

Air quality evaluation of London Paddington train station

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Abstract

Enclosed railway stations hosting diesel trains are at risk of reduced air quality as a result of exhaust emissions that may endanger passengers and workers. Air quality measurements were conducted inside London Paddington Station, a semi-enclosed railway station where 70% of trains are powered by diesel engines. Particulate matter (PM_{2.5}) mass was measured at five station locations. PM size, PM number, oxides of nitrogen (NO_x), and sulphur dioxide (SO₂) were measured at two station locations. Paddington Station's hourly mean PM_{2.5} mass concentrations averaged 16 $\mu\text{g m}^{-3}$ [min 2, max 68]. Paddington Station's hourly mean NO₂ concentrations averaged 73 ppb [49, 120] and SO₂ concentrations averaged 25 ppb [15, 37]. While UK train stations are not required to comply with air quality standards, there were five instances where the hourly mean NO₂ concentrations exceeded the EU hourly mean limits (106 ppb) for outdoor air quality. PM_{2.5}, SO₂, and NO₂ concentrations were compared against Marylebone, a busy London roadside 1.2 km from the station. The comparisons indicated that train station air quality was more polluted than the nearby roadside. PM_{2.5} for at least one measurement location within Paddington Station was shown to be statistically higher (P -value < 0.05) than Marylebone on 3 out of 4 days. Measured NO₂ within Paddington Station was statistically higher than Marylebone on 3 out of 5 days, while measured SO₂ within Paddington Station was statistically higher than Marylebone on all 3 days.

1. Introduction

UK train stations are major transport hubs servicing eight million travellers daily [1]. Train journeys within the UK are predominantly electrically powered (62% by passenger kilometres) [2], although only 41% of train tracks are electrified (0% in Wales and 3% in Western England) [3]. European standards regulating emissions of carbon monoxide (CO), unburned hydrocarbons, oxides of nitrogen (NO_x), and particulate matter (PM) for new off-road heavy duty diesel vehicles initially exempted railway engines between 1999 and 2006 at the Stage I to Stage II level of the non-road mobile machinery (NRMM) regulations [4]. From 2006, railway diesel engines were subject to the NRMM regulations (Stage III) [5]. Despite these standards, the mean age of British rail rolling stock in

2013 was 18 years [6], implying that most trains were initially deployed 11 years before EU emissions regulations took effect. As a result, diesel trains that operate in enclosed stations have the potential to emit large quantities of pollutants, leading to poor air quality and threatening the wellbeing of frequent travellers and workers. Train station air quality is also poorly documented. While researchers have studied air quality within indoor environments (railway coaches [7], residential homes [8], commercial offices [9, 10], and electrified train stations) [11–16], none have evaluated indoor stations that serve diesel trains. Air quality in parking garages that host gasoline and diesel vehicles have also previously been evaluated [17–19], but differ from train studies due to the different emissions composition of on-road vehicles. Stricter on-road vehicle emissions regulations have resulted in

the adoption of advanced exhaust aftertreatment technologies that are not present on UK trains (such as catalyzed particle filters that alter the NO₂-PM composition of unfiltered diesel exhaust). The UK Parliament has identified the potential dangers of poor air quality in indoor settings, but also noted that indoor public health standards are neither well understood nor controlled by a specific government agency [20]. To better understand the air quality inside stations serving diesel-powered trains, a measurement campaign was conducted in London Paddington Station, a semi-enclosed building that hosts a disproportionate share of the Greater London diesel train fleet. In Paddington Station, 70% of trains are powered by diesel engines (compared to 30% in Greater London). Paddington Station serves 38 million passengers annually (the seventh busiest station in Great Britain) [1] and is the terminus of the Great Western Main Line, which is the longest non-electrified line in the UK [21]. More broadly, about half of the train lines in Europe remain non-electrified with 97% of Irish, 71% of Danish, 47% of French, 41% of German, and 29% of Italian train lines running without electric power [22]. While the cumulative number of passengers exposed to diesel emissions within train stations throughout Europe is unknown, there is significant potential risk if train station air quality is poor, given the large number of stations required to serve non-electrified lines, high rail use (~6.5% of all European travel is via train compared to 0.5% US) [23], and passenger time spent within the station (>7 min per journey) [24].

Air quality inside Paddington Station has never been directly measured and publicly reported. Neville (2005) [25] measured SO₂ on a train platform immediately outside of the Paddington Station building. The study found no evidence that the area surrounding Paddington Station was in breach of national air quality standards, but suggested that concentrations inside the building could be higher than those standards even though they do not apply to indoor settings [25]. Other reports from the City of Westminster indicated that more work needs to be done quantifying the air quality inside Paddington Station given the high proportion of diesel trains that are hosted in the station [26]. There is an ongoing £6 billion effort to modernise the Great Western Main Line, which includes electrification [27]. While electrification will eliminate diesel trains and ultimately improve Paddington's air quality, the project is not expected to be completed until 2018 and could possibly be delayed even further [28]. As a result of the prevalence of diesel trains, lack of indoor regulations, and absence of study, Paddington Station is a meaningful site in which to evaluate potential air quality hazards for UK stations serving diesel trains. Study of train station air quality would provide context for challenges reported at other UK stations such as London Marylebone [29], Edinburgh Waverley [30, 31], and Birmingham New Street [32].

Air quality in Paddington Station is influenced by diesel train operation, food cooking, and indoor/outdoor air exchange. The purpose of this study is to (i) quantify indoor air quality inside Paddington Station, (ii) compare indoor Paddington Station air quality to regulated outdoor sites, and (iii) inform indoor air quality regulations and diesel train technology adoption decisions in Greater London.

