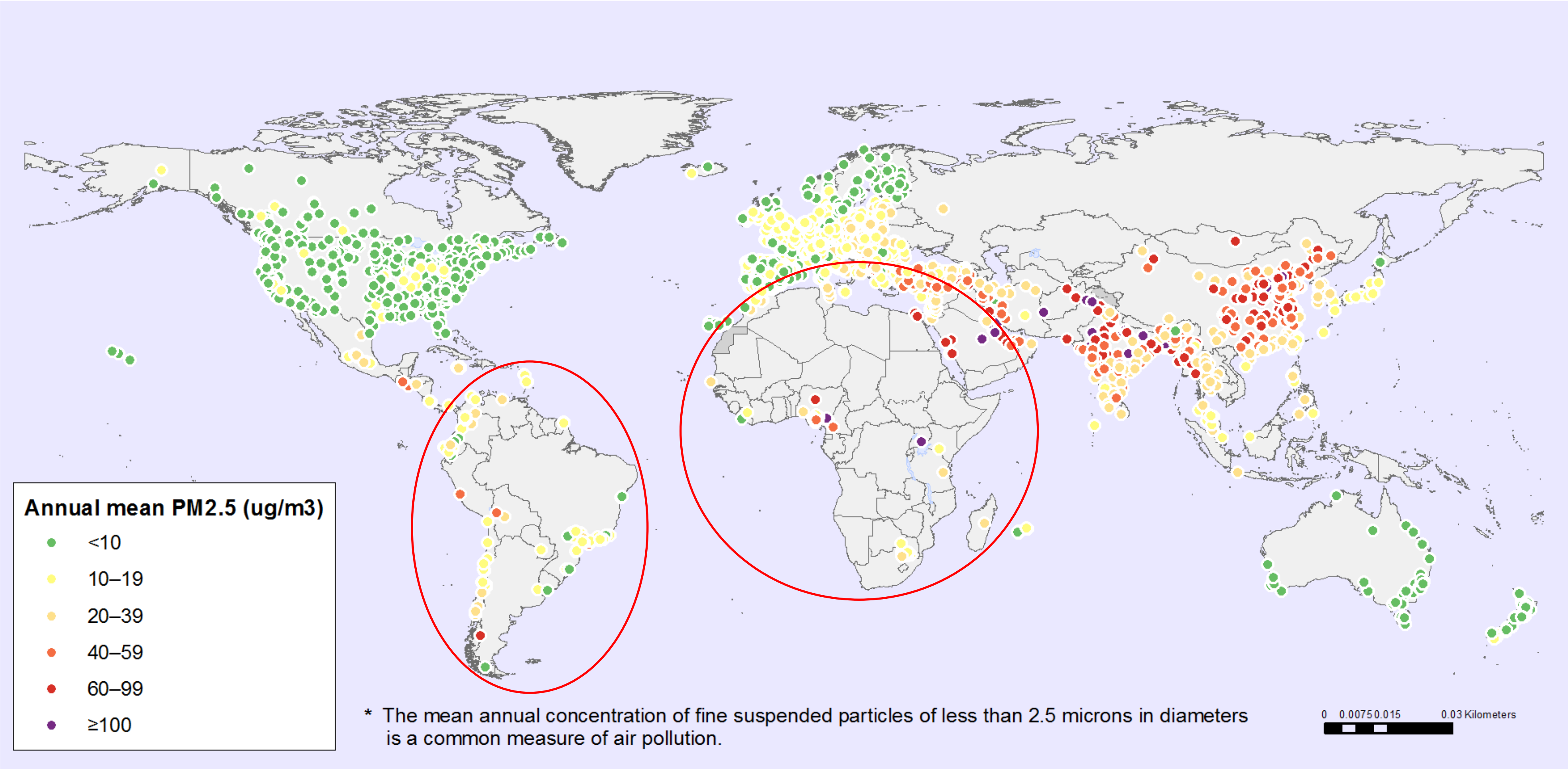

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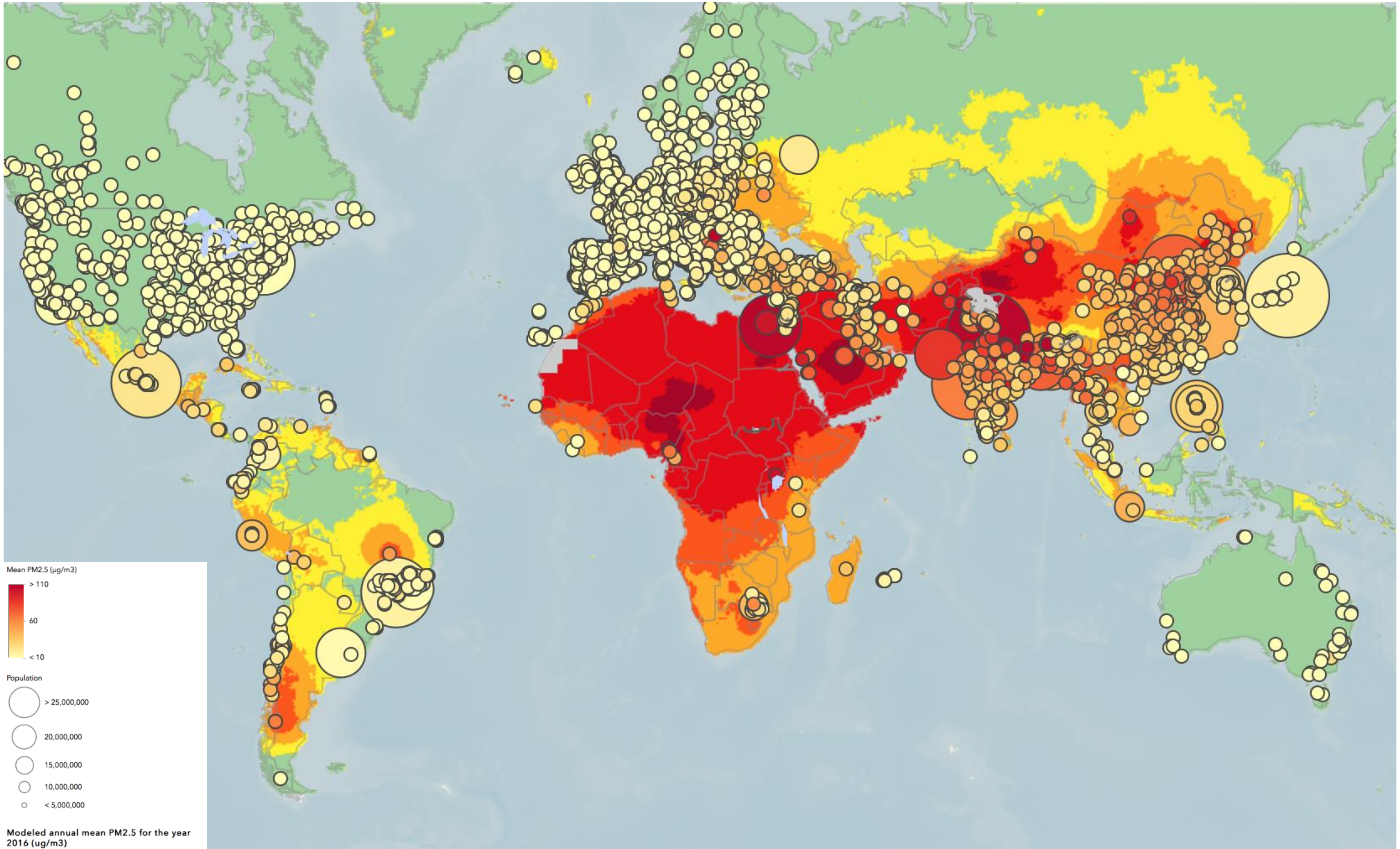
Sparse monitoring networks



http://maps.who.int/airpollution/

Applications

INDOOR AIR QUALITY & ENERGY EFFICIENCY

Developing models for assisting building design and modification whilst ensuring energy efficiency and good indoor air quality.

CITIZEN SCIENCE - INDOOR:OUTDOOR AIR QUALITY

Air quality toolkit for citizen science measurements. Capturing real-time pollution levels during school drop off/pick up times, as well as levels of student exposure in the classroom

VEHICLE INTERIOR AIR QUALITY

Air Quality, Noise, and Vibration

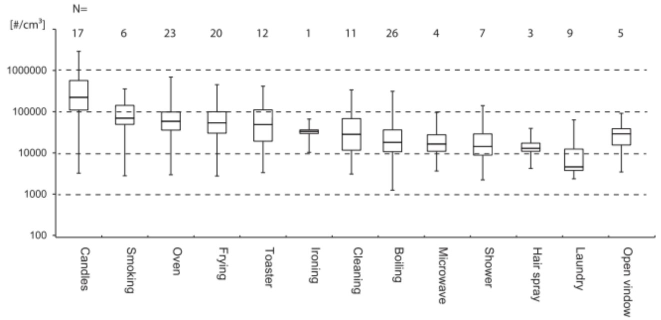
Data on in-cabin comfort from 100s of vehicles

