TRANSITION Clean Air Network

Exposures to particles and volatile organic compounds across multiple transportation modes

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report

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Executive summary

Personal exposure to a wide range of air pollutants were tested in real-world conditions across nine different transport modes on journeys from London Paddington to Oxford City Centre. Exposures to particles and volatile organic compounds (VOCs) varied significantly between the modes. Walking and cycling between Oxford Station and the city centre were included as a reference, and these modes saw the lowest average exposures to VOC concentration, low particle mass exposures and low ultrafine particle exposures.

A material fraction of the exposures during train travel appear to arise from while accessing the platform, waiting for the train, boarding and disembarking. The diesel train from Paddington to Oxford saw the highest exposures to polycyclic aromatic hydrocarbon and other nitrogen-containing compounds, which are often carcinogens. On average, the diesel trains had good filtration of particles in the carriage, but poor fresh air in terms of concentration of carbon dioxide. In contrast, the electric train had poor filtration but good fresh air.

Both the London Underground and overground electric train saw the highest concentrations in particle mass. This would be accounted for by larger particles, which in the case of the Underground may be due to metallic particles from rail abrasion, fluff and higher concentrations of human debris than on other modes of transport.

The coach had the weakest performance overall, with the highest exposure to alkanes and aromatics, the second highest levels of ultrafine particles and poor air freshness. Furthermore, the journey length was the longest, and so the total human impact was magnified.

The nine-year-old diesel internal combustion engine car saw low VOC and particle mass exposures, which are consistent with good filtration on this premium-segment vehicle; the filtration may be less effective on non-premium cars. Ultrafine exposures were higher. The battery electric vehicle, which was new but drawn from a lower vehicle segment, saw similar particle exposures but VOC exposures were significantly higher, suggesting fresh air was prioritised over cabin filtration of pollutants.

Across all the modes, the single biggest source of VOC exposure appears to be from personal care products. The second most prevalent source is vehicle fuel and lubricants, leading to the inhalation of hydrocarbon vapours, which have potentially serious health effects. VOCs from plastics, clothes and interior materials were prevalent particularly on the diesel train and coach journeys.

As a general observation, it should be noted that otherwise 'low pollution' journeys can be affected by short exposures to high concentrations, which was seen on some of the journey segments on foot, for example when passing a restaurant emitting cooking smells or a cigarette smoker, when changing trains, and when stationary in roadside 'hotspots'.

Key Findings and Impacts

Human exposures to pollution while travelling are often instinctively associated with emissions from road vehicles. An association line of thought is that public transport in automatically better for human health than private transportation. This initial piece of research comparing pollution exposures on different types of transportation – public, private and active – indicate a much more complex picture, in which exposures are governed less directly by the type of vehicle propulsion. Key findings include:

- Exposures during train journeys are dominated by time spent waiting on platform, boarding and alighting from the train, when the doors open at stops, and from emissions from other passengers
- The coach journey tested saw some of the highest exposures due to the relatively long length of the trip and the number of passengers in a relatively confined space.
- Private cars typically afford a high level of protection to the driver and passengers, through a combination of better filtration on the ventilation system together will less time spend in public spaces.
- Active travel, whether cycling or walking, saw generally low exposures, even in city centre areas. While the traveller may be exposed to occasional large pollution spikes from hotspots, these effects were diluted as a result of the fresh air exposures on the rest of the journeys.

The impact of should be to direct further research to develop the understanding of the casual links. From there, more effective mitigations can be considered in policy development and consumer behaviours. For example, it may be more about the design of the ventilation system in vehicles and train stations that effects exposures than the vehicles themselves. In doing so, it may be possible to improve health outcomes amongst travellers more efficiently and cost effectively using targeted interventions. Further, it should give further momentum to standardisation activates – especially at UNECE and CEN – on measuring and comparing in-vehicle pollution levels.

Acknowledgement and Funding

This project was funded by the TRANSITION Clean Air Network through the first round of its Discovery & Innovation Fund in 2021. TRANSITION is a UK-wide network, led by the University of Birmingham in collaboration with nine universities and over 20 cross-sector partners, aiming to optimise the air quality and health outcomes of transport decarbonisation. The network (NERC ref. NE/V002449/1) is itself funded by UK Research & Innovation through its Clean Air Strategic Priorities Fund, administered by the Natural Environment Research Council.

Link to data

The raw data is available at the Centre for Environmental Data Analysis via the following link: https://catalogue.ceda.ac.uk/uuid/96c912c7c0094da2a8627d446cb06708.

Background

Founded in 2011, Emissions Analytics has established itself as a global specialist in real-world vehicle emissions. Amid a rapidly changing political and industry narrative around vehicle emissions and air quality, Emissions Analytics contributes to work in the European Union, for policymakers and for emissions industry stakeholders globally.

In contrast to tailpipe emissions, non-exhaust emissions, such as tyre wear, and cabin air quality remain largely unregulated by governments. New regulations from Asia are addressing volatile organic compounds particularly associated with the new car smell, but little beyond that. This greatly enhances the value of a dependable, repeatable test in a poorly understood area.

In 2019, Emissions Analytics initiated CEN Workshop 103, aimed at defining a standard test procedure to collect in vehicle air quality test data for different makes and models. In particular, it will focus on how well the vehicle filters out particles from incoming air, and how well the ventilation system keeps the cabin air fresh.

Emissions Analytics' testing and data services help organisations understand the relationship between ambient pollution and the air breathed inside a vehicle. Emissions Analytics has been awarded SAE International's *Environmental Excellence in Transportation Award* for developing a Cabin Air Quality Index method.

Project Summary

The harm caused by emissions from vehicles to air quality and the health of humans outside is increasingly well understood. It is generally accepted that it is a policy priority to remove high-emitting vehicles from the road and to swap for low-emission vehicles or public transport. What is less well understood is the exposure of the occupants in various transportation modes. Aggregate time spent in vehicles is significant and can be measured in hours per day for certain commuters and professional drivers. There is a widespread misconception that people are well protected from pollution when inside vehicles, when in fact their exposure may increase in the cabin due to accumulation of air pollutants.

The focus of the project was on particulates and volatile organic compounds (VOCs). Particles measured included ultrafines, and VOCs were analysed into the component species using highly sensitive equipment. Therefore, a much wider range of pollutants was tested than in standard air quality monitoring.

The study was based upon a variety of routes, starting at London Paddington and ending in Oxford City Centre. The modes of transport that were studied included diesel and electric trains, the London Underground, diesel and electric buses, and old and new cars, including a battery electric vehicle. As a baseline and reference, exposures of pedestrians and cyclists were also measured.

The main output was average 'profiles' describing typical exposures by transport mode.

Objective

The aim was to develop a better understanding of pollution exposures comparatively across transport modes, to inform policy makers, researchers, operators and the wider public, with a view to priorities under Net Zero.

Mostly, the measured pollutants are currently unregulated, despite the known health risks of certain compounds. Vehicles can come within health and safety at work regulations, and the use of certain materials is restricted in manufacture under REACH.

The risk is that ultrafine particles and certain VOCs are associated with health effects ranging from respiratory disease to cancer, while high CO_2 concentrations can impair cognition. Measuring ultrafine particles and speciated VOCs will help characterise pollutants currently little researched and poorly understood.

The project aligns with TRANSITION's concept of emerging air quality challenges by considering this largely unregulated space, at the interface with active mobility options.

Test dates

Testing was carried out between the 17 May and 25 May 2021.

Transportation types

Testing was carried out on several transportation types, as shown in the table below.