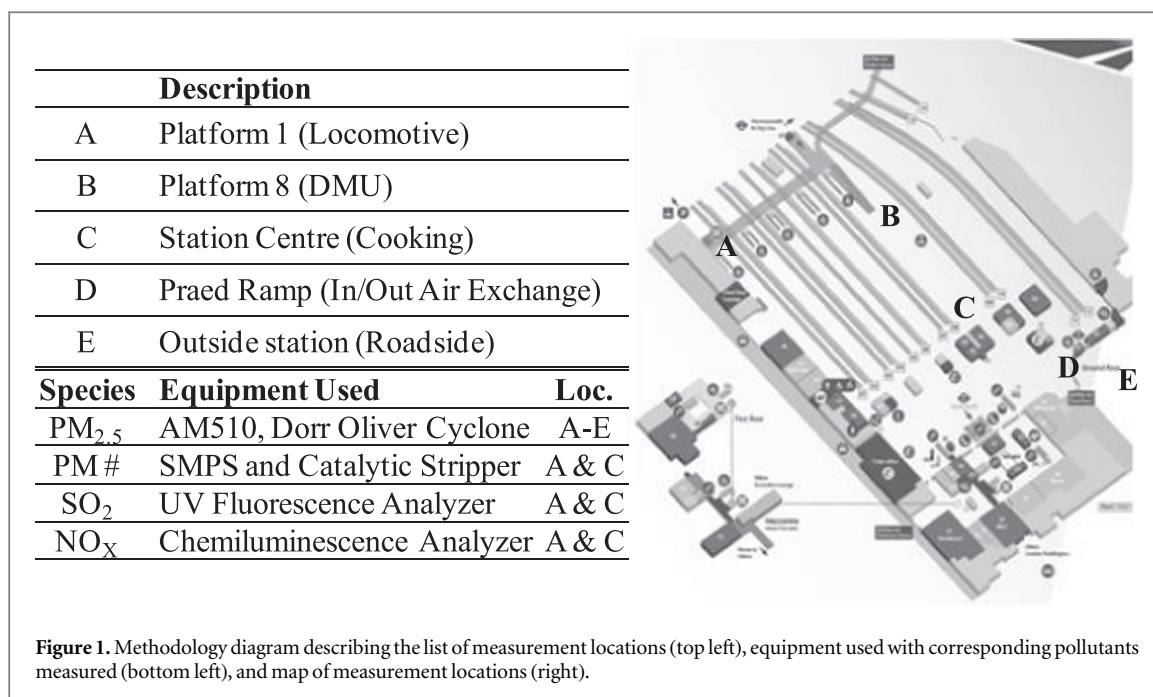
2. Methodology

2.1. Equipment and measured pollutants

Pollutants that were measured included PM (mass, number, and size), sulphur dioxide (SO₂), and NO_x. The experimental equipment and operational parameters are described below with more details included in section 1 of the supporting information (SI, available at stacks.iop.org/ERL/10/094012/mmedia). The concentration of metals (As, Ba, Be, Cd, Cr, Cu, Fe, Hg, Mo, Ni, Pb, Sb, Se, V, and Zn) and elemental to organic carbon fraction (EC/OC) of PM were also measured. These results are presented in sections 2 and 3 of the SI.

PM mass concentration was measured with a photometer (TSI Inc. SIDEPAK Personal Aerosol Monitor AM510). The AM510 was operated in series with a 10 mm Dorr Oliver nylon cyclone at 1.7 L min⁻¹, which induces centrifugal airflow to remove larger particles such as tire and road dust from outdoor traffic (50–75 μm [33]) and abrasion and wear from railway train brakes (3–25 μm [34]). The AM510 measurements were corrected using gravimetric measurements that collected in parallel to the AM510 [35]. Gravimetric measurements were sampled with a pump and a polytetrafluoroethylene (PTFE) filter (SKC Ltd). The 37 mm PTFE filter was housed in a plastic cassette with a padded spacer and connected to the pump using conductive tubing [36]. Gravimetric filters were neutralized and weighed five times each using a 10 μg mass balance before and after the samples were collected. Pumps were operated at 3.0 L min⁻¹. At this flowrate, the penetration of 2.5 μm particles (PM_{2.5}) through the Dorr Oliver cyclone was 54% [37–39].

Particle number concentrations (PNCs) were measured using a condensation particle counter (CPC, TSI 3022A). Particle mobility distributions were measured using a TSI scanning mobility particle spectrometer (SMPS) consisting of a long column classifier and 3025 CPC. Particle size distributions were also measured with and without a catalytic stripper (CS). The CS removes the semi-volatile fraction of the aerosol, which results in measurement of only solid particles [40]. The CS used in this study contained two geometrically dissimilar catalyzed ceramic substrates: an oxidizing catalyst and a sulphur trap, both heated to 350 °C. The purpose of the oxidation catalyst is to remove the semi-volatile hydrocarbon particles and vapour by oxidation. Typically, most combustion-



