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Full length article

Air quality on UK diesel and hybrid trains

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ABSTRACT

Concentrations of particulate matter (PM₁₀, PM_{2.5}), ultrafine (UFP), particle number (PNC), black carbon (BC), nitrogen dioxide (NO₂) and nitrogen oxides (NO_x) were measured in train carriages on diesel and bi-mode trains on inter-city and long-distance journeys in the United Kingdom (UK) using a high-quality mobile measurement system. Air quality on 15 different routes was measured using highly-time resolved data on a total of 119 journeys during three campaigns in winter 2020 and summer 2021; this included 13 different train classes. Each journey was sampled 4–10 times with approximately 11,000 min of in-train concentrations in total. Mean-journey concentrations were 7.552 µg m⁻³ (PM₁₀); 3.936 µg m⁻³ (PM_{2.5}); 333–11,300 # cm⁻³ (PNC); 225–9,131 # cm⁻³ (UFP); 0.6–11 µg m⁻³ (BC); 28–201 µg m⁻³ (NO₂); and 130–3,456 µg m⁻³ (NO_x). The impact of different factors on in-train concentrations was evaluated. The presence of tunnels was the factor with the largest impact on the in-train particle concentrations with enhancements by a factor of 40 greater than baseline for BC, and a factor 6 to 7 for PM and PNC. The engine fuel mode was the factor with the largest impact on NO₂ with enhancements of up to 14-times larger when the train run on diesel compared to the times running on electric on hybrid trains. Train classes with an age < 10 years observed the lowest in-train PM, BC and NO_x concentrations reflecting improvements in aspects of rail technology in recent years. Air quality on UK diesel trains is higher than ambient concentrations but has lower PM_{2.5} and PNC than most other transport modes, including subway systems, diesel and petrol cars. This paper adds significantly to the evidence on exposure to poor air quality in transport micro-environments and provides the industry and regulatory bodies with reference-grade measurements on which to establish in-train air quality guidelines.

1. Introduction

Rail is considered a green mode of passenger transport due to lower carbon emissions compared to other transport modes (Givoni et al., 2009). However, rail transport does emit pollutants into the atmosphere which are of concern for both climate change and air quality. In the UK, it was estimated that railway emissions contributed 11 %, 13 % and 12 % of non-road transport emissions of nitrogen oxides (NO_x), particulate matter with aerodynamic diameter < 10 µm (PM₁₀) and < 2.5 µm (PM_{2.5}), respectively in 2019 (EEA, 2022). In 2020, 62% of the UK rail tracks were non-electrified and journeys on diesel trains were responsible for almost 1400 gCO₂e per vehicle km, three times larger than emissions from journeys on electric trains (Office of Rail and Road,

2020). Emissions from trains are the result of both engine exhaust and non-exhaust wear processes. Exhaust emissions are a by-product from the diesel combustion and comprise a mixture of gases (mainly CO₂ but also NO_x, SO₂ and VOCs) and particles, the latter mainly in the ultrafine and fine fractions (Hesterberg et al., 2006). Non-exhaust emissions are common to both diesel and electric trains and include particles arising from mechanical wear (e.g., interaction between wheels, rails, pantographs or catenary) and brake wear, mainly in the coarse fraction due to friction (Abbasi et al., 2013). However, fine and ultrafine particles can also be generated by friction and vaporisation at high temperatures (Sundh et al., 2009; Zimmer and Maynard, 2002) and when using rail lubricant (Abbasi et al., 2013).

Train emissions from diesel and electric trains impact air quality in

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train stations, especially those enclosed with a tunnel-like configuration (Gustafsson et al., 2016; Cha et al., 2018a; Font et al., 2020; Hickman et al., 2018; Loxham et al., 2013), and also on outdoor concentrations close to railway lines (Jaffe et al., 2015). Train emissions have further been shown to elevate concentrations measured inside train carriages (e.g., Andersen et al., 2019). Considering that most people spend longer inside trains than at platforms (Kam et al., 2011), the air quality in train carriages is of special concern for both passengers and train staff. Concentrations onboard diesel trains are enriched in NO_x (Andersen et al., 2019) and nitrogen dioxide (NO₂) (Maggos et al., 2016; Andersen et al., 2019), PM_{2.5}, black carbon (BC), ultrafine particles (UFP) (Ham et al., 2017; Jeong et al., 2017), PAHs (Andersen et al., 2019) and benzene (Madl and Paustenbach, 2002; Maggos et al., 2016). Diesel engine emissions can ingress into train carriages through the ventilation system, windows if opened or poorly sealed rolling stock when moving (Abramesko and Tartakovsky, 2017) and doors once opened at station platforms (Cha et al., 2018a).

Exposure to diesel exhaust poses a health risk. The World Health Organisation (WHO) reclassified diesel engine exhaust emissions as 'carcinogenic to humans' based on the associated exposure with an increased risk of lung cancer (WHO-IARC, 2012). Approximately 1.3 % (United States) and 4.8 % (United Kingdom) of annual lung cancer deaths at age 70 were due to past occupational and environmental diesel exposures (Vermeulen et al., 2014). Occupational exposure to diesel exhaust in the rail environment was evidenced to have a quantifiable increase in cancer risk associated with the inhalation of diesel exhaust (Rosenfeld et al., 2022) and exposure could be substantial to both staff and passengers. Guerra Andersen et al. (2019) reported that exposure to diesel exhaust on healthy volunteers inside diesel-powered trains was associated with reduced lung function, altered heart rate variability and increased DNA strand breakage in peripheral blood mononuclear cells compared to exposure to indoor air on electric trains. Advanced-technology diesel engines (including both new and retrofitted) might incorporate emissions reduction systems – i.e., diesel particulate filters (DPFs) or Selective Catalyst Reduction (SCR) (Hesterberg et al., 2012) which may reduce exposure onboard trains.

Here we present the most up-to-date and complete characterization of air quality inside diesel train carriages in the UK. The major health-related pollutants including nitrogen dioxide (NO₂), particle mass concentrations in two size fractions (PM₁₀ and PM_{2.5}), black carbon (BC) and ultrafine particles (UFP) were measured on 13 different train classes (eleven fully diesel-powered trains and two diesel bi-mode trains) on 15 different routes across the country using high-time resolved portable instrumentation. The factors affecting air pollution inside train carriages were explored and their impact quantified. The concentrations measured in different train classes were compared based on age, exhaust after-treatment, braking system and the influence of the sampling location.

2. Methods

2.1. Measurement campaigns

Measurement campaigns were undertaken during three periods: 13 January 2020 to 12 March 2020; December 2020; and July–August 2021. Ninety separate train journeys were sampled, in both directions of travel, over fifteen selected routes (Fig. S1). All measurements took place on weekdays (Monday to Friday) and encompassed some of the highest passenger usage periods. The longest journey was between London St Pancras and Nottingham, covering 172 km in approximately 90 min. The shortest route was Bletchley to Ridgmont and Bedford, covering 23 km in under 20 min. Arrival and departure times at each station were recorded by the operator, extracted from train GPS data or from recorded arrival and departure times on <https://www.realtimetrains.co.uk/>.

2.2. Instrumentation

Concentrations of NO_x, NO₂, PM₁₀, PM_{2.5}, UFPs, particle number concentration (PNC) and BC were measured on each journey using a portable measurement system containing reference-grade instrumentation, positioned at the breathing height of sitting passengers. The design, testing and operation aspects of the system are described in Hedges et al. (2023). Nitrogen oxides (NO_x and NO₂) were measured using the ICAD (Iterative Cavity enhanced DOAS, Airyx GmbH, DE) by optical absorption at 458 and 480 nm. In the third campaign (July–August 2021) a new model of this instrument was used where NO was converted to NO₂ by reaction with O₃ to provide total NO_x concentrations. Regular baseline checks were performed throughout with a PurafilTM activated charcoal scrubber; and NO₂ and NO standard gases. NO_x concentrations were only available in the third campaign (July–August 2021). PM₁₀ and PM_{2.5} were measured using a Mini-WRAS (Model 1371, Grimm Aerosol Technik GmbH, DE) which combines 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). The aerosol sample was dried internally using a silica gel desiccant and a monotube gas dryer (MD-700-06F-1, Perma Pure LLC, USA). UFP concentrations, expressed in number of particles per cm³ (# cm⁻³), were calculated adding particle counts in bins with mid-point sizes from 10 to 100 nm; PNC concentrations, also in # cm⁻³, were calculated adding particles counts from 10 to 943 nm. The selection of size bins for the latter was done to match with reported PNC from the literature in other transport microenvironments (20 nm–1 μm) (Briggs et al., 2008; Kaur et al., 2005; Rivas et al., 2017; Seaton et al., 2005). Regular baseline checks were performed with a HEPA filter, and the response of the Mini-Wras was periodically checked against a Scanning Mobility Particle Sizer (Model 3080, TSI, UK) using an atomised 0.1 % NaCl solution to ensure peak modal concentrations were within 20 %. BC mass concentrations were measured using a microaethalometer (Model MA350, microAeth, USA), two additional units were used to measure concentrations at various locations in the same train in the campaign on 30 January 2020. All the microaethalometers measured the rate of decrease of light at 880 nm through a sample filter loaded with a continuous collection of BC particles. The ICAD, Mini-Wras and microaethalometers were collocated with reference instruments (Teledyne API T200, USA; Fidas 200, Palas, Finland; AE33 Magee Scientific, USA, respectively) at the London Marylebone kerbside site (51.523°N; 0.155°E) to provide correction scaling factors most applicable to diesel train exhaust, calculated using Deming regression (Wu and Yu, 2018). The scaling factors used to correct the data from the portable instruments are shown in Fig. S2.

2.3. Influencing factors

According to Otuyo et al. (2023), different factors are responsible for the in-train concentrations of air pollutants and those include train characteristics (engine mode, braking system, emission standards, etc.) which are defined by the train class, route characteristics (tunnels, stations, track gradient, etc.), environmental conditions (outdoor air), among others (Fig. 1).

The evaluation of the impact of the following factors was undertaken as follows:

2.3.1. Train class

In the UK railway network, the rolling stock is classified by train classes. Each train class has distinctive characteristics based on the design, power source, top speed, etc. In this study, a total of current 13 train classes were tested, 11 fully-diesel trains and 2 bi-mode trains. The engine type, engine age, engine power, exhaust after treatment, emission standard, transmission, and braking technology of each train class can be found in Table S1. None of the train class tested had windows that could be opened by passengers.

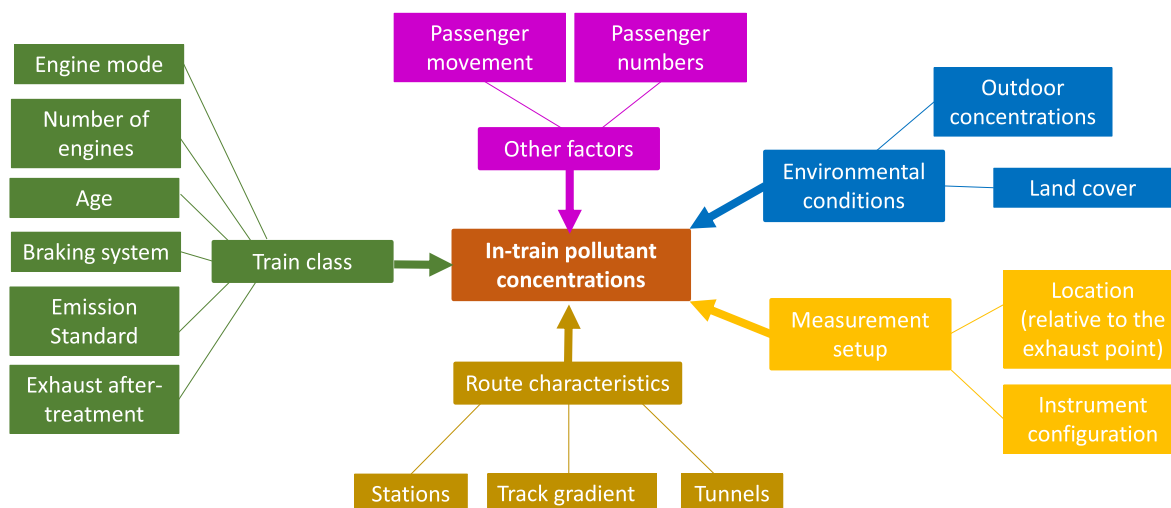


Fig. 1. Factors affecting in-train concentrations (adapted from Otuyo et al., 2023).

