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Characterising a mobile reference station (MoRS) to quantify personal exposure to air quality

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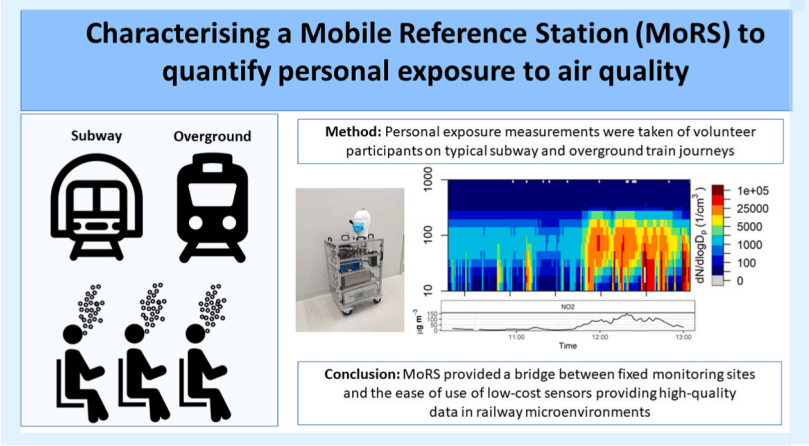
HIGHLIGHTS

- A mobile measurement system was built for use in confined environments.
- It measured multiple air pollutants – NO_2, O_3, particle size, $PM_{2.5}$ and PM_{10}.
- It collected $PM_{2.5}$ onto multiple filters for subsequent laboratory analysis.
- Co-location at reference stations showed excellent agreement.
- It was tested on journeys on subway and diesel trains in the UK.

GRAPHICAL ABSTRACT



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ABSTRACT

There is increasing clinical, epidemiological, and toxicological evidence linking exposure to air pollution with multiple health outcomes that lead to increased mortality and morbidity. Traditionally, fixed air quality monitors have been used to provide ambient air pollution measurements, but they have spatial and temporal limitations. Rapid advances in instrument miniaturisation have made novel sensing technologies more accessible but these are prone to high sensitivity and inaccuracies. To bridge the gap between fixed monitors and small sensors we have developed a Mobile Reference Station (MoRS) – a portable platform delivering high quality measurements of air pollutants using smaller, low power reference grade instruments at high time resolutions. MoRS enables the simultaneous measurement of a broad aerosol size distribution (10 nm–35 µm), gaseous pollutant concentrations (nitrogen dioxide (NO_2) and ozone (O_3)), environmental parameters (noise, relatively humidity (RH) and temperature) as well as collecting filter samples for laboratory analysis. The MoRS instrumentation is described and

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the major challenges in ensuring that high data quality standards are maintained are discussed. Laboratory and field tests were used to derive scaling factors for all the MoRSinstrumentation. Field testing of MoRS showed excellent intercomparability against reference instrumentation ($R^2 > 0.98$) and good agreement with reference instruments in the ultrafine aerosol range, although there was an overestimation of fine particle aerosols. Measurements taken during example mainline train and London Underground (LU) journeys are displayed showing the value of the high-quality data derived from MoRS and how this can help to disentangle multiple confounding environmental pollutants and enrich epidemiological studies.

1. Introduction

There is increasing clinical epidemiological and toxicological evidence linking exposure to air pollution with multiple adverse health outcomes (Arroyo et al., 2021; Hoek et al., 2013; Makri and Stilianakis, 2008) leading to increased mortality and morbidity (Dockery et al., 1993; Amiri et al., 2019) with elevated levels of cancer, respiratory and pulmonary cardiovascular disease (Doiron et al., 2019; Han et al., 2019; Loomis et al., 2013). Traditionally, fixed air quality monitoring stations have been used to provide ambient air pollution measurements for epidemiological studies. Their limitations in providing data at high spatial and temporal resolutions do not reflect the additional microenvironments that people are exposed to each day (Castell et al., 2017, Kitagawa et al., 2022). People spend the majority of their time indoors (Klepeis et al., 2001), exposed to indoor air pollutants (Barkjohn et al., 2021; Zhang and Srinivasan, 2020) and often being subjected to their highest exposures in transport environments (de Nazelle et al., 1987; Cepeda et al., 2017; Saunders et al., 2019), neither of which are captured with fixed monitoring stations. This can lead to bias in individual personal air pollution exposure estimates (Smith et al., 2016) that does not capture the heterogeneity of exposures within a population (Brokamp et al., 2019).

Rapid advances in instrument miniaturisation have made novel sensing technologies more widely available. These are portable, easy-to-use and low-cost making real-time, high-resolution air pollutant monitoring possible (Castell et al., 2017; Kang et al., 2021) increasing the potential to monitor in-depth personal exposure to air pollutant concentrations on an individual and population scale (Chatzidiakou et al., 2019). Novel sensing technologies can enhance the understanding of the high spatial variability of air pollutants, thus opening up personal exposure measurements and accounting for the significant disparity between air pollutant concentrations encountered when moving between different microenvironments (Evangelopoulos et al., 2021). However, sensors are often highly sensitive to changing environmental metrological conditions, making accurate measurements difficult when moving sensors between different environments (Cross et al., 2017). Data quality can be further compromised by sensor age, pollutant cross-sensitivities, sensor drift and chemical interference requiring complex algorithms to adjust for these factors which often lack reproducibility (Aleixandre and Gerboles, 2012; Karagulian et al., 2019; Kumar et al., 2010). Uncertainties remain regarding quality control and validation of these instruments and without long-term laboratory and field calibrations (Jiao et al., 2016; Barkjohn et al., 2020; Liu et al., 2020) their role in scientific studies remains questionable (Cross et al., 2017; Feinberg et al., 2018; Wang et al., 2021) and could lead to misleading data and exposure misclassification (Chatzidiakou et al., 2020). Therefore, there is a need for stable measurements in a range of differing microenvironments that allows intercomparability with reference instrumentation to enable high-quality personal exposure data that can enrich environmental epidemiological studies (Snyder et al., 2013).