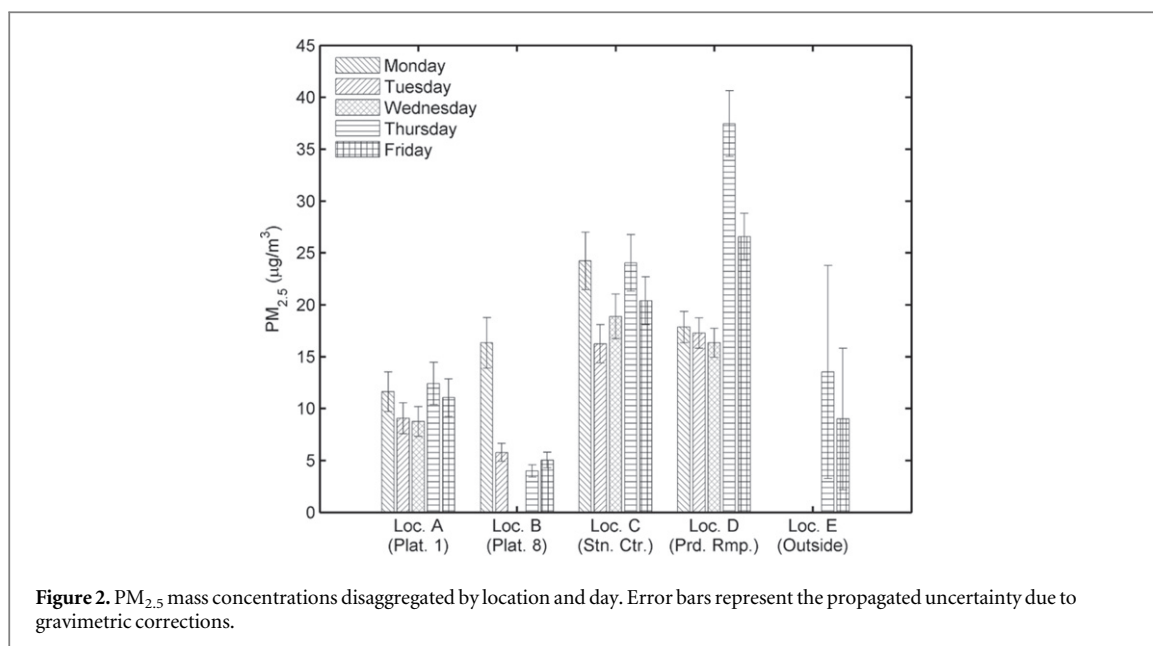
generated particles evaporate at relatively low temperatures (~ 100 °C) [41], but the CS is operated at a much higher temperature to enable catalyst functionality. The sulphur trap removes sulphur species by adsorption to prevent oxidation of species to SO₃ and subsequent sulphuric acid nucleation. Laboratory results show at the operating flowrate (1.5 L min^{-1}) and temperature, the CS removes $>99\%$ of 30 nm tetracontane particles. Results were corrected for losses in the CS, as described in section 4 of the SI [40]. SO₂ and NO_x were measured using ultraviolet (UV) fluorescence and chemiluminescence analyzers (Teledyne 100A and Teledyne 200A, respectively) that were zeroed and spanned according to manufacturer recommendations.

2.2. Measurement locations and schedule

One scoping (12 January 2012), one test (7 May 2012 to 11 May 2012), and one measurement campaign (17 September 2012 to 21 September 2012) were conducted. The scoping and test campaigns were used to establish the study methodology (location with time intervals) and equipment operational requirements. The results from the September campaign are presented. It was not possible to conduct a longer campaign because of security constraints and logistical conflicts with daily station operations. This study provides the first measurement of such a location and justifies further in-depth regulatory-style measurements, similar to the EU Ambient Air Quality Standards. Subsequent studies would not only require longer measurements, but also an evaluation of the exposure frequencies for passengers and workers. This study's duration is not unusual compared to other measurement campaigns in indoor environments,

which have lasted 2–8 days [12, 14, 42–45]. Figure 1 shows a diagram of the methodology used in the main campaign and the measurement locations selected. There were five locations where measurements were taken using both remote and continually attended equipment. Location A is next to Platform 1, which serves locomotives that travel to west England and Wales. Location B is next to Platform 8, which serves smaller diesel multiple unit (DMU) trains that travel to regions in the immediate vicinity of Greater London such as Oxford and Reading. Location C is in the centre of the station and is close to idling train emissions as well as gas food cooking. Location D is in the entry archway of Praed Ramp at the boundary of the building. Location E is at the top of the Praed Ramp completely outside of the station and next to Praed Road. All measurements were taken above ground away from Paddington's underground subway station that serves electric trains.

A schedule and methodology was developed based on scoping and pre-measurement evaluations. The remote devices (AM510 and pump) were installed ~ 3 m above ground on structural columns using ratchet straps. Station security policies limited measurement times, allowing a start time of $\sim 04:00$ and operation for the full battery life (~ 8 h), resulting in morning mean measurements ($\sim 04:00$ to 12:00). Exact measurement intervals are provided with the statistical summary of results in section 5 of the SI but are discussed as 'morning mean' in text. The continually attended equipment (gas analyzers, SMPS, CPC, and CS) were connected to external power near the locations indicated. A measurement schedule is summarized in section 6 of the SI.



2.3. Statistical testing

Measurement results were compared to time-equivalent (same hours and dates) concentrations at Marylebone Road (a busy London roadside) and North Kensington (a London urban background reference site). London data were taken from the London Air Quality Network (LAQN) database [46]. Comparisons were interpreted to a 95% confidence interval threshold (P -value < 0.05) using the Mann–Whitney–Wilcoxon (MWW) two sample test, a nonparametric statistical metric to determine the significance of the difference between independent samples. A left tailed condition was imposed to determine if published concentrations at Marylebone and North Kensington were statistically smaller than measured concentration at Locations A–D.