2.3.2. Engine mode on hybrid trains

Class 755 and 800 are bi-mode trains running on both electric and diesel modes along some parts of the journeys. The mean concentration measured for each transect run on electric and diesel mode were calculated for each journey. Only concentrations measured between stations were used to calculate means excluding those measured at the departure, arrival and within stations.

2.3.3. Relative position of the exhaust

The impact of the location of the exhaust relative to the measurement (or exposure location) was evaluated in two situations. First, the location of the exhaust in relation to the measurement point was evaluated for the train classes sampled in the first campaign (Classes 168, 230 and 755). Only concentrations measured between stations were compared. The exhaust was either located in front of the measurement point (for pull-in trains) or behind the measurement point (push-out trains). Second, the impact of the distance from the engine was quantified in train Class 43 (HST) which has a diesel engine at each end. BC measurements at three locations were undertaken on 30 January 2020. The same train was sampled in the outward and in the inward journeys. Aethalometers were installed in carriages 2 and 7 (positions A and B in Fig. 2). Measurements in carriage 5 (position C) were used as a control, providing measurements at approximately the same distance from an engine in both directions. Duplicate assessments of exposure were therefore undertaken using data in locations A and B.

2.3.4. Tunnels

Data measured in the London Marylebone to Birmingham Snow Hill route (Class 168) was used to evaluate the impact of tunnels on in-train concentrations. This route had two long tunnel sections. Prior to arrival at London Marylebone the train entered a 1500 m tunnel followed by a short a bridge section, then another tunnel of 63 m. At the other end of the route, the Snow Hill tunnel was 58 m long. The time that train was inside tunnels was short (2.4 and 2 min on average, respectively), but the effect lasted longer. To estimate concentration enhancements in the tunnels, a baseline was first calculated as the 5 % lowest concentration measured in the 15 min before and 30 min after the tunnel. The enhancement associated with the tunnels was calculated by subtracting

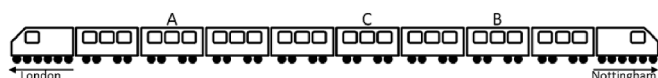


Fig. 2. Schematic representation of the Class 43 (HST) train servicing London St Pancras to Nottingham and position of the measurement points.

the baseline from the 1-minute concentration from the time the train entered the tunnel until the baseline concentration was reached following exit. This end time was calculated based on when the first pollutant baseline was reached.

2.3.5. Stations

In-train concentrations measured at the times when trains were at stations were compared to those when trains ran between stations (also referred as free-run). At station vs free-run mean concentrations by each individual journey were compared for the ensemble of journeys.

2.3.6. Track gradient

The impact of the track gradient on in-train concentrations was evaluated using measurements collected on the section of track between Camden Junction and Tring on the London Euston to Birmingham New Street route (Class 221). The section was characterized by a steep gradient, rising 72 m in 17–19 min with a mean gradient 0.08 % and a maximum of 0.3 %. Class 221 trains have multiple exhaust points along the train and the effect of the position of the exhaust was therefore minimised.

2.3.7. Passenger movement

The movement of passengers inside train carriages was expected to have an impact on particulate concentrations, especially the coarse fraction ($PM_{\text{coarse}} = PM_{10} - PM_{2.5}$) (Nasir and Colbeck, 2009). The impact of passenger movement on in-train air quality was evaluated using two approaches. First, the mean concentrations measured in the outward journeys were compared against the inward for Class 220 trains, in the route Birmingham New Street to Manchester Piccadilly. The outward journey took place in the morning rush hour (between 8:00 and 9:30 local time) while the inward took place off-peak (10:30 to midday). Journeys in rush hour were expected to have more passenger attendance than off-peak. Second, PM_{coarse} measured two minutes before and after arriving at a station were compared. Those stations in which the time elapsed between them was less than four minutes were excluded. It is hypothesized that PM_{coarse} before arriving at a station should be a combination of both brake-wear emissions and passenger movement; while concentrations after leaving the station should be mainly associated with the latter. Concentrations before and after at the same station were compared.

2.3.8. Outdoor air and land cover

Data measured onboard trains were compared to ambient concentrations reported by fixed monitors in urban background areas belonging to the UK Automatic Rural and Urban Network (AURN) for

PM₁₀, PM_{2.5}, NO_x and NO₂; to the UK Black Carbon Network for BC (Ciupek et al., 2021); and to the UK Particle Concentrations and Numbers Network for UFP. Ambient data was reported as hourly means for all pollutants except for UFPs, which were reported as 15-minute means. Data from the nearest fixed monitoring site in urban background locations from either or both the origin and destination stations were extracted for those hours when train journeys took place. Data from rural background AURN sites were extracted for the nearest sites for in-between stations. However, the number of available rural background sites were limited and specially for PM₁₀ and PM_{2.5} data and sometimes not available. For UFPs, only two sites were available in 2021 – London North Kensington (urban background site) and Chilbolton Observatory (rural background site). Only those journeys passing by near these two sites were compared for UFPs. The AURN monitoring sites used in this study are summarized in Table S2.

Land use data was available from www.diva-gis.org/gdata which resampled data from the Global Land Cover 2000, originally at 30 s grid, onto 0.2° × 0.2° resolution. The location of the train (latitude, longitude) at each sampling time (i.e., minute) was overlaid onto the land cover map and a land cover category assigned. Only two main categories were considered: urban and non-urban.

2.4. Estimation of the inhaled dose

The inhaled dose of pollutants (D) that passengers experience inside trains carriages can be quantified as in Ramos et al. (2015):

$$D = C \times VE \times t \quad (1)$$

where C refers to the in-train concentration expressed in $\mu\text{g m}^{-3}$ (BC, NO_x, NO₂, PM₁₀ and PM_{2.5}) or $\# \text{ cm}^{-3}$ (PNC, UFP); VE refers to the ventilation (in m^3 per min); and t the time of exposure, here expressed in min. VE depends on the physical effort, physical condition, age, gender, etc., of the individual considered. The VE considered here was taken from US-EPA (2011) for light intensity activities for adults > 16 years old and valued $1.2 \cdot 10^{-2} \text{ m}^3 \text{ min}^{-1}$. This VE rate was also considered in the literature in train environments (Ramos et al., 2015) and agreed with physical activity for both passenger and train staff. The units of inhaled dose are expressed in μg (BC, NO_x, NO₂, PM₁₀ and PM_{2.5}) or $\text{M}\#$ (PNC, UFP).

2.5. Statistical test

The Wilcoxon signed-rank test was used to compare the means of two dependent variables. This test is suitable for variables that do not have a normal distribution, i.e., pollution concentrations. The Wilcoxon signed-rank test is considered as alternative to the t -test for comparing two means. For two matched samples, the Wilcoxon paired test was undertaken. The null hypothesis (i.e., means of the two groups compared are the same) is confirmed whenever $p > 0.05$.

3. Results

3.1. Summary results

Mean in-train journey concentrations measured on UK diesel and bi-mode trains were $538 \mu\text{g m}^{-3}$ for NO_x, $71 \mu\text{g m}^{-3}$ for NO₂, $25 \mu\text{g m}^{-3}$ for PM₁₀, $16 \mu\text{g m}^{-3}$ for PM_{2.5} and $4.6 \mu\text{g m}^{-3}$ for BC, and sampled more than 2,800 and 3,6000 $\# \text{ cm}^{-3}$ for UFP and PNC, respectively (Table 1). These concentrations varied along the journey transect, at specific locations and depending on the journey. Fig. 3 shows the in-train concentration variability observed in different journeys serviced by Class 43 (HST). Elevated concentrations of particulate metrics (PM₁₀, PM_{2.5}, BC, PNC) were observed, some of them associated with the arrival and/or departure from a station (i.e., Market Harborough, Leicester and East Midlands Parkway). Enhancement in NO₂ concentrations were observed

in some journeys after leaving St Pancras International Station (outward journeys) but those were less evident on the inward journeys (Fig. 3).

3.2. Engine mode on hybrid trains

Mean concentrations of BC and NO₂ when Classes 755 and 800 bi-mode trains run on diesel were larger than when running on electric. Mean BC were $0.7 \mu\text{g m}^{-3}$ (Class 755) and $2.4 \mu\text{g m}^{-3}$ (Class 800) when running on diesel and 0.13 and $0.55 \mu\text{g m}^{-3}$ on electric mode, respectively (Fig. 4). For NO₂, mean concentrations were 39 and $375 \mu\text{g m}^{-3}$ when running on diesel and 22 and $57 \mu\text{g m}^{-3}$ on electric, for Class 755 and Class 800, respectively. However, differences were only statistically significant for Class 800 (Fig. 4). For PM and particle counts, differences when the train ran either on diesel or electric were not statistically significant (Fig. 4) despite mean concentrations being higher when running on diesel for PM_{2.5}, PNC and UFP for both classes; and PM₁₀ for Class 800.

3.3. Position of the sampling point relative to the exhaust

In-train concentrations were generally larger when the exhaust was in front of the sampling point (pull-in trains) (Fig. 5A). Mean concentrations considering all train classes were $2.4 \mu\text{g m}^{-3}$ (pull-in) vs $0.53 \mu\text{g m}^{-3}$ (push-out trains) for BC; $78 \mu\text{g m}^{-3}$ vs $42 \mu\text{g m}^{-3}$ for NO₂; $14 \mu\text{g m}^{-3}$ vs $7.8 \mu\text{g m}^{-3}$ for PM₁₀; 12 vs $5.1 \mu\text{g m}^{-3}$ for PM_{2.5}; 4470 vs 1508 $\# \text{ cm}^{-3}$ for PNC; and 3590 vs 1202 $\# \text{ cm}^{-3}$ for UFP. Considering individual journeys, the mean concentration measured in pull-in mode trains was 7 times larger for BC, 3 times larger for NO₂, PNC and UFP, 1.9 and 2.3 times larger for PM₁₀ and PM_{2.5}, respectively (Table 2). Expressed in percentage difference, BC was 600 % larger when running on pull-in mode; ~200 % for PNC, UFP and NO₂; almost 90 % for PM₁₀ and 140 % for PM_{2.5}. By train classes, the position of the exhaust had a clear impact on the concentration measured onboard Classes 755 and 168 trains with statistically larger concentrations in pull-in mode. These were six (Class 755) and two times larger (Class 168) for NO₂; 13 times (Class 755) and 4 times (Class 168) larger for BC; 4 times (Class 755) and almost 3 times larger (Class 168) for UFP and PNC; 1.4 times (Class 755) and 1.7 times larger (Class 168) for PM₁₀; and two-fold larger for PM_{2.5} for both classes. Class 230 observed significantly larger concentrations when the train was on pull-in mode with enhancements 4 times larger for BC, around three times larger for PM₁₀ and PM_{2.5}, and around twice for both PNC and UFP. Conversely, NO₂ concentrations were similar and non-statistically different (Fig. 5A).