AIR QUALITY MAPPING

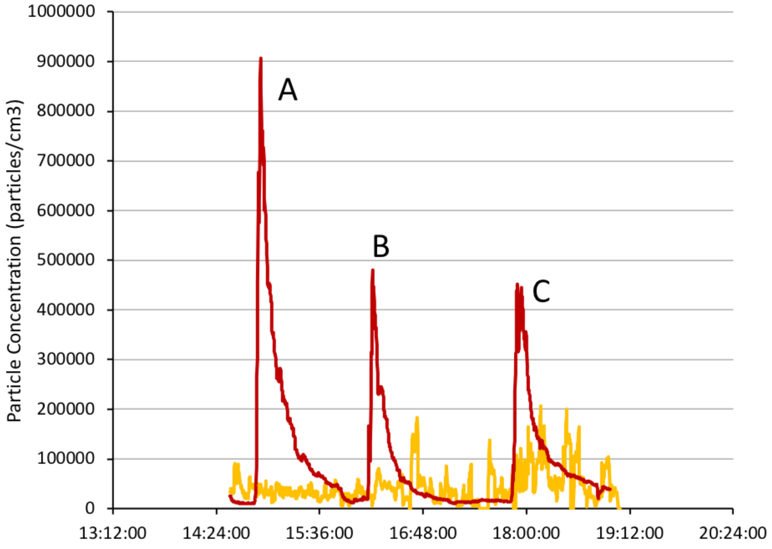
Routine mobile monitoring for measuring time-integrated concentrations at high spatial resolution

Indoor Air Quality & Energy Efficiency

- **<u>90% of our time indoors – potential for high concentrations</u>**
- Energy efficiency agenda has sealed up buildings
  - CO_2 concentration decay method for Air Change Rate
- Indoor sources can become ”trapped”
- Majority of UFP in domestic environments self-generated



Summary of PNC from various activity influenced periods (Isaxon et al., 2015)

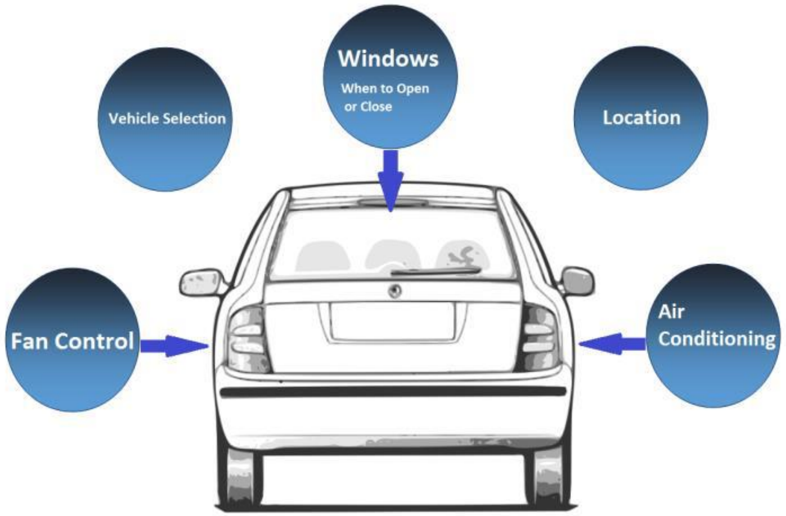


PNC with effect of various ventilation strategies, A (No Ventilation), B (Extract Fan On) and C (Windows Open) upstairs (red) and downstairs (yellow)

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

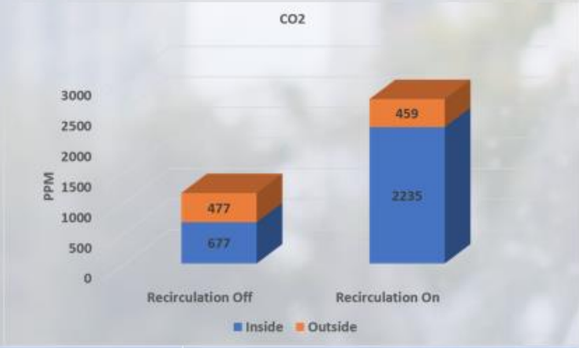


Vehicle Interior Air Quality

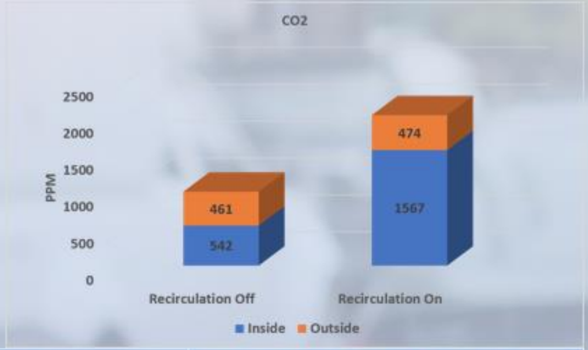
EMISSIONS ANALYTICS NAQTS

HOW MUCH AMBIENT AIR POLLUTION PENETRATES INTO THE CABIN?