To address this gap between static reference monitoring stations and easy-to-use novel sensing technologies, we have developed a highly portable air pollution Mobile Reference Station (MoRS). This can provide reference equivalent exposure measurements delivering reliable, reproducible data suitable to address scientific and policy questions. In its current configuration, MoRS provides simultaneous measurements of a broad aerosol size distribution (10 nm–35 μm), gaseous pollutant concentrations (nitrogen dioxides (NO_2) and ozone (O_3), carbon dioxide (CO_2)), environmental parameters (noise, relatively humidity (RH) and temperature) as well as collecting filter samples for laboratory analysis. Thus far it has been deployed in subway and overground railway environments and can be rapidly adapted to measure other chemical and physical parameters as required. This paper describes the instrumentation used on MoRS and evaluates its performance against reference standards and measurement techniques in different environments.

2. Materials and methods

The Mobile Reference Station (MoRS) was developed to offer a small, flexible, wheeled platform for obtaining high quality measurements of air pollutants over relatively short timescales (minutes to hours), where power was not available (e.g. transport microenvironments). This was achieved using recent advances in commercially available monitoring equipment which has resulted in smaller, lower power technology. The modular design means that power and PC data logging can be supplied for several different instruments (depending on the experimental requirements) either from instrument internal batteries (Mini-Wras) or up to four external 12V 22Ah Lithium polymer batteries (for all other instruments), resulting in independent run times of 7.8–20 h between charges. MoRS has, so far, been configured to house all the instrumentation listed in Table 1; fully laden it weighs 35 kg and is shown in detail in Fig. 1.

Nitrogen dioxide was measured using the ICAD (Iterative CAvity enhanced DOAS, Airyx GmbH, DE). It measured NO_2 directly using optical absorption at 458 and 480 nm: NO is converted to NO_2 by reaction with O_3 to provide a NO_X measurement. The ICAD approach has been used in mobile vehicle measurements (Farren et al., 2023) and is described in detail by Horbanski et al. (2019). Regular baseline checks were performed with a Purafil Chemisorbant/activated charcoal scrubber and NO_2 and NO standard gases (NPL, 2023) and NO_2 ICAD data was scaled accordingly. Ozone was measured at a 10s resolution using UV absorption at 254 nm (Model 205 Dual Beam, 2B Technologies, USA). This is a US Environmental Protection Agency Federal Equivalent Method (EPA, 2023) which overcomes relative humidity changes (Wilson and Birks, 2006). The Mini-Wras (Model 1371, Grimm Aerosol Technik GmbH, DE) combines two technologies; a stepping-mode-operated electrode with a Faraday cup electrometer Nano-Sizer (10–200 nm in 10 size bins) and an optical aerosol spectrometer (0.2–35 μm in 31 size bins). A major advantage of the additional Mini-Wras NanoSizer over conventional Optical Particle Counter (OPC) instruments is the reporting of ultrafine particles (<100 nm). This is important when assessing the health impacts of personal exposure to particulate matter as it is known that ultrafine particles have the potential to cause great harm (Loxham et al., 2013). The aerosol sample was dried internally using a silica gel desiccant, and to prolong the life of this desiccant, a monotube gas dryer (MD-700-06F-1, Perma Pure LLC, USA) was installed in the sample stream. Regular baseline checks were performed with a HEPA filter and the response of the Mini-Wras was periodically checked against a TSI SMPS 3080 (TSI, 2023) using an atomised 0.1% NaCl solution to ensure peak modal concentrations were

within 20%. $PM_{2.5}$ samples were collected onto two 25 mm filters, which were changed before each individual train journey, for laboratory and gravimetric analysis using a $PM_{2.5}$ cyclone at 16.7 l/min with an isokinetic split (Model 1102, Bechtel, USA) via two pumps (Air Cadet, Cole Palmer, UK) controlled by two mass flow controllers (Model MCP-20SLPM, Alicat, USA) set to 8.35 l/min each. The filters were pre-weighed and post-weighed after conditioning for 48 h at 19-21^{O}C and 45–50% relative humidity in accordance with the European reference standard (EN12341) (Green and Fuller, 2006, European Commission, 2023). The small mass collected during the overground journeys (0–35 μg) is below the limit of detection. To ensure consistency of approach between the overground and underground measurements, the technique adopted by Smith et al. (2020) was used here. This used contemporaneous concentrations of ambient and subway air and applied different density corrections to the ambient and subway fractions. Mini-Wras measurements of mean $PM_{2.5}$ using the Smith et al. (2020) approach and $PM_{2.5}$ mass concentrations measured on the filters are compared in Fig. S1 and shows a reasonable agreement (Slope = 1.36, R = 0.85).