The distance of the measurement point to the engine also had an impact on pollutant concentrations. Location A, at the rear of the train, and furthest from the exhaust, on the outward journey in Class 43 (HST), observed a mean concentration of $12 \mu\text{g m}^{-3}$, significantly larger than those closer to the exhaust in locations B ($4.9 \mu\text{g m}^{-3}$) and C ($7.7 \mu\text{g m}^{-3}$) (Fig. 5C). This suggests that the exhaust emissions do not enter the train until some distance after the exhaust outlet and it is concentrated towards the rear of the train. The train exhaust may be either entering via the air conditioning intake underneath the carriages; or from poorly sealed windows and doors along the train. This was also observed in a diesel train in Greece with the maximum PM mass concentrations and organics at the tail end of the train (Maggos et al., 2016). Conversely, concentrations at the three locations were similar in the inward journey: $8.4 \mu\text{g m}^{-3}$ (A), $8.3 \mu\text{g m}^{-3}$ (B) and $7.6 \mu\text{g m}^{-3}$ (C) and statistically similar as per the Wilcoxon test (Fig. 5C). Comparing the two legs of the journey, location C (in the middle of the train) observed similar concentrations in both the inward and outward journeys. Location A observed the largest BC concentrations in the outward journey when at the tail of the train ($12 \mu\text{g m}^{-3}$) compared to the inward journey ($8.4 \mu\text{g m}^{-3}$) when being in the front but those were not statistically significant. Location B observed significantly larger concentrations in the inward journey (furthest from the exhaust) than in the outward journey (Fig. 5B). This may be due to an accumulation of air pollutants in the

Table 1
Mean journey concentration ± 1 standard deviation for the pollutants measured on-board UK diesel and bi-modal trains. Mean-journey concentrations (“All”); and mean concentrations when the train ran between stations (“free-run”). The number of available trips as well as the average duration and the distance covered by each train class are also indicated.

Class	N	Duration (min)	Distance (km)	NO _x ($\mu\text{g m}^{-3}$)		NO ₂ ($\mu\text{g m}^{-3}$)		PM ₁₀ ($\mu\text{g m}^{-3}$)		PM _{2.5} ($\mu\text{g m}^{-3}$)		UFP (# cm ⁻³)		PNC (# cm ⁻³)		BC ($\mu\text{g m}^{-3}$)	
				All	Free run	All	Free run	All	Free run	All	Free run	All	Free run	All	Free run	All	Free run
Class 43 (HST)	10	102	172	–	–	56 \pm 8.5	59 \pm 14	24 \pm 4.6	24 \pm 13	18 \pm 4.3	19 \pm 11	3593 \pm 674	3800 \pm 2600	4615 \pm 832	4,900 \pm 3100	9.8 \pm 4.5	9.9 \pm 8.4
Class 68	8	53	56.3	130 \pm 134	130 \pm 140	28 \pm 19	28 \pm 20	16 \pm 7.4	13 \pm 14	6.3 \pm 3	6.0 \pm 3.9	423 \pm 631	440 \pm 680	623 \pm 862	640 \pm 930	3.9 \pm 3.7	3.9 \pm 4.2
Class 156	9	58	31.6	544 \pm 510	610 \pm 760	52 \pm 22	52 \pm 25	28 \pm 13	26 \pm 17	15 \pm 6.8	15 \pm 9.2	2310 \pm 2284	2500 \pm 4400	2739 \pm 2532	3,000 \pm 4800	2.7 \pm 1.8	2.8 \pm 2.2
Class 158/9	4	89	126	–	–	71 \pm 9.1	72 \pm 11	51 \pm 24	48 \pm 23	36 \pm 18.6	34 \pm 18	9131 \pm 5840	9400 \pm 7100	11231 \pm 7181	11000 \pm 8300	11 \pm 7.7	11 \pm 7.4
Class 168	10	110	160	–	–	57 \pm 6.7	52 \pm 28	17 \pm 6.7	16 \pm 19	13 \pm 6.9	13 \pm 17	3731 \pm 2446	3700 \pm 4100	4839 \pm 3183	4700 \pm 5300	3.1 \pm 2.5	3.0 \pm 4.1
Class 172	6	53	32.6	335 \pm 175	360 \pm 230	37 \pm 5.9	36 \pm 11	27 \pm 11	28 \pm 22	16 \pm 6.6	16 \pm 10	1008 \pm 729	1100 \pm 1200	1538 \pm 1034	1600 \pm 1600	3.5 \pm 1.3	3.4 \pm 3.0
Class 185	10	74	73	1053 \pm 675	1100 \pm 800	94 \pm 37.2	96 \pm 43	31 \pm 25	22 \pm 14	16 \pm 6.9	15 \pm 8.1	1176 \pm 1220	1500 \pm 1500	1735 \pm 1663	2200 \pm 2100	7.8 \pm 5.8	8.8 \pm 7.1
Class 195	8	68	46.5	3456 \pm 173	340 \pm 230	43 \pm 30	41 \pm 33	8.8 \pm 2.2	7.2 \pm 5.6	3.9 \pm 1	3.7 \pm 1.6	225 \pm 127	240 \pm 210	333 \pm 179	350 \pm 290	2.4 \pm 1.9	2.3 \pm 2.3
Class 220	8	88	117	823 \pm 491	850 \pm 610	59 \pm 24.7	61 \pm 31	31 \pm 11	31 \pm 20	18 \pm 7.3	19 \pm 9.3	1465 \pm 1177	1600 \pm 1400	2130 \pm 1602	2300 \pm 2000	5.3 \pm 2.8	5.6 \pm 3.9
Class 221	10	94	160	–	–	94 \pm 18.5	82 \pm 33	52 \pm 21	40 \pm 30	31 \pm 14	28 \pm 16	8172 \pm 2809	7700 \pm 4600	10307 \pm 3549	9800 \pm 5600	7.3 \pm 2.7	7.5 \pm 4.0
Class 230	10	85	23	–	–	76 \pm 19.2	73 \pm 15	24 \pm 22	25 \pm 27	17 \pm 17	18 \pm 21	1721 \pm 1122	1800 \pm 1400	2056 \pm 1,320	2100 \pm 1600	0.6 \pm 0.6	0.65 \pm 0.89
Class 755	9	41	70.6	–	–	40 \pm 28.7	36 \pm 36	7.5 \pm 2.1	6.5 \pm 6.3	4.4 \pm 2.1	4.1 \pm 3.4	1550 \pm 1174	1500 \pm 1700	1867 \pm 1398	1800 \pm 2000	0.6 \pm 0.7	0.57 \pm 1.1
Class 800	10	77	166	–	–	201 \pm 115	200 \pm 230	12 \pm 3.7	11 \pm 6.8	7.6 \pm 2.4	7.3 \pm 4.2	2456 \pm 876	2400 \pm 2200	2963 \pm 1063	2900 \pm 2600	1.4 \pm 0.7	1.3 \pm 1.5
All				538 \pm 344	565 \pm 361	71 \pm 47	68 \pm 44	25 \pm 14	23 \pm 12	16 \pm 10	15 \pm 9	2843 \pm 2790	2898.5 \pm 2743.7	3613 \pm 3437	3638 \pm 3284	4.6 \pm 3.4	4.7 \pm 3.6

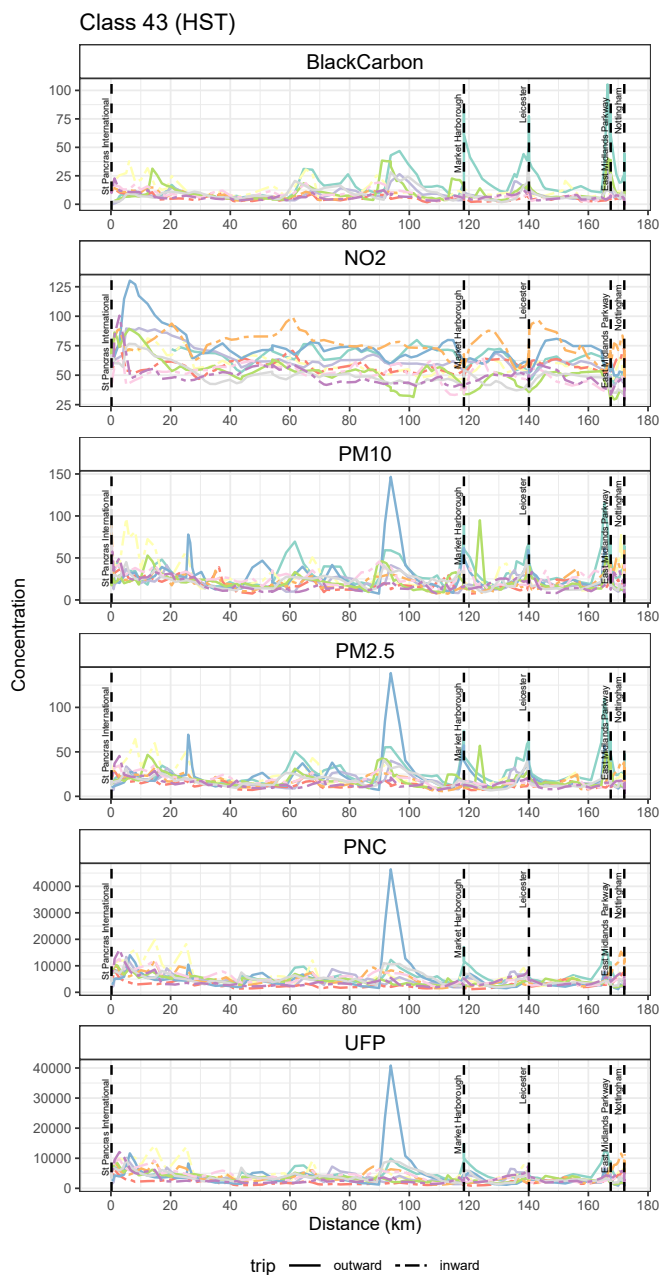


Fig. 3. Distribution of minute mean concentrations measured along the route by Class 43 (HST) trains for each sampled journey represented by individual-coloured lines. Solid line: outward journeys; dotted line: inward journeys. Vertical lines indicate the stations where the train stopped.

train carriages during the outward journey which were not properly ventilated during the inward journey; however, the train waited at the platform in the open-air station for 30 min before the inward journey started which would have allowed enough time for concentrations to equilibrate with outdoor air. Therefore, differences in air exchange rates in Locations A and C are more likely to lead to these inconsistencies.

3.4. Tunnels

There was a clear enhancement of pollutant concentrations when the Class 168 trains were inside tunnels, especially when leaving/approaching London Marylebone station (Fig. 6A, C). Concentrations in all pollutants observed a sharp increase and it took 5 to 15 min for concentrations to decrease to baseline. Similar decay times were

reported by Hill and Gooch (2010) when trains remained in an underground station. This effect was not as clear at Birmingham Snow Hill tunnel as the enclosed station masked the effect of the tunnel (Fig. 6B). Therefore, the effect of the tunnel on in-train concentrations was evaluated using the data before or after Marylebone Road. BC concentrations were on average 40 times larger than the baseline (range: 9 to 71). NO₂ was almost 3 times higher as measured in the tunnels; and the enhancements in PM₁₀, PM_{2.5}, PNC and UFP were similar, with mean increases above the baseline ranging from 6.4 to 7.6 (Table 2). The measured concentrations in the tunnels, baseline levels and the time when measured concentrations attained baseline after the tunnel are shown in Fig. S3 and Fig. S4.

