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

Douglas Booker

NAQTS

Safe Nanotechnology - Exposure assessment, Risk Management and Regulatory challenges| 25th September 2018

Background

National Air Quality Testing Services (NAQTS) is a social business, founded in 2015, 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 V2000 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), Ann Arbor, Michigan, USA, and Guangzhou, China.

Lancaster Environment Centre | Lancaster University

NAQTS

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

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

NAQTS V2000: Integration for holistic monitoring

NAQTS Air Quality Bench integrated into **NAQTS V2000**
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

NAQTS V2000: Integration for holistic monitoring

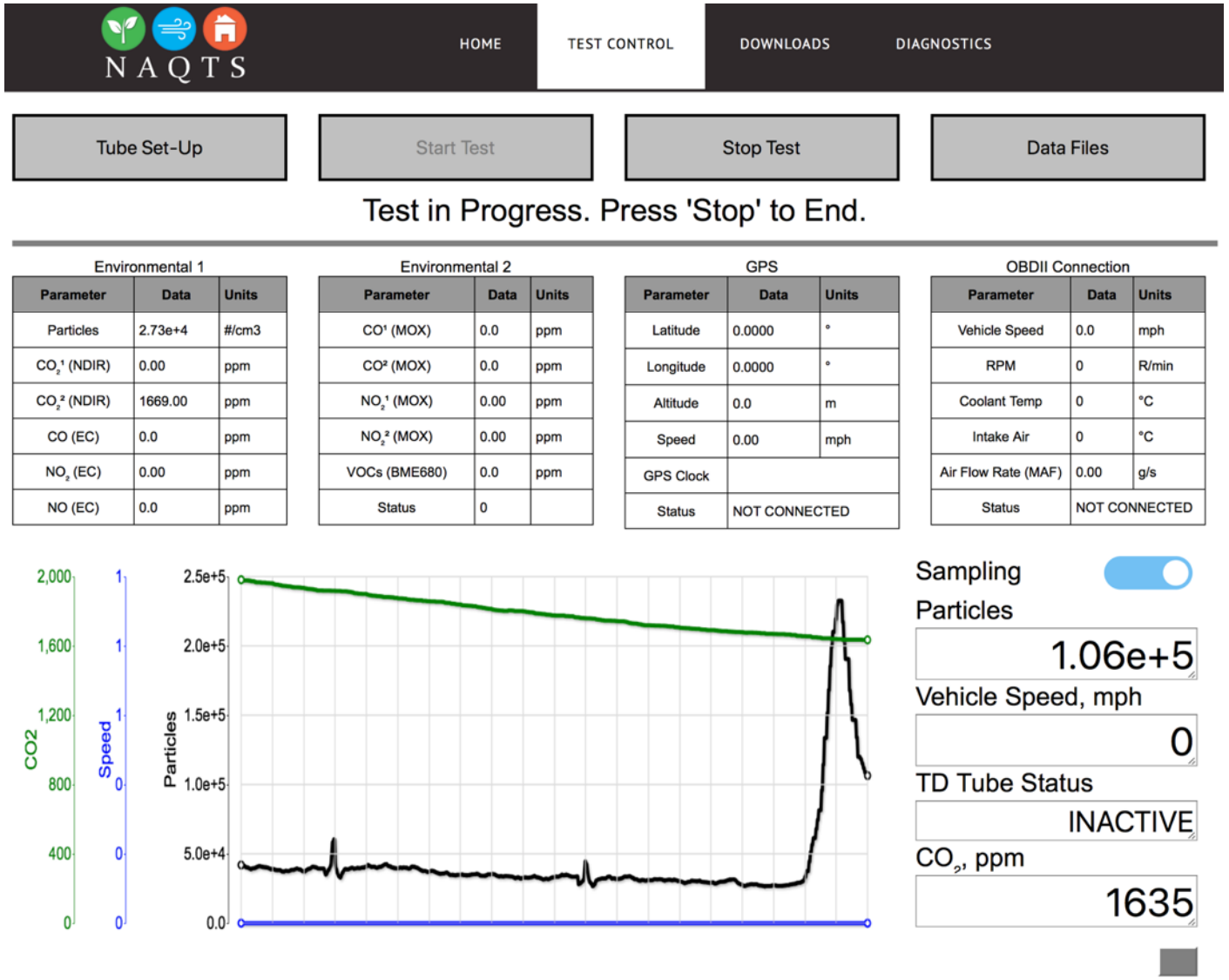
WiFi

Automatic ACH Calculation

Geofencing

Embedded Linux OS

Cloud Connectivity (GSM)



Condensation Particle Counter (CPC)

Regulatory grade PN: ISO 27891

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

CERTIFICATE OF CALIBRATION

ISSUED BY Ricardo Energy & Environment
a trading name of Ricardo-AEA Ltd.

DATE OF ISSUE | CERTIFICATE NUMBER | DRAFT

0401

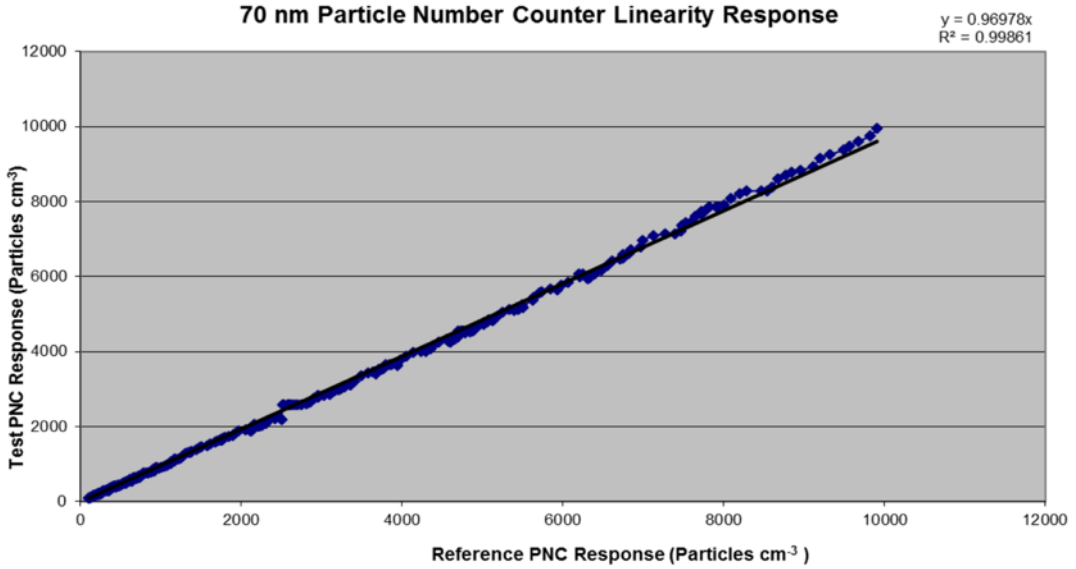
Ricardo Energy & Environment
Particle Measurement Centre
Unit 2 Ludbridge Mill
Reading Road, East Hendred
Wantage, Oxfordshire
OX12 8LN

Telephone: 01235 861343 Email: PMC.EE@Ricardo.com Web: ee.Ricardo.com

Page 1 of 5 pages
Approved Signatory
Name
Signature

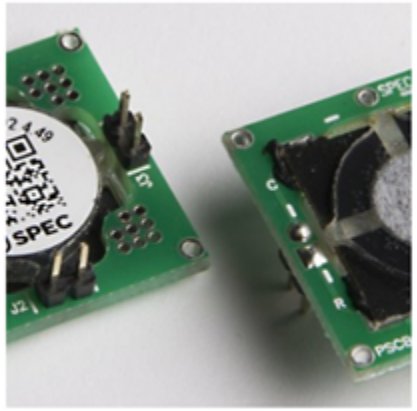
EXAMPLE ONLY

Particle counting efficiency against d_{50}=10 nm transfer standard				
Diameter (nm)	Efficiency	$\|x_{min.}(a_1-1)+a_0\|$ ≤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



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.

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

	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	---	---	---	---	---	---	---	---	---

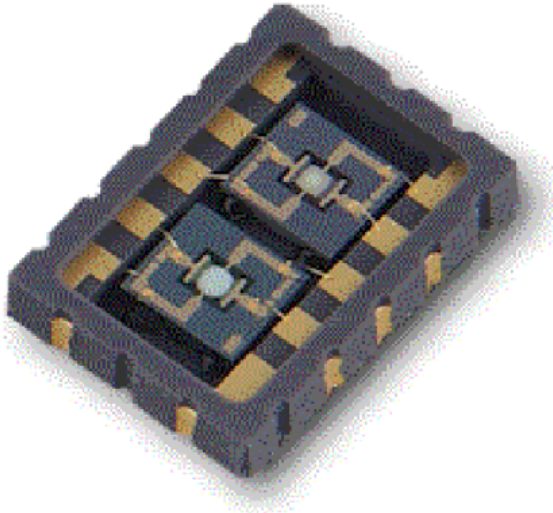
Metal Oxide

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.



Product shown without cap

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

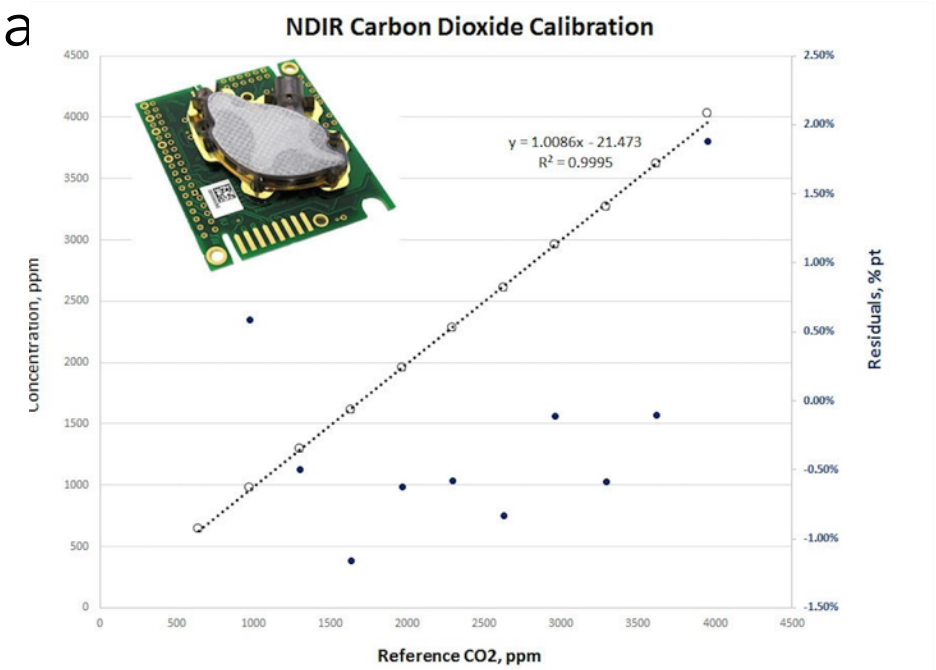
SENSOR CONFIGURATION

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 ada



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.

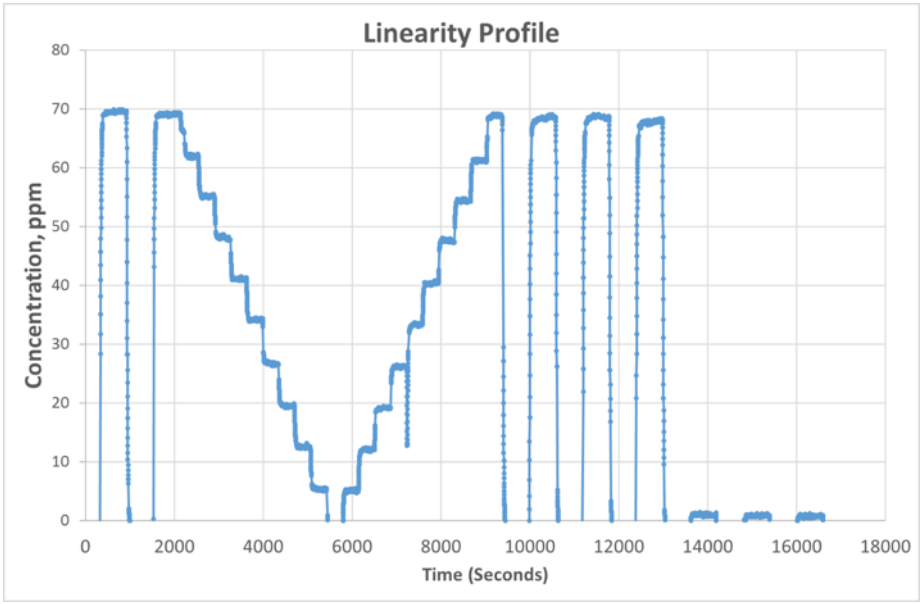
Key Benefits | Applications | **Specifications** | Art.no. | Download

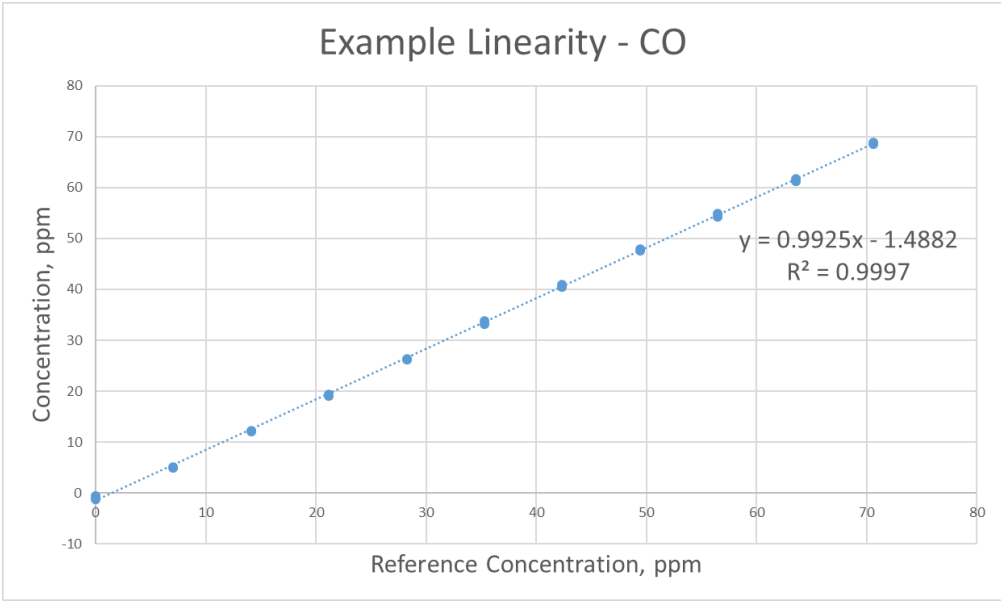
Operating Principle	Non-dispersive infrared (NDIR)
Measured gas	Carbon dioxide (CO_2)
Measurement range CO_2	0 to 5000 ppm / 0 to 3%vol
Accuracy	±30 ppm ±3% of reading
Dimensions	57 mm x 51 mm x 14 mm
Maintenance	Maintenance-free*
Life Expectancy	> 15 years
Operation temperature range	0 to 50 °C
Operation 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





Applications of the NAQTS V2000

BENCHMARKING VEHICLES "COMFORT"
Air Quality, Noise, and Vibration
Data on in-cabin comfort from 100s of vehicles per year

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

OCCUPATIONAL HEALTH AND SAFETY
Evaluation of exposure to nanomaterials

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

Vehicle Interior Air Quality

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

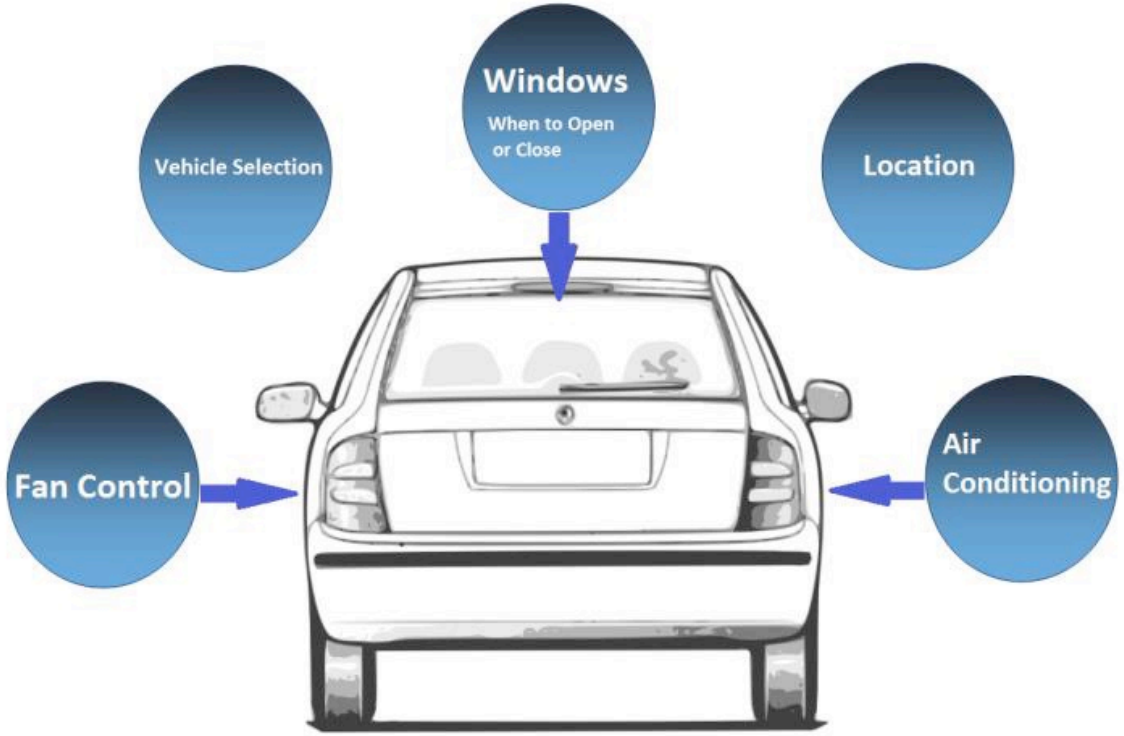
Immediate proximity to significant pollutant sources (other vehicles), plus in urban areas, high outdoor concentrations

Simultaneous indoor and outdoor measurements

Vehicle Interior Air Quality

Key questions:

1. How much ambient air pollution is coming into the vehicle?
2. What are the in-vehicle sources of air pollution?



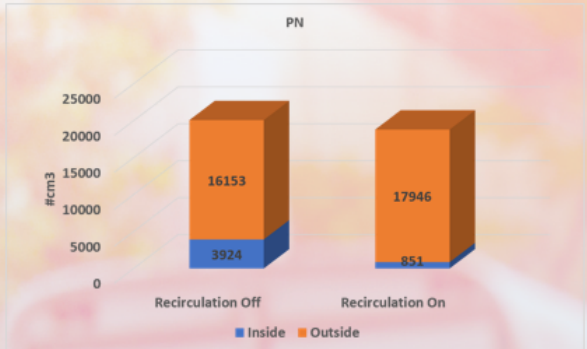
(Müller et al. 2011)

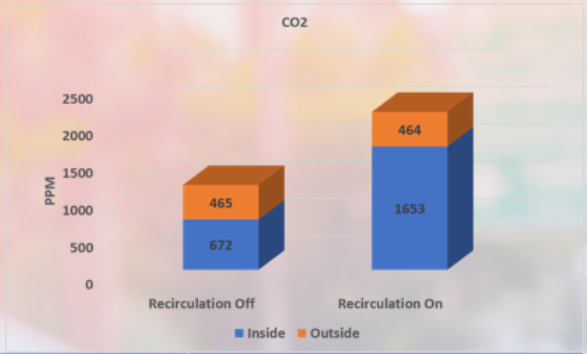
Vehicle Interior Air Quality

EMISSIONS ANALYTICS

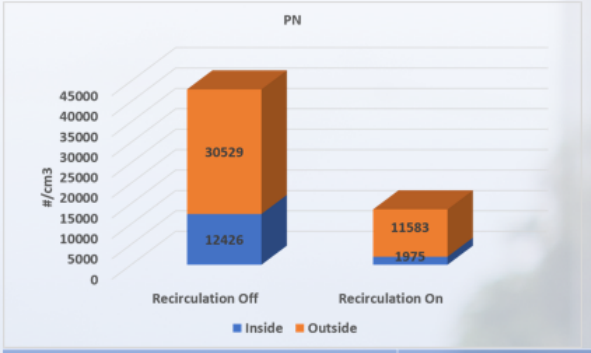
NAQTS

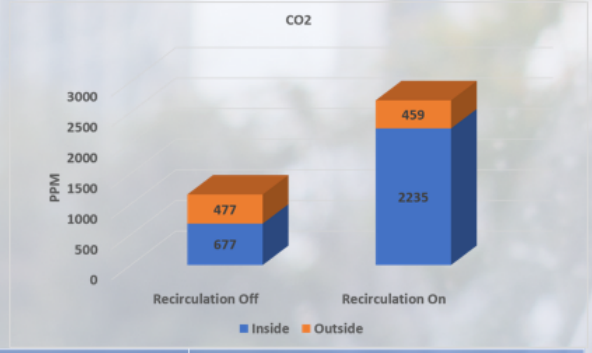
HOW MUCH AMBIENT AIR POLLUTION PENETRATES INTO THE CABIN?



