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Analysing the impact of diesel trains on air quality in a semi-enclosed railway station through mixed monitoring methods and XGBoost modelling

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ABSTRACT

This study assessed air quality in a semi-enclosed train station using both personal and fixed monitoring and applied eXtreme Gradient Boosting (XGBoost) modelling to identify key factors influencing pollutant levels. The investigation also examined the effects of train idling time and engine speed on fuel consumption and pollutant emissions. Personal monitoring showed the average $PM_{2.5}$ concentrations of 17–137 μg/m^3 during active train operations, with higher levels observed in enclosed platforms and when diesel multiple unit (DMU) trains were present. Continuous fixed monitoring captured 24-h average concentrations of 3.18–32.56 μg/m^3 for $PM_{2.5}$, with DMU-dominated platforms exceeding WHO $PM_{2.5}$ limits during 90% of the monitoring period. The 24-h average NO_2 levels ranged from 135.6 to 169.8 μg/m^3, with 11–15% of hourly values in a month exceeding the EU hourly limit. The XGBoost model demonstrated a moderate fit (RMSE: 15.12 μg/m^3, R^2: 0.61) and identified ambient temperature and average train idling time as the most influential predictors of NO_2 levels. Partial dependence analysis indicated that reducing average idling time by 2 min could reduce NO_2 concentrations by approximately 2.5 μg/m^3 per train. Operational analysis suggests shutting down engines when the next operation is more than 30 min, restarting them 15 min before departure, and maintaining idle speeds below 600 RPM. These measures could save over 7,000 L of diesel per month, reduce fuel consumption by 40–45%, and lower NO_x and PM emissions by around 54%, offering actionable strategies to improve station air quality.

1. Introduction

Poor air quality is one of the biggest risks to public health globally and is known to worsen pre-existing health conditions such as cardiovascular and respiratory diseases. Approximately 99% of the global population lives in areas where air quality levels exceed the limits set by the World Health Organization (WHO, 2022). It is estimated that 4.2 million premature deaths were linked to exposure to outdoor air pollution worldwide in 2019 (WHO, 2022). Despite significant efforts to reduce emissions across various anthropogenic sources, the transport sector continues to be a major contributor to elevated pollution levels in urban environments (Zhu et al., 2021). While much attention has been focused on reducing vehicle emissions at the urban scale, air quality in transport hubs such as ports, bus terminals, and train stations are likely to be concentrated locations for pollution, and a lack of literature suggests that air pollution in these potential hotspots is poorly understood (Priyan et al., 2025).

Understanding urban form and the contribution of pollution between different sources is important to inform decision making for recommending pollution mitigation measures that protect human health (Hassan et al., 2020; Jin et al., 2024a; Kumar et al., 2019). In particular, studies focusing on transport hubs like train stations are important, as they represent point sources within cities that affect large numbers of the urban population on a daily basis (Priyan et al., 2024). Local environmental conditions e.g. wind direction, are recognised to affect the dispersion of nitrogen dioxide (NO_2) and additional resuspension of $PM_{2.5}$ in urban settings, at both street- and city-level scales (Linda et al., 2025; Priyan et al., 2024; Gallagher, 2016). In addition to the

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environmental factors, the distinct urban morphological context in the built environment plays a role (Augusto et al., 2025; Jiang et al., 2021; Jin et al., 2024b).

While air quality in Ireland is generally good compared to other European countries, it's capital city Dublin has still promoted a recent 2021 city level Air Quality Plan to address pollution as an exceedance in NO_2 was observed in 2019 (Dublin City Council, 2021). Recent research has reported increased short-term admission for respiratory and cardiovascular diseases due to poor ambient air quality (Quintyne & Kelly, 2023). In comparison to other transport modes, the rail sector contributes a relatively small share to national transport emissions in Ireland (approximately 1%) (Energy Ireland, 2023). However, it is a major contributor to air pollution hotspots, particularly in the railway stations, due to the use of diesel-powered trains. Railway stations in Ireland present a unique case study within the European context because of their roofed design with enclosed platforms that host a large proportion of diesel-powered trains and function without any active mechanical ventilation systems. Although the public typically spends only a limited amount of time at train stations, exposure to high levels of pollution over short periods can still have a significant impact on their health. In contrast, rail staff are likely to face a much higher health risk due to their prolonged occupational exposure, when spending a significant amount of time within the station environment.

The concentration of air pollutants in railway stations hosting diesel trains are greatly influenced by internal sources (Hickman et al., 2018). These include: gas and particle emissions from diesel-powered train exhaust, particularly elevated during activities such as arrival, departure and idling; particles generated from the mechanical wear and tear of rails and trains wheels; and emissions from on-station food outlets (Chong et al., 2015; Font et al., 2020). Among these sources, train idling is a significant contributor to pollutant emissions within the station (RDG, 2021). Trains typically idle their engines to maintain onboard electrical and pneumatic systems (RDG, 2021). However, excessive idling leads to inefficient fuel consumption, resulting in higher operational costs and increased carbon and pollutants emissions (RSSB, 2026).