These were selected to cover a range of public, private and active types of transportation that are used in current practice between London and central Oxford. Due to the limitations of this study, only one test was generally possible per route. Additional repeats would require further investigation.

Route	Day	Vehicle
Diesel train, London to Paddington	1	South Western Railway Class 159
Diesel bus, Oxford	1	Alexander Dennis Enviro400
Underground, Paddington to Waterloo	2	Mark 2 1972 Stock
Electric train, Waterloo to Basingstoke	2	GWR Hitachi Class 800
Diesel train, Basingstoke to Oxford	2	Virgin Cross Country Class 220 Voyager
Hybrid bus, Oxford	2	Alexander Dennis Enviro400 Electric Hybrid
Diesel internal combustion engine car	3	2012 Mercedes-Benz C-Class C220 CDI BlueEfficiency SE G-Tronic Estate
Underground, Paddington to Victoria		As above and 2009 Stock
Diesel coach	4	Alexander Dennis 34 Plaxton Panorama
Battery electric vehicle	5	2021 Vauxhall Corsa E SRI NAV Premium

Test Equipment

Portable In-cabin measurement system (PIMS)

Emissions Analytics has developed measurement technology and techniques to analyse real cabin air quality generically called PIMS (Pollution In-Cabin Measurement System).

The PIMS analyser is a portable air quality system which can measure Particle Number (PN), Carbon Dioxide (CO_2), Carbon Monoxide (CO), Nitrogen Dioxide (NO_2) and Volatile Organic Compounds (VOCs). Ambient Temperature, Pressure and Relative Humidity conditions can also be recorded.

An accompanying carry case can be used for testing whilst walking or cycling. When in this configuration sample is drawn from the top of the case, and exhausted through the bottom. Thermal desorption tubes are affixed to the outer shell of the case, sampling both actively and passively. There is also a GPS unit on the case for measuring speed, location and altitude.

Equipment configuration for carry case

GCxGC-TOF-MS

The second dimension of compound separation enabled by two-dimensional gas chromatography (GCxGC) enables discovery and identification of both known and unknown compounds, a capability that is rarely available. Only 20% of this smaller group of organic compounds can be analysed easily by one-dimensional gas chromatography (GC). For everything else, the second dimension offers a significant advantage.

Compounds with similar chemical and physical properties elute in clusters in a GCxGC analysis. This means that identifying one component in the cluster can provide clues as to the identity of neighbouring peaks. Complex samples contain thousands of individual analytes; by using GCxGC, the number of identifiable peaks compared to a one-dimensional GC analysis increases exponentially. Detecting and identifying more peaks in a sample can give meaningful information that would otherwise be impossible with single GC alone, and can increase certainty.

Figure 1A - GCxGC-TOF-MS

Time-of-Flight (TOF) is a mass analyser that utilises an electric field to accelerate generated ions through the same electrical potential, and then measures the time each ion takes to reach the detector. If the ions all have the same charge, their kinetic energies will be identical and, therefore, each ion's velocity will depend only on its mass. This means that lighter ions reach the detector first, while heavier ions take longer.

Thermal desorption (TD) is a readily automated gas extraction technology based on standard gas chromatography and providing an efficient, high-sensitivity alternative to conventional solvent extraction. The process of thermal desorption involves the extraction of volatile or semi-volatile organic compounds from a sorbent or adsorbent material by heating the sample in a flow of inert gas. Either pumped or diffusive monitoring are versatile sampling options for packed tubes, being compatible with both single- and multi-bed sorbents.

Figure 1B - Thermal desorption (TD) Tube

Testing methodology

The research tested multiple transport modes in real-world conditions, with primary measurements being particulate number (PN), mass (PM) and VOCs. Secondary measurements for carbon dioxide (CO_2) will be a surrogate for air "freshness".

PN was measured with a lower size cut-off of 15nm. VOCs were captured on thermal desorption tubes and then measured on a GCxGC-TOF-MS instrument in order to perform a non-targeted analysis in the C_2 to C_{44} range. The principal compounds identified were quantified using external standards. An internal standard was used across all the tests to ensure comparability.

The method involved testing multiple modes over six days with consistent weather conditions in terms of temperature and precipitation, to allow good comparability. The test route was from London Paddington to Oxford city centre. Ventilation settings on the cars were standardised, using automatic settings at 21 degrees Celsius and mid fan speeds where applicable. Windows were closed in all cases.

The deliverables are total mass for PM and VOCs and total PN by journey and mode. Distance- and time-specific emissions factors can then be derived, with uncertainties. For VOCs, the profiles were identified for each significant species. These factors can be combined with journey times from Department for Transport travel study data to estimate total exposures.

The relevant journeys and modes, from here referred to as the deliverables, were:

1. Diesel public transport
    - -Diesel train from London Paddington to Oxford
    - -Diesel bus from Oxford railway station to Oxford Queens Lane

2. Electrified public transport
    - -London underground service from London Paddington to Waterloo
    - -Electric overground train from Waterloo to Basingstoke
    - -Diesel train from Basingstoke to Oxford
    - -Hybrid bus from Oxford railway station to Oxford Queens Lane

3. Internal combustion engine car – 10+ years old
    - -Driving from London Paddington to Oxford Queens Lane

4. Diesel coach service

   -London underground service from London Paddington to London Victoria
   -Oxford coach service from London Paddington to Oxford

5. Battery electric car – Less than one year old
   -Driving from London Paddington to Oxford railway station

6. Walking
   -Walking between Oxford railway station and Oxford Queens Lane (repeated 5 times)

7. Cycling
   -Walking between Oxford railway station and Oxford Queens Lane (repeated 5 times)

Test protocol

The PIMS analyser was measuring constantly throughout the test days. Upon completion of the testing, the data was downloaded and segmented, based on GPS and time.

Vehicles

1. The PIMS analyser was installed into the vehicle.
2. The analyser was powered up and allowed to warm up and settle.
3. The GPS unit was fixed to the roof of the vehicle and the climate probe was run through the door to outside the vehicle.
4. A sample bracket was mounted for the interior measurements at head height between the two front headrests, to ensure consistent data capture.
5. Climate control was set to; fans – automatic, air conditioning on, recirculation off and temperature at 21 degrees centigrade.

Public transport, walking and cycling

1. On public transport, seating was taken in the centre of the carriage. If there were any strong odours in the area, then an alternative seat was found.
2. The analyser was powered by a 100Ah battery for this test and placed inside the carry case, whilst ensuring there was adequate ventilation to the analyser.
3. The GPS unit was fixed to the top of the carry case.
4. The equipment was bolstered with impact and vibrational dampening material.
5. For the cycling test, the analyser was securely fastened to the stowage rack above the rear wheel with foam for dampening.

Desorption tubes

Desorption tubes were used for each journey. Two tubes were used for each journey, one was used to collect a passive sample, the other used a pump to collect the sample.

When using the analyser within the carry case, the pump was mounted inside the carrying case. The sample was drawn from a position in close proximity to the sample inlet for the analyser. The passively sampled tube was attached to the top of the carry case before each journey began.

Following each journey, the tubes were sealed and placed into a labelled bag and sent for analysis.