Due to mask wearing restrictions brought in on public transport from 15 Jun 20–24 Feb 2022 during the COVID-19 pandemic, exposure assessments were also required to reflect any subsequently reduced exposure that resulted from mask wearing. All aerosol measurements were therefore configured to route through a dummy head so that a mask could be placed over the inlets; the combined flow though the mask was 16.7 l/min. All instruments were returned for service and calibration to individual manufacturers on an annual basis and maintained according to the manufacturer's guidelines. The Mini-Wras was operated with the data inversion algorithm included in software version 10 (Ahlawat et al., 2022). Auxiliary measurements of ambient relative humidity and temperature were made using an external sensor attached to the Mini-Wras (model 1158-EE) and noise was measured using a sound meter (RS PRO DT-8852).

2.1. Field intercomparison campaigns

In addition to regular checks against pollutant-free air and gas standards (where available) an additional set of field experiments were undertaken to ensure accurate responses of the instruments in environments representing the differing exposures. As metrological and environmental factors can affect instrument response in relation to reference instruments, MoRS was co-located alongside certified reference instrumentation in the locations, or comparable geographical locations, to where it was deployed for exposure assessments. Field intercomparison campaigns were therefore carried out in London at urban background and roadside monitoring sites and on a subway station platform, chosen to be representative of the locations where MoRS was used for exposure assessments. Co-location of MoRS alongside reference instrumentation allowed the performance of instruments to be assessed against reference instrumentation (NO_2 and O_3) and location/source specific scaling factors to be developed using gravimetric filter measurements in the subway where reference instrumentation was not available ($PM_{2.5}$) to maximise transferability to other locations (Clements et al., 2017).

Field campaigns were undertaken in four locations: Honor Oak Park, North Kensington, Marylebone Road and Hampstead subway station. Honor Oak Park (51.449674, −0.037418) and North Kensington (51.521050, −0.213492) are background monitoring stations, sited away from any immediate influence of traffic. $PM_{2.5}$ (Fidas 200E, Palas, DE) and NO_2 (N500, TAPI, USA) reference instruments were used at Honor Oak Park, while the O_3 reference instrument (T400, TAPI, USA) was used at North Kensington. The Marylebone Road roadside station (51.522530, −0.154611) was used to represent locations that are exposed to elevated levels of vehicle emissions where a BAM (1020, MetOne, USA) was used for the $PM_{2.5}$ intercomparison. An air quality measurement facility containing a Partisol 2025; Thermo Scientific Partisol 2025, Waltham, Ma, USA) was installed on the northbound platform at Hampstead London Underground station platform (51.5569, 0.1783) and filters were weighed according to the protocol detailed above. The performance of the Mini-Wras when measuring subway particles was assessed through an inter-comparison alongside a Dekati Electrical Low Pressure Impactor (ELPI^{+}, Dekati, FI) at Hampstead station. This facility is in the deepest part of the network to give a representation of air with a strong subway source. The inter-comparability of MoRS measurements at representative geographical locations was assessed against reference instrumentation using the Deming Regression technique (Wu and Yu, 2018).

2.2. Transport microenvironment exposure assessments

MoRS was deployed in two different transport microenvironments: diesel trains and subway trains. Diesel train passenger exposure was assessed in an intensive measurement campaign of almost 100 return train journeys (13 Jan 20–02 Dec 21). MoRS was placed in a train carriage in a pre-agreed location with the train operator, with minimal interference with other passengers and remained in the same location for both outbound and return journeys. Details of the position in relation to the engine exhaust, passenger numbers, station arrival and departure, and door opening and closing times were maintained in addition to the location via GPS where MoRS was used in overground settings but not reported here. London Underground train passenger exposure was assessed as part of a panel study examining the response of volunteer participants with Chronic Obstructive Pulmonary Disease (COPD) and healthy volunteers using previously employed methodologies (McCreanor et al., 2007; Sinharay et al., 2018). MoRS was located in the rear carriage of a LU train travelling on a Bakerloo Line return journey between Willesden Junction station and Elephant & Castle station over 44 separate journeys (09 Feb 22–21 Jun 23), with MoRS mimicking the mask status (wearing/not wearing) of the participants on each journey. The position of MoRS inside the train carriage was maintained in both directions with a total journey time of 80 min. As no GPS was available underground a detailed diary of time of arrival and departure at each station was linked to logged concentrations.

3. Results and discussion

3.1. Urban background and roadside site field campaigns

The slope, intercept and R^2 values of the inter-comparisons between MoRS measurements and reference instrumentation is shown in Table 2

Table 1
Instruments and configuration settings and typical runtimes between charges of equipment used in the Mobile Reference Station (MoRS).

Model	Manufacturer	Measurement	Time Resolution (sec)	Run Time (hours)
ICAD	Airyx	NO_2	10	7.8
205 Dual Beam	2B Technologies	O_3	10	16.6
Mini-Wras 1371 Spectrometer	Grimm Aerosol Technik GmbH	PM Mass (PM_1, $PM_{2.5}$, PM_{10}) Aerosol Size Distribution (10 nm - 35 μm)	60	8.3
Li-820	Li-Cor	CO_2	1	18.0
MicroAeth MA350	Aethlabs	Black Carbon	1	20.0

(Fig. S2 for correlation plots). Mean, median and range for all instrument deployments are shown for each location. At background sites, all instruments displayed excellent performance in comparison with reference instruments with R^2 values of 1.00 and 0.99, for NO_2 and O_3, respectively. The slopes and intercepts of NO_2 and O_3 were very close to 1 and 0 respectively, showing there was no need to adjust the data in these different environments. Similarly, the slopes and intercepts for $PM_{2.5}$ at both urban background and roadside sites were close to 1 and 0 respectively (and R^2 values also close to 1), showing that no substantial advantage would be gained from adjusting to account for different ambient environments. However, the slope of 3.14 and intercept of 3.12 μg m^{-3} measured in Hampstead station demonstrates the significant adjustment required when measuring concentrations in subway environments, which is described in section 3.2.