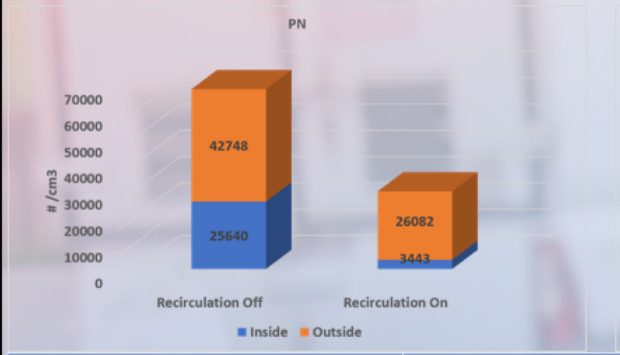


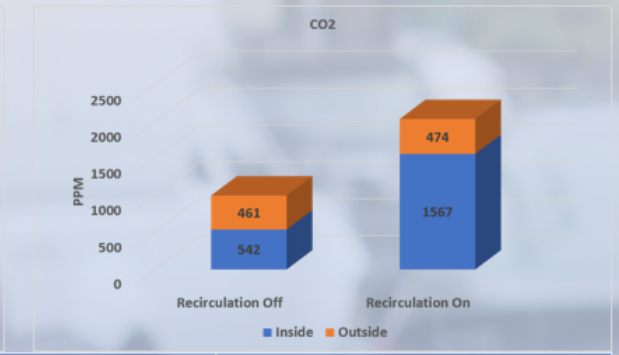
	INGRESS RATIO	STUFFINESS FACTOR
Recirculation Off	24%	1.4
Recirculation On	5%	3.6



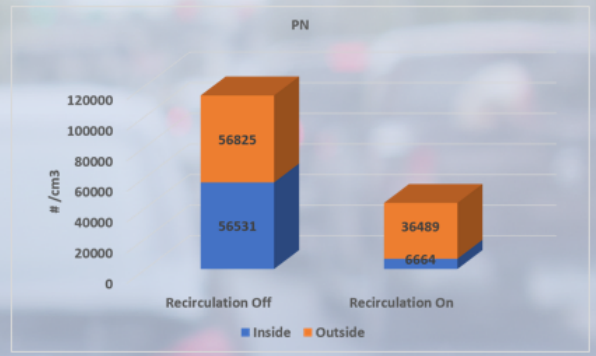


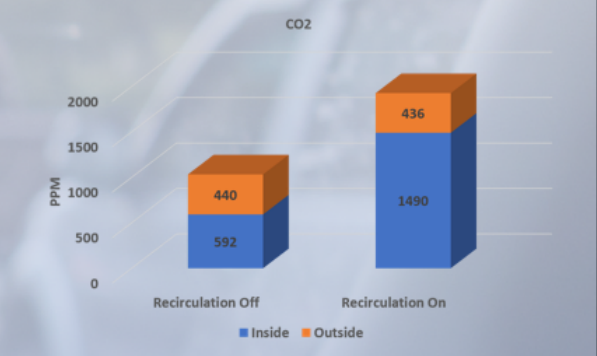
	INGRESS RATIO	STUFFINESS FACTOR
Recirculation Off	41%	1.4
Recirculation On	17%	4.97





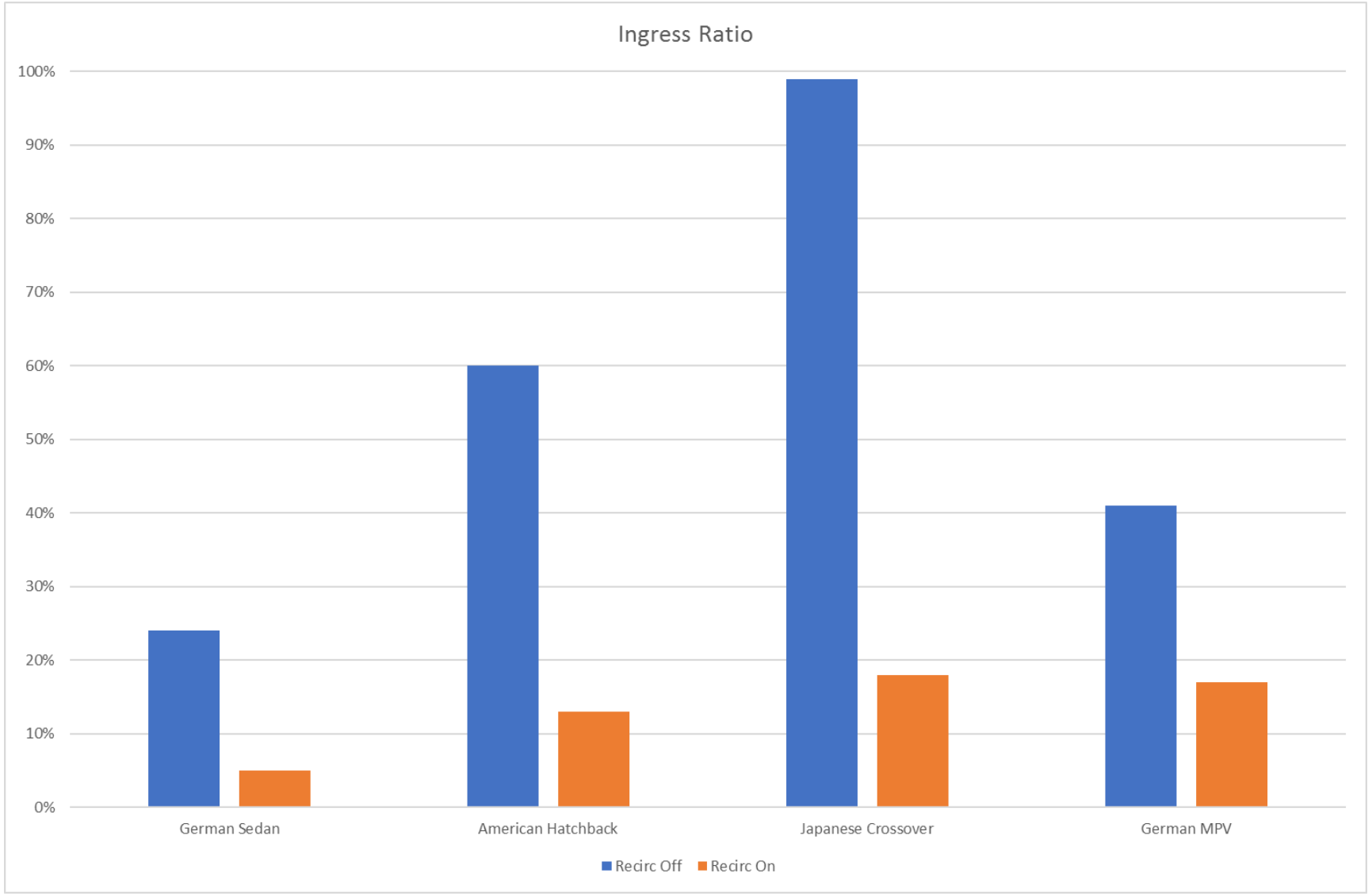
	INGRESS RATIO	STUFFINESS FACTOR
Recirculation Off	60%	1.2
Recirculation On	13%	3.3



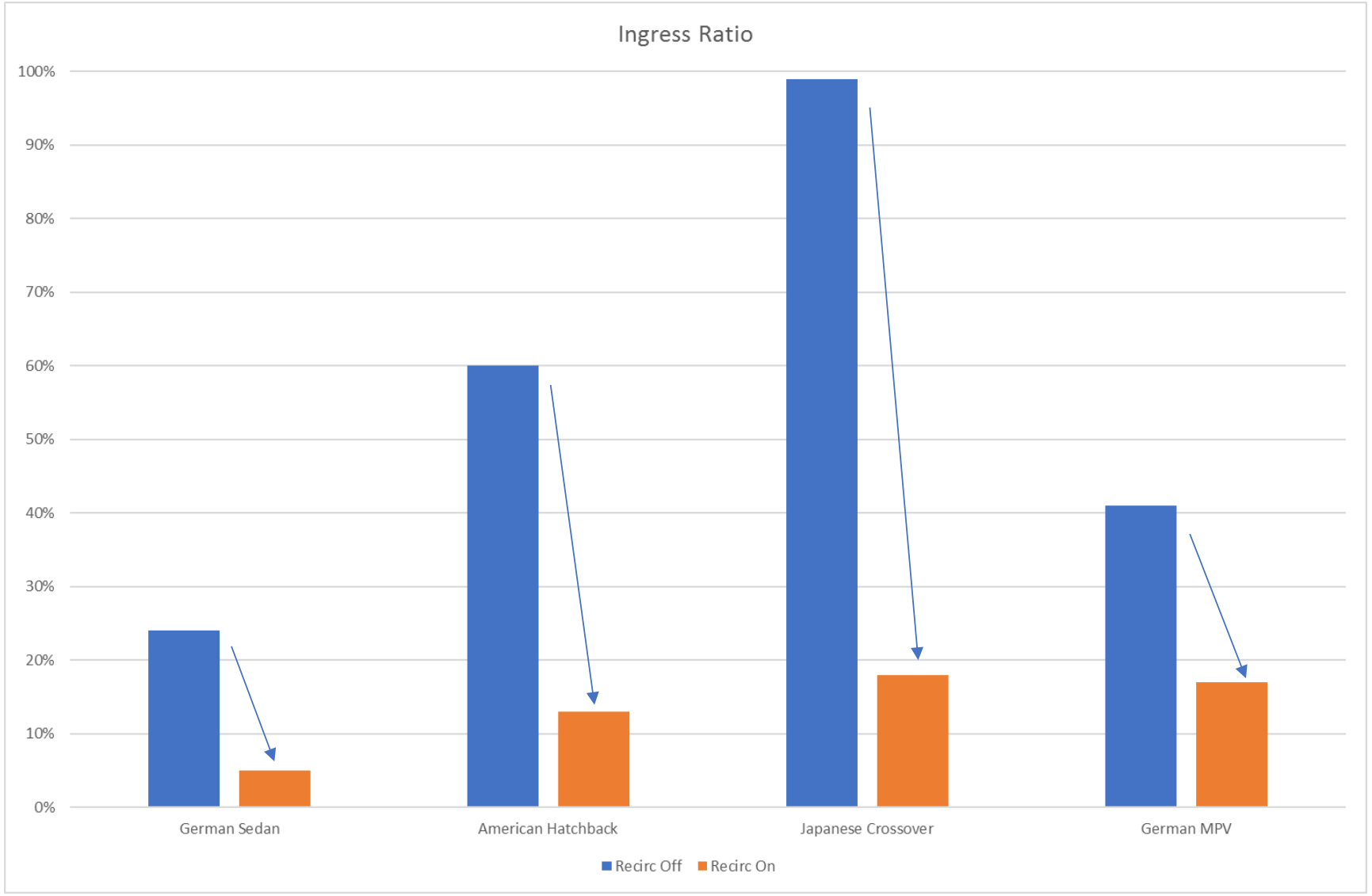


	INGRESS RATIO	STUFFINESS FACTOR
Recirculation Off	99%	1.3
Recirculation On	18%	3.4

Ultrafine Particles – Ingress Ratio



Ultrafine Particles – Ingress Ratio

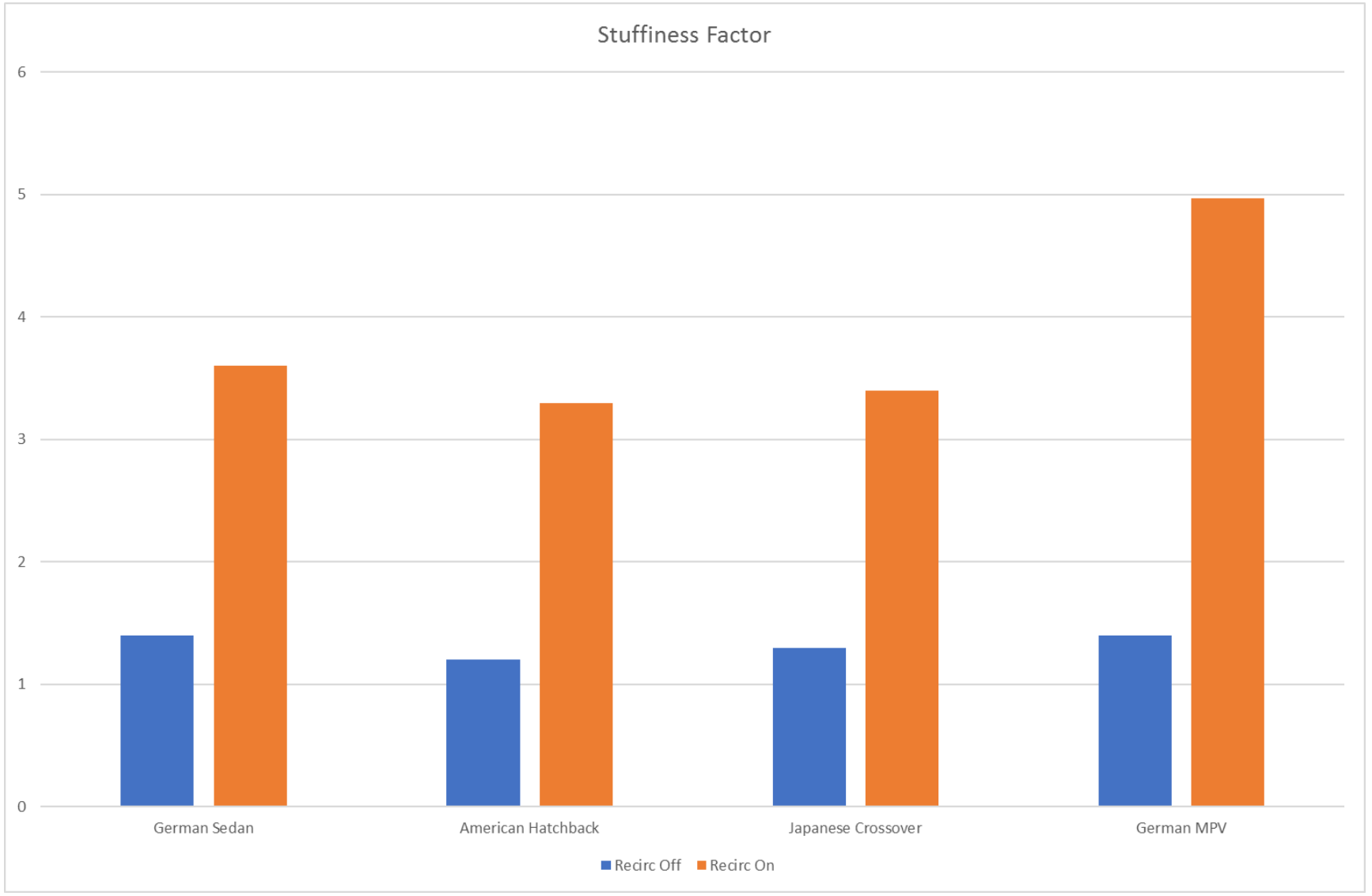


The data from these four vehicles shows the **heterogeneity of Ingress Ratios**

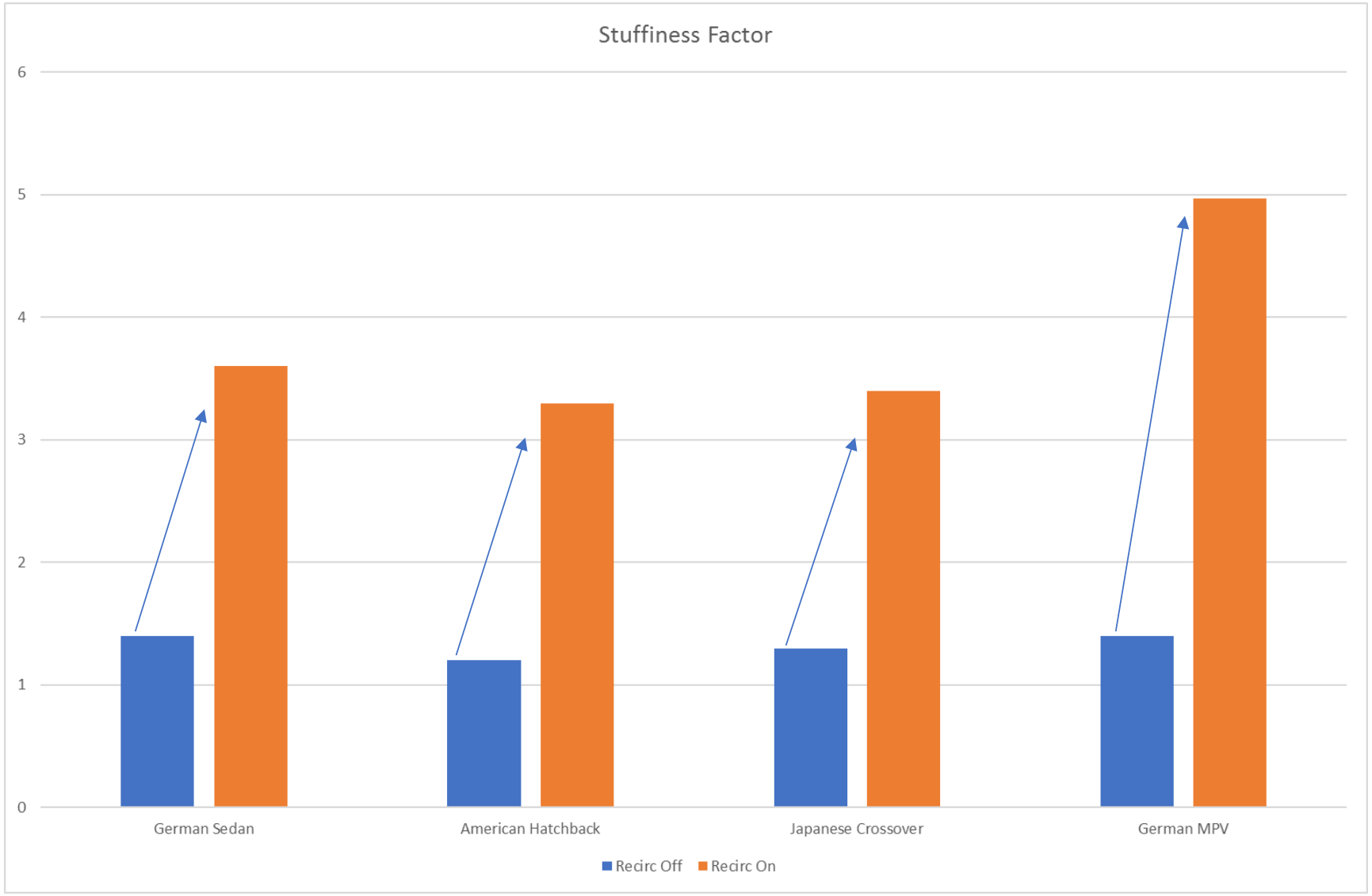
24-99% with recirculation mode off

5-17% with recirculation mode on

CO2 – Stuffiness Factor

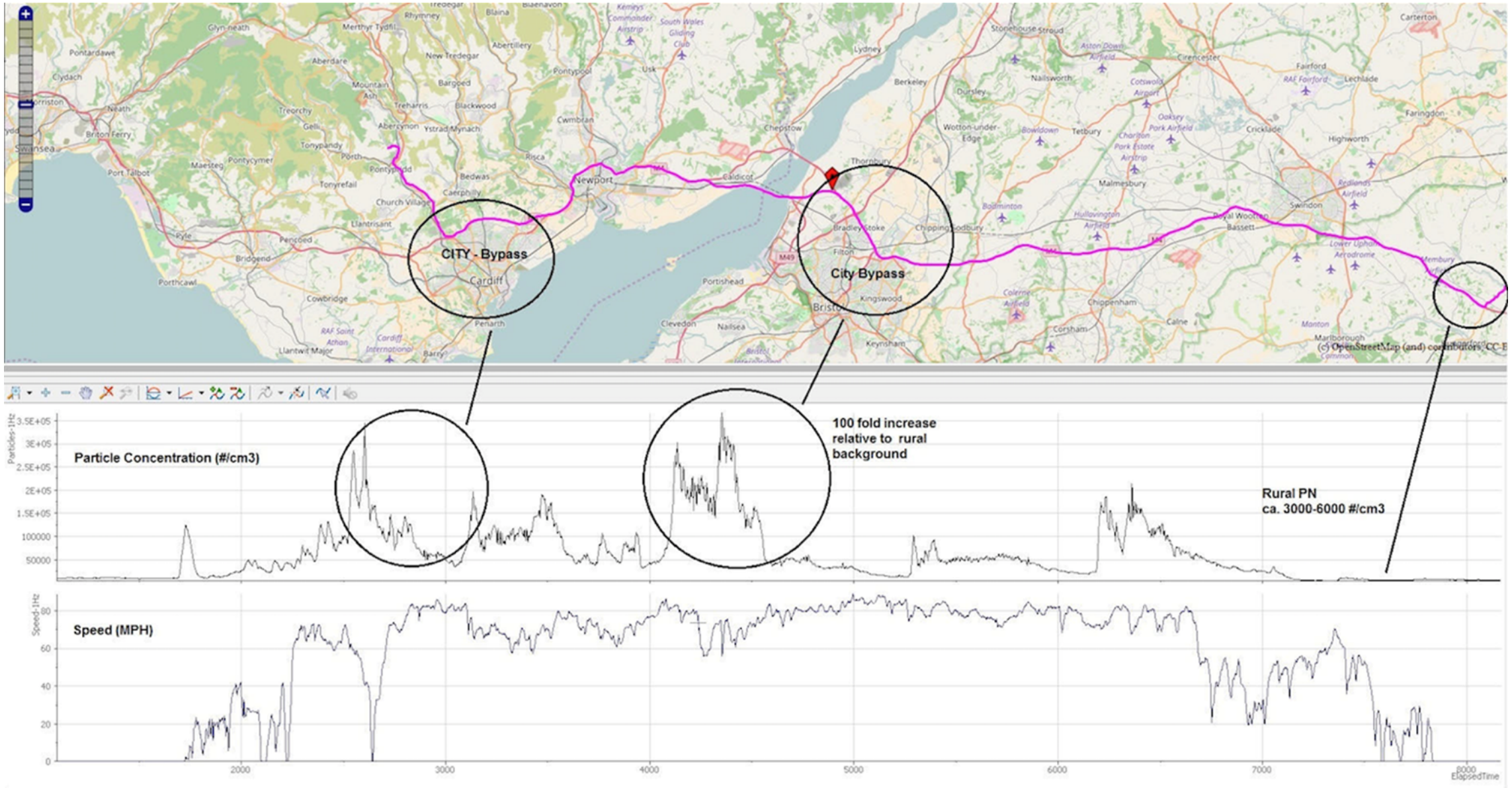


CO2 – Stuffiness Factor



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

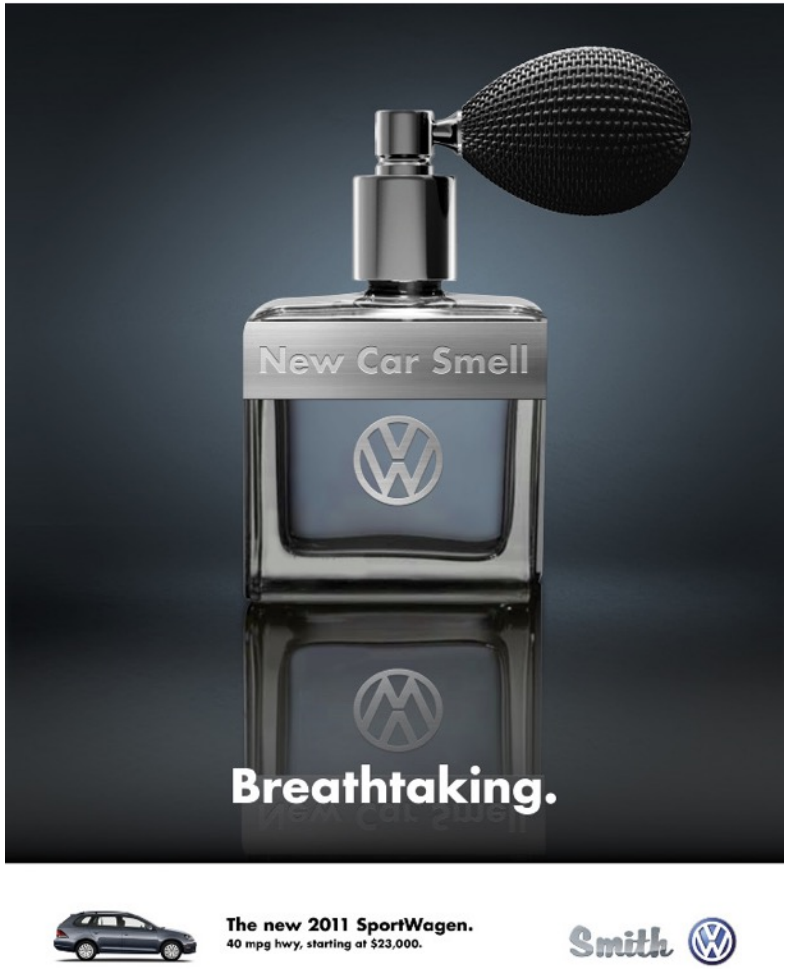

CITY - Bypass
City Bypass
Particle Concentration (#/cm3)
100 fold increase
relative to rural
background
Rural PN
ca. 3000-6000 #/cm3
Speed (MPH)
ElapsedTime

Q2: Vehicle Interior Pollutants

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



Regulatory Context

Who is setting standards?

