AIR POLLUTION AT TRANSPORT INTERCHANGES

by

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ABSTRACT

Air pollution from DEEEs is becoming an increased international concern, and whilst attention has been primarily focused on the automotive industry, concerns have also been raised about emissions from diesel rail vehicles. The research is designed to assess the hypothesis that diesel rolling stock severely impacts air quality at Birmingham New Street station due to the station's enclosed nature. To assess this hypothesis, an extensive series of long term measurements were made at Birmingham New Street station. The monitoring campaign consisted of diffusion tube measurements, to measure NO_2 at locations in and around the station, followed by measurements of NO_x, PM, CO_2 and BC at stationary and mobile sites at the platform level. The results illustrated that diesel trains serving the station elevated pollutant concentrations, particularly oxides of nitrogen. During the sampling campaign the average NO_2 concentration in the centre of platform 10/11 was 407 $\mu g/m^3$, approximately 10 times greater than the EU ambient air quality limit. NO exceed its WEL 35% of the time during the monitoring campaign for the same site. Furthermore, this research concludes that CO_2 is not suitable as a surrogate for assessing DEEEs exposure. NO_2 concentrations exceeded their relevant exposure limits, whilst CO_2 did not exceed the ventilation system's 50% speed threshold, as a result it is unlikely than harmful pollutants were being successfully exhausted from the station. The environmental analysis identified a potential trapped vortex in the West end of the station, which could have an impact on the ventilation system in place at Birmingham New Street station. It is clear that this research has been pivotal in driving a focus towards air quality with the railway industry and has prompted further research at other enclosed railway stations.

For Marion and Bernard

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LIST OF ABBREVIATIONS AND ACRONYMS

AURN	Automatic Urban and Rural Network
BADC	British Atmospheric Data Centre
BCRRE	Birmingham Centre for Railway Research and Education
BEIS	Department of Business, Energy and Industrial Strategy
BTEX	Benzene, Toluene, Ethylbenzene, Xylene
CIRAS	Confidential Incident Reporting & Analysis System
CLD	Chemiluminescence Detector
CO	Carbon Monoxide
CO_2	Carbon Dioxide
COSHH	Control of Substances Hazardous to Health
DECC	Department of Energy and Climate Change
DEEE	Diesel Engine Exhaust Emissions
DEFRA	Department of Environment Food and Rural Affairs
DifTPAB	Diffusion Tube Precision Accuracy Bias
EC	Elemental Carbon
EU	European Union
FDMS	Filter Dynamics Measurement System
GRP	Fiberglass
HMSO	Her Majesty's Stationery Office
HSE	Health and Safety Executive
HSG	Health and Safety Guidance
HST	High Speed Train

IOELV	Indicative Occupational Exposure Limit Value
IPCC	Intergovernmental Panel on Climate Change
MIDAS	Met Office Integrated Data Archive System
ms^{-1}	Metres per Second
NaN	Not a Number
NO	Nitrogen Oxide
NO_2	Nitrogen Dioxide
NO_x	Oxides of Nitrogen
NRMM	Non-Road Mobile Machinery
O_3	Ozone
OLE	Overhead Line Equipment
ORR	Office of Rail and Road
PAHs	Polycyclic Aromatic Hydrocarbons
PM	Particulate Matter
$PM_{0.1}$	Particulate Matter: Diameter < 0.1 μm
PM_1	Particulate Matter: Diameter < 1 μm
PM_{10}	Particulate Matter: Diameter < 10 μm
$PM_{2.5}$	Particulate Matter: Diameter < 2.5 μm
PM_{resp}	Particulate Matter: Diameter < 4 μm
PM_{total}	Total Particulate Matter
ppb	Parts Per Billion
ppm	Parts Per Million
ROSCOs	Rolling Stock Operating Companies
SCOEL	Scientific Committee on Occupational Exposure Limits

SO_2	Sulphur Dioxide
SO_x	Oxides of Sulphur
TEOM	Tapered Element Oscillating Microbalance
TKE	Turbulent Kinetic Energy
TOCs	Train Operating Companies
UK	United Kingdom
UKAS	United Kingdom Accreditation Service
VOC	Volatile Organic Compound
WEL	Workplace Exposure Limits
WHO	World Health Organisation
$\mu g/m^3$	Micrograms per Metre Cubed

1. INTRODUCTION

The concern surrounding urban air quality is not new. Since the middle of the 19th century, acts of parliament relating to air quality have been passed in the UK, many of which related to the production of coal smoke from industrial sources (Lyness, 2009). Notably, early winter 1952 was particularly cold resulting in the people of London becoming reliant upon their coal fires leading to excessive amounts of smoke pouring from their chimneys (Met Office, 2015). Due to anti-cyclonic conditions and a temperature inversion, the smog was unable to disperse through the atmosphere and instead became trapped in a layer approximately 100-200 metres deep (Met Office, 2015). There are believed to have been 3500-4000 excess deaths in December 1952 (Anderson, 1999), with enhanced mortality in the months that followed (Brimblecombe, 2006). This event resulted in the UK government passing its first Clean Air Act in 1956, which prohibited dark smoke from chimneys, introduced regulations regarding chimney height and enforced smoke control areas (HMSO, 1956).

Over the last 60 years, cities have been transformed and contemporary society has influenced the nature of air pollution, consequently, air pollution is now associated more with automobile sources rather than with industrial and domestic sources (Brimblecombe, 2006). As a result, the composition of air pollution has shifted from smoke and sulphur dioxide, to oxides of nitrogen, particulate matter, ozone and other pollutants generated from vehicles. This led to

the creation of the UK automatic urban monitoring network in 1987, monitoring the compliance with the emerging air quality directives (DEFRA, 2011). This later became Automatic Urban and Rural Network (AURN), when the urban and rural networks combined in 1998 (DEFRA, 2011), and is still in operation today with 146 sites (DEFRA, 2017a).

Analysis of the 2010 emission statistics from the IPCC fifth assessment report shows that transport accounted for 14% of global greenhouse gas emissions (Edenhofer et al., 2014), in comparison to 20.7% in the United Kingdom for the same period (DECC, 2012). In 2010, globally, transportation was the third highest producer of emissions and in the UK, ranked second below energy supply (DECC, 2012; Edenhofer et al., 2014). Subsequently, the percentage of gas emissions accountable to transportation in the UK has risen to 26.9%, surpassing energy supply and has become the UK's largest source of greenhouse gas emissions (BEIS, 2018). With transport responsible for a large proportion of emissions, further encouragement to use public transport, walk, cycle and/or car share is required to reduce the number of private cars and consequently improve air quality. In addition, encouraging a greater shift to these greener modes of transportation leads to co-benefits for health. Fewer cars will result in cleaner air and reduce health implications to the public and there would be increased health and well-being amongst the public due to a more active lifestyle.

Whilst outdoor air quality is improving, in enclosed or semi-enclosed transport environments air quality remains unaddressed. In such an environment, vehicle emissions can rapidly build up due to restricted interaction with the outdoor environment (Department for Transport, 2015; Zhou et al., 2014). Due to an influx of demand, public transportation services are under greater stress. Although active, green transportation methods provide health benefits in

outdoor environments, commuting through transport hubs across cities may place a greater risk on health due to the abundance of harmful exhaust emissions.

One type of transport hub of great interest is enclosed railway stations due to the high volume of passengers passing through an area that hosts high numbers of non-road mobile machinery (NRMM). NRMM, such as trains, are not bound by the stricter regulations posed on on-road vehicles, hence pollution levels in indoor environments hosting these vehicles will differ greatly from those that serve on-road vehicles, such as car parks (Kim et al., 2007). Therefore, those passing through such environments are exposed to the unintended consequences of encouraged methods of transportation.

Since privatisation of the railways in the UK, passenger numbers have dramatically increased. As reported by the Office of Rail and Road (ORR), more than 1.7 billion passenger journeys were made in 2016-17, the highest number of passenger journeys since the records began in 1950 (ORR, 2017c). Year-on-year growth has slowed slightly to 0.8%; however, growth has only fallen once post privatisation in 2009-10 when passenger journeys fell by 0.7% (ORR, 2017c).This growth is greater than in other European countries, with passenger numbers doubling in the UK since 1997-98, compared with increase of 37% in France, 21% in Germany and 18% in the Netherlands (RDG, 2015).

The British rail network comprises of 15,811 km of rail track, of which 5,374 km (34 %) is electrified as of 2016-17 (ORR, 2017c). By passenger miles, electrification counts for approximately 60% (Department for Transport, 2009). Therefore, there is still a heavy reliance upon diesel trains across the rail network, especially for journeys outside London, and in particular Wales, when at time of writing, virtually no track is electrified.

In 2012, the World Health Organisation's (WHO) International Agency for Research on Cancer (IARC) reclassified diesel engine exhaust emission and related ambient air pollution to be carcinogenic and associated with increased mortality from lung cancer (WHO, 2012). Air pollution already accounts for 29,000 excess deaths in the UK, but this does not take into account levels of nitrogen dioxide (NO_2) emitted by diesel engines. With record number of passenger journeys being made across the UK rail network, a considerable proportion of which are on diesel services, commuters are exposed to such emissions and therefore, their health may be at risk as they are exposed to NO_2 emitted from diesel train engines.

Further analysis of the 2016-17 rail statistics highlighted that out of the top 10 busiest stations for entries and exits, nine are located within London and the other is Birmingham New Street station, which is ranked 5th (ORR, 2017a). For interchanges, eight out of the top ten are within London and the two outside London are Birmingham New Street and Reading, ranked 4th and 7th, respectively (ORR, 2017a). Birmingham New Street has risen considerably in the ranking since its redevelopment, rising three places from 8th to 5th for entries and exits and two places from 6th to 4th for interchanges over the previous two years (ORR, 2015; 2017a).

Greater London and the West Midlands are renowned for their poor air quality, which is highlighted by their expected non-compliance with European Union (EU) law until 2030, 20 years after the limits were set (DEFRA, 2014). Thus passengers are placed at a greater risk whilst commuting through these areas and the presence of diesel trains intensifies this risk.

A survey carried out by Environmental Systems Research Institute (Greener Business, 2008) found that Birmingham is the worst city in the UK for commuting times, with workers spending on average more than 1 hour per day (61.2 minutes) travelling to and from work due to the complex network of roads and motorways and the crowded rail network. Edinburgh

came in second (55.3 minutes), London third (52.4 minutes) and Oxford fourth (51.5 minutes). There is a need to assess the impact of air pollution on cities with long commuting times and to examine the key sources of air pollution associated with these commutes.

Birmingham New Street station is a semi-enclosed railway station situated in the centre of Birmingham, UK (Figure 1.1). Currently, over 170,000 people use the station each day and as a result, Birmingham New Street is the 5th busiest station in the UK and the busiest outside of London. It is also the 4th busiest interchange station and again, the busiest outside of London (ORR, 2017a). To meet this demand, Birmingham New Street underwent an extensive redevelopment, at both concourse and platform level, which was completed in September 2016. The station now has the capacity to handle 300,000 people per day (Network Rail, 2015). On 19th November 2016, Birmingham New Street station had a record number of people, 230,000, using the station (Network Rail, 2016). With the station situated in one of the UK's most polluted cities with one of the longest commute times and high passenger numbers, it will be the focal point for this research.

Figure 1.1. Location of the Birmingham New Street station; Black circle highlights the location of the Birmingham New Street station in the centre of Birmingham City Centre at 52°28'40.08" N, 1°53'56.04"W (Bing, 2017).

Birmingham New Street station has been previously identified as a potential pollution hotspot, due to its unique underground nature (Thornes et al., 2017). The station comprises of twelve platforms, across seven "islands" (Figure 1.2), which are situated below the redeveloped concourse in a tunnel-like environment. The semi enclosed tunnel-like environment is approximately 5m high, 160m wide, 240m long, making the volume at platform level approximately 100,000m^3 and is significantly smaller than other semi-enclosed railway stations, such as London Paddington (Thornes et al., 2017). Trains approach the station via three tunnels, which pass under the city centre; these are from the South West, North West and East. There is little gap between the tunnel-like platforms and the tunnels that lead in and out of the city centre restricting the dispersion of pollutants into the atmosphere.

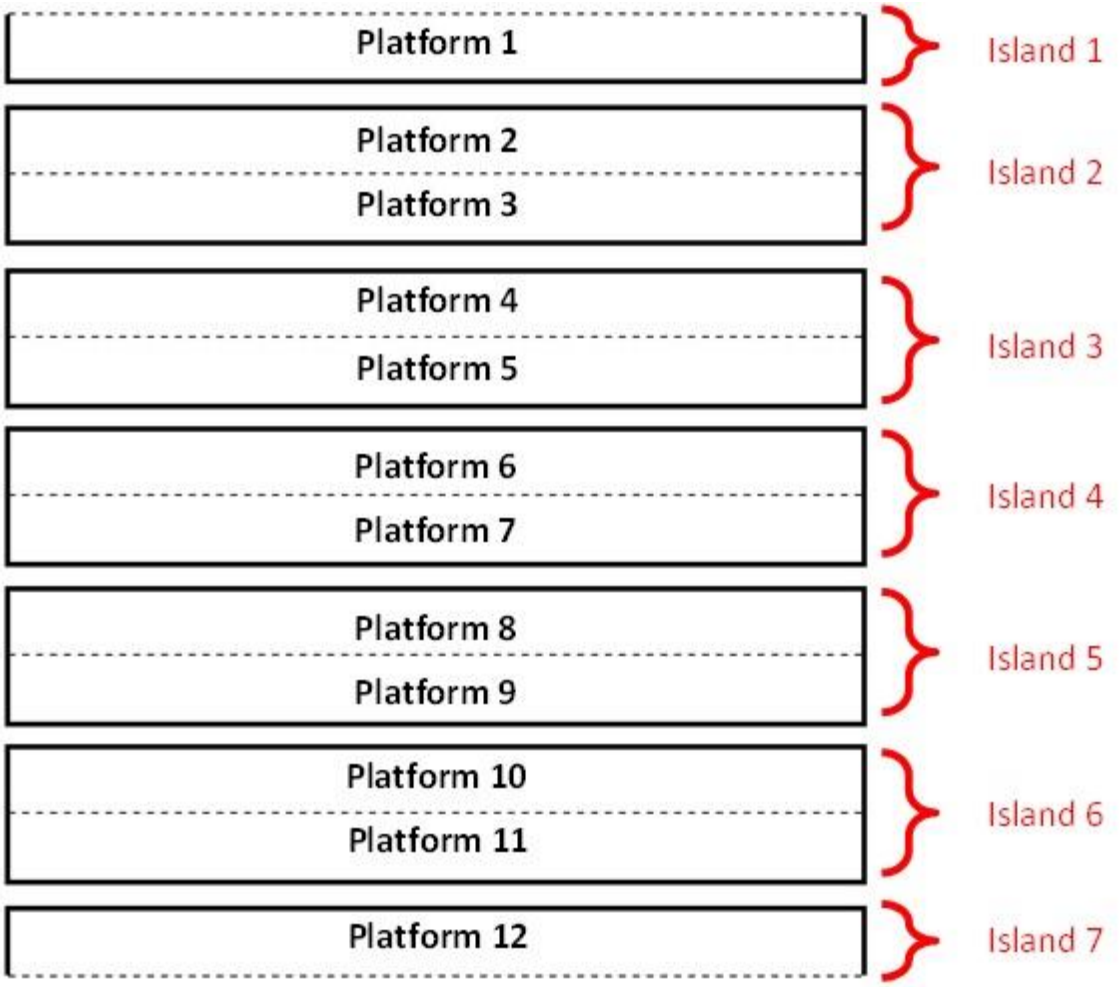

Figure 1.2. Schematic diagram of platform layout at Birmingham New Street station.

Although all tracks through the station are electrified, many of the train services run on non-electrified routes and as a result, there are approximately 600 diesel train movements per day at the station, this accounts for approximately 45% of services. In addition, the station is also a focal point for buses, taxis and local traffic, including delivery vehicles to on-site and local shopping centres. These factors create a congested environment, where there is a lack of mixing and convections; therefore it can become a daily air pollution "hot spot" for both passengers and staff. For these reasons, Birmingham New Street will be the focal point of this air quality evaluation.

In 2009, a contractor carried out an air quality assessment at the station prior to its redevelopment. This work consisted of a three-month monitoring campaign measuring oxides of nitrogen (NO_x), particulate matter (PM_{10}), carbon dioxide (CO_2), sulphur dioxide (SO_2) and polycyclic aromatic hydrocarbons (PAHs). As well as numerous limitations with the methodology (as discussed in Chapter 2.2.6), this work was carried out prior to the redevelopment of Birmingham New Street station, where changes been made to the platforms and there have also been operational changes across the network, for example, timetable changes, both of which may have altered air quality within and around the station.

It is clear that air quality is an on-going issue at Birmingham New Street station as there have been a number of complaints made to the Confidential Incident Reporting & Analysis System by staff regarding the air quality at the station (CIRAS, 2013a; b).

A more extensive sampling campaign is required at Birmingham New Street to evaluate the air quality across the entire station, at both platform and concourse level, and its implication on/from the surrounding area. Therefore, this research was undertaken in collaboration with Network Rail to better understand the environment in and around the station over a longer period in order to provide a comprehensive analysis of the complex environment at the station and the contributing factors.

The outcomes of this research will provide an insight into the unique nature of transport interchanges, highlighting key parameters that may influence air quality and propose possible strategies for future assessments in other semi-enclosed transport interchanges.

1.1 Thesis Structure

The contents of the following sections are organised as follows:

- **Chapter 2** examines current literature, including applicable legislation and previous studies conducted in similar environments, and states the aim and objectives of the thesis.
- **Chapter 3** denotes the methodology used to evaluate air quality at Birmingham New Street railway station and the subsequent data analysis methodologies used to analyse the results of Birmingham New Street, as presented in Chapters 4 – 6.
- Pollutant concentrations at Birmingham New Street station are quantified in **Chapter 4**.
- **Chapter 5** examines the difference in meteorological conditions at Birmingham New Street station and Coleshill weather station and explores the implication of meteorological factors on pollutant concentrations in the station.
- The implications of vehicle movement through Birmingham New Street station is analysed and discussed in **Chapter 6**.
- **Chapter 7** summaries the key research findings and discusses subsequent mitigation strategies that have been executed.
- **Chapter 8** provides a synthesis of the outcomes of the thesis and highlights key parameters that should be considered when conducting future air quality monitoring at transport interchanges.

2. LITERATURE REVIEW

2.1 Introduction

Chapter 1 highlights the growing concern with air quality in railway environments, with passenger numbers increasing year-on-year resulting in a greater number of passengers exposed to harmful pollutants. Yet, minimal research has been undertaken to quantify air quality in railway stations. Previous research work has mainly been focused on particulate matter (PM) concentration and composition from railway traffic in subway and metro systems, both outside and inside carriages (Aarnio et al., 2005; Cheng et al., 2012; Fridell et al., 2011; Kim et al., 2012; Kim et al., 2008; Kim et al., 2007; Martins et al., 2016; Moreno et al., 2014; Moreno et al., 2015; Onat and Stakeeva, 2014; Querol et al., 2012). As these systems are by and large electrified, the PM originates from non-exhaust emissions of electric services, such as wear from wheel–rail contact. The origin and composition of these non-exhaust emissions have also been extensively researched (Abbasi et al., 2012; Abbasi et al., 2011). However, apart from very small-scale trials to monitor staff exposure on an occasional basis, there has been limited research into concentrations of NO_X and particulates at enclosed

railway stations with only a handful of stations being previously investigated (Chong et al., 2015; Gardner, 2012; Loxham et al., 2013).

This literature review will explore the pollutants present in railway environments, including both exhaust and non-exhaust emissions, the relevant legislation applicable to these pollutants and the environment, and the few studies that have already been undertaken to quantify air quality in railway environments. This chapter will not explore studies that have primarily examined PM composition. Although Birmingham New Street is an electrified station, diesel engine exhaust emissions (DEEE) are believed to have a more significant contribution of the air quality. Therefore, the focus of this research is to quantify air quality in the station and assess the factors influencing air quality and the literature discussed reflects this.

2.2 Air Quality in Railway Stations

2.2.1 Pollutants Present in Railway Stations

Air pollutants in railway stations come from both diesel engine exhaust emissions and electric train emissions, of which diesel emissions are more polluting and hazardous (AEA Technology, 2001).

The constituents of diesel exhaust gas can be considered as three groups (Davis and Holtz, 1955; Elliott et al., 1951; Schrenk and Berger, 1941):

1. Products of complete combustion; carbon dioxide, water vapour and oxides of sulphur (if the fuel contains sulphur).
2. Products of incomplete combustion; carbon monoxide, aldehydes, hydrogen, methane and smoke.

3. Exhaust products originating from the intake air; nitrogen, excess oxygen and oxides of nitrogen.

Diesel engines emit a complex mixture of gases, vapours, liquid aerosol and particulate substances as a result of combustion, the main chemical constituents are presented in Table 2.1.

Table 2.1. The major chemical constituents of diesel engine exhaust emissions (DEEEs) (HSE, 2012).

Carbon (soot)
Water (H_2O)
Carbon monoxide (CO)
Carbon dioxide (CO_2)
Nitrogen (N_2)
Oxides of nitrogen (NO_x)
Oxides of sulphur, including sulphur dioxide
Alcohols
Aldehydes
Ketones
Various hydrocarbons (HC)
Polycyclic aromatic hydrocarbons (PAHs)

Investigation into the elemental composition of diesel exhaust particles found a number of additional factors could influence the characteristics and concentration of these particles. These factors include: engine load, speed, technology, elemental composition of the fuel,

lubricant, engine type and after-treatment (Abbasi et al., 2013). Therefore, particulate composition will vary in different railway environments.

In additions to DEEEs, particulates are also emitted from non-exhaust sources associated with both diesel and electric trains. These particles originate from wear, such as wheel-rail contact, pantograph-overhead line contact and braking materials (Abbasi et al., 2013). The elemental composition of these particles often mirrors the elemental composition of the component the trains are making contact with. For example, quartz measured in the Rome underground railway was due to the use of silica sand on the emergency braking system, a different braking system to what was used in the Budapest and London underground railway where quartz was not present (Salma et al., 2007; Sitzmann et al., 1999).

As a result, both passengers and workforce are likely to be exposed to harmful pollutants in railway environments, in particular enclosed railway environments, where there is little ventilation prohibiting the dispersion of pollutants into the atmosphere. There are regulations in place to reduce the amount of harmful pollutants emitted by rolling stock and to protect both passengers and workers.

2.2.2 Relevant Legislation

Legislation relevant to air quality in railway environments can be split into three sections: NRMM regulations, EU ambient air quality legislation and occupational health legislation. Together they contribute towards tackling air quality at railway stations and in the surrounding area.

Non-Road Mobile Machinery Regulations

The outputs of diesel engines are controlled by NRMM regulations, regulating carbon monoxide (CO), unburned hydrocarbons, NO_x and PM emissions. However from its introduction in 1999 until 2006, stages I to II, railway engines were exempt from the regulation (Chong et al., 2015; Department for Transport, 2018). From Stage III, phased in from 2006 to 2013, railways diesel engines were subject to NRMM regulations, which have subsequently tightened over the last 10 years (Figure 2.1) (Chong, 2013; Chong et al., 2015; DieselNet, 2012; 2014). Engines must meet the emission regulations in place on the date they first came into service, resulting in older rail engines abiding by older, outdated NRMM regulations and new engines meeting the new, stricter NRMM regulations. Thus, it is important to consider the age of the UK rolling stock when investigating emissions, as the age of the train indicates which emission regulations it passed and therefore its emissions.

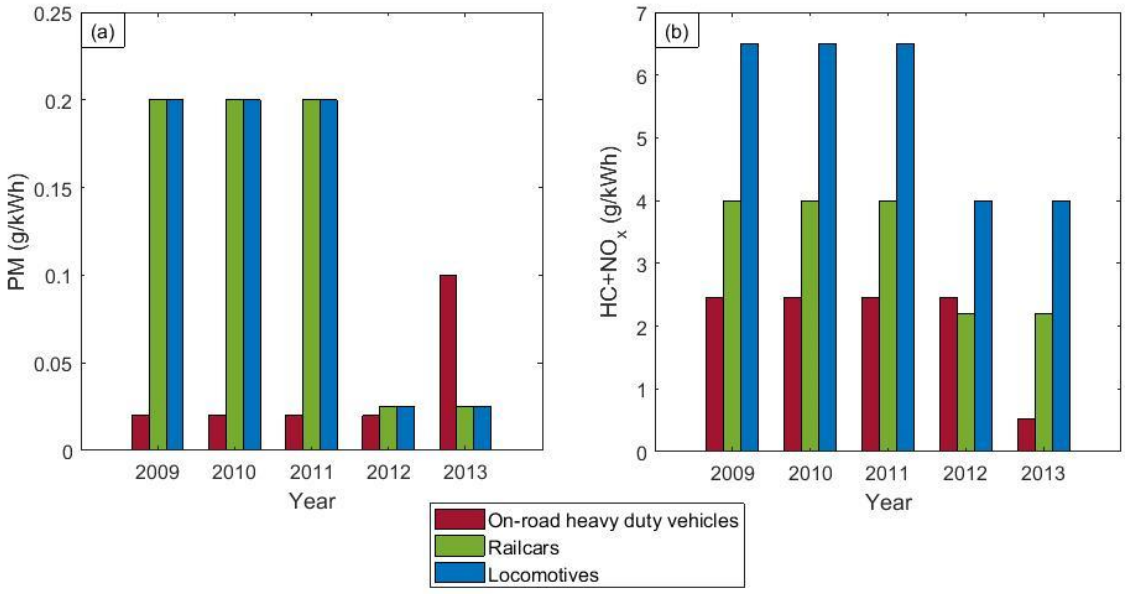

Figure 2.1. European emissions regulations for on-road heavy duty vehicles, railcars and locomotive diesel engines from the NRMM regulations. (a) particulate matter emission limit in g/kWh. (b) total unburnt hydrocarbons and oxides of nitrogen in g/kWh (DieselNet, 2014).

In 2016-17, the British rolling stock had a mean age of 21.1 years; its oldest since 2000-01 (Figure 2.2) and whilst the age of rolling stock in London decreased by 0.5 year since last year to 18.4 years, the remaining rolling stock saw an increase (ORR, 2017b). This means that a considerable proportion of the British rolling stock was deployed before the NRMM emissions regulations were enforced twelve years ago (Department for Transport, 2018). Therefore, these trains are not bound by any regulations. Network Rail states that historically diesel trains serve for approximately 30 years and electric trains for 35 years but research has highlighted that rolling stock life can be extended by five years (Network Rail, 2011). Such changes would allow the highly polluting trains to be present on British Railways for years to come, further damaging the environment, as they are not obliged to meet any emission regulations. The latest statistics for 2016-17 support this statement with the rolling stock fleet

for half of the train operating companies (TOCs) remaining unchanged and the rolling stock for three out of the 20 TOCs had an increase in average age as older stock has been put back into service, or younger stock has been removed (ORR, 2017b).

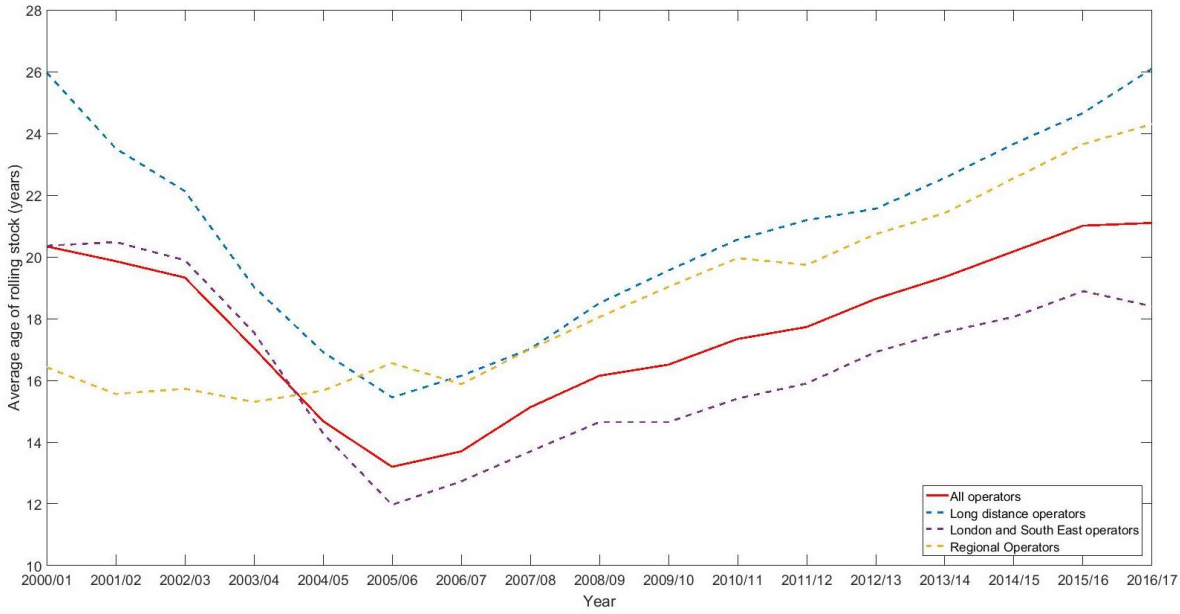

Figure 2.2. Average age of rolling stock in the UK in years for all operators, long distance operators, London and South East operators and regional operators. Since 2005/06, trains for all operators (red) have been ageing on average by 0.72 years (to 2 s.f.) per annum (Department for Transport, 2016; ORR, 2017b).

Consequently, it is important to consider air quality legislation relating to public and workplace exposure, as these regulations will still be applicable regardless of rolling stock age.

European Union Ambient Air Quality Legislation

The European Union's policy on air quality aims to develop and implement appropriate strategies to improve air quality. Part of the policy is a series of air quality directives, setting limits on ambient air quality to prevent excessive exposure which could impact public health (European Commission, 2018).

The Ambient Air Quality Directive, 2008/50/EC sets legally binding limits for concentrations of pollutants in ambient air, these include ozone (O_3), CO, particulate matter ($PM_{2.5}$ and PM_{10}) and NO_2 (CEC, 2008). This directive, combined with Directive 2004/107/EC, relating to arsenic, cadmium, mercury, nickel and polycyclic aromatic hydrocarbons, provides the current framework for the control of ambient concentrations of air pollution in the EU (CEC, 2005; DEFRA, 2018; European Commission, 2018). The framework consists of standards and objectives; standards are legally binding limits and member states can face repercussions if they are not met, and objectives provide target values (Table 2.2).

Table 2.2. European Union Air Quality Standards for ambient air, which relate to DEEEs (see Table 2.1) (European Commission, 2017).

Pollutant	Concentration	Averaging Period	Permitted Exceedances Each Year
Fine particles ($PM_{2.5}$)	25 µg/m^3	1 year	n/a
Sulphur dioxide	350 µg/m^3	1 hour	24
	125 µg/m^3	24 hours	3
Nitrogen dioxide (NO_2)	200 µg/m^3	1 hour	18
	40 µg/m^3	1 year	n/a
Particulate matter (PM_{10})	50 µg/m^3	24 hours	35
	40 µg/m^3	1 year	n/a
Carbon monoxide (CO)	10 mg/m^3	Maximum daily 8 hour mean	n/a
Polycyclic Aromatic Hydrocarbons	1 ng/m^3 (expressed as concentration of 1 year Benzopryne)	1 year	n/a

Occupational Health Legislation

The European Union's air quality directives are not applicable to Birmingham New Street station and other enclosed railway environments. Instead, occupational exposure limits are in place to regulate the concentration of potentially harmful pollutants. The scientific committee on occupational exposure limits (SCOEL) advise the European Union on limit values. The committee evaluate the scientific knowledge available on hazardous substances and makes recommendations for the establishment of an indicative occupational exposure limit value (IOELV). As IOELVs are listed in European Union Directives, member states must abide by these limits and implement national occupational exposure limits for the substances listed. In the UK, these limits are known as the Workplace Exposure Limits (WEL) and have been set up to protect the health of employees in Britain from harmful substances in the workplace, such as chemicals, dust and fumes (HSE, 2013).

In addition to the current WELs, there are also recommendations from SCOEL incorporated in the commission directive (EU) 2017/164 that are yet to be established in WELs. These include the pollutants nitrogen oxide (NO) and NO_2, both of which are relevant to this research. Member states are now required to establish a WEL for NO and NO_2 and Health and Safety Executive (HSE) will incorporate these into WELs to come into force in August 2018.

In comparison with the European Union's ambient air quality limit (Table 2.2), occupational health limits (Table 2.3) are substantially higher. Furthermore, out of the constituents emitted from DEEEs only two are accounted for in the workplace exposure limits in comparison to six for public health limits, and NO and NO_2 are, at time of writing, only recommendation values from SCOEL. There is no WEL to adhere to for oxides of nitrogen or oxides of sulphur. The regulated WEL for CO is much higher than the limits set for public health. The

probable reason for the higher occupational limit is that those working among potentially harmful substances are considered fitter and healthier than the more vulnerable general public. Although the atmospheric concentration of PAHs is not assessed, they are one of the substances that are biologically monitored and a guidance value has been set by HSE (HSE, 2013).

Table 2.3. Occupational workplace exposure limits (HSE, 2013).

Pollutant	Workplace exposure limits	
	8-hour (TWA)	15-minute (TWA)
Carbon dioxide (CO_2)	5000 ppm	15000 ppm
Carbon monoxide (CO)	30 ppm	200 ppm
	SCOEL Recommendations	
Nitrogen dioxide (NO_2)	955 µg/m^3	1910 µg/m^3
Nitrogen monoxide (NO)	2500 µg/m^3	n/a

2.2.3 Use of CO_2 to Assess Exposure to DEEEs

HSE's Heath and Safety Guidance (HSG) 187 guidance states that *"as a measurement of the CO_2 level is easily carried out and because it is a useful indicator of the overall adequacy of control measures, it may be used as one of the steps in any assessment of the level of exposure to DEEEs"* (HSE, 2012). HSE's statement is supported by Groves and Cain (2000) finding

that CO_2 may be an indicator of the adequacy of control measures for DEEEs, however, Groves and Cain concludes that elemental carbon (EC) is a preferential method for assessing DEEEs exposure as diesel engines are likely to be the only significant source of EC in the workplace. The use of EC over CO_2 is mirrored across research, with findings demonstrating it is a better surrogate and correlates well with diesel engine particulates (Birch and Cary, 1996; Leeming and Dabill, 2004; McAlinden, 2013).

There is some questionability surrounding the use of CO_2 as a surrogate, Leeming and Dabill (2004) found only a loose correlation between CO_2 and diesel particulate EC. Furthermore, Forder (2016) informs that the HSG 187 guidance of low DEEE exposure where CO_2 is < 1000 ppm should not be relied upon and CO_2 can come from confounding sources. For example, CO_2 could not be used in coal mines as CO_2 also comes from other sources, not solely DEEEs. Therefore, the use of CO_2 as a surrogate should be evaluated for each environment, to determine its accuracy in indicating DEEE exposure, in particular, at transport interchanges, which are unique environments that adhere to the HSE guidance.

2.2.4 Air quality Assessment in Railway Environments

There have been a handful of studies that have aimed to quantify air pollution across a variety of stations in the UK and Europe. All stations examined in the UK serve both diesel and electric trains but the study conducted in the Netherlands (Loxham et al., 2013) only serves electric trains. However, this study is still valuable to this research as the methodology used could be adapted to railway environments that serve diesel trains. Furthermore, it quantifies PM concentration at various size fractions, illustrating the considerable PM concentrations present in railway environments, even with the absence of diesel trains, and thus environments with DEEEs may only exacerbate this.

Underground railway station, Netherlands

Loxham et al. (2013) study investigates the elemental composition of PM_{10}, $PM_{2.5}$ and $PM_{0.1}$ in an underground railway station and compares the composition against that of other PM sources. The railway station is situated below a major European airport terminal in the Netherlands and is near the middle of a 5.1km long tunnel. The station is used by 60000–150000 people each day and to cope with demand there are three platform islands approximately 400 m long, serving 25–30 trains per hour, all of which are electrically powered by overhead catenary. All the platforms are cleaned daily using electrically powered ride-on machines. There is no active ventilation other than the 'piston action' of the trains. Loxham et al. (2013) conducted sampling in July 2010, monitoring for 9 hours a day, between 08:30 and 17:30, on three sampling days. The instruments were located halfway along the central platform approximately 3m from the platform edge. The research design of this study is sufficient to determine the characteristics of PM; however, it is not a sufficient for quantifying PM concentrations. The study provides little information about the station's train timetable or the days of the weekend the sampling was performed. It is likely that trains may have ran a more limited service throughout the night, which could ultimately influence the concentration, and this period was not monitored. Furthermore, there may be a variation in the train timetable at weekends, which could also affect concentration. As a result, future research to quantify air pollution in railway environments should the take timetable into consideration.

As the station only serves electric rolling stock, there is an absence of DEEEs, instead the elevated PM concentrations are the result of interaction between wheels, rails and brakes and the friction caused by the pantograph and overhead catenaries. Loxham et al. (2013) reported that abrasion and shearing generated coarse PM, whilst fine and ultrafine PM did not show signs of abrasion, instead their formation might be the result of high temperature processes.

Over three sampling days in the underground platform tunnels beneath the airport, Loxham et al. found 'coarse' PM_{10} at concentrations of 169 μg/m^3, 'fine' $PM_{2.5}$ at 75.3 μg/m^3 and 'ultrafine' $PM_{0.1}$ at 37.7 μg/m^3. These concentrations are well in excess of the annual EU ambient air limits for PM_{10} and $PM_{2.5}$, 40 μg/m^3 and 25 μg/m^3 respectively. Although these are not legally binding limits, it is possible that these concentrations will pose a risk to passenger health.

Edinburgh Waverley Station, United Kingdom

Edinburgh Waverley station is a semi-enclosed railway station located in the steep, narrow valley between the old town and new town. The station has 18 platforms serving both diesel and electric trains. A study conducted at Edinburgh Waverley station quantified air quality (Gardner, 2012), however, this study primarily addressed occupational exposure, rather than public exposure, at the request of the client as this was deemed more significant to Network Rail employees and sub-contractors. Monitoring was conducted in four locations in the station, but all were located in the concourse area of the station, as opposed to on the platforms, as in Loxham et al. (2013) study. PM_{10}, PAHs and NO_2 were monitored for 21 days from 15:00 on 15th October to 6th November 2012. PM_{10} and PAH were only monitored at one site; PM was monitored continuously to obtain an infra-red and gravimetric average and the particulate sample was subsequently dispatched from PAH analysis. NO_2 was monitored at all sites using diffusion tubes. All sampling methods resulted in long-term averages for the entire monitoring period. Results from this study highlight that trains are major contributing factors to air quality as location A, closest site to the platforms, had a higher NO_2 concentration than the other three sites.