Test deliverables

Day 1 – Deliverables 1 and 6

- The analyser was driven to London Paddington station.
    - Upon arrival the analyser was removed from the car and placed into the carrying case.
    - The car was then driven to Oxford, to await the completion of the first leg.
- The PIMS analyser, contained in the carrying case was taken into London Paddington station and carried onto the Great Western Railway service to Oxford.
    - The journey was approximately 60 minutes in duration.
    - Upon alighting the train in Oxford, the analyser was carried to the bus stop outside the rail station. This analyser was then taken onto the Stagecoach bus service (route 1).
    - The journey started from Oxford rail station and ended at Oxford city centre – Queens Lane (stop K1).
    - This journey was approximately 12 minutes.
    - Upon arriving at Queens Lane, the test reconvened with the test vehicle.
    - A data check was carried out at this point.
- The walking phase was completed next. Commencing at Oxford rail station and continuing for 20 minutes to Queens Lane, and then returning to the rail station.
- At least five repeats were conducted.

Day 2 – Deliverables 2 and 7

- The analyser was driven to London Paddington station.
    - Upon arrival the analyser was removed from the car and placed into the carrying case.
- The analyser, contained in the carrying case, was then taken into London Paddington station. This was then taken onto the London underground service on the Bakerloo Line towards Elephant and Castle. The journey was nine stops and lasted approximately 20 minutes, culminating at Waterloo station.
    - The analyser was then transported to the rail station at Waterloo.
    - The analyser was carried onto the Network Rail service to Basingstoke on the South Western Mainline.
    - Upon alighting the train in Basingstoke, the analyser was then carried onto the Cross-Country Service to Oxford.
- The analyser in the carry case was then taken on a hybrid bus to Queens Lane (route 5).
- The next phase was the cycling phase.
    - A bicycle was hired, with a stowage rack above the rear wheel.
    - The analyser was secured to the stowage rack using foam for dampening and a ratchet strap for securing.
    - At least five repeats of the cycling route were conducted.

Day 3 – Deliverable 4

- The analyser was driven to London Paddington station.

  - Upon arrival the analyser was removed from the car and placed into the carrying case.
  - The analyser was taken onto the London underground service on the Circle Line to Victoria station. The journey was six stops and lasted approximately 15 minutes in duration.
  - Upon arrival the analyser was taken to Victoria bus station.
  - The analyser was taken onto the Oxford Tube bus service to Gloucester Garden bus station.

Day 4 – Deliverables 3 and 5

- The analyser stored within the carry case was loaded into the company vehicle.
  - The analyser was then driven to London Paddington Station.
  - Data collection was started upon arrival at London Paddington station.
  - The car was then driven under test conditions, to Oxford (Queens Lane).
- Following this, the analyser was then removed from the company vehicle and loaded into the hired battery electric vehicle (BEV).
  - The test was then repeated on the same vehicle.

Test route

🟩	Deliverable 1	Diesel public transport
🟦	Deliverable 2	Electrified public transport
🟨	Deliverable 3 and 5	Internal combustion engine vehicle/battery electric vehicle
🟪	Deliverable 4	Diesel coach service
🟥	Deliverable 6 and 7	Walking and cycling

Figure 2 – Routes between London and Oxford

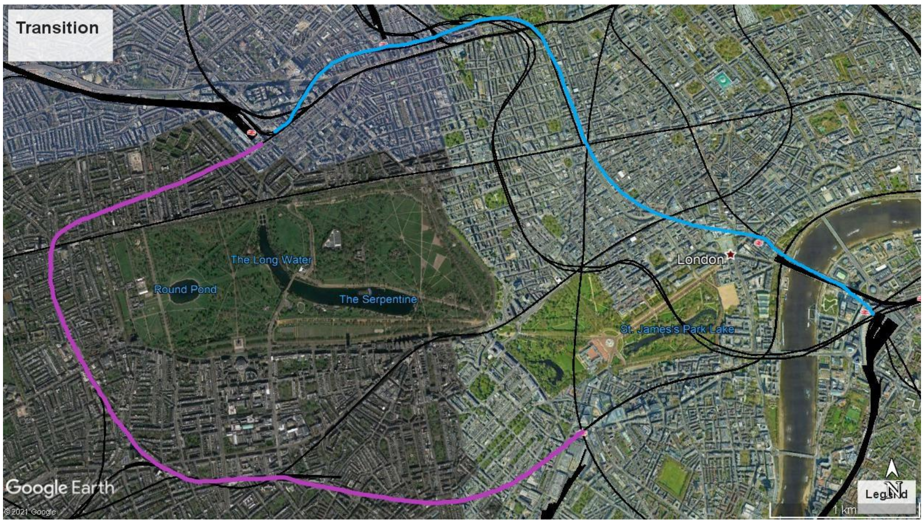


Figure 3 – London Underground Routes

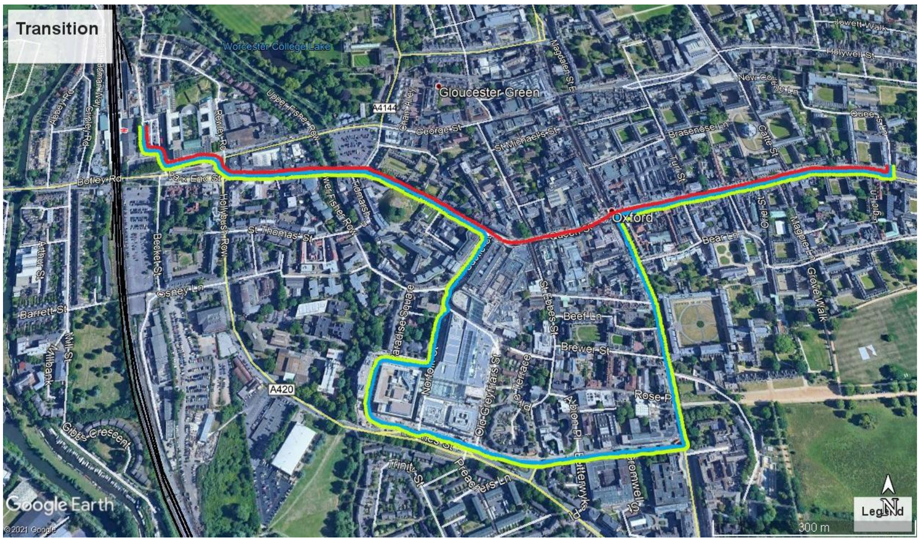


Figure 4 - Oxford City Center Routes

Results analysis

VOC exposure by type and journey leg

The following table shows the average VOC concentration exposure across each major segments of the journeys. Mass values are calculated on a toluene equivalent basis. The VOCs are grouped into relevant broad groups, which tend to reflect similar chemical and toxic effects.

Mass concentration (ng/ml of air)	Day	Alcohols	Alkane, alkene, alkyne and cyclo-	Aromatics + Aldehydes and Ketones	PAH and Nitro-containing group	Total
Paddington platform	1	0.10	0.02	0.01	0.00	0.13
Diesel train - Paddington to Oxford	1	0.06	0.04	0.01	0.07	0.18
Bus - Oxford Station to Queens Lane	1	0.29	0.07	0.03	0.01	0.41
Underground - Paddington to Waterloo	2	0.05	0.06	0.02	0.01	0.14
Electric train - Waterloo to Basingstoke	2	0.03	0.03	0.01	0.01	0.08
Diesel train - Basingstoke to Oxford	2	0.10	0.12	0.03	0.01	0.26
Station to QL & back by Bus	2	0.06	0.02	0.01	0.00	0.09
Underground - Paddington to Victoria	3	0.02	0.02	0.01	0.01	0.06
Coach - Victoria to Oxford	3	0.02	0.11	0.02	0.02	0.17
Foot - Oxford Station to Queens Lane	3	0.07	0.03	0.01	0.01	0.12
BEV - Paddington to Oxford Station	4	0.07	0.18	0.02	0.01	0.28
Foot - Oxford Station to Queens Lane	4	0.01	0.01	0.00	0.00	0.03
Diesel ICE - Paddington to Queens Lane	5	0.04	0.02	0.01	0.01	0.08
Foot - Oxford Station to Queens Lane	6	0.00	0.02	0.01	0.01	0.04
Bicycle - Oxford Station to Queens Lane	6	0.00	0.01	0.01	0.00	0.02

Taking the previous average concentrations and applying to the actual durations of each journey leg, the table below estimates the total exposures by inhalation, again on a toluene equivalent basis. The estimated inhalation rates of air are shown in the final column.