- **Automobile Associations** (JAMA, ACEA, TÜV Rhineland Group etc.)
- **Manufacturers** (GM, BMW, VW, etc.)
- **ISO** (ISO 12219-1 – ISO 12219-7)

Monitoring techniques?

- **Environmental Chambers** (BMW GS97014-3, ISO 12219-3 - ISO 12219-5)
- **Bag method** (TSM0508G, ISO 12219-2)
- **TD GC-MS** (PB VWL 709; VDA 278)

What are they monitoring?

- Interior materials (GMW15634)
- Full vehicle (GMW15654, ISO 12219-1)

Move towards harmonisation…

"Shall include provisions and harmonized test procedures for the measurement of interior VOCs taking into account existing standards"

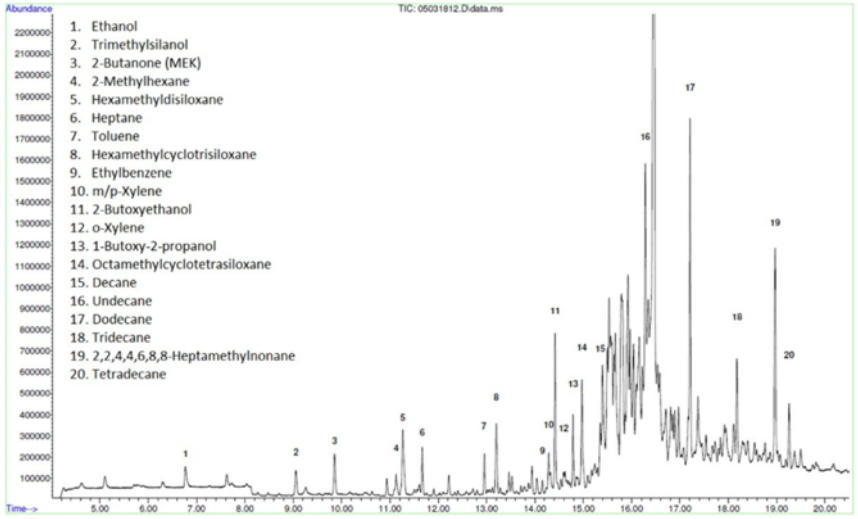
UNECE

Experimental Set-Up (Static Baseline)

Hydrophobic TnxTA/Cg1

Integrated into NAQTS V2000

Tested inside Emissions Analytics' Stokenchurch Emissions Lab



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

Experimental Set-Up (Real World Driving)

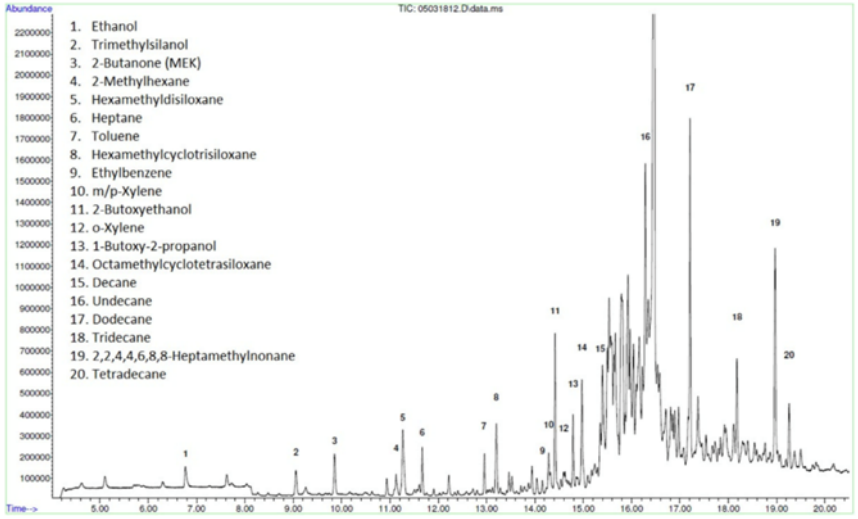
Hydrophobic TnxTA/Cg1

Integrated into NAQTS V2000

Tested dynamically on RDE-type route (Geofencing – Urban, Rural, Highway etc.) at same time as indoor-outdoor research to see VOCs ingress

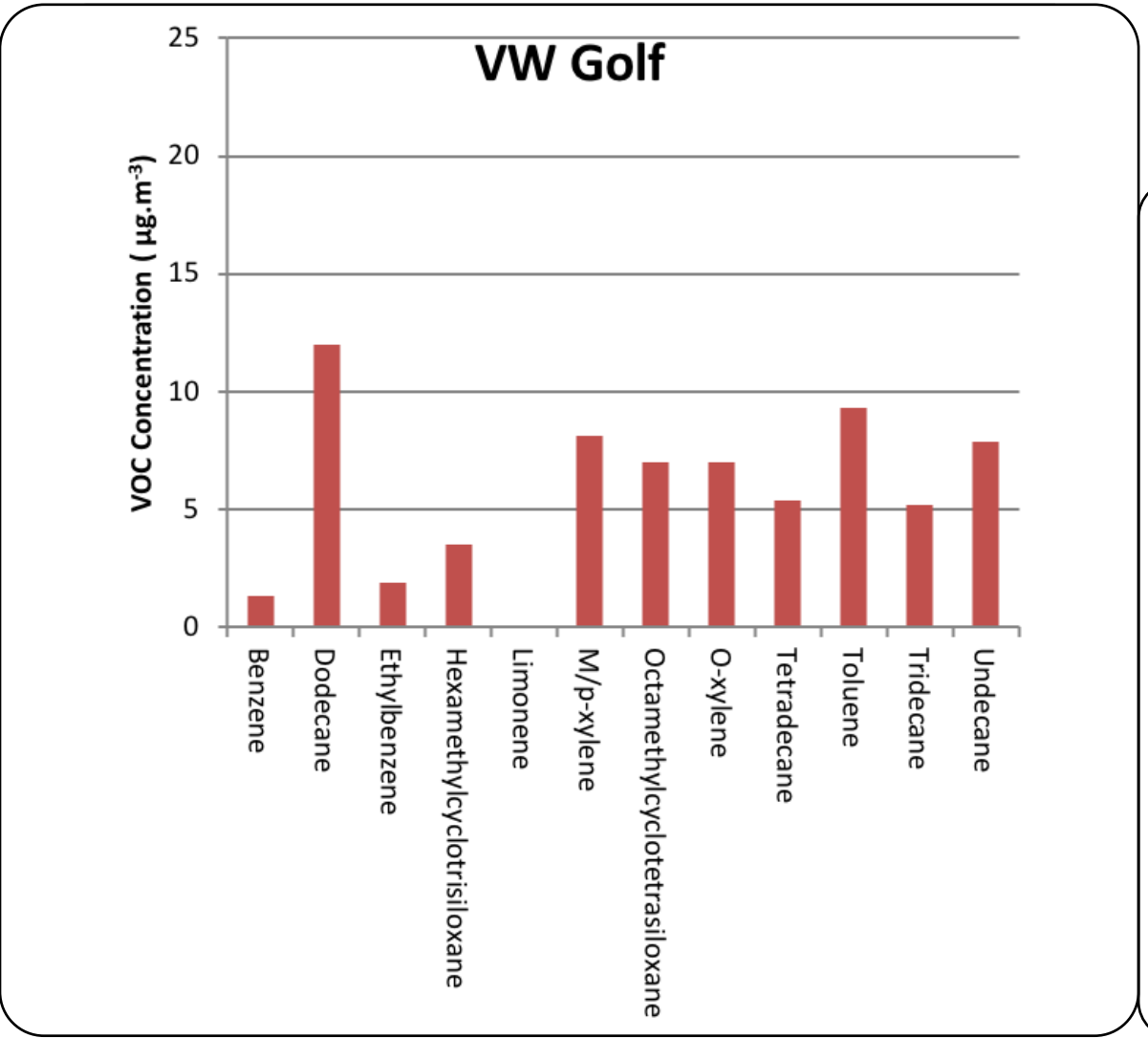
Thermal Desorption

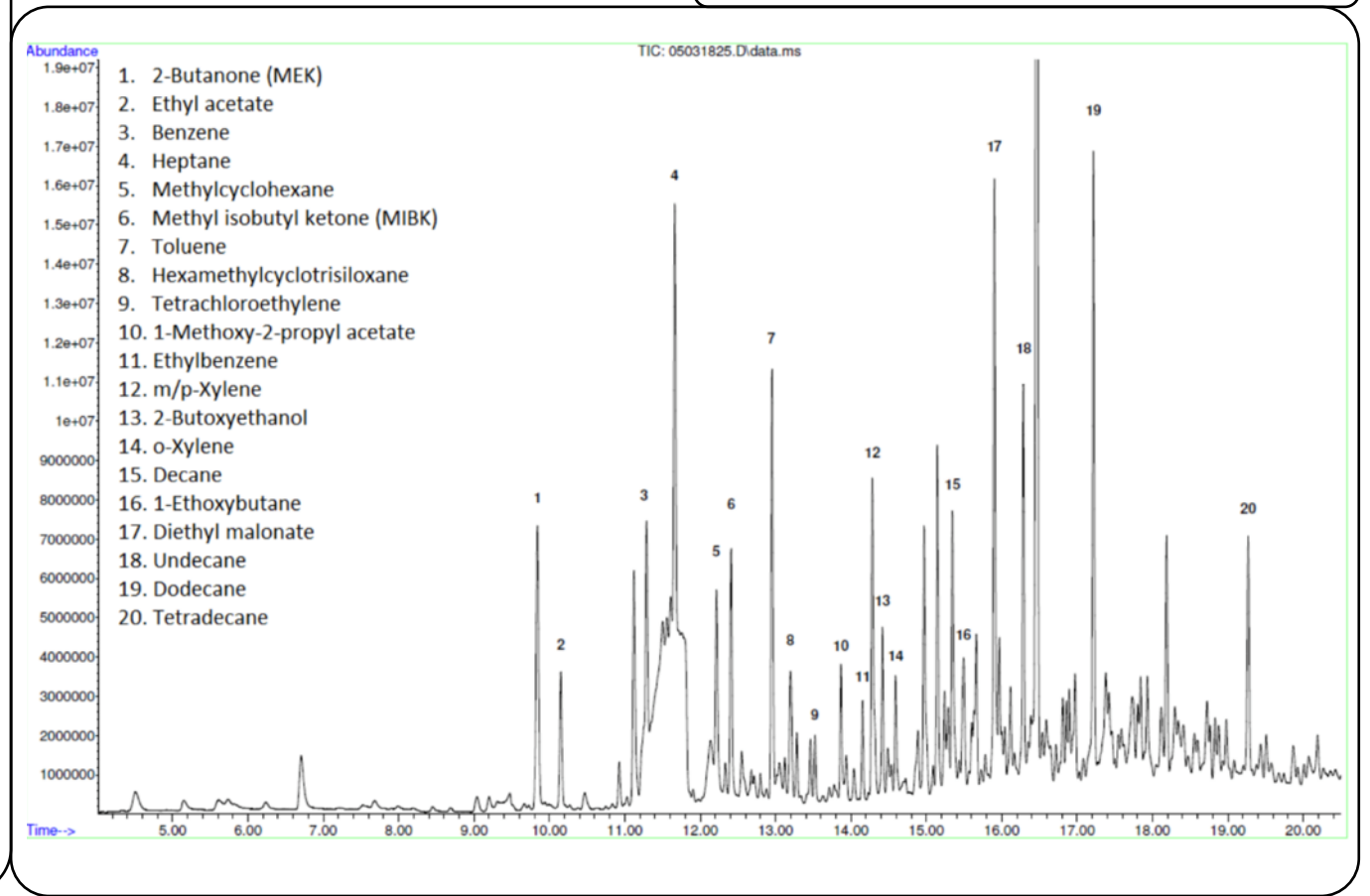
Agilent GC-MS, samples run on full scan mode



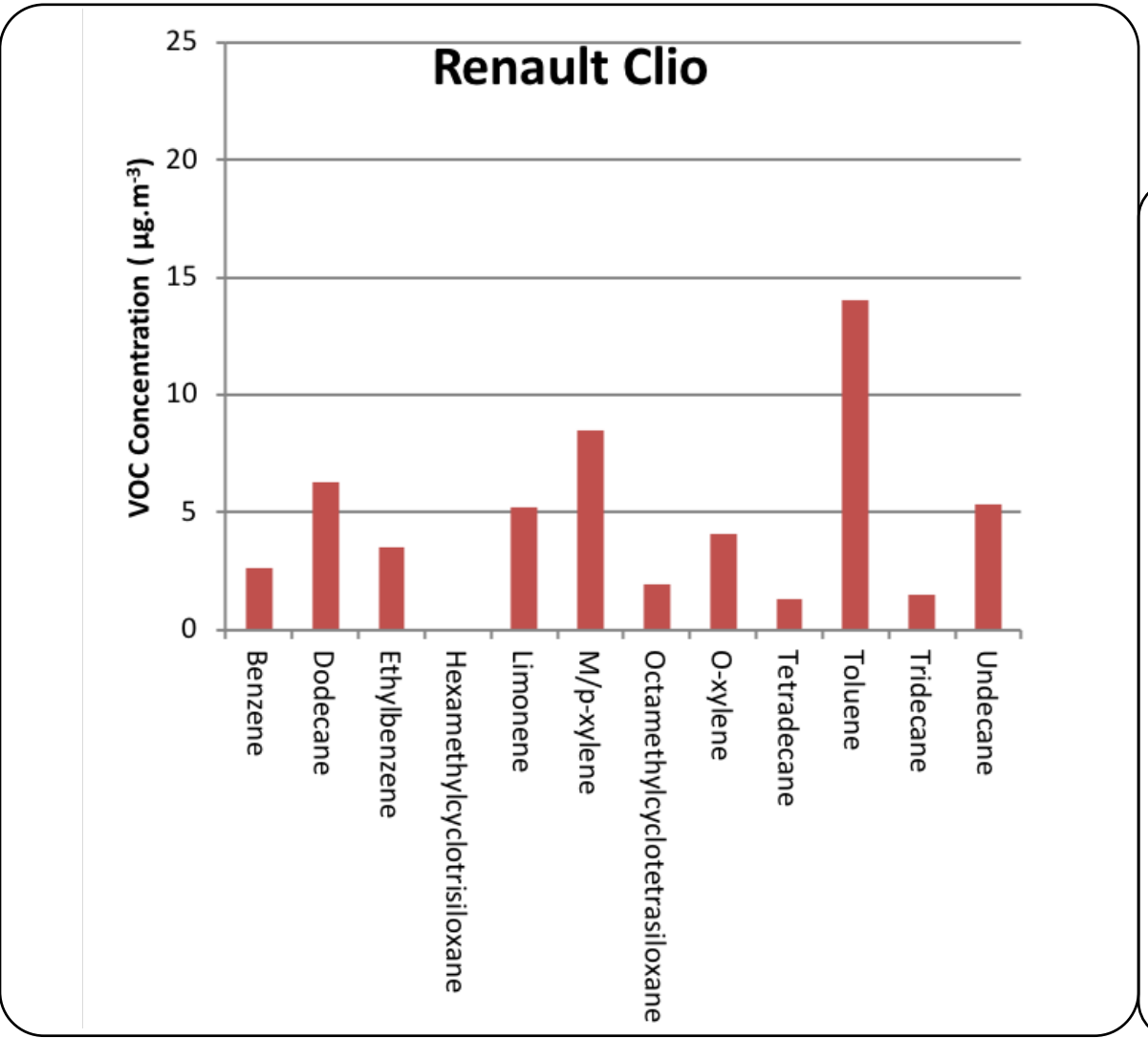
Top 20 peaks, Semi-quantitative (spiked with d8-Toluene, d6-benzene and d4-dichlorobenzene)

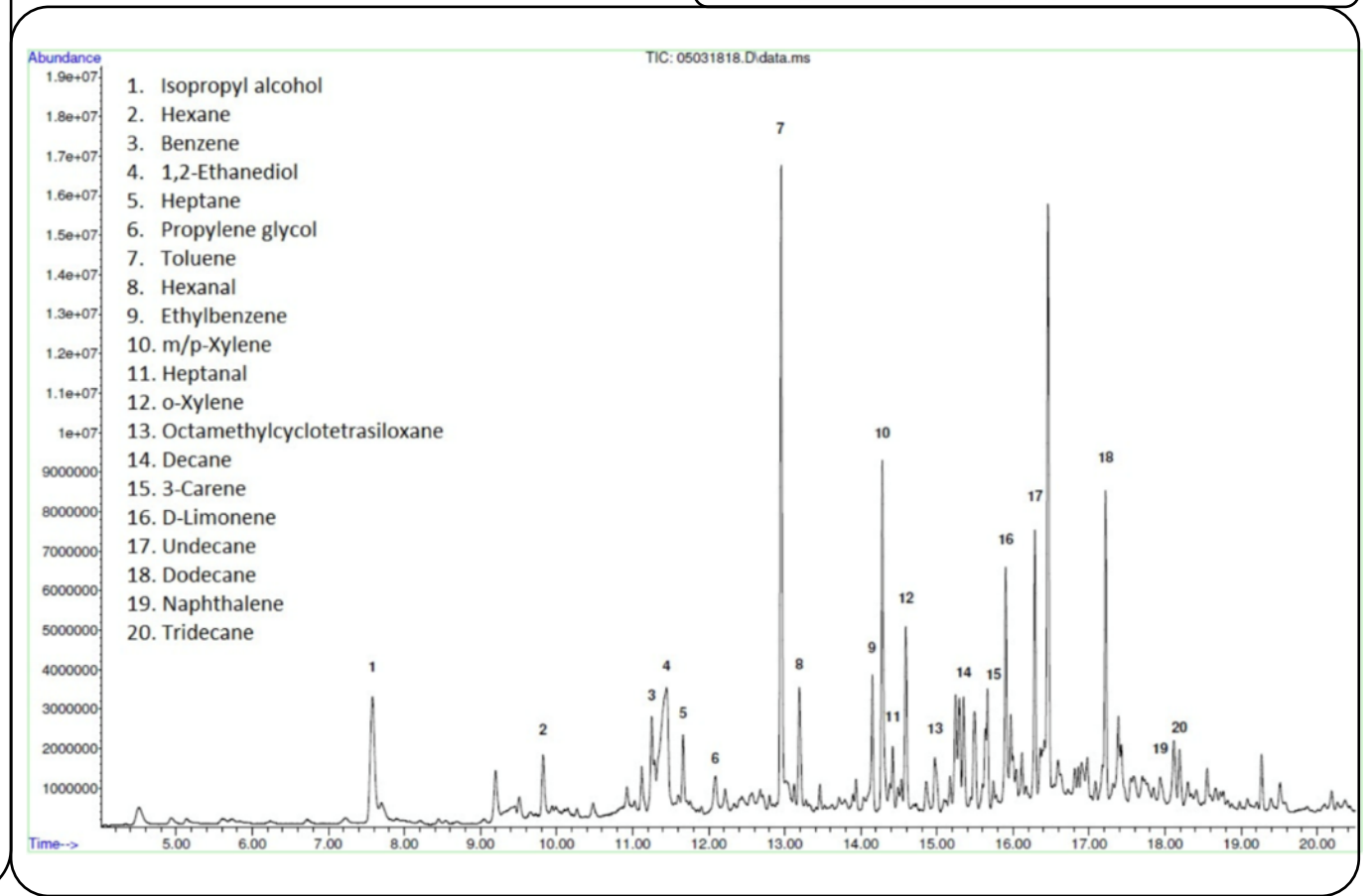
VW Golf (2011)


VW Golf
VOC Concentration (µg.m-3)
25
20
15
10
5
0
Benzene
Dodecane
Ethylbenzene
Hexamethylcyclotrisiloxane
Limonene
M/p-xylene
Octamethylcyclotetrasiloxane
O-xylene
Tetradecane
Toluene
Tridecane
Undecane

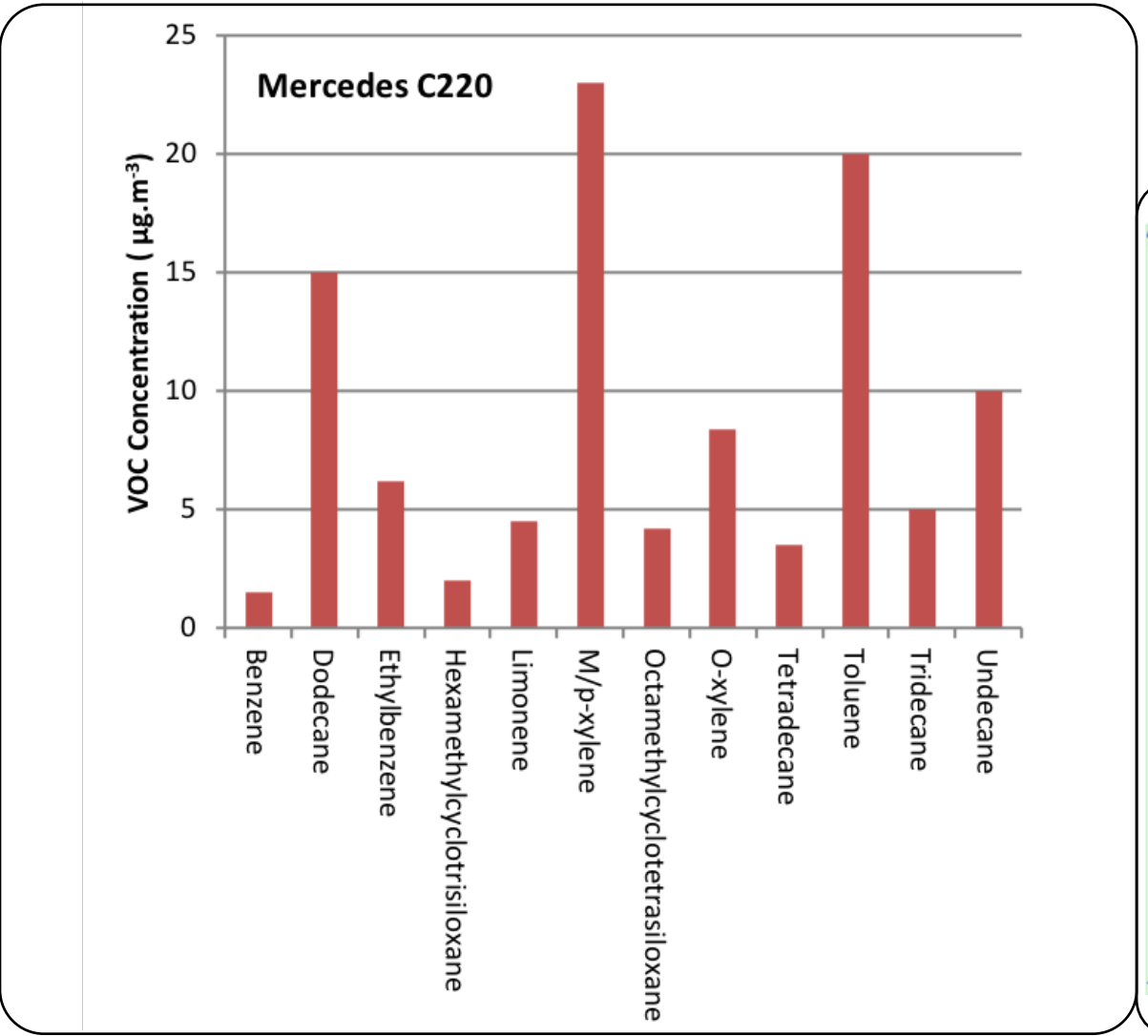

Abundance
TIC: 05031825.D\data.ms
1. 2-Butanone (MEK)
2. Ethyl acetate
3. Benzene
4. Heptane
5. Methylcyclohexane
6. Methyl isobutyl ketone (MIBK)
7. Toluene
8. Hexamethylcyclotrisiloxane
9. Tetrachloroethylene
10. 1-Methoxy-2-propyl acetate
11. Ethylbenzene
12. m/p-Xylene
13. 2-Butoxyethanol
14. o-Xylene
15. Decane
16. 1-Ethoxybutane
17. Diethyl malonate
18. Undecane
19. Dodecane
20. Tetradecane
Time-->