	INGRESS RATIO	STUFFINESS FACTOR
Recirculation Off	24%	1.4
Recirculation On	5%	3.6



	INGRESS RATIO	STUFFINESS FACTOR
Recirculation Off	41%	1.4
Recirculation On	17%	4.97

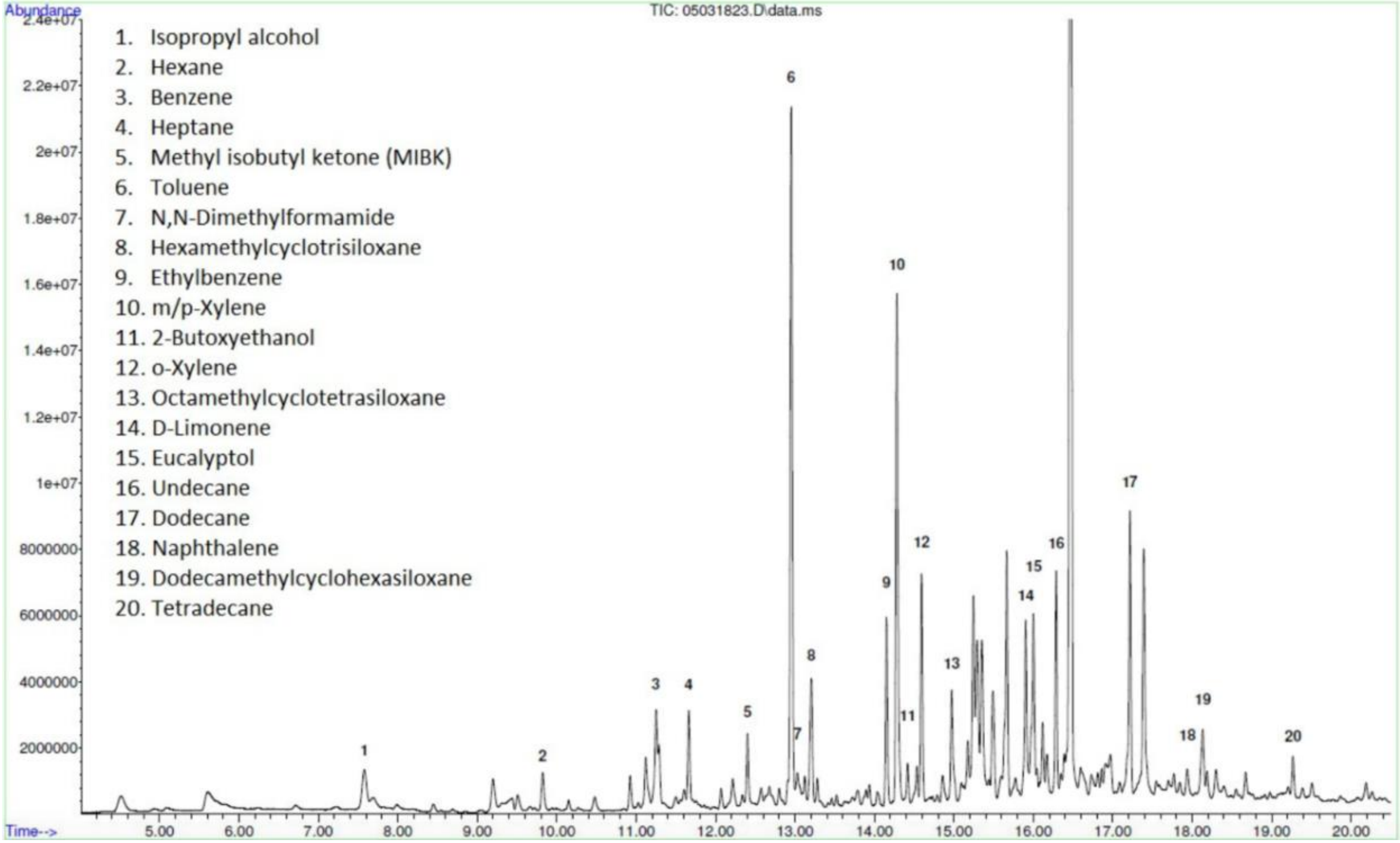


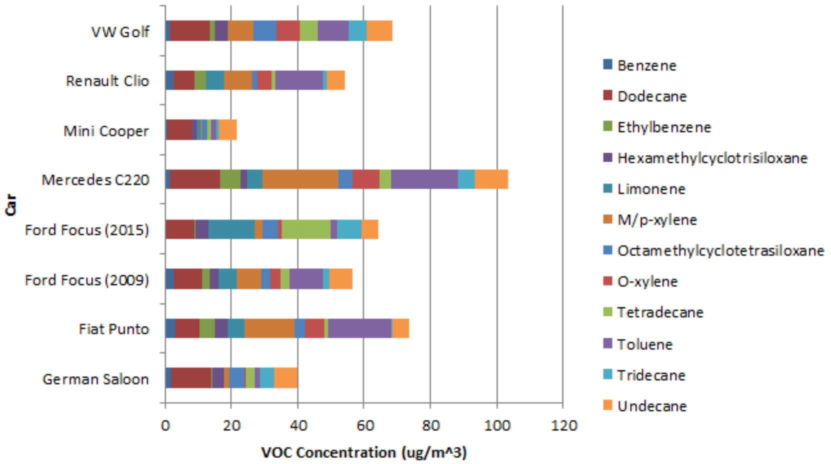
	INGRESS RATIO	STUFFINESS FACTOR
Recirculation Off	60%	1.2
Recirculation On	13%	3.3

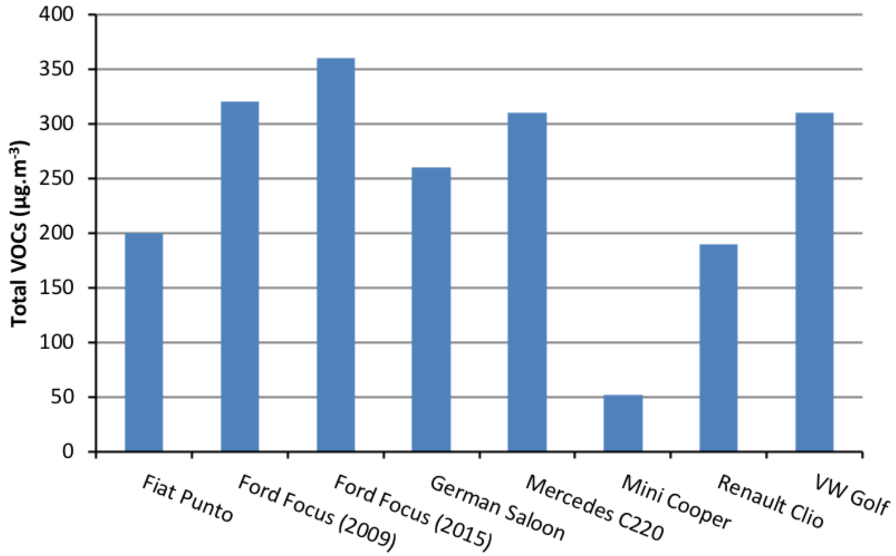
	INGRESS RATIO	STUFFINESS FACTOR
Recirculation Off	99%	1.3
Recirculation On	18%	3.4

Vehicle Interior Air Quality

Quantifying “new-car smell” and dynamic VOCs using four integrated TD tubes in the NAQTS V1000