3.1.1. Mini-Wras inter-comparison using roadside ambient aerosol

The inter-comparison of particle size distributions of ambient aerosol from an urban roadside measured by the Mini-Wras was compared to a SMPS (3080, TSI Inc, USA) at the Marylebone Road urban roadside site. The Mini-Wras and SMPS inlets were both placed equidistantly within 2 m of the roadside. Ambient air was separately drawn into both instruments to assess the performance of the Mini-Wras when measuring ambient aerosol in an urban roadside location (Fig. 2). The Mini-Wras performed within ±20% of the SMPS for all particle number size distributions (PNSD) below 52 nm demonstrating the Nano-Sizers ability to successfully report PNSD in the nanoparticle size range when compared to the more complex SMPS instrument. The Mini-Wras had a modal particle size diameter within 16% of the SMPS at 19 nm. Between PNSD's of 50–110 nm the Mini-Wras overestimated particle numbers by up to 55%.

3.2. Hampstead Station platform field campaign

The particles emitted by trains in the subway are physically and chemically different to those above ground. They are primarily the result of mechanical abrasion processes with an additional contribution from non-train sources such as passengers (Salma et al., 2007; Moreno et al., 2015). Most of the subway $PM_{2.5}$ is created in the subway environment and is dominated by iron (Fe) containing particles (Martins et al., 2016) giving subway particles their very distinct physio-chemical properties (Querol et al., 2012). The Mini-Wras is designed for indoor environments and consequently uses a particle density of 1.7 g cm^{-3} to represent typical indoor air particle density (Buonanno et al., 2009). However, this is not representative of particle density in the subway (Smith et al., 2016) which has been estimated at 5 g cm^{-3} (Cha et al., 2018; Cha et al., 2018). Applying a density of 1.7 g cm^{-3} would report misleadingly low $PM_{2.5}$ concentrations, consequently a $PM_{2.5}$ scaling factor is required to account for the higher particle density of subway air. To ensure accurate scaling factors for measurements of $PM_{2.5}$ in the subway system the Mini-Wras was co-located alongside a Partisol 2025, which took 13 2-h filter measurements on the platform at Hampstead subway station. By using time-averaged 2-h means for the Mini-Wras corresponding to the 2-h time periods of the gravimetric samples obtained from the Partisol a regression slope was calculated of 3.14 with an intercept of 3.12 μg m^{-3} (R^2 = 0.99) to give a specific subway scaling factor for use when measuring subway $PM_{2.5}$. However, particles in subway air comprise a mixture of above-ground and below-ground aerosol sources and to reflect these differing sources urban background and subway scaling factors were proportionally applied (Smith et al., 2016) (Fig. S3). The performance of the Mini-Wras when measuring the PNSD of subway particles was assessed through an inter-comparison alongside a Dekati Electrical Low Pressure Impactor at Hampstead station (Fig. 3). The $ELPI^+$ is a real-time spectrometer measuring a size range from 6 nm to 10 μm over 14 size bins. The modal peak of the Mini-Wras was between 14 nm and 19 nm, close to the $ELPI^+$ first peak of 16 nm. The modal peak of the $ELPI^+$ occurs at 41 nm and the Mini-Wras is outside of the ±20% uncertainty range of the Dekati modal peak at this particle size. For PNSD's between 72 and 139 nm the Mini-Wras shows excellent agreement with the Dekati (±20%) although larger fractions greater than 139 nm are overestimated by the Mini-Wras. The dominant Mini-Wras and Dekati modal particle sizes of 19 nm and 41 nm, respectively, are lower than the mean subway particle size diameter of 77 nm found by Smith et al. (2016).

3.3. Transport microenvironment exposure assessments

MoRS was evaluated in two differing transport microenvironments relevant to personal exposure: diesel mainline trains and London Underground subway trains. Both environments have rapidly changing air pollutant concentrations and environmental influences and therefore represent a challenging performance assessment of MoRS.