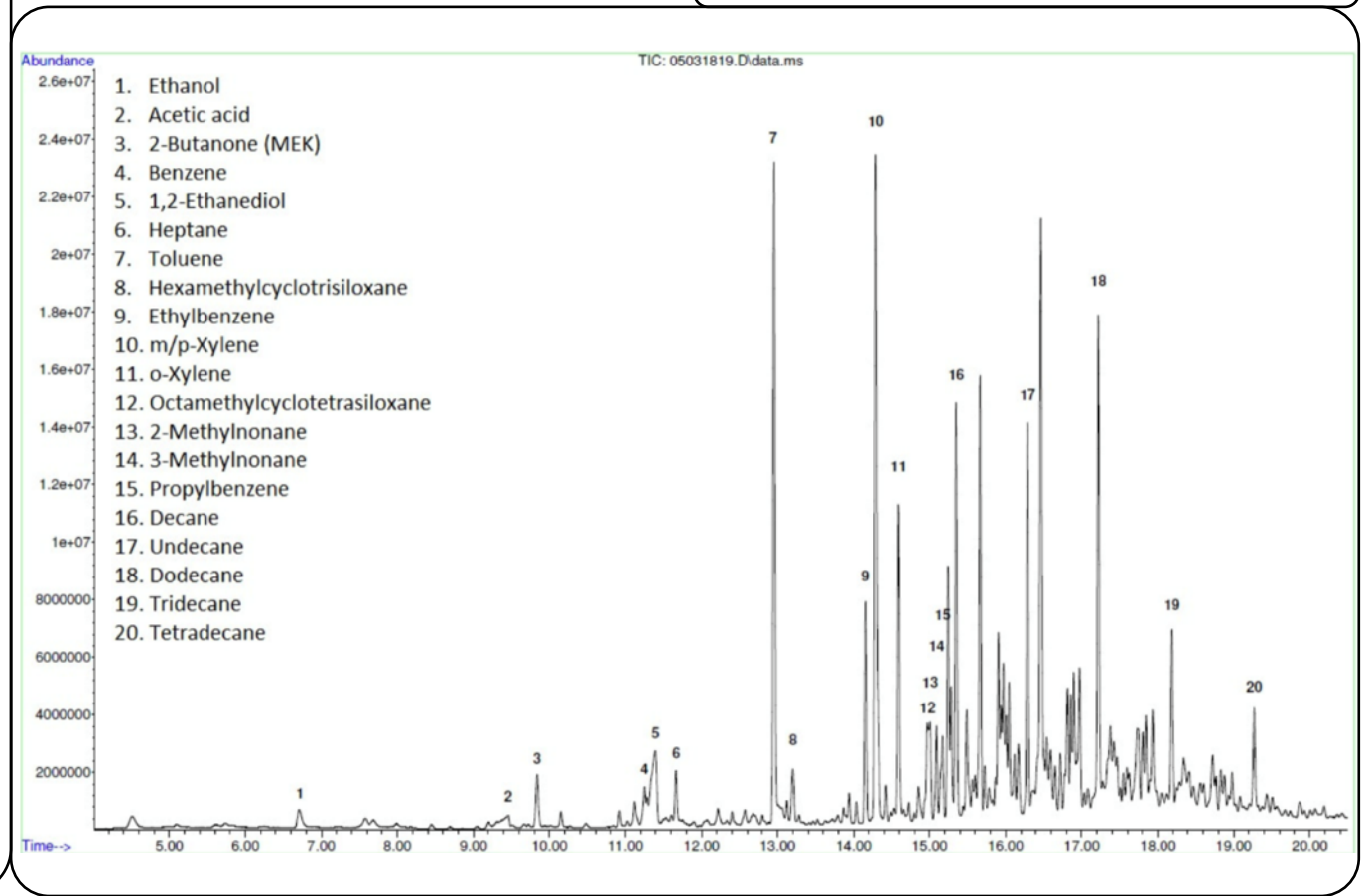
Renault Clio (2016)



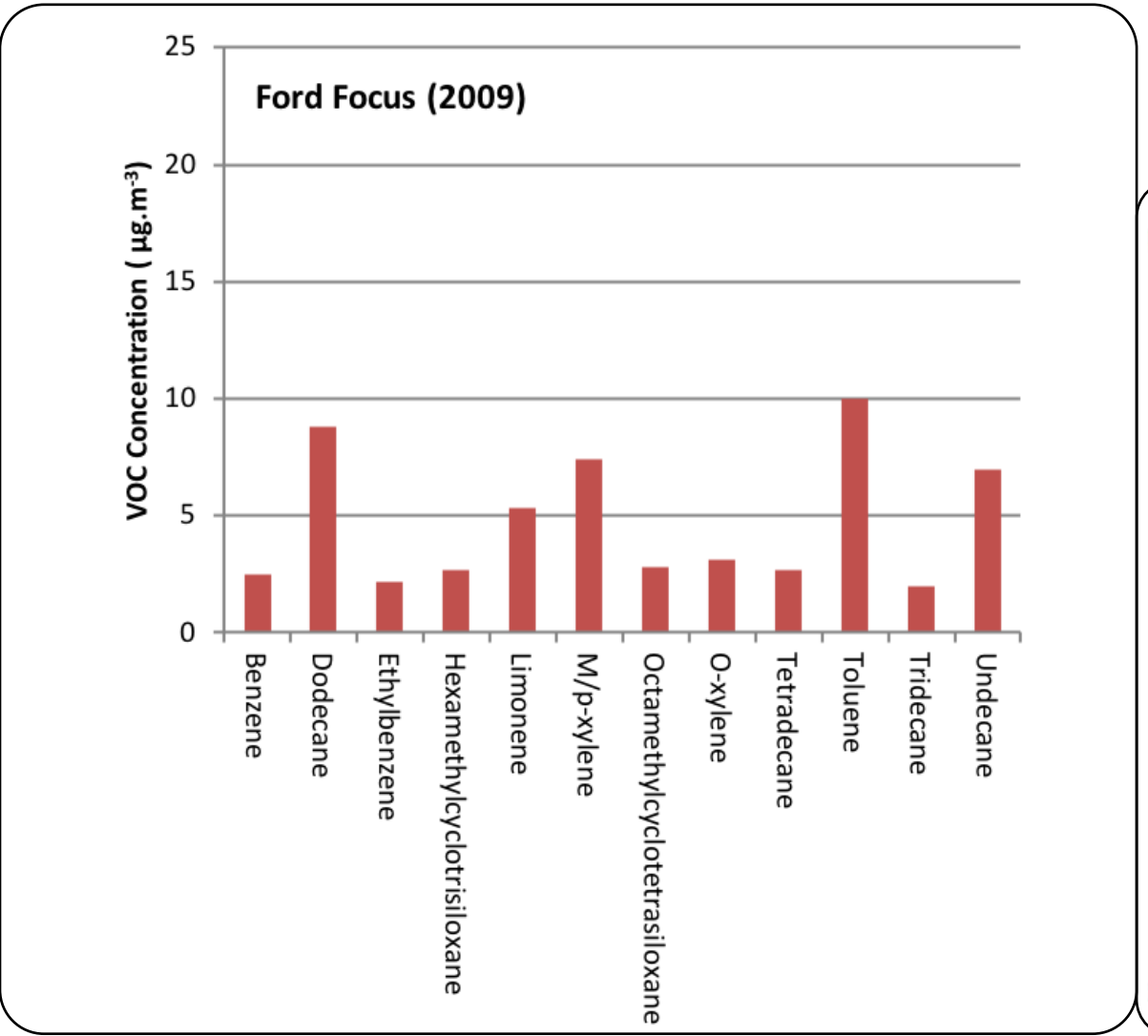


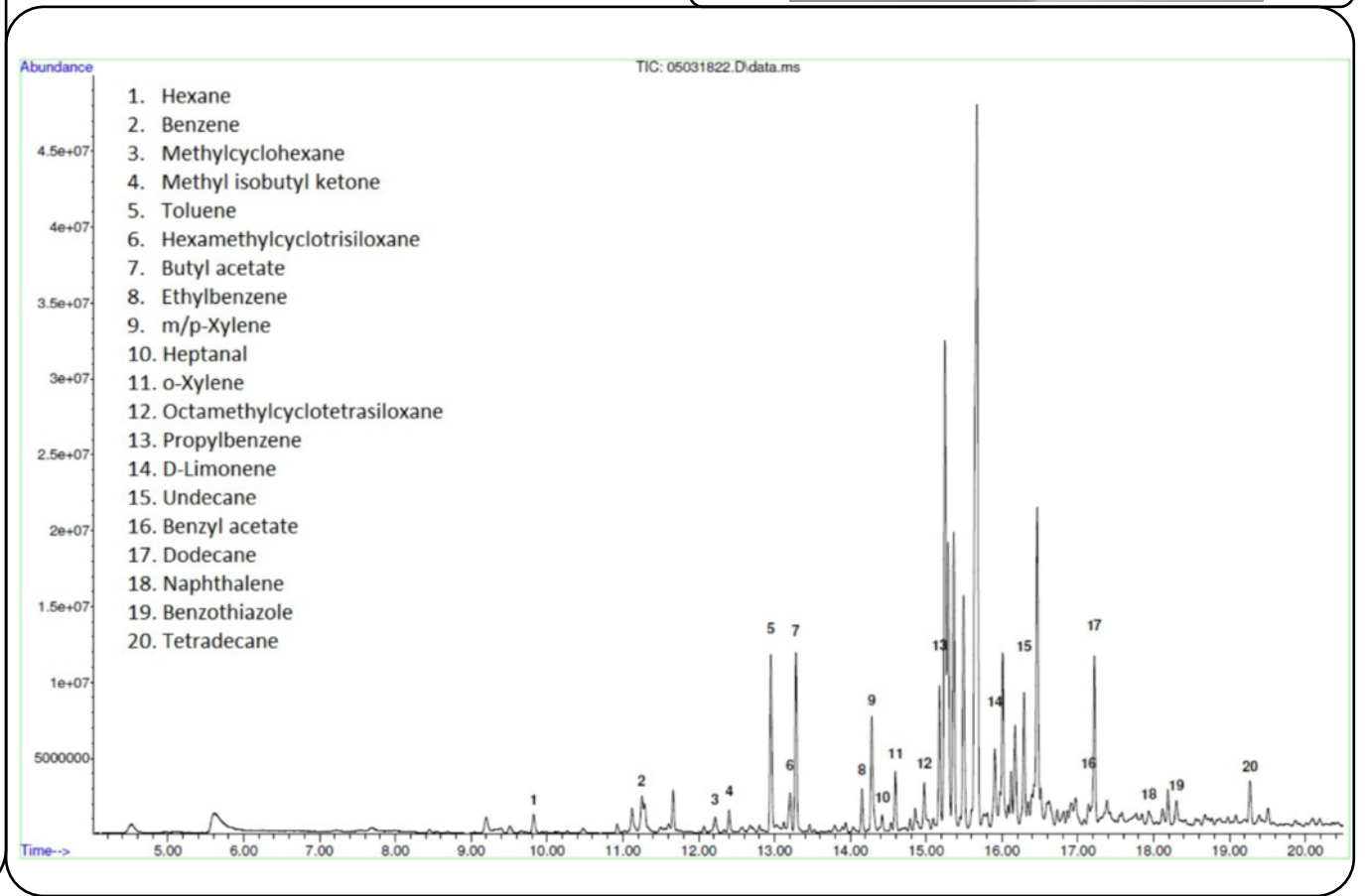
Mercedes C220 (2005)



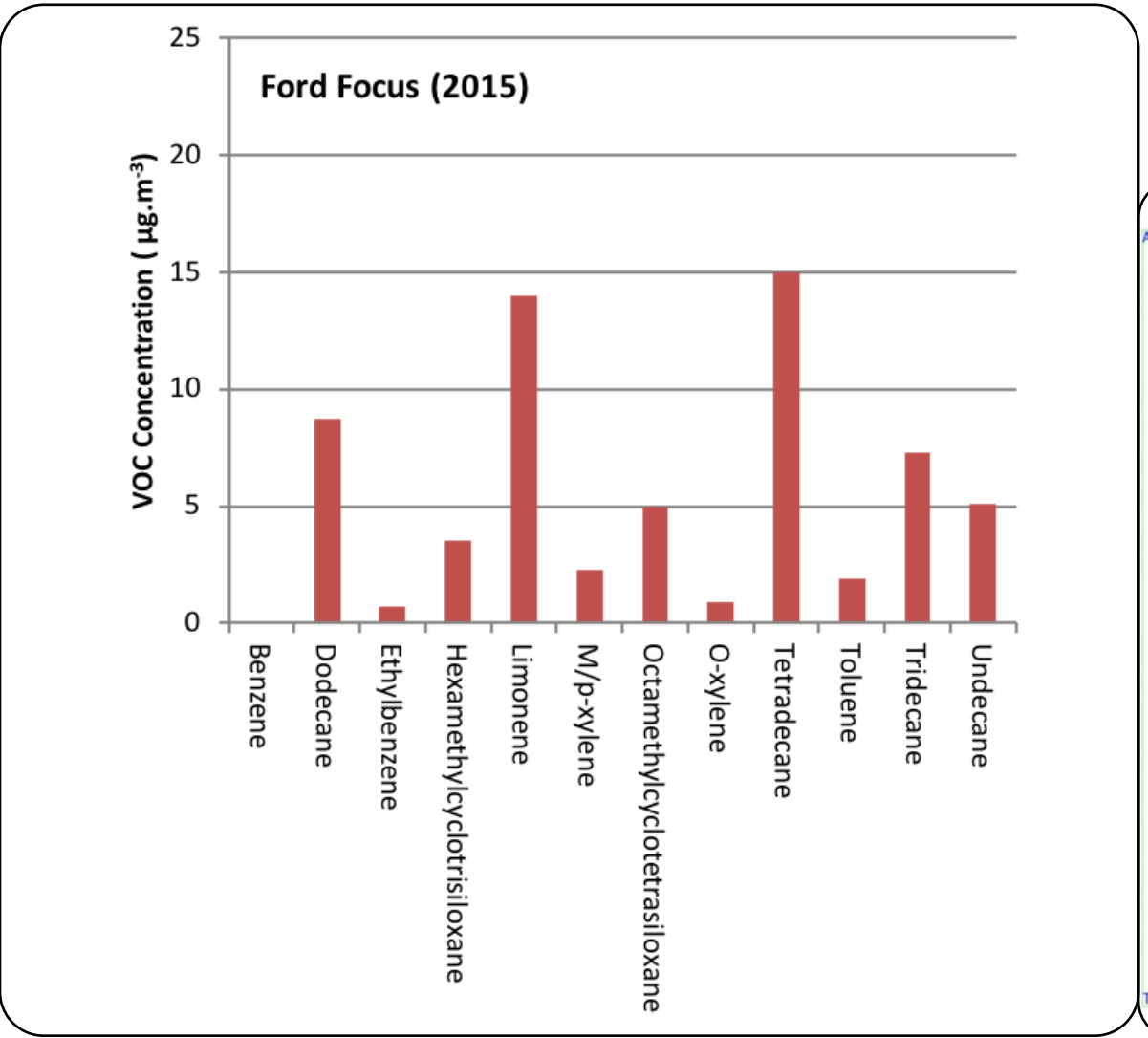


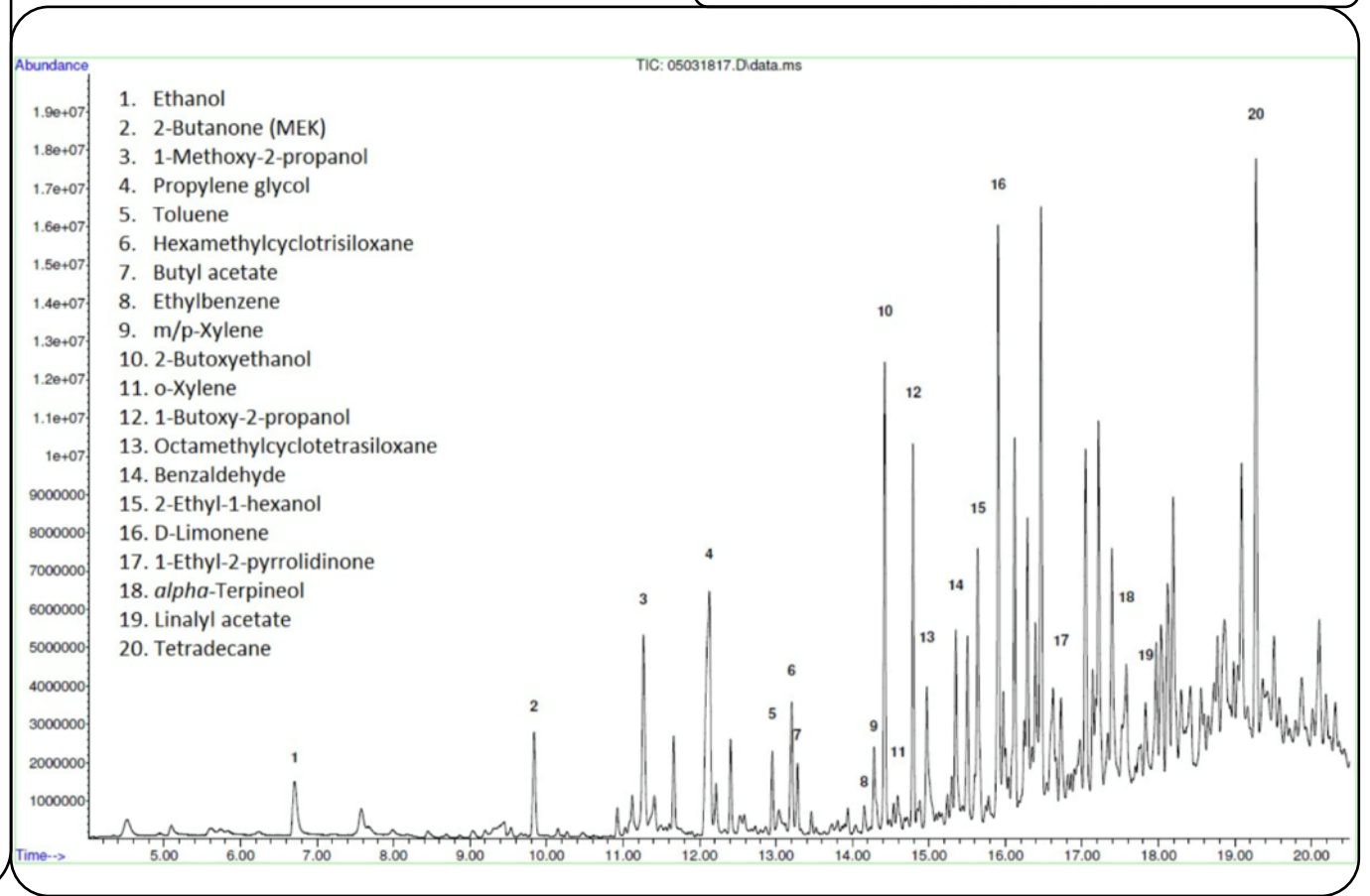
Ford Focus (2009)