Travel by foot and bicycle is included, based on one return journey between Oxford Station and the city centre. These are not comparable with the other journeys for total exposure, due to the much shorter length and duration.

Mass (µg)	Alcohols	Alkane, alkene, alkyne and cyclo-	Aromatics + Aldehydes and Ketones	PAH and Nitro-containing group	Total	Breathing volume (l/min)	Duration (minutes)
Paddington platform	12.5	3.0	1.5	0.2	17.3	10	13
Diesel train - Paddington to Oxford	40.0	22.9	7.9	44.5	115.4	8	80
Bus - Oxford Station to Queens Lane	32.7	8.4	3.7	1.1	45.9	8	14
Underground - Paddington to Waterloo	12.2	15.3	5.1	1.7	34.4	10	25
Electric train - Waterloo to Basingstoke	24.1	25.8	5.2	3.9	59.0	8	93
Diesel train - Basingstoke to Oxford	45.2	54.4	12.4	5.5	117.5	8	57
Station to QL & back by Bus	23.9	7.4	3.1	0.7	35.1	8	48
Underground - Paddington to Victoria	7.1	7.4	3.3	2.4	20.2	10	33
Coach - Victoria to Oxford	23.1	173.6	34.0	30.4	261.1	8	191
Foot - Oxford Station to Queens Lane	103.2	50.3	21.8	15.8	191.1	40	39
BEV - Paddington to Oxford Station	48.7	128.0	12.4	7.2	196.2	8	87
Foot - Oxford Station to Queens Lane	34.1	38.1	15.9	12.3	100.4	40	90
Diesel ICE - Paddington to Queens Lane	31.0	16.8	5.1	4.5	57.3	8	89
Foot - Oxford Station to Queens Lane	*1.1*	*15.5*	*6.2*	*3.4*	*26.3*	*40*	*33*
Bicycle - Oxford Station to Queens Lane	*5.7*	*13.2*	*20.4*	*3.5*	*42.8*	*60*	*17*

VOC exposure by potential source and journey

The VOCs identified are grouped into the most likely source and analysed across each day, as measured by the peak area on the chromatogram. Personal care products include deodorants, perfumes, shampoos, and so on. Fuel and lubricants are typically evaporated components from diesel and gasoline fuel. Synthetic fibres and plastics could come from clothing, food packaging, vehicle interiors and so on. Human respiration is the carbon dioxide exhaled by the vehicle occupants.

VOC grouping, peak area (mV.minute)	Diesel train	Electric train	Coach	Electric car	Diesel car	Active
	Day 1	Day 2	Day 3	Day 4	Day 5	Day 6
Personal care	684,491,847	1,529,328,134	2,195,457,140	1,607,962,225	225,221,687	280,237,081
Fuel and lubricants	249,937,572	469,089,697	1,370,761,811	1,304,455,221	172,667,323	184,938,688
Synthetic fibres, plastics	213,364,338	44,094,382	279,663,970	73,797,262	3,564,666	181,498,875
Human respiration (CO2)	109,616,945	138,458,368	57,950,486	95,709,161	53,434,231	95,424,581
Total	1,257,410,702	2,180,970,581	3,903,833,407	3,081,923,869	454,887,907	742,099,224

Speciated VOCs by journey

This table shows the full breakdown of the most prevalent compounds, as measured by the peak area on the chromatogram. Of 275 compounds discovered in total, the top 30 are shown below.

Compound, peak area (mV.minute)	Formula	Diesel train	Electric train	Coach	Electric car	Diesel car	Active	Total	Potential source	Health risk
n-Nonadecanol-1	$C_{19}H_{40}O$	31,467,044	82,411,136	588,560,886	251,618,008	13,449,426	13,718,736	981,225,235	Personal care	n/a
Nonadecane	$C_{19}H_{40}$	48,983,938	65,968,039	261,850,805	478,118,395	63,450,330	25,910,101	944,281,607	Diesel component	Lung irritation
1-Octanol, 2-butyl-	$C_{12}H_{26}O$	24,762,538	85,513,752	293,671,283	459,292,871	24,202,449	19,637,314	907,080,209	Personal care	Aquatic
Cyclopentasiloxane, decamethyl-	$C_{10}H_{30}O_5Si_5$	63,220,647	596,697,174	109,204,667	1,644,859	7,099,218	4,262,351	782,128,916	Personal care	Aquatic
1-Eicosanol	$C_{20}H_{42}O$	3,034,890	12,065,147	268,822,468	312,331,500	8,831,569	7,411,748	612,497,322	Personal care	Eye irritation, aquatic
Cyclotetrasiloxane, octamethyl-	$C_8H_{24}O_4Si_4$	32,882,445	127,591,847	98,984,445	128,910,127	42,924,557	121,541,512	552,834,933	Personal care	Aquatic
Carbon dioxide	CO_2	109,616,945	138,458,368	57,950,486	95,709,161	53,434,231	95,424,581	550,593,772	Human respiration	At high concentrations only
Behenic alcohol	$C_{22}H_{46}O$	109,034,280	74,574,991	239,395,954	40,040,388	33,315,389	16,417,292	512,778,294	Personal care	n/a
4-Amino-1-butanol	$C_4H_{11}NO$	230,622,796	236,770,540	7,647,571	9,418,439	2,353,479	2,203,228	489,016,054	Personal care	Skin burns, eye damage
Oxirane, tetradecyl-	$C_{16}H_{32}O$	989,323	38,464,719	187,526,323	227,471,246	12,723,528	5,403,809	472,578,948	Lubricant, additive	Skin, eye irritation, potentially carcinogenic
p-Xylene	C_8H_{10}	14,533,167	31,585,518	140,257,066	71,691,561	2,561,177	181,257,652	441,886,141	Plastics, polyester	Skin, eye, lungs irritation, aquatic