3.5. Stations

Mean-journey PM₁₀ and NO_x concentrations were larger compared to those only considering the free-run transects for the majority of train classes (Table 1). Overall, there was no difference between in-train BC, NO₂, PM_{2.5}, PNC and UFP concentrations during free-run and those when the train stopped in a station (Fig. S5). However, in-train PM₁₀ concentrations were larger ($p < 0.001$) when the train stopped in a station ($29.8 \mu\text{g m}^{-3}$) than when it ran between them ($21.2 \mu\text{g m}^{-3}$). Similarly, in-train NO_x concentrations were larger ($p < 0.05$) when the train stopped in a station ($555 \mu\text{g m}^{-3}$) than when it ran between them ($478 \mu\text{g m}^{-3}$) (Fig. S5). When disaggregated by train class there was no statistical difference for any of the pollutants (Fig. S6). Overall, the mean enhancement of in-train concentrations when the trains were at stations compared to free-run times were 1.6 for PM₁₀, 1.3 for PM_{2.5} and 1.2 for NO₂ (Table 2). However, some of the journeys observed enhancements that were < 1 indicating that in some journeys in-train concentrations at the stations were less than those observed in-between. For, BC, NO_x, PNC and UFP the mean ratio considering the mean concentration at the stations compared to the times when running between stations was 1.0 (Table 2) indications there was not a clear enhancement.

3.6. Track gradient

The distribution of concentrations measured in the transect between Camden and Tring on Class 221 is shown in Fig. S7. Overall, NO₂ concentrations measured in Class 221 trains between Camden Junction and Tring were significantly larger ($p < 0.05$) on the uphill journeys ($97 \mu\text{g m}^{-3}$) than on the downhill journey ($74 \mu\text{g m}^{-3}$) which represented an enhancement of 33 % (Fig. S8). PM₁₀, PM_{2.5}, PNC and UFP concentrations were also larger on the uphill journeys (mean of $42 \mu\text{g m}^{-3}$, $33 \mu\text{g m}^{-3}$, $12,371 \text{ \# cm}^{-3}$ and $9,760 \text{ \# cm}^{-3}$, respectively) than the downhill journeys ($32 \mu\text{g m}^{-3}$, $24 \mu\text{g m}^{-3}$, $8,951 \text{ \# cm}^{-3}$ and $6,930 \text{ \# cm}^{-3}$, respectively) and differences were statistically significant except for PM_{2.5}. The uphill enhancement represented an average increase in PM₁₀, PNC and UFP concentrations of 30 %, 38 % and 43 %, respectively, in comparison to downhill journeys. Mean BC concentrations were similar at both uphill ($7.8 \mu\text{g m}^{-3}$) and downhill journeys ($7.7 \mu\text{g m}^{-3}$) (Fig. S8). The average enhancement in the uphill stretches compared to downhill were 1.4 for NO₂, PM₁₀ and UFP; and 1.3 for both PM_{2.5} and PNC (Table 2). However, only the enhancement for NO₂ was above one for all the journeys compared. The average enhancement for BC was 1, spanning from 0.4 to 2 (Table 2).

3.7. Outdoor air and land cover

In-train concentrations were larger than outdoor concentrations measured by fixed monitors in both urban and rural areas (Fig. S9). For NO_x, NO₂ and BC, in-train enhancements above outdoor concentrations were 100, 12 and 11 times larger in non-urban areas; and 21, 4 and 3 times larger in urban areas, respectively (inverse ratios reported in Table 2). For PM and UFP, in-train enhancements were approximately 2 to 3 times larger than outdoor concentrations (Table 2). Overall,

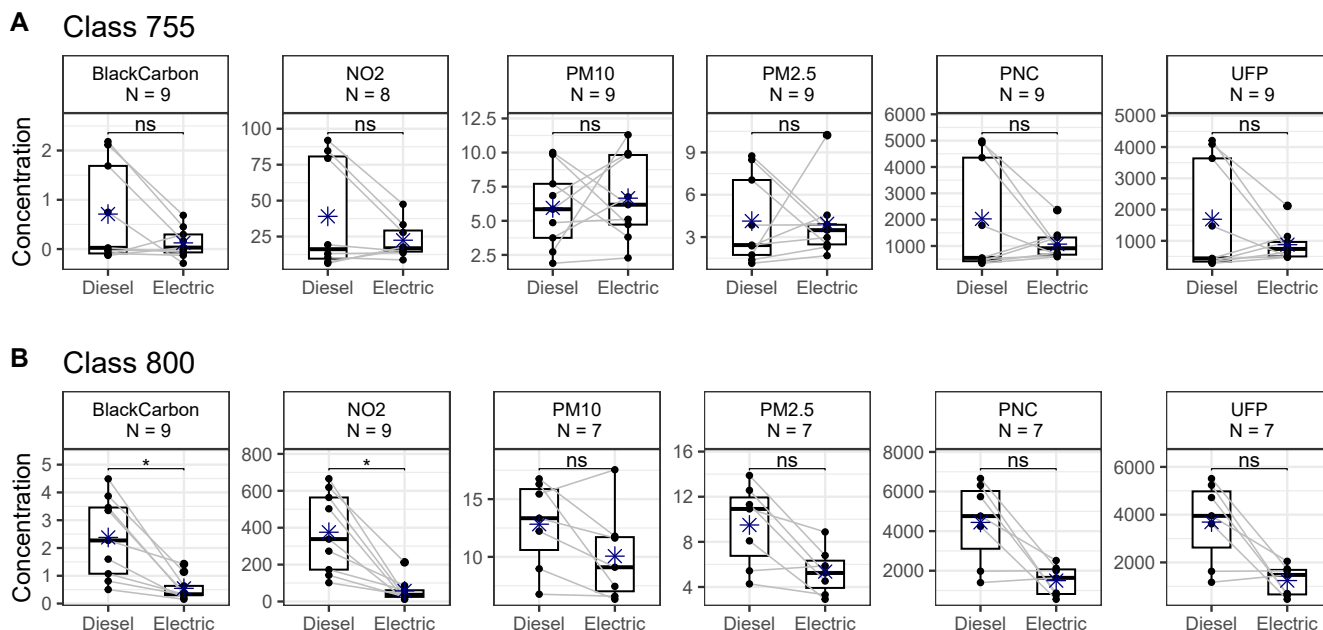


Fig. 4. Distribution (boxplots) of the mean concentrations on each journey (dots) measured when the train run on diesel and electric mode measured on bi-mode trains (Class 755 and 800). Pairs were defined as mean concentrations for the same trip, shown as lines. Number of available pairs indicated in the title of each panel. Wilcoxon-paired test was used to compare means. *** differences statistically different at $p < 0.001$; ** at $p < 0.05$; (ns) differences in mean non-statistically significant. Mean concentration for all times running on diesel and electric shown with a star. Concentrations are expressed in $\mu\text{g m}^{-3}$ for Black Carbon, NO_2 , PM_{10} and $\text{PM}_{2.5}$; and in $\# \text{cm}^{-3}$ for PNC and UFP.

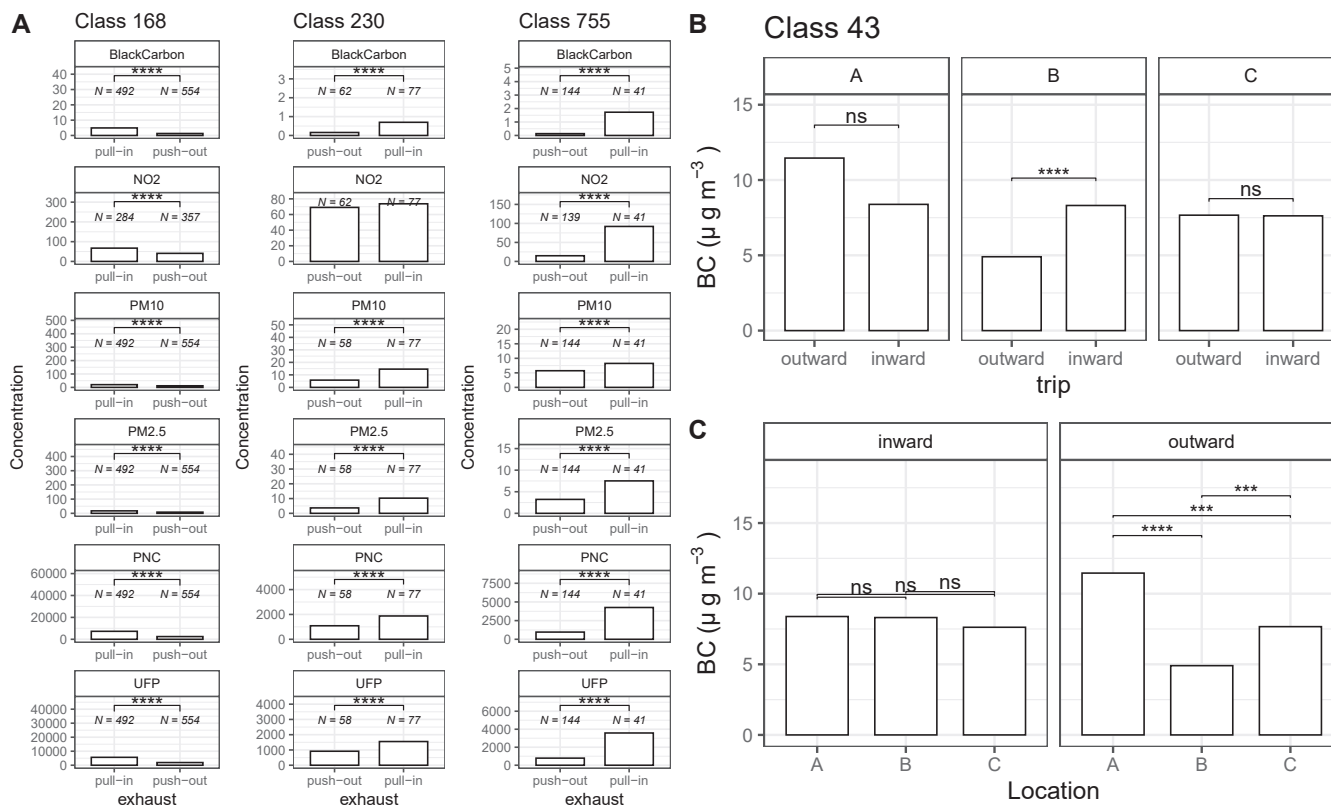


Fig. 5. Impact of the position of the exhaust. (A) Mean concentrations measured by each train class when the exhaust was in the front or behind the measurement point. The number of available concentrations is shown on top of each column. Concentrations are expressed in $\mu\text{g m}^{-3}$ for black carbon, NO_2 , PM_{10} and $\text{PM}_{2.5}$; and $\# \text{cm}^{-3}$ for PNC and UFP. (B) Mean concentrations in black carbon as measured at different locations on a class 43 (HST) trains split by outward and inward journeys. (C) Comparison of the black carbon concentrations measured in a class 43 (HST) trains at different locations of the train. Comparison of the means by the Wilcoxon test. *** differences statistically different at $p < 0.001$; ** at $p < 0.01$; ns: difference not statistically significant.

Table 2

Mean ratios [min–max in brackets] of air pollutants measured onboard trains per controlling factor, with the number of instances (N) used to calculate the ratio.