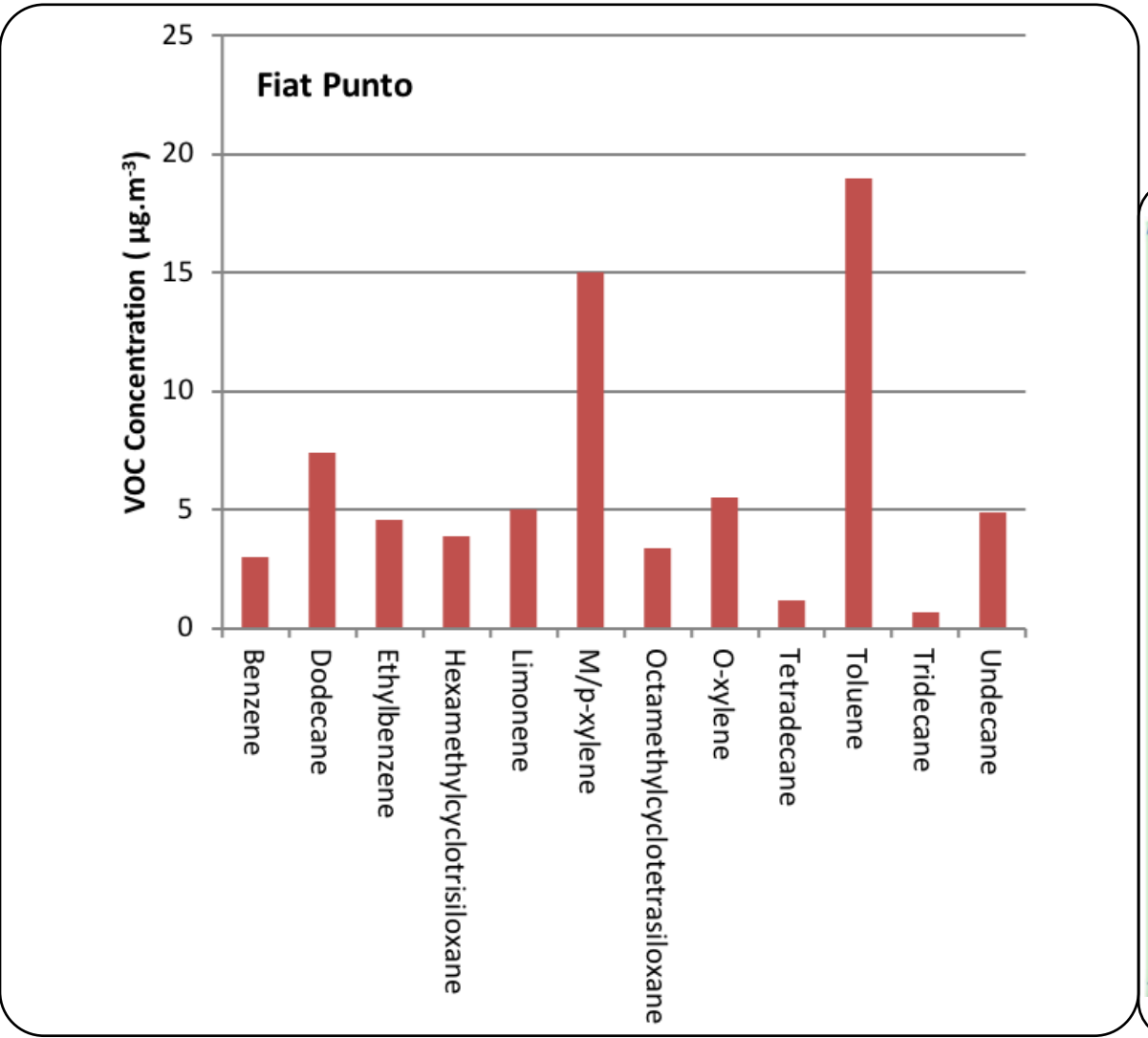


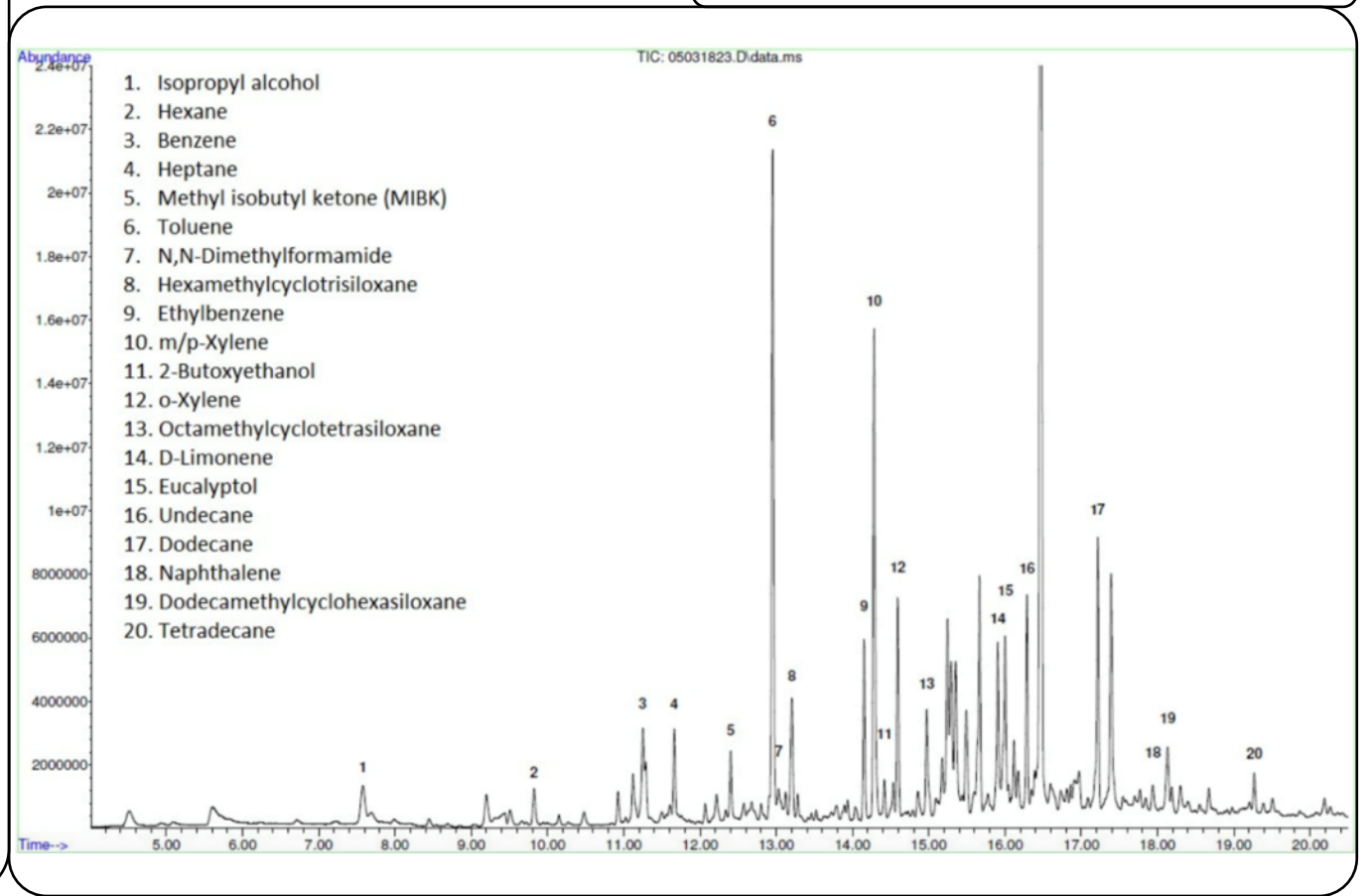
Ford Focus (2015)



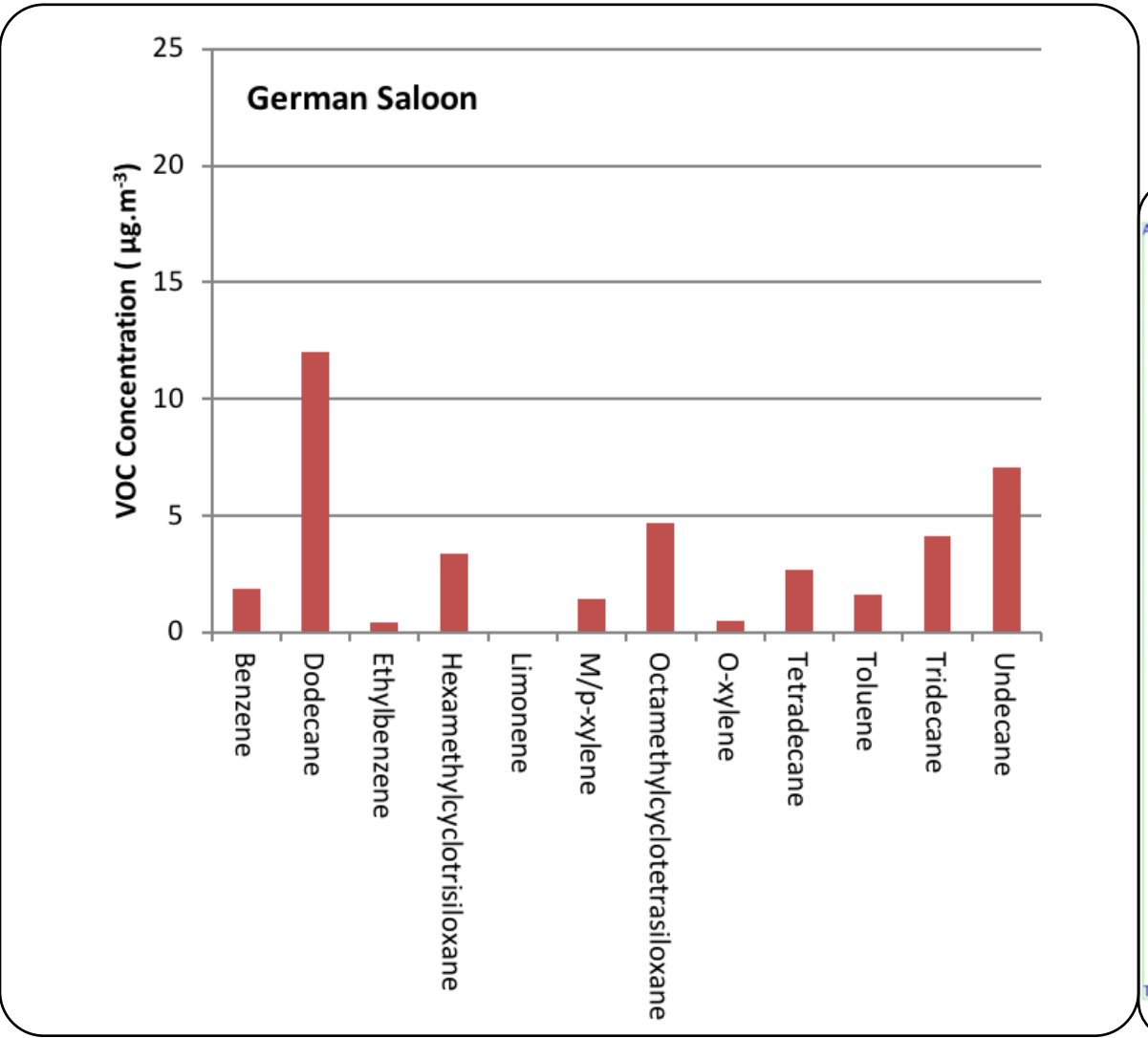


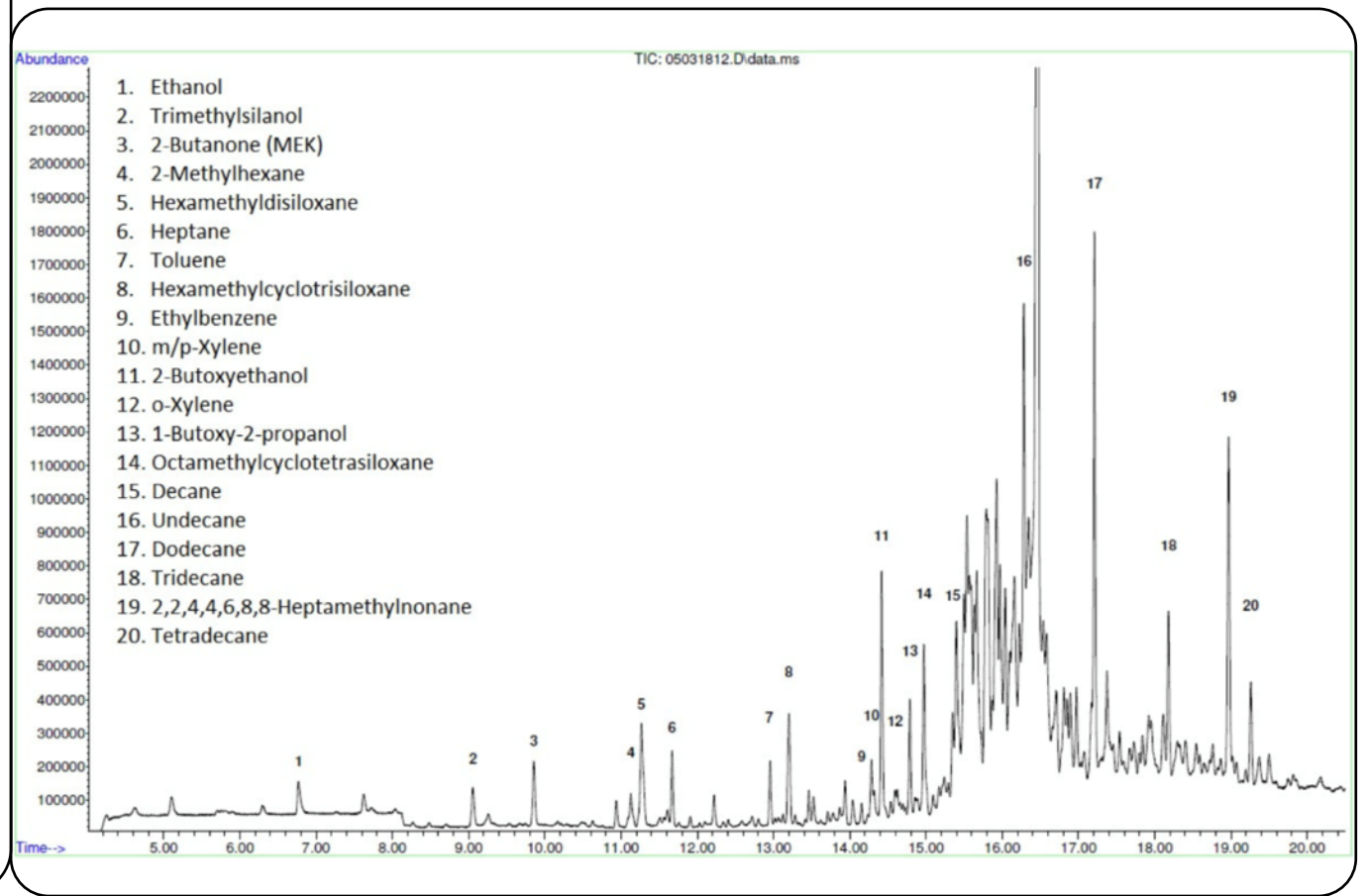
Fiat Punto (2008)



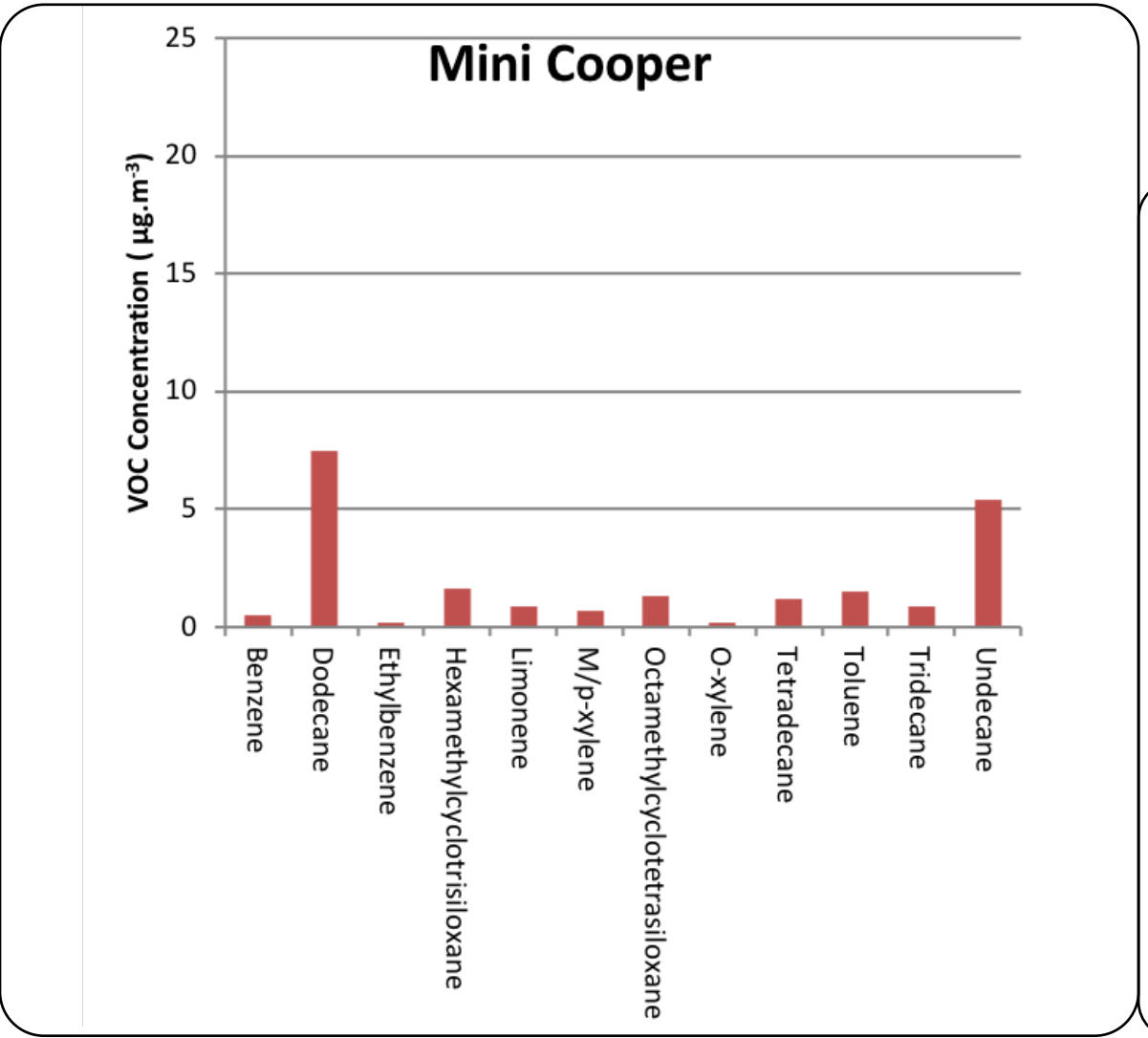


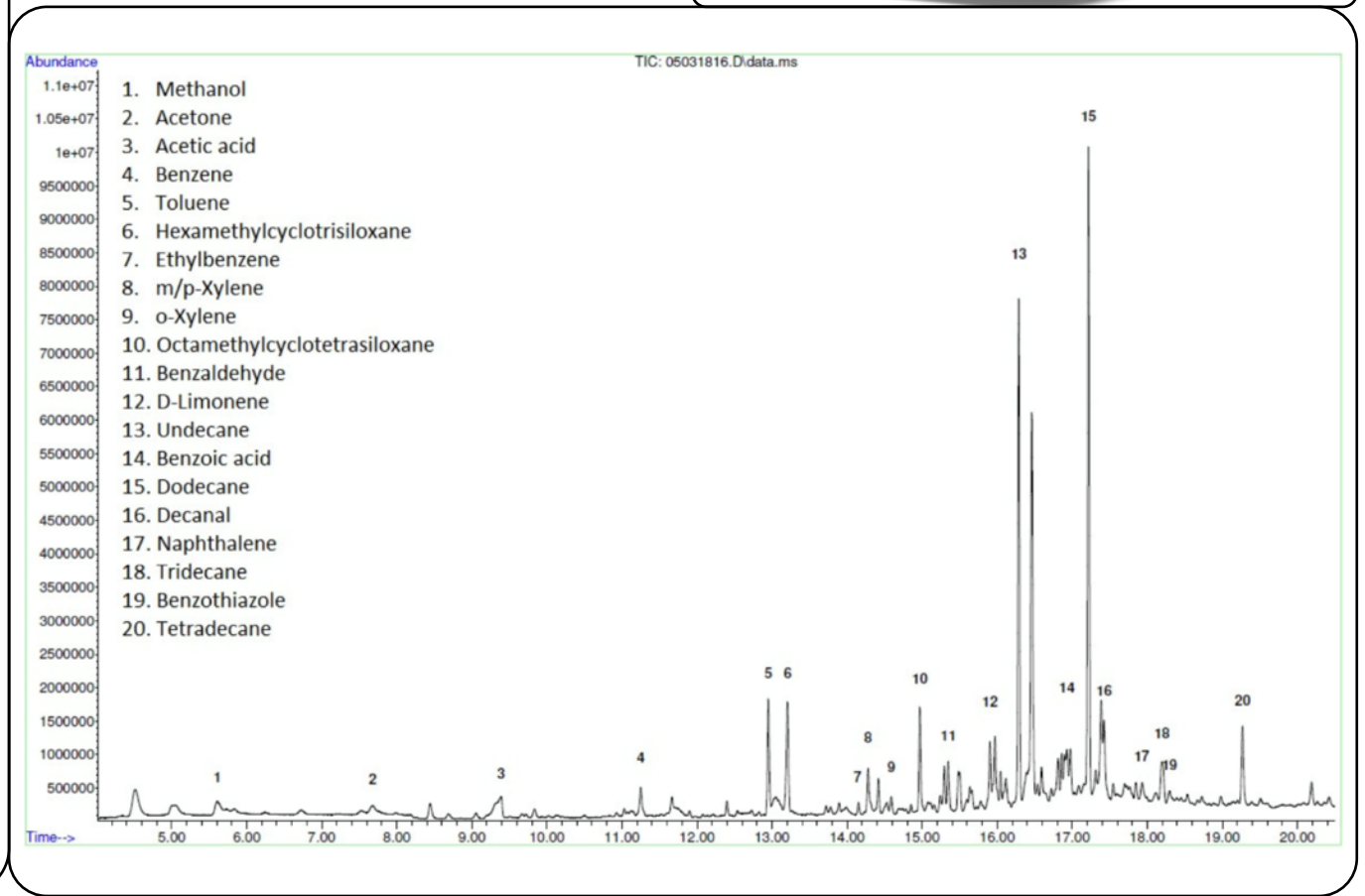
German Saloon (2017)



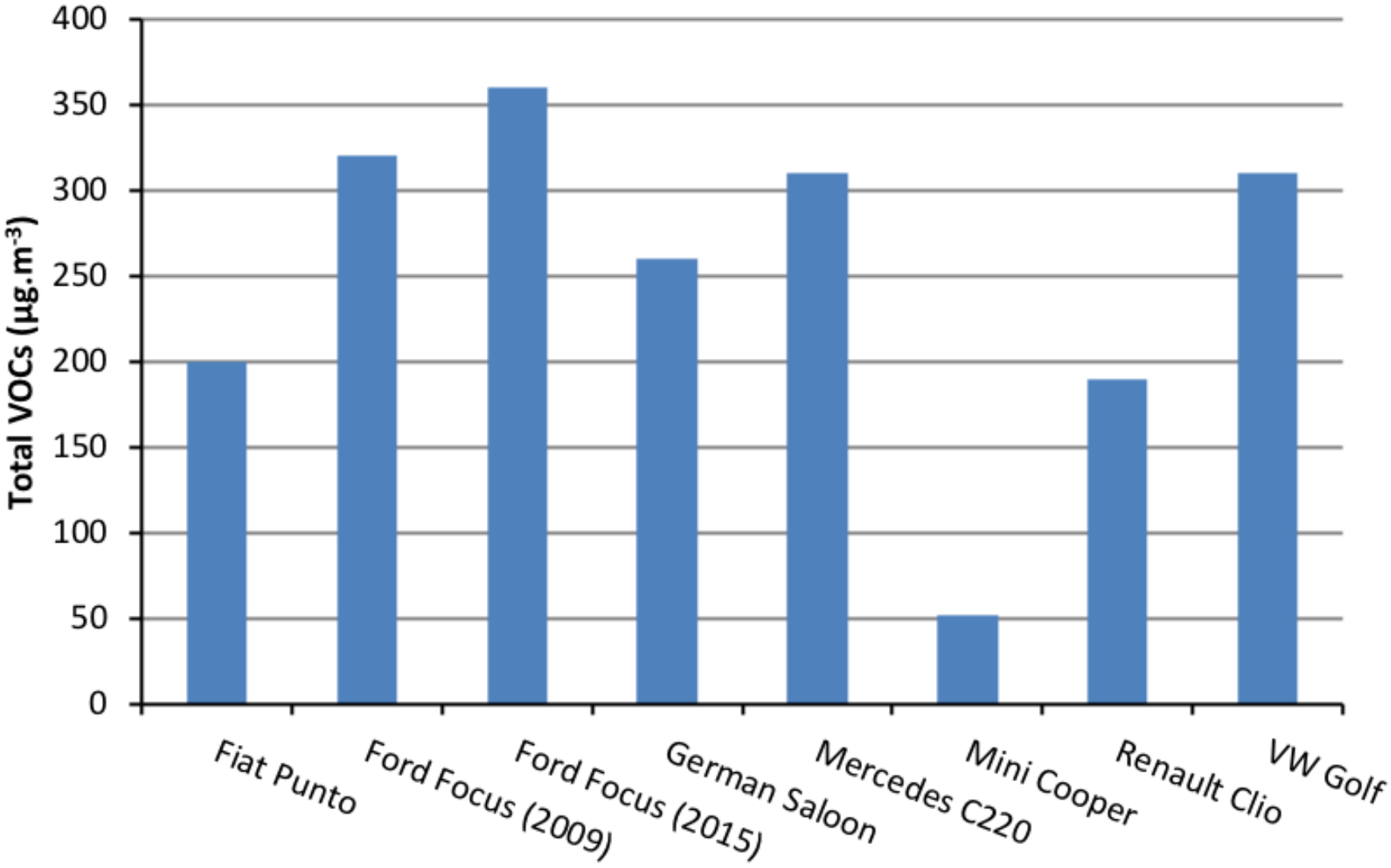


Mini Cooper (2006)