Research on air quality in ground-level train stations remains limited (Priyan et al., 2025). While numerous studies have examined air quality in subway systems, focusing on PM_{10}, $PM_{2.5}$, and ultrafine particle concentrations (Grana et al., 2017; Kim et al., 2008; Passi et al., 2021; Vilcassim et al., 2014). These studies, all conducted in the UK, include investigations at Birmingham New Street (Hickman et al., 2018), London Paddington (Chong et al., 2015), Edinburgh Waverly and London King's Cross (Font et al., 2020). At London Paddington, mean hourly $PM_{2.5}$ and NO_2 ranged from 16.2 to 37.5 μg/m^3 and 52 to 120 ppb, respectively. Hickman et al. (2018) found that NO_2 concentrations at Birmingham New Street were the highest as compared to other studies, with values of between 170 and 407 μg/m^3, and a maximum hourly concentration of 2020 μg/m^3, while average $PM_{2.5}$ over the monitoring period varied between 29 and 42 μg/m^3, with a maximum hourly average of 180 μg/m^3. The findings from Edinburgh Waverly and London King's Cross observed NO_2 and $PM_{2.5}$ levels ranged between 53.2 and 103 μg/m^3 and 11.5 to 14.5 μg/m^3 respectively, over the measurement period (Font et al., 2020). The study also investigated the influence of train numbers, rolling stock type and meteorological variables on NO_2 and $PM_{2.5}$ levels using random forest models. This highlighted that NO_2 is strongly associated with diesel trains, while $PM_{2.5}$ is dominated by background concentrations.

Several studies have recommended mitigation strategies such as improved ventilation, reduced idling time, the use of diesel particulate filters with catalytic regeneration, scheduling diesel trains in open areas of the station, installing platform screen doors to minimize public exposure, and electrifying trains as a long-term solution (Chong et al., 2015; Font et al., 2020; Hickman et al., 2018). These studies solely adopted continuous fixed monitoring and reported monthly and hourly pollutant levels as part of their analysis. While they assessed the influence of train traffic and meteorological conditions on pollutant levels, they did not examine the impact of train idling time on pollutant levels.

This study aims to assess air quality using both personal and fixed monitoring, and to identify the factors dominating elevated pollutant concentrations at Connolly railway station, a busy city centre train terminal in Dublin, Ireland with seven platforms facilitating cross-city and inter-city trains. The study was designed in sequential phases, whereby findings from the initial short-term monitoring campaign informed the selection of the platform for the subsequent long-term fixed-site monitoring. Personal monitoring was initially carried out to evaluate commuter exposure to $PM_{2.5}$ concentrations on the platforms during periods of train idling, arrivals, and departures for different rolling stock and platforms. The second phase consisted of a month-long measurement campaign of $PM_{2.5}$ and NO_2 concentrations to assess the spatiotemporal variability of these pollutants and to identify the most polluted platform for long-term monitoring. A modelling approach was then applied to the long-term measurements to characterise the impact of train idling, along with other contributing factors such as train frequency and ambient conditions, on NO_2 levels within the station. Furthermore, the effects of idling duration and engine speed on fuel consumption, as well as NO_x and PM emissions, were analysed to evaluate potential measures for reducing source emissions. The impact of this study will help to identify the dynamic air quality conditions occurring within this transport hub, and this can inform the design of mitigation strategies to reduce pollution in the station.

2. Overview of the study

This study integrates multiple monitoring components and was conducted in sequential phases.

i) **Device Performance Evaluation:** The performance of the monitoring devices used in this study was first evaluated against data from the EPA fixed monitoring station to assess accuracy and reliability.
ii) **Phase I – Personal Exposure Monitoring:** Personal monitoring was conducted to obtain high-resolution $PM_{2.5}$ data for assessing commuter exposure over short sampling periods. Measurements were performed across different platforms and train services to capture spatial and operational variability in exposure levels.
iii) **Phase II – Identification of Vulnerable Platforms (A month pilot study):** To identify the most polluted platform, a one-month pilot study was conducted using NO_2 diffusion tubes and $PM_{2.5}$ monitors. Based on these results (descriptive statistics), the most vulnerable platform was selected for continuous long-term monitoring to facilitate a focused investigation of the factors contributing to elevated pollutant levels.
iv) **Phase III – Long-term Monitoring and XGboost modelling:** XGboost modelling techniques were applied to the long-term hourly monitoring data from the identified vulnerable platform to evaluate the influence of train idling, train frequency, traffic intensity, and ambient conditions on NO_2 concentrations.
v) **Emission and Operational Analysis:** Finally, the effects of engine idling duration and idling speed on fuel consumption, as well as NO_x and PM emissions, were analysed to assess potential mitigation measures aimed at reducing source emissions.

3. Methods

3.1. Site description

Connolly Station, located on Amiens Street in Dublin city centre, is one of Ireland's busiest railway hubs in the country's capital. The Station is located within a densely developed urban area, with office buildings, residential properties, and commercial premises situated within 30 m of the station. The station serves approximately 12,260 commuters daily. In addition to regular commuters, the surrounding area accommodates a significant population of residents and employees, who live and work near the station. The station is semi-enclosed and comprises seven platforms, accommodating both terminus and through tracks aligned in a north-east & south-west direction (Fig. 1). Platforms 2 to 4 are partially enclosed, with major portions of the platforms are placed under an enclosed triangular glazed roof, which is ventilated passively at the roof peaks (Fig. 1). Platform 1 is open, located outside the enclosed glazed roof, and shares its platform with Platform 2.

Platforms 1 to 4 serve as terminus tracks. In contrast, Platforms 5 to 7 are open and serve as through tracks. Platforms 6 shares its platform with Platform 7. The primary external opening for enclosed Platforms 2 to 4 is located where trains enter and exit the station. Additional openings include pedestrian access points at Platform 2 to the east connecting to the parking area, and at Platform 4, providing access to Platform 5. Trains stationed at enclosed Platforms 1 to 4 are powered by diesel engines. Platforms 5 to 7 accommodate both electric and diesel trains, though they predominantly serve electric trains that connect to suburban areas of Dublin. Connolly Station operates approximately 229 diesel services per weekday and 141 and 107 diesel services on Saturday and Sunday, respectively. Additionally, the station handles approximately 200 electric services every weekday as a through station, via their outdoor platforms.