Controlling factor	Train class	Ratio	PM ₁₀	PM _{2.5}	PNC	UFP	BC	NO _x	NO ₂
Engine mode	755	Diesel/electric	1.1 [0.24–2.1] N = 9	1.3 [0.17–2.8] N = 9	1.9 [0.32–5.0] N = 9	2.0 [0.35–5.2] N = 9	1.5 [-4.3–10] N = 9	–	1.5 [0.36–2.9] N = 8
Engine mode	800	Diesel/electric	1.4 [0.88–2.2] N = 7	1.9 [0.9–2.8] N = 7	4.2 [0.86–8.1] N = 7	4.3 [0.79–8.4] N = 7	5.3 [1.6–10] N = 9	–	13 [2.8–38] N = 9
Exhaust	168, 755, 230	In front/behind	1.9 [1.4–2.5] N = 3	2.4 [2.1–2.8] N = 3	3.0 [1.7–4.4] N = 3	3.1 [1.7–4.5] N = 3	7.0 [3.8–12.8] N = 3	–	3.0 [1.1–6.2] N = 3
Tunnel	168	Tunnel/baseline	6.9 [5.1–8.7] N = 10	6.4 [4.3–8.6] N = 10	7.6 [5.6–9.7] N = 10	7.6 [5.3–9.9] N = 10	40 [9.4–71] N = 10	–	2.8 [2.8–2.9] N = 6
Station	All	Station/free-run	1.6 [0.5–7.2] N = 109	1.2 [0.5–3.9] N = 109	1.0 [0.3–4.2] N = 109	1.0 [0.2–4.3] N = 109	1.0 [-33; -42] N = 117	1.0 [0.3–2.6] N = 55	1.2 [0.4–6.8] N = 114
Track gradient	221	Uphill/downhill	1.4 [0.8–2.7] N = 5	1.3 [0.7–2.7] N = 5	1.3 [0.7–2.5] N = 5	1.4 [0.7–2.6] N = 5	1.0 [0.4–2] N = 5	–	1.4 [1.0–1.9] N = 5
Land cover	All	Outdoor (urban)/in-train	0.60 [0.24–1.3] N = 14	0.53 [0.16–1.2] N = 3	–	0.64 [0.33–1.65] N = 6	0.33 [0.06–1.8] N = 14	0.05 [0.01–0.1] N = 7	0.28 [0.08–0.56] N = 14
Land cover	All	Outdoor (rural)/in-train	0.35 [0.23–0.45] N = 3	0.37 [0.23–0.45] N = 3	–	0.36 N = 1	0.09 [0.02–0.25] N = 10	0.01 [0.02–0.02] N = 7	0.08 [0.02–0.16] N = 10

15 Jan 2020: Marylebone to Birmingham Snow Hill (Class 168)

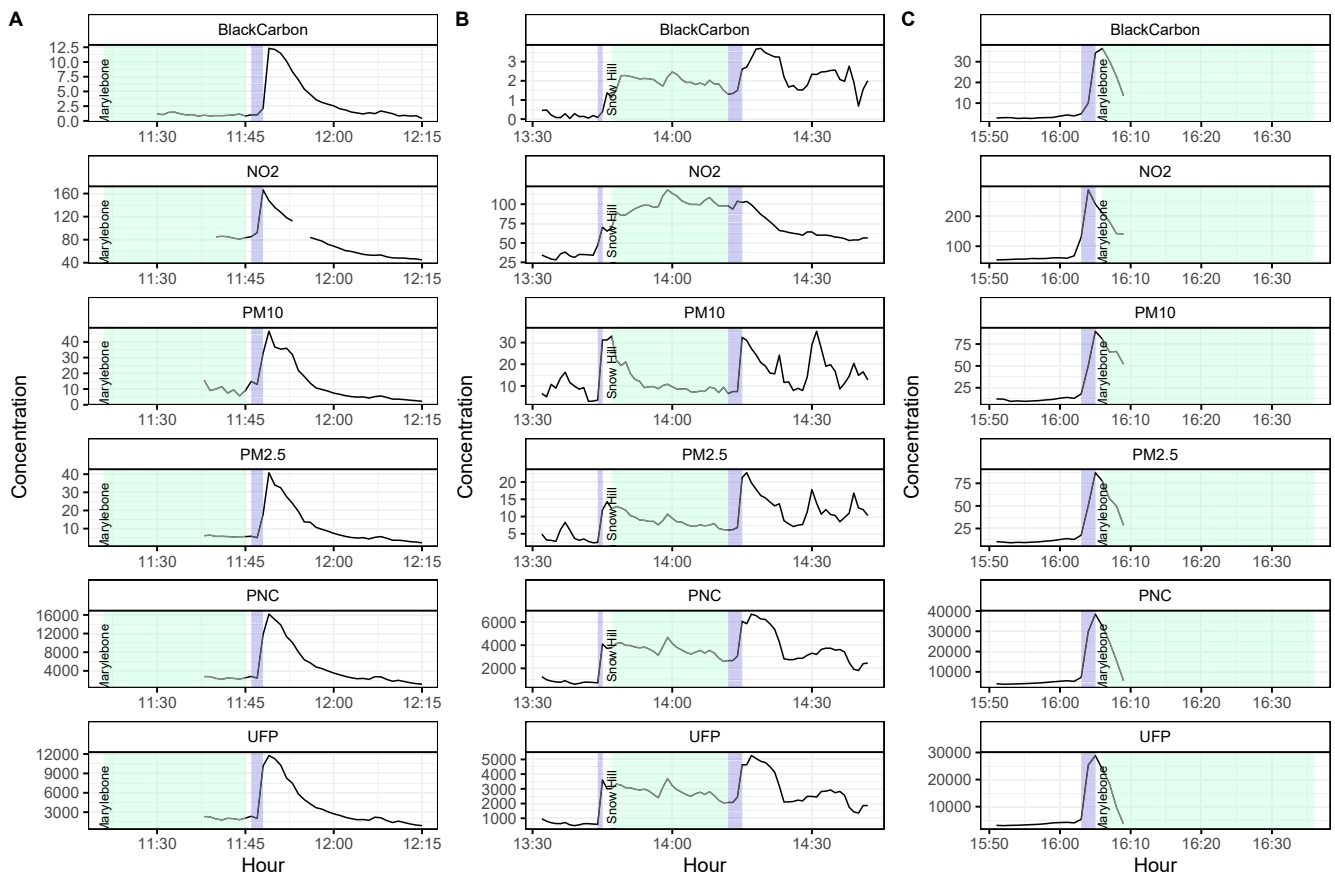


Fig. 6. Concentrations of air pollutants measured after (A)/before (C) entering the tunnels at London Marylebone and Birmingham Snow Hill (B) on 15 January 2020. The green areas indicate the times when trains were at a train station; the blue shaded area indicates the times when train where inside tunnels. Concentrations are expressed in $\mu\text{g m}^{-3}$ for black carbon, NO₂, PM₁₀ and PM_{2.5}; and in $\# \text{cm}^{-3}$ for PNC and UFP.

outdoor concentrations measured in urban areas were larger than rural areas for the times that the train campaigns took place: 58 % (BC), approximately 70 % for both NO_x and NO_2 , 33 % for UFP, and 15 % (PM_{10}) and 5 % ($\text{PM}_{2.5}$). However, concentrations measured onboard UK diesel trains when trains passed by either non-urban or urban areas were only statistically different for BC on Class 172 with larger concentrations over the urban areas ($5.7 \mu\text{g m}^{-3}$) compared to non-urban ($2.1 \mu\text{g m}^{-3}$) (Fig. S9). Therefore, the land cover did not have a measurable impact on the in-train concentrations in this study despite it influencing the baseline in-train concentrations.

3.8. Passenger movement

Except for the concentrations measured in the tunnel environment around Birmingham New Street on 2 July, $\text{PM}_{\text{coarse}}$ concentrations were lower during peak time than off-peak for Class 220 trains (Fig. S10). The mean outward concentration was 33 % lower than the inward mean. However, the presence of $\text{PM}_{\text{coarse}}$ peaks after the serviced stations is clear from the outward journey on 29 June, attaining values up to $100 \mu\text{g m}^{-3}$ as 1-minute means (Fig. S10). That indicates an increase in $\text{PM}_{\text{coarse}}$ is possibly associated with passenger movement. Overall, ten of the 12 train classes observed larger $\text{PM}_{\text{coarse}}$ concentrations after leaving a station compared to the concentrations before arriving at it with differences ranging from 16 % to 865 % (Fig. 7). Only train Classes 156 and 230 observed larger concentrations before arriving at the station than after departure, with mean differences of -9.7% and -24% , respectively, statistically significant at $p < 0.001$. Overall, $\text{PM}_{\text{coarse}}$ after departing serviced stations were almost 6 times larger than concentrations observed just before arriving at the stations (range: 0.76–35).

3.9. Train class

The largest PM, PNC and UFP concentrations were measured on Class

221 and Class 158/9 trains with journey means of 52 and $51 \mu\text{g m}^{-3}$ (PM_{10}), 31 and $36 \mu\text{g m}^{-3}$ ($\text{PM}_{2.5}$), and more than $10,000$ and $8,000 \# \text{cm}^{-3}$ in PNC and UFP, respectively (Table 1). Class 158/9 also measured the largest BC concentrations ($11 \mu\text{g m}^{-3}$) along with Class 43 (HST) ($9.8 \mu\text{g m}^{-3}$). The routes with the lowest PM concentrations ($< 10 \mu\text{g m}^{-3}$ for PM_{10} and $< 5 \mu\text{g m}^{-3}$ for $\text{PM}_{2.5}$) were those by Classes 755 and 195 trains (Table 1). Class 195 also observed the lowest UFP and PNC with means of $225 \# \text{cm}^{-3}$ and $333 \# \text{cm}^{-3}$, respectively, followed by Class 68 with means of $424 \# \text{cm}^{-3}$ (UFP) and $623 \# \text{cm}^{-3}$ (PNC). Average NO_2 concentrations measured inside carriages in diesel trains in the UK ranged from 28 to $201 \mu\text{g m}^{-3}$ (Table 1). The largest average-journey NO_2 concentration was onboard Class 800 trains followed by Classes 185 and 221, both with an average trip concentration of $94 \mu\text{g m}^{-3}$. Classes 230 and 158/9 observed NO_2 mean concentrations above $70 \mu\text{g m}^{-3}$ (Table 1). The lowest NO_2 concentrations were measured in train Classes 68 ($28 \mu\text{g m}^{-3}$) and 172 ($43 \mu\text{g m}^{-3}$). NO_x in-train concentrations were available for only 6 of the train classes (Classes 68, 156, 172, 185 and 195) and the range of NO_x concentrations was from $130 \mu\text{g m}^{-3}$ to approximately $3,500 \mu\text{g m}^{-3}$ (Table 1). The largest NO_x concentrations were measured in train Classes 195 and 185, with more than $1,000 \mu\text{g m}^{-3}$ as mean-journey concentrations. As for NO_2 , train Classes 68 and 172 measured the lowest in-train concentrations.

The correlation between pollutants helps to identify the sources of poor air quality measured inside train carriages. Only the times when trains run between stations were considered. Combustion sources dominated concentrations measured onboard the Classes 800 and 755 trains as indicated by the high correlations between $\text{PM}_{2.5}$ and BC ($R^2 = 0.87$ and 0.79 , respectively), BC and NO_2 ($R^2 = 0.83$ and 0.79 , respectively), BC and UFP ($R^2 = 0.81$ and 0.85 , respectively), and NO_2 and UFP ($R^2 = 0.71$ and 0.79 , respectively) (Fig. S11). Correlations between UFP and BC and NO_2 were also high in Class 168 ($R^2 = 0.86$ and 0.70 , respectively), indicating the presence of diesel exhaust in train carriages. In contrast, abrasive sources and/or resuspension of particles may have