3. Results and discussion

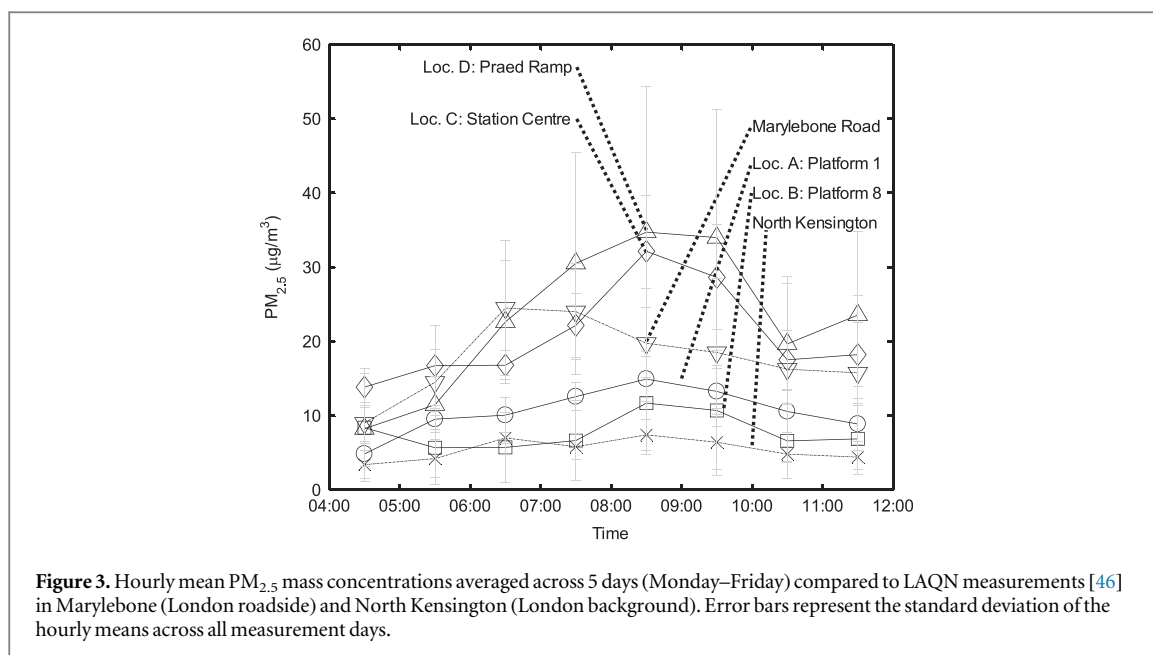
3.1. PM_{2.5} mass concentrations

Morning mean PM_{2.5} mass concentrations for each location are shown in figure 2, as determined by gravimetrically-corrected AM510 photometer measurements (correction factor methods are presented in section 1 of the SI). Daily-averaged concentrations at Locations A and B ranged from 4.0 to 16.3 $\mu\text{g m}^{-3}$, respectively. Concentrations at Locations C and D ranged from 16.2 and 37.5 $\mu\text{g m}^{-3}$, respectively. The higher PM_{2.5} mass concentrations near the terminus of the rail line and retail station area (Locations C and D) are likely the result of more emissions sources, higher train emissions, and decreased outdoor air mixing when compared to the platform locations. Locations C and D are closer to the end of the platforms inside the station and hence they are closer in proximity than other measurement sites to the idling locomotives, which makes up the vast majority

of train activity (by time). Trains are allowed to idle for a maximum of 10 min in Paddington Station. Based on this policy and station control room schedules, idling activity makes up 37.8 train-hr daily while acceleration activity was calculated to make up 1.6 train-hr daily. Using Paddington Station train specific emissions factors (g kWh^{-1}) from Silver (2007) [47] and general locomotive/DMU energy consumption factors (kWh km^{-1} and kWh h^{-1}) from Lindgreen and Sorenson (2005) [48], idling emissions were estimated to be 4 to 6 times greater than acceleration emissions in Paddington Station. The hourly profile of idling and acceleration activity is provided in section 7 of the SI.

Figure 3 shows the hourly mean PM_{2.5} concentrations averaged across all measurement days for Paddington Station and other London sites. There were peaks in morning PM_{2.5} concentrations between 07:00 and 10:00, which correspond to idling train activity that also peak at the same time (see section 7 of the SI). The peaks were more pronounced in Locations C and D, which had a maximum hourly mean of 41.3 and 68.4 $\mu\text{g m}^{-3}$, respectively, on Thursday at 08:00–09:00. This corresponds to the peak idling activity (2.5 train-hr per hour), which occurred between 08:00 and 10:00 (section 7 of the SI).

Hourly mean PM_{2.5} concentrations in Paddington Station exceeded hourly mean PM_{2.5} at Marylebone and North Kensington. At Location C, 24 out of the 36 hourly mean PM_{2.5} measurements were greater than the corresponding hourly mean PM_{2.5} measurements at Marylebone. At Location D, 23 out of the 34 hourly mean PM_{2.5} measurements were greater than the corresponding hourly mean PM_{2.5} measurements at Marylebone. All hourly mean PM_{2.5} measurements at Locations C and D were higher than their corresponding hourly mean PM_{2.5} measurements at North



Kensington. Overall, Paddington Station's hourly mean PM_{2.5} mass concentrations was $16 \mu\text{g m}^{-3}$ [min 2, max 68] across all measurement sites.

PM_{2.5} concentrations at North Kensington (London background) were statistically lower than Locations A, C, and D for all days (P -value < 0.05) and lower than Location B from Monday to Tuesday. Similarly, PM_{2.5} concentrations at Marylebone roadside were lower than Location D from Tuesday to Thursday and lower than Location C from Tuesday to Wednesday. The results of the MWW test are provided in table S2 in section 5 of the SI.

3.2. Particle number and size distributions

Figure 4 presents PNC measurements at Location A and C, which were averaged over the days that they were taken. On average, Location C had a similar PNC ($1.24 \times 10^5 \text{ cm}^{-3}$) to Location A ($1.10 \times 10^5 \text{ cm}^{-3}$). At Marylebone, Jones *et al* [49] reported the mean PNCs decreased by 41% from $8.4 \times 10^4 \text{ cm}^{-3}$ (from October 2005 to September 2007) to $3.4 \times 10^4 \text{ cm}^{-3}$ (from February 2008 to January 2009) after 'sulphur-free' diesel ($< 10 \text{ ppm}$) was implemented in 2007 [49]. These Marylebone values were lower than the Paddington Station concentrations in figure 4. However, while Paddington Station results included only measurements during peak periods in the daytime, the Marylebone results included measurements across peak and non-peak periods (days and nights).