Gardner (2012) reported all pollutants were in-line with expectations for a work environment but acknowledged they exceeded background urban concentrations and EU ambient air quality limits. However, Gardner's approach of weighting exposure relative to percentage of time spent at Edinburgh Waverley can be argued invalid. Long term averages for the three week period monitored, included weekends and overnight periods. There is minimal train activity overnight and a reduced timetable is run at the weekends. As a result, these periods will have lower NO_2, PM_{10} and PAH concentrations, as one of the main sources, DEEEs, is minimal or absent, thus lowering the long term concentration average. Some staff may be working for 8 hours during the day, others overnight, and therefore it cannot be stated for certain that all staff are exposed to a percentage of this long term concentration; some staff may be exposed to higher concentration, others lower. It is clear that further research should assess the diurnal air pollutant concentration, in order to investigate this difference.

Gardner (2012) advised against respiratory protection for employees, due to the alarm this may cause amongst passengers, but expressed that pollutants should be controlled under the COSHH regulations 2002. Consequently, taxis were banned from entering the station from 2 June 2014 and now have to park in the open air outside.

Paddington Station, London, United Kingdom

Paddington station is a semi-enclosed railway station with 70% of trains powered by diesel. The enclosed canopy space is about 15 m high, 100 m wide and 250 m long. Chong et al. (2015) carried out a five day air quality survey from 17th –21st September 2012 monitoring PM, SO_2 and NO_2. The survey length was heavily restricted due to security constraints and logistical conflicts with the daily operation of the station. Although similar studies had similar monitoring periods (Kam et al., 2011; Loxham et al., 2013; Salma et al., 2007), Chong et al

acknowledges a longer sampling campaign is required. A short sampling campaign possesses a number of limitations including little variation in meteorological conditions and train timetables.

Chong et al. (2015) selected four monitoring locations inside Paddington station (locations A-D) and one monitoring location just outside the station (Location E). Locations A and B were situated on platforms 1 and 8, respectively, both of which predominantly served diesel trains. Locations C and D were located close to the food and retail outlets, near the ends of the platforms. As a result, locations C and D had higher $PM_{2.5}$ concentrations than location A and B, as there are more emission sources, higher train emissions due to train idling nearby and decreased mixing with the outdoor air. This further supports Gardner (2012) results, illustrating idling diesel engines emitting DEEEs are a key contributor to exacerbated pollutant concentrations. NO_2, only monitored at locations A and C, further supports these findings with concentrations at site C exceeding that at A.

Hourly mean $PM_{2.5}$ mass concentrations averaged 16 $\mu g/m^3$ (range 2–68 $\mu g/m^3$) and hourly mean NO_2 concentrations averaged 140 $\mu g/m^3$ (range 94–229 $\mu g/m^3$). Additionally, Chong et al. (2015) compared results to nearby Marylebone Road (1.5km away), a road renowned for poor air quality in London (Carrington, 2017). $PM_{2.5}$ was statistically higher than Marylebone Road on three out of four measurement days, NO_2 on three out of five days and SO_2 on all days. These results highlights the concern with enclosed railway environment, where restricted pollutant dispersion and the presences of DEEEs results in high pollutant concentrations.

Chong et al. (2015) compares findings to the EU ambient limits, acknowledging that Paddington station is not legally bound by these regulations. NO_2 exceeded the hourly limit of

200 µg/m^3 five times in 59 hours at location C. Whilst this method allows a comparison with other studies around London reporting high NO_2 concentrations (Carslaw et al., 2007; Carslaw et al., 2011), it does not show if staff are exposed to pollution concentrations above the workplace exposure limits. At the time of publication, there were no workplace exposure limits for NO_2, however, as of 2018, NO_2 is now a legally binding WEL (Table 2.3). It is imperative that future research assesses air quality relative to these WELs as they can provide valuable information for employees.

This study is the first study to conduct in-depth analysis into air quality in an enclosed railway environment in the United Kingdom, identifying pollution hotspots within the station. Although this study provides a strong basis for future research, a longer sampling period is required with a finer temporal resolution, in order to investigate the effect of DEEEs on air quality.

Birmingham New Street station, United Kingdom

In 2009, a contractor carried out baseline air quality monitoring at Birmingham New Street station prior to the redevelopment. At the time of monitoring, platforms were enclosed in a tunnel like environment below the main concourse and Palisade shopping centre. The Pallasades shopping centre has since been refurbished to form the new Grand Central shopping centre. Birmingham New Street serves both diesel and electric trains, with diesel trains accounting for approximately 45% of services and consequently, DEEEs are present in the station. The three-month monitoring campaign measured NO_2, PM, CO_2, SO_2 and BTEX (benzene, toluene, ethylbenzene, xylene).

A combination of passive and automatic monitoring techniques was used; NO_2, SO_2 and BTEX were monitored using diffusion tubes and PM and CO_2 were monitored using

automatic instruments. Automatic sampling techniques are more advantageous than passive sampling due to having a high temporal resolution rather than a long-term average, however the contractor presents PM_{10} and CO_2 results as 8 hour running means. Analysis of finer temporal resolution data would have allowed the identification of concentration peaks and troughs, which may have proved more informative for future intervention strategies.

The passive samplers were placed at the west end of the platform, towards the tunnel opening, of each even platform and a "background" site was set up in the main concourse. The passive samplers were changed every month, however, the contractor only provided a three month average for the pollutants. Results show that platform 2 had the highest concentration of NO_2, 303.1 µg/m^3 and platform 12 the lowest, 127.3 µg/m^3. All concentrations exceeded the EU annual air quality objective of 40 µg/m^3 and were likely to have exceeded the 200 µg/m^3 hourly limit on several occasions, although the contractor stated this would not be a problem in this environment and no further monitoring during redevelopment was required.

The "background" site in the concourse had a concentration higher than platform 12, this show that DEEEs may be leaking into the concourse or the urban air quality is influencing concentrations at this site. This result questions its validity as a background site and a more appropriate background site should have been selected. Furthermore, it is clear that air quality in the concourse is influenced by the surrounding area and therefore should be assessed in future monitoring campaign to identify its source, especially as there are additional escalators, stairs and lifts to assess the platform where DEEEs could disperse through.

There are limitations to sampling with passive samplers as they take a long-term average irrespective of operation use. Moreover, the diffusion tubes used to measure pollutants were placed near the open end of the platform 'tunnels' rather than in the centre where passengers

are more likely to wait for their service. As demonstrated by Chong et al. (2015) there are higher concentrations in areas where pollution dispersion is restricted and it is assumed that dispersion would be more restricted in the middle of the platform, thus a higher concentration.

PM and CO_2 were monitored on platform 6a and 6b using automatic samplers. The contractor found that PM concentrations were similar at either end of the station suggesting dispersion is not influenced by prevailing wind. However, analysing the results given in the report, there were more exceedance of the EU annual air quality limit of 25 $\mu g/m^3$ and 40 $\mu g/m^3$, for $PM_{2.5}$ and PM_{10} respectively, on platform 6b suggesting a difference between the two locations. It would be advisable that future monitoring incorporates wind analysis and investigates the relationship with pollutant concentrations. CO_2 concentration conformed to HSE WEL limits on platform 6a, but there were 8 exceedances of the 1000 ppm limit on platform 6b, further implying that external factors may be causing the difference in concentration.

This report was intended to asses air quality in Birmingham New Street station due the concern of potential health effects of pollutant emissions from DEEEs on employees, hence, the report compared finding against workplace exposure limits where possible. Since the report, the workplace exposure limits have been updated introducing WEL for NO_2 and future monitoring should consider this. However, it is important to assess the impact of pollutant exposure on the public; therefore it is not redundant to compare concentrations against the EU air quality limits for ambient air.

2.3 Ventilation in Semi-Enclosed Environments

Previous studies quantifying railway station air quality (Chong et al., 2015; Gardner, 2012; Loxham et al., 2013) do not assess the station's ventilation patterns nor does the research

assess the implications of such ventilation on pollutant concentrations. Other research has outlined the ventilation present in different transport environments (Chen et al., 1998; Katolicky and Jicha, 2005; Yoon et al., 2006). Ventilation can be natural, vehicle-driven or mechanical, but often these are utilised simultaneously to create an optimal ventilation system. Mechanical ventilation falls broadly into two categories; longitudinal ventilation systems, which use jet fans to move air along a tunnel, or transverse systems, which use air ducts to extract air at periodic locations (WHO, 2009). Each environment will exhibit different ventilation patterns because of their differing geometries, vehicle-flows and meteorological conditions (Bring et al., 1997; Gilbert et al., 2013; Yoon et al., 2006).

Chen et al. (1998) investigated the piston in model vehicle tunnels, finding that the piston effect in one way traffic tunnels but its effect is concentrated around the vehicles and decreases with height. Furthermore, the piston effect is still present in two-way traffic studies, but is only 35% of one-way traffic. This highlights the influence of an adjacent, opposing traffic flow. Katolicky and Jicha (2005) concluded that the flow rate of air entrained into the tunnel is dependent on traffic rate, speed of cars and length of the tunnel. As well as vehicle driven ventilation, there is a meteorological component influencing the ventilation of road tunnels. Yoon et al. (2006) found that the natural ventilation pressure was greatest in the summer than the winter due to a greater temperature difference between inside and outside of a mountain road tunnel. It is clear that the differing characteristics of road tunnels will influence the ventilation of the tunnel.

Railway tunnels are also subject to the piston effect and extensive research has been undertaken to assess and utilise this effect (Cross et al., 2015; 2017). Additionally, the piston effect has been investigated in underground subway stations (Gonzalez et al., 2014; Li et al., 2013; Moreno et al., 2014; Pan et al., 2013). However, research suggests that a slight opening

of such stations would cause the loss of the piston effect (Gilbert et al., 2013); therefore it would be unwise to assume all enclosed railway environments, which resemble a tunnel-like nature, would possess a piston effect.

In transport interchanges where vehicle flow is not unidirectional, rather it is randomised, and the environment is not a tunnel, there will be no piston effect present, instead vehicle driven ventilation will result in turbulence. This type of ventilation is applicable to car parks, bus terminals and urban streets where vehicle direction and movement is largely unrestricted. The effect of vehicle induced ventilation and its ability to disperse pollutants has been researched within street canyons and urban environments (Sahlodin et al., 2007; Solazzo et al., 2008; Vachon et al., 2002).

This literature highlights the need to assess each transport interchange on its own merit due to their varying characteristics, which play a vital part in influencing the ventilation. Therefore, it would not be good practice to transfer the conclusions made in one transport interchange to another.

2.4 Concluding Remarks and Research Gap

This review has provided an overview of air quality in enclosed railway stations and explored the factors that influence pollutant concentrations. The literature demonstrates that there has been a lack of extensive air quality sampling at enclosed railway stations, with previous studies limited to a few days or conducted with passive samplers. Furthermore, research has been restricted to quantifying air pollution and does not investigate how vehicle movement, ventilation or meteorological conditions may influence pollutant concentrations. Future

research should aim to incorporate these factors to assess their implications on air quality and highlight possible intervention methods.

There is an abundance of legislation applicable to air quality however, that relevant to railway stations is particularly limited. Whilst railway stations are predominantly designed for the use of the general public, semi-enclosed railway station, are not subject to the EU air quality legislation, instead they are required to abide by WELs. Section 2.2.2 illustrates a clear gap between these public health limits and occupational health limits; hence it is important to assess the impact of this in railway stations. Furthermore, NRMM regulations, which are applicable to rolling stock, are dependent upon vehicle age. As each railway station will serve a different combination of rolling stock, some rolling stock will be subject to NRMM regulations but others may not. Ultimately, the age of the rolling stock serving each railway station will influence pollutant concentrations at the station and for that reason it is important to assess each railway station or other transport interchange individually to identify what legislation is applicable and its resulting consequences.

Currently CO_2 is used to provide an indication of the efficiency of control measures for DEEEs, however, as Section 2.2.3 demonstrates, this has frequently been taken out of context and used in transport environments as an indicator of high levels of DEEEs. There has been little research to support its use as a surrogate for measuring high levels of DEEEs. Therefore, subsequent research should assess its capability of indicating high levels of DEEEs by assessing its performance in transport interchange environments. Guidelines highlight that the use CO_2 as a control measure may not be suitable in all locations, thus its suitability should be assessed in transport environments where high levels of DEEEs are present.

Finally, current literature on ventilation of transport environments, including semi-enclosed transport interchanges; suggest that it only requires a small change to the geometry to alter the ventilation patterns. Hence, ventilation is dependent upon a variety of factors, such as meteorological factors and vehicle flow, which will alter in each transport interchange. Therefore, future research should not attempt to apply conclusions from similar transport interchanges, but rather assess each environment individually and investigate the effect of this on pollutant concentrations.

2.5 Aim and Objectives

The aim of this research is to investigate air quality and its controlling mechanisms in and around Birmingham New Street railway station and to expand knowledge on transport interchanges, which shall be achieved through the following objectives:

1. Develop a comprehensive air quality monitoring campaign.
2. Quantify the air quality at Birmingham New Street railway station.
3. Determine the extent of which CO_2 measurements are a suitable surrogate for air quality assessment.
4. Assess meteorological condition within and around the station, as well as vehicle-induced turbulence, and investigate their impact on station air quality.
5. Analyse the response of air quality to emissions produced by the presence of diesel and electric rolling stock.
6. Inform development methodologies for interventions to reduce pollutant concentration.
7. Identify key parameters that should be considered in future air quality sampling campaigns at transport interchanges.

3. METHODOLOGY

3.1 Overview

Air quality monitoring at Birmingham New Street station consisted of four types; diffusion tube sampling, continuous monitoring, mobile monitoring and personal monitoring. Diffusion tube sampling, conducted first, provided an indication of the areas most significantly affected by air pollution. The diffusion tube results were used to understand the variation in pollution concentration across the entire station. Diffusion tubes provided a good spatial resolution at an affordable cost, making diffusion tubes ideal for preliminary sampling. Furthermore, diffusion tubes are widely used across cities around the UK, including Birmingham, therefore a comparison with this wider network can be made.

To understand the dispersion of pollutants within the station and their contributing factors, continuous monitoring was conducted. Continuous monitoring provided a high temporal resolution and as a result showed the sub-hourly, hourly, daily and weekly variations of air quality and the impact of meteorological conditions and train movements on pollutant concentrations, as discussed in Chapters 5 and 6.

As continuous monitoring was only conducted along one ‘island’, it was important to gather high temporal resolution data from other areas of the station and therefore mobile monitoring was carried out alongside the continuous monitoring. The mobile monitoring site was relocated around the station on a weekly basis. These measurements illustrated platform variation whilst maintaining high temporal resolution. Coupling these two methods provided a clear representation of air pollution in all areas of Birmingham New Street station.

Finally, personal monitoring provided an insight to staffs’ exposure to air pollution. The results highlighted the difference in exposure for those who spend the majority of their shift at concourse level and those who are working at platform level. However, due to instrument limitations and sampling errors, these results were not deemed reliable; therefore analysis of the data has not been included in the thesis. Instead, a report on personal monitoring at Birmingham New Street station can be found in Appendix A including detailed methodology for future reference for other air quality monitoring campaigns at transport interchanges.

The air quality sampling campaign commenced at 0000 on Tuesday 18th October 2016 and continued until 0000 on Tuesday 24th January 2017.

Following the Birmingham New Street sampling campaign, data from all aspects of the campaign was pooled together and validated in preparation for analysis. Three analysis areas were identified to address the aims and objectives of the research (Section 1.1). These analysis areas were:

1. Evaluation of air quality at Birmingham New Street station; analysing the diffusion tube results, continuous monitoring results and mobile monitoring results.

2. Environmental analysis; assessing contribution of meteorological factors to air quality at Birmingham New Street station.

3. Vehicle movement analysis; assessing the impact of train movements on air quality at Birmingham New Street station.

3.2 Birmingham New Street Station Sampling Campaign

3.2.1 Diffusion Tubes

Monitoring Technique

To monitor NO_2 in Birmingham New Street station and the surrounding areas, Palmes-Type diffusion tubes with 20% triethanolamine in 80% water were used (Gradko, 2012; 2014). These plastic monitoring tubes, which measure inorganic compounds, are 7cm tall and 1.5cm in diameter. The NO_2 diffusion tubes are sealed by a grey cap, at the top, containing grids and absorbents and a white cap at the bottom, which is removed during sampling. An image of the diffusion tubes used can be found in Appendix B.1.

Diffusion tubes work via a process known as molecular diffusion, during which compounds move from highly concentrated areas to areas of lower concentration. These compounds are absorbed by the absorbent in the grey cap at the top of the tube, thus a low concentration within the tube is maintained and molecular diffusion continues.

The tubes were resealed using the white cap at the end of the sampling period and returned to Gradko for analysis. Gradko used the in house Laboratory Method GLM7, UKAS accredited, to calculate the mass of nitrate in the tube. The average NO_2 concentration was then calculated, by Gradko, using a series of equations and known variables, as found in appendix B.2.

As the diffusion tube sampling was only for a limited period of time, a vandalised site would create a considerable gap in the data. Thus, to prevent the loss of data, the diffusion tubes

were placed in triplicates at each site; therefore if one tube were to be vandalised or stolen this would not have a significant impact on results. Furthermore, to deter vandals and thieves, all diffusion tubes were placed at approximately 3m above the platform. In addition, sets of triplicates allowed the possibility of determining the uncertainty in the data.

Monitoring Locations

There were three sites on each of the 12 platform in Birmingham New Street station and each site comprised of three diffusion tubes. The sites were located at the both ends and middle of each platform (Figure 3.1). Due to the platforms being open at either end, it was suspected that the exchange of air would cause the NO_2 concentrations at the ends of the platform to differ from that in the middle. Therefore, placing the tubes in these locations examined the variation along the platform.

Whilst alterations to the platforms have been made during the recent redevelopment, such as the removal of waiting rooms, air flow between platforms is still restricted by escalators, lifts, stairs and staffs' break rooms. As a result, pollutant concentrations may vary significantly between platforms as pollutants have restricted dispersion to less polluted areas of the station. Installing diffusions tubes across all 12 platforms of the station allowed visibility of variation in pollutant concentration across all platforms.

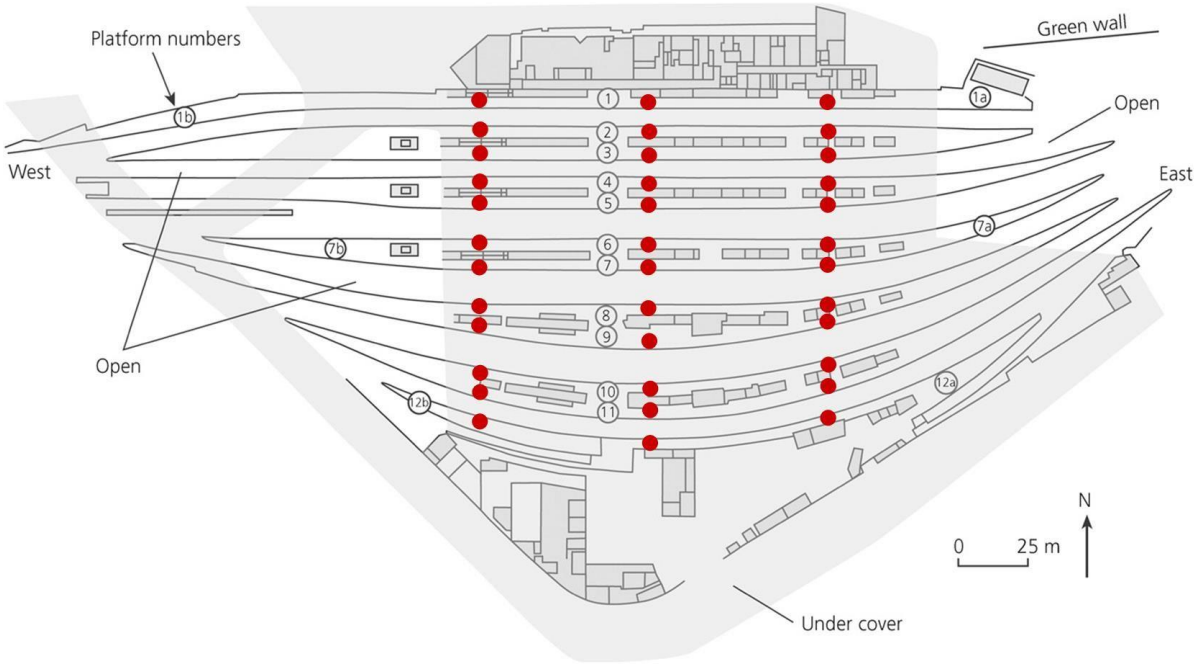

Figure 3.1. Diffusion tube monitoring location at platform level in Birmingham New Street Station.

The lifts, stairs and escalators leading up from platforms to access the concourse could allow pollutants to rise up into the concourse above. To investigate this there were three diffusion tube sites in the concourse, one in the red, blue and yellow lounge (Figure 3.2). The blue and yellow lounges are located in the East end of the concourse, the blue lounge diffusion tube site was located near the seating area between platforms 1 and 2 and the yellow lounge site was located near the seating area between platforms 11 and 12. The red lounge is located in the West end of the concourse and the respective diffusion tube site near the seating area between platforms 5 and 6. All three sites had three diffusion tubes each.

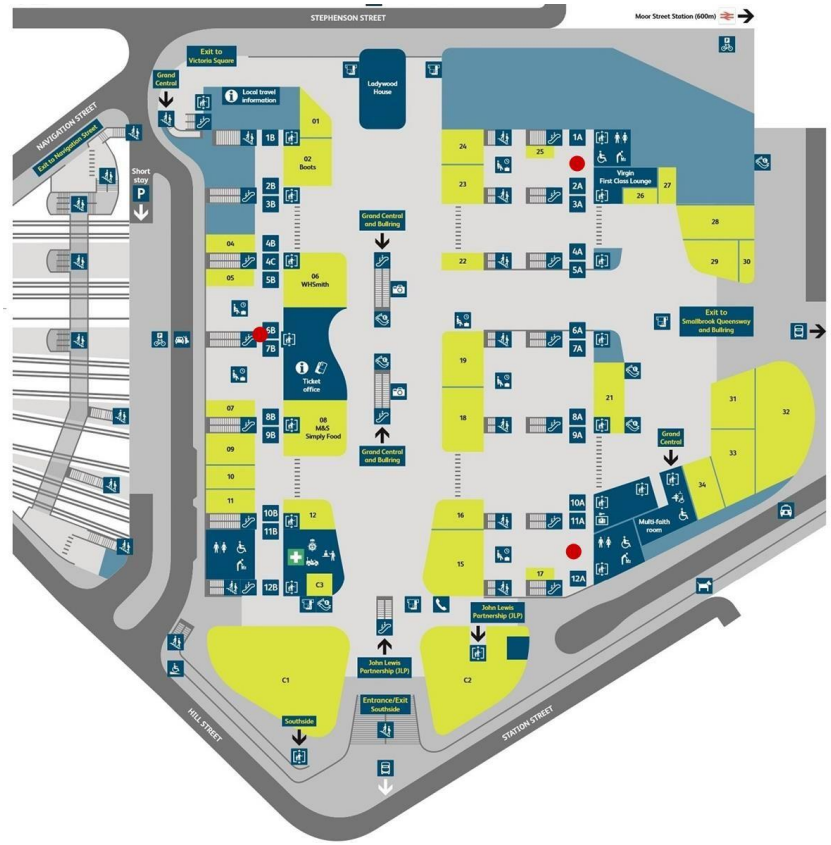

Figure 3.2. Diffusion tube monitoring location at concourse level in Birmingham New Street Station.

As Birmingham New Street station is a semi enclosed environment there will be air exchange between the city centre and the station. Therefore, diffusion tubes were also placed in streets surrounding Birmingham New Street station to analyse the impact the station has on the surrounding area and the impact the surrounding area has on the station. A variety of locations were systematically selected with the guidance of Birmingham City Council. Some sites were in close proximity to the station, to gain an understanding of the implication on/from the immediate area, and other sites further away (Figure 3.3), to examine the variation of NO_2 concentration across the city centre.

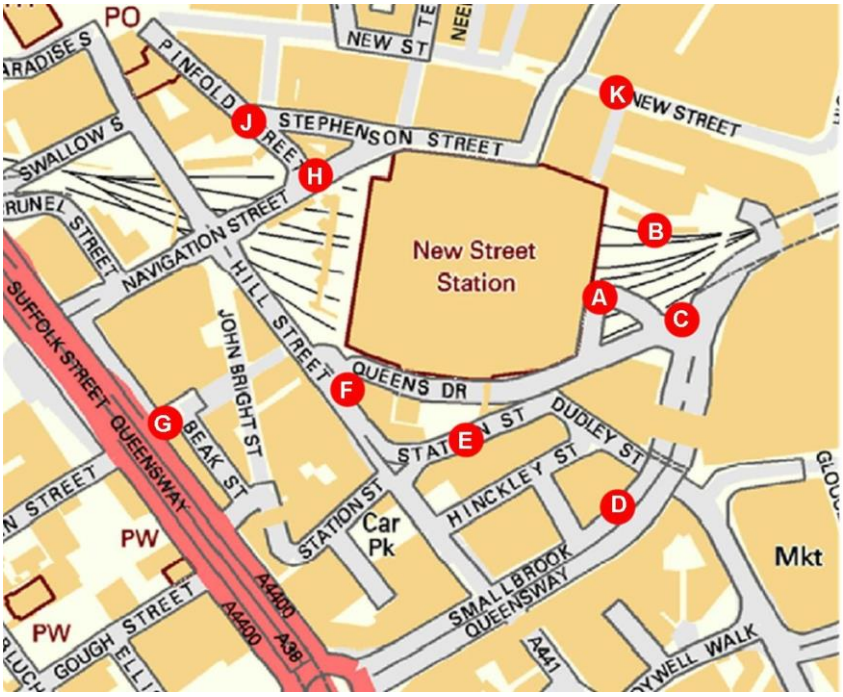

Figure 3.3. Diffusion tube monitoring locations surrounding Birmingham New Street Station (A-K, excluding I).

Monitoring Schedule

Diffusion tube monitoring was performed over a four week period from Tuesday 18th October 2016 until Tuesday 15th November 2016.

The monitoring period was split into two 2-week sampling periods; Tuesday 18th October until Tuesday 1st November 2016 and Tuesday 1st November until Tuesday 15th November 2016. The diffusion tubes were replaced with new diffusion tubes after the first monitoring period, creating two sets of results. Two 2-week sampling periods were selected over one 4-week sampling period to improve the accuracy of the results.

Diffusion Tube Bias Adjustment

Diffusion tubes are an indicative sampling technique and can help identify areas with high NO_2 concentrations, however, they are not as precise or accurate as automatic chemiluminecense analysers and have a high uncertainty (Targa et al., 2008). Therefore, DEFRA's Local Air Quality Management Technical Guidance 16 TG(16) (DEFRA, 2016b) recommends co-locating a set of diffusion tubes alongside a chemiluminescence analyser and comparing the results of the two techniques with the AEA's DifTPrecisionAccuracyBias (DifTPAB) spreadsheet in order to investigate their accuracy and precision (Targa, 2011).

For both diffusion tube monitoring periods, 18th October 2016 to 1st November 2016 and 1st November 2016 to 15th November 2016, three diffusion tubes were co-located alongside the Horiba Ambient NO_x monitor APNA-360 on Moor Street Expressway, B4100, in Birmingham. Details of the Horiba Ambient NO_x monitor APNA-360 can be found in Section 3.2.2 – Monitoring Technique. The tubes were placed within 1m of the analyser inlet and the tubes were spaced 10cm apart. The results from the diffusion tube analysis were compared with the Horiba APNA-360 analyser to determine a bias factor.

To determine the bias factor AEA's DifTPAB spreadsheet was used, as recommended by DEFRA (DEFRA, 2017b). The spreadsheet requires the input of the diffusion tube results from the co-location site, the mean NO_2 value from the automatic analyser for the same period and the percentage data capture of the automatic analyser. The tool outputs a bias factor with 95% confidence interval. For the diffusion tubes in this campaign the bias adjustment was **0.89 ± 0.02**. All diffusion tube results from Birmingham New Street station and the surrounding area were multiplied by this factor.

3.2.2 Continuous Monitoring

Monitoring Technique

After the diffusion tube sampling, continuous monitoring was conducted on platform 10/11. Platform 10/11 was chosen as it predominantly serves diesel trains, many of which idle for a significant period of time, resulting in platform 10/11 having one of the highest NO_2 concentrations during the diffusion tube monitoring. Furthermore, due to the curved nature of the platforms on the south side of the station (higher platform numbers), the platforms in this area of the station are likely to experience the poorest ventilation, resulting in minimal dispersion of pollutants and therefore, higher concentrations.

Three monitoring stations were set up on platform 10/11, one at each end of the platform and another in the middle of the platform. The monitoring stations comprised of an air quality enclosure, housing all monitoring and data logging equipment. The fiberglass (GRP) enclosures (Figure 3.4), supplied by EnviroTechnology, were 1100 mm wide, 1250 mm high and 650 mm deep, however, they were placed on a pallet for easy removal, raising the overall height by 150 mm. The enclosures were connected to a mains supply at the station and had

electrical distribution with RCD/MCB consumer unit and multiple 13A power sockets to power the equipment inside. A mesh cage with a top opening lid, secured with a padlock, was mounted to the top of the cage over the instrument inlets, to stop the public tampering with the equipment inlets. The mesh cage dimensions were 500 mm wide, 550 mm high and 600 mm deep. Following the advice of Birmingham City Council, the enclosure was not fitted with an air conditioning unit, as it was perceived unnecessary as sampling was conducted during autumn and winter. Instead, an extractor fan was fitted to each enclosure to reduce the build-up of heat within the enclosure.

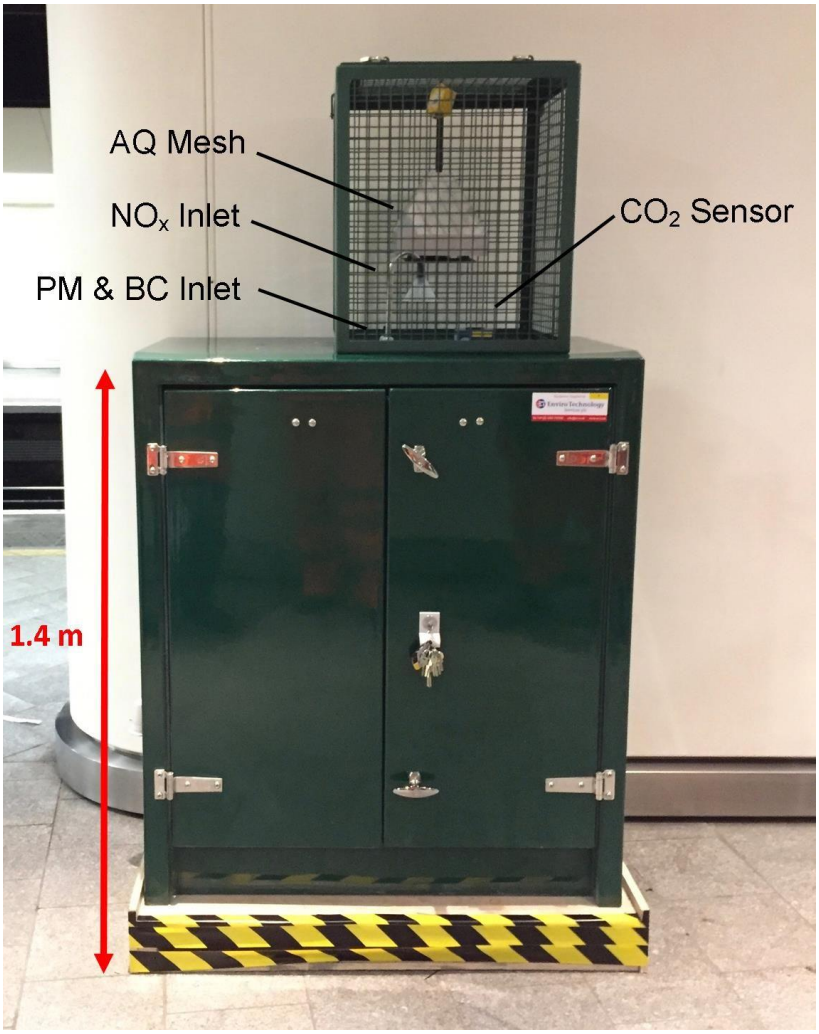

Figure 3.4. Image of continuous monitoring site with labels to the monitoring inlets and sensors in the cage on the top of enclose.

The monitoring sites measured oxides of nitrogen, particulate matter, black carbon, carbon dioxide and meteorological variables. NO_x, PM, BC and CO_2 were all measured at one second intervals. Some trains are only present at Birmingham New Street station for a minute, therefore sampling at a frequency of more than one-minute would not be adequate, as this would not capture the difference in pollution concentrations for these services. For the purpose of this study, concentrations were averaged to minute, hourly and daily concentrations. However, sampling at such a high frequency enables the possibility of more

in-depth analysis in future research. In addition, the lag times of the individual instruments can be taken into consideration.

For the same reason as above, wind velocity was also monitored at 1 Hz frequency, enabling the anemometers to capture the turbulence caused by rolling stock arriving and departing the station. Moreover, it is particularly beneficial to match the monitoring frequency of the pollutants and wind velocity, as the relationship between these variables is investigated in Chapter 5.

Temperature was monitored at a lower frequency of 10 minute averages. It was assumed that temperature would not vary significantly with the arrival and departure of trains into the station. Instead, outdoor ambient environment would be influencing the temperature inside the station most significantly.

Similarly to diffusion tube monitoring, three monitoring sites were placed along the platform as it was suspected that the open ends of the platform would be influencing concentrations in these locations. Furthermore, services with fewer cars may only serve one half of the platform and as a result, could cause concentrations to rise at one end of the platform. Therefore, monitoring sites A and B were set up at the A and B ends, respectively, to investigate the variation along the platform.

Each monitoring station housed a bespoke data logging system designed by Birmingham Centre for Railway Research and Education (BCRRE). Each data logger fed data back to the central site system via Wi-Fi. The data files for each site were stored on the central site system every 10 minutes and uploaded to Google Drive enabling near immediate access to the data. In addition, a live data feed was created to allow the monitoring of instruments away

from site and errors with the instruments could be identified, resulting in errors being resolved efficiently.

Oxides of Nitrogen

Oxides of nitrogen are one of the pollutants present in diesel engine exhaust emissions (DEEEs) and there is a European Air Quality Standard and a WEL to limit NO_2 concentration in order to prevent excessive exposure of this pollutant. Hence, it was of significant interest to monitor oxides of nitrogen during the continuous sampling.

Concentrations of NO, NO_2 and NO_x were continuously monitored at one second intervals by a Horiba Ambient NO_x APNA-360 analyser. This analyser uses the cross-flow-modulation type semi-pressure-reduced chemiluminescence method (CLD method) (Horiba, 2002). An image of the instrument can be found in Appendix B.1 and the specification in Appendix B.3.

The instrument was placed inside the air quality enclosure with the inlet exposed at the top of enclosure, close to breathing height (Figure 3.4). The instrument was connected to the data logging system designed by BCREE.

In addition, an AQ Mesh was also used to measure oxides of nitrogen. The AQ Mesh is a compact and affordable instrument that uses electrochemical sensors. These work by reacting to the target gas, in this instance oxides of nitrogen, and generating an electric output that varies with the amount of target gas present (Townend, 2017). An image of the instrument can be found in Appendix B.1 and the specification in Appendix B.3.

The AQ Mesh was housed inside the cage mounted to the top of the enclosure, which prevented the instrument from being vandalised (Figure 3.4). As the instrument is self-

sufficient, it did not require a power source or external data logger; instead, it fed data back to a cloud based system at 15-minute intervals via a GRPS signal.

The primary use of this instrument was to provide a reference for the AQ Mesh instrument that was used for mobile monitoring, as discussed in Section 3.2.2 – Instrument Correction Factors.

Particulate Matter

Particulate matter is another pollutant present in DEEEs and $PM_{2.5}$ and PM_{10} are both bound by EU air quality standards, therefore it was appropriate to measure this pollutant in the continuous monitoring.

A TSI DustTrak DRX Desktop 8533 was used to measure particulate matter. The DustTrak uses a method that simultaneously measures size segregated mass fraction concentration. The method combines photometric measurement, for mass concentration, and a single particle detection measurement, to differentiate particle size in the sampled aerosol (TSI Inc, 2012). An image of the instrument can be found in Appendix B.1 and the specification in Appendix B.3.

The DustTrak measured particulate matter mass concentration at four size fractions (PM_1, $PM_{2.5}$, PM_{resp}, PM_{10}) and the total particulate matter concentration (PM_{total}) every second. However, only $PM_{2.5}$ and PM_{10} were used recorded during the sampling campaign.

The instrument was situated inside the enclosure and the inlet exposed from the top of the enclosure, similar to the Horiba Ambient NO_x analyser (Figure 3.4). This instrument was also connected to the data logger designed by BCRRE. Although the instrument can be self-sufficient, it did not have enough memory to store the data at such a high frequency.

Black Carbon

Black carbon is a good indicator of diesel emissions and therefore was included in the continuous monitoring.

Black carbon was measured with an AE33 Aethalometer. The AE33 Aethalometer works by continually collecting aerosols on a filter with simultaneous measurement of attenuation of transmitted light at seven wavelengths from 370 nm (near ultraviolet) to 950 nm (near infrared) to give a full spectrum analysis (Magee Scientific, 2015). Black carbon concentration measurement is obtained by the absorption measurement at 880 nm only, therefore this was the only measurement recorded from the AE33 during this sampling campaign. An image of the instrument can be found in Appendix B.1 and the specification in Appendix B.3.

The Aethalometer measured black carbon concentration at one-second intervals in order to capture variation with train activity. As with the Horiba APNA-360 and DustTrak DRX 8533, the inlet for the AE33 aethalometer was exposed from the top of the enclosure, inside the cage (Figure 3.4). This instrument was connected to the data logger designed by BCRRE.

Carbon Dioxide

To determine whether CO_2 is an appropriate surrogate for other pollutants, a COZIR CO_2 sensor was used to monitor CO_2 at one second intervals. The COZIR CO_2 sensor uses a diffusion sampling method and non-dispersive infrared (NDIR) absorption sensing method. The CO_2 sensor was connected to the data logger designed by BCRRE.

An image of the instrument can be found in Appendix B.1 and the specification in Appendix B.3.

Temperature

TGP-4500 Tingtags were used to monitor temperature during the sampling campaign. These instruments were attached to the top of the cage on each enclosure at approximately 1.95 m high. As temperature would not fluctuate significantly in this environment, unlike air pollution, temperature was measured as 10-minute averages in degrees Celsius.

The instrument is self-sufficient; it is powered by its own internal battery, with a battery life of one year, and can store 320,000 readings on its internal logger (Gemini, 2011). Therefore, it was capable of storing all readings throughout the duration of the campaign and measurements were downloaded directly from the instrument at the end of the campaign. Prior to deployment, the Tinytags were connected to a PC to ensure that their timestamp aligned with the data logging system.

An image of the instrument can be found in Appendix B.1 and the specification in Appendix B.3.

Wind Velocity

To measure wind speed and direction Gill R3-100 Ultrasonic Anemometers were mounted at both ends of the platform, close to the monitoring sites at either end of the platform (Figure 3.5 - 3.7). The ultrasonic anemometers were connected to the PCs at the respective sites to log 3-component wind velocity at 1 Hz sampling rate. From this, wind speed, wind direction and turbulent kinetic energy (TKE) were calculated. TKE was calculated using the following equation:

$$TKE = \sqrt{(u - \bar{u})^2 + (v - \bar{v})^2 + (w - \bar{w})^2} \tag{3.1}$$

Monitoring Locations

The three monitoring sites were located on platform 10/11, one site at each end of the platform (site A and B), near the tunnel openings, and one site in the centre of the platform. Two wind sonic anemometers monitored wind velocity at the extreme ends of the platform and were connected to their respective monitoring site.