3.2. Measurement campaign

3.2.1. $PM_{2.5}$ monitoring

3.2.1.1. Personal monitoring. Personal monitoring was conducted to assess short-term $PM_{2.5}$ exposure experienced by commuters during train idling, arrival, and departure at the station. $PM_{2.5}$ concentrations were measured using the real time aerosol monitor (SidePak AM520, TSI Inc., Shoreview, MN, USA). The SidePak uses a laser photometer to measure particulate mass concentrations with a resolution of 1 s. Sampling was carried out from 10 October 2022 to 13 December 2022. Six to seven samples were collected at each enclosed (Platform 2 & 4) and open platform (Platform 5 & 6/7), with three to four samples taken in the morning and evening on different weekdays. Sampling was conducted at the central sections of the platforms near the seating areas. Each sampling session lasted 20 min. Morning sampling (10–11 a.m.) was carried out during periods of low train traffic to assess concentration patterns for different train types when only one train was present on the platform where measurements were taken. Evening sampling (5–7 p.m.) was conducted during peak hours to evaluate concentrations when train traffic was high on the platforms. In addition to $PM_{2.5}$ measurements, observations such as train type and the timing of train arrivals and departures were also recorded. In each sample, concentrations corresponding to different train activities were averaged. Prior to sampling, the instrument was calibrated with emery oil calibration standard, and the photometric calibration factor was determined and adjusted in accordance with ISO 12103-1, A1 test dust.

3.2.1.2. Continuous fixed $PM_{2.5}$ monitoring (pilot study). Continuous fixed monitoring of $PM_{2.5}$ were collected out using the Elichens ELOS Outdoor Station (https://www.elichens.com/) from 15th August to 21st September 2023. These devices operated using the light-scattering principle to measure pollution concentrations. The devices were co-located with EPA continuous monitoring stations before (Ringsend (17 days)) and after (Pearse Street (11 days)) their installation at the train station to test the accuracy of the devices (Fig. S1 in Supplemental Material (S.M.)). Ringsend and Pearse Street were two urban air quality monitoring stations in Dublin city, representing two urban traffic or roadside conditions (Perillo et al., 2022). The devices recorded $PM_{2.5}$ concentrations at 20-min intervals, however, for analysis purposes, the data were averaged hourly. Following the completion of the co-location exercise, the devices were installed at Platforms 2–4, 6/7, and in the Concourse area of Connolly train station. On each platform, the PM devices were positioned approximately halfway along the platform length. This device also recorded hourly temperature data to supplement the analysis.

3.2.2. NO_2 monitoring

3.2.2.1. Diffusion tubes (pilot study). The measurement of NO_2 in the platforms were made using Palmes-type passive diffusive tubes (PDTs) from 15 August to 21 September 2023. The tubes were exposed for five weeks at 18 locations in the station. A set of diffusion tubes were co-located alongside an EPA station air quality monitoring site (St. John's Road) (Fig. S1 in S.M.), the diffusion tubes results were compared with EPA NO_2 gas analyser and a correction factor was determined using the well-established DEFRA bias adjustment tool (DEFRA, 2011). The correction factor (0.89) is then multiplied with all the diffusion tubes values to obtain the adjusted results.

3.2.2.2. Long term continuous fixed NO_2 monitoring. The continuous fixed NO_2 monitoring was carried out in middle of Platform 4 for a period of 90 days, from 01 March to 31 May 2024. This location on

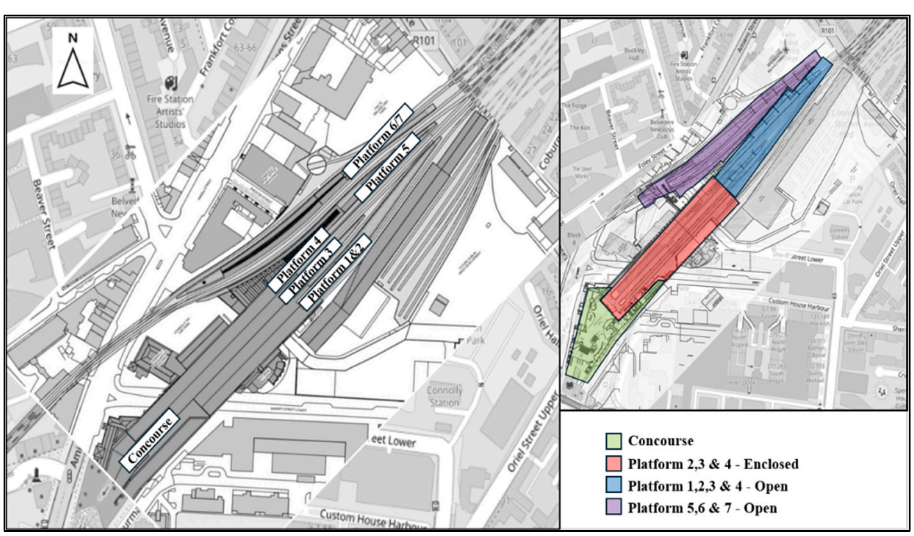

Fig. 1. Layout of Connolly train station located in the city centre of Dublin, Ireland.