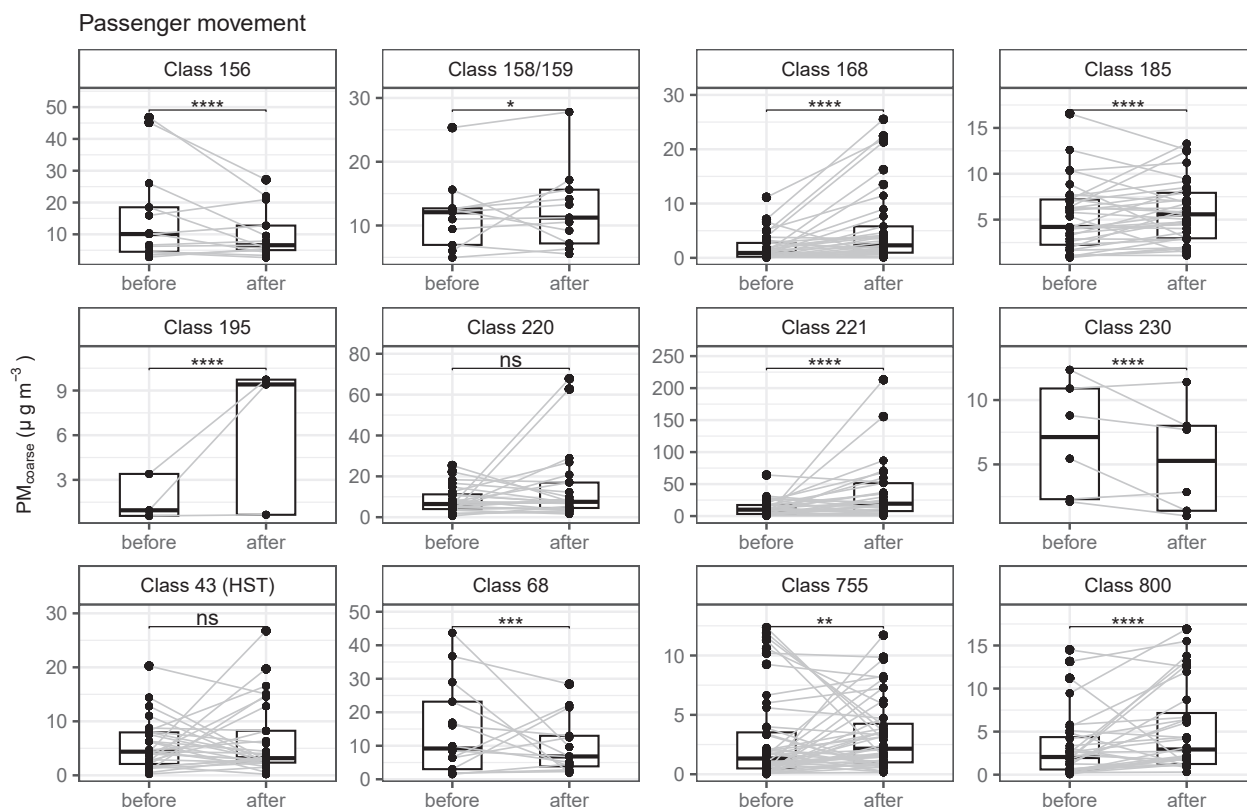


Fig. 7. Distribution in $\text{PM}_{\text{coarse}}$ in-train concentrations measured before arriving at a station compared to after leaving the station with Wilcoxon paired test. **** differences statistically different at $p < 0.001$; ** at $p < 0.05$; (ns) differences in mean non-statistically different.

dominated concentrations in Classes 43 (HST), 156, 158/9, 172 and 230 as only PM₁₀ and PM_{2.5} correlated ($R^2 > 0.79$). A combination of diesel fumes and abrasive sources might influence in-train concentrations in Classes 68, 185, 220 and 221, with moderate correlations between PM₁₀ and PM_{2.5} ($R^2 = 0.47 - 0.76$), NO_x and UFP ($R^2 = 0.49 - 0.52$) and/or UFP-BC ($R^2 = 0.42 - 0.62$) (Fig. S11).

Train classes with an engine age < 10 years (Classes 195, 230, 755 and 800 – Table S1) where the cleanest in terms of NO_x, NO₂, PM, PNC, UFP and BC concentrations (Fig. 8A). There was not much difference in mean concentrations for trains older than 10 years (Fig. 8A). Class 800 had the highest mean NO₂ concentrations (200 µg m⁻³) followed by Class 185 trains (96 µg m⁻³) (Table 1). It was expected that trains fitted with SCRs would lead to the lowest in-train NO₂ concentrations but this was not the case in this study (Fig. 8B). However, trains fitted with SCRs did have lower NO_x, BC, PM₁₀, PM_{2.5}, PNC and UFP concentrations than those without an exhaust after-treatment device (Fig. 8B) and expressed in percentage difference it was 42 %, 75 %, 69 %, 72 %, 66 % and 64 %, respectively. However, trains fitted with SCRs were the newest rolling stock tested and PM and particle counts in-train concentrations might be due to other factor associated with the age of the train. Abramesko and Tartakovsky (2017) found that UFP concentrations were larger in older trains associated with less efficient air filters, less tight doors and window sealing and leaks in the carriage structure. Train classes fitted with

DPF had the lowest mean BC concentrations, lower than those without after-treatment (not significant) and those with SCRs ($p < 0.001$). However, in-train PM₁₀, PM_{2.5}, PNC and UFP concentrations in train classes with DPF were similar to PM and particle counts in trains without DPF (Fig. 8B). Mean PNC and UFP concentrations in trains with DPFs (2,880 and 1,740 # cm⁻³, respectively) were lower than in trains without exhaust after-treatment (4435 and 1250 # cm⁻³, respectively) but not statistically significant (Fig. 8B).

Trains with electropneumatic + regeneration braking system had the lowest mean BC, PM₁₀, PM_{2.5}, PNC and UFP concentrations as measured two-minutes prior arriving at stations (1.3 µg m⁻³, 8.9 µg m⁻³, 6.1 µg m⁻³, ~2500 and 2100 # cm⁻³, respectively). However, these were not significantly lower compared to other braking systems (Fig. 8C). Conversely, the air braking system had the largest BC and PM_{2.5} concentrations (15 and 26 µg m⁻³, respectively). Trains with air, electropneumatic and rheostatic + electropneumatic braking systems all had similar in-train PM₁₀ (around 25–30 µg m⁻³) and PM_{2.5} concentrations (range 14–25 µg m⁻³) (Fig. 8C). The elevated NO₂ concentrations associated with the electropneumatic + regeneration braking system was likely due to engine emissions on hybrid train class (Classes 755 and 800) which observed the largest NO₂ concentrations. PNC and UFP in-train concentrations in trains with different braking systems were similar, in the range of 2,020 – 4,700 and 1,300 – 3,900 # cm⁻³,

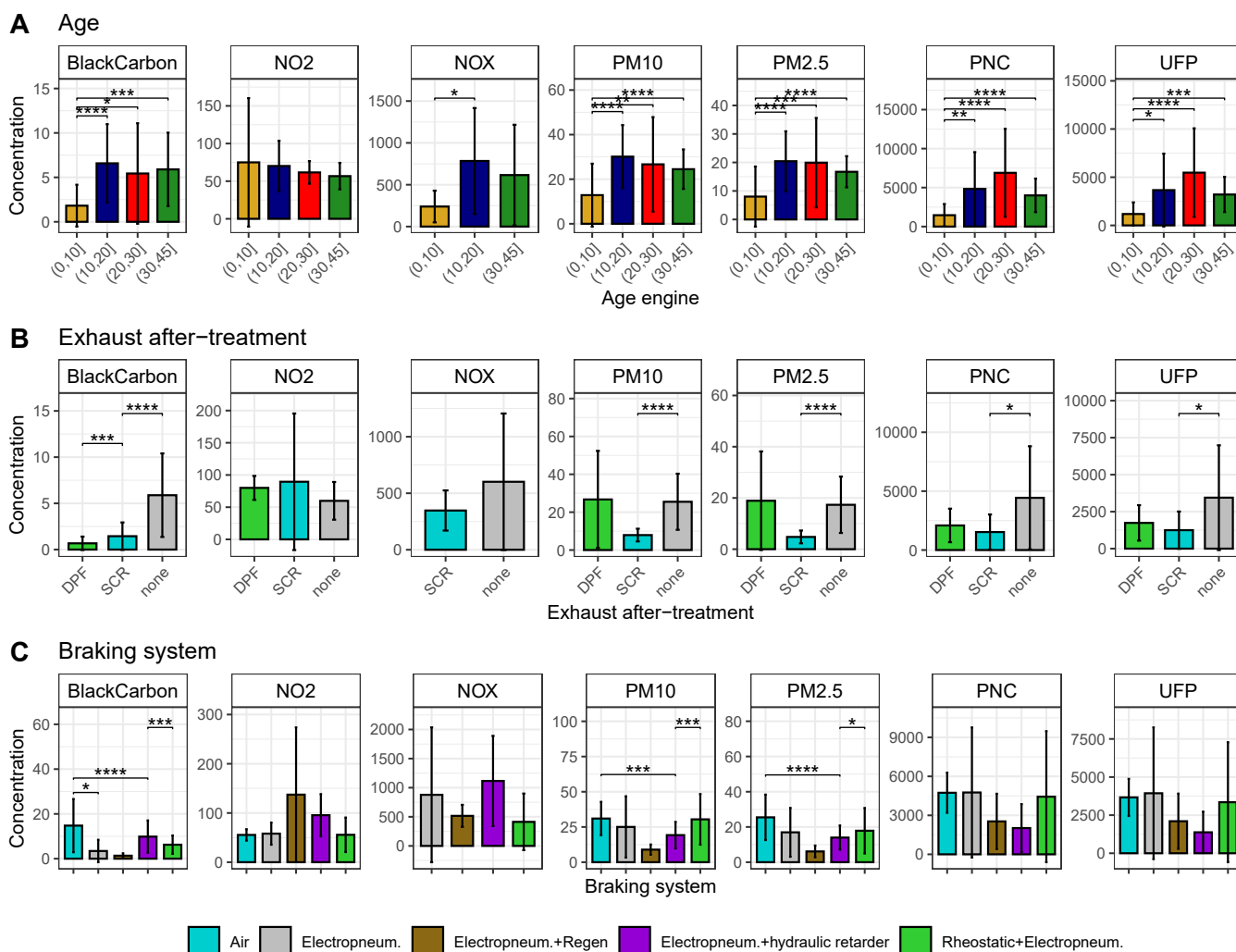


Fig. 8. Bar plots showing the mean (and standard deviation as error bars) in in-train journey concentration grouped by train classes based on (A) engine age; (B) exhaust after-treatment devices; and (C) braking systems. Only free-run concentrations were considered in A and B; concentrations two-minutes before arriving at stations were considered in C. Concentrations expressed in µg m⁻³ for black carbon, NO₂, NO_x, PM₁₀ and PM_{2.5}; and in # cm⁻³ for PNC and UFP. Comparisons made by the Wilcoxon test, only statistically significant differences are indicated; *** differences significant at $p < 0.001$; ** at $p < 0.01$.

respectively, in agreement with braking as a source of coarse particles (Fig. 8C).

3.10. Estimation of the inhaled dose

In-train concentrations are clearly influenced by different factors, by estimating inhaled dose (Eq. (1)), we have assessed which are most important for exposure. Firstly, when considering mean concentrations measured on all train classes, stations (terminus or intermediate), the period before and after the station, and free-run were not statistically different (Fig. 9A). Conversely, the inhaled dose was significantly higher for free-run periods than other periods for all pollutants (Fig. 9B) with mean values of 3.1 μg for BC, 45 μg (NO_2), 279 μg (NO_x), 14 μg (PM_{10}), 10 μg ($\text{PM}_{2.5}$) and more than 2,600 and 2,000 M# for PNC and UFP, respectively. The range of mean dose in the other parts of the journey were 0.36 – 0.77 μg for BC, 11 – 12 μg (NO_2), 5.7 – 97 (NO_x), 3.5 – 4.6 μg (PM_{10}), 2.2 – 2.6 μg ($\text{PM}_{2.5}$), 514 – 619 M# (PNC) and 400–502 M# (UFP) (Table S3). Generally, the dose in the free-run periods were statistically larger than in the other parts of the journey, with the exception of NO_x . This reflects the length of time in free-run, 51 min on average, compared to the other situations: 14 mins (at stations); 12 mins (before/after); 10 mins (start/end journey). NO_x measurements were only available in 6 of the 13 train classes tested limiting the number of observations for effective comparison. However, there is a noticeable higher tendency during the free run, although it is not statistically significant. The most effective way to reduce dose received by passengers is to improve the quality of the air in the carriage during these periods through filtration and air purification.