Figure 3.5 illustrates the location of the continuous monitoring sites and the respective wind sonic anemometers.

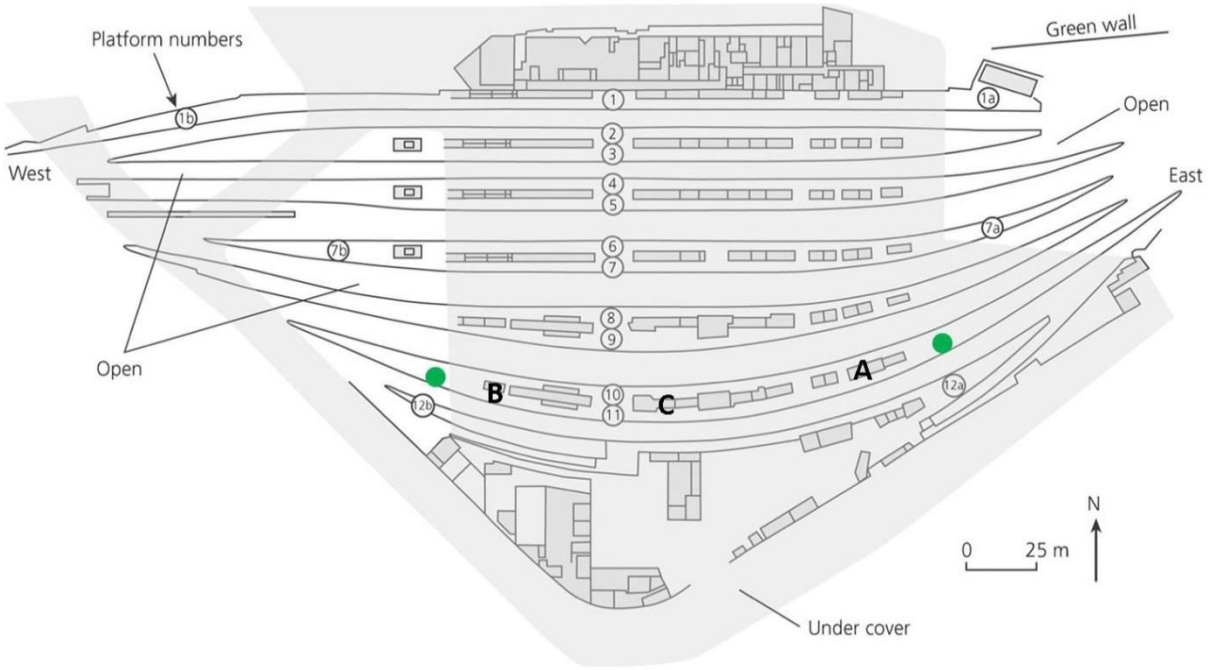

Figure 3.5. Continuous monitoring locations (A, B and C) at platform level in Birmingham New Street station. Green circles indicate location of the respective wind sonic anemometers.

Site A was situated at the east end of platform 10/11, with its respective wind sonic anemometer mounted within close proximity (Figure 3.6) and site B was at west end of the platform (Figure 3.7), with its wind sonic anemometer mounted nearby. The air quality monitoring station at both locations consisted of a Horiba Ambient NO_x APNA-360 analyser, a DustTrak DRX Desktop 8533, a CozIR CO_2 sensor, and a TGP-4500 Tinytag, monitoring NO_x, PM, CO_2 and temperature.

Site C, the central monitoring station in the middle of platform 10/11 (Figure 3.8), included a Horiba APNA-360 Ambient NOx analyser, a DustTrak DRX Desktop 8533, an AE33 Aethalometer, an AQ Mesh, a CozIR CO2 sensor and a TGP-4500 Tinytag, monitoring NO_x, PM, black carbon, CO_2, and temperature.

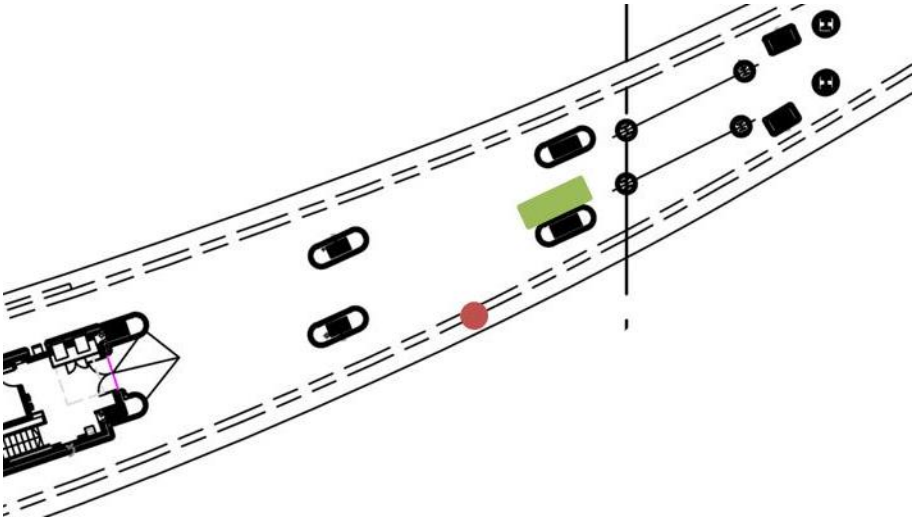

Figure 3.6. Diagram of the location of Site A monitoring site at the east of platform 10/11 (green box) and its respective wind sonic (red circle).

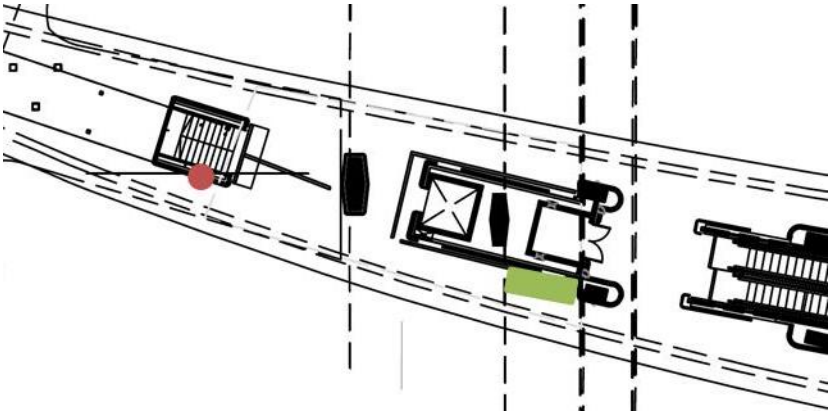

Figure 3.7. Diagram of the location of Site B monitoring site at the west of platform 10/11 (green box) and its respective wind sonic (red circle).

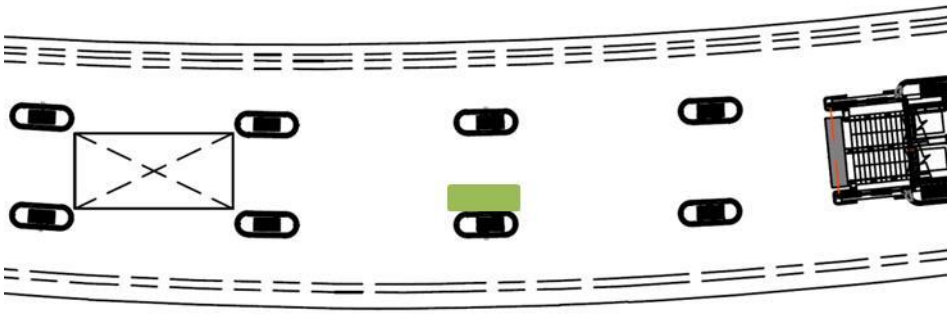

Figure 3.8. Diagram of the location of Site C monitoring site in the centre of platform 10/11.

Monitoring Schedule

Monitoring commenced on Thursday 17th November 2016 at 0000 and continued until Tuesday 24th January 2017 at 0000.

All three Horiba APNA-360 NO_X analysers were returned to the manufacturer to be rescaled due to the instrument previously being scaled for ambient conditions and concentrations within Birmingham New Street were greatly exceeding the instruments upper range. Consequently, all three instruments were removed from site on Tuesday 6th December 2016 at 0000 and were returned on Thursday 8th December 2016 at 0000. As the instrument was breaching the upper range prior to the rescaling of the instrument, data prior to their return on Thursday 8th December 2016 was deemed inaccurate and therefore discarded from the data set.

Due to a delivery delay, the COZIR CO_2 sensors were late to be installed on site and sampling commenced on Thursday 1st December at 0000.

Instrument Correction Factors

For the continuous monitoring, only the DustTraks and AQ Mesh required co-location, as these were not deemed to be 'reference' instruments. As a result, their reliability was investigated and a correction factor for each instrument was determined.

The correction factors were derived from the gradient and intercept of the linear regression line when plotting the concentration from the instrument against the concentration from a reference instrument.

The following equation was applied to the raw data to obtain corrected data for the pollutant measured:

$$x_c = \frac{x_r - C}{M}, \tag{3.2}$$

where x_c is the corrected data, x_r is the raw data, C is the intercept of the linear regression line and M is the gradient of the linear regression line.

AQ Mesh

Two AQ Mesh instruments were used during the Birmingham New Street sampling campaign; one at the central site and another for mobile monitoring, discussed in Section 3.2.3.

The central site AQ Mesh was situated alongside a Horiba APNA-360 analyser at the central site on platform 10/11 between 0000 on Thursday 8th December 2016 and 2359 on Monday 23rd January 2017. Due to the rescaling of the Horiba APNA-360 analyser beginning of the

monitoring campaign, the first 21 days of data, Thursday 17th November 2016 to Thursday 1st December 2016, were discarded from both datasets before calculation correction factors.

The mobile AQ Mesh was used for mobile monitoring and was co-located with the central site AQ Mesh from 0000 on 25/01/2017 until 2359 on 01/02/2017 on platform 12 at the B end of the platform.

Error readings were removed from each data set and the corresponding data set prior to co-location analysis. Error readings included 9999 and -999 values from the Horiba APNA-360 analyser when the instrument had an error or the data logger was unable to communicate with the instrument respectively and blank readings from the AQ mesh when it was unable to record.

AQ Mesh monitors at one-minute intervals, whereas the Horiba APNA-360 logs data every second, consequently one minute averages of NO, NO_2 and NO_x were taken from the Horiba APNA-360 in preparation for comparison with the AQ Mesh.

The central site AQ Mesh was plotted against the Horiba APNA-360 ambient for the pollutants NO, NO_2 and NO_x, and linear regression lines were applied (Figure 3.9). AQ Mesh instruments have a range of 8000 ppb for NO_x and 4000 ppb for NO and NO_2 (full specification can be found in Appendix B.3), which can be clearly seen in Figure 3.9 as NO_x and NO begin to plateau as they reach ~ 10000 ppb. The AQ Mesh calculates NO_x as a sum of NO and NO_2, hence, NO begins to plateau at a slightly lower concentration than NO_x, therefore it is impossible to correct data above this threshold and data analysis should take this into consideration.

The mobile AQ Mesh was plotted against the central site AQ Mesh for the same pollutants, after the correction factor was applied to the central site AQ Mesh data, and linear regression

lines were applied. The equation of the linear regression lines denotes the correction factor for the corresponding pollutant (Table 3.1).

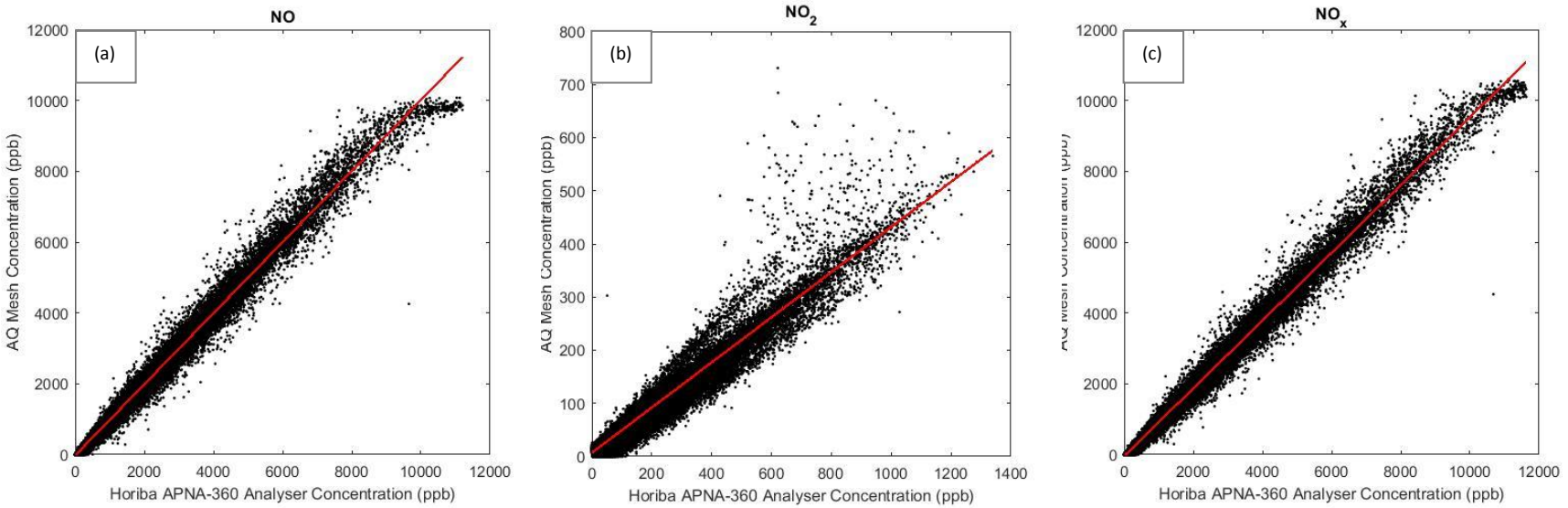

Figure 3.9. Co-location plots for the central site AQ Mesh against the central site Horiba APNA-360 Analyser for the pollutants (a) NO, (b) NO_2, (c) NO_x between 08/12/2016 and 23/01/2017 with a linear regression line (red line) Note, the red lines do not take the plateau region into account.

Table 3.1. Correction factors for NO, NO_2 and NO_x for both the central site AQ Mesh and the mobile AQ Mesh, the Pearson correlation coefficient and R-squared value. Note, all correlation coefficients are statistically significant to 99% confidence interval. The corresponding correlation plot for the mobile AQ Mesh can be found in Appendix B.4.

Instrument	**Variable**	**Gradient**	**Intercept**	**Pearson correlation co-efficient**	**R^2**
Central Site AQ Mesh	NO	1.00	22.3	0.994	0.987
	NO_2	0.425	7.08	0.967	0.934
	NO_x	0.957	-0.0488	0.994	0.989
Mobile AQ Mesh	NO	0.696	60.9	0.970	0.941
	NO_2	0.383	7.00	0.975	0.951
	NO_x	0.673	48.2	0.971	0.943

As with a lot of air quality monitoring equipment, the AQ Mesh is primarily used in ambient conditions and in such environments, the AQ Mesh correlates well with reference instruments (Borrego et al., 2016; Carruthers et al., 2016). However, there has been diminutive research into its performance against reference instruments in highly polluted environments, such as Birmingham New Street station. Table 3.1 illustrates that the central site AQ Mesh NO and NO_x concentrations correlate well with NO and NO_x concentrations measured by the Horiba APNA-360 analyser. However, Table 3.1 shows that NO_2 concentration is being under predicted by the central site AQ Mesh and concentrations in the station are in fact twice as

high. This under prediction of NO_2 concentration may be the result of the instrument not coping as well in a highly polluted environment.

Comparison of the raw data from both the central site and mobile AQ Mesh instruments shows some discrepancy between the instruments, therefore, contributing to greater correction factors for the mobile site AQ Mesh when correlated against the central site AQ Mesh after the correction factor was applied.

It is clear that the accuracy of the AQ Mesh is limited in highly polluted environments, however, despite this, all correlations were statistically significant, therefore it is still possible to apply a correction factor to obtain suitable data from these instruments.

TSI DustTrak DRX Aerosol Monitor 8533

Four DustTraks were used in total during the Birmingham New Street sampling campaign, three were used for the continuous monitoring (DustTrak A-C) and another was used for mobile monitoring (DustTrak D), discussed in Section 3.2.3.

The DustTraks were co-located against the TEOM FDMS analyser at Birmingham City Council's Tyburn Road air quality monitoring site, located north east of the city centre (Figure 3.10). TEOM FDMS instruments are used in DEFRA's Automatic Urban and Rural Network (AURN) for air quality monitoring. However, unlike the Horiba APNA-360 NO_x analyser, the TEOM FDMS is not MCERTS certified for UK particulate matter, instead it is DEFRA approved and meets their equivalence criteria (DEFRA, 2016a). As a result, it is acceptable to use the TEOM FDMS as a reference for other particulate matter instruments.

Figure 3.10. Location of the Tyburn Road monitoring site; Black circle highlights the location of the Tyburn Road monitoring site, north east of Birmingham City Centre at 52°30'42.2" N, 1°49'50.1"W (Bing, 2017).

Co-location with the TEOM FDMS analyser was conducted from Friday 28th October 2016 at 1700 until Tuesday 1st November 2016 at 1000. The hourly averages during this period were compared to the hourly averages from Birmingham City Council's TEOM FDMS.

During this period two errors occurred with the DustTraks. Between 0400 and 1000 on Monday 31st October 2016, DustTrak D recorded very high levels of particulate matter, which did not align with the results from the other DustTraks or the TEOM FDMS at Tyburn Road. It was assumed that the inlet had been obstructed during these hours, therefore, the data was removed from the data set prior to co-location analysis to avoid skewing the results. DustTrak C also experienced a flow error and stopped recording at 1400 on Monday 31st October 2016; hence, the correction factor for this instrument was calculated using data from Friday 28th October 2016 at 1700 to Monday 31st October 2016 at 1400.

In addition, no data was recorded by the TEOM FDMS at Tyburn Road at 0300 on Monday 31st October 2016 and 0300 on Tuesday 1st November 2016 and thus, the respective data from the DustTraks was also removed from the datasets before calculating a correction factor.

The DustTraks record particulate matter concentration in mg/m^3; so, prior to analysis taking place, the concentrations were converted to $\mu g/m^3$, by multiply concentrations by 1000, in order to be in line with the TEOM FDMS measurements.

For each of the four DustTraks, for both $PM_{2.5}$ and PM_{10}, the concentrations were plotted against the Tyburn Road TEOM FDMS concentration and a linear regression line applied. An example of this is shown in Figure 3.11 for DustTrak A. The equation of the linear regression line represented the correction factor for that instruments and pollutant (Table 3.2).

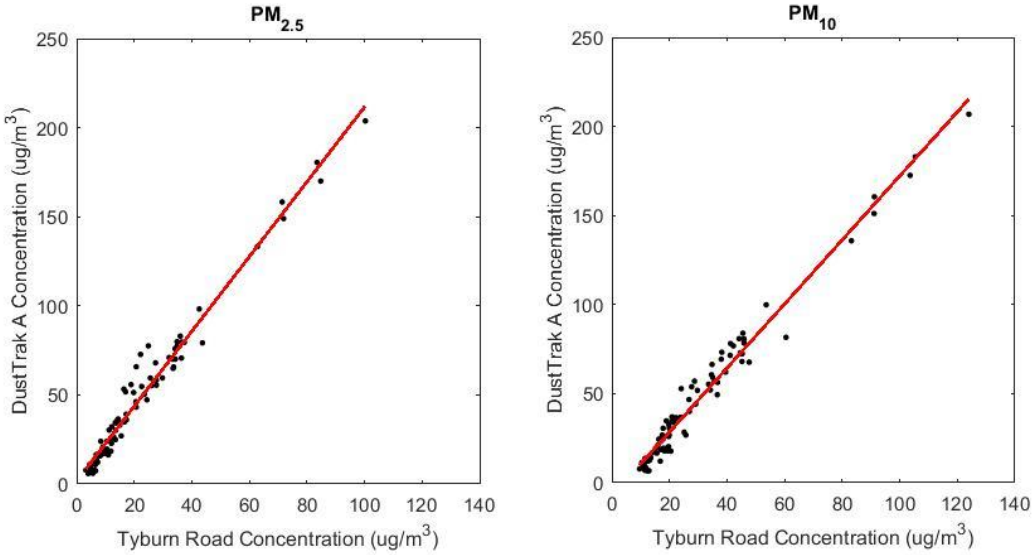

Figure 3.11. DustTrak A correlated against Tyburn Road FDMS TEOM for $PM_{2.5}$ (left) and PM_{10} (right). Co-location took place between 1700 on 28/10/2016 and 1000 on 01/11/2016, excluding the data at 0300 on 31/10/2016 and 0300 on 01/11/2016. Red line is linear regression line.

Table 3.2. Correction factors for DustTraks A-D and correlation coefficient, R-squared value and p-value for the correction factor. Note, all correlations are statistically significant to 95% confidence interval. Corresponding correlation plots for DustTraks B-D can be found in Appendix B.5.

Instrument	Variable	Gradient	Intercept	Pearson correlation co-efficient	R^2
DustTrak A	$PM_{2.5}$	2.10	1.68	0.987	0.971
	PM_{10}	1.80	-7.49	0.987	0.974
DustTrak B	$PM_{2.5}$	1.79	3.57	0.987	0.973
	PM_{10}	1.53	-4.28	0.987	0.974
DustTrak C	$PM_{2.5}$	2.32	-1.63	0.973	0.945
	PM_{10}	2.09	-13.7	0.966	0.931
DustTrak D	$PM_{2.5}$	2.61	8.93	0.987	0.974
	PM_{10}	2.26	-2.09	0.987	0.974

Unlike the AQ Mesh, the DustTrak overestimated PM concentration during its co-location with the FDMS TEOM at Tyburn Road. The overestimation for the DustTrak instruments ranged from a factor of 1.79 to 2.32 and a systematic bias ranging from -13.7 to 8.93 $\mu g/m^3$ (Table 3.2). Previously research as speculated that the bias in the intercept may be *"related to the nonlinearities in the relationship between measures at very low concentrations, or related to how particles of different composition affected the reading"* (Wang et al., 2016). Furthermore, the overestimation factor calculated during the co-location aligns with the overestimation calculated in other DustTrak co-location studies (Osman et al., 2007;

Ramachandran et al., 2000; Wallace et al., 2011; Wang et al., 2016; Yanosky et al., 2002). As all correlations are statistically significant to a 95% confidence interval and the correction factors lie within previous findings, it is reasonable to conclude that the correction factors displayed in Table 3.2 can be applied to the raw $PM_{2.5}$ and PM_{10} concentrations measured with the DustTraks during the Birmingham New Street sampling campaign.

Data Quality Assurance

A series of data quality control procedures were undertaken prior to analysis to ensure data recorded reflected actual observations at Birmingham New Street station. To aid this, a log book was kept throughout the duration of the monitoring campaign to record any instrument errors or failures, any losses of data or any events that may have impacted the reliability of the results.

Incidents where errors were recorded, such as 9999 or -999 values, were removed from the dataset and replaced with NaN (Not a Number).

Due to being situated in a polluted environment, the AE33 filter tape ran out quicker than expected and was replaced every 2 to 3 weeks. This resulted in periods where no data was recorded during a filter change and a short three day period where no data was recorded as the delivery of more filter tape was awaited. These periods were assigned NaN in the dataset.

Furthermore, occasionally some instruments crashed due to internal errors, i.e. flow error, or external errors, i.e. WiFi router crashed, these periods were also assigned NaN in the dataset.

Once all the data had been cleaned and combined into a single master file per monitoring site, the units used to measure pollutants were converted to the units used in the air quality standards.

Horiba APNA-360 NO_x analyser concentrations were converted from ppm to µg/m^3 using the following equation:

$$\mu g/m^3 = \frac{(ppm \times 1000) \times P \times M}{R \times T} \quad (3.3)$$

Where P is pressure in kPa, M is molecular weight, R is the gas constant (8.3144 $J \cdot mol^{-1} \cdot K^{-1}$) and T is temperature in K. The pressure and temperature at the time of monitoring was used in this equation to execute the most accurate conversion. Pressure measurements were obtained from the central site AQ Mesh. Furthermore, the molecular weight of NO_x was calculated by calculating the percentage of NO and NO_2 at a given time and using these percentages to estimate the molecular weight of NO_x.

The AQ Mesh also required conversion from ppb to µg/m^3 using the following equation:

$$\mu g/m^3 = \frac{ppb \times P \times M}{R \times T} \quad (3.4)$$

where pressure measurements were obtained from the respective AQ Mesh.

Particulate matter was recorded as mg/m^3, therefore concentrations were multiplied by 1000 to obtain concentrations in µg/m^3.

Once all data was cleaned and converted to the correct units, data across all three sites was compared to assess its validity. In addition, NO_2 data was compared against the diffusion tube results to determine whether the Horiba APNA-360 analyser and AQ Mesh were outputting realistic results. The comparison of the diffusion tube and continuous monitoring results is discussed in Section 4.3.1.

3.2.3 Mobile Monitoring

Monitoring Technique

A limitation of the continuous monitoring was that only one platform was sampled at a high temporal resolution, therefore to support the continuous monitoring a mobile sampling method was used simultaneously, using a similar high temporal resolution. The main purpose of the mobile measurements was to understand how air pollution on other platforms compared with platforms 10/11, where continuous monitoring was taking place, and to determine which areas of the station are most significantly impacted by pollutants. The mobile monitoring site was moved between platforms on a weekly basis and monitored oxides of nitrogen and particulate matter.

Due to instrument limitations, it was not possible to monitor PM and NO_x at a one second frequency to align with the continuous monitoring. One minute averages for PM and NO_x were selected instead. This was deemed to be sufficient to compare the mobile monitoring sites to the continuous monitoring sites of platform 10/11.

Furthermore, as the mobile monitoring sites were not a permanent fixture on the platforms, a suitable and accessible location with adequate power supply was required. This could only be found near to the escalators at the B-end of the platforms. Note, due to the narrow width of platform 1, it was deemed unsafe to mount mobile monitoring equipment on this platform.

Oxides of Nitrogen

An AQ Mesh was used to monitor NO, NO_2 and NO_x during the mobile monitoring. This instrument was chosen over the Horiba APNA-360 analyser as it is lightweight and portable, at 2 kg, whereas the Horiba APNA-360 analyser is large and heavy, therefore it would have been difficult to move this instrument on a weekly basis. An additional benefit of the AQ

Mesh is its self-sufficiency, as it does not require a power source or external data logger; instead data was downloaded each week from its cloud based system.

As previously discussed, the AQ Mesh is not as accurate as the Horiba APNA-360 analyser; hence an additional AQ Mesh was installed alongside the Horiba APNA-360 analyser at site C on platform 10/11 to determine a correction factor for the AQ Mesh instruments, as discussed in Section 3.2.2 – Instrument Correction Factors.

The AQ Mesh was unable to sample at a one second frequency, unlike some of the other equipment used for continuous monitoring, instead oxides of nitrogen were measured as one minute averages.

The instrument was mounted against the wall at approximately 3m above the platform.

Particulate Matter

For consistency, particulate matter was monitored using a TSI DustTrak DRX Desktop 8533, details of which can be found in Section 3.2.2 – Monitoring Technique. Using the same instrument as the continuous monitoring allowed the results to be compared without considering any discrepancies between different instruments. Furthermore, the DustTrak is small and lightweight, weighing only 2.5 kg; therefore, making the instrument easy to move between platforms on a weekly basis.

The monitoring technique for mobile monitoring of particulate matter differed slightly from the continuous monitoring. Data was stored on the DustTrak's own internal logger as opposed to an external logger. The DustTrak has a capability of storing 60,000 data points, therefore, it was impossible to store one week of data at one second intervals. Instead, $PM_{2.5}$ and PM_{10} concentrations were recorded as one minute averages aligning with the sampling frequency of the AQ Mesh.

The DustTrak was placed securely behind a grid panel, situated at the bottom of the B-end escalator and the inlet was exposed from the grid panel at approximately 3m above the platform.

Monitoring Location

The mobile monitors were located at the B end of selected platforms, approximately 3m high (Figure 3.12). The B end of the platforms had more suitable locations to mount the instruments. No mobile monitoring was conducted on platform 1, due to it being a narrow platform, it was considered unsafe to mount these instruments at 3m high, as this would require being within an unsafe distance from the overhead line equipment (OLE).

In addition to conducting mobile monitoring at platform level, a period of monitoring was also carried out in the yellow lounge of the concourse (Figure 3.13). As the diffusion tube results (Section 4.2) indicated that pollutants were dispersing up into the concourse, it was beneficial to monitor NO_x in the concourse with a higher temporal resolution.

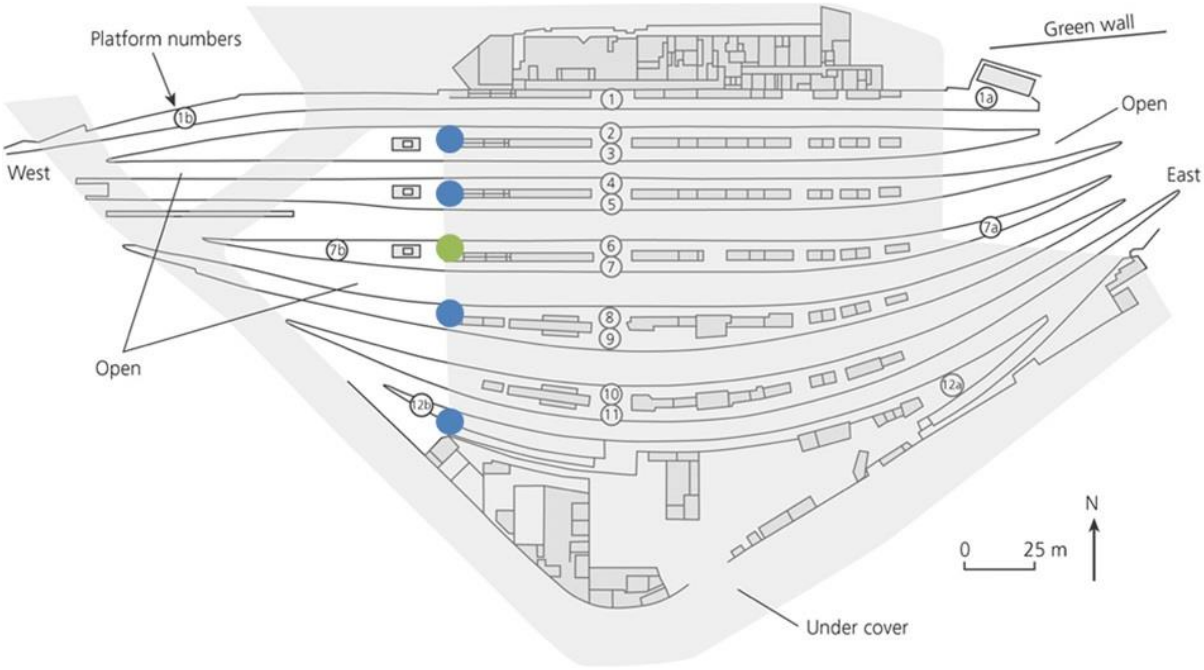

Figure 3.12. Mobile monitoring locations at platform level in Birmingham New Street station. Blue circles indicate where a DustTrak and AQ Mesh were present and green circles where only the AQ Mesh was present.

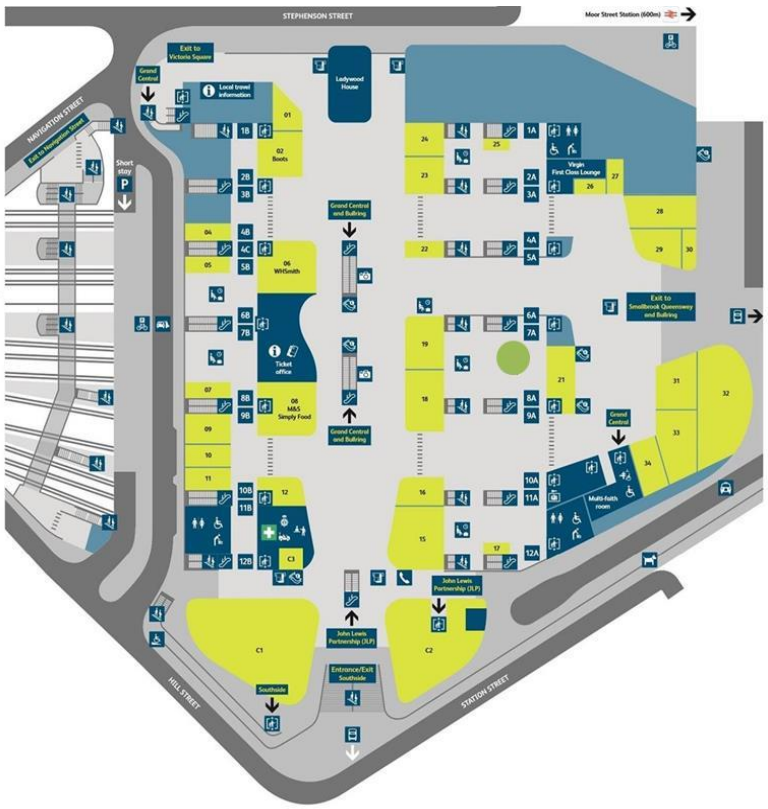

Figure 3.13. The green circle indicates the location of the AQ Mesh during the mobile monitoring in the concourse at Birmingham New Street station.

Monitoring Schedule

Mobile monitoring began on Tuesday 15th November 2016 at 0200 and continued until Tuesday 24th January 2017 at 0000 (Table 3.3). The AQ Mesh sampled for the entire 10-week period, however, the DustTrak was absent from sampling during week 2 and weeks 4-8.

In week 2, the instrument was returned to the lab at the University of Birmingham for some vital testing, which was required to aid the running of the continuous monitoring sites. In weeks 4 and 5, despite being present at the site, there was a flow error on the instrument, therefore these results were discarded. Over Christmas, weeks 6 through to 8, the DustTrak was not mounted in the concourse alongside the AQ Mesh as there was no power source for the DustTrak and the DustTrak internal battery would only last up to 12 hours.

In addition, a DustTrak error occurred during week 3 of sampling, as a result, the measurements made after the error occurred were removed and the data for week 3 was reduced to three days of sampling.

Table 3.3. Mobile monitoring schedule at Birmingham New Street detailing the location of the mobile AQ Mesh and DustTrak on a weekly basis.

Week	Date/Time	DustTrak Location	AQ Mesh Location
1	15/11/16 0200 – 22/11/16 0100	Platform 2/3	Platform 2/3
2	22/11/16 0200 – 29/11/16 0000	Not Present	Platform 4/5
3	29/11/16 0100 – 06/12/16 0000 (29/11/16 0100 – 01/12/16 0000 for DustTrak)	Platform 4/5	Platform 4/5
4	06/12/16 0100 – 13/12/16 0100	Not Present	Platform 6/7
5	13/12/16 0200 – 19/12/16 2300	Not Present	Platform 8/9
6			
7	20/12/16 0000 – 10/01/17 0000	Not Present	Concourse
8			
9	10/01/17 0300 – 17/01/17 0000	Platform 8/9	Platform 8/9
10	17/01/17 0100 – 24/01/17 0000	Platform 12	Platform 12

Data Quality Assurance

Periods where the DustTrak was not present at site or where an error occurred were replaced with NaN in the dataset. For the AQ Mesh, errors, recorded as blank cells, were replaced with NaN values.

Data was downloaded from each instrument at the end of each monitoring period at the given location. The NO_x concentrations, recorded on the AQ Mesh, were converted from ppb to $\mu g/m^3$ using equation 3.4 and PM concentrations, recorded on the DustTrak, were converted from mg/m^3 to $\mu g/m^3$ by multiplying concentrations by 1000.

3.3 Environmental Analysis

Temperature was selected as one of the variables for the environmental analysis as temperature can vary significantly day-to-day. Wind velocity was chosen as the second variable for environmental analysis in order to established if external wind conditions influence the flow patterns within the station and to investigate the effect of these flow patterns on concentrations.

3.3.1 Coleshill Weather Station

Meteorological measurements obtained from the Birmingham New Street station sampling campaign were compared against external meteorological conditions. Therefore, hourly temperature and wind velocity measurements were obtained from the Met Office Integrated Data Archive System (MIDAS) through the British Atmospheric Data Centre (BADC) for Coleshill WMO Weather Station, which is located 4.5 km East of Birmingham (Figure 3.14). This weather station was chosen as it was nearest weather station to Birmingham New Street station which monitored both temperature and wind velocity at one-hour time intervals.

Figure 3.14. Location of Coleshill Weather Station; orange star indicates the location of the Coleshill Weather Station, East of Birmingham City Centre at 52°28’47.3” N, 1°41’21.3”W (Bing, 2017).

3.3.2 Comparison with Christmas Day and Boxing Day

A key component of the environmental analysis was the comparison of the daily meteorological conditions within the station to meteorological condition of Christmas Day and Boxing Day. As no passenger train served Birmingham New Street station on Christmas Day and Boxing Day, these days provided a valuable insight into the influence of rolling stock on meteorological factors, such as Turbulent Kinetic Energy (TKE).

3.4 Vehicle Movement Analysis

3.4.1 Timetabling Data

The timetable for Birmingham New Street station was obtained from Real Time Trains, with a detailed timetable downloaded for each day of the monitoring period. Only the train timetable for Platform 10/11 was used for vehicle movement analysis, as the continuous monitoring instrument were located on this platform. The timetable was manually analysed to determine the classification of each train and length of its idling.

3.4.2 Selection of Analysis Days

Due to the large amount of data collected, only a limited number of days could be selected for in-depth train movement analysis. Therefore, an estimation of idling time was used to select three days for vehicle movement analysis.

In order to estimate idling time, the difference in actual arrival/departure time and scheduled arrival/departure time was calculated (Appendix B.6). Theoretically, if the delay in leaving the station was greater than delay in arriving at the station, idling time would be greater, and if the delay in arrival exceeded delay in departure then idling time would be shorter. The average delay in arrivals and departures for each day was calculated using a MatLab script (Appendix B.7).

Out of the 68 days of continuous monitoring three days were selected using the above methodology:

1. **12th December 2016** - Difference between delay in arrival and delay in departure was the greatest, suggesting a prolonged idling time.

2. **2nd January 2016** – Difference between delay in arrival and delay in departure was one of the shortest, suggesting a shortened idling period. One day has a smaller difference, however, it occurred whilst the Horiba APNA-360 analyser was absent from site, resulting in no NO_x results at sites A and B, hence it was deemed inappropriate to select this day for vehicle analysis.

3. **6th January 2017** - Difference in delay in arrival and departure was close to the average for the sampling period, therefore, using the above theory, would have an idling time similar to the average idling time. The day with a difference closest to the average could not be selected as the Horiba APNA-360 analysers were absent from site. Again, would not have been appropriate to analyse this day as it had an incomplete dataset.