Particle size distributions measured with and without the CS at Location A and C are shown in figure 5. All particle size distributions were unimodal with a mean diameter 61 nm [50, 68]. Figure 6 shows the hourly mean total particle concentration, mode diameter, and geometric mean diameter (GMD) at Location A and C with and without the CS averaged over the days that the measurements were taken. The

Station Centre (Location C) is influenced by a greater number and variety of emissions sources, which resulted in a larger GMD, mode diameter, and concentration. When compared across the same time range without a CS, the hourly mean total particle concentration at Location C was 59.7% [−36.5, 146.6] higher than at Location A. The use of the CS resulted in lower particle concentrations due to the removal of the semi-volatile particles. With a CS, total particle concentration was lower at Location A (2.3×10^4 – $1.0 \times 10^4 \text{ cm}^{-3}$) and Location C (3.5×10^4 – $2.0 \times 10^4 \text{ cm}^{-3}$). At Location A and C, 51% and 33% of particles smaller than 100 nm were removed, respectively. The reduction in total PNC without a significant size-shift suggests the presence of externally mixed aerosol. The removal of semi-volatile particles only slightly increased the GMD and mode to 6.9% [−4.2, 27.9] at Location C and to 12.4% [−19.4, 91.0] at Location A, respectively. Surprisingly, particle size distributions were not appreciably different in shape to those observed at Location A, even though there are potentially more sources of semi-volatile material and differences in concentration. The use of a thermal denuder operated at a range of temperatures [50, 51] or aerosol mass spectrometer would help enable source apportionment because diesel emissions have significantly different organic aerosol profiles than meat cooking emissions [52].

Size distribution measurements in both locations showed unimodal particle size distributions. These results differ from diesel engine tailpipe measurements of semi-modern engines without emission control that typically show distinct bimodal particle distributions with a nucleation mode at $\sim 20 \text{ nm}$ and accumulation mode at $\sim 80 \text{ nm}$ [53]. The nucleation mode is nearly always semi-volatile although idling engines are known to emit some solid nucleation

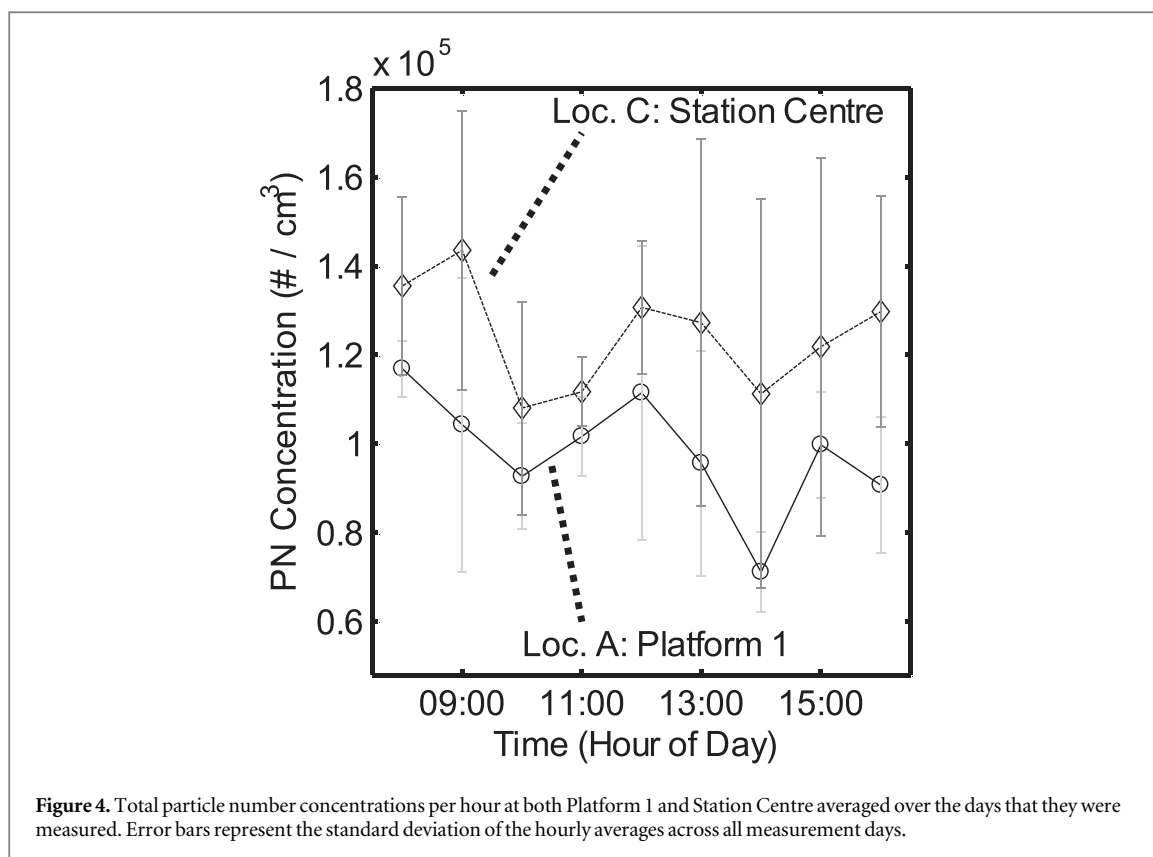


Figure 4. Total particle number concentrations per hour at both Platform 1 and Station Centre averaged over the days that they were measured. Error bars represent the standard deviation of the hourly averages across all measurement days.