4. Discussion

4.1. Comparison with other studies

Mean-journey PM_{10} concentrations in this study (7.5 – 52 $\mu\text{g m}^{-3}$, mean 27 $\mu\text{g m}^{-3}$) were approximately 50 % of both the concentrations measured in diesel trains in Greece (49 $\mu\text{g m}^{-3}$; Maggos et al., 2016), and in an electric train in Korea (42 $\mu\text{g m}^{-3}$; Ma and Kang, 2022). Only Class 221 and Class 158/9 trains observed similar PM_{10} concentrations, with mean concentrations of approximately 50 $\mu\text{g m}^{-3}$. Mean-journey $\text{PM}_{2.5}$ concentrations in this study (3.9–36 $\mu\text{g m}^{-3}$, mean 16 $\mu\text{g m}^{-3}$) were close to the average concentration of 11 $\mu\text{g m}^{-3}$ measured at multiple locations in a diesel train in Greece (Maggos et al., 2016), indicating that the fine fraction dominated UK in-train concentrations (~60 % of particles were fine) compared to 22 % in Greek diesel trains. Surprisingly, most of the UK diesel trains observed lower $\text{PM}_{2.5}$ concentrations than those measured in international electric trains in Europe (mean: 38 $\mu\text{g m}^{-3}$; Winiger (2022) and in Korea (25 $\mu\text{g m}^{-3}$; Ma and Kang, 2022), and also lower than diesel trains in Boston and New York (average 36 $\mu\text{g m}^{-3}$; Hill and Gooch, 2010). This may be due to lower emissions from the trains or reduced ingress into the carriages in the UK, or higher outdoor concentrations at those locations which may have provided a larger background concentration onto which train sources were added. The UFP measured in UK diesel train carriages (below 4,000 # cm^{-3}) were the lowest compared to those reported in the literature (range: ~42,000–185,000 # cm^{-3}) (Table 3). Mean-journey BC concentrations (4.2 $\mu\text{g m}^{-3}$) were similar to those from diesel trains from the CSX transportation company in the US (3.7 $\mu\text{g m}^{-3}$) measured as elemental carbon (Hewett and Bullock, 2014) but smaller than those measured in diesel trains in Denmark and on Canadian locomotives (Seshagiri, 2003) both with means of 10 $\mu\text{g m}^{-3}$ (Table 3).

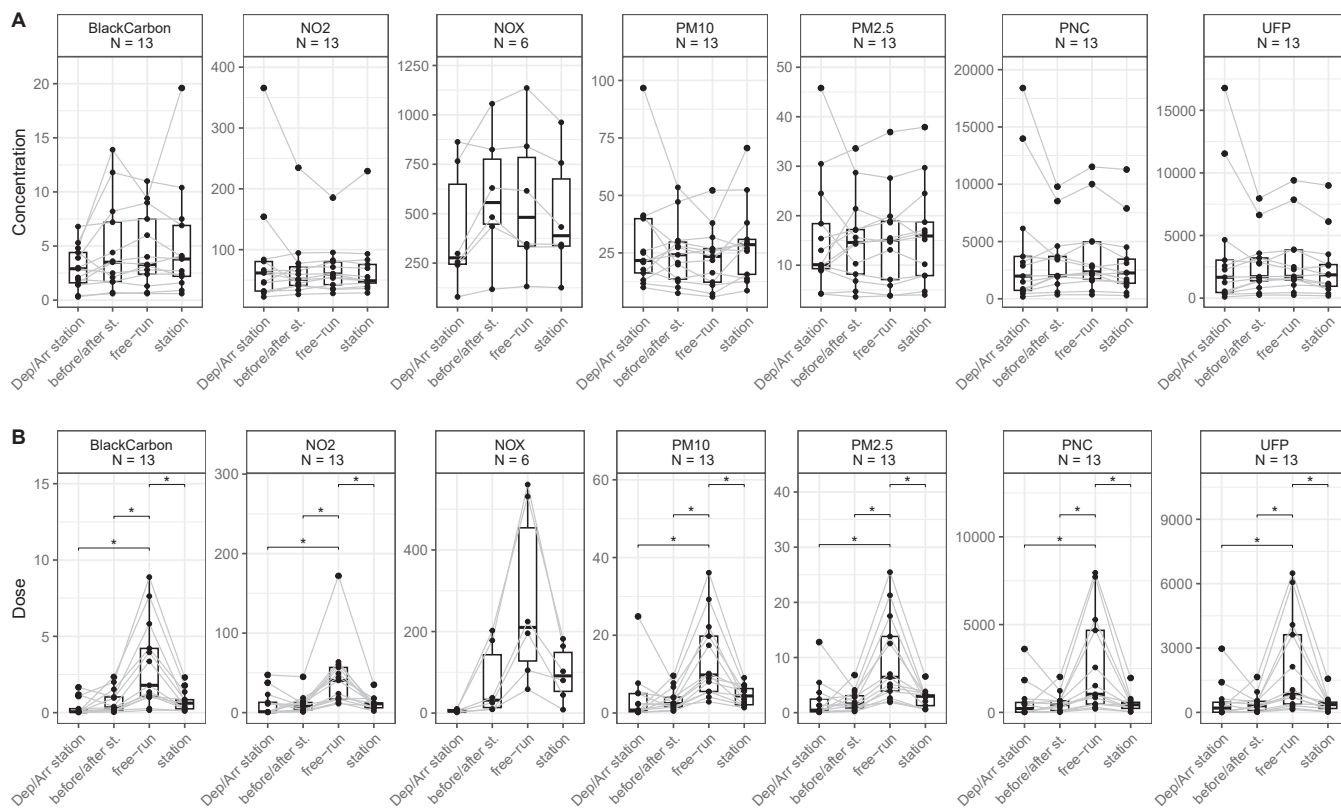


Fig. 9. Paired boxplots of the mean journey concentration by train class (A) and mean dose (B) at the different locations along the journey with Wilcoxon test. ** significant at $p < 0.01$; * $p > 0.05$; (blank) not statistically significant. Number of available pairs indicated in the title of each panel. Concentrations expressed in $\mu\text{g m}^{-3}$ for black carbon, NO_2 , NO_x , PM_{10} and $\text{PM}_{2.5}$; and in # cm^{-3} for PNC and UFP; dose in μg for black carbon, NO_2 , NO_x , PM_{10} and $\text{PM}_{2.5}$; and in M# for PNC and UFP.

Table 3

Mean PM₁₀, PM_{2.5}, UFP, BC and NO₂ concentrations measured onboard diesel and hybrid trains in the UK (this study) and mean concentrations found in the literature including both diesel and electric trains.

Study	City, country	Type of train	N trips	PM ₁₀ (µg m ⁻³)	PM _{2.5} (µg m ⁻³)	UFP (# cm ⁻³)	BC (µg m ⁻³)	NO ₂ (µg m ⁻³)
This study	Multiple routes, UK	Diesel	117	27 ± 15	16 ± 9.9	2,946 ± 2974	4.6 ± 3.2	87 ± 98
Andersen et al. (2019)	Multiple routes, UK	Electric	19 ^A	9.2 ± 2.5	4.8 ± 1.1	1,196 ± 104	0.3 ± 0.3	36 ± 16
		Diesel	14	–	–	218,000 ± 140,000	10 ± 3.3	53 ± 16
Jeong et al. (2017)	Toronto, Canada	Electric	7	–	–	6,150 ± 2,310	1.7 ± 0.6	16 ± 10
		Diesel	43	–	–	90,300 ± 82,164 ^C	12 ± 11	–
Hill and Gooch (2010)	Boston, New York, US	Diesel	17	–	36 ± 32	80,196 ± 57,638	5.6 ± 3.7	–
Ham et al. (2017)	Sacramento, US	Diesel	19	2.5 ± 0.6	33 ± 4	42,000 ± 49,000 ^C	–	–
Maggos et al. (2016)	Athens – Thiva (Greece)	Diesel	2*	49 ± 19	11 ± 6	–	–	181 ± 62
Hewett and Bullock (2014)	Unites States (not specified)	Diesel	234, 190	–	–	–	3.7 ^B	134
Chertok et al. (2004)	Sydney, Australia	Electric	11	–	–	–	–	49.9
Seshagiri (2003)	Canada	Diesel	48	–	–	–	10 ± 12	–
Ma and Kang (2022)	Iksan – Gwangmyeong, Korea	Electric	52	42 ± 9.2	25 ± 4	–	2.1	–
Winger (2022)	Zurich (Switzerland)- Frankfurt (Germany) – Amsterdam (The Netherlands)	Electric	1	–	38	–	2.4 ± 3.0	–

^A Those relates to the number of transects measured in electric mode.

^B Measured as elemental carbon (EC).

* Multiple locations in the same train

Mean-journey BC concentrations on bi-mode trains when running in electric mode was smaller (0.3 µg m⁻³) than those measured in an electric super high-speed train in Korea (1.85–2.25 µg m⁻³) (Ma and Kang, 2022). Mean-journey NO₂ concentrations measured onboard UK diesel trains ranged from 28 µg m⁻³ (Class 68) to 201 µg m⁻³ (Class 800) (Table 1) with an overall mean of 84 µg m⁻³. Bi-mode trains running on electric mode had a mean concentration of 44 µg m⁻³ (Table 3). NO₂ concentrations measured in this study were larger to those on diesel trains in Copenhagen (53 µg m⁻³) (Andersen et al., 2019), but lower than diesel locomotives tested by the CSX transportation in the US (134 µg m⁻³) (Hewett and Bullock, 2014). Mean NO₂ concentrations when running on electric mode in this study (44 µg m⁻³) were larger than those electric trains measured in Copenhagen (16 µg m⁻³) but were similar to those in Sydney (50 µg m⁻³) (Chertok et al., 2004) (Table 3). This is likely due to an accumulation of NO₂ concentrations when the train run on diesel that did not disperse when it changed to electric mode.

4.2. Influencing factors

Emissions from trains and onboard activity were responsible for elevated in-train concentrations of PM₁₀, PM_{2.5}, PNC, UFP, BC, NO_x and NO₂ measured in UK diesel trains. There was a general enhancement of in-train concentrations compared to outdoor air in all trains used in this study. In-train NO₂ and BC were on average ~4 to ~3 times larger than urban background concentrations; and 17–18 times larger than in non-urban environments (inverse of reported ratios in Table 2). BC increments above urban air were of a similar magnitude than those reported by Jeong et al. (2017) for diesel-powered commuter trains in downtown Toronto (Canada) which were 3 times larger than outdoor air. Large BC enhancements (11 times larger) compared to outdoor air were also found in Boston, US (Schneider and Bill, 2007). Enhancements of particulate matter and particle counts were about 1.5–2 times larger in UK diesel and bi-mode trains than urban background concentrations. In the USA, similar results were found in trains in Boston and New York, with a one to four-fold enhancement above outdoor air sampled the same day (Schneider and Bill, 2007). In Sweden, both PM₁₀ and PM_{2.5} concentrations inside trains were higher than background concentrations regardless of the location (Cha et al., 2018b). Mean UFP exposures

in diesel trains in Boston were slightly larger than in diesel UK trains, with enhancements ranging from 3 to 20 times the concentrations in outdoor air (Hill and Gooch, 2010).

The presence of tunnels on the journey had a clear impact on air quality in-train concentrations and was the factor associated with the largest enhancements inside train carriages: between 6 and 7 times larger for PM and particle counts respectively; and 40 for BC. Enhancements here were larger than those reported inside passenger compartments in trains in tunnels in Sweden (Cha et al., 2018b) where PM₁₀ and PM_{2.5} concentrations were almost two-fold higher when trains ran in tunnels. However, only electric trains used the tunnel-like route in Sweden. Mean enhancements in NO₂ associated with the presence of tunnels was 2-fold higher compared to baseline concentrations. A possible solution to reduce the onboard concentrations when trains run in tunnels is to avoid the accumulation of exhaust emissions in tunnels by installing forced ventilation systems in tunnels, especially those with the highest presence of diesel trains. Ventilation systems have proven to be effective in reducing PM on underground platforms in urban underground systems (Moreno et al., 2017); and NO₂ concentrations in tunnel-like railway stations (Clegg et al., 2022).