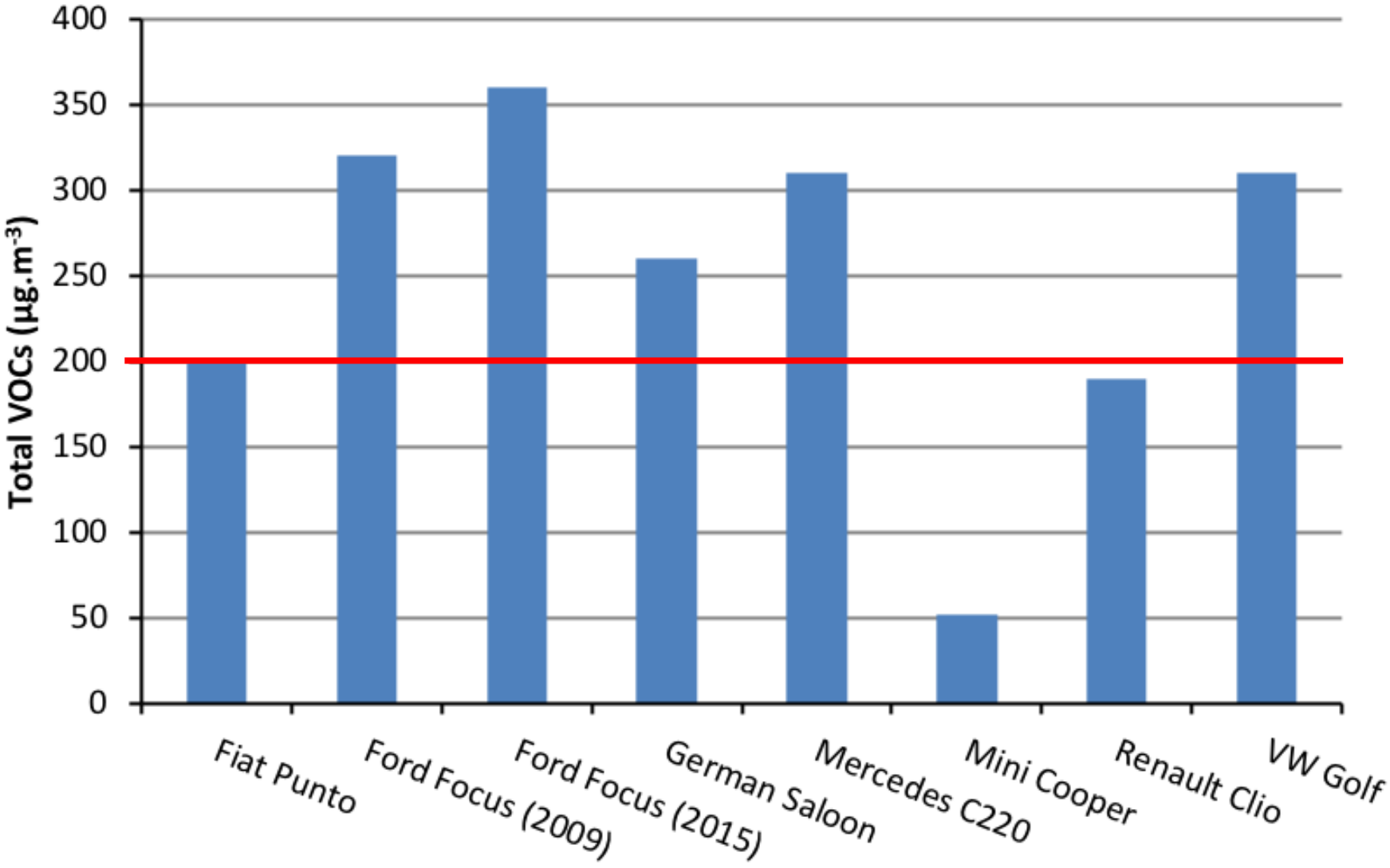




Comparisons - TVOCs



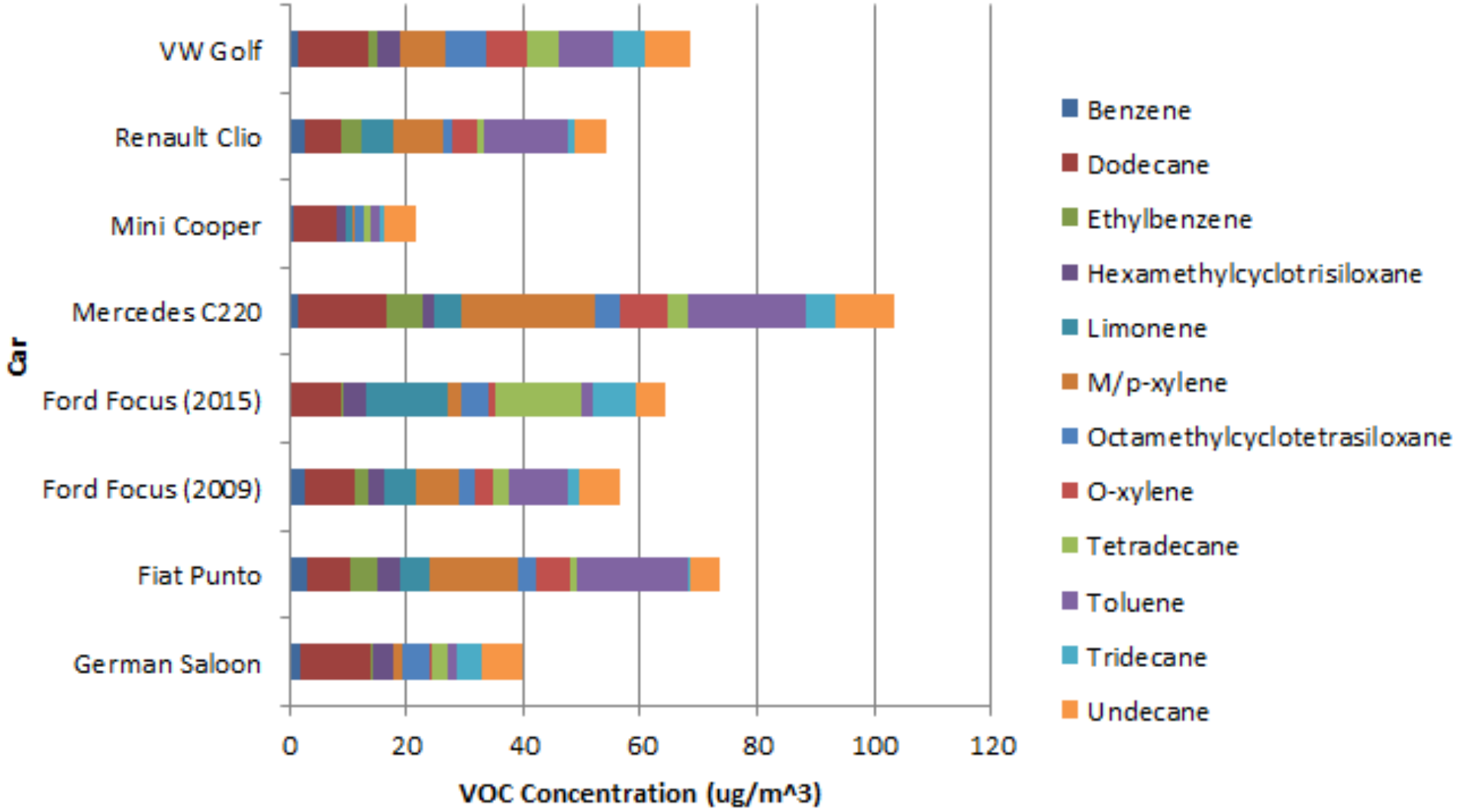
Comparisons - TVOCs



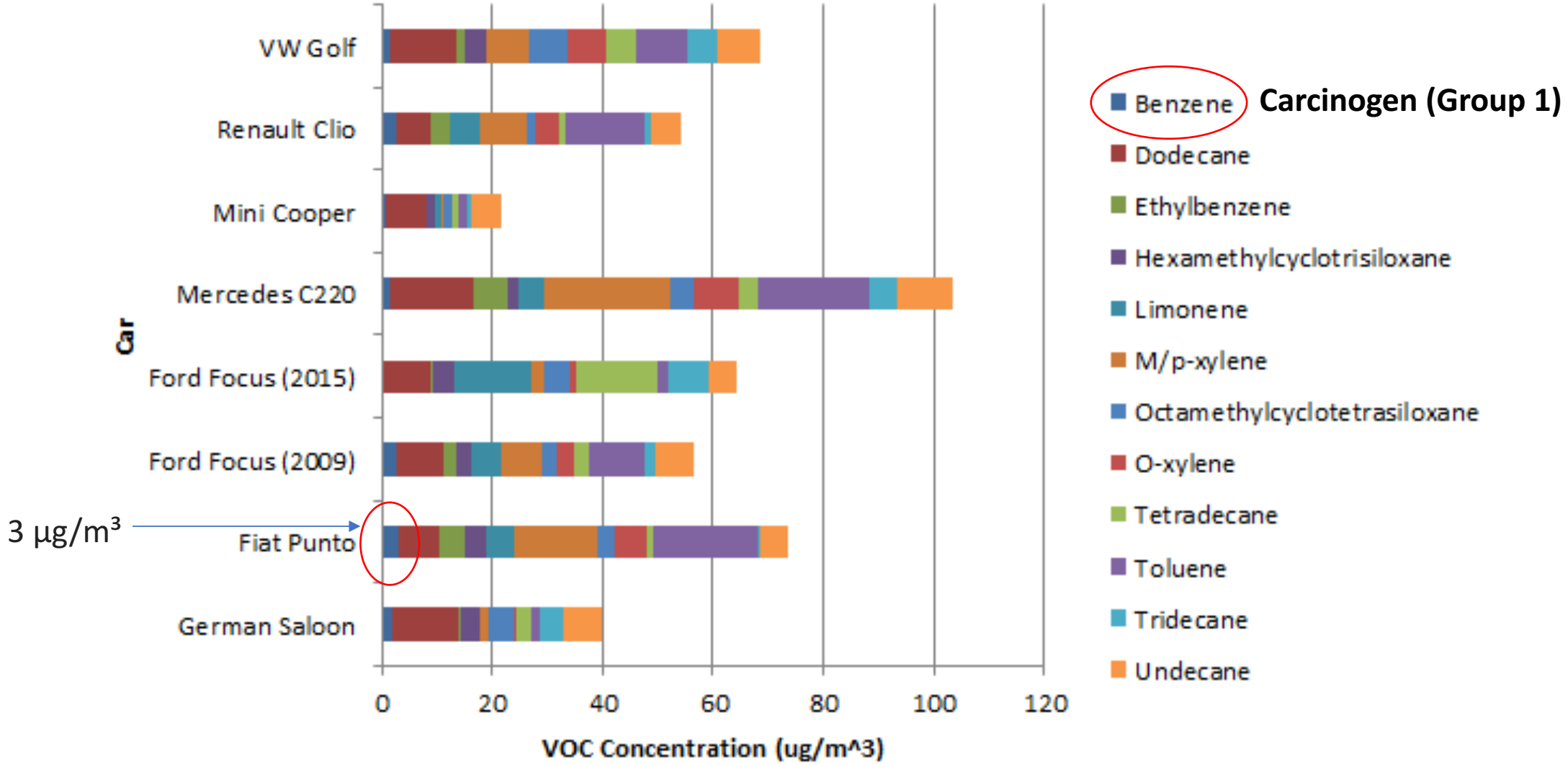
Health Effects

- <200 µg/m³ - No irritation or discomfort
- 200-3000 µg/m³ - Irritation and discomfort possible
- 3000-25000 µg/m³- Discomfort expected and headache possible
- >25000 µg/m³ - toxic

Comparisons II - Speciation



Comparisons II - Speciation



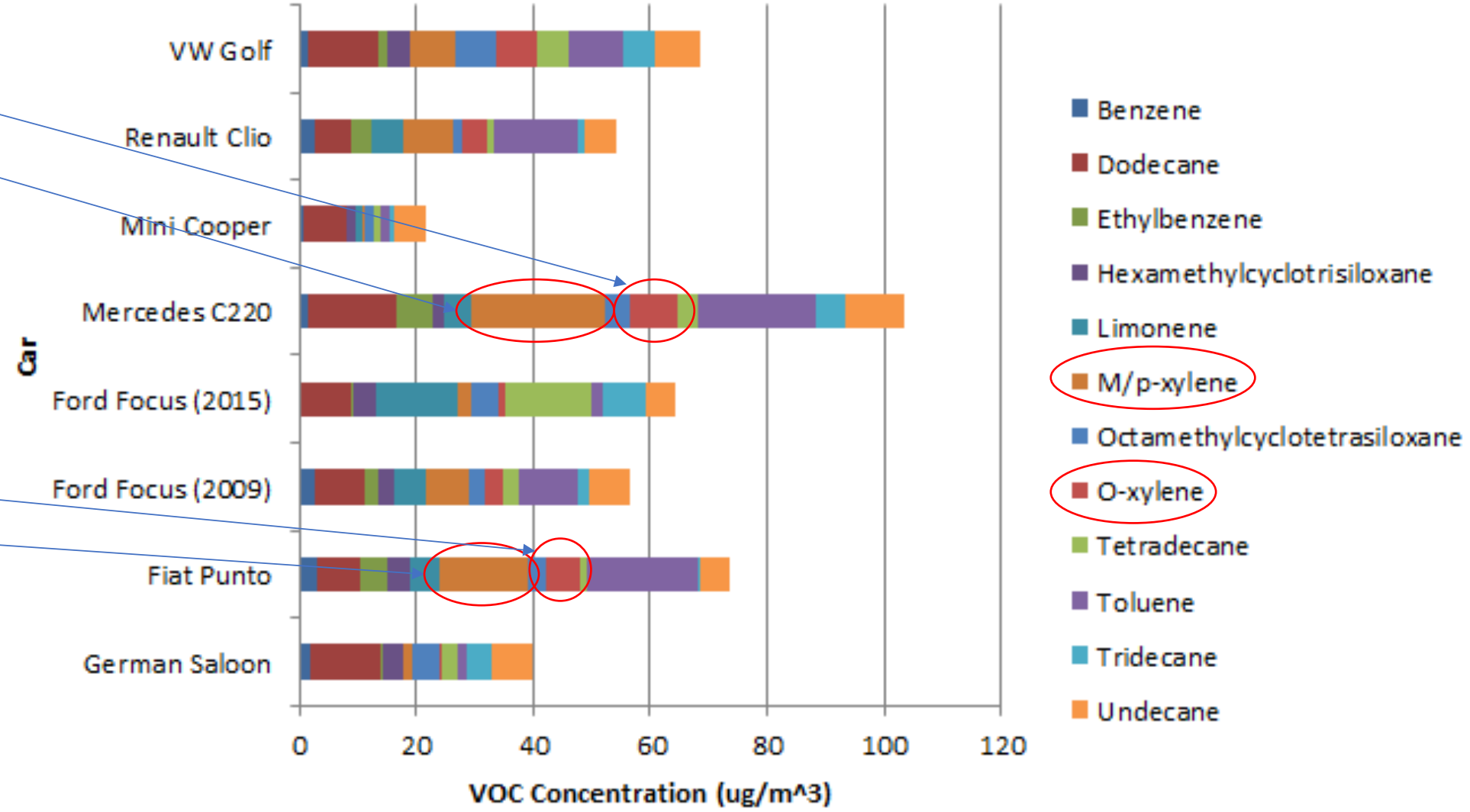
Comparisons II - Speciation

8.4 µg/m³

23 µg/m³

5.5 µg/m³

15 µg/m³

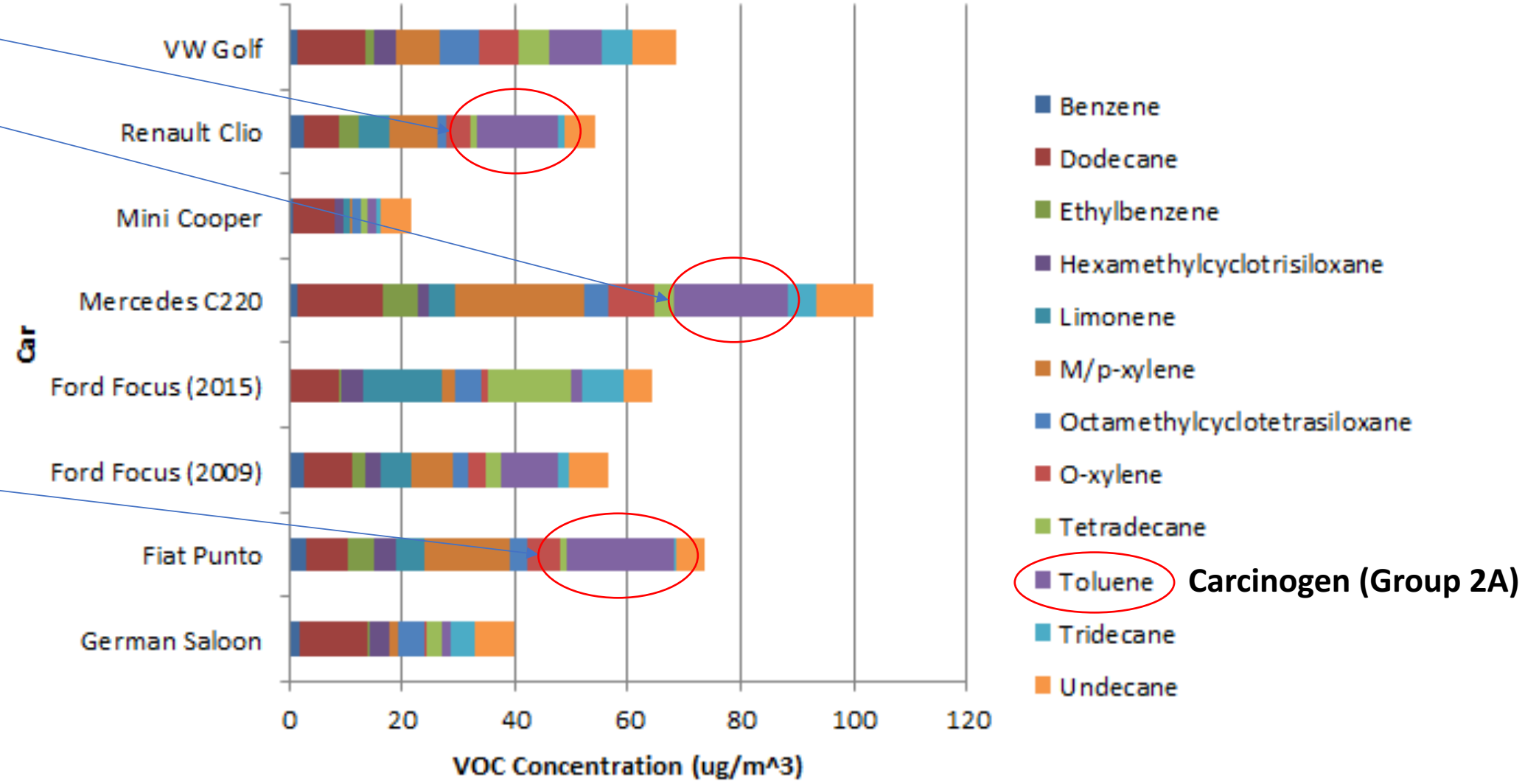


Comparisons II - Speciation

14 µg/m³

20 µg/m³

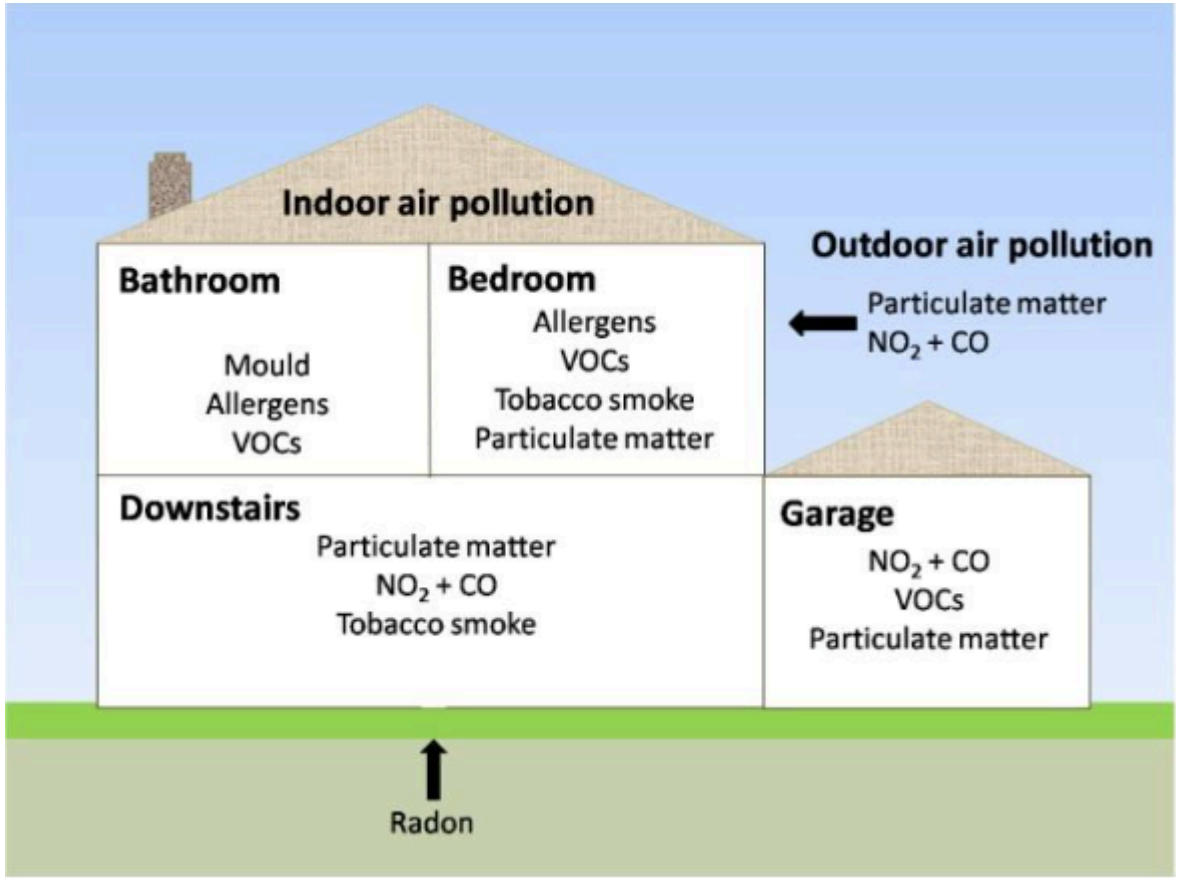
19 µg/m³



Carcinogen (Group 2A)

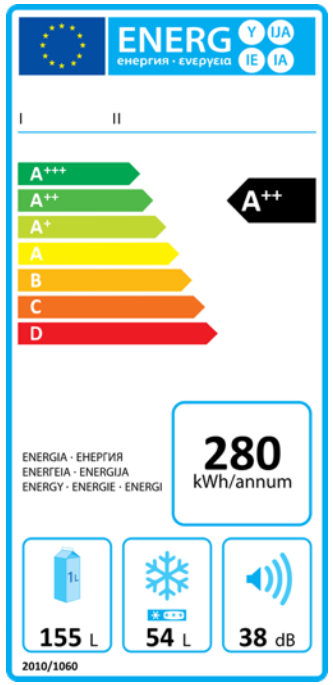
Indoor Air Quality

- Levels of air pollution inside the home are often **two to five times higher** than outdoors.
- Indoor air pollution is associated with a host of health problems.
- Average person spends **90% of their time indoors**.
- There is far less information / public knowledge on it!