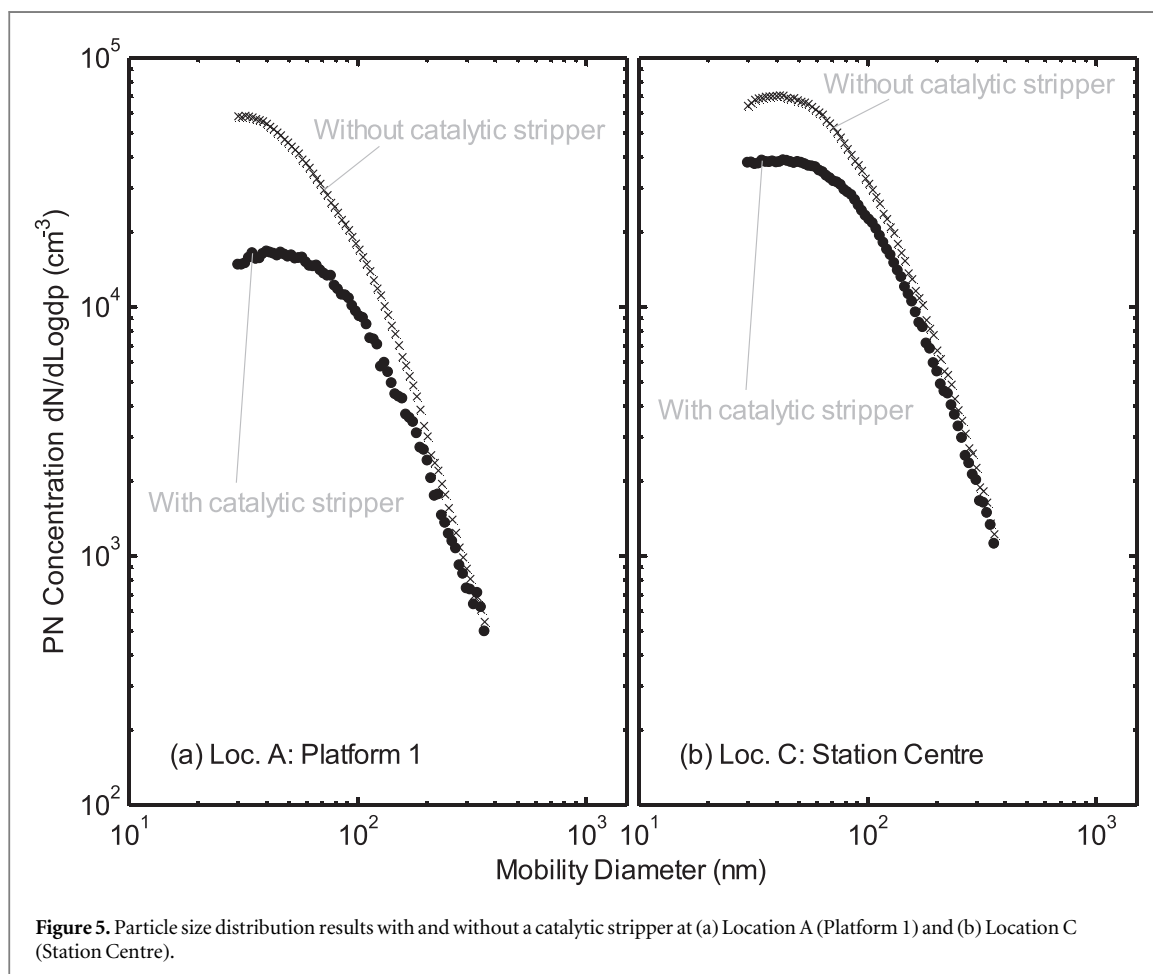
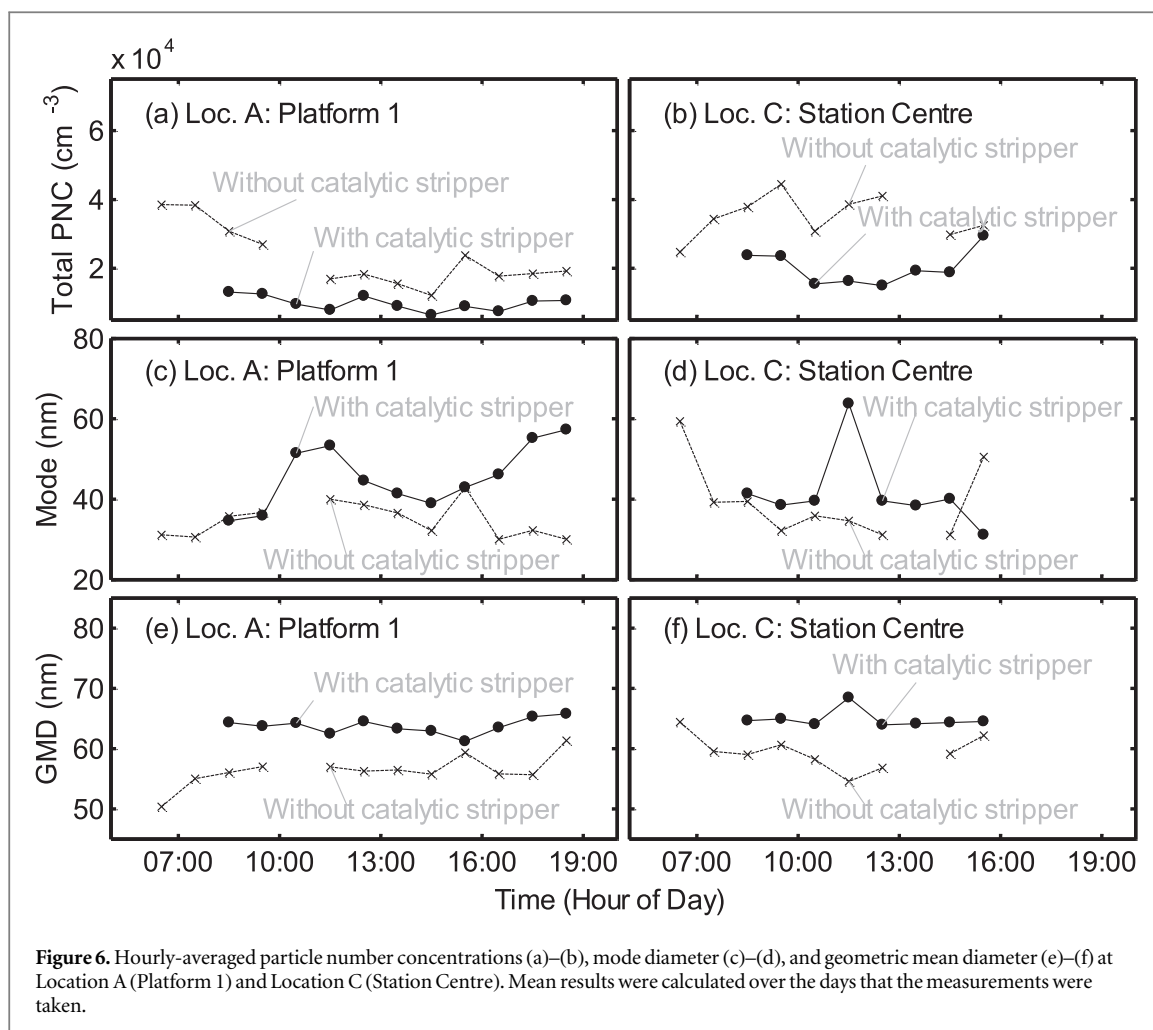