Platform 4 was chosen as it was identified with high NO_2 levels (based on the diffusion tubes results). NO_2 was measured continuously using an NO_2 monitor (https://www.sonitussystems.com/) which employs an electrochemical sensor to measure NO_2 concentrations in a 1-min resolution. However, for analysis purposes, the NO_2 readings were hourly averaged. Similar to the $PM_{2.5}$ monitoring activity, the NO_2 monitor was co-located with the Pearse street EPA air quality monitoring station for 10 days to determine the adjustment factor before installing it into the station. Additionally, a diffusion tube was installed alongside the NO_2 monitor each month to evaluate its monthly average performance. Overview of the all the measurements carried out in the study is presented in Table S1 of S.M.

3.3. Additional data resources

3.3.1. Meteorology data

A weather station (HOBO U30, Onset Computer Corporation, MA, USA) was installed in the open end of Platform 2 to record outdoor meteorological parameters for a period of one month (01 to 31 March 2024). The weather station was moved to the enclosed Platform 4 and installed along with the continuous NO_2 monitoring from 01 April to 31 May 2024. Data were collected at a 5-min resolution and subsequently averaged to hourly values for analysis.

3.3.2. Train operational data

Information on train traffic, idling duration, engine idling speed, engine power, and fuel consumption were obtained from Irish Rail for the abovementioned period. Irish Rail operates two types of diesel trains at Connolly: Diesel Multiple Units (DMUs), where engines are incorporated into the carriages and multiple exhausts are found along the length of the train, and push-pull trains, where the train is operated by a locomotive at the front.

3.4. Statistical analysis

The increment of the station concentration over the background level was used to quantify the contribution from internal sources, similar to the approach adopted by (Lenschow et al., 2001). The method assumes that station background concentration is similar to the outside background. In this study, we used data from an EPA monitoring station located on Amiens Street, directly outside Connolly Station, as the outside background. This EPA monitoring station is classified as a traffic site. This station offers lower uncertainty at high time resolution, as both the railway station and the outside background are influenced by the same localized variations.

The study adopted the eXtreme Gradient Boosting (XGBoost) algorithm to evaluate the impact of various factors, including ambient conditions, train idling, and train traffic on NO_2 concentrations. XGBoost is an ensemble model that employs the boosting technique and is commonly used in the literature for predicting air quality and calibrating low-cost sensors (Le et al., 2025; Li et al., 2022; Qian et al., 2024). The model was evaluated using the k-fold cross-validation approach, where the dataset was divided into k folds. The model was trained and tested k times, with a different fold used as the validation set in each iteration. The RandomizedSearchCV function was used to optimize the model's hyperparameters. The analysis was performed using the Python libraries scikit learn and XGBoost to implement regression.

The dataset included hourly NO_2 concentrations (measured from 01^{st} April to 31 May 2024), adjusted by subtracting urban background NO_2 levels, as the response variable. The explanatory variables consisted of meteorological data (hourly wind speed in m/s and temperature in °C), as well as operational factors such as hourly train traffic, fuel consumption and average train idling time with the engine running. The models were trained using 1,440 data points, with 20% of the data reserved for testing, using a random state of 42 and 5-fold cross-validation. For each fold, the trained models were evaluated on the test dataset using performance metrics including Root Mean Squared Error (RMSE) and the Coefficient of Determination (R^2). These metrics were averaged to derive the final evaluation scores for the model. Additionally, a Partial Dependence Plot (PDP) was used to understand the marginal effect of each explanatory variable on the model's output, while averaging out the influence of all other variables. XGBoost regression was not performed for $PM_{2.5}$ due to the unavailability of train activity data.

3.5. Fuel consumption & associated emissions

The effect of idling time and idling engine speed on fuel consumption and NO_x and PM emissions, was analysed. Hourly NO_x and PM emissions during idling were estimated based on engine output power and idling duration, as presented in Equation (1):

$$Emission_{pollutants} = \sum_{i=1}^{N} P_i \times ID_i \times EF_i \qquad \text{Equation (1)}$$

where N is the total number of trains in an hour, P_i is the engine output power of each train(kW), ID_i is the idling time of each train (hr), EF_i is the emission factor (g/kWh). EU Stage IIIA railcar emission factors corresponding to the output power range less than 130 kW were used, as the engine power of the train during idling was found to fall within this range (EU, 2024).

4. Results & discussion

4.1. Performance of $PM_{2.5}$ and NO_2 devices

Performance statistics of the devices prior to monitoring activities are shown in Table 1. Performance statistics (R^2 and RMSE) and adjustment factors for $PM_{2.5}$ were calculated by combining data from both the Ringsend and Pearse EPA stations. A strong agreement was observed among ELOS $PM_{2.5}$ devices, with inter-device correlations

Table 1
Performance statistics and adjustment factors of the air pollution monitoring devices.

$PM_{2.5}$ devices inter site performance (coefficient of variation, CV = σ/μ) (Campaign from 4th to 17th May 2023 and 24th September to 4th October 2023)			
		Ringsend	Pearse
Device A		1.3	1.2
Device B		1.2	1.3
Device C		1.1	1.32
Device D		1.1	1.22
Device E		1.4	1.19
$PM_{2.5}$ device with EPA continuous air quality station (Campaign from 4th to 17th May 2023 and 24th September to 4th October 2023)			
	R^2	RMSE	Adjustment factor
Device A	0.79	2.7 μg/m^3	0.74x+2.6
Device B	0.82	2.4 μg/m^3	0.79x+2.5
Device C	0.87	2.3 μg/m^3	0.77x+2.51
Device D	0.83	2.6 μg/m^3	0.77x+2.62
Device E	0.8	2.4 μg/m^3	0.78x+2.56
Personnel $PM_{2.5}$ monitor with Electrospray Aerosol Generator (TSI)			
SidePak $PM_{2.5}$ device	0.99	0.04 mg/m^3	1.02
NO_2 device with EPA continuous air quality station (16th to 26th February 2024)			
Device 1	0.71	19.3 μg/m^3	1.14
NO_2 device with diffusion tubes values			
		Error	
March 2024	-	4.7 μg/m^3	-
April 2024	-	4.4 μg/m^3	-
May 2024	-	4.5 μg/m^3	-