The position of the exhaust relative to the sampling point was the second element with the largest impact on the in-train concentrations, this is of course analogous to where a passenger would sit. This was especially true for particulate concentrations, with enhancements 2-fold larger for PM, 3-fold for PNC and UFP, and 7-fold larger for BC when the sampling point was downwind of the exhaust. In-train NO₂ concentrations were also larger by a factor of 3. Similar results were reported by Jeong et al. (2017) and Seshagiri (2003) with BC concentrations four and three times larger in carriages in pull-in trains compared to push-out ones, respectively. Abramesko and Tartakovsky (2017) measured UFPs in diesel locomotives along the main railway route in Israel and observed larger UFP concentrations in carriages in pull-mode trains, by a factor of 3–43 depending on the carriage type, compared to push mode. It was also observed that exhaust emissions entered train carriages after some distance and not immediately after the exhaust point. Andersen et al. (2019) also observed UFP enhancement of 20–33 times larger when the train run on pull mode compared to push mode in diesel trains.

Engine mode in bi-mode trains (diesel or electric) also significantly influenced concentrations. Concentrations in Class 800 bi-mode trains,

when running on diesel mode, were statistically larger than those measured on electric mode with clear enhancements in all pollutants. Those were 4-fold, 2-fold and 5-fold larger for PNC, $PM_{2.5}$ and BC, respectively, similar to ratios observed in Denmark (6-fold, 2-fold and 6-fold, respectively; Andersen et al., 2019). However, enhancements in NO_2 were much larger for the UK trains (14 times larger) compared to 3 times larger observed in the Danish rolling stock. Large enhancements were also observed in Class 755 trains when running on diesel for BC, NO_2 and UFP but those were not statistically significant compared to the concentrations when the train ran on electric. The electrification of the railway network may be beneficial in the reduction of in-train concentrations in diesel UK trains. Gradient enhanced NO_2 and PM concentrations, uphill stretches increased by a factor of 1.4 (for NO_2 , PM_{10} and UFP) and 1.3 (for both PNC and $PM_{2.5}$) compared to downhill stretches. It is difficult to minimize the effect of gradient on in-train concentrations; however, using the cleanest trains in the journeys with the steepest gradients might reduce the ingress of pollutants in train carriages.

Previous studies highlighted the effect of the interior ventilation as beneficial to reduce PM concentrations inside train carriages (Cha et al., 2018b). Ventilation was also suggested as a factor that might explain the difference between in-train PM concentrations in two diesel trains in the UK sampled the same day (Molden et al., 2023). The effect of ventilation was not investigated in the current study. However, the other studies suggest that ventilation systems in train carriages might be beneficial to reduce exposure to in-train pollutants.

4.3. Comparison between train classes

In-train concentrations measured in this study were dominated by diesel emissions (Classes 168, 755 and 800), abrasion emissions (Classes 43 (HST), 156, 158/9, 172 and 230) or both. The reduction of diesel exhaust emissions might be accomplished by fitting exhaust after-treatment devices. Classes 755 and 800 were fitted with SCRs, nevertheless NO_2 concentrations measured on these train classes were the highest of all classes tested, possibly due to poorly functioning SCR which has also been observed in construction machinery due to temperature reductions following engine idling (Desouza et al., 2020). However, NO_x concentrations on trains with SCRs were smaller by 40 % but differences were not statistically significant. DPF was only fitted to Class 230 trains and measured the lowest BC in-train concentrations demonstrating its efficacy in reducing diesel exhaust emissions. However, the impact of DPFs was less clear for PM_{10} , $PM_{2.5}$ and PNC

indicating the influence of non-exhaust emissions and outdoor sources. Overall, the newest train classes (< 10 years old) had the lowest in-train PM_{10} , $PM_{2.5}$, PNC, UFP, BC and NO_x concentrations; new rolling stock would therefore reduce in-train PM concentrations, particle number concentrations and diesel combustion gases.

Braking systems may have an impact on in-train PM concentrations associated with abrasive sources. Trains with electropneumatic and regeneration braking system observed lower particles concentrations (both PM_{10} and $PM_{2.5}$) associated with abrasive sources but they were not statistically different compared to trains with other braking systems. Conversely, trains with air and rheostatic + electropneumatic braking systems were associated with larger PM concentrations.

4.4. Exposure in UK transport modes

Comparing exposure in UK trains against other commuting transport is important to assess their relative impact on population exposure. Several studies have reported concentrations of PM_{10} , $PM_{2.5}$, PNC and BC in the UK (Table S4), however none have reported either NO_x or NO_2 , principally due to the measurement challenges. However, the number of studies characterizing BC and PM_{10} concentrations in the transport microenvironments is not extensive enough to draw robust conclusions and the comparison is limited to $PM_{2.5}$ and PNC. The underground was the mode with the largest observed $PM_{2.5}$ concentrations (median of $157 \mu g m^{-3}$), almost ten times larger than median $PM_{2.5}$ concentrations in diesel trains (median: $14 \mu g m^{-3}$) (Fig. 10). The other transport modes in the UK were associated with median $PM_{2.5}$ concentrations ranging from $11 \mu g m^{-3}$ (petrol car) to $36 \mu g m^{-3}$ (bus). Bi-mode trains had the lowest $PM_{2.5}$ concentrations ($4.6 \mu g m^{-3}$). Similarly, bi-mode trains showed the lowest PNC concentrations (median: $\sim 4,000 \# cm^{-3}$). Median particle counts in diesel trains were slightly lower compared to other transport modes ($\sim 22,800 \# cm^{-3}$) but the range of concentrations agreed with the range of reported PNC in other transport modes. The transport mode with the largest median PNC was cycling, with median concentrations above $52,000 \# cm^{-3}$ (Fig. 10).

5. Conclusions

This study reports air quality measured on 13 different train classes on 15 separate routes, 119 journeys in all, with a total of approximately 11,000 min of sampling in-train concentrations. The train classes sampled represent a range of rolling stock, both diesel and bimodal, of different ages and with different exhaust after-treatment and

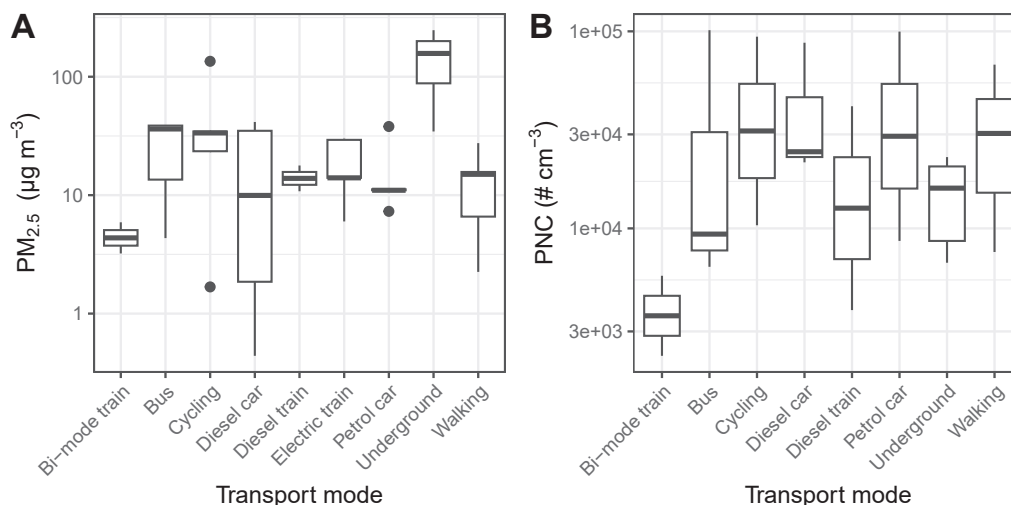


Fig. 10. $PM_{2.5}$ and PNC concentrations measured on different transport microenvironments in the UK. The list of studies used to build this graph can be found in Table S4.

braking systems. Measurements of the major health-related pollutants made inside train carriages included PM₁₀, PM_{2.5}, UFP, PNC, BC and NO₂. Each route and train class were sampled 4 to 10 times providing a robust characterization of the in-train concentrations and exposure in the UK diesel train fleet. Mean-journey concentrations ranged from 7.5 to 52 µg m⁻³ (PM₁₀), 3.9–36 µg m⁻³ (PM_{2.5}), 333–11,300 # cm⁻³ (PNC); 225–9131 # cm⁻³ (UFP); 0.6–11 µg m⁻³ (BC); 28–201 µg m⁻³ (NO₂); and 130–3456 µg m⁻³ (NO_x). The in-train concentrations varied depending on the train type, the exhaust after-treatment, the braking system, the location of the exhaust relative to the sampling location, the track gradient and whether the train was in a tunnel. Of all the elements studied, the presence of tunnels along the journey had the greatest impact. For NO₂, running on diesel mode was also a factor associated with the largest enhancements in in-train concentrations. Other architectural factors such as track gradient had an impact on in-train NO₂, PM₁₀ and UFP concentrations. The effect of outdoor air in the in-train concentrations was not clearly observed; similar concentrations were measured when the train passed over either urban or non-urban areas. However, low background concentrations in the UK, especially for PM₁₀ and PM_{2.5}, might explain the lower PM concentrations measured in the UK diesel trains compared to other trains (both diesel and electric) in other countries (Ma and Kang, 2022; Winiger, 2022). The lowest NO_x, BC, PM mass and particle number concentrations were measured on the newest train classes; the renovation of the diesel rolling stock would therefore lead to clear reductions of in-train exposure to diesel fumes and PM pollution, alongside the electrification of the railway network, which would lead to a reduction to both exhaust PM and NO₂ concentrations. The bi-mode trains fitted with SCRs did not observe the lowest NO₂ concentrations compared to the other train classes; this may be due to the SCR not reaching operational temperature following the mode switch. However, trains fitted with SCRs systems observed NO_x reductions of approximately 40 %.

Some limitations of the study included the lack of characterization of in-train concentrations of other health-relevant air pollutants such as PAHs; and the complete characterization in element and metal composition in PM for source characterization. However, state-of-the-art instrumentation for these pollutants do not include high-time resolved portable instrumentation. Additionally, the calibration of data from portable instrumentation in the same type of environment (i.e., train carriages) was not possible due to space, power and safety restrictions. The collocation of portable instruments against the reference instrumentation in a kerbside site in central London was used to approximate an environment rich in diesel exhaust.

Compared to other transport modes, exposure to PM_{2.5} and particle counts in UK diesel trains was lower than many other commuting modes. When dose was considered, despite higher concentrations in tunnels as well as in around stations, the longer periods of time spent between stations explained the largest dose that passengers received. The industry should therefore focus on air filtering and purification during the journey as the most effective way to reduce passenger exposure.

CRedit authorship contribution statement

Anna Font: Writing – original draft, Visualization, Software, Resources, Methodology, Investigation, Formal analysis, Data curation, Conceptualization. **Michael Hedges:** Writing – review & editing, Resources, Investigation, Conceptualization. **Yiqun Han:** Resources, Investigation. **Shanon Lim:** Writing – review & editing, Resources, Investigation. **Brendan Bos:** Writing – review & editing, Resources, Investigation. **Anja H. Tremper:** Writing – review & editing, Validation, Methodology, Data curation, Conceptualization. **David C. Green:** Writing – review & editing, Validation, Supervision, Software, Project administration, Methodology, Formal analysis, Data curation, Conceptualization.

Declaration of competing interest

The authors declare the following financial interests/personal relationships which may be considered as potential competing interests: The authors reports financial support was the UK Rail Safety and Standard Board.

Data availability

The authors do not have permission to share data.

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Appendix A. Supplementary material

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