3.3.1. Diesel train journeys

This study was designed to measure the air pollution concentrations

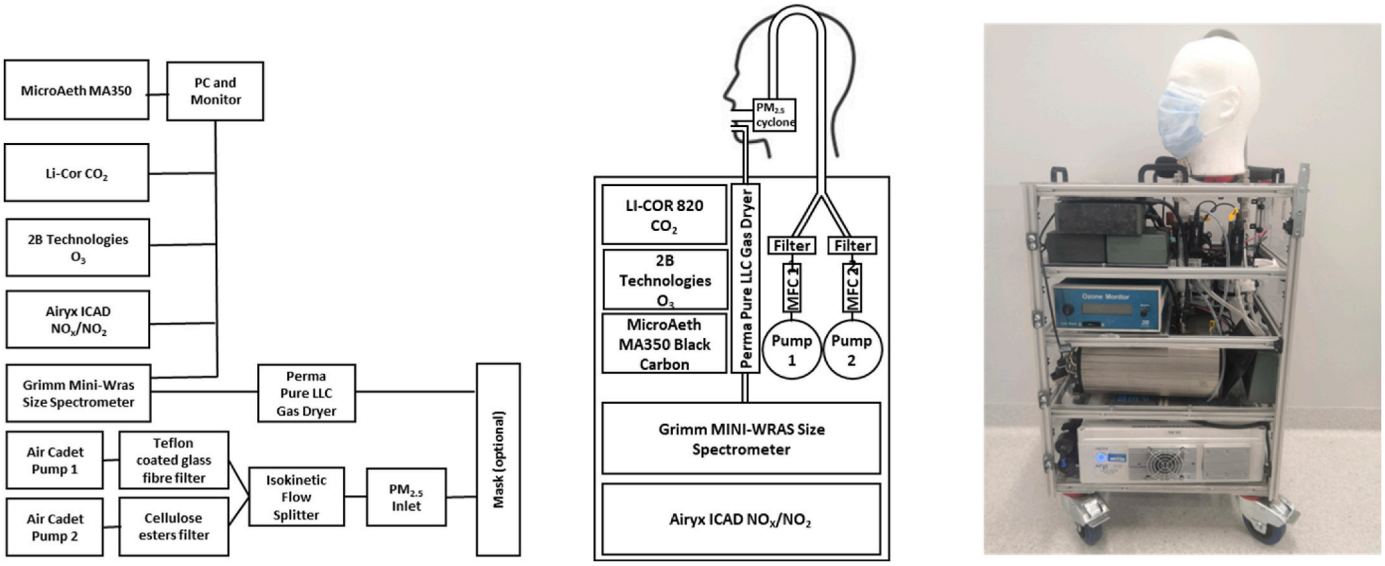

Fig. 1. Mobile Reference Station (MoRS) (schematic (left), sampling configuration (centre), picture (right)).

Table 2
Field co-location comparisons between MoRS and reference instrumentation at Hampstead subway station, an urban roadside site and an urban background site (mean, median, range and intercept are displayed as μg m^{-3}).

Location	Site Name	Instrument	Mean	Median	Range	Slope	Intercept	R^2
Subway	Hampstead Station	Mini-Wras 1371 Spectrometer	453.7	489.8	26.5–904.3	3.14 (±0.09)	3.12	1.00
Urban Roadside	Marylebone Road	Mini-Wras 1371 Spectrometer	7.1	6.2	0.0–31.2	0.97 (±0.02)	−0.77	0.98
Urban Background	Honor Oak Park	Mini-Wras 1371 Spectrometer	14.5	12.8	1.8–68.2	0.88 (±0.02)	−2.24	0.99
Urban Background	Honor Oak Park	Airyx ICAD NO_2 Analyser	43.0	38.5	11.5–93.2	0.96 (±0.00)	0.25	1.00
Urban Background	North Kensington	2B Technologies O_3 Analyser	60.1	68.6	2.6–107.4	0.93 (±0.02)	0.70	0.99

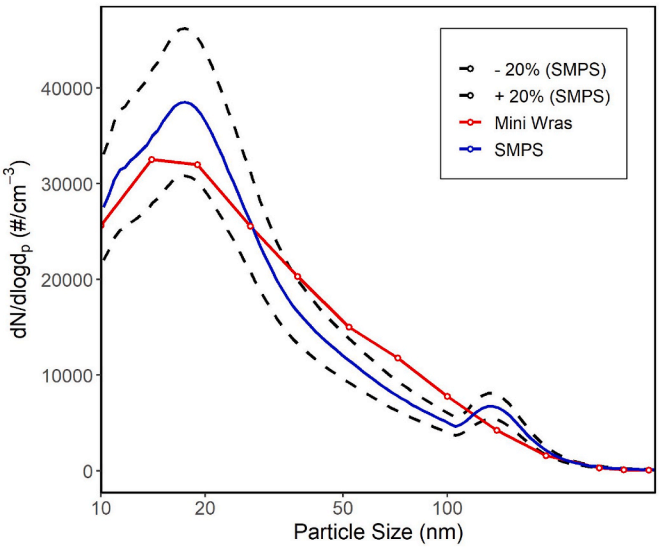

Fig. 2. Inter-comparability of the GRIMM Mini Wras spectrometer 1371 and SMPS sampling ambient air at an urban roadside site. The blue solid line shows the SMPS with the black dotted lines showing the SMPS ±20% range. The Mini-Wras is shown as a solid red line with particle size midpoint diameters shown as white dots.

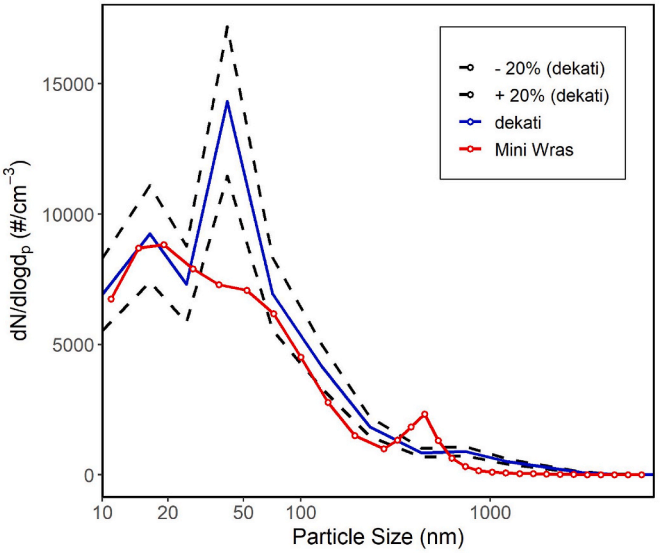

Fig. 3. Inter-comparability of the GRIMM Mini Wras spectrometer 1371 and a Dekati Electrical Low Pressure Impactor ($ELPI^+$) simultaneously sampling $PM_{2.5}$ on the northbound platform at Hampstead subway station. The solid blue line shows the Dekati with the black dotted lines showing the Dekati ±20% range. The Mini-Wras is shown as a solid red line with particle size mid-point diameters shown as white dots.