ranging from $R^2 = 0.96$ to 0.98 and low measurement errors between 0.9 and 1.6 μg/m^3 (Fig. S2 in S.M.). All devices also demonstrated good inter-site consistency, with coefficients of variation (C_V = SD/mean) ranging from 1.1 to 1.4 at the Ringsend site and from 1.2 to 1.32 at the Pearse Street site (Table S2 in S.M.). C_V value greater than 1 is common in low-cost air quality devices, as higher measurement noise is typically observed at lower concentrations. Furthermore, the devices effectively captured relative values compared to the EPA station readings, with R^2 values ranging from 0.8 to 0.86 and errors between 2.3 and 2.7 μg/m^3 (Table S3 in S.M.). However, the devices consistently reported zero values when the reference concentration was below 3 μg/m^3 and were more effective in capturing higher concentrations (Fig. S3 in S.M.).

Similarly, the NO_2 device showed good consistency with EPA station measurements, with an R^2 value of 0.71 and an error of 19.3 μg/m^3 (Fig. S4 in S.M.). Linear adjustment factors were applied to adjust the values for both $PM_{2.5}$ and NO_2 (Table 1). After adjustment, the $PM_{2.5}$ measurements from the ELOS exhibited C_V values (0.73–0.8) close to those of the EPA reference station (C_V = 0.71-0.74) (Table S2 in S.M.). Similarly, after applying the NO_2 adjustment factor, the monthly averaged NO_2 concentrations demonstrated strong agreement with the diffusion tube results, with an average error of 4.53 μg/m^3. The overview of the PM, NO_2 and meteorological monitoring results are presented in Tables S4 and S5 of S.M.

4.2. Personal $PM_{2.5}$ concentrations for different train types and platforms

Personal monitoring on the enclosed platforms revealed significantly higher $PM_{2.5}$ concentrations during train activities. The average concentrations reported here represent the $PM_{2.5}$ levels measured over the duration of each specific train activity (i.e., idling, arrival, and departure), and the ranges given correspond to the averages observed on different days for each activity. During the morning hours, when only one train was present at the station, the average $PM_{2.5}$ concentrations during DMU train idling (calculated over the idling duration) ranged from 26 to 55 μg/m^3. When a DMU train departed and completely exited the station, the average $PM_{2.5}$ concentrations ranged from 86 to 101 μg/m^3. During train arrival at the platform, the average $PM_{2.5}$ concentrations ranged from 71 to 75 μg/m^3. An example of the typical trend in concentrations observed at Platform 4 during idling and departure of a DMU train is presented in Fig. 2. In comparison, during the idling of a push-pull train, average $PM_{2.5}$ concentrations ranged between 17 and 35 μg/m^3. When a push-pull train departed and completely exited the station, concentrations increased to 42–54 μg/m^3, while during train arrivals at a platform, average concentrations ranged from 22 to 24 μg/m^3. Average $PM_{2.5}$ concentration during train idling, arrival, and departure at different platforms are given in Tables S6–S9 in S.M.

During the evening, when multiple trains were idling simultaneously at the enclosed platforms, average $PM_{2.5}$ concentrations ranged from 62 to 72 μg/m^3 on platforms with DMU trains and 35–41 μg/m^3 on platforms with pull-push trains. During train arrivals and departures, average concentrations increased to 84–137 μg/m^3 for DMU platforms and 38–59 μg/m^3 for pull-push platforms.

The open platforms (Platforms 5–7) at the station accommodate both electric (predominantly) and diesel trains, where trains typically idle for a short duration (1–5 min). During the morning hours, the average $PM_{2.5}$ concentrations on these platforms, when a DMU train was present, ranged from 23 to 34 μg/m^3 averaged across arrival, idling, and departure periods. These concentrations indicate that when DMU trains operate on open platforms, commuter exposure is substantially lower compared to enclosed platforms. When an electric train was present, the average concentrations ranged from 15 to 41 μg/m^3 across arrival, idling, and departure periods.

During the evening hours, when diesel trains were present on the enclosed platforms, the average $PM_{2.5}$ concentrations on the open platforms ranged from 19 to 62 μg/m^3. The high concentration in open platforms during evening hours are likely due to the influence of emissions from the adjacent enclosed platforms. In the absence of train activity, concentrations were substantially lower, ranging from 4 to 9 μg/m^3. On the open platforms during the evening hours, diesel trains were associated with higher $PM_{2.5}$ concentrations (47–62 μg/m^3) compared to electric trains (19–31 μg/m^3). There is a clear decrease in $PM_{2.5}$ concentrations after the departure of the trains, which is attributed to train-induced airflow (piston effect) (Fig. S5 in S.M.).

4.3. Continuous $PM_{2.5}$ concentrations

The 24-hr average $PM_{2.5}$ levels in the station, measured using ELOS devices, ranged from 3.2 to 32.6 μg/m^3, with elevated concentrations observed on enclosed Platforms 3 and 4 (Fig. S6 in S.M.).