The Original Business Concept

- Regional based franchise model
- Pick up / drop off centres, similar to carpet cleaners
- 2-3 day rental period
- Translate this scientific information into labelling schemes that can improve consumer choice
- Develop an indoor “comfort” metric



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NEWS

Home UK World Business Politics Tech Science Health Family & Education

England Regions London

Homebuyers could get air quality data, say estate agents

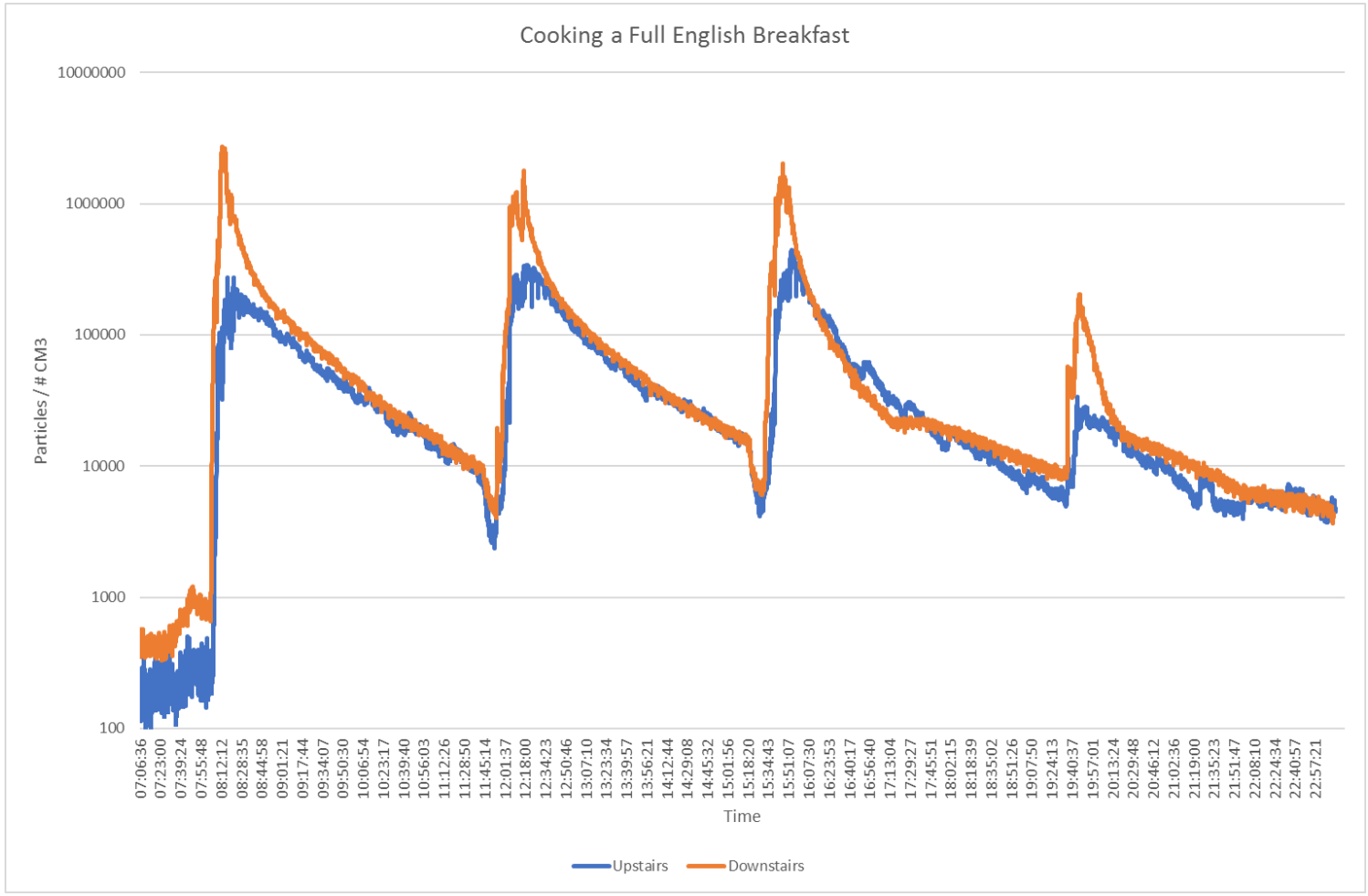
15 May 2017 | London Share

London mayor Sadiq Khan has previously described declining air quality in the capital as an emergency

Property listings may contain data about the air quality in an area in the future, according to estate agents.

The National Association of Estate Agent (NAEA) said it believes the data will soon be a compulsory part of property adverts.

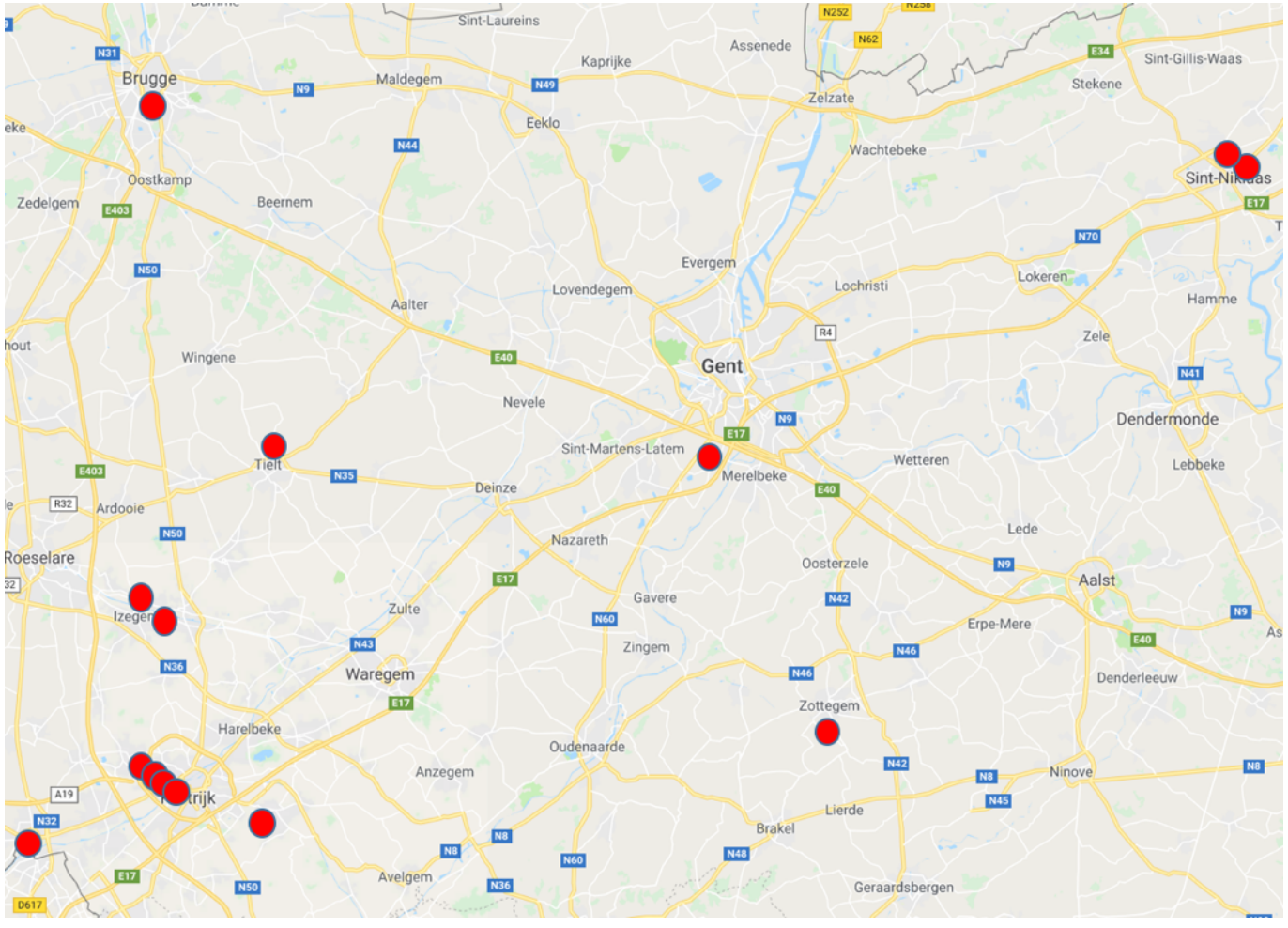
Cooking up an –indoor air quality– storm



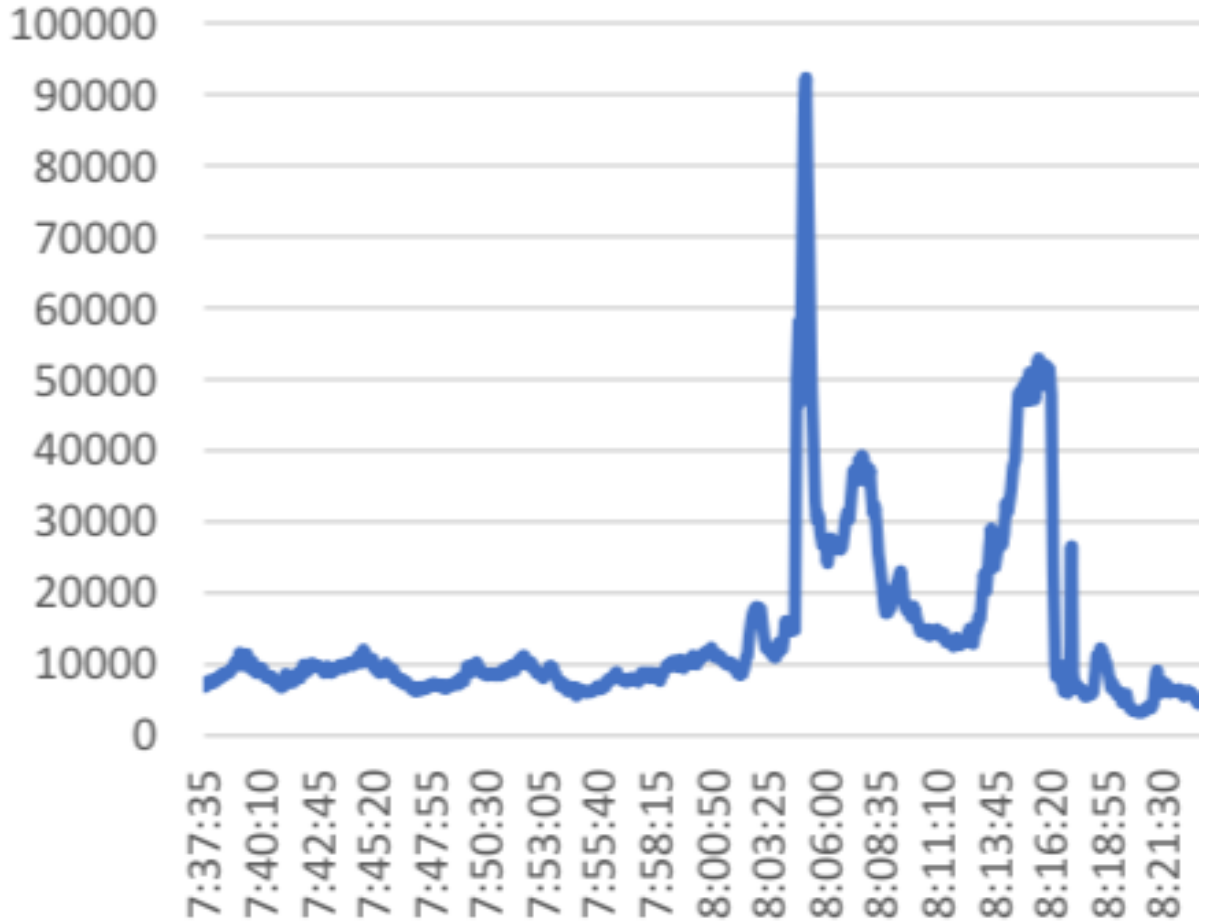
Particles with effect of various ventilation strategies: No Ventilation, Extract Fan On, Windows Open, Extract Fan on & Windows Open

Citizen Science

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



Citizen Science



Occupational Health and Safety

Development of information, modelling and sensorisation systems to boost the application of nanotechnology and safe use of nanomaterials in traditional sectors of the Valencian Community.

OBJECTIVE:
To boost investment in nanotechnology

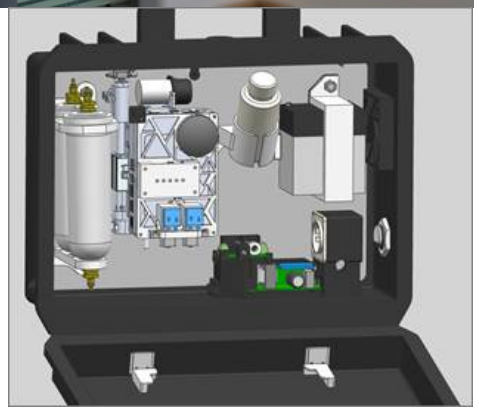
- PROMOTION OF NANOTECHNOLOGY
- SAFE USE OF NANOTECHNOLOGY

DEVELOPMENT OF R+D

- **TECHNOLOGICAL OBSERVATORY**
  Online platform for technological surveillance making it possible to:
  · Consult documentation to adapt products or processes.
  · Monitor publications, events or related regulations.
  · Gain recognition in the nanotechnology sector.
- **PREDICTIVE MODELS**
  Predictive tools based on real estimations for characterising exposure to nanomaterials and health and environmental risk assessment.
- **MEASUREMENT DEVICE**
  For the quantitative evaluation of the daily exposure to nanomaterials in normal synthesis and/or processing processes.

SCOPES OF APPLICATION

Plastic (including packaging); Ceramic products; Construction; Textile industry; Cosmetics / Household products; Inks, putties, paints, varnishes and coatings; Chemical industry; Biotechnology; Automotive industry; Footwear; Non-ceramic materials; Renewable energies.



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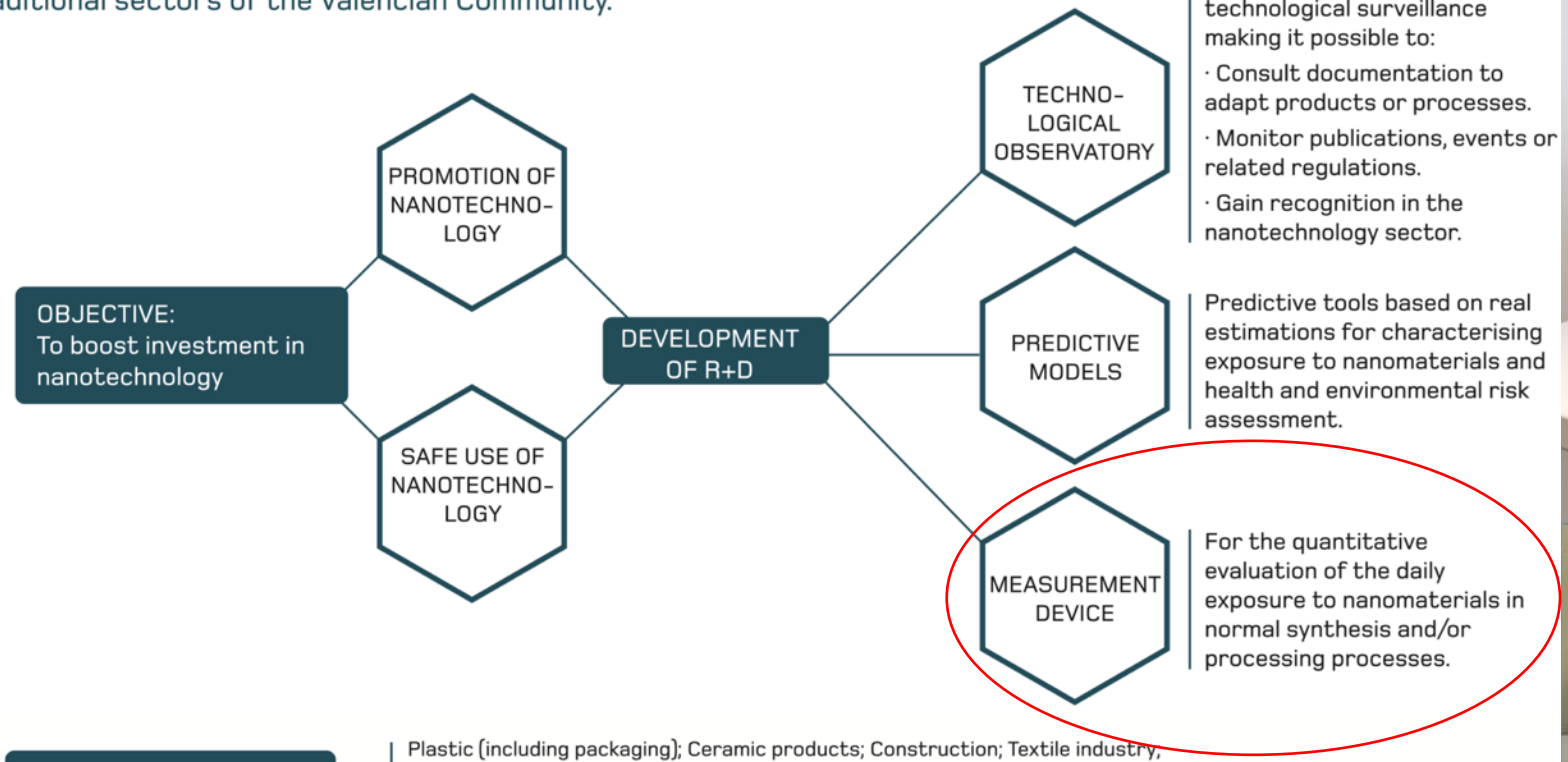

SCOPES OF APPLICATION

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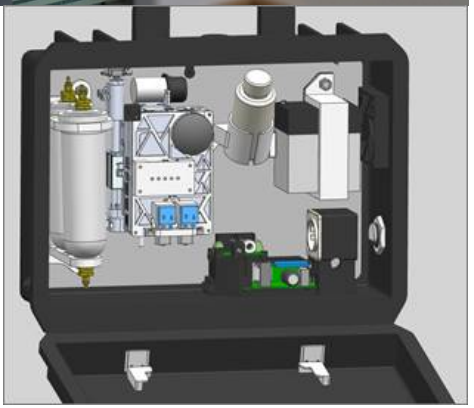

Integration of NAQTS AQB

Mobile Air Quality Monitoring

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

ENVIRONMENTAL Science & Technology

Article

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

Joshua S. Apte,[†,‡] Kyle P. Messier,[†,§] Shahzad Gani,[†] Michael Brauer,[∥] Thomas W. Kirchstetter,[⊥,#] Melissa M. Lunden,[▽] Julian D. Marshall,[○] Christopher J. Portier,[◆] Roel C.H. Vermeulen,[◇] and Steven P. Hamburg[▽]

[†]Department of Civil, Architectural and Environmental Engineering, University of Texas at Austin, Austin, Texas 78712 United States
[‡]Environmental Defense Fund, New York, New York 10010 United States
[§]School of Population and Public Health, University of British Columbia, Vancouver V6T 1Z3 Canada
[∥]Energy Technologies Area, Lawrence Berkeley National Laboratory, Berkeley, California 94720 United States
[⊥]Aclima, Inc., 10 Lombard St., San Francisco, California 94111 United States
[#]Department of Civil and Environmental Engineering, University of Washington, Seattle, Washington 98195 United States
[▽]Environmental Defense Fund, New York, New York 10010 United States
[○]School of Population and Public Health, University of British Columbia, Vancouver V6T 1Z3 Canada
[◆]Energy Technologies Area, Lawrence Berkeley National Laboratory, Berkeley, California 94720 United States
[◇]Aclima, Inc., 10 Lombard St., San Francisco, California 94111 United States
[○]Department of Civil and Environmental Engineering, University of Washington, Seattle, Washington 98195 United States
[◆]Institute for Risk Assessment Science, Utrecht University, Utrecht 3584 CM Netherlands

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, NO₂, 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.[1−3] Air pollution measurements are crucial for epidemiologic and air quality management, but the extent of ground-based air pollution observations is limited.[4,5] 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 80% 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.[6−8] Such gradients are not well represented with routine ambient measurements, but have important implications for exposure assessment, epidemiology, air quality management, and environmental equity.[9−11]