The timetable for Platform 10/11 for each of the three days was compared against pollutant concentrations on Platform 10/11 for the respective day. The comparison is displayed in Chapter 6 as a series of daily time series graphs, with shading representing platform occupancy, and pollutant concentration ratios.

4. BIRMINGHAM NEW STREET AIR QUALITY EVALUATION

This chapter has been derived from the following paper:

Hickman, A., Baker, C., Cai, X., Delgado-Saborit, J. and Thornes, J. (2018). Evaluation of air quality at the Birmingham New Street Railway Station. Proceedings of the Institution of Mechanical Engineers, Part F: Journal of Rail and Rapid Transit, 232(6), pp.1864-1878.

A copy of this paper can be found in Appendix C.

4.1 Overview

This chapter presents the results of the air quality monitoring campaign at Birmingham New Street station. The diffusion tube, continuous monitoring and mobile monitoring measurements have been analysed to assess the long-term concentration of pollutants and the daily variation in concentrations. Subsequently the results have been compared against the EU ambient air quality limits and workplace exposure limits, where appropriate. Through this analysis the objectives *"quantify air quality at Birmingham New Street railway station"* and *"determine the extent of which CO_2 measurements are suitable for air quality assessment"*

will be addressed. This chapter discusses the implications of these findings and highlights aspects that are key to air quality assessment at transport interchanges.

4.2 Diffusion Tube Monitoring

4.2.1 Results and Interpretation

Platform Level

NO_2 concentrations from diffusion tubes at the platform level are shown in Table 4.1. The concentration at platform level ranges from 178 to 508 µg/m^3. Results from the second sampling period were generally higher than the first with an overall average across the platforms of 358 and 306 µg/m^{3,} respectively. Conversely, in the West end (B-end) of the station, results from the second sampling period were slightly lower than the first. The results highlight variation in NO_2 concentration both across and along the platforms. NO_2 concentration is higher in the centre of the platform and lower at the East and West ends of the platform, near the open ends of the platform. This is due to NO_2 interacting with the outdoor ambient air allowing the NO_2 to disperse at these locations whereas, the centre of the platform is more restricted and dispersion is more limited. The average ratio of the concentrations at the East and West end of the platform to the average concentration at the platform centre is 0.75 and 0.65, respectively.

Platform 2 had the highest average NO_2 concentration across the whole platform (380 µg/m^3) and platform 6 had the lowest average concentration (269 µg/m^3). This is a reflection on the rolling stock serving these platforms. Platform 6 is predominately served by electric trains, therefore there is an absence of DEEEs being emitted at this platform and the low NO_2 concentration is likely to be the result of DEEE dispersion across the station. However, platform 2 serves diesel rolling stock hence, there is an abundance of DEEEs at this location, and this results in platform 2 having the highest average concentration.

Table 4.1. Average NO_2 concentration ($\mu g/m^3$) from the three diffusion tubes at platform level locations. Sample one refers to the first sampling period from 17th October to 1st November 2016 and sample two refers to the second from 1st November to 15th November 2016.

	West (B-End)		Centre		East (A-End)	
	Sample One	Sample Two	Sample One	Sample Two	Sample One	Sample Two
Platform 1	276	285	440	464	250	384
Platform 2	318	318	437	508	287	412
Platform 3	278	244	411	504	284	392
Platform 4	325	271	344	427	238	361
Platform 5	271	236	341	405	210	399
Platform 6	236	234	297	368	178	298
Platform 7	204	197	364	375	205	302
Platform 8	251	240	355	412	262	331
Platform 9	280	264	428	452	323	449
Platform 10	298	280	420	501	297	389
Platform 11	232	214	398	500	287	332
Platform 12	361	360	380	427	252	353

Concourse Level

Table 4.2 shows the NO_2 concentrations in the station concourse. NO_2 concentrations in the red lounge are the lowest, with an average of 149 µg/m^3, which could be attributed to the close proximity of the tubes to the escalators leading up from platform 5 and 6, of which, platform 6 had the lowest average concentration at platform level. On the other hand, he blue and yellow lounges, with tubes situated close to the escalators and stairs for platforms 1-3 and platforms 10-12, respectively, had higher concentrations. NO_2 concentrations in the blue and yellow lounges, on the East side of the concourse and above the A-end of the platforms, were approximately double the concentrations in the red lounges on the West side, above the B-end of the platforms. There is greater accessibility to platforms at the East end of the station, with escalators, lifts and stairs available to access the platform, than the West end of the station, which has only escalators and lifts. Therefore, more pollutants are able to disperse up into the concourse at the East end of the station, exacerbating NO_2 concentrations in the blue and yellow lounges, whereas pollutant dispersion at the West end of the station, into the red lounge, is more restricted. Similarly to platform concentrations, NO_2 concentrations in the concourse were higher during the second monitoring period.

Table 4.2. Average NO_2 concentration ($\mu g/m^3$) from the three diffusion tubes at concourse level locations. Sample one refers to the first sampling period from 17th October to 1st November 2016 and sample two refers to the second from 1st November to 15th November 2016.

	Sample One	**Sample Two**
Red Lounge	152	145
Blue Lounge	295	354
Yellow Lounge	310	353

Outside the Station

Concentrations outside the station (Table 4.3) are significantly lower than inside the station. Site A, Birmingham New Street Eastern Plaza, had the highest average concentration across both sampling periods of 79 $\mu g/m^3$ and Site K, New Street (shopping high street), the lowest concentration of 46 $\mu g/m^3$. As well as being situated close to Birmingham New Street station, Site A also has a taxi rank and bus stops nearby, whereas Site K is situated in a pedestrianised area of New Street. The overall average NO_2 concentration for the area surrounding Birmingham New Street station, across both sampling periods, was 62 $\mu g/m^3$. This is significantly in excess of the 40 $\mu g/m^3$ annual NO_2 limit enforced by the EU.

Similar to concentrations at platform and concourse level, NO_2 concentrations outside the station were greater during the second sampling period. This indicates that the concentrations across all locations are influenced by external factors. Bonfire Night, November 5th, fell within the second monitoring period on a Saturday; therefore it is likely that there were many events surrounding the city setting off fireworks. Research has investigated the effect Bonfire

Night has on air quality, showing elevated NO_x, PM and SO_x concentrations (Ravindra et al., 2003; Singh et al., 2015; Vecchi et al., 2008; Wang et al., 2007).

Table 4.3. Average NO_2 concentration ($\mu g/m^3$) from the three diffusion tubes at locations surrounding the station. Sample one refers to the first sampling period from 17th October to 1st November 2016 and sample two refers to the second from 1st November to 15th November 2016.

	Sample One	**Sample Two**
A	72	85
B	70	80
C	64	69
D	60	64
E	61	67
F	55	60
G	50	53
H	62	74
J	51	54
K	45	47

4.2.2 Concluding Remarks

Whilst diffusion tubes help to provide a valuable overview of NO_2 concentration in and around Birmingham New Street station, it is extremely challenging to assess whether the emissions from the station is impacting the outdoor air quality. There are a number of NO_2 sources in close proximity to the station, including bus stops, taxi ranks, car parks and many busy roads. This makes it difficult to quantify the impact of the station's emissions alone on the city's air quality. However, the elevated concentrations measured at the platform, concourse and outside the station during the second sampling period is likely to be due to Bonfire Night occurring during this period. Bonfire Night events will cause pollutant concentrations to rise across the city and in the surrounding area; this elevated background air quality results in NO_2 concentrations inside and outside the station to be greater than the first monitoring period.

The diffusion tube data highlighted key pollution hotspots inside the station. Platform 2/3 had the highest NO_2 concentrations, followed by Platform 10/11. This identified potential areas where the subsequent air quality monitoring could take place. In addition, Table 4.1 indicates clear variation along each platform, with the East and West ends of the platform having lower NO_2 concentration due their close proximity to the open ends of the platform, and hence, a greater rate of dispersion. Due to platform restrictions, platform 2/3 was deemed unsuitable for continuous monitoring, so instead, platform 10/11 was selected with three sites along the platform at the East end, middle and West end of the platform to investigate the variation along the platform.

Another pollution hot spot identified by the diffusion tube monitoring was the East end of the concourse, situated above the A-ends of the platform. Although the diffusion tube monitoring acknowledged the dispersion of pollutants from the platform up into the concourse, the

diurnal variation of NO_2 concentration is unknown, therefore this location was chosen for mobile monitoring.

Whilst assessing a pollution hot spot will provide an insight into the worst case scenario, the diffusion tube results display a vast variation between platforms, which can be attributed to the rolling stock serving that platform. Therefore, mobile monitoring was selected to assess pollutant concentration on other platforms and this can be compared back to the continuous monitoring on platform 10/11, demonstrating how the air quality varies across the station at a higher temporal resolution.

4.3 Continuous Monitoring

4.3.1 Results and Interpretation

Long-Term Concentration

Long-term average concentrations and respective data capture percentage for the entire monitoring period can be found in Table 4.4. Data capture for the sampling period ranges from 51% for NO_2 at Site B to 100% for CO_2 at all sites. 5 out of the 13 sets of data had a data capture of less than 90%, the EU data quality objective (European Parliament and Council of the European Union, 2008), for their monitoring period. Data capture fell below 100% when errors occurred with the instrument and/or data logging system and therefore was unable to record concentrations during these periods.

The values at the central site, Site C, are higher than at the platform ends, Sites A and B, for all measured pollutants, as would be expected, due to Site A and B's close proximity to the open ends of the platform. This mirrors the results from the diffusion tube analysis, confirming that there are mechanisms occurring towards the open end of the platform

encouraging the dispersion of pollutants. Wind driven ventilation will be investigated in Chapter 5.

The values shown in Table 4.4 for NO_2 are broadly consistent with the diffusion tube results of Tables 4.1 to 4.3, but were, of course, obtained over a different time period.

Table 4.4. Long-term averages for the monitoring period at Birmingham New Street for NO_2 (Horiba APNA-360 analyser and AQ Mesh), $PM_{2.5}$, PM_{10}, black carbon and CO_2 and the percentage data capture (DC) for the monitoring period.

		Site A		Site B		Site C	
	Monitoring Period	Concentration	DC (%)	Concentration	DC (%)	Concentration	DC (%)
NO_2 (Horiba)	8th Dec 2016 – 23rd Jan 2017 (8th Dec 2016 – 7th Jan 2017)	251 µg/m^3	87	170 µg/m^3	51	407 µg/m^3	93
NO_2 (AQ Mesh)	17th Nov 2016 – 23rd Jan 2017					383 µg/m^3	99
$PM_{2.5}$	17th Nov 2016 – 23rd Jan 2017	29 µg/m^3	93	26 µg/m^3	96	42 µg/m^3	85
PM_{10}	17th Nov 2016 – 23rd Jan 2017	40 µg/m^3	93	36 µg/m^3	96	53 µg/m^3	85
Black Carbon	17th Nov 2016 – 23rd Jan 2017					20 µg/m^3	75
CO_2	1st Dec 2016 – 23rd Jan 2017	472 ppm	100	438 ppm	100	658 ppm	100

The long-term average for $PM_{2.5}$ was 29 and 26 µg/m^3 at Sites A and B, respectively; however the concentration at Site C was greater, with a concentration of 42 µg/m^3. For PM_{10}, which is coarser with a shorter lifetime, Sites A and B have concentrations of 40 and 36 µg/m^3, respectively, and again Site C had a greater concentration of 53 µg/m^3. This is likely to be due to the limited dispersion processes at this site.

Particulate matter with a size of less than 1µm, known to be in the accumulation mode, typically have a lifetime of around 7 – 30 days (Air Quality Expert Group, 2005). Particles with a diameter greater than 1 µm, in the coarse particle mode, have a shorter lifetime from a few minutes to several days, yet still significant. Research highlights that ultra-fine particulate matter is abundant in railway environments (Loxham et al., 2013), and hence, at Birmingham New Street, a significant proportion of particulate matter is likely to be PM_1, with a diameter less than 1 µm. Therefore it is probable that particulate matter exhausted from trains at Birmingham New Street has a long lifetime and will be predominantly removed from the station through dispersion processes dispersion and these processes are far more limited in the middle of the platform, resulting in higher particulate matter concentrations at Site C.

CO_2 concentrations along platform 10/11 support the theory of enhance dispersion towards the open ends of the platform, with much lower CO_2 concentrations at Sites A and B than Site C.

Daily and Hourly Concentrations

Figure 4.1(a) shows the daily averages of NO_2, as measured by the Horiba APNA-360 and AQ Mesh instruments, at Site C over the measurement period. The agreement can be considered good and thus the AQ Mesh was chosen to be used for further comparison as it recorded NO_2 for the entire monitoring campaign, unlike the Horiba APNA-360.

Figure 4.1(b) shows a comparison between the AQ Mesh NO_2 measurements at Site C and the Horiba NO_2 measurements at Sites A and B at the ends of platform 10/11. NO_2 concentrations at Sites A and B are lower than at Site C for the majority of the monitoring period. Furthermore, for all sites there is a large day-to-day variation of average NO_2 concentration, which could be attributed to meteorological factors and train operating conditions.

Figure 4.1(c) and (d) illustrates the $PM_{2.5}$ and PM_{10} concentrations, respectively, at all three monitoring sites on platform 10/11. Like NO_2, $PM_{2.5}$ and PM_{10} concentrations are lower at sites A and B than at Site C. Particulate matter appears to follow the same trend at all three sites (Figure 4.1(c) and (d)), whereas NO_2 (Figure 4.1(b)) shows some differences. This is likely to be due to atmospheric chemistry affecting the concentration of NO_2, primarily by NO oxidation, at varying rates at each site.

All pollutant concentrations fall considerably on Christmas Day and Boxing Day, when there were no passenger trains at Birmingham New Street, to values of 39 $\mu g/m^3$ for NO_2, 10 $\mu g/m^3$ for $PM_{2.5}$, 17 $\mu g/m^3$ for PM_{10}, 875 ng/m^3 for black carbon and 414 ppm for CO_2.

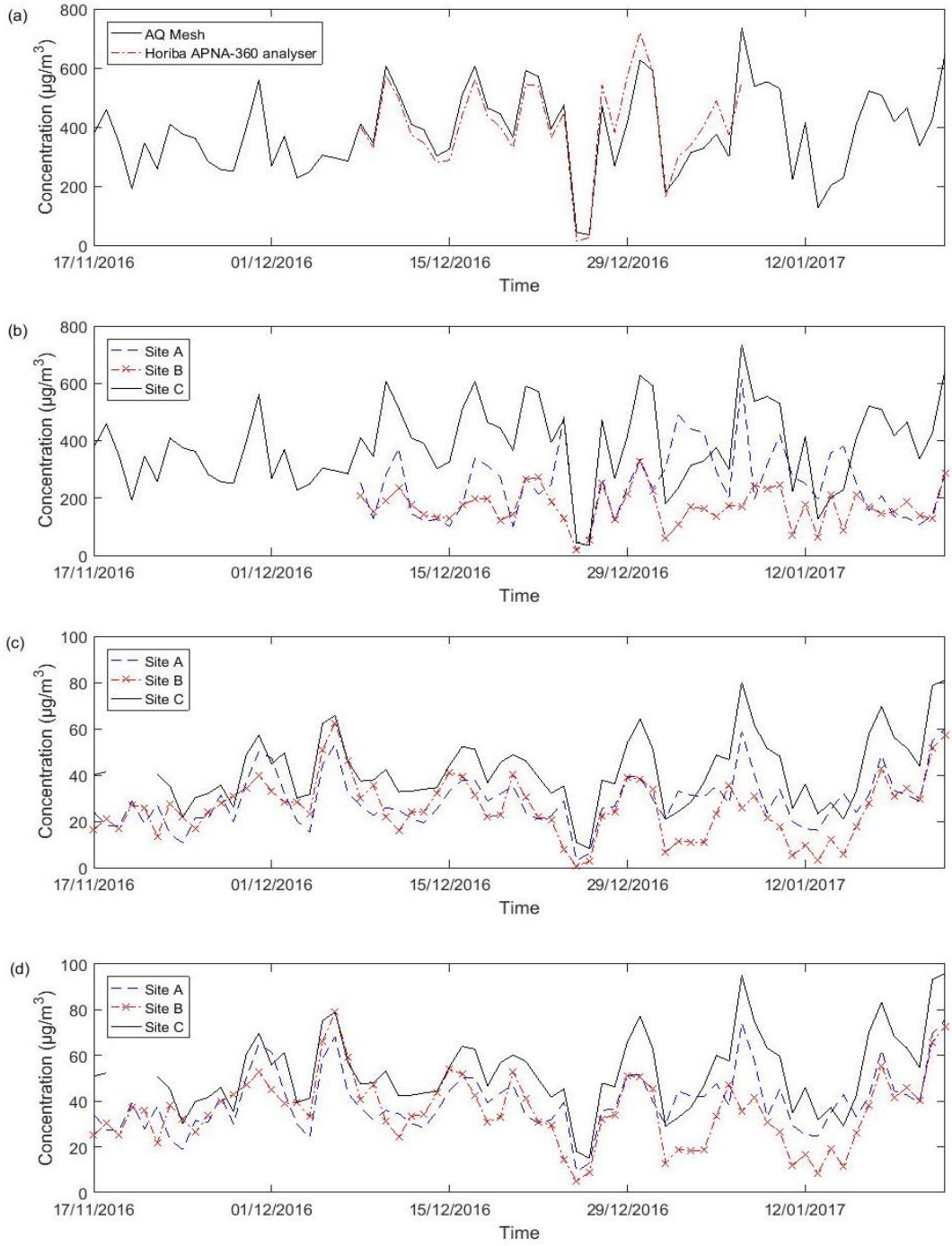

Figure 4.1. (a) NO_2 concentrations from the AQ Mesh (solid line) and Horiba APNA-360 analyser (dashed line) at Site C on platform 10/11, (b) daily NO_2 concentration, (c) daily $PM_{2.5}$ concentration, (d) daily PM_{10} concentration for Site A (dashed line), Site b (cross-dashed line), Site C (solid line) on platform 10/11. Note daily NO_2 concentration for Site C was measured using the AQ Mesh.

The average hourly concentrations of all pollutants are in good agreement with both the daily and long-term concentrations, demonstrating higher concentrations at Site C and lower concentrations towards the open ends of the platform (Table 4.5). For the pollutants measured at all three sites, the concentrations at Site B were the lowest out of the three. There are a couple of possible explanations for this finding. Firstly, Site B is situated closer to the open end of the platform than Site A; therefore there may be greater ventilation in this area. Secondly, Site B is situated on the platform 11 side of platform 10/11, whereas Site A is situated more centrally between the two, which may have influenced the resulting concentration. Despite this, a conclusion can still be made regarding the influence of open ends of the platform on pollutant concentrations at these locations.

Table 4.5. Average hourly concentrations for the monitoring period at Birmingham New Street for NO_2 (Horiba APNA-360 analyser and AQ Mesh), $PM_{2.5}$, PM_{10}, black carbon and CO_2.

	Site A	Site B	Site C
NO_2 (Horiba)	232 µg/m^3	131 µg/m^3	309 µg/m^3
NO_2 (AQ Mesh)			387 µg/m^3
$PM_{2.5}$	29 µg/m^3	26 µg/m^3	43 µg/m^3
PM_{10}	40 µg/m^3	36 µg/m^3	53 µg/m^3
Black Carbon			19 µg/m^3
CO_2	481 µg/m^3	471 µg/m^3	694 ppm

Public Health and Occupational Health Limits

As stated in Chapter 2, EU ambient air quality limits are not applicable to Birmingham New Street station; however, they are beneficial as comparative measures as outdoor environments, as well as previous research, compares concentrations to these limits.

The average NO_2 concentrations were significantly in excess of the EU regulatory limit for ambient air of 40 $\mu g/m^3$ at all three sites. Furthermore, NO_2 is subject to a short-term EU limit that NO_2 concentrations must not exceed an hourly average of 200 $\mu g/m^3$ on more than 18 times per annum in ambient environments. Examination of Table 4.5 indicates that concentrations are likely to regularly exceed this limit with an average hourly concentration above the 200 $\mu g/m^3$ at sites A and C. Table 4.6 shows the maximum hourly NO_2 average at each site and the number of times NO_2 exceeded the EU ambient air limit of 200 $\mu g/m^3$. Site C, in the middle of platform 10/11, exceeds the 200 $\mu g/m^3$ limit most frequently, with 1079 exceedances, and sites A and B, 477 and 374 times, respectively.

Table 4.6. Maximum hourly average concentration ($\mu g/m^3$) for the entire monitoring period and the number of times hourly NO_2 concentration exceeded 200 $\mu g/m^3$ for the monitoring period for sites A, B and C.

	Number of hours monitored	Maximum hourly concentration ($\mu g/m^3$)	Number of Exceedances
Site A	1128	1818	447
Site B	1128	1288	374
Site C	1632	2020	1079

$PM_{2.5}$ has an annual limit of 25 µg/m^3 in ambient air. Table 4.4 illustrates that all sites exceeded this limit. For PM_{10}, the annual limit is 40 µg/m^3 and PM_{10} concentration at Birmingham New Street exceeded this value at sites A and C. There is also a 24 hour limit for PM_{10} of 50 µg/m^3, which is not be exceeded more than 35 times per annum in ambient conditions. At Site C, the 24 hour PM_{10} average was over 50 µg/m^3 on 33 out of the 68 measurement days and would almost certainly exceed this limit. Sites A and B only exceed the limit on 14 and 12 days, respectively, and again are highly likely to breach the annual limit for ambient air.

Another way to assess air quality is through the workplace exposure limits; however, these limits often assess different pollutants to the ambient EU limits. There is currently an 8-hour and 15-minute limit for CO_2 and an 8-hour limit for NO and 15-minute and 8-hour limits for NO_2 are to be introduced in August 2018 – details limits and recommendations can be found in Chapter 2. Comparison of the Birmingham New Street results to these limits has been made to provide a valuable insight into the air quality in the station in order to quantify air quality and establish mitigation strategies required in the future to meet these recommendations, in particular those which come into force in August 2018.

CO_2 complies with the 8-hour and 15 minute limits, 5000 and 15000 ppm respectively, at all three sites. In contrast, the NO and NO_2 concentration at Birmingham New Street exceed the NO and NO_2 SCOEL recommendations at Site A and C, but not Site B (Table 4.7). It is important to reiterate that these limits were not enforceable at the time of monitoring. Instead, the SCOEL recommendations demonstrate that if air quality at Birmingham New Street remains the same as during the monitoring campaign, the station may not be compliant with the NO and NO_2 limits when they become enforceable WELs. Although, the limits are surpassed on several of the monitoring days, the percentage of time where the NO and NO_2

concentration was greater than the limit value is minimal in comparison, with the exception of NO at Site C. These results indicate that reducing NO concentration should be made a priority, in order to meet the future limits.

Table 4.7. Number of days which exceeded the 15-minute and 8-hour limits for NO and NO for the respective monitoring period and percentage (%) of monitoring period the limits were exceeded in brackets. NO and NO_2 exceedances at Site C were calculated using the AQ Mesh data.

		Site A		Site B		Site C	
Monitoring Period		15-minute	8-hour	15-minute	8-hour	15-minute	8-hour
NO	47 days at Site A and B 68 days at Site C		13 (4%)		0		57 (35%)
NO_2	47 days at Site A and B 68 days at Site C	5 (0.05%)	1 (0.04%)	0	0	26 (0.6%)	1 (0.1%)

Investigation into the use of carbon dioxide as a surrogate for other pollutants

HSE/HSG 187 guidance advises that CO_2 *"may be used as one of the steps in any assessment of the level of exposure to DEEEs"* (HSE, 2012) and at Birmingham New Street station, CO_2 concentration is used to active the fan system. Table 4.8 details the thresholds for the fan system in place at the time of monitoring.

Table 4.8. Birmingham New Street fan system operating conditions including the fan speed (%) at each mode and the CO_2 concentration (ppm) required for each mode.

Mode	Fan Speed	CO_2 Range (ppm)
Standby	0 %	< 1000
Low Pollution	25 %	1000 – 2000
High Pollution	50%	2000 – 3500
Emergency Pollution	100 %	> 3500

The correlation between CO_2 and other pollutants has been evaluated to determine if it is a suitable surrogate for these pollutants. Figure 4.2 shows a weak correlation between CO_2 and NO_2, this can be supported by its low R^2 value of 0.33. During the monitoring period, CO_2 concentration does not exceed the threshold for the 'emergency pollution' or 'high pollution' modes, resulting with fans only running at a maximum of 25% of their full capacity. Table 4.9 shows estimations of the NO_2 concentrations when the fan system is triggered at each mode. It is clear that there would be high concentrations of NO_2 when the fan system is in 'standby' mode (CO_2 < 1000 ppm).

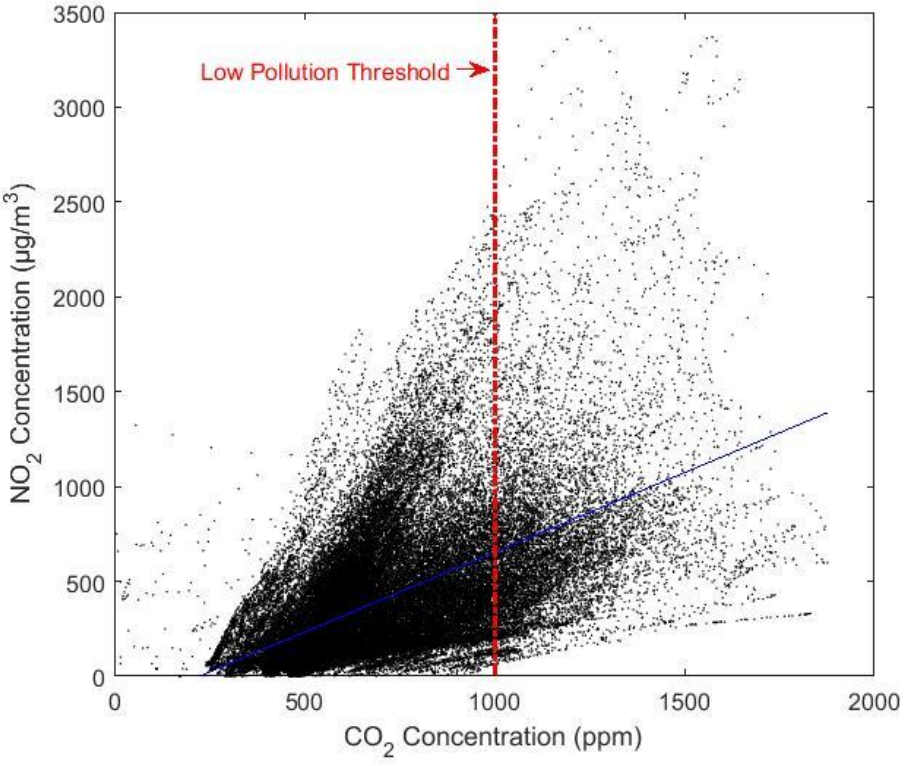

Figure 4.2. Correlation between 15-minute moving mean of CO_2 (ppm) and NO_2 ($\mu g/m^3$) at Site C, fitted with a linear regression line (blue solid line) and the 'low pollution' threshold (red dashed line).

Table 4.9. Estimate values for NO_2, $PM_{2.5}$, PM_{10} and black carbon concentrations ($\mu g/m^3$) when CO_2 exceeds the threshold for the 'low pollution', 'high pollution', and 'emergency pollution' modes. Estimations were calculated from where the respective correlation's linear regression line and fan system threshold intercepts.

	Low Pollution	High Pollution	Emergency Pollution
NO_2	653 $\mu g/m^3$	1493 $\mu g/m^3$	2754 $\mu g/m^3$
$PM_{2.5}$	61 $\mu g/m^3$	119 $\mu g/m^3$	206 $\mu g/m^3$
PM_{10}	74 $\mu g/m^3$	139 $\mu g/m^3$	235 $\mu g/m^3$
Black Carbon	29 $\mu g/m^3$	62 $\mu g/m^3$	112 $\mu g/m^3$

Figure 4.3 (a) demonstrates a weak correlation between CO_2 and $PM_{2.5}$ with a low R^2 value of 0.26. Table 4.9 provides an estimation of the $PM_{2.5}$ concentration when CO_2 exceeds each mode threshold and highlights that $PM_{2.5}$ concentration may already exceed the EU limit of 25 $\mu g/m^3$ before the fan system is trigged. PM_{10} also demonstrates a weak correlation with CO_2 (Figure 4.3 (b)) and has the same low R^2 value as $PM_{2.5}$. Again, Table 4.9 shows that PM_{10} has the potential to reach its annual and daily EU limit without the fan system being triggered.

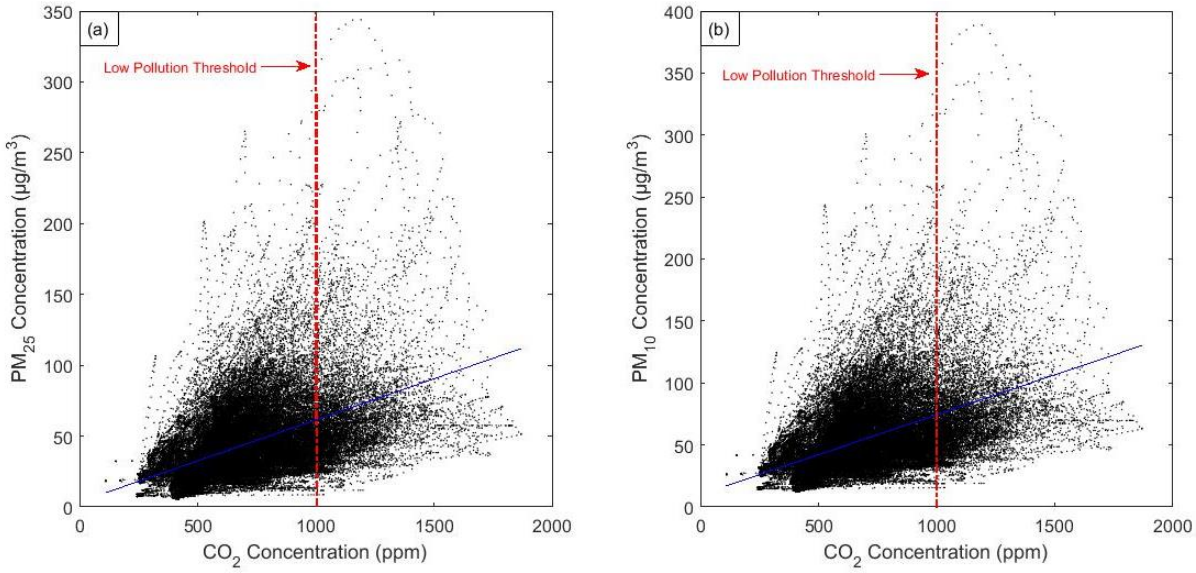

Figure 4.3. Correlation between 15-minute moving mean of CO_2 (ppm) and (a) $PM_{2.5}$ (µg/m^3) and (b) PM_{10} (µg/m^3), at Site C, both are fitted with a linear regression line (blue solid line) and the 'low pollution' threshold (red dashed line).

Black carbon is perceived to be an indicator of DEEEs, therefore, if CO_2 can be used in the assessment of exposure to DEEEs, black carbon and CO_2 should correlate well. However, Figure 4.4 displays a weak correlation between the two variables. Out of all the pollutants, black carbon has the lowest R^2 value of 0.18. It is clear that, in this environment, using CO_2 to trigger the fan system may not be the most suitable solution.

All pollutants show moderate level of correlation with CO_2, but not as high as one might wish to justify using CO_2 measurements as a surrogate for high levels of other pollutants.

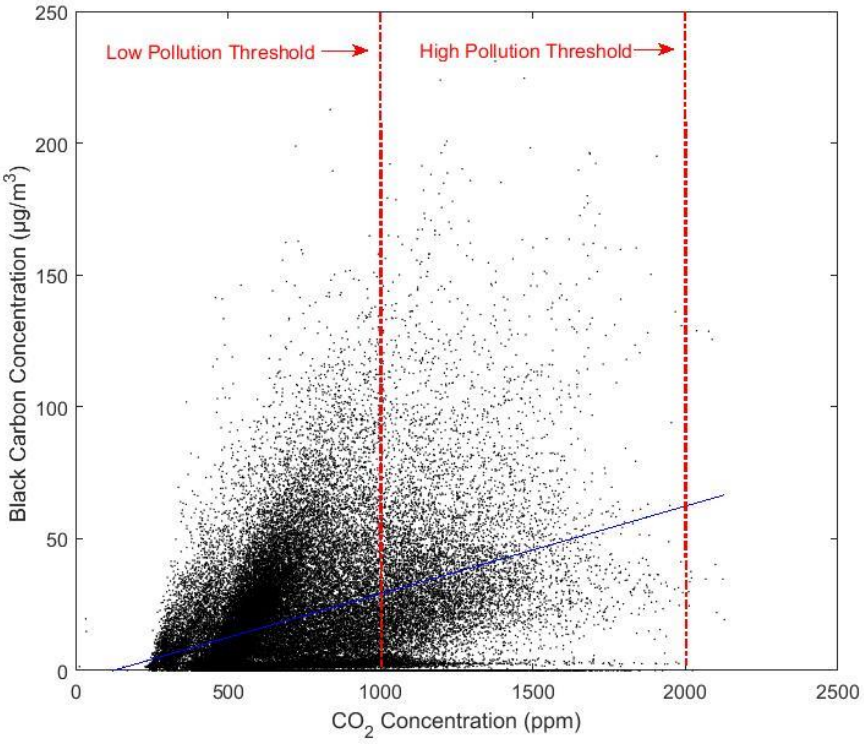

Figure 4.4. Correlation between 15-minute moving mean of CO_2 (ppm) and black carbon ($\mu g/m^3$) fitted with a linear regression line (blue solid line) and the 'low pollution' threshold (red dashed line).

NO/NO_2 Ratio

There is an indirect source of NO_2 production, from NO oxidation (Equation 4.1), which makes it increasingly difficult to identify peaks with particular trains as the day goes on, due to the effect of previous trains.

Figure 4.5 shows the variation of the NO/NO_2 ratio for 14th and 30th December 2016, as measured at Site C using data from the Horiba APNA-360 analyser. During the day, the ratio is around 5. It can be seen that the ratio falls in the night, when there are no train movements, and increases around 5 am, when train activity resumes. This could be mainly attributed to the

lack of NO emissions from diesel trains during the night, due to lack of train activity. The oxidation of NO to NO_2 would contribute to the observed pattern of small NO/NO_2 ratio during the night since small peaks of NO_2 are observed throughout the night period.

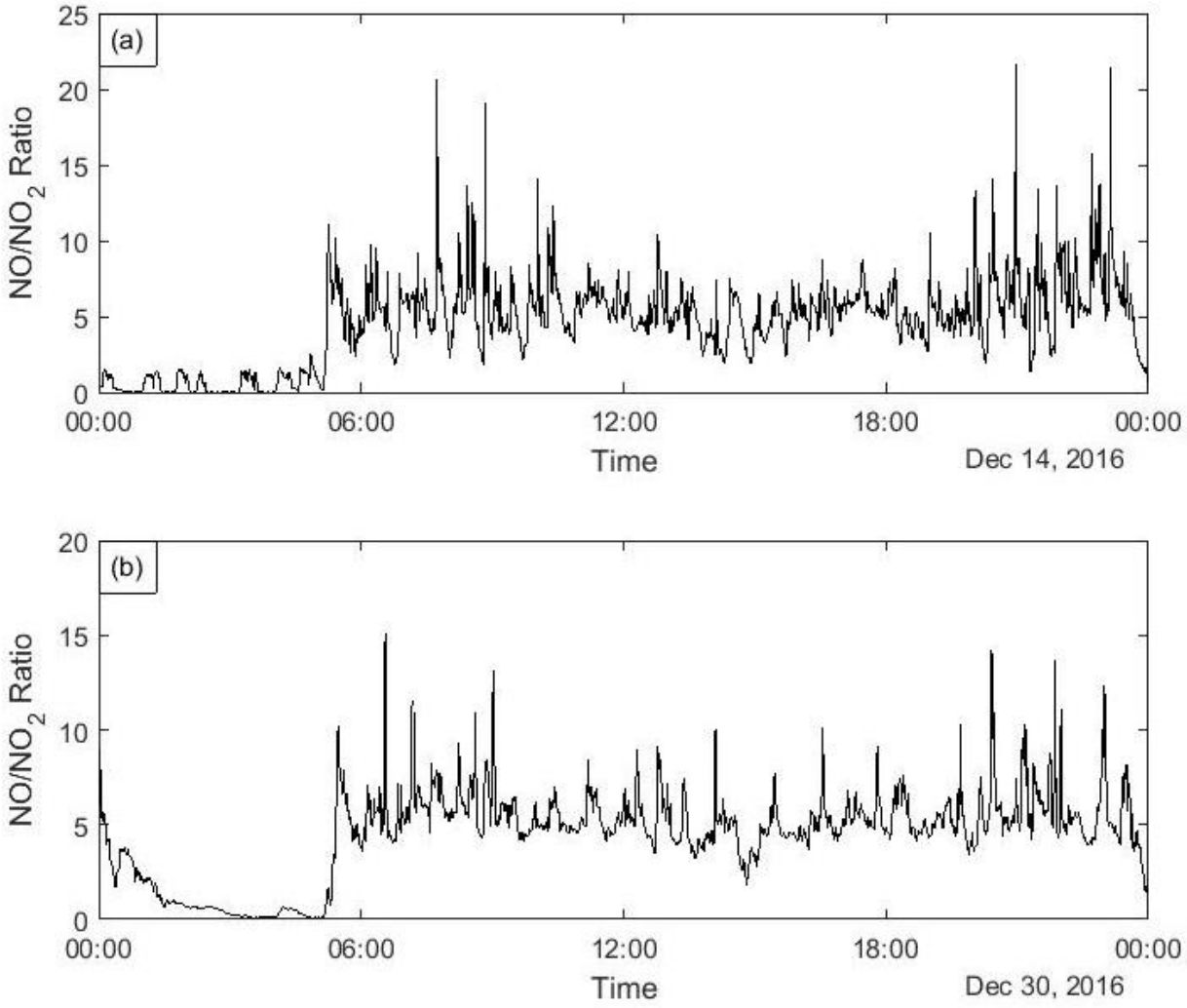

Figure 4.5. NO/NO_2 ratio for (a) 14th December 2016 and (b) 30th December 2016.

Table 4.10 shows that for both days, NO/NO_2 ratio is slightly greater at Site A than Site C. Unfortunately, due to the poor data capture at Site B (Table 4.4), NO/NO_2 ratio could not be calculated for that site.

At Site C, there was more primary emitted NO_2 causing a higher NO/NO_2 ratio, whereas at Site A, the following equations would be more dominant due to the close proximity to the open ends of the platform causing the NO/NO_2 ratio to be greater:

$$NO + O_3 \rightarrow NO_2 + O_2 \quad (4.1)$$

$$NO_2 + O \rightarrow NO + O_2 \quad (4.2)$$

Table 4.10. Average NO/NO_2 ratio for Site A and C on 14th and 30th December 2016.