Figure 5. Particle size distribution results with and without a catalytic stripper at (a) Location A (Platform 1) and (b) Location C (Station Centre).



mode particles resulting from high lube-oil consumption at idle [54]. Without similar train tailpipe measurements, it is difficult to determine whether the measured unimodal distributions have evolved from initially bimodal distributions due to atmospheric coagulation and adsorption processes [55] or are emitted in a single mode. A possible explanation of the latter is that these train engines do not have diesel particulate filters so it is reasonable to assume that reasonably high concentrations of carbonaceous agglomerates are emitted while entering (low load condition) and exiting (high load condition) the station. These high-surface area particles tend to adsorb semi-volatile nucleation mode precursors and prevent the formation of a nucleation mode [56], even when high concentrations of semi-volatile material exist. This effect has been observed in measurements with and without a CS in laboratory evaluations of off-road engines operated at high load [57].

3.3. NO_2 and SO_2 concentrations

Figure 7(a) shows the location-averaged NO_2 concentrations compared to other London sites. North Kensington NO_2 concentrations were lowest and Location C concentrations were highest. At Location C, the hourly mean NO_2 concentrations ranged from

72 to 120 ppb. At Location A, the hourly mean NO_2 concentration values ranged from 52 to 80 ppb. Marylebone Road and North Kensington hourly mean NO_2 concentration ranges were 54–92 and 10–27 ppb, respectively. The total weeklong NO_2 mass concentrations within Paddington Station averaged 73 ppb [49, 120]. The results of the MWW analysis (table S4 of section 5 in the SI) show that on Tuesday, Wednesday and Friday, Paddington Station NO_2 concentrations were higher than Marylebone Road (P -value < 0.05). NO_2 concentrations at North Kensington were lower than Paddington Station on all measurement days. In the context of the EU hourly mean limit (106 ppb), which can only be exceeded 18 times per year, the NO_2 concentrations at Location C were not in compliance with this regulation five times in 59 h of measurements (shown in section 8 of the SI). Although EU limits do not apply within Paddington Station, it provides a point of comparison demonstrating a trend that is in line with other studies that have reported high NO_2 concentrations in other locations around London [58, 59]. The mean NO_2 fraction of NO_x was calculated to be 0.19. This is in between NO_2/NO_x mass fractions for heavy duty diesel engines with (0.24–0.54) and without (0.03–0.08) catalytic oxidation [60–62].