The 24-hr average $PM_{2.5}$ on enclosed Platform 2 ranged from 7.8 to 16.0 μg/m^3. The 24-h average concentrations of $PM_{2.5}$ on enclosed Platforms 3 and 4 ranged from 10.7 to 51.1 μg/m^3 and 9.7 to 58.7 μg/m^3, respectively. The 24-h average $PM_{2.5}$ concentration exceeded the WHO 24-h limit of 15 μg/m^3 during 90% of the monitoring period on platform 3 & 4. The high concentrations on these platforms are attributed to the operation of DMU trains. In contrast, lower 24-hr averages of $PM_{2.5}$ ranging from 3.18 to 7.89 μg/m^3 were observed on Platforms 6/7, which are open and predominantly serve electric trains. The 24-hr

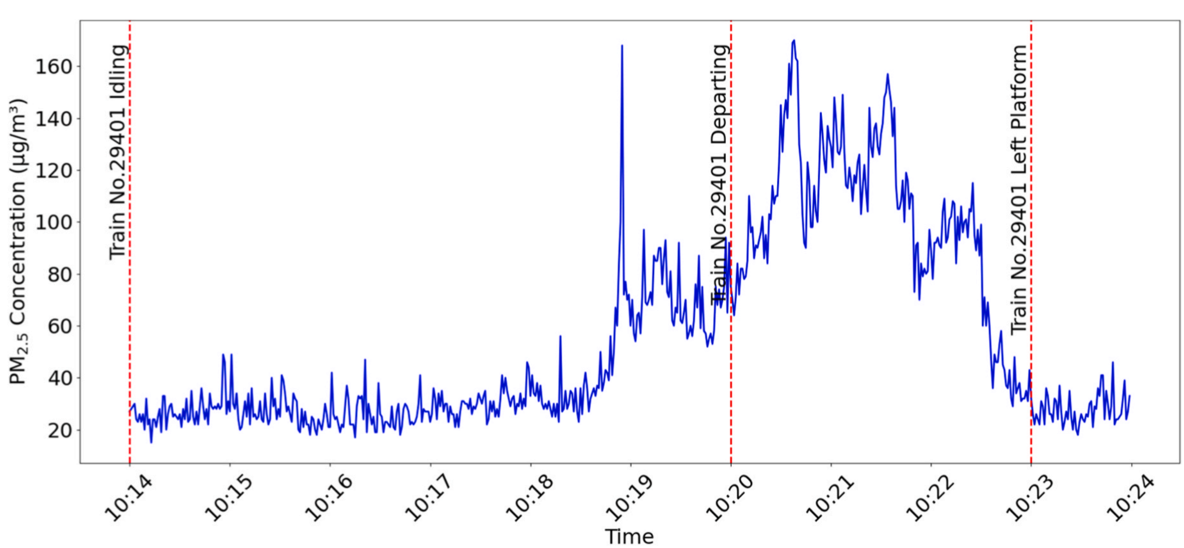

Fig. 2. Profile of PM2.5 concentrations measured on Platform 4 on Tuesday 13 December 2022, when Diesel Multiple Units (DMUs) are in operation.

average $PM_{2.5}$ in the Concourse area ranged from 3.3 to 7.78 μg/m^3 and rarely exceeded the WHO 24-h guideline values. The diurnal variation of $PM_{2.5}$ showed higher concentrations during periods of low train traffic, which can be attributed to the longer idling times of trains. The $PM_{2.5}$ concentrations were also observed during non-service hours (12 a.m. to 4 a.m.), when train engines remain running to supply heating and lighting required for cleaning and maintenance activities (Fig. S7 in S. M.). Additionally, $PM_{2.5}$ concentrations on weekdays were slightly lower than those observed on weekends, possibly associated with the longer idling times of the trains (Fig. S8 in S.M.). The scatter plot of $PM_{2.5}$ averaged over the diffusion tube NO_2 exposure period of all measured locations revealed stronger correlation between the NO_2 and $PM_{2.5}$, ($R^2 = 0.91$, $p < 0.001$). This suggests that both $PM_{2.5}$ and NO_2 share common sources, primarily from diesel emissions (Fig. S9 in S.M.).

Though the 24-hr average $PM_{2.5}$ levels in the enclosed platforms were only slightly above WHO limits, the personal monitoring showed very high short-term concentrations when trains are actively engaged in the platforms. Even brief exposure to such elevated levels can pose short-term health risks, particularly in enclosed or poorly ventilated areas.

4.4. Variation of NO_2 across station

Fig. S10 in S.M. shows the spatial distribution of NO_2 concentrations measured using diffusion tubes at the station. Average NO_2 concentrations varied significantly between the enclosed and outdoor platforms. On the enclosed platforms, concentrations during the measurement campaign ranged from 83.0 to 162.7 μg/m^3, with particularly high levels observed across the full length of the enclosed Platform 4.

In contrast, NO_2 concentrations on the open platforms ranged from 40.5 to 71.5 μg/m^3, with elevated levels observed at the open end of Platform 3. Concentrations in the Concourse area and station entrance ranged from 63 to 68 μg/m^3 and 56 to 59 μg/m^3, respectively. All fixed monitored locations across the station exceeded the EU annual NO_2 limit of 40 μg/m^3.

4.5. Continuous NO_2 concentrations

The 24-hr average NO_2 concentrations at enclosed Platform 4 measured using an NO_2 monitor during the measurement period ranged from 135.6 to 169.8 μg/m^3, exceeding the WHO 24-h limit by 5.4 to 6.7 times. Diurnal variations in NO_2 levels were analysed in relation to train traffic and the idling time of trains (Fig. S11 in S.M.).