	Site A	Site C
14th December 2016	4.86	4.54
30th December 2016	4.83	4.47

4.3.2 Concluding Remarks

The results from the continuous monitoring campaign align well with the diffusion tube results (Section 4.2.), and also demonstrate greater rate of dispersion at Sites A and B, resulting in lower pollutant concentrations. Furthermore, the experimental results described in this chapter indicate that NO_2, $PM_{2.5}$ and PM_{10} concentrations were all very high and in significant excess of the various EU ambient air quality limits given in Chapter 2, particularly significant with regard to NO_2. Note however, that these EU limits are not legally applicable to stations in the UK. The concentrations of NO_2 can approach and exceed the WELs at times, although as staff exposure times were not measured, it is not possible to say if these guidelines were exceeded for the station staff. The average of the daily maximum hourly concentrations at Site C over the measurement period was 1048 $\mu g/m^3$, which compared to an average of 75 $\mu g/m^3$ on the A4540, Birmingham Ring Road, over the same period.

The significant fall in concentrations on Christmas Day and Boxing Day suggests that rolling stock is the key contributor to high pollutant concentrations in the station, as they were absent on these days. As a result, it is likely that different classes of rolling stock will have a different impact on air quality in the station. For example, it is highly improbable that electric rolling stock, such as class 390 or 323, will cause an increase in NO_2 concentration due to the absence of DEEEs. The implications of rolling stock will be further investigated in Chapter 6.

Finally, Figure 4.4 concludes that CO_2 is not a sufficient indicator of DEEEs and should not be used as a surrogate for other pollutants in air quality assessments in transport interchanges. Despite being recommended by HSE, transport interchanges are unique environments which service a large number of public transport vehicles in a confined space, resulting in high

concentration of DEEEs that fluctuate drastically throughout the day and CO_2 does not respond in the same manner.

4.4 Mobile Monitoring

4.4.1 Results and Interpretation

Long term averages

Table 4.11 shows that platform 12 and the yellow lounge in the concourse had exceptionally high NO_2 concentrations during their respective mobile monitoring periods and concentrations exceeded the long term NO_2 average at Site C of 383 µg/m^3. The high concentration in the concourse indicates that DEEEs are dispersing up into the concourse, through the numerous stairs, escalators and lifts. On platform 12, average NO_2 concentration exceeded the average NO_2 concentration of Site C, despite NO_2 being monitored at the B-end of the platform for the mobile monitoring period. The continuous monitoring period found that the B-end of platform 10/11 had the lowest concentration. Furthermore, platform 12 predominately serves electric rolling stock; hence why the high average NO_2 concentration is unprecedented. It is possible that rolling stock on the adjacent platform 11 could be exhausting pollutants towards platform 12, and in addition, wind could possibly be a contributing factor for the dispersion of pollutants towards platform 12. Wind analysis can be found in Chapter 5.

Analysis of the limited particulate matter results also show platform 12 to have the highest average concentration. Both $PM_{2.5}$ and PM_{10} concentration exceeded the EU ambient air quality limits. Surprisingly, despite platform 2/3 having the lowest NO_2 concentration, approximately half the long term average NO_2 concentration on platform 10/11, particulate

matter concentrations are similar to the long term $PM_{2.5}$ and PM_{10} concentrations on platform 10/11 from the continuous monitoring.

Platform 8/9 had the lowest NO_2 and particulate matter concentrations, resulting in the compliance of particulate matter with the EU ambient air quality limits. This platform predominately serves electric rolling stock and appears to be unaffected by the adjacent platform 10/11, unlike platform 12.

Table 4.11. Long-term average NO_2, $PM_{2.5}$, PM_{10} concentration ($\mu g/m^3$) for each mobile monitoring period. $PM_{2.5}$ or PM_{10} concentrations were not monitored during weeks 2 and 4-8. Monitoring dates and time can be found in Table 3.3 in Methodology.

Week	Location	NO_2 Concentration	$PM_{2.5}$ Concentration	PM_{10} Concentration
1	Platform 2/3	150 $\mu g/m^3$	38 $\mu g/m^3$	48 $\mu g/m^3$
2	Platform 4/5	316 $\mu g/m^3$		
3	Platform 4/5	341 $\mu g/m^3$	14 $\mu g/m^3$	22 $\mu g/m^3$
4	Platform 6/7	201 $\mu g/m^3$		
5	Platform 8/9	206 $\mu g/m^3$		
6	Concourse (Weeks 6-8)	450 $\mu g/m^3$		
7				
8				
9	Platform 8/9	87 $\mu g/m^3$	16 $\mu g/m^3$	24 $\mu g/m^3$
10	Platform 12	477 $\mu g/m^3$	69 $\mu g/m^3$	54 $\mu g/m^3$

Daily Concentrations

Whilst comparing the long term average concentrations can provide a valuable insight into pollution hotspots in the stations, it is likely that meteorological and train operating factors are influencing the results, Hence, the daily mobile monitoring concentrations were compared against the daily concentrations from platform 10/11 Site C for NO_2 and Site B for particulate matter (Figure 4.6). NO_2 measurements from Site B were not used as a reference due to poor data capture and shorter monitoring period (see Table 4.4).

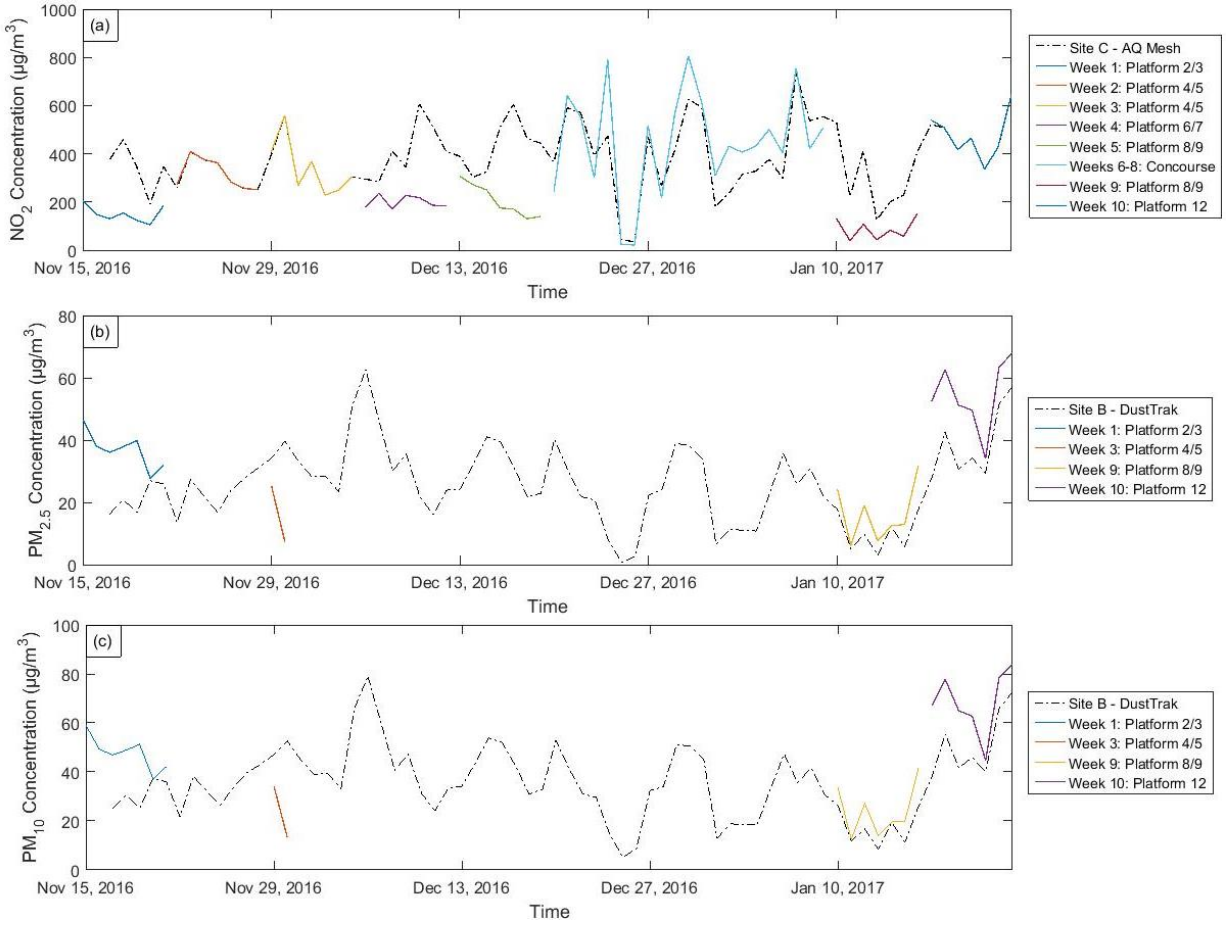

Figure 4.6. Daily time series of mobile monitoring for (a) NO_2 (b) $PM_{2.5}$ and (c) PM_{10},(in $\mu g/m^3$). Continuous monitoring results from Site C for NO_2 and Site B for particulate matter are plotted as a reference (black dashed line).

Figure 4.6 (a) shows that platforms 2/3, 6/7 and 8/9 had a lower NO_2 concentration than platform 10/11 Site C and platforms 4/5 and 12 had similar daily NO_2 concentrations to Site C. A lower concentration was to be expected as the mobile monitoring was conducted at the B-end of the platform, near the platform opening. As previously discussed platform 12 is likely to have experienced high NO_2 concentrations due to DEEEs emitted from rolling stock serving the adjacent platform 11. Conversely platform 4/5 had a greater NO_2 concentration than the surrounding platforms. It is possible that the NO_2 concentration on platform 4/5 is greater due to the unusual platform layout, with an additional platform, platform 4C, located at the B-end of platform 4/5 (Figure 4.7), resulting in up to three trains idling in this area of the station at any given point.

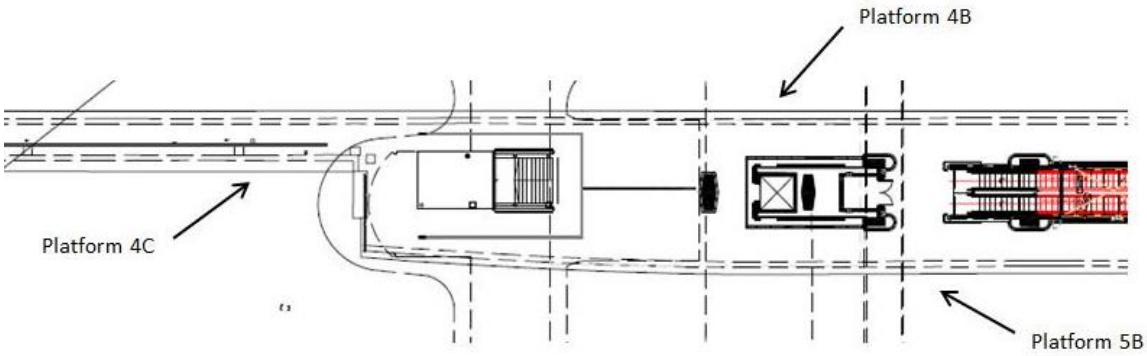

Figure 4.7. Diagram of the West (B-end) of platform 4/5 showing the additional platform/track on this platform island.

On 13 out of the 21 days that NO_2 was monitored in the concourse, NO_2 concentration in the concourse exceeded that at Site C (Figure 4.6 (a)). On Christmas Day and Boxing Day, when there were no passenger trains serving the station, NO_2 concentration in the concourse fell below that at platform level. This provides a clear indication that rolling stock is the main contributing factor to high NO_2 concentrations in the station and concourse.

Figures 4.6 (b) and (c) show that for all platforms, with the exception of platform 4/5, $PM_{2.5}$ and PM_{10} concentrations were greater than Site B. However, due to the incomplete results, it is difficult to draw conclusions. Further mobile monitoring for particulate matter is required to investigate the behaviour of particulate matter in these locations.

4.4.2 Concluding Remarks

A couple of conclusions can be made from the mobile monitoring element of the Birmingham New Street air quality monitoring campaign. Firstly, platform 12 had surprisingly high NO_2 and particulate matter concentrations. It is hypothesised that DEEEs from rolling stock on the adjacent platform 10/11 are dispersing towards platform 12 and this dispersion is enhanced by wind. This hypothesis will be further investigated in Chapter 5, where wind direction and speed will be analysed.

Secondly, the unique layout of the West end (B-end) of platform 4/5 means the platform island has a greater capacity and can serve more trains. At full capacity, there would be three trains idling at the West end of the platform, which could lead to exacerbated pollutant concentrations. To investigate the difference between this location and a platform which does not have this additional capacity, further continuous monitoring with a high temporal resolution would be required on platform 4/5, along with vehicle analysis.

4.5 Conclusion

The Birmingham New Street air quality monitoring campaign was successful in quantifying pollution in the station, providing an in depth analysis of air quality in the station, which is comparable to other studies of a similar nature (Chong et al., 2015; Gardner, 2012; Loxham et al., 2013). Chong et al. (2015), which used a similar continuous monitoring technique albeit over a shorter period of time, found Paddington Station's hourly mean NO_2 concentration averaged 140 µg/m^3, whereas Birmingham New Street exceeded this with an mean hourly average of 237 µg/m^3 (Table 4.5) across all three sites.

Furthermore, the use of CO_2 as a surrogate for other pollutants was concluded to be insufficient at Birmingham New Street and therefore, the use of CO_2 to trigger the ventilation system may not be appropriate, especially with the threshold values in place when this campaign was conducted.

Whilst the monitoring campaign had some limitations, it was the first monitoring campaign of its magnitude to be carried out in the UK rail industry and highlighted aspects that are key to quantifying air pollution in a transport interchange environment. Future monitoring campaigns in transport interchanges should monitor NO_x, in particular NO_2, and particulate matter. Black carbon was useful to determine the suitability of using CO_2 as a surrogate for DEEEs as black carbon is an indicator of DEEEs, however it was not a key parameter in this campaign. Monitoring of CO_2 would be required if its suitability to assess exposure to DEEEs was being investigated. However, this research concludes that using CO_2 as a surrogate for DEEEs not suitable at Birmingham New Street station and this is likely applicable at other enclosed railway environments. CO_2 could also be monitored if workplace exposure was

being assessed, in addition, PAHs, volatile organic compounds (VOC) and elemental carbon could also be monitored for the same purposes.

Regarding monitoring types, diffusion tubes provided a useful overview of the area investigated, however, future monitoring campaigns should support this type of monitoring with continuous monitoring. A minimum monitoring frequency of one minute for key pollutants should be applied, as concentrations varied dramatically throughout the day, with peaks in concentrations in the early morning and late evening when trains were arriving from the depot or getting ready to depart for the depot.

5. Environmental Influence on Air Quality in Enclosed Railway Stations

5.1 Overview

This chapter will investigate the affect Birmingham New Street station, and the rolling stock serving the station, have on meteorological conditions through a comparison with Coleshill weather station. The chapter will also investigate the influence of meteorological factors on pollutant concentrations in the station. To assess this and address the aim *"Assess meteorological conditions within and around the station and investigate their impact on station air quality"*, temperature and wind velocity measurements have been analysed, as well as their relationship with oxides of nitrogen, particulate matter, carbon dioxide and black carbon concentrations. The implications of these findings will be discussed and

meteorological factors that should be considered in future air quality monitoring campaigns at transport interchanges will be identified.

5.2 Correlation of weather variables between Birmingham New Street Station and Coleshill Weather Station

5.2.1 Temperature

Both the maximum and minimum temperatures at Birmingham New Street station positively correlated with Coleshill weather station (Figure 5.1) with correlation coefficients of 0.823 and 0.746 respectively and are statistically significant. It can also be noted that minimum temperature at Birmingham New Street station is always greater than Coleshill weather station.

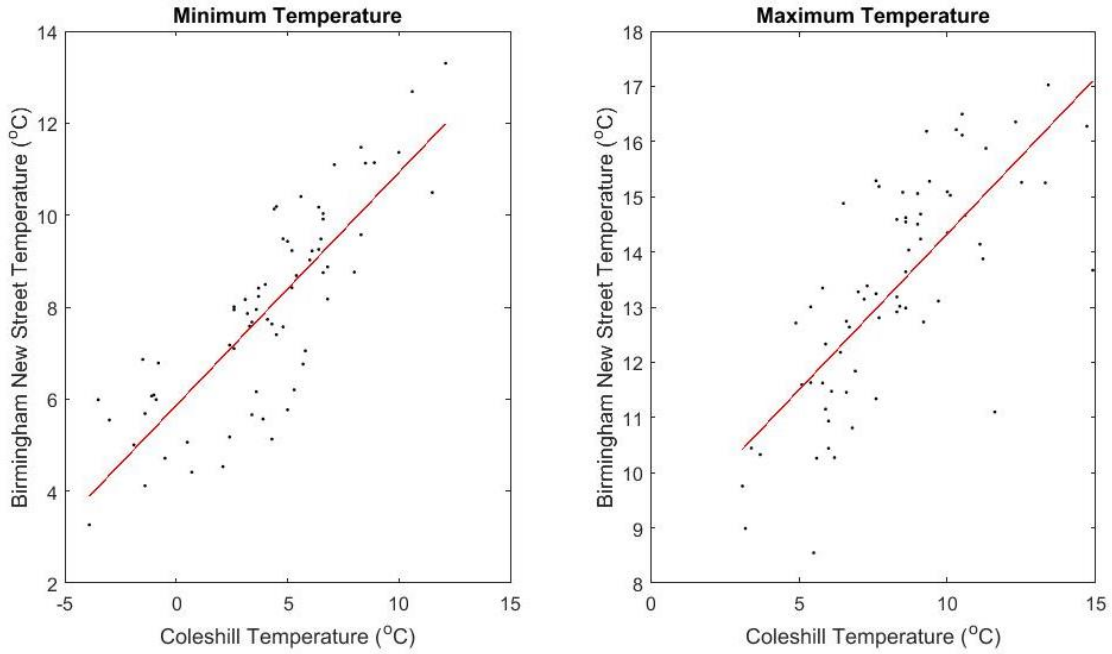

Figure 5.1. Correlation plots of daily minimum temperature (left) and daily maximum temperature (right) at Coleshill weather station against Birmingham New Street station in °C, with a linear regression line (red).

Typically, in outdoor environments, daily minimum temperature occurs just after sunrise; however, the outdoor daily minimum coincides with peak train activity during the sampling at Birmingham New Street station, as during the sampling campaign sunrise was between 07:33 and 08:02. As a result, minimum temperatures at Birmingham New Street station are likely to be at a different time than Coleshill; hence the correlation coefficient is lower than if maximum and minimum temperatures occurred at the same time at both sites. Figure 5.2 shows the average daily temperature variation at Birmingham New Street station and Coleshill, indicating a minimum temperature at 03:30 and maximum at 15:20 at Birmingham New Street station and for Coleshill minimum sometime between 04:00 and 05:00 and maximum between 13:00 and 14:00. Note Coleshill data is hourly averages whereas Birmingham New Street station is 10-minute averages. Furthermore, there is a spike in temperature at 07:00 and temperature does not follow the expected diurnal cycle, however this is likely to be the result of train activity.

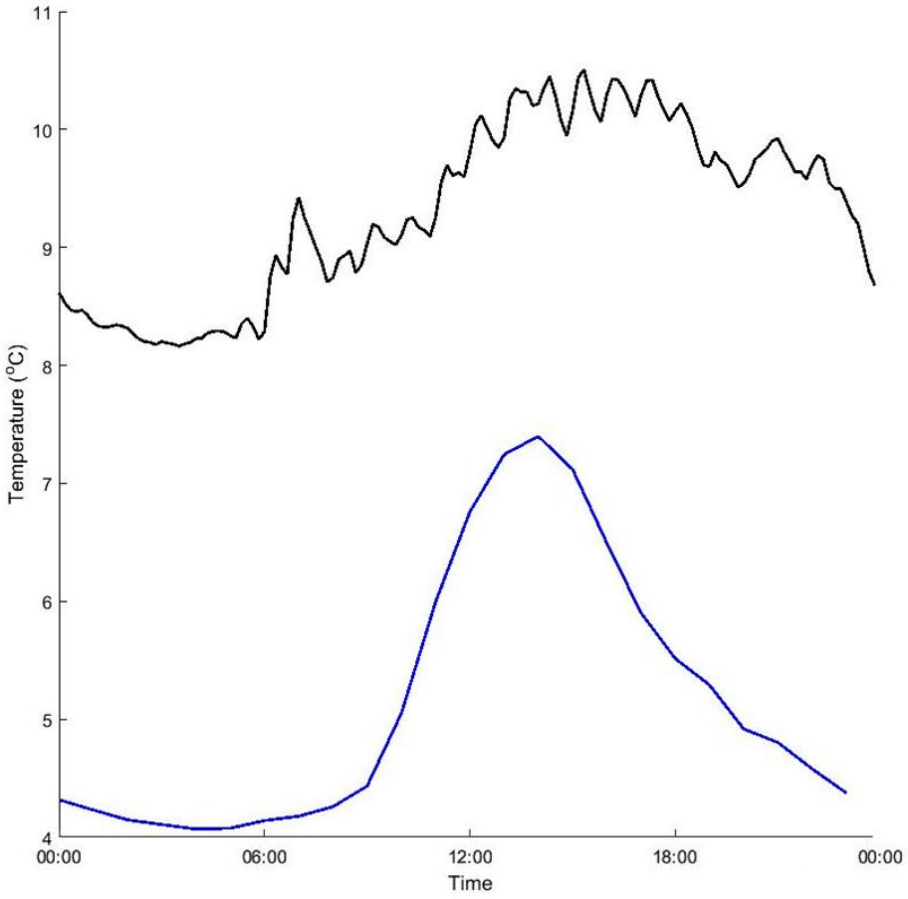

Figure 5.2. Daily temperature time series averaged over 68 days from 17/11/2016 to 23/01/2017 in °C for Birmingham New Street station (black line) and Coleshill weather Station (blue line).

To investigate this hypothesis, a period with no train activity was analysed as a comparison. On Christmas Day 2016, when there were no trains serving Birmingham New Street station, the maximum and minimum temperatures were similar to that at Coleshill weather station and there is no spike in temperature at 07:00 (Figure 5.3). Furthermore, temperature at Birmingham New Street station does not drop significantly overnight, unlike Coleshill (Figure 5.3). This is due to the urban area retaining heat, known as the urban heat island effect (Mohajerani et al., 2017).

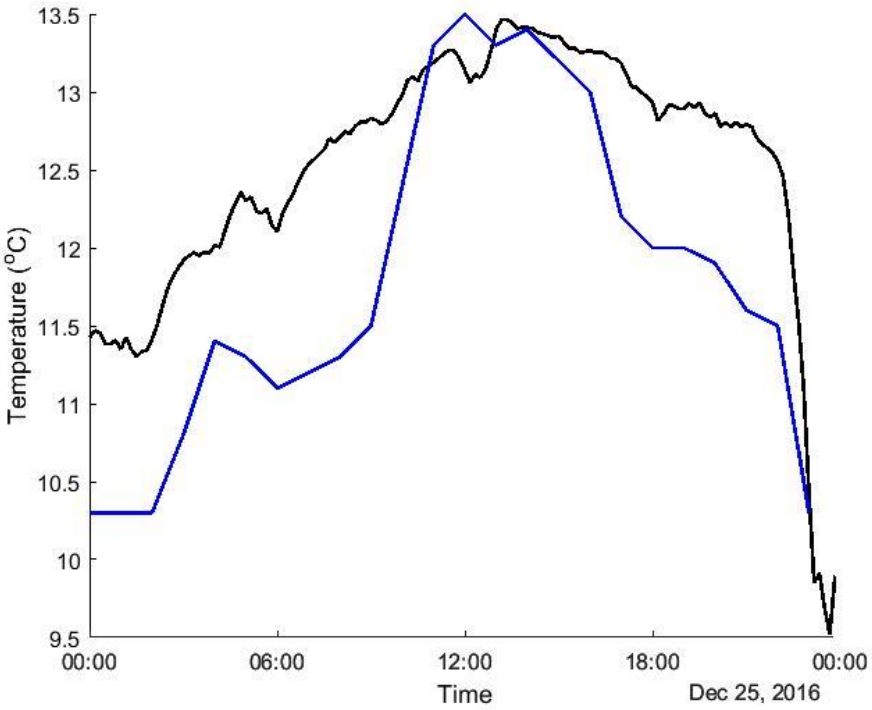

Figure 5.3. Temperature time series on 25/12/2016 in °C Birmingham New Street station (black line) and Coleshill weather station (blue line).

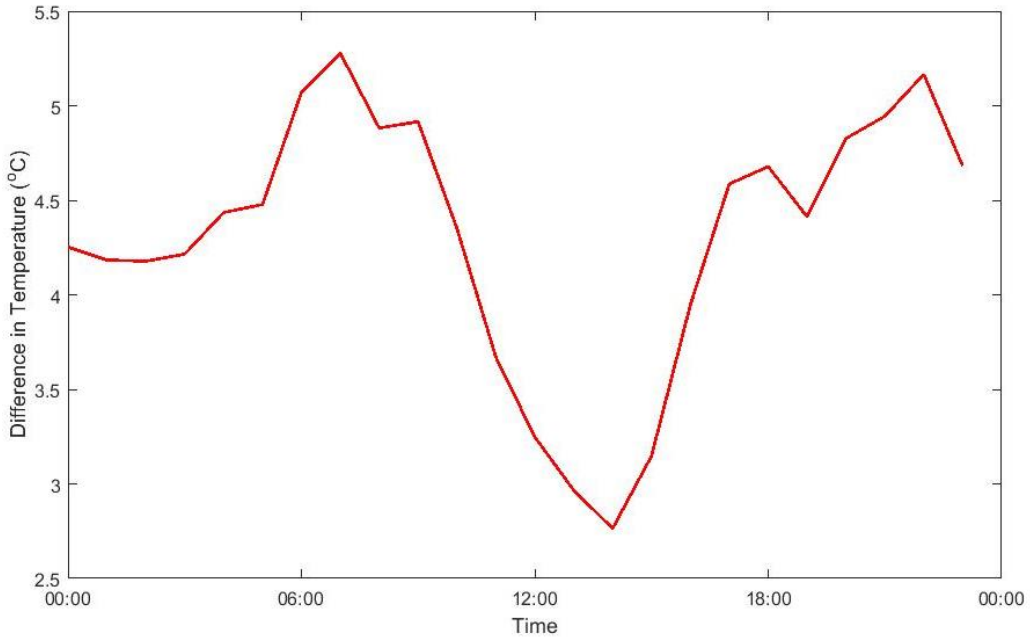

Figure 5.4. The difference in hourly temperature at Birmingham New Street station compared to Coleshill weather station averaged across weekdays for the monitoring period 17/11/2016 until 23/01/2017 and omitting Christmas Day and Boxing Day due to no train movements.

Figure 5.4 further supports the idea that train activity is elevating temperature at Birmingham New Street station, showing greater temperature difference around the morning rush hour and in the late evening. The morning peak, at 07:00, correlates to when there are a high number of trains frequenting the station and trains arriving from depot. The evening peak, at 22:00, correlates with numerous trains idling at Birmingham New Street station in preparation to return to depot.

Table 5.1. The average daily maximum and average daily minimum temperature at Birmingham New Street station and Coleshill weather station during the period 17/11/2016 to 23/01/2017 in °C.

	Birmingham New Street	Coleshill
Average Maximum	13.3	8.2
Average Minimum	7.9	4.1

Furthermore, the average maximum and minimum temperatures at both locations during the sampling period supports these findings, showing elevated temperatures at Birmingham New Street station (Table 5.1). Findings suggest that this is the result of train activity, as heat is emitted from rolling stock.

Rolling stock emits heat from a variety of components, including: engines, auxiliary systems, braking and air conditioning. When trains are present, particularly when idling in Birmingham New Street station, this loss of heat will influence the overall temperature of Birmingham New Street station resulting in elevated temperatures, potentially creating a thermal component of ventilation in the station.

5.2.2 Wind Velocity

At low wind speeds there is little correlation between wind speed and direction because local influences, particularly thermal effects, drive intermittent flows. In order to explore this, wind speed and direction at Birmingham New Street station were correlated against Coleshill weather station for hours where wind speed exceeded 0.5 ms^{-1}, as well as for all wind speeds.

Table 5.2 shows that the wind speed at the A-end of platform 10/11 is not significantly correlated with Coleshill when wind speed exceeds 0.5 ms^{-1}. However, at the B-end wind speed at Birmingham New Street station and Coleshill are significantly correlated when winds exceed 0.5 ms^{-1}. The correlation for direction, conversely, is strong for the A-end when wind speed exceeds 0.5 ms^{-1} but much weaker for the B-end. This would appear to suggest that flow at the B-end of the platform is driven by external wind speed, regardless of direction, whereas for the A-end wind direction is the significant factor.

Without the wind speed threshold, therefore including low-wind conditions, the correlation with wind direction decreases at both ends of the platform, as might be expected, and the correlation of speeds increases. However, this may be an artefact of the analysis with low-wind conditions at both locations having no direct linkage other than the overarching meteorology.

Table 5.2. Correlation coefficients for hourly wind speed and hourly wind direction at the A and B ends of platform 10/11 in Birmingham New Street station against Coleshill weather station, for wind speeds above 0.5 ms-1 and without a wind speed threshold. Correlation coefficients which are not statistically significant to a 95% confidence interval are in red.

	A-End (East)		B-End (West)	
	Direction	Speed	Direction	Speed
Wind speed > 0.5 ms^{-1}	0.963	0.0751	0.281	0.419
No wind speed threshold	0.519	0.277	0.151	0.634

Therefore, although the A-end of platform 10/11 is effectively sheltered, it is sensitive to the driving wind direction, indicating that there is some direct wind driven ventilation at the A-end of platform 10/11. Conversely, the B-end has a more complex relationship with wind direction (Figure 5.5). Winds at Coleshill >0.5 ms^{-1} with directions 0°-90° and approximately 150°-250° generate responses at Birmingham New Street station of between 90°-270° but with no discernible pattern. The absence of any Birmingham New Street station measured wind directions in the range 270°-90° is highly suggestive, given the position of platform 10/11 on the southern side of the station, of a component of circulatory flow within the canyon driven by high-level wind when wind speeds > 0.5 ms^{-1}. This is suggestive of a large scale trapped vortex which would provide only indirect ventilation. When the wind is coming from other directions, there is a different flow pattern within the station, which is likely be the result of the local topography but potentially provides more direct ventilation.

These findings therefore suggest that the A-end of platform 10/11 has more direct wind driven ventilation, whereas the B-end has more indirect ventilation, and typically a trapped vortex which may retain pollution.

The mobile monitoring results discussed in Chapter 4 further support the finding of a trapped vortex at the B-end of the platform, as NO_2 concentration is particularly high on platform 12 during the mobile monitoring. It is likely that NO_2 is dispersed away from platform 10/11, to the South towards platform 12 by the vortex. Due to the presence of the vortex restricting dispersion, these pollutants will be become trapped in this area of the station.

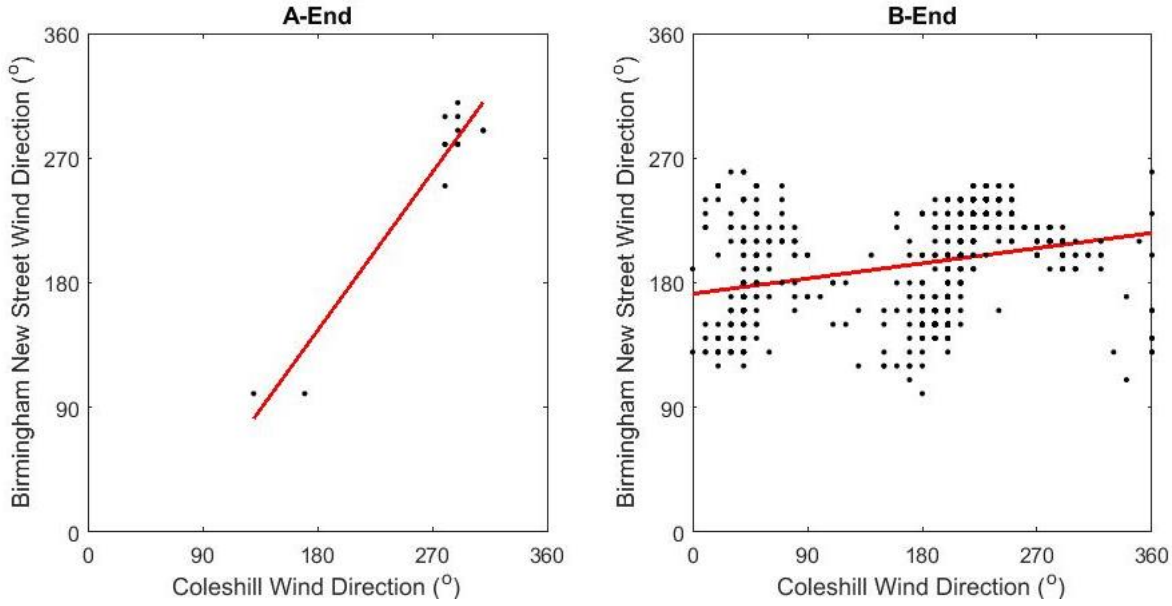

Figure 5.5. Mean hourly wind direction at Coleshill weather station against Birmingham New Street station, for wind speeds > 0.5 ms^{-1}, at the A end (left) and B end (right) in °, where 0 is North, and fitted with a linear regression line (red).

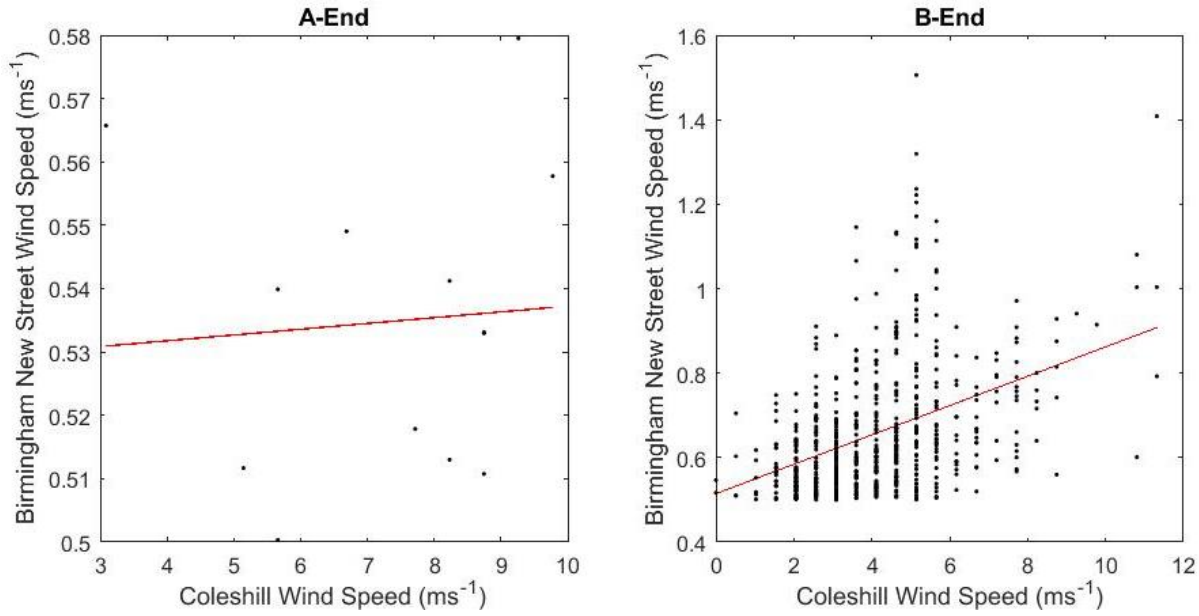

Figure 5.6. Mean hourly wind speed at Coleshill weather station against Birmingham New Street at the A end (left) and B end (right) in ms^{-1}, fitted with a linear regression line (red), for wind speeds > 0.5 ms^{-1}.

Turbulent Kinetic Energy

Turbulent kinetic energy (TKE) is purely as measure of turbulence the fluctuations in the wind conditions and is applicable in low-mean-flow situations. As such as at Birmingham New Street it can be used in this case as a useful measure of transient wind effects, including those generated by the vehicles, regardless of the low mean flow. Therefore, TKE was used to further investigate the effect of train movement on wind speed at Birmingham New Street station. The calculation of TKE can be found in the Methodology, Section 3.3.3. Hourly TKE averaged over 66 days monitored when trains were present (i.e. Christmas day and Boxing day excluded) was compared against hourly TKE for Christmas day at both the A and B ends of the stations. At the A-end, TKE was not significantly different on Christmas Day in comparison with the rest of the monitoring period, however at the B-end there was a significant difference. From this, it can be concluded that train movement does not influence wind speed at the A-end and thus can be disregarded, however at the B-end its influence must be considered.

Although it is assumed that this difference must be related to the different flow regimes at either end of the station, with vehicle induced TKE also trapped by the vortex at the B-end of the station, it is also possible that this effect may be coincidental given the small sample of train-free days.

5.3 Correlation of Weather Events and Pollution Levels at Birmingham New Street Station

5.3.1 Atmospheric Chemistry

Ozone is hypothesised to play a key part in the chemistry of Birmingham New Street station. Ozone is formed in the troposphere by the photodissociation of NO_2 at with available radiation (Lagzi et al., 2013):

$$NO_2 + hv\ (\lambda < 420nm) \rightarrow O + NO \tag{5.1}$$

$$O + O_2 \rightarrow O_3 + M \tag{5.2}$$

As there is no UV radiation along the majority of the platforms at the station, due being a tunnel-like environment, O_3 will be produced externally and disperse into the station. Once in the presence of NO in the station, O_3 is destroyed as it reacts with NO (Lagzi et al., 2013) through the following reaction through the following reactions:

$$NO + O_3 \rightarrow NO_2 + O_2 \tag{5.3}$$

$$NO_2 + O \rightarrow NO + O_2 \tag{5.4}$$

Meteorological factors will influence the formation of O_3, and therefore will impact the oxidisation of NO to NO_2. When there is more UV radiation, ozone production is likely to

increase, therefore more background ozone will result in more NO_2, thus encouraging the oxidisation of NO to NO_2. Enhanced UV radiation, i.e. little cloud cover, is often associated with anti-cyclonic conditions in the UK. In the winter, anticyclonic conditions lead to colder temperatures, whereas in the summer, a build-up of UV radiation leads to warmer temperatures.

As the Birmingham New Street station monitoring campaign was conducted through late-autumn and into winter, it can be concluded that there would be more O_3 on colder days, hence temperature may indirectly be impacting NO and NO_2 concentration in the station.

5.3.2 Temperature

Nitrogen Oxide

All three sites (A-C) exhibit a positive correlation between daily mean temperature and NO concentrations (Figure 5.7). Site B has the greatest correlation coefficients, followed by site A and C respectively (Table 5.3). The Horiba APNA-360 analyser at site C has a very low correlation coefficient compared to the AQ Mesh. This could be due to the fact that the Horiba analyser was only present at site C for 31 days, whereas the AQ mesh was present for 68 days. Section 5.2.1 found that rolling stock is a predominant heat source at Birmingham New Street station. The weak correlation between NO and temperature suggests that heat and NO are being emitted simultaneously from trains. Whilst taking daily averages will remove some of this influence, some days have more trains than others, hence a greater average NO concentration and higher average temperature.