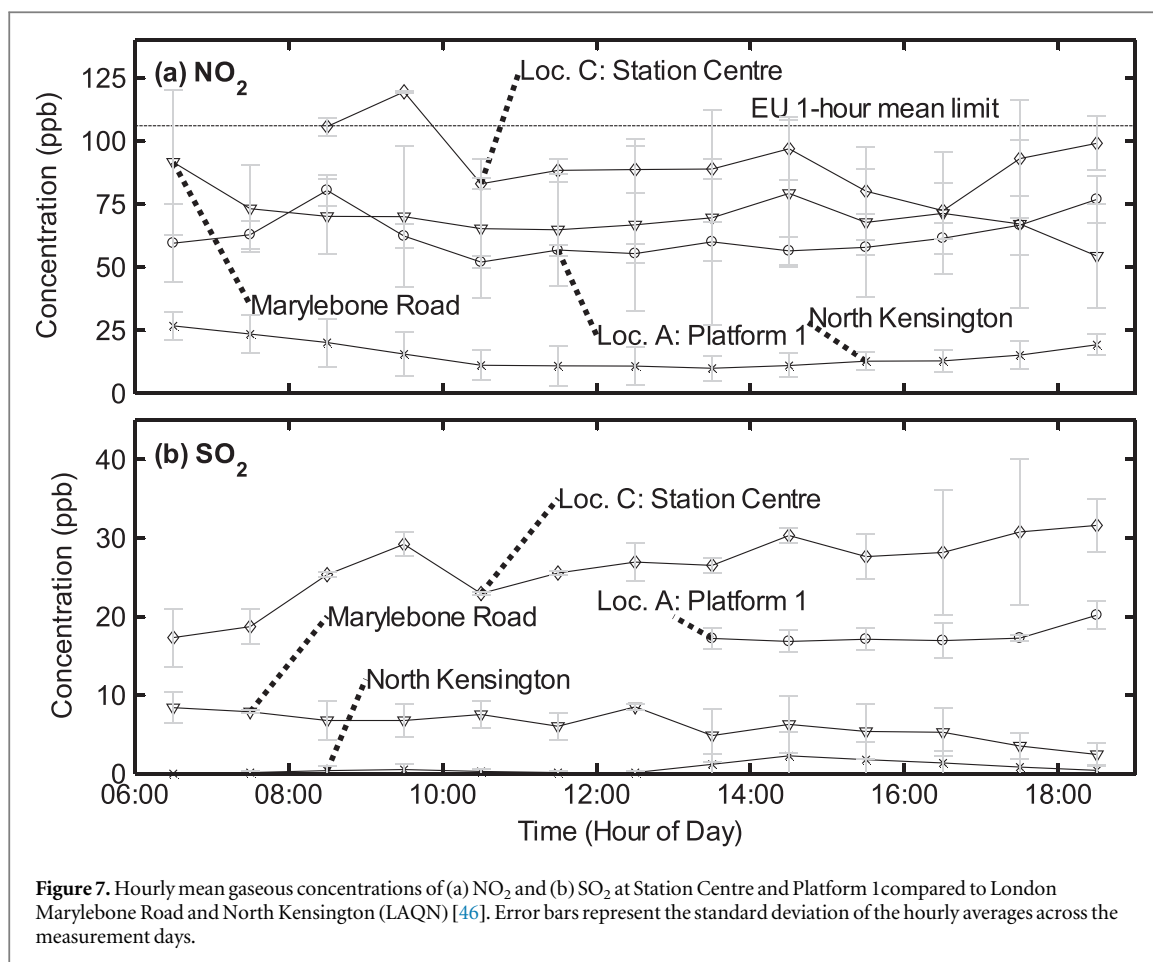


Figure 7(b) presents the location-averaged SO₂ results. At Location A on Wednesday, SO₂ hourly mean concentrations ranged from 17 to 20 ppb. At Location C, the hourly mean concentration ranges for Thursday and Friday were 15–30 ppb and 20–37 ppb, respectively. Marylebone Road and North Kensington SO₂ concentration ranges were 2–9 ppb and 0–2 ppb, respectively. The total weeklong SO₂ mass concentrations within Paddington Station averaged 25 ppb [15, 37]. The results of the MWW analysis are provided in table S5 in section 5 of the SI. On all measured days, Paddington Station SO₂ concentrations were statistically higher than Marylebone roadside and North Kensington concentrations (P -value < 0.05).

SO₂ concentrations at all locations were significantly lower than the outdoor EU hourly limit (132 ppb), which can only be exceeded 24 times per year (not enforced for train stations). SO₂ at Location A and C (15–37 ppb) were higher than Neville (2005) [25], who reported an outdoor mean SO₂ concentration of 13 ppb over 15 min averaged intervals from May–June 2004. Neville's (2005) [25] SO₂ measurements were lower because they were taken outside of the Paddington Station building where pollutant dispersion would have been greater than at Location A and C. Neville's [25] measurements were greater than concentrations at Marylebone (2–9 ppb) and North Kensington (0–2 ppb), which is partially the result of

different diesel fuel sulphur concentration limits (2000 ppm in 2004 [25] and 10 ppm in 2012 [63]).

4. Conclusions

This study has sought to determine whether a potential air quality risk exists within enclosed train stations that service passengers travelling on diesel trains. The measurement campaign revealed that particle number and mass concentrations are in range of Marylebone Road LAQN values. At Station Centre and Praed Ramp, mean PM_{2.5} mass concentrations ranged from 16.2 to 37.5 $\mu\text{g m}^{-3}$, while the Marylebone PM_{2.5} ranged from 4.0 to 36.0 $\mu\text{g m}^{-3}$. Since measurements were constrained by station security to ~8 h per day for 5 days, the regulatory implications for station PM_{2.5} are limited. However, there were instances where hourly PM_{2.5} averages at Station Centre and Praed Ramp exceeded annual average EU Ambient Air Quality Standards (25 $\mu\text{g m}^{-3}$). These results provide the first glimpse of PM_{2.5} concentrations in a train station with enclosed diesel emissions to inform the regulatory significance of PM_{2.5} concentrations. The results of the MWW analysis showed that the majority days of Paddington Station measured concentrations of PM_{2.5}, NO₂, and SO₂ were statistically higher than London Marylebone roadside and North Kensington

background values. Unlike the PM_{2.5} results, there is greater regulatory relevance for the NO₂ results because the EU legislates NO₂ by hourly mean exceedances and it was possible to capture hourly means in this study timeframe. NO₂ measurements at Station Centre exceeded outdoor EU hourly mean standards (106 ppb) five times in 59 h of measurements, even though only 18 hourly exceedances are allowed per year. Presently, Paddington Station, a semi-enclosed building, is not governed by any air quality standard. These results indicate that if comparable standards to indoor and ambient air standards are applied to Paddington Station, action would likely be needed to comply with such standards. If Paddington Station trains adopt diesel particulate filters with catalytic regeneration to meet emissions regulations (which is common with heavy duty on-road diesel vehicles), PM emissions would decrease by >90% [64]. Simultaneously, as described by Melendez *et al* [60], Ayala *et al* [61], and Lanni *et al* [62], catalytic oxidation would increase the NO₂/NO_x fraction from 0.03–0.08 to 0.24–0.54. Such an increase would likely exacerbate the already high local NO₂ concentrations shown in figure 7(a). In addition to stricter emissions standards, public exposure to diesel train emissions could be minimized by physically isolating the passenger waiting area with platform screen doors. This solution already exists in underground railway stations [65].

The measured particle size distributions within the station may be relevant to future NRMM emissions regulations. When a CS was applied to particle size measurements, total PNCs decreased by 57% and 42% at Platform 1 and Station Centre, respectively. The EU is considering the adoption of solid particle number (SPN) limits at Stage V of the NRMM standards that are in line with the particle number regulations for on-road heavy duty diesel engines at the EURO VI level [66, 67]. If SPN standards are introduced for NRMM, particle number measurement methods used in this Paddington Station measurement campaign (SMPS + CS) can be implemented to evaluate the air quality impacts of such standards.

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