(NO_2, $PM_{2.5}$ and PM_{10}) that railway passengers are exposed to while travelling inside diesel trains in the UK. PM concentrations were not adjusted for different scaling factors to account for background and diesel influenced concentrations as the particle densities are similar and no significant differences were shown at the background and roadside intercomparisons (Table 2). An example train journey between Ipswich and Cambridge on board a bi-modal Class 755 train is shown in Fig. 4. The diesel engine was switched on at Stowmarket (10.33) on the outbound journey and concentrations of $PM_{2.5}$ and NO_2 remained close to background, although there was some ingress of diesel exhaust, particularly at Stowmarket and Bury St Edmunds (10.54) (Fig. 5). On the return journey concentrations of $PM_{2.5}$ and NO_2 built up between Cambridge and Ipswich when the exhaust was located at the front of the train demonstrating the push/pull effect of the train (Ham et al., 2017, Jeong et al., 2017). PM mass concentrations were dominated by $PM_{2.5}$ due to diesel exhaust ingress into the train carriage for long periods of the journey from Cambridge. Ultrafine particles dominated for much of the out bound journey with ultrafine particle orders of magnitude higher when the train was in pull mode on the return journey (Fig. 5). This shows the value of the Mini-Wras approach over an OPC in sampling aerosols <200 nm, which would have remained undetected by an OPC. High concentrations of PM_{10} relative to $PM_{2.5}$ during station stops such as Cambridge showed the influence of coarse material, either from braking events or, more likely, passenger movement in the carriage. Overall, the results showed that the in-bound journey average exposures were higher than typical urban centres and demonstrates how MoRS can accurately capture exposures of commuters and staff. During 400 h of on-train measurements a data capture of 99% of all instruments was maintained; demonstrating the reliability of this system.

3.3.2. *Subway train journeys*

Measuring in London Underground train carriages is challenging due to the confined space, lack of power sources, differing contributing sources, and rapidly changing environmental and pollutant conditions as the train moves between below-ground tunnels and above-ground. Noise, as well as $PM_{2.5}$, NO_2 and O_3, was measured as this can be an environmental stressor in subway systems (Manohare et al., 2022; Singh et al., 2020). The scaling factors of slope 3.14 and intercept of 3.12 μg m^{-3} derived at Hampstead station and slope 0.88 and intercept of −2.24 at the urban background site for $PM_{2.5}$ were proportionally applied to $PM_{2.5}$ measurements in the tunneled section of the subwayto represent the portion of subway air that is derived from ambient aerosol. $PM_{2.5}$ measurements at the urban background site were used to scale $PM_{2.5}$ measured outside of the tunnel sections in ambient air (Fig. S3).

It was noticeable that during an example return train journey (Fig. 6), concentrations of $PM_{2.5}$ increased rapidly as soon as the train entered the tunnel and remained elevated until it stopped at Elephant & Castle where it waited for 6 min. During that time $PM_{2.5}$ concentrations fell from 223 to 57 μg m^{-3}, before rising again after the train left the station. At the same time, NO_2 concentrations rose from 18 to 26 μg m^{-3}. This suggests that the fall in $PM_{2.5}$ concentrations was a combination of a lack of train movement, as train movement leads to the resuspension of previously emitted dust, and ambient air penetrating onto the platform. The variability of $PM_{2.5}$ concentrations throughout the tunneled sections of the journey was inversely correlated with NO_2 concentrations which