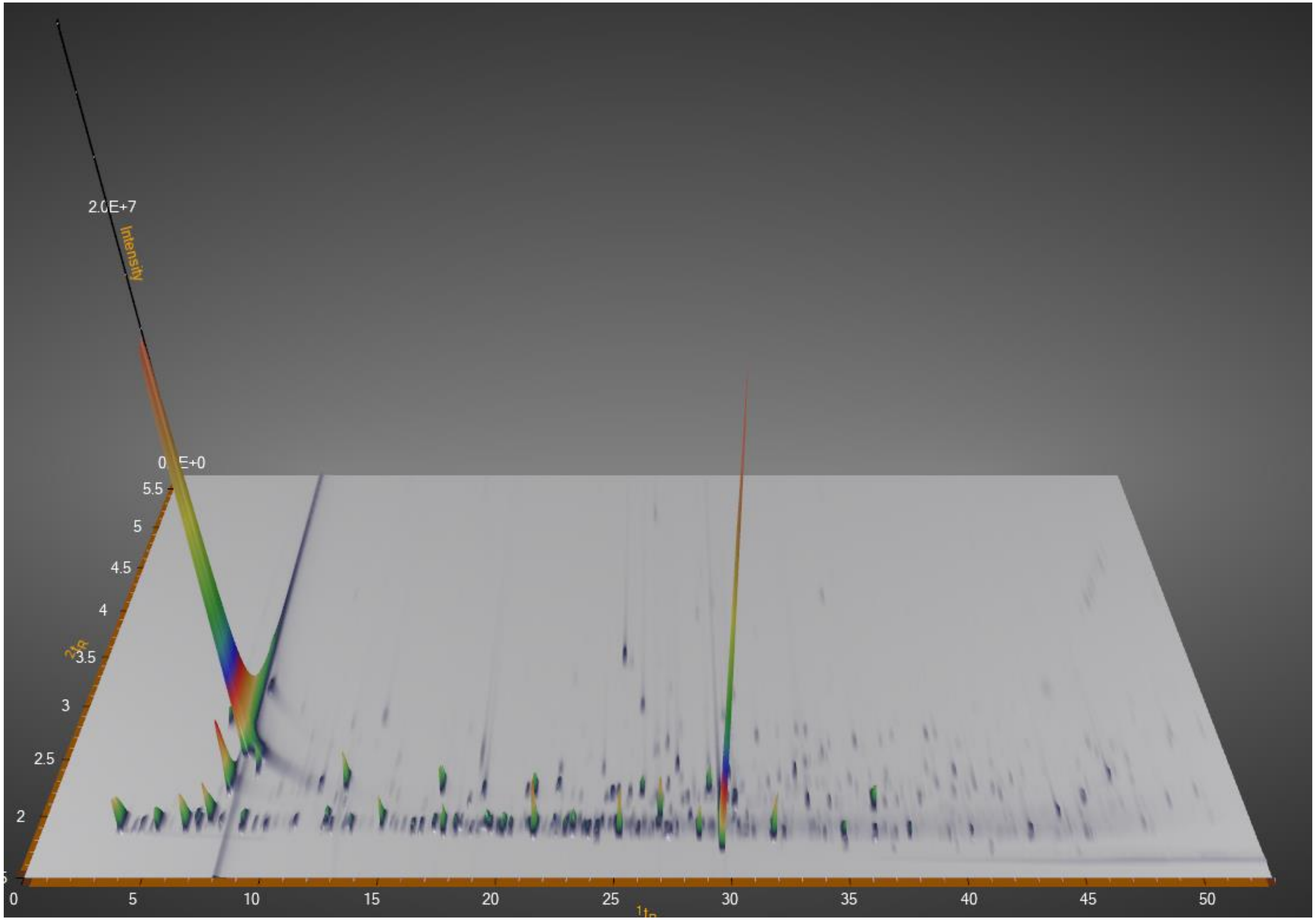
Tetradecane	$C_{14}H_{30}$	15,714,536	34,726,549	237,061,186	65,668,420	10,132,947	16,470,023	379,773,660	Diesel component	Lung irritation

Compound	Formula	Diesel train	Electric train	Coach	Electric car	Diesel car	Active	Total	Potential source	Health risk
Acetonitrile	C_2H_3N	67,107,593	104,993,421	14,819,316	60,566,637	57,916,029	62,530,503	367,933,499	Cigarette smoke, plastics, clothes, personal care	Skin, eye, lungs irritation
Tridecane	$C_{13}H_{28}$	9,115,341	28,886,434	173,399,488	118,988,790	10,094,846	24,563,040	365,047,939	Diesel, gasoline component	Lung irritation
Undecane	$C_{11}H_{24}$	7,997,187	37,011,907	125,661,271	167,665,238	5,384,583	8,225,058	351,945,244	Diesel, gasoline component	Lung irritation
Acetone	C_3H_6O	74,827,321	123,605,489	50,118,780	46,683,616	13,569,687	10,564,890	319,369,783	Plastics, personal care	Eye irritation, drowsiness
Dodecane	$C_{12}H_{26}$	15,204,010	46,646,727	153,953,103	69,516,537	6,218,499	5,827,431	297,366,307	Diesel, gasoline component	Lung irritation
9-Octadecen-1-ol, (Z)-	$C_{18}H_{36}O$	498,178	621,428	198,187,864	53,010,446	0	84,987	252,402,902	Personal care	n/a
Decane	$C_{10}H_{22}$	10,039,097	55,119,578	126,522,474	45,908,190	4,320,626	9,675,938	251,585,903	Diesel, gasoline component	Lung irritation
1-Decanol, 2-hexyl-	$C_{16}H_{34}O$	0	1,059,104	96,348,965	130,823,557	2,940,723	1,196,573	232,368,922	Personal care	n/a
Caprolactam	$C_6H_{11}NO$	193,702,636	2,001,384	81,034	0	0	0	195,785,054	Synthetic fibres, plastics	Skin, eye, lungs irritation
2-Dodecen-1-yl(-)succinic anhydride	$C_{16}H_{26}O_3$	22,028,244	3,102,675	82,044,081	81,056,853	0	1,030,243	189,262,094	Personal care	Skin, eye irritation, aquatic
Cetene	$C_{16}H_{32}$	0	6,707,399	45,443,421	26,666,566	44,356,658	61,141,925	184,315,970	Lubricant, additive	Lung irritation
Toluene	C_7H_8	22,664,108	52,469,267	49,980,787	20,259,718	14,482,335	22,525,749	182,381,964	Gasoline component	Skin, lung irritation, drowsiness,

reproductive toxicity

Compound	Formula	Diesel train	Electric train	Coach	Electric car	Diesel car	Active	Total	Potential source	Health risk
1-Dodecanol, 3,7,11-trimethyl-	$C_{15}H_{32}O$	8,501,319	10,857,743	120,150,137	19,991,444	2,272,867	3,726,145	165,499,656	Personal care	n/a
Heptacosane	$C_{27}H_{56}$	76,529,896	968,543	3,917,391	78,793,922	564,470	3,200,343	163,974,564	Diesel component	n/a
Butane, 2-methyl-	C_5H_{12}	42,700,136	102,120,536	5,445,561	5,398,200	938,503	1,995,271	158,598,206	Gasoline component	Lung irritation, drowsiness, aquatic
Styrene	C_8H_8	5,128,535	10,507,479	139,325,870	2,105,701	1,003,489	241,224	158,312,297	Plastics	Skin, eye, lung irritation, reproductive toxicity
Silicic acid, diethyl bis(trimethylsilyl) ester	$C_{10}H_{28}O_4Si_3$	16,504,553	69,463,687	27,500,722	12,573,480	16,346,293	15,911,559	158,300,295	Personal care	n/a

This wide range of species identified is illustrated on the two-dimensional chromatogram from the diesel train test below.


2.0E+7
Intensity
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5
4.5
4
^2t_R
3.5
3
2.5
2
0
5
10
15
20
25
30
35
40
45
50
^1t_R

Particle number, mass and CO_2 concentration by journey leg

This table shows the average PN, $PM_{2.5}$ and CO_2 concentration measured by the PIMS analyser in chronological order of cycle completion.