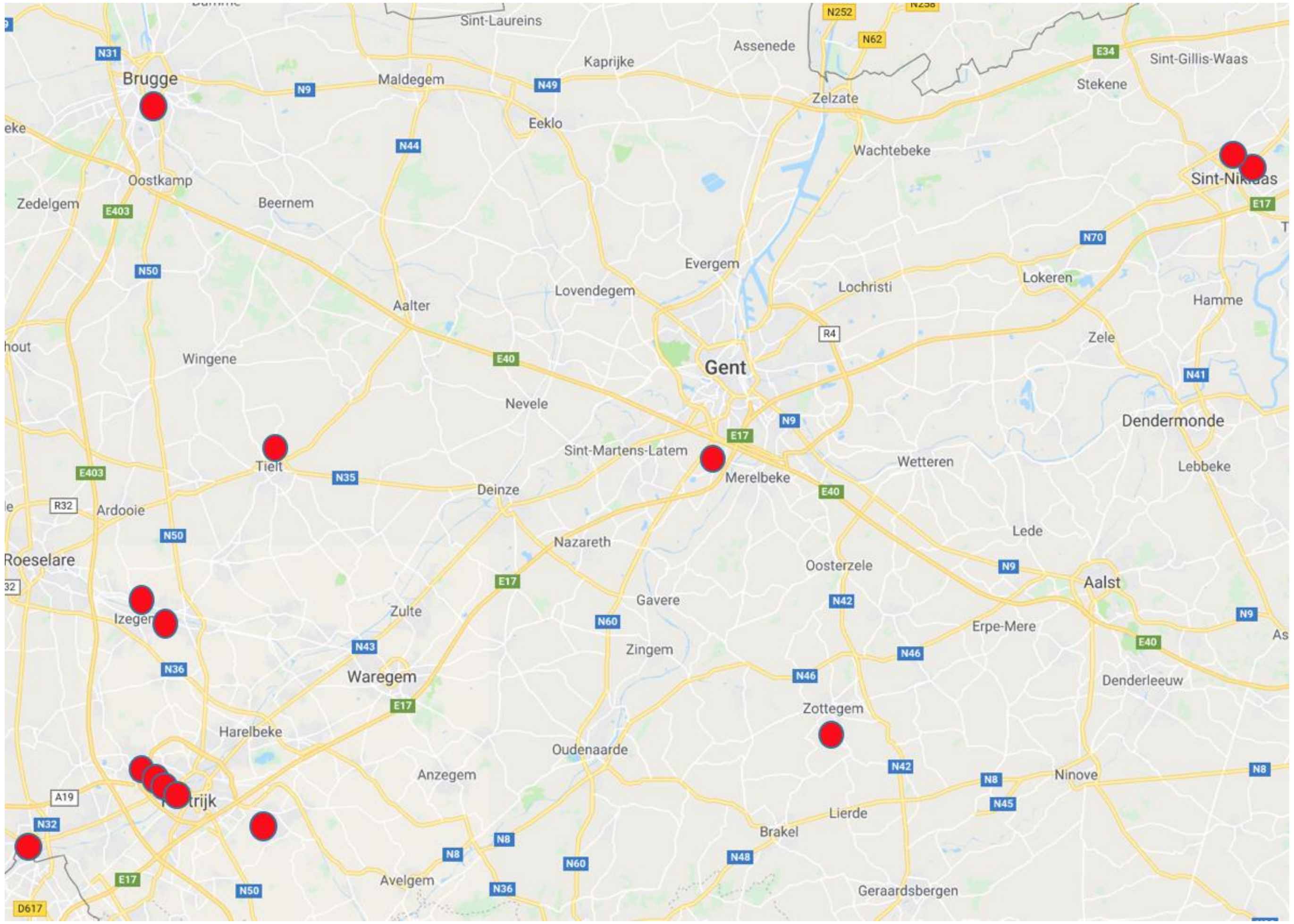




vives CALL CLEAN AIR LOVERS & LOBBYISTS NAQTS

Citizen Science

PNC Indoor:outdoor at 13 schools in the Flanders region of Belgium
Project ran by the students at VIVES Ecotechnology