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.[12,13] 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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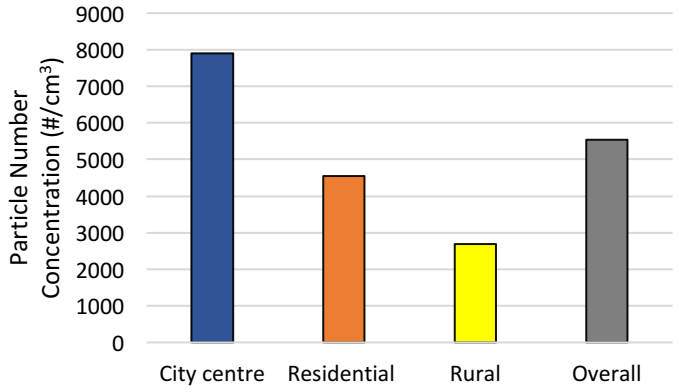
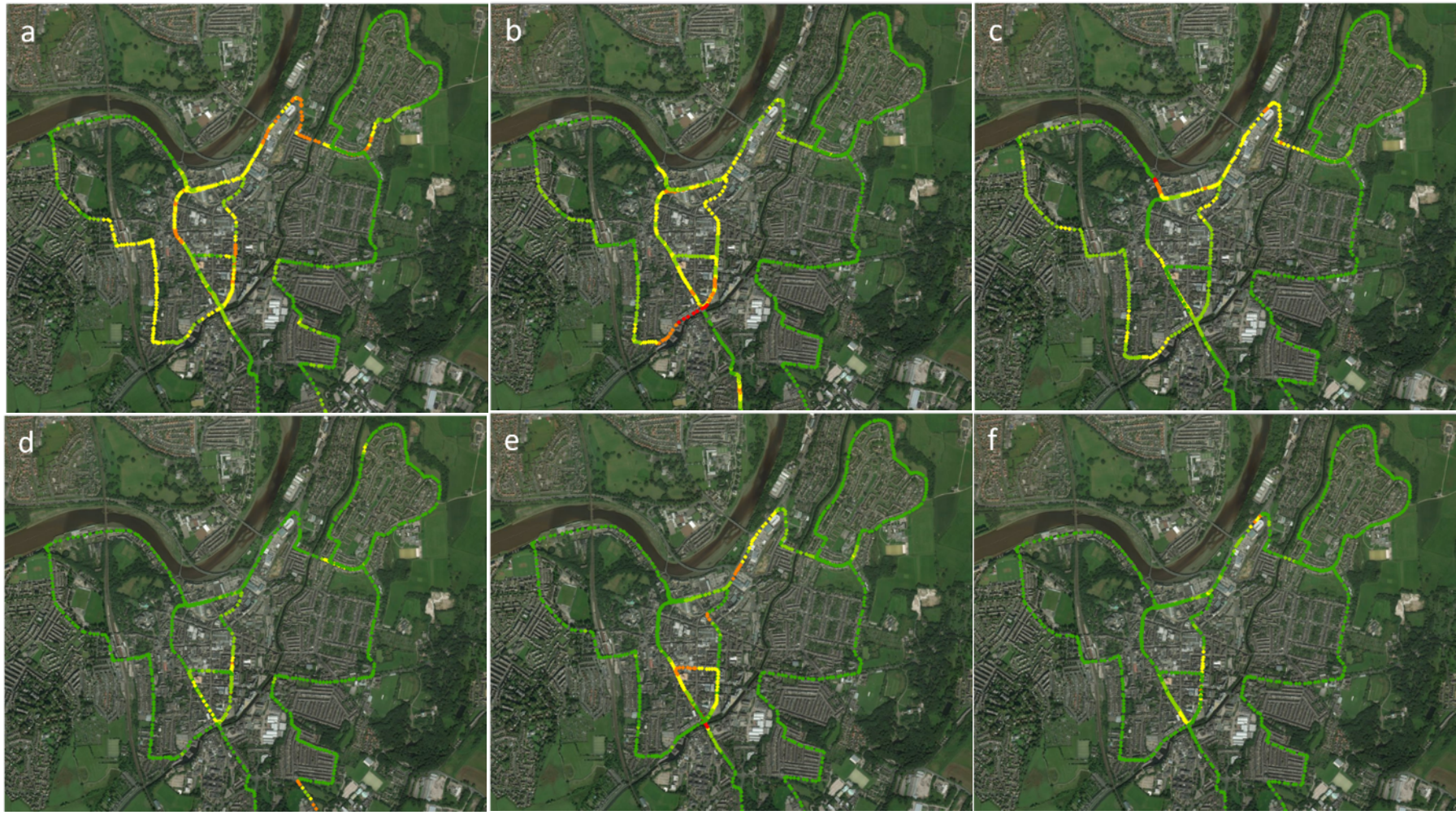
NAQTS V2000 Can be mounted on the vehicle, or placed inside with a sample tube to outside

Mapping the Air Quality in Lancaster

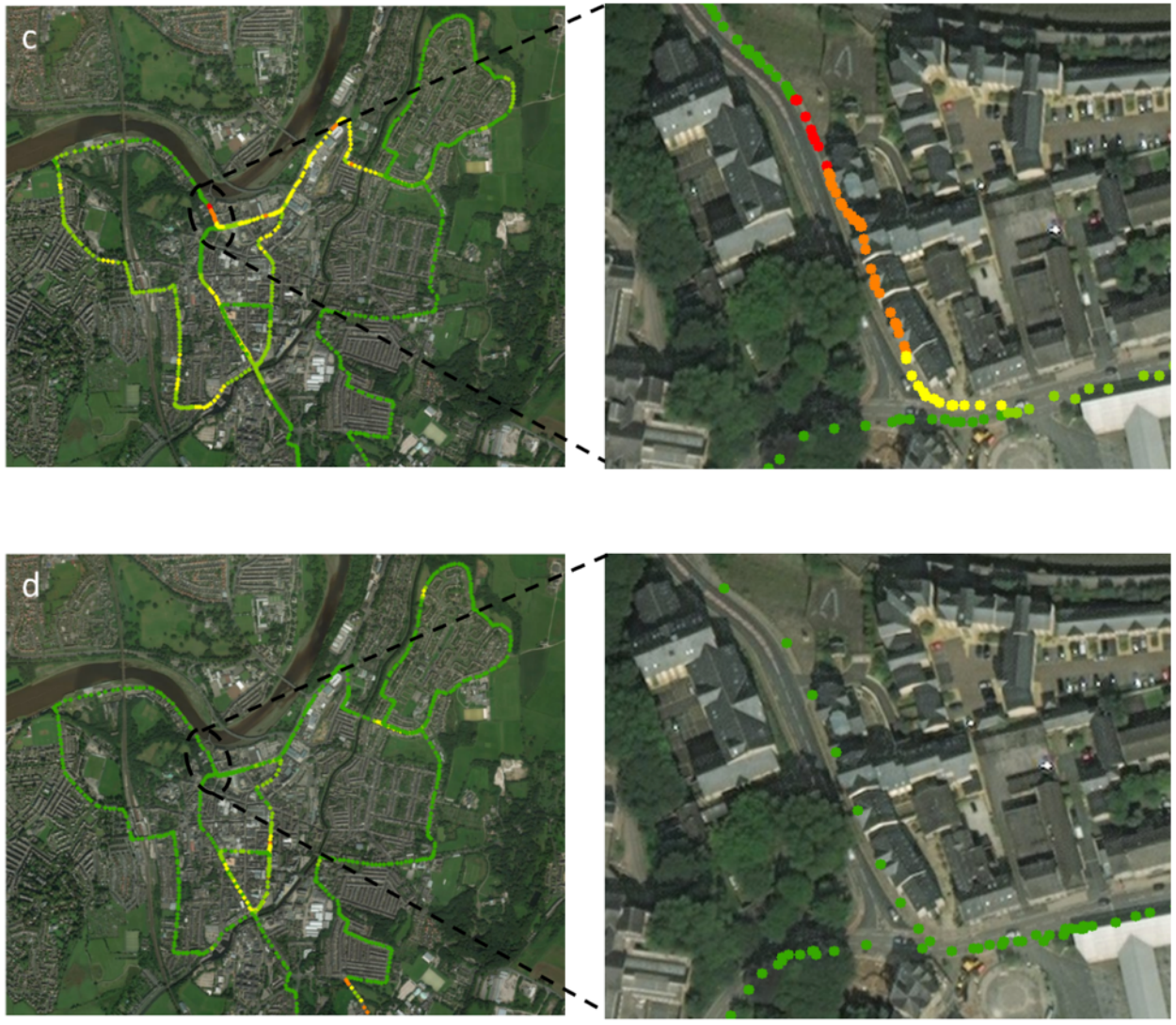
Lancaster is a small city of 138,000 people in the North-West of England

Over a period of 1 week, particle number concentrations were recorded every second over a 20-mile route during evening rush hour



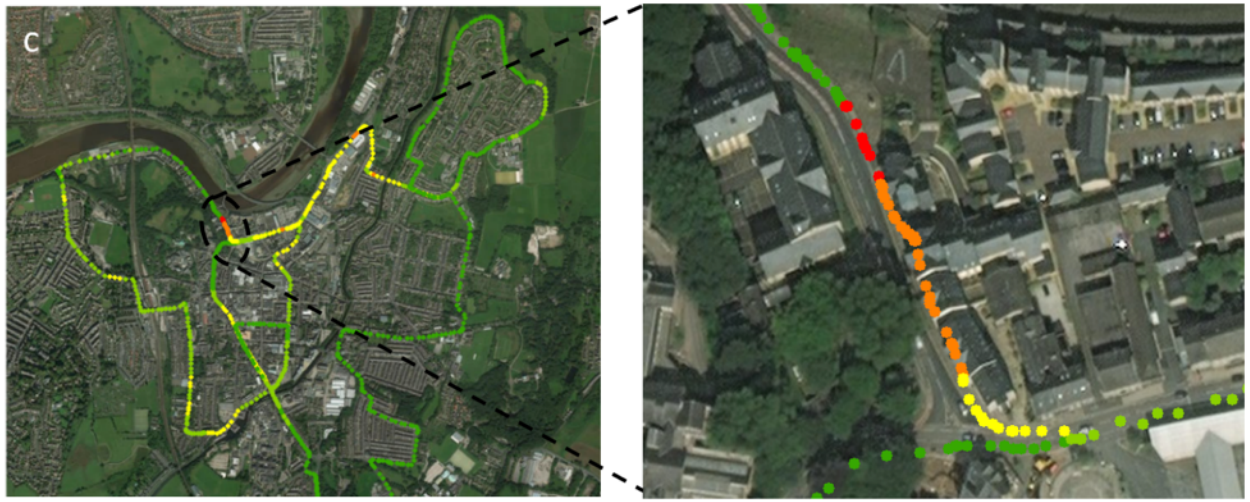


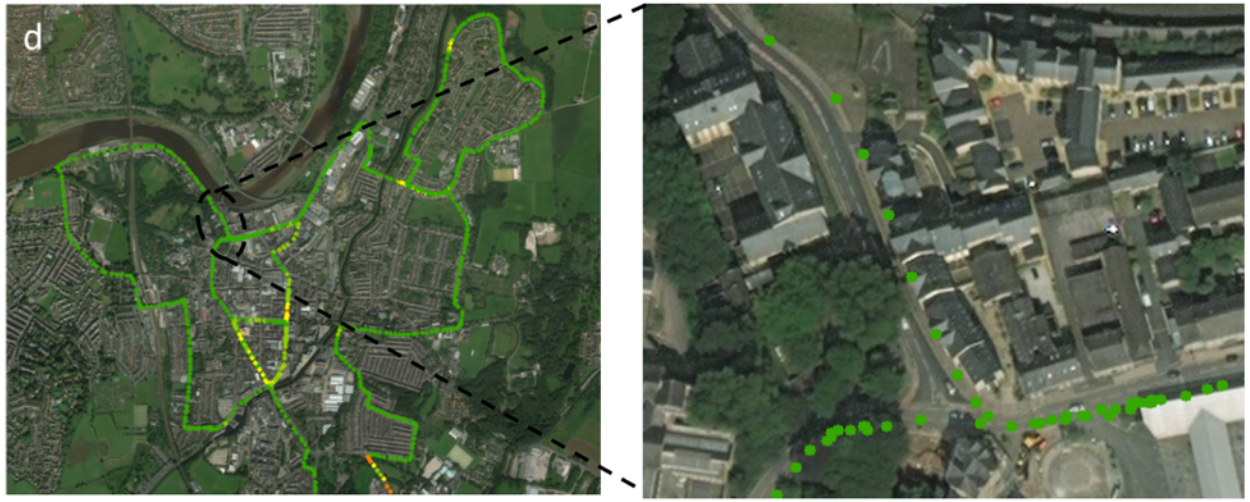
Mapping the Air Quality in Lancaster

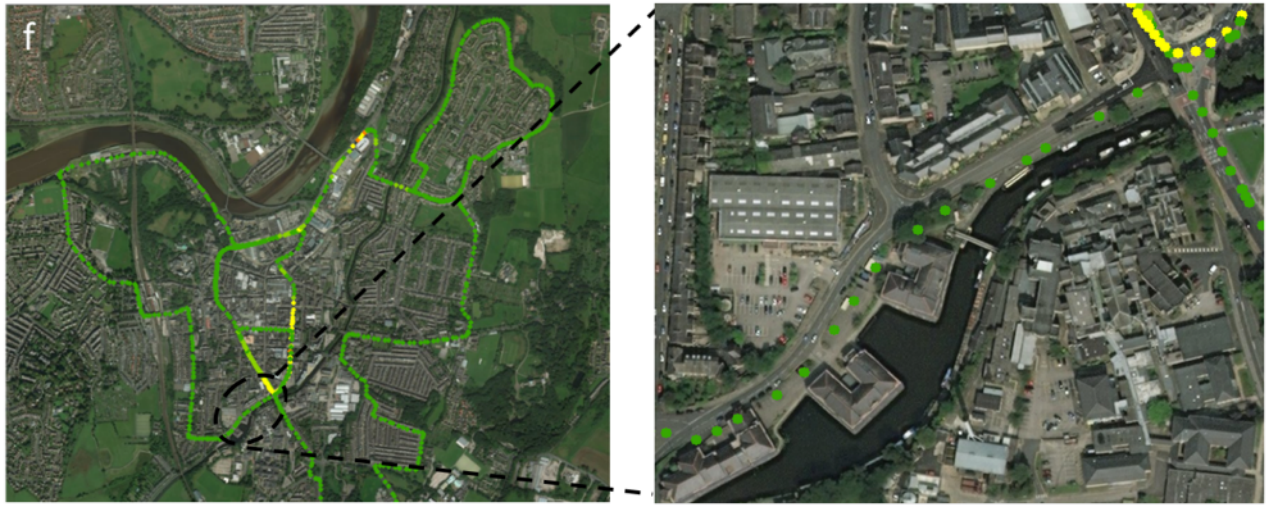


Mapping the Air Quality in Lancaster

NAQTS







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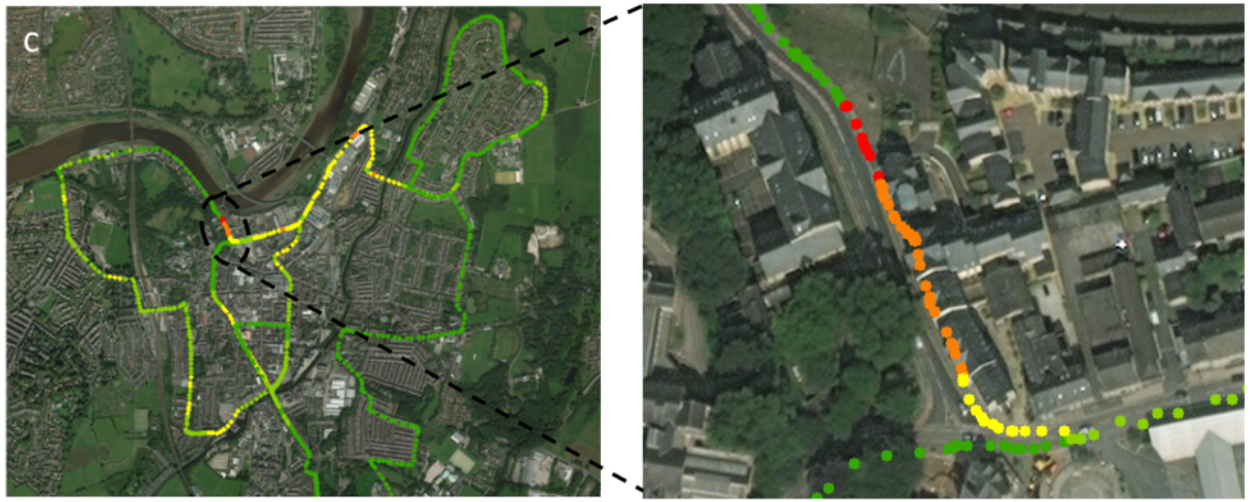
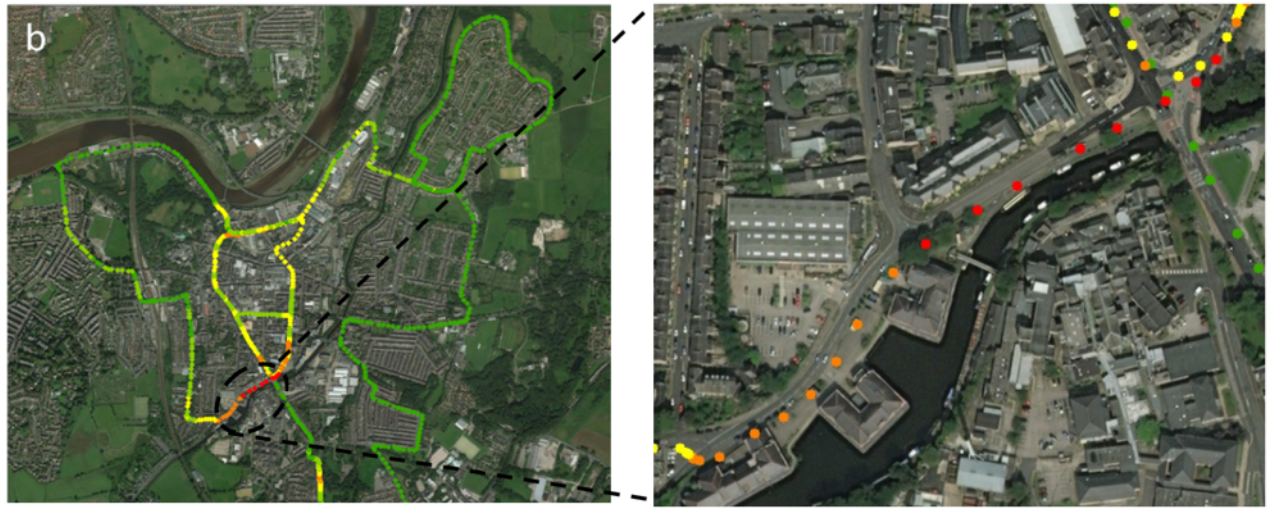
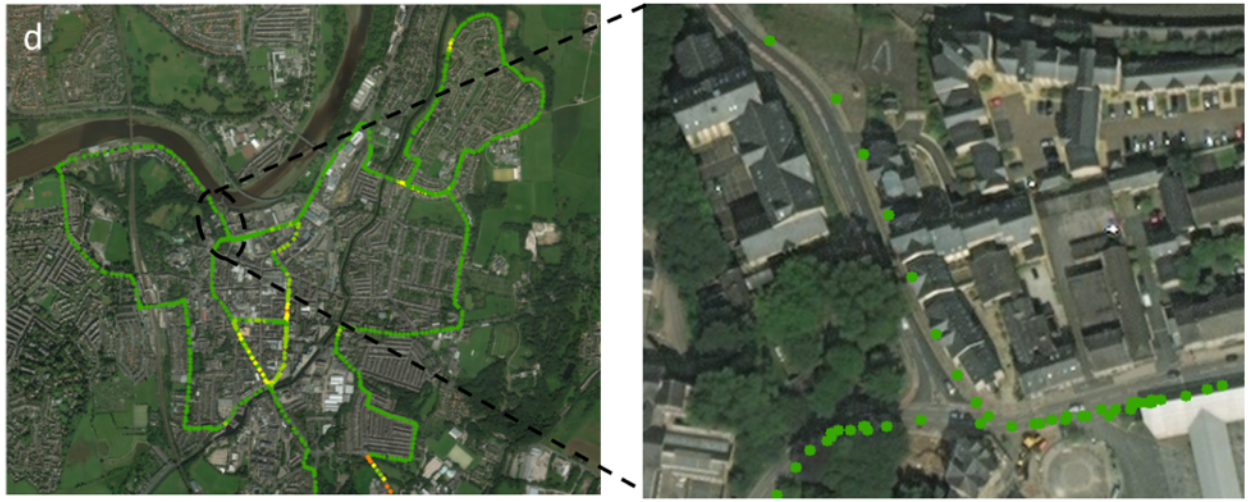
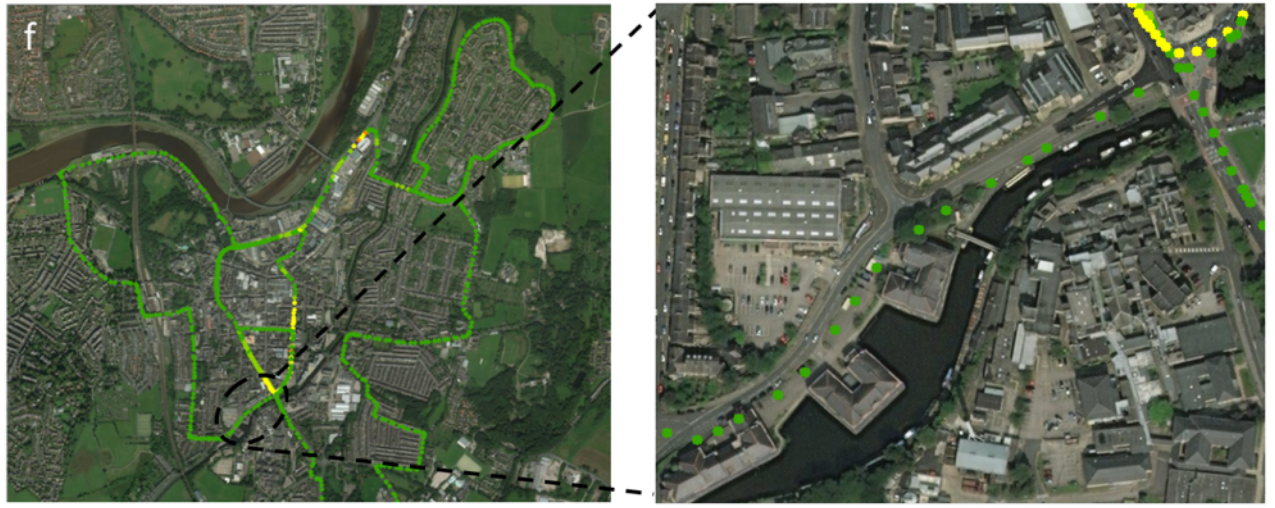




Air Quality "hotspots" change in space and time!





Air Quality Mapping

2 year project in Guangzhou (megacity)

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

Will map UFP and other pollutants

Developing an **app to predict air pollution exposure**

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

Thank you for listening.

Any questions?