Segment	Duration (seconds)	Average PN (#/cm^3)	Average $PM_{2.5}$ (µg/m^3)	Average CO_2 (ppm)
Platform	780	4,114	8.37	403
Diesel train	3,480	5,748	3.22	456
Platform	1,320	3,145	1.58	369
Bus	720	6,351	10.45	380
Foot	720	6,922	2.21	371
Bus	840	5,414	1.39	380
Platform	300	6,266	10.56	329
Underground train	900	6,204	70.63	323
Platform	300	5,819	80.63	331
Electric train	3,180	77,478	17.68	353
Platform	2,400	25,965	3.67	303
Diesel train	3,120	5,886	3.89	436
Platform	300	2,748	2.64	423
Bus	2,880	7,384	1.17	309
Platform	240	33,471	5.43	400
Underground train	1,740	8,146	8.73	424
Foot	1,440	11,240	6.47	402
Coach	10,020	31,363	1.11	444
Foot	2,340	5,606	0.11	396
BEV	5,220	17,206	0.64	312
Foot	5,400	7,905	0.65	241
ICE	5,340	24,491	0.44	388
Cycling	3,960	10,375	1.68	391
Foot	7,980	6,275	1.82	400

Particle number, mass and CO_2 concentration by journey leg type

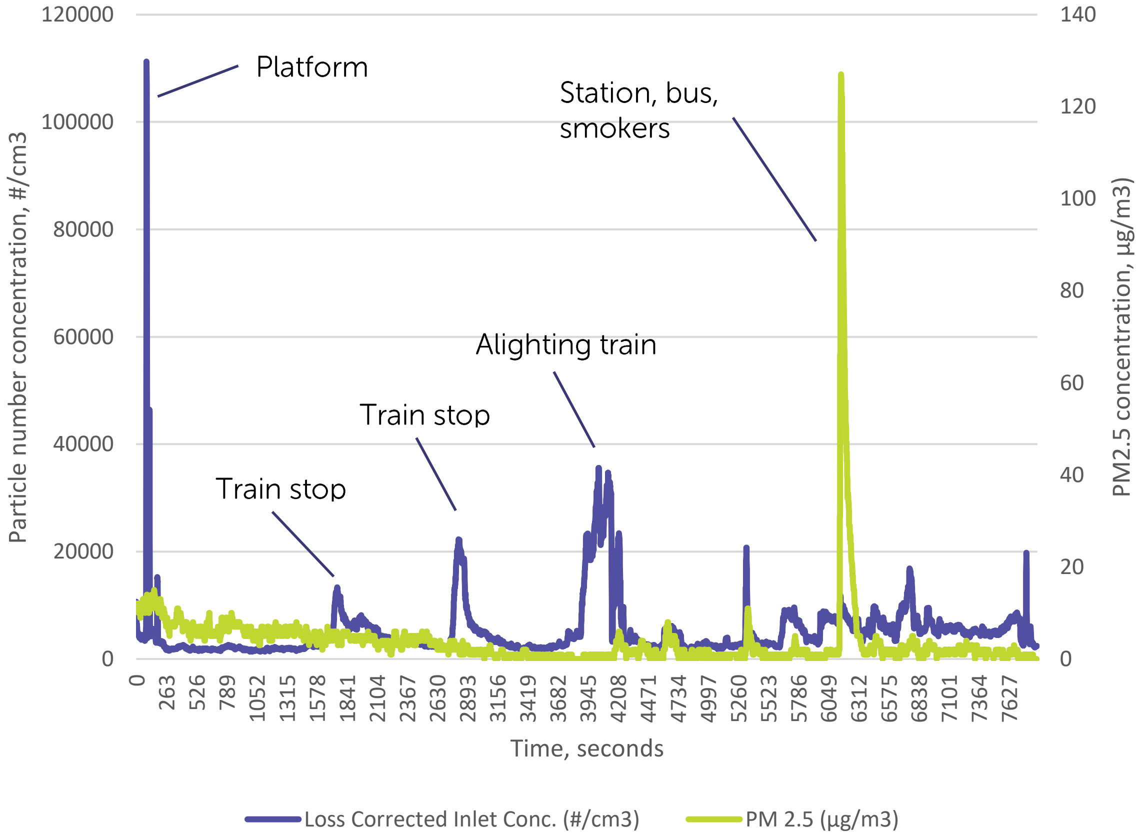
This table shows the average PN, $PM_{2.5}$ and CO_2 concentration measured by the PIMS analyser across each mode of transportation.

Generic group	Average PN concentration (#/cm^3)	Average PM concentration (μ/m^3)	Average CO_2 concentration (ppm)	Comments
Electric train	77,478	17.68	353	Poor filtration, but fresh air
Coach	31,363	1.11	444	Ultrafines a problem; stuffy
ICE	24,491	0.44	388	Little mass, all ultrafines
BEV	17,206	0.64	312	High ultrafines, fresh air
Platform	11,647	16.13	366	More large than small PM
Cycling	10,375	1.68	391	Ambient PN, little mass
Foot	7,590	2.25	362	Ambient PN, little mass
Underground	7,175	39.68	373	Worst for larger particles
Bus	6,383	4.34	356	More large than small PM
Diesel train	5,817	3.55	446	Stuffiest mode
Average	13,563	10.22	374	

The particle number measurement here are "loss corrected". Around 5% of the particles are lost in the sampling line and through the optimal sensor, which is corrected for in the results presented.

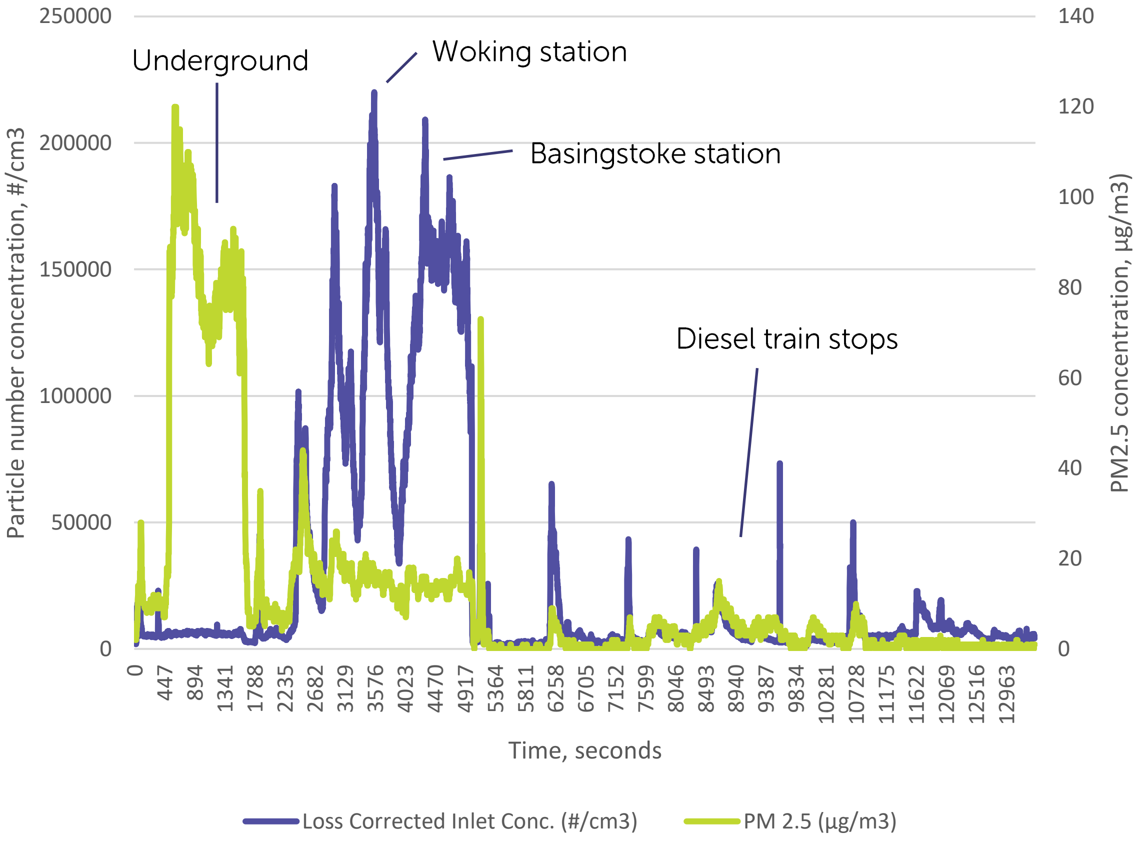
Day 1 – Paddington to Oxford via diesel train