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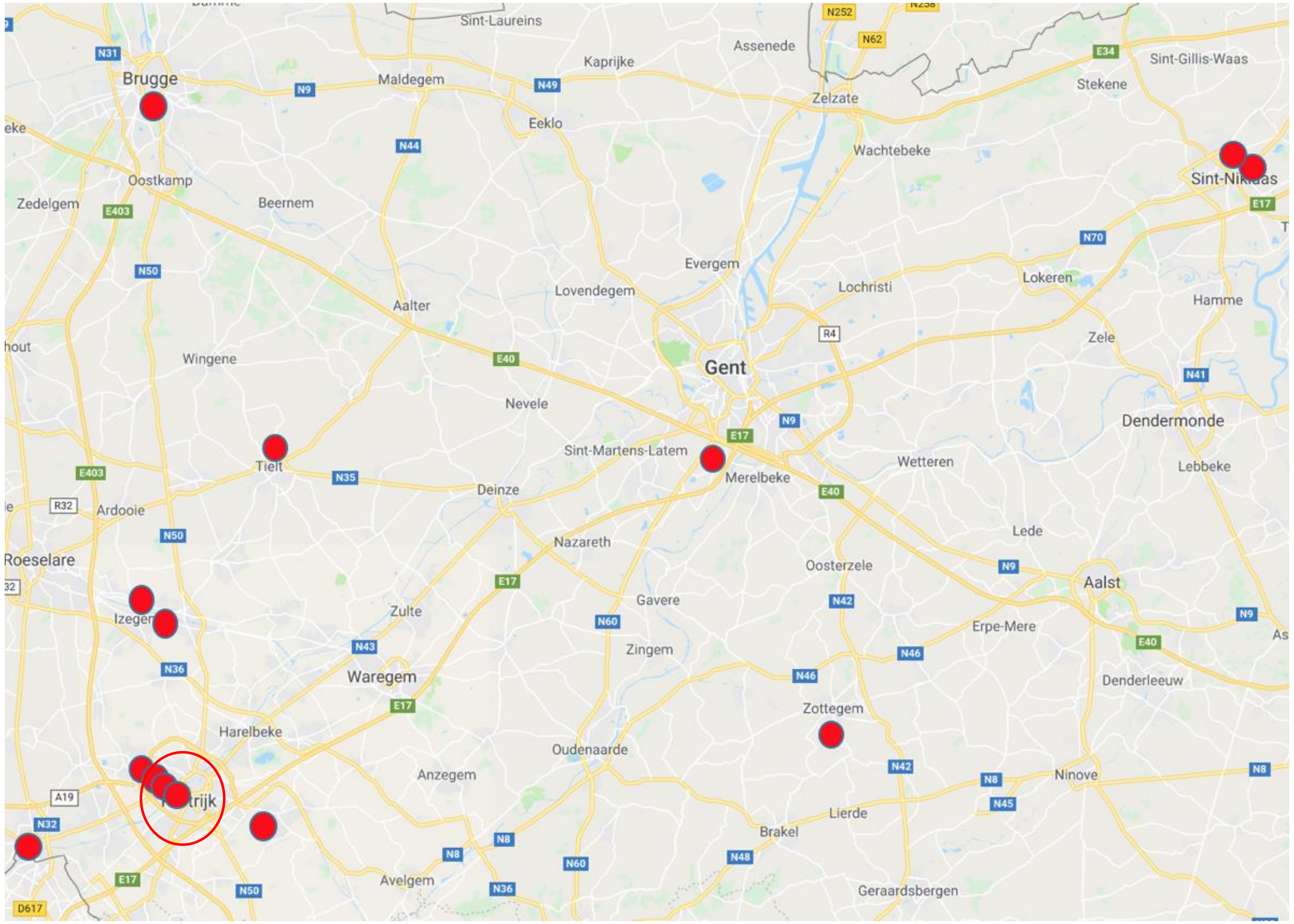
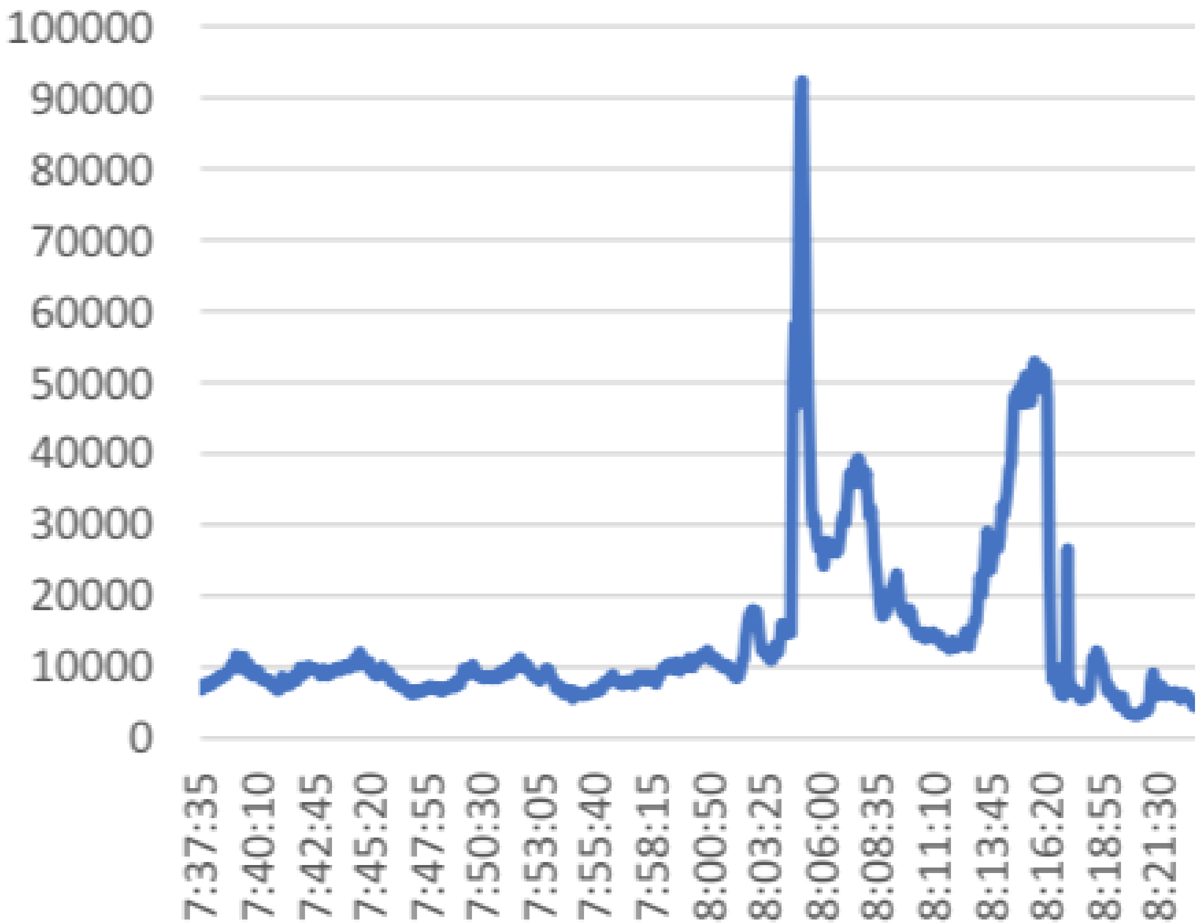


vives

CALL
CLEAN AIR LOVERS & LOBBYISTS

NAQTS

Citizen Science



Air Quality Mapping

Routine mobile monitoring for measuring time-integrated concentrations at high spatial resolution