It was observed that NO_2 concentrations were higher during periods of low train traffic, where trains experienced longer idling time before departure. Elevated idling time and consequent higher NO_2 levels were most prominent during the early morning hours (5:00–7:00 AM), late evening (10:00 p.m.–12:00 AM), and midday (11:00 AM–2:00 p.m.). Peak concentrations ranging between 309 and 429 μg/m^3 were observed during these periods. Hourly average concentrations ranged from 220 to 257 μg/m^3 when the total idling time of the trains exceeded 80 min. The average concentrations on weekends were 1.2 to 1.25 times higher than on weekdays, due to lower train frequency and consequently longer idling times (Fig. S12 in S.M.).

The average NO_2 concentrations (165 μg/m^3) over the monitoring period were significantly higher than outside background concentration (37 μg/m^3), exceeding it by 4.45 times. The temporal correlation coefficient between the station NO_2 and the outside NO_2 background was low and lacked statistical significance ($R^2 = 0.056$) (Fig. S13 in S.M.). This supports the conclusion that indoor NO_2 concentrations on the enclosed platforms were strongly influenced by the local sources and independent of the outside background level. Furthermore, a decrease in NO_2 was observed when increases occurred in temperature and wind speed within the station. Temporary decreases in NO_2 concentrations were observed when a train left the platform due to piston effect; however, these reductions lasted only a few minutes, until the next train arrived at adjacent platforms (Fig. S14 in S.M.)

There are uncertainties associated with the monitoring. The measured concentrations are influenced by temporal variability, seasonal effects, and changes in train operations during personal monitoring, as well as by seasonal variability during fixed-site monitoring. Therefore, the results reflect the specific sampling periods rather than representing annual estimates. However, these uncertainties do not affect the primary objectives or the overall conclusions of the study.

4.6. Impact of meteorological conditions

Meteorological variables at the station, both on the enclosed and outdoor platforms, were observed to vary depending on the time of day and train traffic. Warmer and windier conditions were observed during the midday hours at outdoor platforms (Fig. S15 in S.M.). On average, the indoor temperature in the enclosed station area was 2.81 °C higher than the outdoor temperature, primarily due to train combustion activities. The average indoor wind speed in the enclosed area was 0.18 m/s, indicating predominantly calm conditions (i.e., $<$0.5 m/s), and was approximately eight times lower than the outdoor wind speed (1.42 m/s). The scatter plot of wind speed versus NO_2 concentration shows that high concentrations are common when wind speeds are between 0 and 0.2 m/s (Fig. S16 in S.M.) Observations also indicate that concentrations drop below 100 μg/m^3 when wind speeds exceed 0.2 m/s, even during peak traffic hours.

4.7. XGBoost modelling

To identify the controlling factors related to idling, several variables were excluded from the XGBoost model after the initial runs. These factors included fuel consumption, which was removed because it was directly correlated with idling time and did not enhance the model's performance. Wind direction was also excluded from the model, as indoor wind speeds in the enclosed station were predominantly reflective of calm conditions (less than 0.5 m/s), which did not produce meaningful prediction. The XGBoost model exhibited a moderate fit, with an RMSE of 15.12 μg/m^3 and an R^2 value of 0.61 on the test data, which represented a reasonable reconstruction for a gaseous pollutant like NO_2, given its sensitivity to multiple influencing factors including chemical reactions, interactions with other reactive pollutants, and dynamic environmental conditions. The model identified station ambient temperature and average train idling time as the most influential factors in predicting NO_2 concentrations (Fig. S17 in S.M.). Train traffic and wind speed were the variables with least importance.

The PDP identified that NO_2 levels increased with a decrease in ambient temperature (Fig. 3). However, meteorological parameters are independent of train management activities and therefore cannot be controlled within the station. Focusing on the idling time, which can be actively managed, PDP showed a steep increase in hourly NO_2 concentrations when the average idling time per train exceeded 10 min.

Conversely, a decrease in NO_2 levels were noted during periods of high train traffic, due to shorter idling time of the trains. Insights from the PDP suggest that reducing the average train idling time per train by 2 min could reduce NO_2 concentrations by approximately 2.5 μg/m^3 per train. While wind speed was not identified as a key influencing factor, the PDP and scatter plot of revealed that when wind speeds exceeded 0.2 m/s, a decrease in NO_2 levels was observed (Fig. S18 in S.M.). This suggests that enhancing ventilation and increasing airflow within the station could also be a strategy to reduce NO_2 concentrations, in addition to managing train idling time.

4.8. Effect of idling on fuel consumption and emissions

Longer idling times not only contribute to elevated pollutant levels within the station but also significantly increase fuel consumption. A train consumes approximately 22 L of diesel per hour while idling. Based on the data collected during the study period (March to May 2024), it

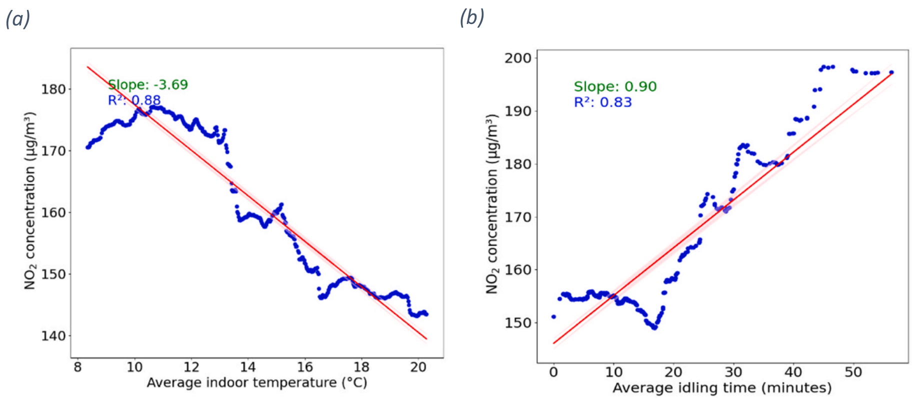

Fig. 3. Partial dependence plots (PDP) for the average NO_2 concentrations against (a) average indoor temperature and (b) train idling time.

was estimated that idling activity resulted in the consumption of almost 13,000 L of diesel per month (or 11 tons/month), generating equivalent emissions of approximately 130 kg/month of NO_x and 11 kg/month of PM.