Segment	Start second	End second	Average PN (#/cm^3)	Average $PM_{2.5}$ (µg/m^3)	Average CO_2 (ppm)
Platform	0	780	4,114	8.37	403
Diesel train	780	4,260	5,748	3.22	456
Platform	4,260	5,580	3,145	1.58	369
Bus	5,580	6,300	6,351	10.45	380
Foot	6,300	7,020	6,922	2.21	371
Bus	7,020	7,860	5,414	1.39	380
Total	0	7,860	5,271	3.82	413



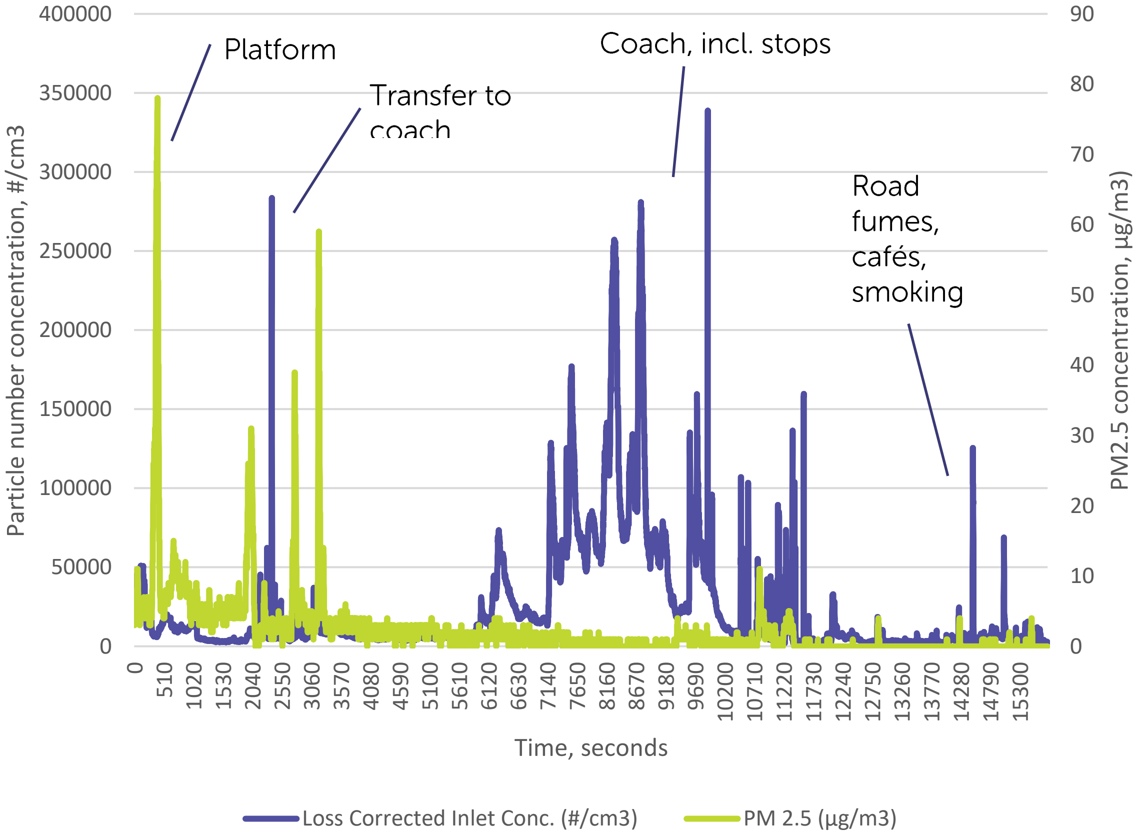
Day 2 – Paddington to Oxford via electric and diesel train

Segment	Start second	End second	Average PN (#/cm^3)	Average PM$_{2.5}$ (µg/m^3)	Average CO$_2$ (ppm)
Platform	0	300	6,266	10.56	329
Underground train	300	1,200	6,204	70.63	323
Platform	1,200	1,500	5,819	80.63	331
Electric train	1,500	4,680	77,478	17.68	353
Platform	4,680	7,080	25,965	3.67	303
Diesel train	7,080	10,200	5,886	3.89	436
Platform	10,200	10,500	2,748	2.64	423
Bus	10,500	13,380	7,384	1.17	309
Total	0	13,380	26,754	12.86	352



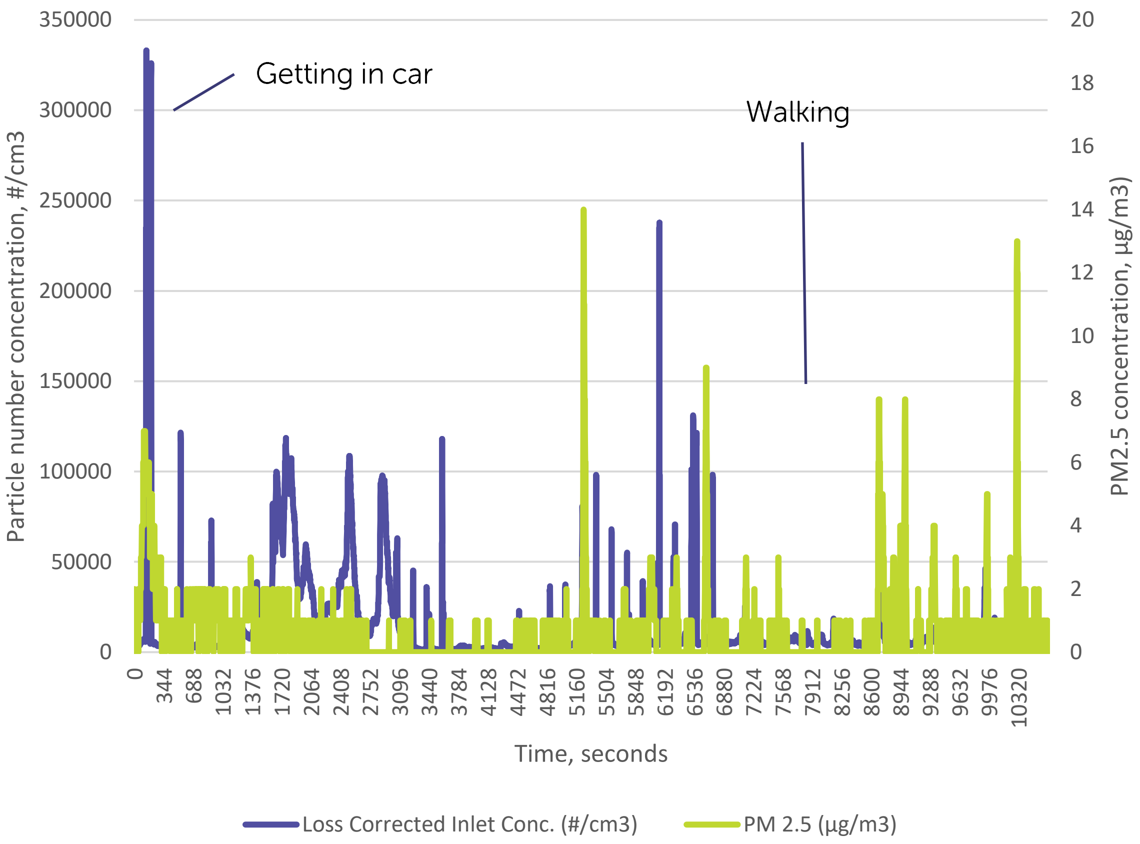
Day 3 – Paddington to Oxford via diesel coach