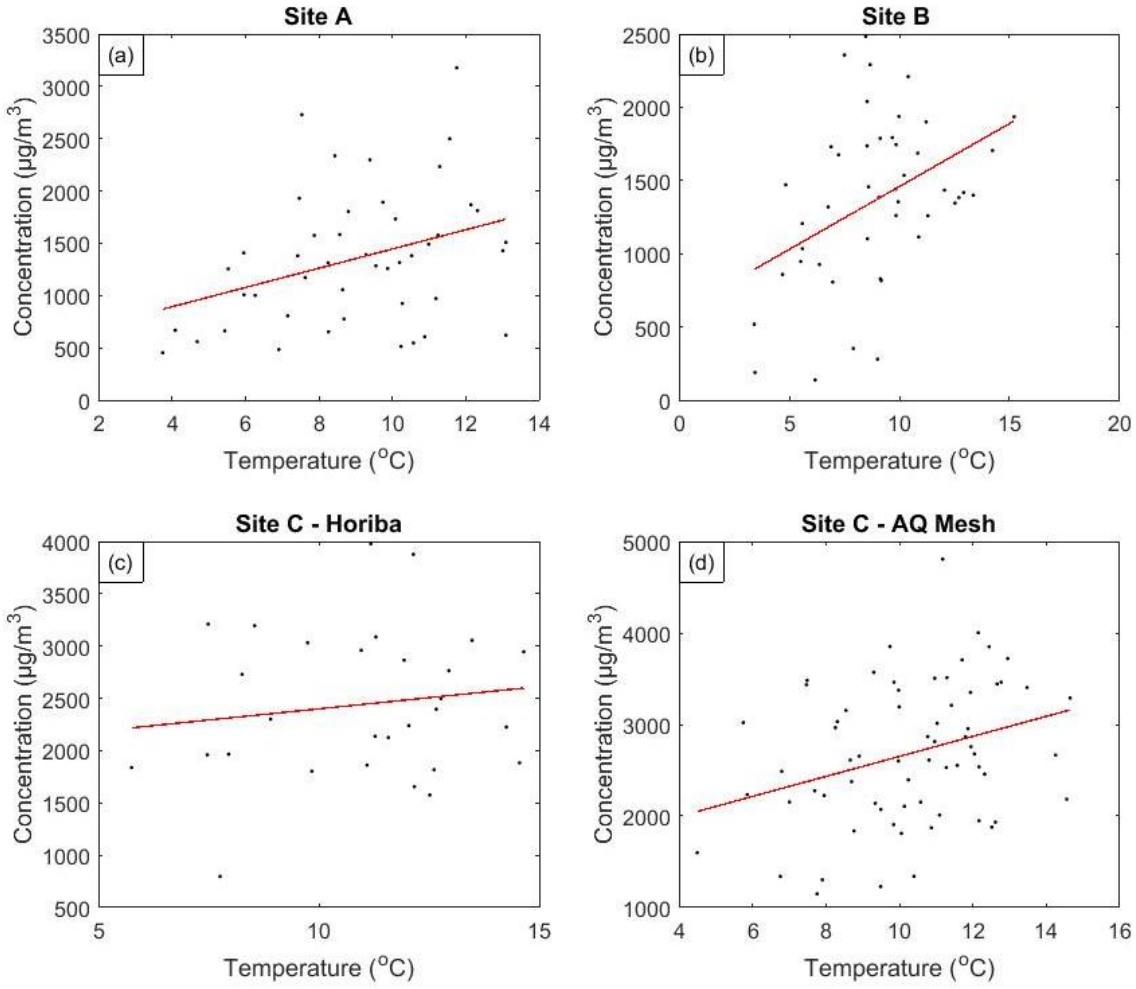

Figure 5.7. Daily mean temperature (°C) against the average NO concentration (µg/m^3) for each day the instruments were present at (a) Site A, (b) Site B, (c) Site C (Horiba Analyser) and (d) Site C (AQ Mesh), fitted with a linear regression line (red). For site C, two different analysers were used; hence these results are demonstrated in separate graphs.

Table 5.3. Correction coefficients for temperature against NO concentration (Figure 5.7), NO_2 concentration (Figure 5.8) NO_x concentration (Figure 5.9) and NO_2/NO_x ratio (Figure 5.10), with those which are not statistically significant to a 95% confidence interval ($p>0.05$) are in red.

		NO	NO_2	NO_x	NO/NO_2 ratio
Site A		0.348	0.342	0.347	0.343
Site B		0.417	0.215	0.404	0.535
Site C	Horiba	0.141	0.254	0.157	-0.271
	AQ Mesh	0.311	0.522	0.457	-0.479

Nitrogen Dioxide

Unlike NO, the AQ Mesh at site C has the greatest correlation coefficient and site A and B have a lower correlation coefficient, which is likely to be due to external factors at the open ends of the platform, such as wind and solar radiation, influencing the concentration levels at these sites, hence a lower correlation coefficient. The role temperature plays in the conversion of NO to NO_2 could be a factor and therefore will be investigated further in Section 5.3.2 – *NO/NO_2 Ratio*.

Similarly to NO, temperature and NO_2 may be positively correlated as primary NO_2 is emitted from trains along with heat. However, the correlation coefficient is not as high as that for NO and this may be due to the secondary formation of NO_2, through reactions 5.3 and 5.4, confounding the results.

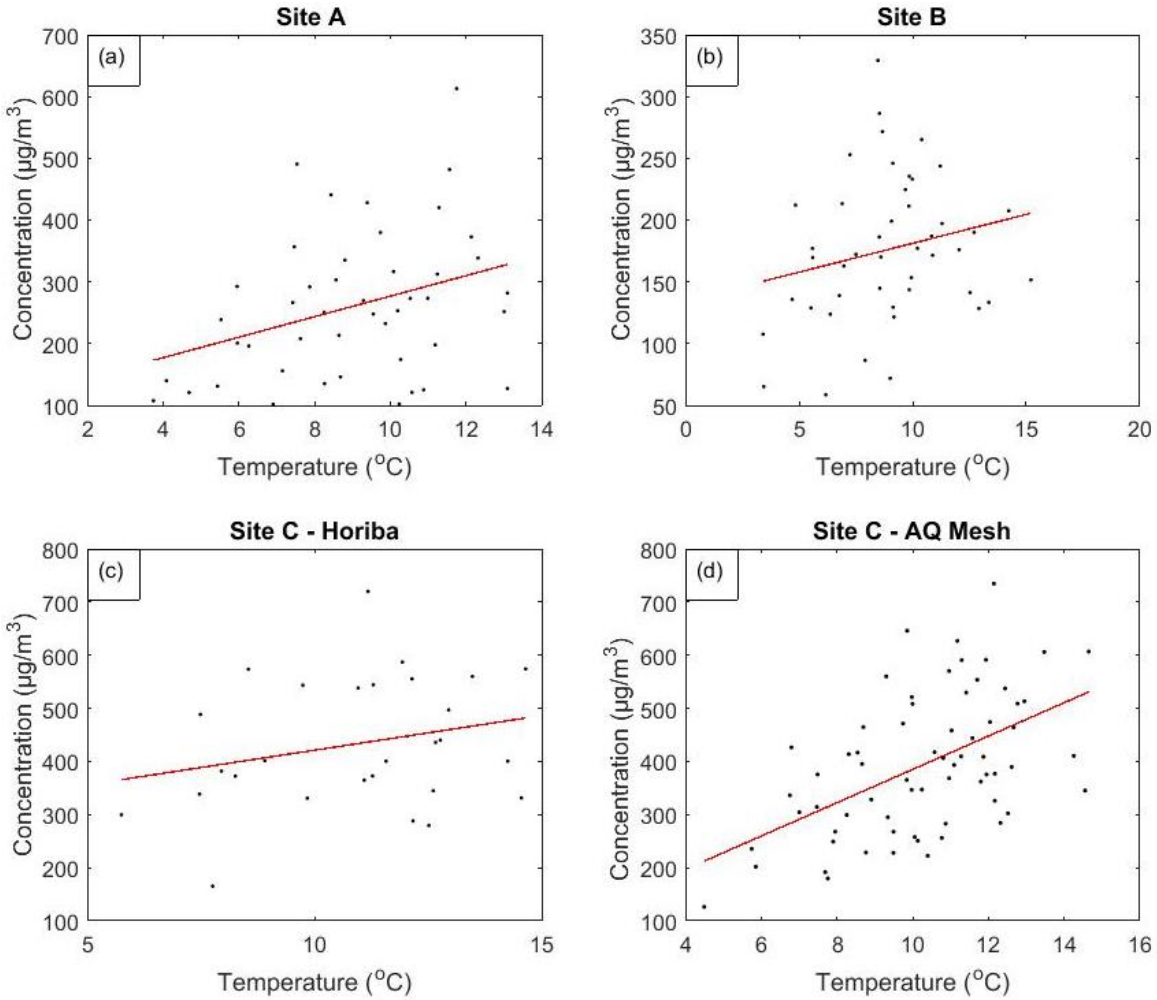

Figure 5.8. Daily mean temperature (°C) against the average NO_2 concentration (µg/m^3) for each day the instruments were present at (a) Site A, (b) Site B, (c) Site C (Horiba Analyser) and (d) Site C (AQ Mesh), fitted with a linear regression line (red). For site C, two different analysers were used; hence these results are demonstrated in separate graphs.

Oxides of Nitrogen

Analysis of NO and NO_2 against temperature shows that the positive correlation may be, in part, due to both heat and nitrogen oxide and nitrogen dioxide being emitted from trains. Therefore, the correlation between NO_x, a primary DEEE, and temperature was analysed, to determine if the correlation is due to heat and oxides of nitrogen being emitted

simultaneously. Figure 5.9 illustrates a positive correlation at all three sites, with similar low correlation coefficients. However, the correlation coefficient at site C is the greatest, where there is little influence from external factors, due to its more sheltered environment, supporting the hypothesis that external temperature is not influencing concentrations, rather the simultaneous emission of NO_x and heat. This influence is harder to distinguish at sites A and B as they are closer to the exposed ends of the platform, where there is a greater dispersion of both NO_x and heat.

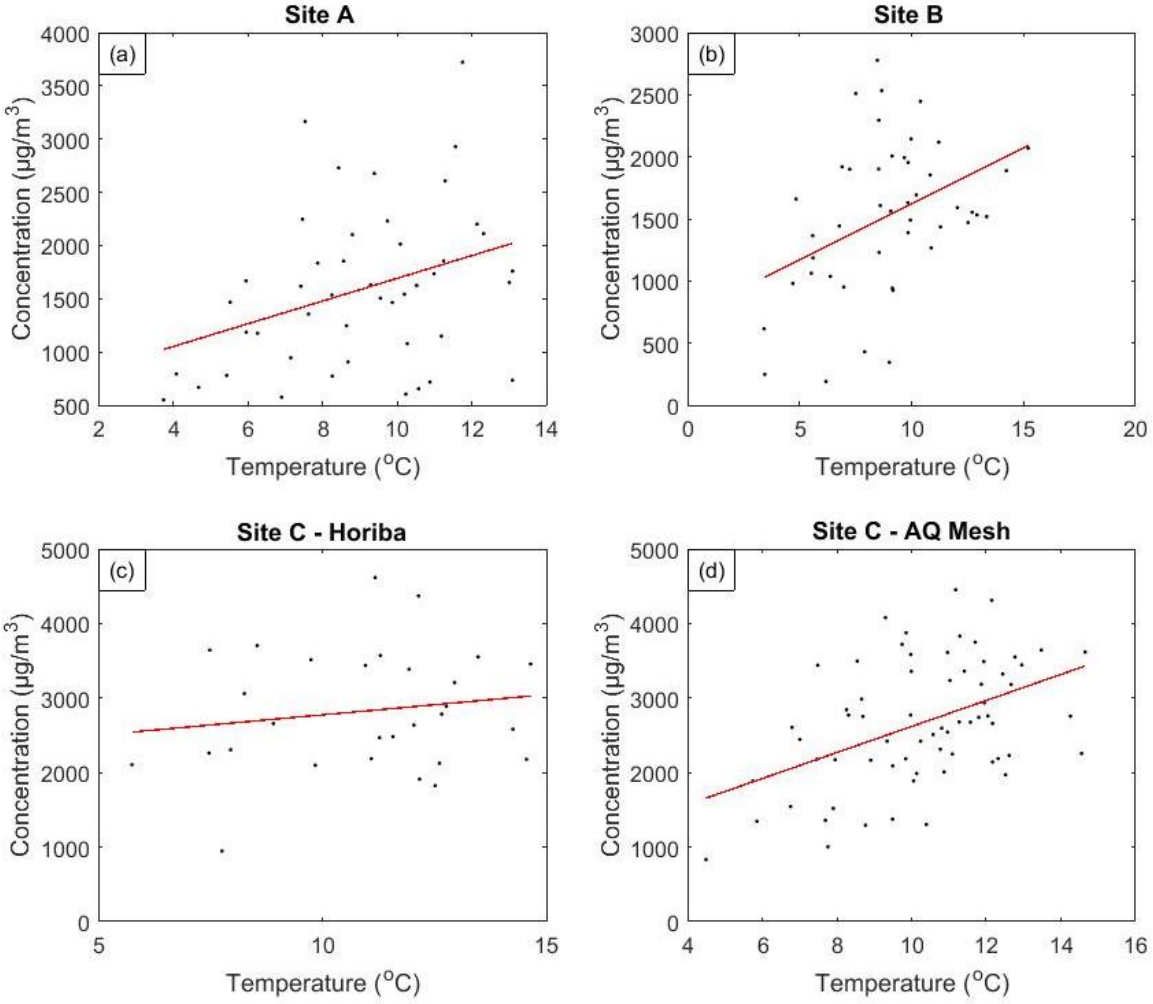

Figure 5.9. Daily mean temperature (°C) against the average NO_x concentration (µg/m^3) for each day the instruments were present at (a) Site A, (b) Site B, (c) Site C (Horiba Analyser) and (d) Site C (AQ Mesh), fitted with a linear regression line (red). For site C, two different analysers were used; hence these results are demonstrated in separate graphs.

NO/NO_2 Ratio

Whilst temperature and NO_x are correlated due to heat and DEEEs being emitted simultaneously, the conversion of NO to NO_2 may potentially be influenced by temperature.

Figure 5.10 demonstrates that sites A and B, the NO/NO_2 ratio is greater at higher temperatures, illustrating that more NO is converted to NO_2 at lower temperatures. As

concluded in Section 5.2.1, higher temperatures likely to be the results of heat emitted from rolling stock. Therefore, when trains are not present and temperature is lower, more NO is converted to NO_2, through the reactions in Section 5.3.1. At higher temperatures indicating the potential presence of rolling stock, there is more primary NO emitted; hence, the NO/NO_2 ratio is greater. The influence of rolling stock on the NO/NO_2 ratio will be investigated further in Chapter 6.

Conversely at site C, there is a negative correlation between the two variables; however, only the correlation between temperature and NO/NO_2 ratio from the AQ Mesh is statistically significant (Table 5.3). Site C is far more sheltered and would not receive natural detergents of the atmosphere as abundantly as the other two sites therefore chemical reactions less predominant in this area of the station and will occur at a much slower rate than site A and B, hence a negative correlation.

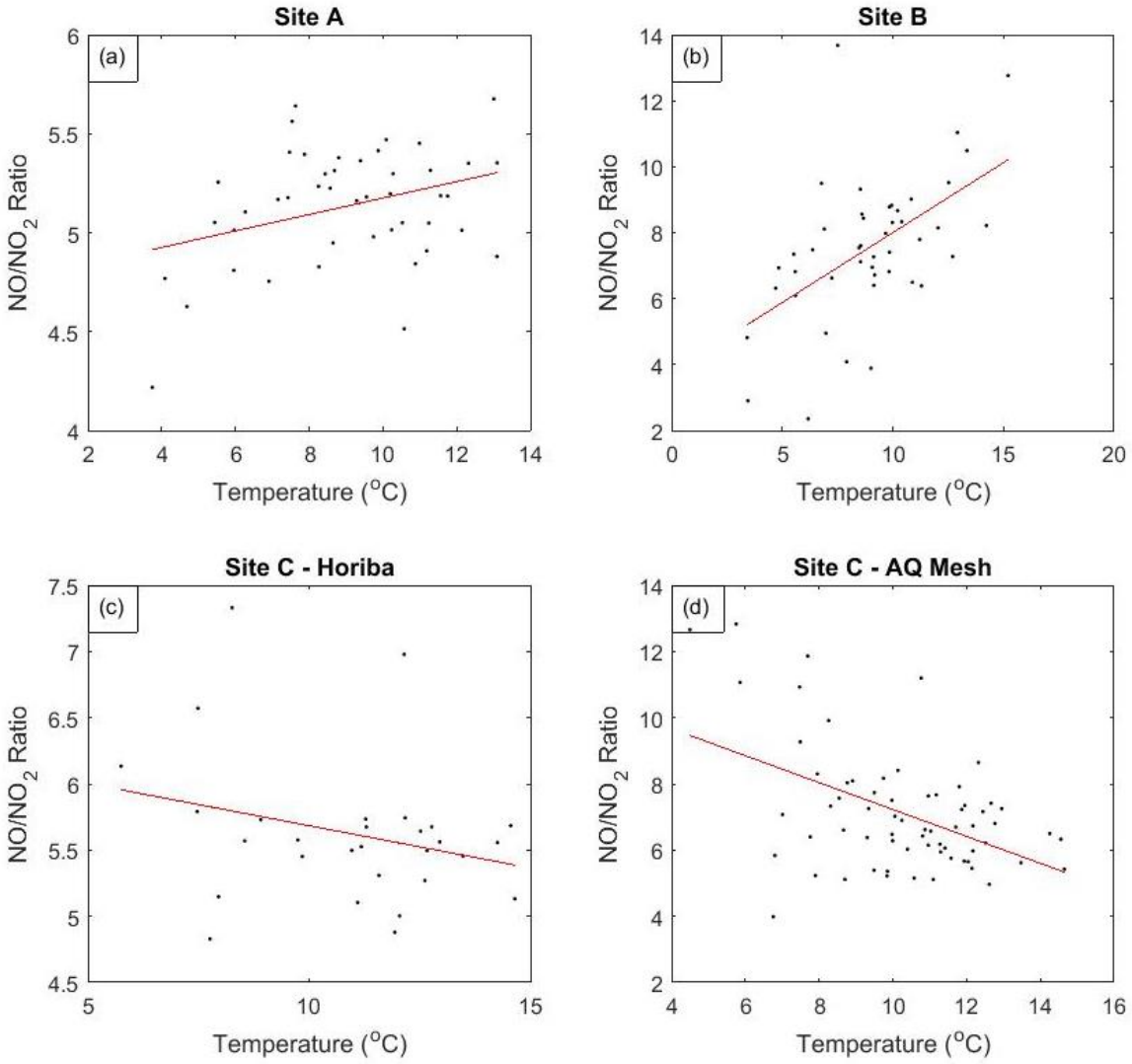

Figure 5.10. Mean daily temperature (°C) against mean NO/NO_2 ratio for each day the instruments were present at (a) Site A, (b) Site B, (c) Site C (Horiba Analyser) and (d) Site C (AQ Mesh), fitted with a linear regression line (red). For site C, two different analysers were used; hence these results are demonstrated in separate graphs.

Particulate Matter

Daily mean $PM_{2.5}$ and PM_{10} concentrations have a weak correlation with temperature (Figure 5.11). Site A has a negative correlation with temperature and the other two sites, sites B and C, have a positive correlation. It is unlikely that temperature is having an influence on PM

concentrations and the weak statistical correlations justify this (Table 5.4) with site B being the only site with a statistically significant correlation.

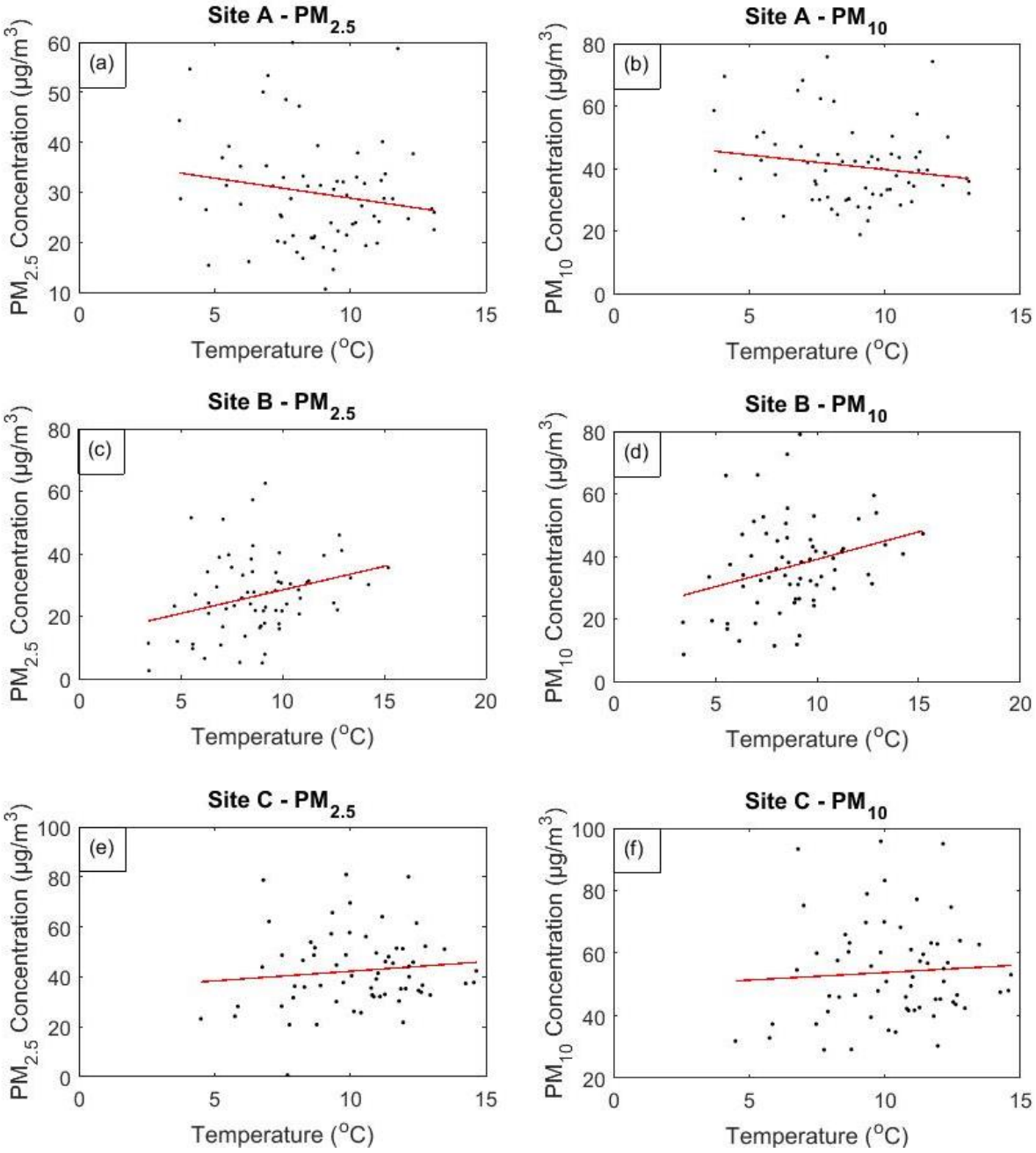

Figure 5.11. Mean daily temperature (°C) against mean daily $PM_{2.5}$ and PM_{10} – (a) Site A $PM_{2.5}$, (b) Site A PM_{10}, (c) Site B $PM_{2.5}$, (d) Site B PM_{10}, (e) Site C $PM_{2.5}$, (f) Site C PM_{10} – in $\mu g/m^3$, with a linear regression line (red).

Table 5.4. Correlation coefficients for temperature and $PM_{2.5}$ and PM_{10} (Figure 5.11). Correlation coefficients that are not statistically significant to a 95% confidence interval ($p>0.05$) are in red.

	$PM_{2.5}$	PM_{10}
Site A	-0.172	0.171
Site B	0.295	0.291
Site C	0.113	0.068

Carbon Dioxide

At site B, at the west end of platform 10/11, CO_2 is positively correlated against temperature (Figure 5.12), however, at sites A and C, carbon dioxide is negatively correlated against temperature but with a much lower correlation coefficient (Table 5.5).

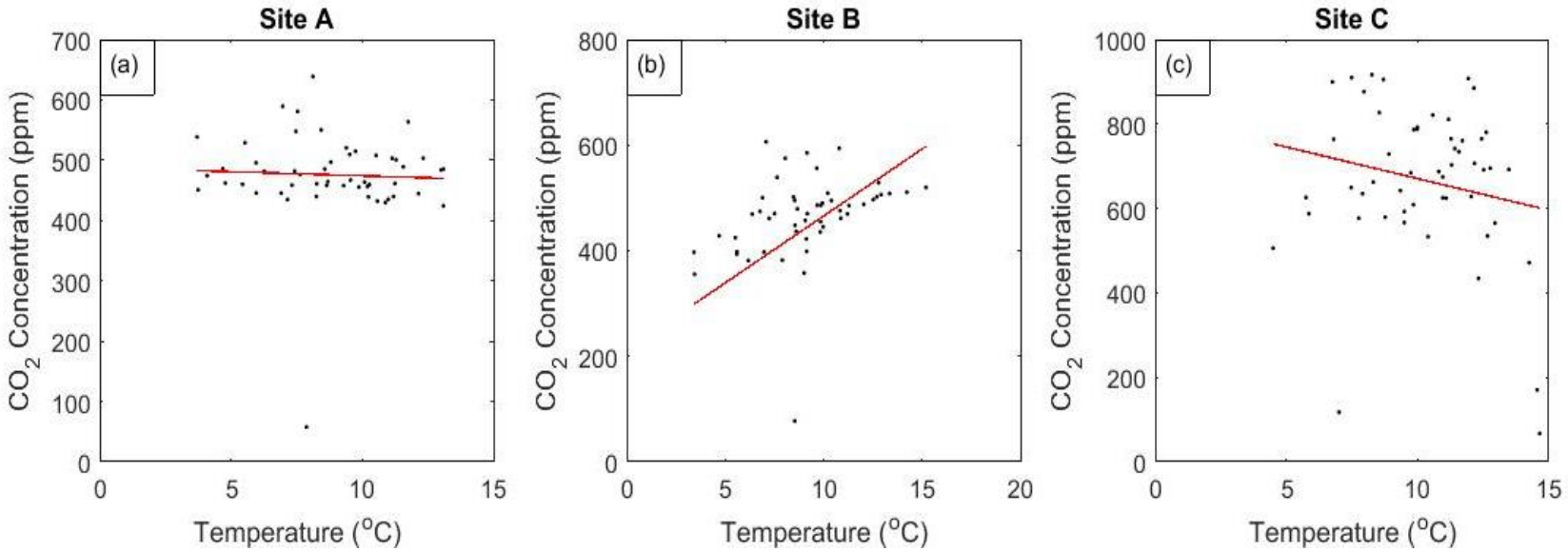

Figure 5.12. Mean daily temperature (°C) against CO_2 concentration (ppm) at (a) site A, (b) Site B, (c) Site C, fitted with a linear regression line (red).

Table 5.5. Correlation coefficients for temperature against CO_2 concentration at sites A, B and C (Figure 5.12). Correlation coefficients that are not statistically significant to a 95% confidence interval ($p>0.05$) are in red.

	CO_2
Site A	-0.045
Site B	0.349
Site C	-0.195

These inconsistent results show that it is unlikely that temperature has an influence on CO_2 at such a small scale. The global correlation between these two factors is unlikely to be mirrored in this environment over such a short time period.

Again, like particulate matter, site B is the only site to demonstrate a statistically significant correlation and this could be due to the trapped vortex present at the B-end of platform 10/11.

Black Carbon

Black carbon and temperature have a positive correlation of 0.347, which is statistically significant to 95% confidence interval (Figure 5.13). Black carbon is an indicator of DEEEs, therefore its correlation with temperature supports the hypothesis that heat and DEEEs are emitted simultaneously.

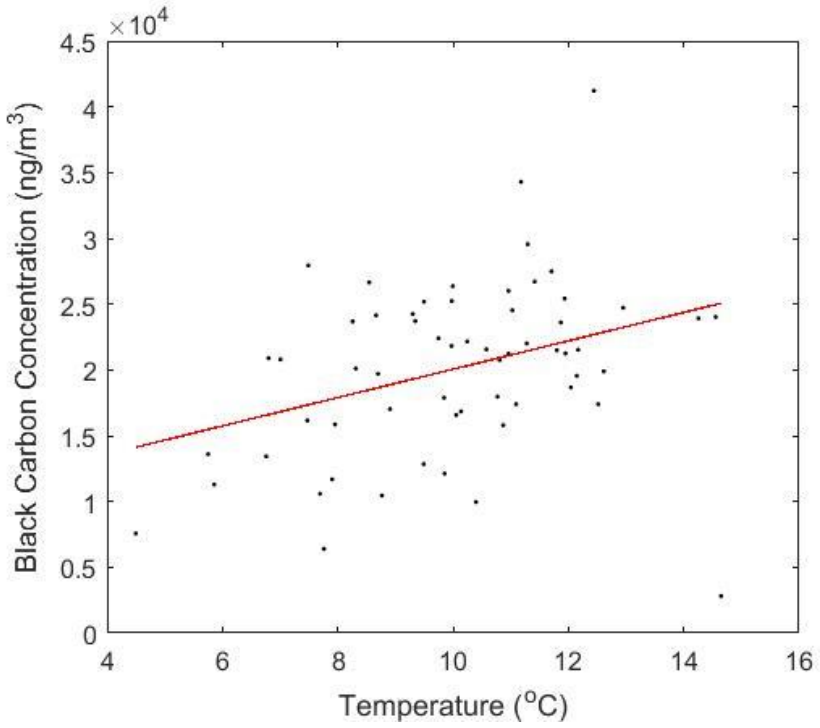

Figure 5.13. Daily Mean Temperature (°C) against black carbon concentration (ng/m^3) at site C, with a linear regression line.

5.3.3 Wind Velocity

Oxides of Nitrogen

Wind speed at site A correlates well with NO, NO_2 and NO_x concentration in both the westerly direction (positive wind speed) and easterly direction (negative wind speed) (Figure 5.14; Table 5.6).

Figure 5.14 illustrates that an increase in wind speed, in either direction along the platform, decreases pollutant concentration as there is wind driven ventilation at this end of the platform dispersing the pollutant.

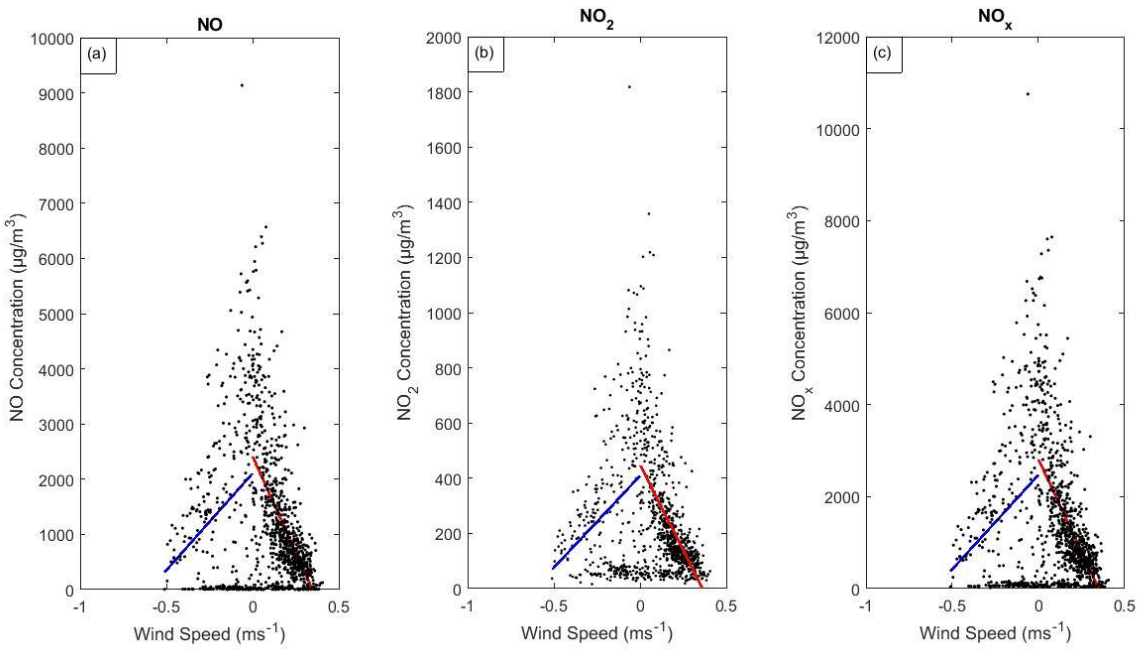

Figure 5.14. Correlation of wind speed (ms^{-1}) in an easterly and westerly direction against (a) NO, (b) NO_2 and (c) NO_x concentration ($\mu g/m^3$), at the A-end of platform 10/11, with two linear regression lines for easterly (blue) and westerly wind (red).

Table 5.6. Correlation coefficients of easterly and westerly wind speed against NO, NO_2 and NO_x for the A end of platform 10/11. Note, all correlation coefficients are statistically significant to 95% confidence interval.

	Easterly	Westerly
NO	0.281	-0.572
NO_2	0.315	-0.590
NO_x	0.286	-0.576

However, site B does not demonstrate the same behavioural pattern. Instead, Figure 5.15 shows weaker correlations for all species in all directions, of which only NO_x and NO with wind speed in a westerly direction are significantly correlated to 95% confidence interval (Table 5.7). Due to the large scale trapped vortex present at the B end of platform 10/11, it is assumed that pollutants become trapped amongst this vortex and are less responsive to wind conditions at platform level.

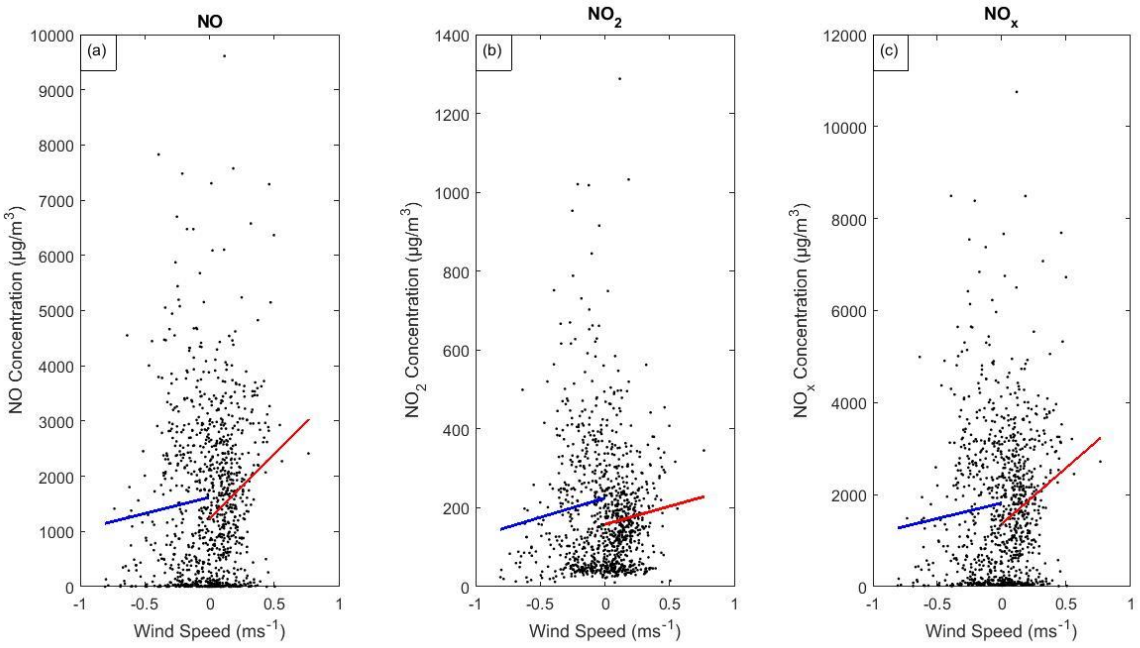

Figure 5.15. Correlation of wind speed (ms^{-1}) in an easterly and westerly direction against (a) NO, (b) NO_2 and (c) NO_x concentration ($\mu g/m^3$), at the B-end of platform 10/11, with two linear regression lines for easterly (blue) and westerly wind (red).

Table 5.7. Correlation coefficients of easterly and westerly wind speed against NO, NO_2 and NO_x for the B end of platform 10/11. Correlation coefficients that are not statistically significant to 95% confidence interval are highlighted in red.

	Easterly	Westerly
NO	0.0633	0.193
NO_2	0.0898	0.0808
NO_x	0.0664	0.186

Particulate Matter

Particulate matter demonstrates a similar response to wind speed as oxides of nitrogen. At the A-end of the platform (Figure 5.16; Table 5.8), pollutants have a statistically significant correlation with wind speed in both directions as there is wind driven ventilation. Conversely at the B-end of the platform (Figure 5.17; Table 5.9), only easterly winds are significantly correlated with $PM_{2.5}$ and PM_{10}, although with a much lower correlation coefficient than the A-end. Westerly winds are not significantly correlated with particulate matter. This further supports the concept of a large scale trapped vortex at the B-end and therefore particulate matter concentrations are not reduced with an increased wind speed; instead it is trapped amongst the vortex.

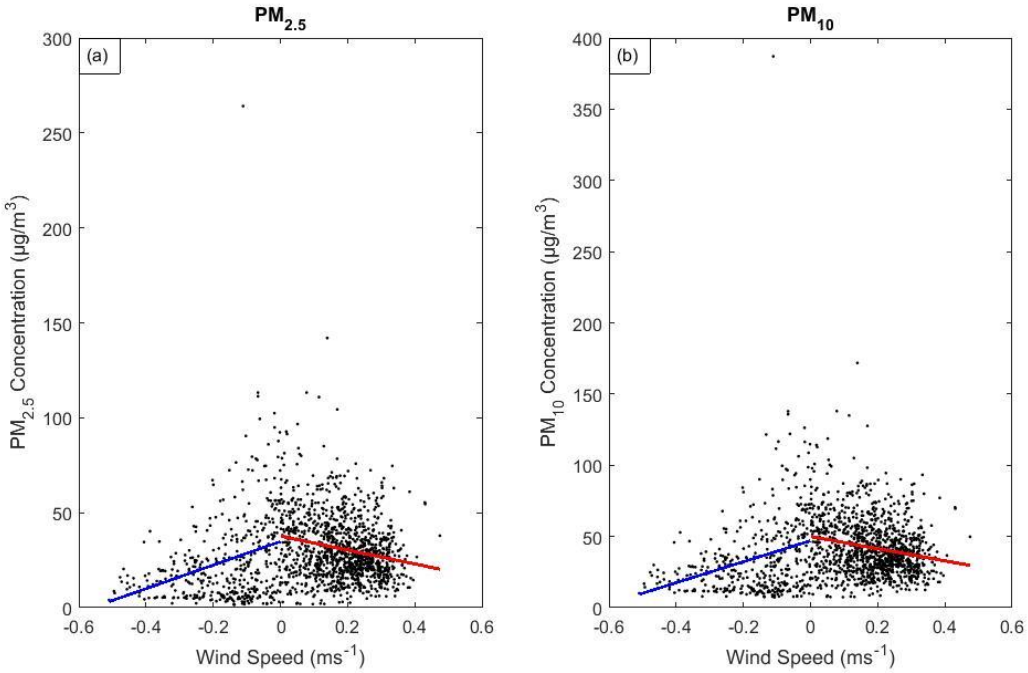

Figure 5.16. Correlation of wind speed (ms^{-1}) in an easterly and westerly direction against (a) $PM_{2.5}$ and (b) PM_{10} concentration ($\mu g/m^3$), at the A-end of platform 10/11, with two linear regression lines for easterly (blue) and westerly wind (red).