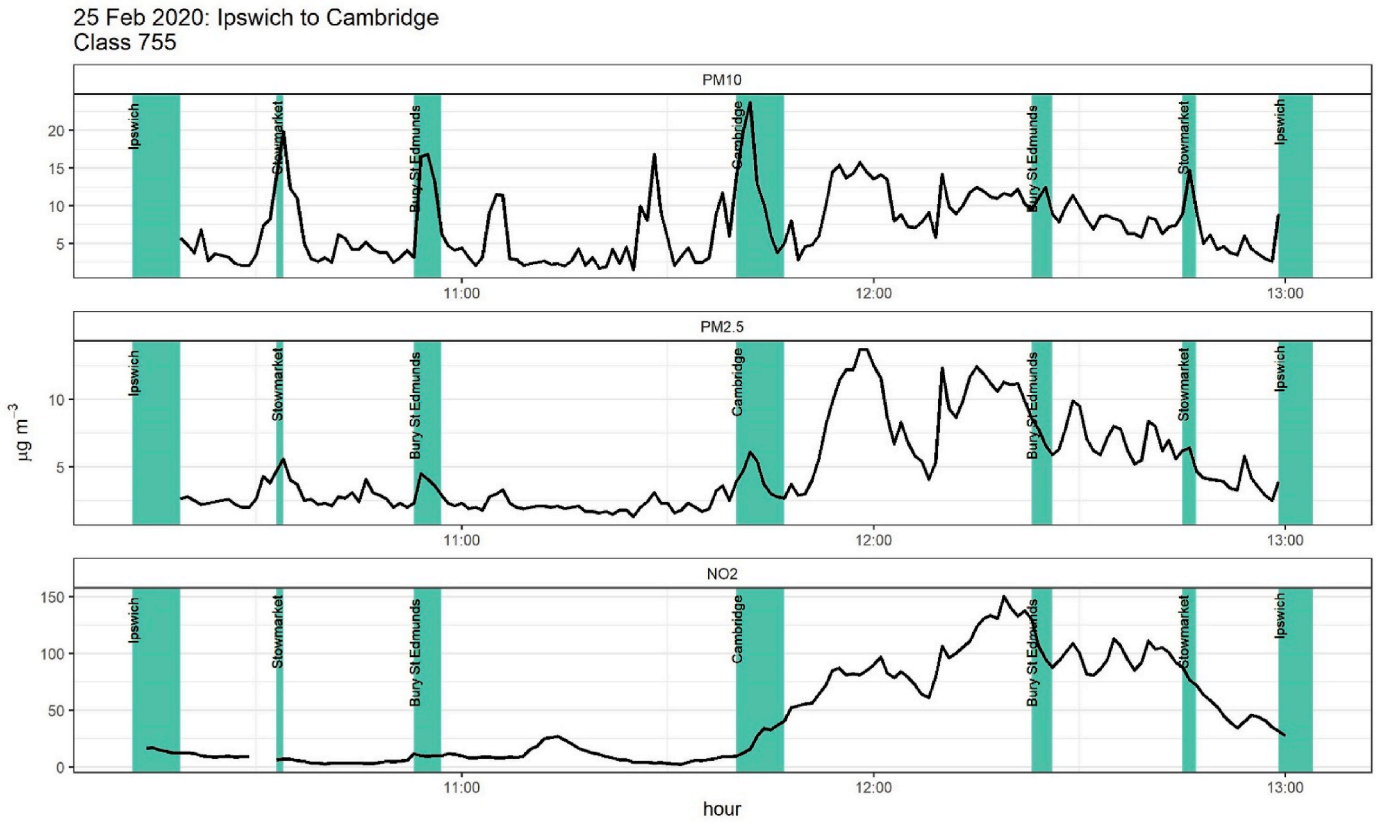

Fig. 4. Concentrations of PM_{10}, $PM_{2.5}$, and NO_2 measured along the journey between Ipswich and Cambridge on 25 February 2020 on a Class 755 bi-modal train.

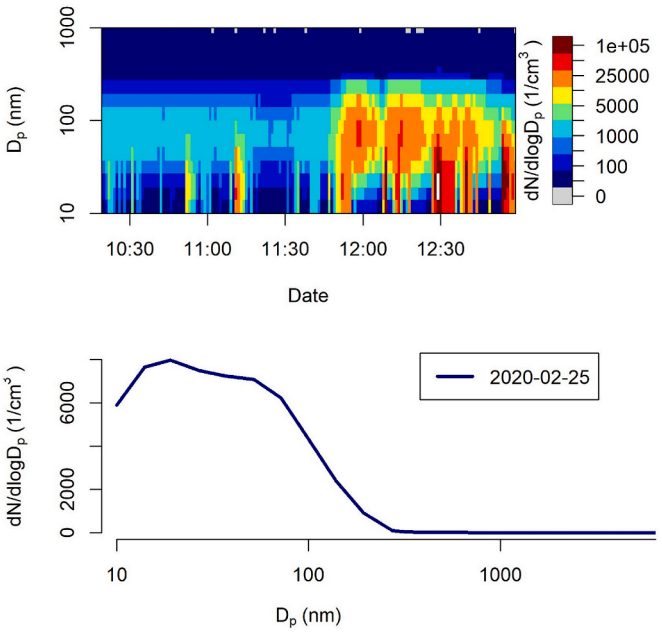

Fig. 5. Temporal variation of particle number distribution and particle number counts measured along the journey between Ipswich and Cambridge on 25 February 2020 on a Class 755 bi-modal train.

demonstrates that air polluted with high levels of NO_2, drawn in from above-ground air, was diluting the subway air $PM_{2.5}$ concentrations. Interestingly, O_3 remained low throughout the tunneled section of the journey as O_3 is not generated in the subway tunneled environment due to lack of light. As all three pollutants have recognised detrimental health impacts, the need to measure all three accurately in health studies such as this demonstrates the measurement value of MoRS.

4. Conclusion

In many modern cities, there are large contrasts between different pollution exposure environments, many with high pollutant concentrations, and relatively short periods spent in these indoor and transport microenvironments can contribute significantly to overall daily exposure. This increases the likelihood of exposure misclassification when relying on fixed outdoor measurement stations for health studies (Smith et al., 2016). However, the differing environmental conditions (particularly in terms of temperature and relative humidity) and the rate of change when moving between environments combined with changes in the aerosol chemical and physical composition all increase the uncertainty in small, sensor-based measurement techniques.