Segment	Start second	End second	Average PN (#/cm³)	Average $PM_{2.5}$ (µg/m³)	Average CO_2 (ppm)
Platform	0	240	33,471	5.43	400
Underground train	240	1,980	8,146	8.73	424
Foot	1,980	3,420	11,240	6.47	402
Coach	3,420	13,440	31,363	1.11	444
Foot	13,440	15,780	5,606	0.11	396
Total	0	15,780	23,174	2.36	430



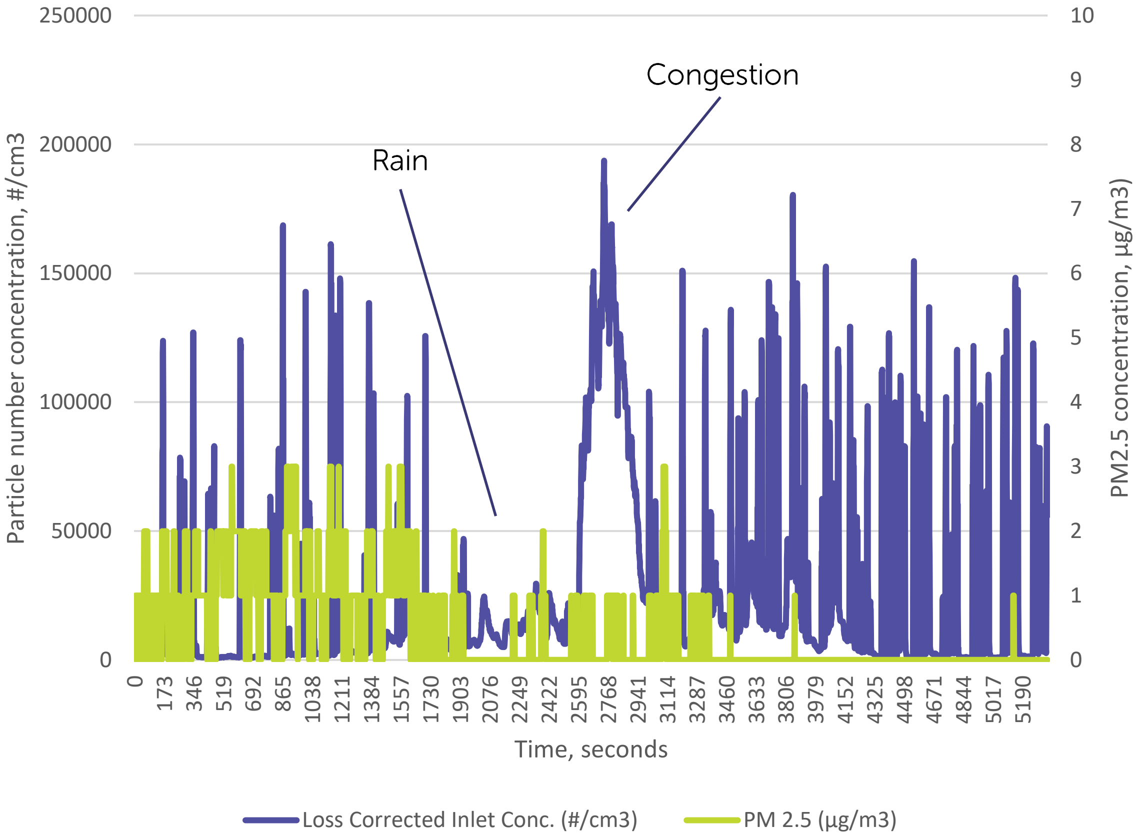
Day 4 – Paddington to Oxford via battery electric vehcile

Segment	Start second	End second	Average PN (#/cm^3)	Average PM$_{2.5}$ (µg/m^3)	Average CO$_2$ (ppm)
Platform	0	240	33,471	5.43	400
BEV	240	5,220	17,206	0.64	312
Foot	5,220	10,620	7,905	0.65	241
Total	0	10,620	12,437	0.65	277



Day 5 – Paddington to Oxford via diesel internal combusiton engine car

Segment	Start second	End second	Average PN (#/cm³)	Average $PM_{2.5}$ (µg/m³)	Average CO_2 (ppm)
ICE	0	5,340	24,491	0.44	388
Total	0	5,340	24,491	0.44	388



Appendix 1 – PIMS analyser specification

Particles	**Specifications**	**Carbon Dioxide**	**Specifications**
Technology	Mixing CPC with embedded diluter	**Technology**	NDIR
Particle Concentration Range	0 - 1,000,000 #/cm^3	**Range**	0 to 5000 ppm
Concentration Accuracy	± 10% compared to reference CPC	**Accuracy**	±30ppm or ±3% reading whichever is larger
Operating Temperature	0 to 30°C	**Operating Temperature**	0 to 50°C
Operating Humidity	0 to 95%	**Operating Humidity**	0 to 95%
Response Time	<3 secs (T10-T90)	**Response Time**	20 secs diffusion time
Working Fluid	IPA	**Supplier**	SenseAir (K30)

Electrochemical	**Specifications**	**Metal Oxide**	**Specifications**
CO (UL2034 Certified)	0-1000ppm. Resolution 0.5ppm	**CO/VOCs (MiCS-4514)**	1 to 1000 ppm
NO_2 (3SP_NO2_5F)	0-5ppm. Resolution <20ppb	**NO_2 (MiCS-4514)**	0.01 to 10 ppm
Technology	Electrochemical	**Technology**	Metal Oxide
Response Rate	<15 secs	**Response Rate**	<60 secs
Supplier	SPEC Sensors	**Supplier**	SGX Sensortech

Environmental Measurements	**Specifications**
Temperature	-10 to 50°C
Pressure	800 to 1100hPa, ±0.25%
Humidity	±3% RH
Time Response	1 secs
Technology	Bosch BME-280
Unit	**Specifications**
Power	<100W, 12V DC
Noise	~55dBA
Data Storage	SD Card, Local MySQL with optional Cloud Storage
Data Acquisition Rate	1Hz
Communications	WiFi. Web-based GUI

Thermal Desorption Tubes	**Use**
Tenax TA	Vapor phase organics from C6/7 to C26
Graphitized Carbon	Vapor phase organics from C5/6 to C14
Tenax GR/Carbopack B	Vapor phase organics from n-C5/6 to n-C20 (EPA Methods TO-14A/TO-15/TO-17)
Tenax TA/Graphitized Carbon/Carboxen 1000	Vapor phase organics from C2/3 to C20
Carbopack C/Carbopack B/Carbosieve SIII	Vapor phase organics from n-C2/3 to n-C16/20 (EPA Methods TO-14A/TO-15/TO-17)
Supplier	Restek / Markes