Table 5.8. Correlation coefficients easterly and westerly wind speed against $PM_{2.5}$ and PM_{10} for the A end of platform 10/11. Note, all correlation coefficients are statistically significant to 95% confidence interval.

	Easterly	Westerly
$PM_{2.5}$	0.301	-0.209
PM_{10}	0.283	-0.208

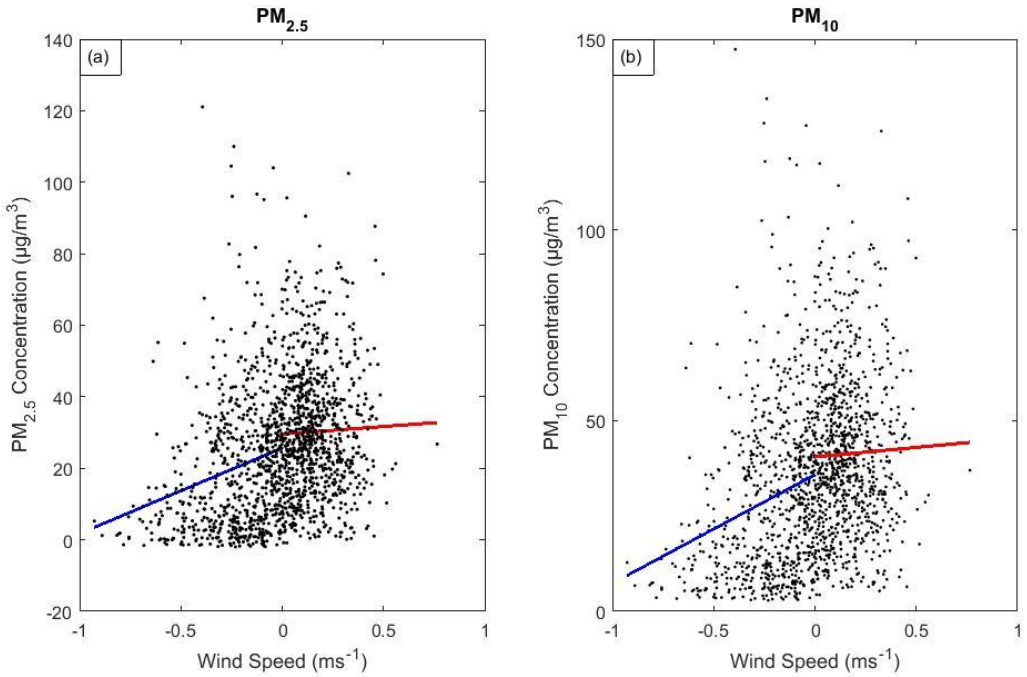

Figure 5.17. Correlation of wind speed (ms^{-1}) in an easterly and westerly direction against (a) $PM_{2.5}$ and (b) PM_{10} concentration ($\mu g/m^3$), at the B-end of platform 10/11, with two linear regression lines for easterly (blue) and westerly wind (red).

Table 5.9. Correlation coefficients of easterly and westerly wind speed against $PM_{2.5}$ and PM_{10} for the B end of platform 10/11. Correlation coefficients that are not statistically significant to 95% confidence interval are in red.

	Easterly	Westerly
$PM_{2.5}$	0.228	0.0287
PM_{10}	0.230	0.0287

Carbon Dioxide

Like oxides of nitrogen and particulate matter, carbon dioxide concentration also responds to changes in wind speed (Figure 5.18). Similarly, at the A-End, an increase in wind speed in either direction reduces carbon dioxide concentration. Whereas at the B-End, only easterly wind has a statistically significant, although weak, relationship with carbon dioxide and an increase in wind in this direction, reduces pollutant concentration. Again, it is clear that the trapped vortex at the B-end of the station is influencing the effect of wind. Note the correlation coefficients for wind speed and carbon dioxide are smaller than those for other pollutants (Table 5.10).

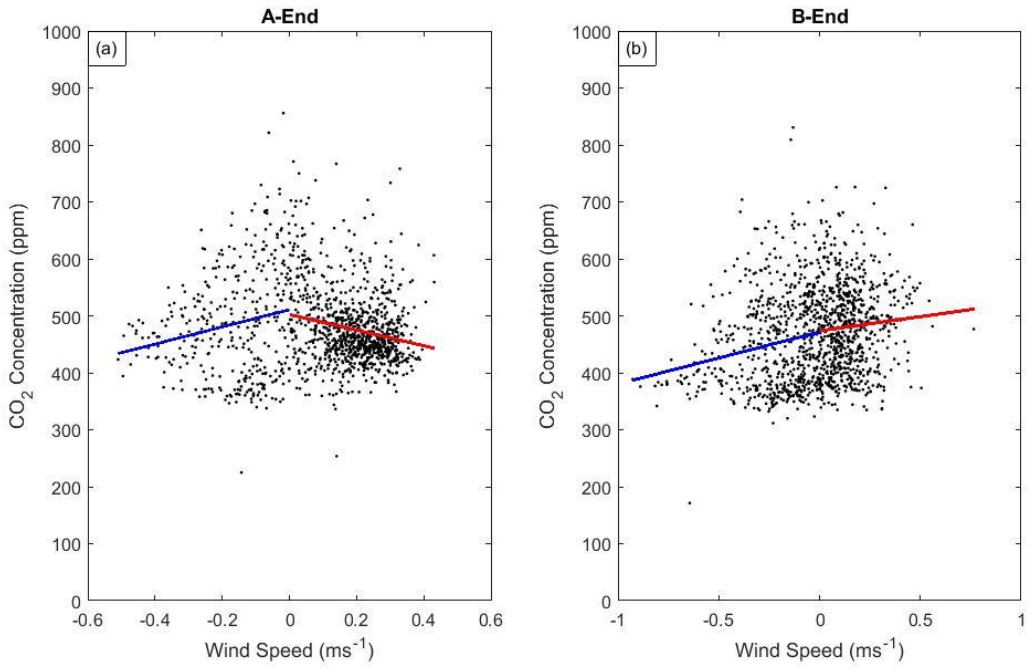

Figure 5.18. Correlation of wind speed (ms^{-1}) in an easterly and westerly direction against CO_2 (ppm), at the (a) A-end and (b) B-end of platform 10/11, with two linear regression lines for easterly (blue) and westerly wind (red).

Table 5.10. Correlation coefficients of easterly and westerly wind speed against CO_2 for the A-end and B-end of platform 10/11. Correlation coefficients that are not statistically significant to 95% confidence interval are in red.

	Easterly	Westerly
A-End	0.191	-0.168
B-End	0.157	0.0745

5.4 Concluding Remarks

The findings of this chapter illustrate that pollution concentrations are largely insensitive to changes in temperature; instead local wind is the dominant meteorological factor influencing concentrations.

The correlations seen between temperature and pollutant concentrations are hypothesised to be the result of the simultaneous emission of heat and pollutants. For NO_x, the correlations coefficients are greater for NO than NO_2, supporting the statement that NO_x is emitted simultaneously with heat. This is because some NO_2 is not directly emitted from rolling stock; rather it is formed through secondary processes (Section 5.3.1) resulting in a weaker correlation coefficient. In addition, black carbon, which is deemed to be a better indicator of combustion sources than undifferentiated PM (Janssen et al., 2012; Janssen et al., 2011; Vanderstraeten et al., 2011), demonstrates a statistically significant relationship with temperature. This highlights the simultaneous emission of DEEEs and heat.

Wind is a key driving force for pollutant dispersion in the station, in particular at the A-end of the platform. Furthermore, a large scale trapped vortex was identified at the B-end of the station and, at the wind speeds monitored during this sampling campaign, pollutants were less well dispersed in this area of the station. The ventilation system in place at Birmingham New Street station during the campaign monitored wind speed and direction at the B-end of platforms 4/5, 6/7 and 8/9. This may be problematic for two reasons. Firstly, the air speed and direction recorded at these locations may not represent that of the entire station and could be the result of a large-scale vortex situated at the B-end of the station. Secondly, if the ventilation system were to exhaust pollutants in the direction of this vortex (easterly wind) then pollutants appear to become trapped. Further analysis would be required to determine a velocity threshold in the easterly direction that might overcome this vortex.

It is clear that Birmingham New Street station is a complex environment and its underground tunnel-like nature within the urban canopy contributes towards unique challenges, in particular for wind and its role in ventilating the station. As no two transport interchanges are identical, each will possess unique characteristics that influence the effect of environmental factors at that interchange. As a minimum, future air quality monitoring campaigns at transport interchanges should monitor temperature and wind velocity at passenger level, with a particular focus on wind. A more extensive wind sampling campaign is required to determine its role in these environments and assist in the development of ventilation systems.

6. VEHICLE MOVEMENT INFLUENCE ON AIR QUALITY IN ENCLOSED RAILWAY STATIONS

This chapter builds upon the analysis approach used for Figure 8 and Table 8 of the paper:

Hickman, A., Baker, C., Cai, X., Delgado-Saborit, J. and Thornes, J. (2018). Evaluation of air quality at the Birmingham New Street Railway Station. Proceedings of the Institution of Mechanical Engineers, Part F: Journal of Rail and Rapid Transit, 232(6), pp.1864-1878.

A copy of this paper can be found in Appendix C.

6.1 Overview

This chapter explores the response of pollutant levels at Birmingham New Street station to different rolling stock serving platform 10/11. To assess this and address the aim "*Analyse the response of air quality to emissions produced by the presence of diesel and electric rolling*

stock", the timetabling information on three days, 12th December 2016, 2nd January 2017 and 6th January 2017, has been compared against pollutants concentrations.

The timetabling information has been grouped by engine type, diesel or electric, and classification, to examine the difference in pollutant level responses. Although, platform 10/11 is electrified, many of the train services run on non-electrified routes, resulting in platform 10/11 predominantly serving diesel trains. Trains serving platform 10/11 are formed by the following train classes (Hickman et al., 2018):

- Class 43 (HST) – locomotive hauled trains, with two power cars and up to eight coaches, built between 1975 and 1982 with a maximum speed of 200 km/h.
- Class 158 (Express Sprinters) – two or three car units built between 1989 and 1992 with a maximum speed of 140 km/h.
- Class 170 (Turbostars) – two or three car units, built between 1998 and 2005 with a maximum speed of 160 km/h.
- Class 220/221 (Voyagers) – four or five car units, built between 2000 and 2002, with a maximum speed of 200 km/h.
- Class 323 (EMU) – electric multiple unit formed of three cars, built between 1992 and 1993, with a maximum speed of 145 km/h.

In addition, idling time for the three analysis days has been calculated and the variation in concentration ratios assessed across all three days, to examine if extending the idling time at Birmingham New Street station can significantly affect pollutant concentrations.

Note, only figures for 6th January 2017 are used in this chapter, respective figures for 12th December 2016 and 2nd January 2017 can be found in Appendix D.

6.2 Results and Interpretation

6.2.1 Diesel vs. Electric Movements

Oxides of Nitrogen

Figure 6.1(a) demonstrates that diesel rolling stock is the key source of NO_x in the station, with NO_x concentrations rising when diesel rolling stock is occupying the platform. Unsurprisingly electric trains have no effect on NO_x concentrations in the station, due to the absence of exhaust emissions on electric rolling stock (Figure 6.1(b)). However, for diesel trains, it is possible, at least in the early morning, to associate these specific trains occupying platform 10/11 with clear peaks in NO_x concentration.

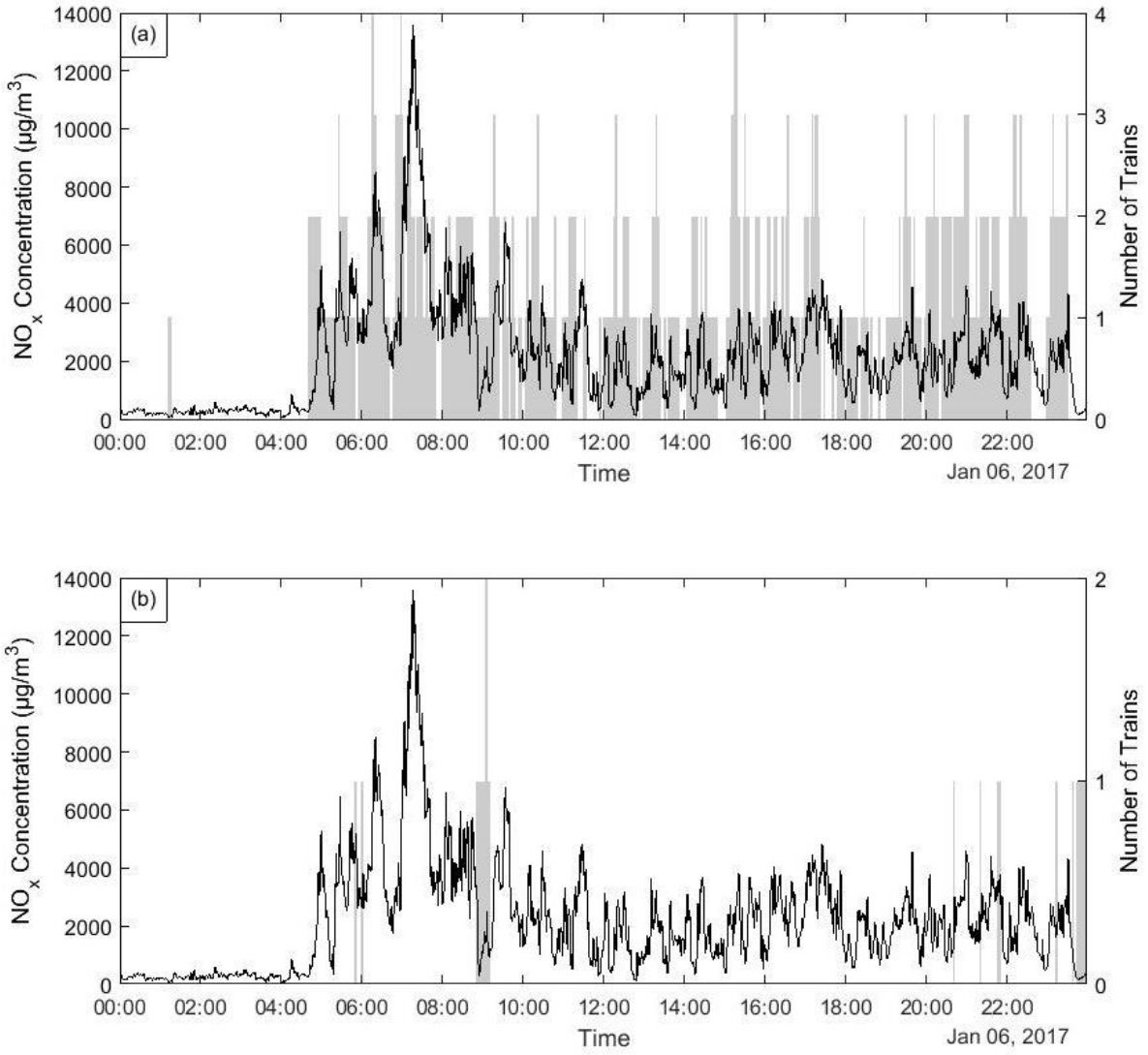

Figure 6.1. One minute NO_x concentration ($\mu g/m^3$) for 6th January 2017 with shading showing number of (a) diesel trains and (b) electric trains occupying platform 10 and/or 11.

Due to the oxidation of NO to NO_2 by O_3, peaks in NO_2 are less likely to occur simultaneously with train idling. Figure 6.2 supports this, showing that NO_2 concentration peaks are approximately a couple of minutes later than the peak in NO_x concentration, aligning with the reaction time of O_3 oxidation. Although, this is much harder to distinguish later in the day due to the ongoing oxidisation of NO from previous rolling stock.

Note, both 12th December 2016 and 2nd January 2017 show the same findings and the respective figures for these days can be found in Appendix D (Figure D.1 – D.4).

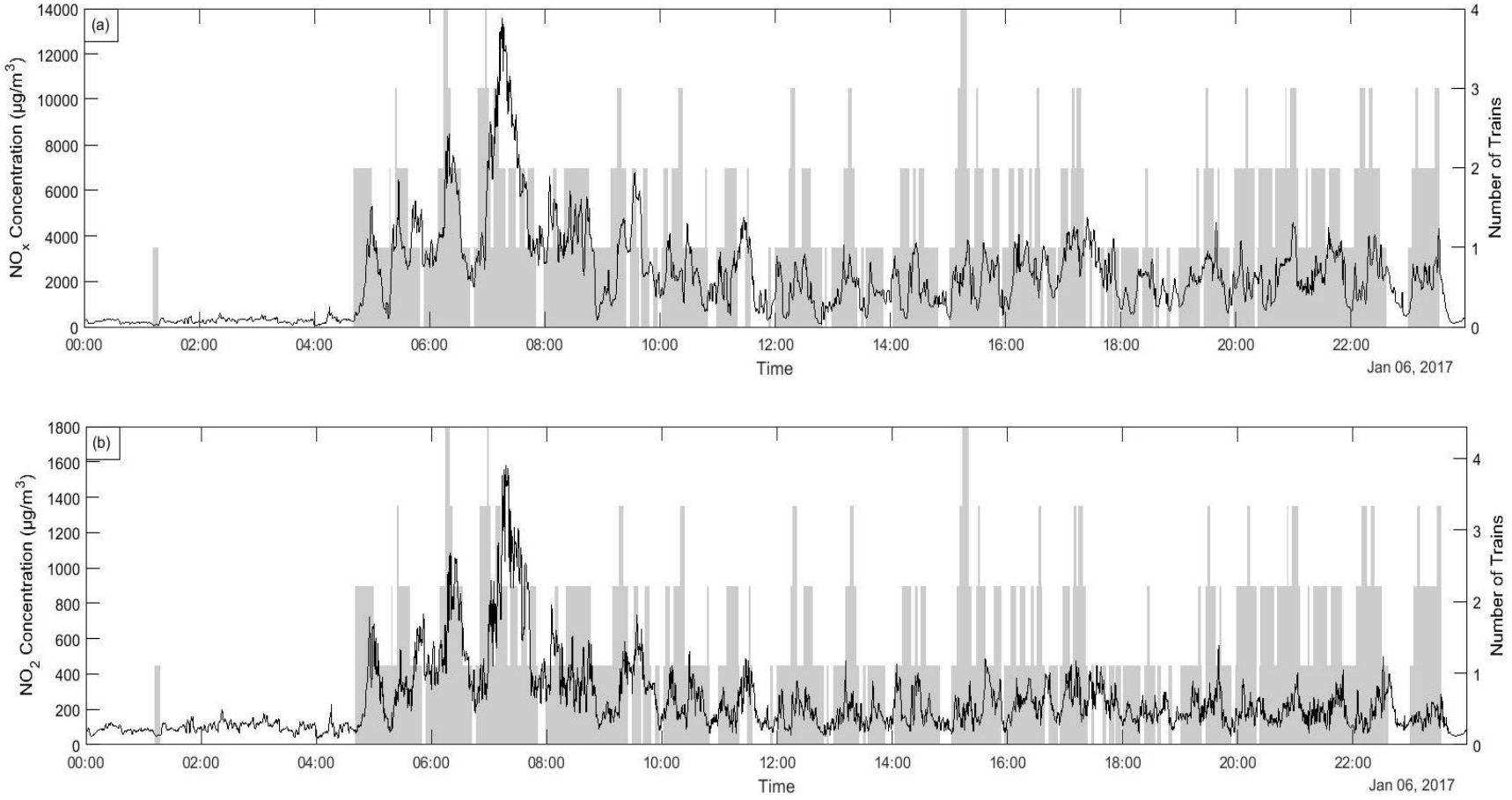

Figure 6.2. One minute concentrations of (a) NO_x and (b) NO_2 for 6th January 2017 with shading showing number of diesel trains occupying platform 10 and/or 11.

Particulate Matter

Abbasi et al. (2013) discussed particle emissions that originate from non-exhaust emissions. The review, coupled with the findings of Loxham et al. (2013) at a subway station in the Netherlands, suggested that electric rolling stock can be a source of particulate matter. However, Figure 6.3 contradicts these findings, showing no clear peak in $PM_{2.5}$ concentrations when electric rolling stock are occupying platform 10/11. Instead, the peaks are associated with the idling of diesel rolling stock. Fine particulates originate from wear between the wheels and the rail and the pantograph and overhead line equipment (OLE). When stationary, there will be little/no friction between these component and particles will not be emitted. The particles, which are emitted when the vehicle enters and leaves the station, are minimal in comparison with the particles within DEEEs, hence there are no clear peaks in $PM_{2.5}$ when electric rolling stock is present as diesel rolling stock is the still the main source of particulate matter.

Again, 12th December 2016 and 2nd January 2017 mirror the findings of 6th January, showing diesel trains as the main source of $PM_{2.5}$. The respective figures for these days can be found in Appendix D (Figure D.5; D.6).

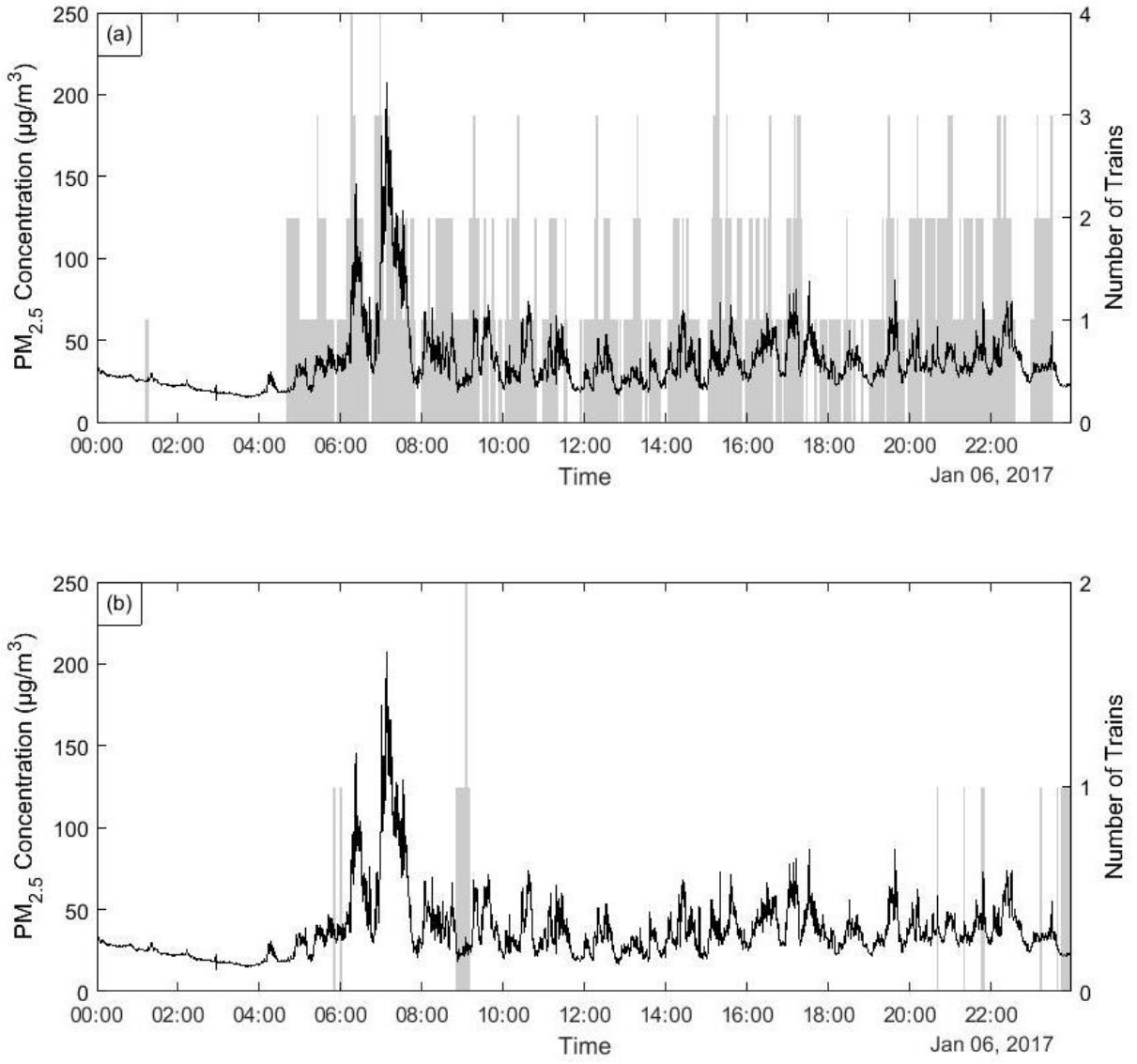

Figure 6.3. One minute $PM_{2.5}$ concentration ($\mu g/m^3$) for 6th January 2017 with shading showing number of (a) diesel trains and (b) electric trains occupying platform 10 and/or 11.

Carbon Dioxide

To further support the argument against using CO_2 to trigger the ventilation system at Birmingham New Street, as discussed in Chapter 4, Figure 6.4 demonstrates that CO_2 is relatively unresponsive to idling of diesel rolling stock.

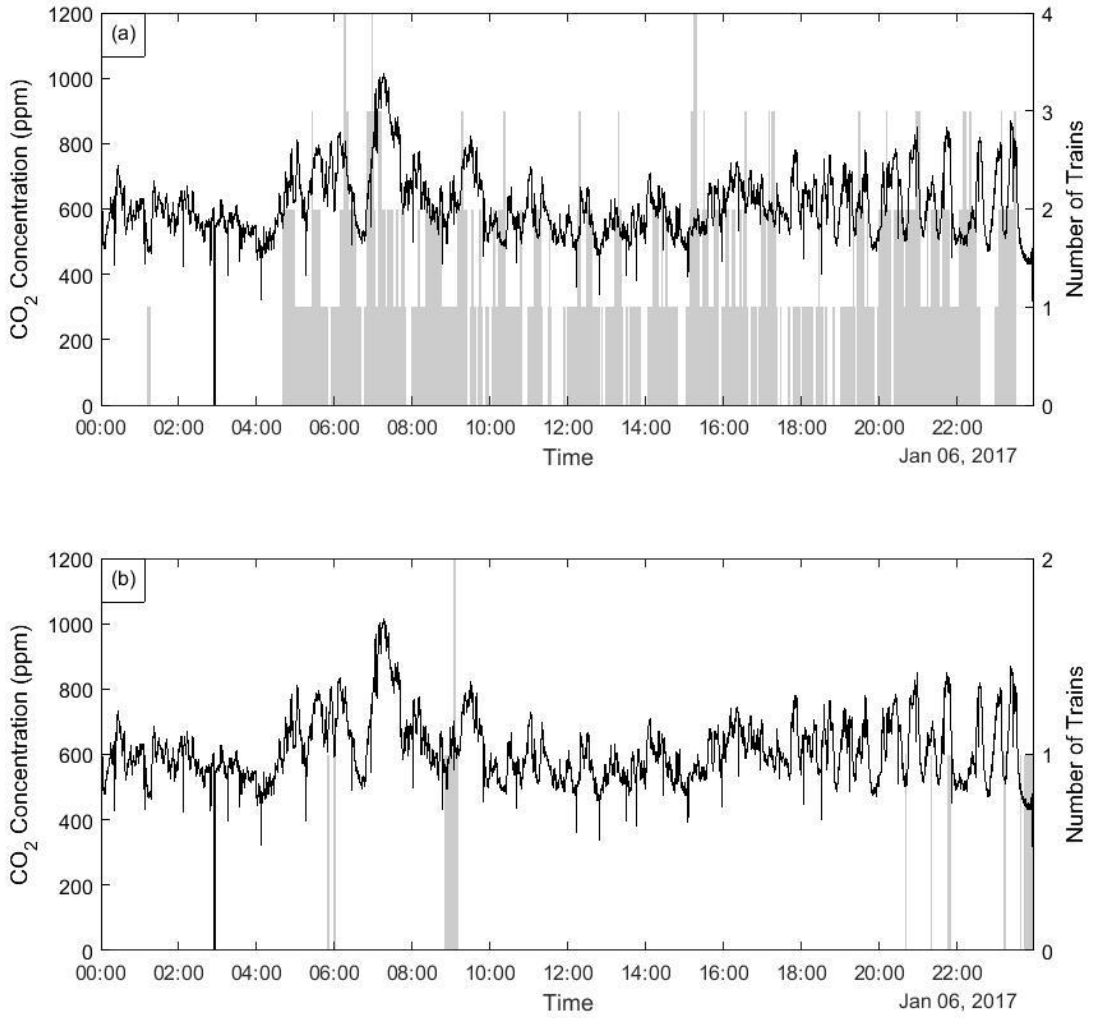

Figure 6.4. One minute CO_2 concentration (ppm) for 6th January 2017 with shading showing number of (a) diesel trains and (b) electric trains occupying platform 10 and/or 11.

The findings are the same on both 12th December 2016 and 2nd January 2017, demonstrating little response in CO_2 to idling diesel trains. Supporting figures for 12th December 2016 and 2nd January 2017 can be found in Appendix D (Figure D.7; D.8).

6.2.2 Investigation of Diesel Train Movements by Classification

Oxides of Nitrogen

Section 6.2.1 indicates that diesel rolling stock is the main source of NO_x at Birmingham New Street station. Diesel train movements can be further categorised by classification to provide an insight into which rolling stock contributes most significantly to elevated NO_x concentrations. Figure 6.5 concludes that peaks in NO_x concentration can be associated with idling of class 158/170 Express Sprinter/Turbostars and class 220/221 Voyagers. Whereas InterCity 125, High Speed Train, driven by class 43 power cars (class 43 HST) have a minimal impact on NO_x concentration (Figure 6.5(c)). However, note that all vehicles have engines that do not comply with NRMM regulations as they were manufactured prior to NRMM regulations being introduced.

Figure 6.5 demonstrates that the idling time of class 158/170 Express Sprinters/Turbostars and class 220/221 Voyager, is often much greater than class 43 HST. It is likely that the length of idling is a key contributing factors to the peaks in NO_x concentrations. In addition, the dimension of the rolling stock is also suggested to impact pollutant concentrations. Class 220/221 Voyagers are the shortest, in height, of the diesel rolling stock serving platform 10/11 (Table 6.1). It is possible that DEEEs may disperse through the gap between the train and platform 'roof', which is approximately the same height as the OLE, elevating concentrations on the serving platform. Class 43 HST are the largest, therefore the gap between the platform 'roof' and the vehicle is smaller, restricting airflow towards the platform (Table 6.1). Furthermore, if there are no vehicles on the adjacent track, pollutants may be able to disperse freely towards other platforms. This potentially may have caused the high NO_2 concentrations on platform 12B during the mobile monitoring – Section 4.4.1. Although all exhausts on

rolling stock serving Birmingham New Street are at roof height, air flow around smaller vehicles is less restricted around the vehicle, allowing the dispersion of pollutants towards the platform.

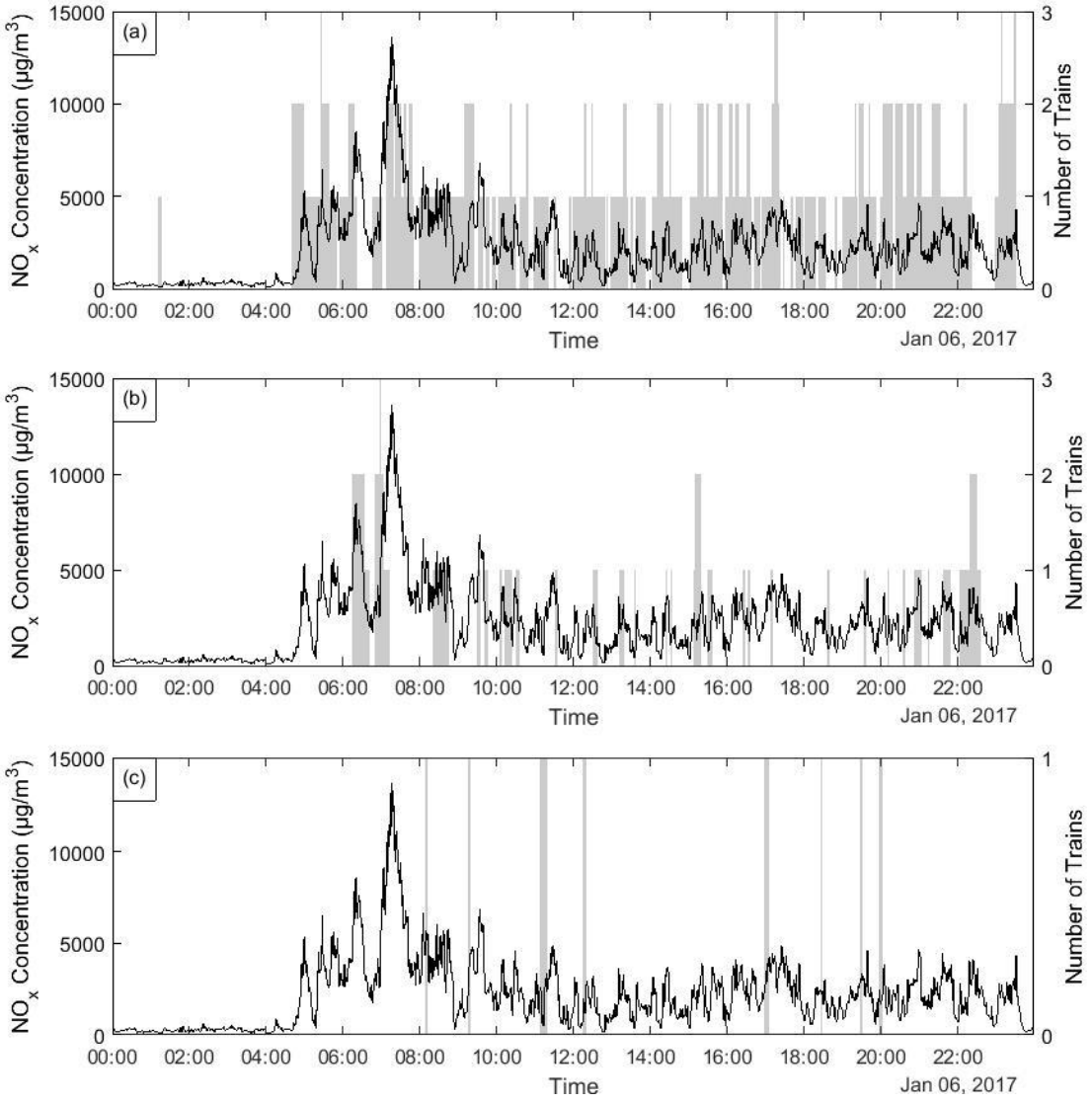

Figure 6.5. One minute NO_x concentration (µg/m^3) for 6th January 2017 with shading showing number of (a) class 158/170 (Express Sprinter/Turbostar), (b) class 220/221 (Voyager) and (c) class 43 (HST) occupying platform 10 and/or 11.

Table 6.1. Dimensions of rolling stock serving platform 10/11 and the location of their exhaust (Locomotive Wiki, 2018; Porterbrook, 2016a; Porterbook 2016b; Pritchard and Fox, 2009).

	Car Width	Car Height	Engine Type	Engine Locations
Class 43 HST	2.72 m	3.91 m	MTU 16V400R41	Power car at front of vehicle (2250 hp, 1678 kW)
Class 158 Express Sprinter	2.70 m	3.81 m	Cummins NTA855R1	One engine per car (350 hp, 260 kW)
Class 170 Turbostar	2.69 m	3.77 m	MTU 6R183TD13H	One engine per car (422 hp, 315 kW)
Class 220/221 Voyager*	2.73 m	3.56 m	Cummins QSK19 I/II	One engine per car (750 hp, 560kW)

* Note, class 220 voyagers are formed of 4 cars and class 221 voyagers are formed of 5 cars

Analysis by classification for 12th December 2016 and 2nd January 2017 mirrors these results, Voyagers have the longest idling periods and impact NO_x concentration most significantly and class 43 HST have little impact on concentrations. The accompanying figures for 12th December 2016 and 2nd January 2017 can be found in Appendix D (Figure D.9; D.10).

Particulate Matter

Figure 6.3(a) demonstrated a response in $PM_{2.5}$ concentration when diesel rolling stock was occupying platform 10/11, hence the response of $PM_{2.5}$ to different classifications of rolling stock has been investigated. Similarly to NO_2, peaks in $PM_{2.5}$ can be clearly associated with idling class 220/221 Voyagers (Figure 6.6(a)) and idling class 158/170 Express Sprinters/Turbostars (Figure 6.6(b)). Again, class 43 HST appear to have little impact on $PM_{2.5}$ concentration (Figure 6.6(c)), this is likely to be due to their infrequent passage and short idling periods, coupled with its high exhaust and large size. Whereas class 220/221 Voyager and class 158/170 Express Sprinter/Turbostar services are more frequent, thus elevating $PM_{2.5}$ concentration most significantly.