An initial consideration noted the relationship between idling time and fuel consumption would suggest that reducing the average train idling time (with the engine running) by 1 min could lower fuel use by approximately 0.3 L per train (Fig. S19a in S.M.). Additionally, the relationship between idling engine speed and fuel consumption indicated that maintaining engine speed below 600 RPM reduces engine output power, thereby lowering both fuel consumption and emissions (Fig. S19b in S.M.). Therefore, two control strategies, related to idling, were considered and evaluated in terms of fuel savings and reduced gaseous and particulate emissions.

4.8.1. Assessment of control strategies

Two strategies were examined to evaluate the impact of reducing idling time and engine speed on fuel consumption and emissions: 1) shutting down train engines if the next scheduled operation is more than 30 min away and restarting the engine 15 min before departure. Shutting down engines when the next scheduled service is less than 30 min away poses operational challenges. Systems such as air brake pressure maintenance, carriage heating, and battery charging require the engine to remain running for at least 15 min prior to departure. Additionally, there is also a risk to service reliability, as the train may not restart on time; or 2) maintaining engine speed at or below 600 RPM during notch 0 can help minimize fuel consumption and emissions before shifting to notch 1.

It was estimated that for control strategy 1, shutting down train engines during idling periods exceeding 30 min, could save approximately 3,530 L (3 tons) of diesel per month. Similarly for control strategy 2, operating engines at idle speeds below 600 RPM during idling periods shorter than 30 min could result in an additional saving of an additional 3,530 L (3 tons) of diesel per month. Overall, implementing a combination of these control strategies could reduce fuel consumption during idling by approximately 40–45%, while lowering NO_x emissions to 64 kg/month and PM emissions to 5 kg/month.

5. Conclusions

This study demonstrated the assessment of air quality using both personal and fixed monitoring with a low-cost measurement device and identified the controlling factors of pollutant levels using XGBoost modelling in a semi-enclosed train station. The study also focused on assessing the effect of idling time and idling engine speed on fuel consumption, as well as NO_x and PM emissions.

The average $PM_{2.5}$ concentration measured during a personal monitoring ranged between 22 and 72 μg/m^3 when trains were actively engaged on the platforms, with higher concentrations observed on the enclosed platforms compared to the outdoor platforms. The $PM_{2.5}$ concentrations were higher when DMU trains were on the platform compared to push–pull trains. The 24-h average $PM_{2.5}$ measured using continuous fixed monitoring ranged between 3.18 and 32.56 μg/m^3. Higher $PM_{2.5}$ averages were observed on enclosed Platforms 3 and 4, which predominantly host DMU trains, exceeding the WHO 24-h limit during 90% of the monitoring period.

NO_2 levels measured using diffusion tubes ranged between 40.5 and 162.7 μg/m^3, with the highest concentrations recorded on enclosed Platform 4 during the exposure period. The 24-h average NO_2 levels on enclosed Platform 4, measured using continuous fixed monitoring, ranged between 135.6 and 169.8 μg/m^3, exceeding the WHO 24-h limit by a factor of 5.4 to 6.7.

The XGBoost model demonstrated a moderate fit, with an RMSE of 15.12 μg/m^3 and an R^2 value of 0.61 on the test data. The model identified station ambient temperature and average train idling time as the most influential factors in predicting NO_2 concentrations. PDP suggested that reducing the average idling time of a train by 2 min could reduce NO_2 concentrations by approximately 2.5 μg/m^3 per train.

Analysis of idling time, speed, and fuel consumption indicates that shutting down train engines when the next scheduled operation is more than 30 min away, and restarting them 15 min before departure, combined with maintaining idle speeds below 600 RPM during shorter idling periods ($<$30 min), could collectively save over 7,000 L of diesel per month. Overall, these strategies could reduce fuel consumption by approximately 40–45% and lower NO_x and PM emissions by about 54%.

CRediT authorship contribution statement

Shanmuga Priyan: Writing – original draft, Methodology, Formal analysis, Conceptualization. **Muireann Kearney:** Formal analysis, Conceptualization. **Neha Jacob:** Visualization, Software. **Yuxuan Guo:** Data curation. **Madhavan Vasudevan:** Writing – review & editing. **Aonghus McNabola:** Writing – review & editing. **Brian M. Broderick:** Writing – review & editing. **Brian Caulfield:** Writing – review & editing. **Margaret O'Mahony:** Writing – review & editing. **John Gallagher:** Writing – review & editing, Supervision, Resources, Funding acquisition.

Declaration of competing interest

The authors declare the following financial interests/personal relationships which may be considered as potential competing interests: Shanmuga Priyan reports financial support was provided by Environmental Protection Agency Ireland. Yuxuan Guo reports financial support was provided by Environmental Protection Agency Ireland. Madhavan Vasudevan reports financial support was provided by Environmental Protection Agency Ireland. If there are other authors, they declare that they have no known competing financial interests or personal relationships that could have appeared to influence the work reported in this paper.

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Appendix A. Supplementary data

Supplementary data to this article can be found online at https://doi.org/10.1016/j.envpol.2026.128029.

Data availability

The authors do not have permission to share data.

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