MoRS has addressed these limitations in small sensors through the miniaturisation and reduced power requirements of higher quality measurement approaches similar to those used in fixed measurement stations. The development and testing locations of MoRS were on-board subway and above ground moving trains, which well-represent the measurement challenges in these environments. MoRS has demonstrated that it can provide a bridge between the accuracy of fixed, monitoring sites and the ease of use and portability of low-cost sensors. It provided a high data capture rate in all tested locations and proved adept at reporting a range of pollutant and environmental stressor values, providing comparable results to reference measurements in a range of conditions for up to 8 h before recharging. The accurate measurement of particle size distribution remains challenging for a portable device, nevertheless, the Mini-Wras showed a good agreement (±20%) with the SMPS at fixed measurement locations. While this approach may not be suitable for wide scale population studies, it could help to improve the understanding of multiple sources in these environments

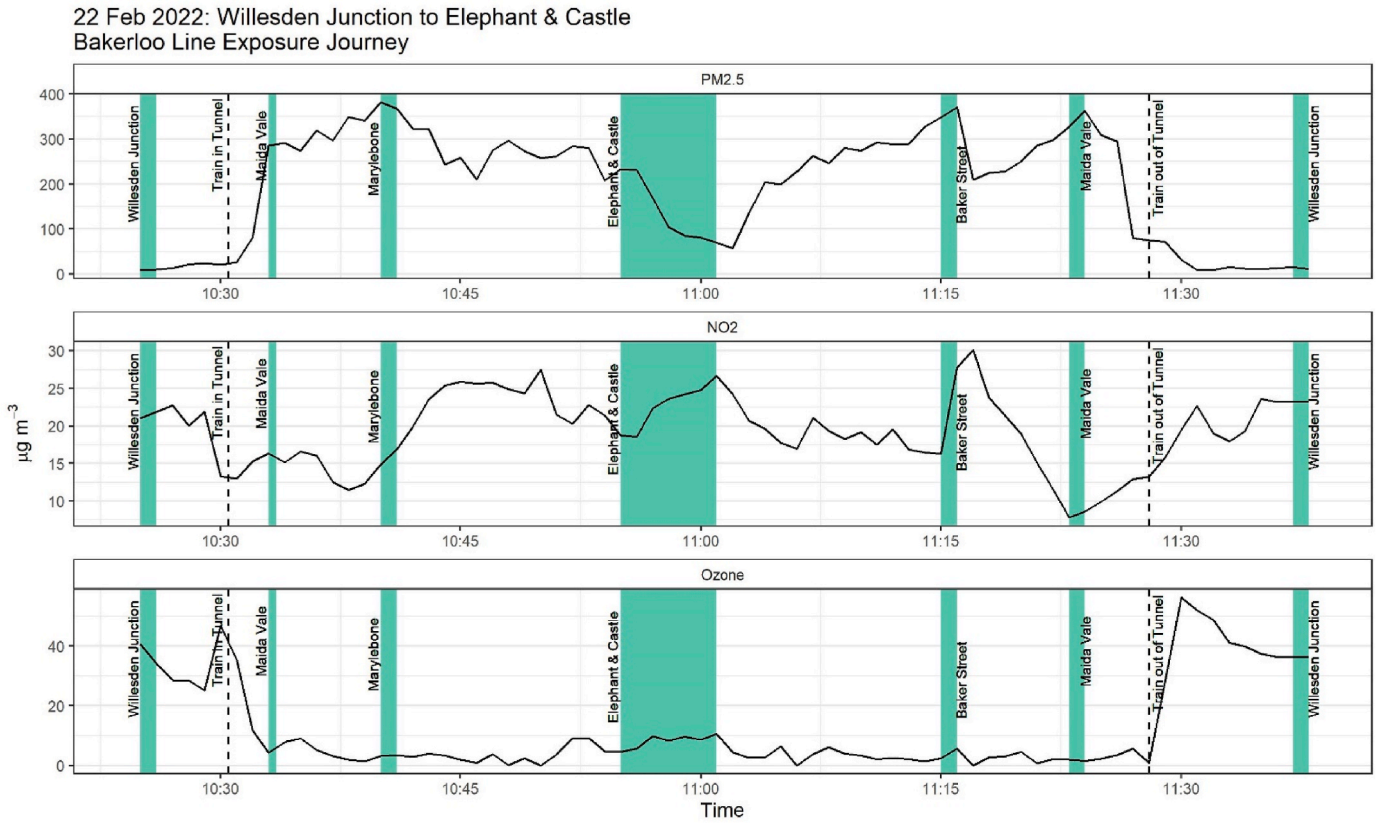

Fig. 6. Concentrations of $PM_{2.5}$, NO_2 and O_3 measured along the journey between Willesden Junction station and Elephant & Castle station on 22 February 2022 on a Bakerloo Line subway train. Shaded green areas indicated the times when the train remained in a station. The dotted black lines indicate when the train entered and exited the subway tunnel.

and disentangle the multiple confounding environmental effects pollutants play in the underlying toxicological mechanisms on health in panel studies.

CRediT authorship contribution statement

Michael Hedges: Conceptualization, Methodology, Formal analysis, Investigation, Data curation, Visualization, Project administration, Software, Writing – original draft, Writing – review & editing. **Max Priestman:** Investigation, Writing – review & editing. **M. Chadeau-Hyam:** Supervision. **R. Sinharay:** Supervision. **Frank J. Kelly:** Resources, Funding acquisition, Project administration. **David C. Green:** Conceptualization, Methodology, Formal analysis, Data curation, Writing – original draft, Writing – review & editing, Visualization, Project administration, Supervision, Resources, Funding acquisition.

Declaration of competing interest

The authors declare that they have no known competing financial interests or personal relationships that could have appeared to influence the work reported in this paper.

Data availability

Data will be made available on request.

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Appendix A. Supplementary data

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