<u>4-5 orders of magnitude improvements</u> in spatial resolution than current central site monitoring stations

However, this approach can be extended:

1. "Future developments in fast- response low-cost sensor technologies could lower the costs of this approach"
2. "In future studies, a considerably less intensive sampling scheme may provide similar results"
3. Extension of this approach into global megacities
4. Extend to the thousands of other cities where air quality management is impaired sparse monitoring infrastructure

Environmental Science & Technology
Article
pubs.acs.org/est

High-Resolution Air Pollution Mapping with Google Street View Cars: Exploiting Big Data

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Supporting Information

ABSTRACT: Air pollution affects billions of people worldwide, yet ambient pollution measurements are limited for much of the world. Urban air pollution concentrations vary sharply over short distances (≪1 km) owing to unevenly distributed emission sources, dilution, and physicochemical transformations. Accordingly, even where present, conventional fixed-site pollution monitoring methods lack the spatial resolution needed to characterize heterogeneous human exposures and localized pollution hotspots. Here, we demonstrate a measurement approach to reveal urban air pollution patterns at 4–5 orders of magnitude greater spatial precision than possible with current central-site ambient monitoring. We equipped Google Street View vehicles with a fast-response pollution measurement platform and repeatedly sampled every street in a 30-km² area of Oakland, CA, developing the largest urban air quality data set of its type. Resulting maps of annual daytime NO, NO_2, and black carbon at 30 m-scale reveal stable, persistent pollution patterns with surprisingly sharp small-scale variability attributable to local sources, up to 5–8× within individual city blocks. Since local variation in air quality profoundly impacts public health and environmental equity, our results have important implications for how air pollution is measured and managed. If validated elsewhere, this readily scalable measurement approach could address major air quality data gaps worldwide.

1. INTRODUCTION

Air pollution is a major global risk factor for ill-health and death.[1−4] Air pollution measurements are crucial for epidemiology and air quality management, but the extent of ground-based air pollution observations is limited.[5,6] For many developing-country regions, especially in populous parts of Asia and Africa, robust air quality monitoring is largely absent.[5] Even for high-income regions, ambient monitors are generally sparsely sited. For the 60% of the U.S. census urban areas with continuous regulatory monitoring, there are a mean of ~2–5 monitors per million people and 1000 km² (Supporting Information (SI) Table S1). However, primary air pollutant concentrations in cities can vary sharply over short distances (~0.01–1 km) owing to unevenly distributed emissions sources, dilution, and physicochemical transformations.[7−10] Such gradients are not well represented with routine ambient measurements, but have important implications for exposure assessment, epidemiology, air quality management, and environmental equity.[10−13]

Advances in air pollution exposure assessment techniques over the past two decades have helped address limitations of (i) data coverage and (ii) spatial resolution that are associated with central-site ambient monitoring.[10,14] These methods include satellite remote sensing (RS), chemical transport models (CTMs), land-use regression (LUR) models, and direct personal exposure measurements.[14] Each of these approaches has distinct advantages and limitations. Satellite RS instruments and CTMs

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Innovate UK

Newton Fund

CHINESE ACADEMY OF SCIENCES

NAQTS

Lancaster University

Air Quality Mapping

2 year project in Guangzhou (megacity)

<u>Land-use regression model</u> combining: mobile air quality monitoring, fixed site stations, meteorological, land-use, traffic volume, POI data etc.

Will map UFP and other pollutants

Developing an **<u>app to predict air pollution exposure</u>**

When combined with cellular GPS data, rich "personal exposure analytics" become possible

Case study to demonstrate feasibility of a low-cost air quality monitoring network

Potential for expansion: >150 cities in China with a population of >1 million

Conclusions

- **CPC technology can be affordable for low-cost applications**
- Significant opportunities
  - Increased spatial resolution
  - Fill data gaps in spare monitoring networks
  - Inspire behavioural change and empower citizens
- Potential for transformative understanding of air quality
  - Environmental management
  - Air pollution science
  - Epidemiology
  - Public awareness
  - Informed public policy
- However;
  - Deeper understanding of low costs sensor performance required for holistic understanding
  - CPCs need to be further “de-skilled” to make accessible to all

Any questions?

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