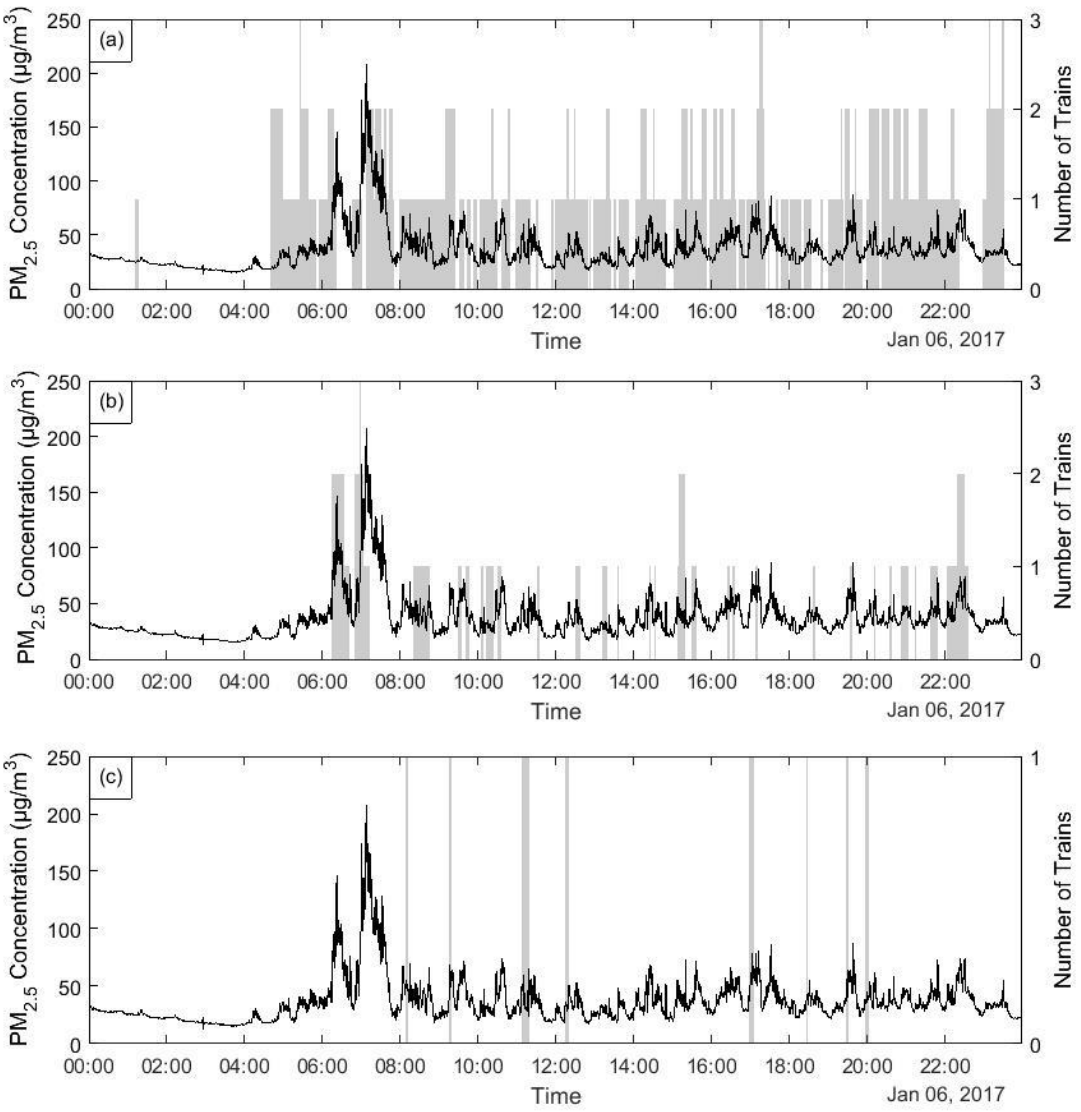

Figure 6.6. One minute $PM_{2.5}$ concentration ($\mu g/m^3$) for 6th January 2017 with shading showing number of (a) class 158/170 (Express Sprinter/Turbostar), (b) class 220/221 (Voyager) and (c) Class 43 HST occupying platform 10 and/or 11.

6.2.3 Platform Occupancy Ratios

Analysis of train classifications suggest that class 220/221 voyagers elevate pollutant concentrations most significantly and long idling periods are responsible for higher pollutant concentrations.

Table 6.2 supports the finding that class 220/221 voyagers are the worst offenders for elevating all pollutant concentrations in Birmingham New Street, with the exception of black carbon. Table 6.2 suggests that idling Class 43 HST increase black carbon concentration the most, however, this scenario only occurred for a period of 45 seconds, therefore it is difficult to conclude if this result is reliable and would be repeated. In addition, 12th December 2016 and 2nd January also provide unreliable results for black carbon due to instrument limitations and short scenario occurrence.

When EMUs are present on platform 10/11, concentrations for all pollutants are lower than when there are no trains idling on platform 10/11. This finding shows that pollutants emitted from rolling stock on adjacent platforms are influencing concentrations on platform 10/11 and it is likely that when EMUs are idling on platform 10/11 this dispersion is obstructed by the EMU.

Further analysis of Table 6.2 indicates shows that the NO_2 concentration ratio is always less than the NO_x and NO concentration ratios, supporting the findings from previous chapters that NO_2 is not only being emitted directly from rolling stock but also being produced through secondary processes.

Finally, the CO_2 ratio does not deviate greatly from 1, indicating there is an insignificant change in CO_2 concentration when rolling stock is occupying platform 10/11 compared with

concentrations when there are no idling trains. This further proves that using CO_2 measurements to control the ventilation system is not sufficient for pollution control within the station.

Table 6.2. NO, NO_x, NO_2, $PM_{2.5}$, PM_{10}, CO_2 and Black Carbon ratio for platform occupancy periods for different train classifications to periods with no trains, where *t* is the length of time, in seconds, the occupancy scenario occurred for. Platform 10/11 was not occupied for 27570 seconds on 6th January 2017.

		Ratio of concentration when platforms occupied to not occupied						
	t	NO	NO_x	NO_2	$PM_{2.5}$	PM_{10}	CO_2	BC
EMU	*1395*	0.75	0.75	0.80	0.94	0.94	0.85	0.58
Class 43	*45*	2.79	2.55	1.21	1.29	1.37	0.92	5.68
Class 158/170	*37545*	2.85	2.71	1.93	1.37	1.45	1.11	2.33
Class 220/221	*3405*	4.17	4.02	3.21	2.23	2.47	1.12	2.98
Class 43 & Class 158/170	*2820*	3.03	2.84	1.79	1.61	1.72	1.06	2.89
Class 158/170 & Class 220/221	*11115*	3.75	3.51	2.16	1.75	1.90	1.10	3.31
EMU & Class 158/170	*2385*	2.19	2.09	1.56	1.19	1.22	1.07	2.00
EMU, Class 158/170 & Class 220/221	*120*	3.87	3.57	1.94	1.68	1.82	1.42	2.92

Previous findings in this chapter suggest that long idling periods are responsible for high pollutant concentrations. Table 6.3 expresses the difference in ratios on 12th December 2016, 2nd January 2017 and 6th January 2017.

Table 6.3. NO, NO_x, NO_2, $PM_{2.5}$, PM_{10}, CO_2 and Black Carbon ratio for when the platform was occupied by rolling stock to periods with no trains, where *t* is the number of seconds platform 10/11 was occupied by rolling stock on each day.

	12th December 2016	2nd January 2017	6th January 2017
	(13 minutes)	*(12 minutes)*	*(12 minutes)*
t	*56820*	*53145*	*58830*
NO	3.75	2.93	3.04
NO_x	2.55	2.19	2.00
NO_2	3.53	2.80	2.87
$PM_{2.5}$	1.76	2.05	1.49
PM_{10}	2.00	2.44	1.59
CO_2	1.28	1.12	1.10
BC	3.31	2.99	2.53

On 12th December 2016, when the average idling time on platform 10/11 was 13 minutes, ratios of concentrations when platform was occupied by rolling stock to when the platforms were vacant were higher than the ratios for 2nd and 6th January 2017, for all pollutants, with the exception of particulate matter. Although 2nd and 6th January had an average idling time of 1 minute less than 12th December 2016, Table 6.3 highlights the possible effect on pollutant concentrations with a slight increase in idling time. Furthermore, it is likely that the increase idling time was mirrored across the station, as often, disruption affects the entire station rather than individual services or platforms. Hence, the average concentration across the whole station will be greater.

The results highlight the importance of analysing timetables, particularly the examination of idling times, which can result in a build-up of pollutants in a confined space. However, whilst analysis of idling times can be beneficial, it is essential to note that there are other external factors that may also be influencing concentrations within the station, including ambient air quality, meteorological conditions and timetabling changes, such as Leaf Fall.

6.3 Concluding Remarks

Analysing the response in pollutant concentration to diesel and electric movements indicated that at Birmingham New Street station, high pollutant concentration can be attributed to diesel rolling stock movements. Previous studies have assessed particulate matter concentrations in subway and other electrified rail environments, finding high concentrations of ultrafine particulate matter as a result (Aarnio et al., 2005; Abbasi et al., 2012; Kam et al., 2011; Kim et al., 2008; Loxham et al., 2013; Moreno et al., 2015; Onat and Stakeeva, 2014; Querol et al., 2012). However, this is not the case at Birmingham New Street as electric rolling stock will

not brake harshly within the station, instead they will often roll in, thus, there will be little friction, resulting in fewer particles emitted.

In addition, the diesel vs. electric analysis further concluded that CO_2 measurements are not suitable for triggering the ventilation system. CO_2 demonstrated little change when diesel rolling stock was idling on platform 10/11, whereas clear peaks could be seen in NO_x and $PM_{2.5}$ concentrations when diesel rolling stock was idling on the platform.

This chapter has also highlighted class 220/221 Voyagers to be the train that contributes most significantly to the high concentrations of pollutants at Birmingham New Street station. Their slightly smaller dimensions and the location of their exhaust are thought to be key contributing factors to higher pollutant concentrations during their idling. It is suggested that their smaller size allows pollutants to disperse more freely around the train and DEEEs would rise up from the exhaust, towards the platform with the heat that is simultaneously emitted.

Finally, the length of idling times is speculated to have an impact on pollutants concentrations in the station. However, the results in this chapter are limited as only timetabling information was examined for Platform 10/11 across 3 days; therefore, further analysis is required to confirm this finding.

Future research at transport interchanges should analyse the timetabling information to consider its impact on pollutant concentrations. The timetables should be analysed for all areas of the transport interchange, including the type of vehicle being used and the length of vehicle idling.

7. OVERALL DISCUSSION

This chapter builds upon the discussion in:

Hickman, A., Baker, C., Cai, X., Delgado-Saborit, J. and Thornes, J. (2018). Evaluation of air quality at the Birmingham New Street Railway Station. Proceedings of the Institution of Mechanical Engineers, Part F: Journal of Rail and Rapid Transit, 232(6), pp.1864-1878.

and

Thornes, J.E., Hickman, A., Baker, C., et al. (2017) Air quality in enclosed railway stations. Proceedings of the Institution of Civil Engineers-Transport, 170: (2): 99-107.

A copy of these papers can be found in Appendix C and E, respectively.

7.1 Overview

This chapter builds upon the findings of Chapters 4-6 and discusses the subsequent improvements that have been made at Birmingham New Street station since the sampling campaign. Chapter 4 highlights the large gap between occupational and public health limits,

with Birmingham New Street exceeding public health limits but would be almost compliant with the occupational health limits that will be introduced in August 2018. Chapter 4 also questions the use of CO_2 to trigger the ventilation system within the station, as it shows little correlation with other present pollutants, such as NO_2. Additionally, Chapter 5 found a large-scale trapped vortex at the B-end of platform 10/11, which may have an effect on the ventilation system. Finally, Chapter 6 highlighted that class 220/221 Voyagers contribute most significantly to high pollutant concentrations on platform 10/11. These four topics and their consequences will be further discussed below in Sections 7.1 – 7.5.

In addition, the limitations of the thesis have also been discussed, expressing factors that should be considered in future research and why care should be taken when reviewing that findings at Birmingham New Street station. It is unlikely that the findings from the 2016/17 monitoring campaign represent the current situation as Network Rail have implemented strategies to address the issues found during this research.

7.2 Occupational vs. Public Health Limits

Chapter 2 details the workplace exposure limits and EU ambient air quality limits, explaining that only the workplace exposure limits are applicable to semi-enclosed railway environments, such as Birmingham New Street station. However, the workplace exposure limits are far higher than the EU ambient air quality limits and particulate matter, oxides of sulphur (SO_x) and polycyclic aromatic hydrocarbons (PAHs) are not included. As a result, pollutants originating from DEEEs could reach high concentrations or even be unregulated in enclosed railway environments. Whilst Network Rail have a duty to adhere to The Management of Heath and Safe at Work Regulation 1999 and the Control of Substances Hazardous to Health Regulations 2002, it is questionable if this is sufficient to ensure those

who are not in Network Rail's employment are not exposed to risks to their health and safety with the current limits in place.

The workplace exposure limits are particularly high due to being time weighted averages for shorter exposure periods, 15 minutes and 8 hours. In addition, the workforce is perceived to be 'fit for work' and can be exposed to these high concentrations for a short period of time, unlike the more vulnerable general public. Typically, in environments where the workplace exposure limits are applicable, the general public do not spend extended periods of time in that environment, if at all. Hence, their exposure time to potentially high concentrations of pollutants is minimal. However, Birmingham New Street is particularly unique in this regard. The station is the busiest railway interchange outside of London, resulting in many passengers waiting in Birmingham New Street station for a connecting service.

This research has highlighted that pollutant concentrations, in particular NO_2, can build up at platform level at Birmingham New Street and even disperse up into the concourse. Furthermore, congestion at the station results in longer idling times, thus further elevating concentrations, which has a potentially to impact both staff and passengers However as personal exposure monitoring was not conducted on passengers and staff, the risk of DEEEs to these individuals cannot be confirmed. Future air quality assessments in the station should consider personal monitoring for both groups.

In response to these findings, Network Rail has developed measures at Birmingham New Street station to reduce staffs' exposure to DEEEs. Train dispatchers, who spend the majority of their shift on the platform, are now rotated throughout their shift, as opposed to spending their entire shift on one platform. As a result, dispatchers will not spend extended periods of their shift on platforms with high pollutant concentrations, for example platform 10/11.

Furthermore, during the redevelopment of Birmingham New Street station the waiting rooms were removed from platform level, now there are three lounges across the concourse and numerous shopping outlets. Network Rail hopes that passengers spend the more time in the concourse and head down to the platform just before the arrival of their train. Located in the concourse is the Network Rail customer service desk, where those requiring assistance attend and the customer service team do not take passengers down to the platform prematurely. This ensures vulnerable passengers are not put at additional risk.

7.3 Ventilation System

Another method of improving air quality at platform level is by ventilating the platforms. During the installation, a ventilation system was installed at platform level at Birmingham New Street station. CO_2 concentrations were used to active the ventilation system and the threshold values for the ventilation system can be found in Section 4.3.1. The results of this study conclude that CO_2 is not a suitable surrogate for assessing DEEEs, with CO_2 showing a weak correlation with NO_2, black carbon and particulate matter, both $PM_{2.5}$ and PM_{10}. In addition, CO_2 concentrations rarely exceeded the 'low pollution' threshold and as a result, the fans were rarely in operation. ORR were made aware of these findings and the following statement is now included in their internal guidance for 'Diesel Engine Exhaust Emissions (DEEE) in the Railway Sector' (ORR, 2018):

"Fume extraction systems within stations in particular require careful design. Where ventilation fan speeds are linked to CO_2 sensors, careful calibration and assurance monitoring is needed to ensure that DEEE exposures are adequately controlled at platform level. Extensive monitoring at one major station where roof level ventilation fans were designed to activate at 1000 ppm CO_2, found little correlation between the levels of CO_2 and

NO_x at platform level. Design changes were made to trigger the roof fans at lower CO_2 levels and platform level NO_x sensors are to be installed as an additional measure in this case. Consideration of the impact of prevailing winds on ventilation systems is also important to ensure that the system works with, rather than against, such effects, for example by installing bi-directional fans."

As stated, Network Rail have subsequently made operational and design changes to the ventilation system at Birmingham New Street station. Firstly, Network Rail has adjusted the CO_2 threshold values (Table 7.1) and as a result the ventilation system is always running at least at 25%.

Table 7.1. Revised fan/sensor setting from January 2018 (Quaiyoom and Blacktop, 2018).

Stage	CO_2 (ppm)	Fan Speed (%)
1	0	25
2	1000	50
3	2250	100

Secondly, work is underway to install NO_x sensors alongside the CO_2 sensors as an additional method of assessing DEEE exposure in the station. However, this will be an ongoing process, as the ventilation system is also used as a fire safety system, exhausting smoke from the station. Therefore if any alteration with the system are to be made, West Midlands Fire Brigade are on standby as the system would not be running at full capacity.

7.4 Trapped Vortex within Birmingham New Street Station

The ventilation system at Birmingham New Street station is bi-directional and exhausts in the same direction as the prevailing wind. The wind sensors that determine the direction of the fan are located at the B-end of platforms 4/5, 6/7 and 8/9. Chapter 5 concluded that there is a large-scale trapped vortex at the B-end of platform 10/11. It is possible that this vortex may also be present at the B-end of other platforms. Consequently, the wind sensors on the platform may be influenced by the vortex and may not be representative of ambient wind conditions.

Furthermore, the wind sensors on each platform are cup anemometers and wind vanes. For the majority of cup anemometers, the starting threshold is ~ 0.5 ms^{-1} and for wind vanes, ~ 0.4 ms^{-1}. However, during the monitoring campaign at Birmingham New Street wind speed at platform level averaged 0.4 ms^{-1}, therefore it is likely that wind speed would often not exceed this threshold. Therefore, the direction indicated by the wind vane may not be accurate when wind speed within the station low, possibly resulting in the ventilation system exhausting pollutants against the direction of ambient wind. In addition, the ventilation system itself could influence the wind sensors at the B-end of the platform and as a result, the ventilation system would not respond to changes in ambient wind direction. Network Rail should look to invest in sonic anemometers to measure wind speed and direction, which would give more accurate measurements, and to locate these outside the station to avoid being affected by the flow regime within the station.

The trapped vortex poses another challenge, if the ventilation system is exhausting pollutants towards the large-scale trapped vortex, in an easterly direction, they could become trapped within the vortex. Further investigation is required to determine if the ventilation system is

sufficient enough to overcome this vortex and to define a threshold value. This threshold value could be integrated into the fan system to ensure all pollutants are exhausted out of the station when the fans are working in an easterly direction.

7.5 Voyagers

Chapter 6 illustrates a spike in pollutant concentration levels when diesel rolling stock, in particular class 220/221 voyagers, is idling on platform 10/11. Furthermore, prolonged idling time increases pollutant concentrations significantly, this can be seen in the early morning and late evening when trains are waiting in the station for an extended period of time whilst cars are attached or detached.

Network Rail stated *"during a regular weekday there are currently 364 trains that have a dwell time of > 5 minutes at New Street. These can be broken down as follows:*

5-9 minutes	*179 trains*
10-14 minutes	*82 trains*
15 + minutes	*103 trains*

TOCs have operational guidelines to turn off engines and prevent engine idling" (Quaiyoom and Blacktop, 2018).

Subsequently, Network Rail has established TOC focus groups, in which train idling and stopping positions have been discussed. Ideally, it would be beneficial for the most polluting trains to stop towards the open end of the platform, allowing pollutants to disperse out of the station, and to reduce idling where possible. Network Rail intend to introduce a TOC

behaviour change programme, where drivers will be encouraged to turn off engines and technical challenges will be overcome. To reduce some of these technical challenges, engine and emission improvement, including an Auto Shutdown System, Start/Stop System and Selective Catalytic Reduction, will be implemented.

Although Network Rail manages Birmingham New Street station, the issue surrounding air pollution does not solely fall upon Network Rail. There are a number of third parties involved in running the day-to-day rail service at Birmingham New Street station. The TOCs, who run services through Birmingham New Street station, lease the trains from the rolling stock operating companies (ROSCOs), however the ROSCOs do not manufacture the vehicles, instead this falls to the manufacturer. As a result, it is difficult to assign responsibility to one particular party and all stakeholders must be consulted in order for an appropriate strategy to be put in place to mitigate air pollution.

7.6 Limitations of Thesis

There are several limitations to this research and these have been discussed throughout the thesis, however this section will summarise these limitations.

Firstly, the air quality monitoring campaign undertaken at Birmingham New Street is one of the most comprehensive air quality projects carried out in the UK rail industry. Despite building upon methodology from previous air quality monitoring campaigns to develop an advanced sampling campaign, the campaign highlighted other areas that required investigation to draw confident conclusions. Whilst in some cases it was possible to incorporate additional monitoring, such as high frequency NO_x sampling within the

concourse, due to a tight schedule and station limitations, additional monitoring was not possible.

Furthermore, the unprecedented pollutant concentrations within the station resulted in instrument limitations. The AQ Mesh has a range of 0-8000 ppb for NO_x and 0-4000 ppb for NO and NO_2, in some instances NO_x concentration exceeded the upper range. Also, the Horiba APNA-360 analyser was returned to the manufacturer for rescaling, as the instrument had previously been scaled for ambient conditions, where pollutant concentrations are much lower than in the station. Finally, the AE33 Aethalometer ran out of filter tape quicker than expected. Magee Scientific advised that a filter tape would last approximately 1 month in a highly polluted environment however, the tapes lasted for 2-3 weeks. Using these instruments in an unfamiliar environment posed challenges, yet it is possible for these to be overcome in any future monitoring campaigns if they are taken into consideration during the campaign design.

Whilst this research clearly indicates that Birmingham New Street station is a pollution hot spot within Birmingham City Centre, it is difficult to determine the risk it poses on both passengers and staff as personal exposure and exposure times were not monitored sufficiently. Although concentrations are much greater than the EU ambient air quality limits, it is likely that the general public would not be exposed to these concentrations for an extended period of time and as a result, there would not be a great risk to health. However, to confidently conclude this, personal monitoring of those using the station is required and their exposure time calculated.

Finally, the ventilation system at Birmingham New Street station was not fully operational during the sampling campaign, as due to constant platform works during the redevelopment, it

had not been possible to validate the settings. It would be valuable to repeat measurements following the revision of the ventilation system thresholds to assess the improvement made to air quality in the station. However this has not been possible and the findings presented in this thesis should not be assumed to represent the current situation at Birmingham New Street station.

8. CONCLUSIONS AND RECOMMENDATIONS FOR FUTURE WORK

8.1 Conclusions

The aim of this research was to investigate air quality and its controlling mechanisms in and around Birmingham New Street railway station and to expand knowledge on transport interchanges. This chapter concludes the findings in this thesis and are presented under each objective.

Objective 1: Develop a comprehensive air quality monitoring campaign.

The air quality monitoring campaign at Birmingham New Street station is the one of the most comprehensive sampling campaigns in the UK rail industry. The campaign used a variety of techniques to assess air quality within the station, including diffusion tube sampling, continuous monitoring and mobile monitoring. The combination of these techniques provided comprehensive evaluation of air quality in the station. Unfortunately, the personal monitoring

conducted with Network Rail staff at Birmingham New Street station was unsuccessful due to instrumental errors however, the methodology used complimented the rest of the sampling campaign and could be used and/or developed in future air quality monitoring campaigns in transport interchanges.

NO_x, PM, CO_2 and BC were selected to be monitored at Birmingham New Street station. However, during the development of the campaign there was some uncertainty regarding which legislation was applicable to Birmingham New Street station due to its unique nature. It was subsequently confirmed that the workplace exposure limits, along with COSHH, were applicable to the station. In light of this information, other pollutants, such as PAHs and VOCs, could have been selected to provide a more detailed evaluation of occupational exposure.

Objective 2: Quantify the air quality at Birmingham New Street railway station.

Air quality at Birmingham New Street station was quantified using diffusion tube sampling, continuous monitoring and mobile monitoring. From the experimental results described in Chapter 4, it is clear that the concentrations of the NO_2, PM_{10} and $PM_{2.5}$ at Birmingham New Street station are all very high and significantly in excess of the various EU limits given in Chapter 2, particularly significant with regard to NO_2. Note again however, that these EU limits are not legally applicable to stations in the UK. The concentrations of NO_2 can approach and exceed the WELs at times, although as staff exposure times were not measured, it is not possible to say whether these guidelines were exceeded for station staff.

The pollutant concentrations measured at the platform ends fall below those at the platform centres. Although the peaks in concentration occur on the platforms with most diesel trains, the concentrations across the station are broadly similar. Furthermore, the experimental results

also illustrate that, at the time of monitoring, pollutants were dispersing up into the concourse and elevating concentrations in this area to above the EU limit for NO_2.

This work resulted in the publication of "Evaluation of air quality at the Birmingham New Street Railway Station" in the Journal of Rail and Rapid Transit (Hickman et al., 2018). This publication can be found in Appendix C.

Objective 3: Determine the extent of which CO_2 measurements are a suitable surrogate for air quality assessment.

Chapter 4 expressed that CO_2 does not have a significant correlation with NO_2, $PM_{2.5}$ or black carbon, therefore questioning its suitability to trigger the ventilation system at Birmingham New Street station, which is used to exhaust pollutants out of the stations. The threshold values in place during the monitoring campaign resulted in the fan system remaining inactive for the vast majority of the campaign. Analysis indicated that concentrations of NO_2, $PM_{2.5}$ and black carbon were able to reach potentially harmful concentrations without the fan system being triggered.

Objective 4: Assess meteorological condition within and around the station, as well as vehicle-induced turbulence, and investigate their impact on station air quality.

The daily average concentrations of all pollutants showed significant day-to-day and week-to-week variation due to environmental factors. Chapter 5 demonstrated that temperature and pollutant concentrations correlated well, as heat and pollutants are emitted simultaneously from vehicle engines. It was also noted that temperature within the station was approximately 3-5 °C greater than Coleshill Weather Station due to the presence of idling rolling stock.

Analysis of wind direction and speed in comparison with Coleshill Weather Station suggested a large-scale trapped vortex driven by high-level wind at the B-end of the station, whereas the A-end had some wind driven ventilation. This resulted in pollutant concentrations at the A-end of the platform to be inversely proportional to wind speed and no distinctive relationship between pollutant concentrations and wind at the B-end of the platform, as the vortex may retain pollution.

Objective 5: Analyse the response of air quality to emissions produced by the presence of diesel and electric rolling stock.

Analysing train timetabling information across three days during the Birmingham New Street station sampling campaign was undertaken to achieve this objective. Previous research highlighted the presence of ultrafine wear particles from electric rolling stock, however at Birmingham New Street station, DEEEs were far greater and no clear relationship could be distinguished between electric rolling stock and spikes in $PM_{2.5}$ concentration. Diesel rolling stock was further group by classification; this analysis indicated that pollutant concentrations rise most significantly when Voyagers are present on the platform and this was confirmed by the ratio analysis. Chapter 6 also suggested that the location of the engine, the size of the vehicle and length of its idling could be elevating concentrations.

Objective 6: Inform development methodologies for interventions to reduce pollutant concentration.

The findings of this thesis highlighted aspects of Birmingham New Street station that need to be addressed in order to improve air quality within the station. Network Rail was simultaneously consulted to discuss these findings and the results, along with the Network Rail's interventions, were published in "Evaluation of air quality at the Birmingham New

Street Railway Station". Since the completion of the monitoring campaign in January 2017, Network Rail has optimised the ventilation system following the findings of the sampling campaign. Furthermore, the results have enabled discussion between Network Rail and TOCs regarding idling times to be based on measured evidence (Quaiyoom and Blacktop, 2018). Finally, this research has address the importance of monitoring air quality in enclosed railway environments and Network Rail have introduced a long term plan to monitor and improve air quality at the station (Quaiyoom and Blacktop, 2018).

Objective 7: Identify key parameters that should be considered in future air quality sampling campaigns at transport interchanges.

Each of the results chapters, Chapters 4-6, identified which aspects of the monitoring campaign were vital for quantifying air quality within the station and the factors influencing pollutant concentrations.

As a result, future air quality monitoring campaigns at transport interchanges should monitor NO_x and PM at a high temporal resolution. Monitoring CO_2 may be valuable if a ventilation system, similar to that at Birmingham New Street, is being assessed. Furthermore, CO_2 should be considered if occupational exposure is to be investigated, along with PAHs, VOCs and EC. Previous research has predominately focused on a singular monitoring type; this research demonstrated the value of coupling different techniques. Therefore, diffusion tube monitoring should be conducted first to identify potential pollution hot spots, followed by continuous monitoring to monitor the interchange at a higher temporal resolution.

Chapter 5 indicated that flow patterns within the station have a significant impact on pollutant concentrations and as no two transport interchanges are identical, each will possess unique

characteristics that influence the flow pattern within them. Therefore, it is of great importance to assess wind velocity in future air quality monitoring campaigns at transport interchanges.

Finally, Chapter 6 illustrated that different train classifications have a different impact on pollution concentration. In addition, longer idling periods increased pollution concentration levels within the station. Future studies should make note of the vehicles serving the transport interchange during the sampling campaign, including engine type and idling time. This will help identify the vehicles that elevate pollutant concentrations levels and this information can subsequently be used in the development of interventions.

8.2 Impact of Research

The air quality monitoring campaign undertaken at Birmingham New Street was the most comprehensive at time of monitoring. The results from the campaign demonstrated how severely polluted enclosed railway environments serving diesel rolling stock can become, especially with insufficient mitigation strategies. This research sparked industry wide conversation on air quality in rail environments. Network Rail have imposed appropriate strategies to mitigate air quality, which include revised ventilation system thresholds, rotations of train dispatchers across different platforms during their shift and reduction of diesel rolling stock idling time. These approaches are further discussed in Chapter 7.

In addition, the campaign at Birmingham New Street prompted the follow-on sampling campaign, 'Research into Air Quality in Enclosed Railway Stations' facilitated by RSSB. Kings College London is leading the research project, which examines air quality at two enclosed railway stations, London King's Cross and Edinburgh Waverly. The sampling campaigns consist of monitoring NO_2, $PM_{2.5}$ and PM_{10}, using smoke tracer to access the

different meteorological conditions and personal monitoring. The results of which will be used to create a pollution model that can be used in enclosed railway stations and provide advice on operational changes that will further reduce pollution in stations (RSSB, 2018).

Finally, as discussed in Chapter 7, this research has provided evidence that CO_2 should not be used as a surrogate to monitor DEEEs. As a result, ORR has provided clarity on this matter in their latest guidance, 'Diesel Engine Exhaust Emissions (DEEE) in the Railway Sector', stating that '*as measurement of CO_2 is relatively easy and inexpensive, it will often be a useful first step in any assessment of DEEE exposure'*, however *'Where ventilation fan speeds are linked to CO_2 sensors, careful calibration and assurance monitoring is needed to ensure that DEEE exposures are adequately controlled at platform level'* (ORR, 2018).

It is evident that this research has been pivotal in driving a focus towards air quality with the railway industry. It is hoped that these efforts are continued to ensure a safe environment for both employees and passengers by enforcing mitigation strategies that will successfully improve air quality within enclosed railway stations.

8.3 Recommendations for Future Work

Considering the wider picture, it is by no means clear whether such high concentrations can be expected in other railway station environments, as Birmingham New Street is in some way unique, with a large proportion of diesel trains in what can be classed as an underground station. Other station topographies, with more open platforms or with much higher train sheds, can be expected to have lower concentration levels. Clearly this is an area where further work is required, to assess pollutant concentrations in other railway station geometries. There are a number of other areas that would also benefit from further research:

- The current data set needs to be more fully analysed to look at the environmental effects of concentration levels, and also to investigate, in depth, the relationship between the concentrations and individual trains.

- An investigation into tail pipe measurements to gain an understanding of the nature of diesel engine emissions from a variety of different train types. Previous emissions data have already been collected for Class 220 (BDSP Partnership, 2002).

- Further exploration of the large scale trapped vortex hypothesised to be present at the B-end of platform 10/11. In order to verify and investigate the presence of this vortex it is suggested that the wind should be monitored simultaneously by an array of anemometers. These anemometers should be located across the B-end of several platforms at Birmingham New Street station, at platform level as well as at the height of the Navigation Street bridge and potentially above bridge level. These wind measurements can then be compared against Coleshill weather station to determine if the vortex is present at Birmingham New Street, along with its properties and characteristics, under different ambient conditions. The measurement of NO_x and PM concentrations on-board trains, and in other enclosed railway environments, such as tunnels and cuttings.

- The measurements of concentrations of metallic particles from brake, rail and overhead line wear.

- The development of an understanding of pollutant dispersion in railway environments, in particular the dispersion by slow moving trains.

In addition, it is likely that railway environments are not the only transport interchange to be impacted by air pollution. It would be of considerably benefit to both the research community and industry to assess air quality in other transport interchanges, such as bus terminals and car parks, using a similar approach to that which has been taken at Birmingham New Street station. Air quality assessments in such environments should not only measure pollutant concentrations, but also assess the flow patterns within the interchanges and investigate the impact the vehicles serving the interchange have on pollutant concentrations, as discussed in objective 7.

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APPENDICES

A. Personal Monitoring at Birmingham New Street Station

1. Introduction

Personal monitoring of staff at Birmingham New Street station was conducted to assess the exposure of staff to Black Carbon and $PM_{2.5}$, both of which are known to have an impact on health. Black carbon concentration is limited by the British workplace exposure limits (WELs), however, $PM_{2.5}$ is not and is only subject to the EU air quality limits. Unfortunately, there are no small, reliable NO_2 sensors.

2. Methodology

2.1.Monitoring Technique

Whilst measuring pollutants at continuous and mobile sites around the station provides a valuable insight into the behaviour of DEEEs in the station, it is difficult to conclude the effect these pollutants will have on staff. Therefore, staff exposure to $PM_{2.5}$ and black carbon were monitored over a week period. Unfortunately, there are no small, reliable NO_2 sensors

which would be suitable for staff to carry round during their shift; therefore oxides of nitrogen were not monitored.

2.1.1. Particulate Matter

Particulate matter was monitored using MicroPEMs, which are portable, battery powered instruments measuring particles less than 2.5 µm. MicroPEMs combines real-time nephelometry and integrated referee filter particulate matter measurements operating simultaneously (RTI International, 2015; South Coast AQMD, 2015). The MicroPEM flow rate was 0.5 l/min and $PM_{2.5}$ concentration was recorded every 10 seconds.

MicroPEMs use a Teflo® filter and these were replaced with a new filter after every sampling period. The data from the MicroPEMs was downloaded after each sampling period and to free up memory on the instrument for further sampling.

An image of a MicroPEM and its technical specification can be found in appendix B.1 and B.3, respectively.

2.1.2. Black Carbon

Black carbon was measured using AE51 MicroAeths. The AE51 is a rechargeable, portable instrument and provides a real time analysis by measuring the rate of change in absorption of transmitted light to continuous collection of aerosol deposit on filter (AethLabs, 2016b). The AE51 filters were replaced after each sampling period.

Black carbon measurements were made every 30 seconds with a flow rate of 50 ml/min. These parameters were selected following the recommendations in the manual for occupational exposure and personal exposure monitoring in high black carbon concentration environments (AethLabs, 2016a).

An image of a MicroAeth and its technical specification can be found in appendix B.1 and B.3, respectively.

2.2.*Monitoring Locations*

For the personal monitoring, three MicroPEMs and three AE51 microAeths were used. Two of each instrument were given to the dispatch staff, who spend the majority of their shift on one platform "island". The remaining MicroPEM and microAeth were given to the customer service staff, who work both in the concourse and at platform level assisting passengers. Four dispatch staff and two customer service staff were chosen for each monitoring period. Staff were randomly selected by the management team at Birmingham New Street and out of the staff selected, the instruments were handed out to get an even distribution of equipment across the platforms, i.e. two of the same instrument were not used on the same or adjacent platforms.

2.3.*Monitoring Schedule*

Personal monitoring was performed in the morning and afternoon from Monday 9th to Friday 13th January 2017, with the exception of Friday where measurements were only made in the morning. Table A1 details the location of each MicroPEM instrument and Table A2 of each MicroAeth instrument during each monitoring period and the time monitoring was conducted. Unfortunately, each monitoring period started and ended at slightly different times, due to working around station operation (i.e. dispatching trains, assisting customers, staff briefings, platform checks).

Table A1. Monitoring times and locations of MicroPEM A-C. Times in red are when the monitoring period was less than two hours.

		MicroPEM A	MicroPEM B	MicroPEM C
Monday	AM	P8/9 *06:40 – 12:15*	P6/7 *07:10 – 14:25*	Concourse *07:20 – 14:00*
	PM	P2/3 *14:55 – 20:00*	P8/9 *14:40 – 22:55*	Concourse *14:05 – 21:45*
Tuesday	AM	P10/11 *07:45 – 13:55*	P8/9 06:45 – 12:55	Concourse 07:25 – 13:55
	PM	P2/3 *14:40 – 22:30*	P6/7 *15:00 – 20:20*	Concourse *14:25 – 20:00*
Wednesday	AM	P4/5 *06:50 – 14:10*	P10/11 *07:10 -12:50*	Concourse *07:15 – 14:00*
	PM	P4/5 *14:55 – 16:40*	P8/9 *14:55 – 15:10*	Concourse *14:05 – 19:30*
Thursday	AM	P10/11 *06:15 – 07:30*	P2/3 *06:30 – 14:45*	Concourse *07:40 – 08:35*
	PM	P4/5 *15:00 – 20:30*	P10/11 *15:00 – 19:55*	Concourse *14:20 – 21:35*
Friday	AM	P2/3 *06:35 – 14:10*	P10/11 *07:10 – 14:10*	Concourse *07:30 – 14:00*

Table A2. Monitoring times and locations of MicroAeth A-C. Times in red are when the monitoring period was less than two hours.

		MicroAeth A	MicroAeth B	MicroAeth C
Monday	AM	P8/9 *06:50 - 14:20*	P4/5 *06:40 - 14:15*	Concourse *07:15 – 14:00*
	PM		P10/11 *15:20 - 20:45*	Concourse *14:00 – 21:50*
Tuesday	AM	P10/11 *05:45 – 13:30*	P1 *06:05 – 14:20*	Concourse *07:35 – 13:55*
	PM	P4/5 *13:45 – 20:00*	P6/7 *15:00 – 20:25*	Concourse *14:10 – 19:00*
Wednesday	AM	P1 *06:10 – 14:05*	P8/9 *07:15 – 14:25*	Concourse *07:15 -14:00*
	PM	P6/7 *14:20 – 20:00*	P8/9 *14:55 – 20:45*	Concourse *14:05 – 21:00*
Thursday	AM	P1 *06:15 – 14:05*	P2/3 *06:55 – 14:15*	Concourse *07:40 – 14:45*
	PM	P2/3 *14:30 – 20:20*	P6/7 *14:15 – 18:30*	Concourse *14:05 – 21:20*
Friday	AM	P1 *06:15 - 14:10*	P6/7 *07:30 – 14:05*	Concourse *08:00 – 14:00*

2.4.Instrument Correction Factors

2.4.1. Particulate Matter

Three MicroPEMs were co-located against the central site DustTrak at Birmingham New Street between 18/01/2017 and 19/01/2017. The co-location period varies for each of the three MicroPEMs, this is due to the instrument being powered by AA batteries, and therefore co-location could only last for the lifetime of the batteries. The exact times and duration of co-location is given in Table A3.

Table A3. Date, time and duration of the co-location period for the three MicroPEMs against the central site DustTrak.

Instrument	Start Date and Time	End Date and Time	Co-location Duration
MicroPEM A	18/01/2017 21:45	19/01/2017 02:25	4 hours 40 minutes
MicroPEM B	18/01/2017 21:45	19/01/2017 07:45	8 hours
MicroPEM C	18/01/2017 21:45	19/01/2017 06:55	7 hours 10 minutes

The MicroPEMs could not be compared directly to the central site DustTrak, as this is not a reference instrument. Instead, the central site DustTrak's correction factor from the Tyburn Road co-location (Table 1) was applied to the DustTrak data prior to co-location analysis of the MicroPEMs.

Error readings were removed from each data set and the corresponding data set prior to analysis. In addition all readings were converted to $\mu g/m^3$.

Five minute averages of $PM_{2.5}$ concentration were taken from the central site dustTrak and the three microPEMs for co-location analysis. Five minute averages were chosen to reduce the noise present on the personal monitoring equipment.

The microPEM data was plotted against the corrected central site dustTrak for each of the three microPEMs (Figures A1-A3) and linear regression lines were applied to each plot to determine the correction factor (Table A4).

Table A4. Correction factors for MicroPEMs A-C, the pearson correlation coefficient, R-squared value and p-value for the correction factor.

Instrument	Gradient	Intercept	Pearson correlation co-efficient	R^2
MicroPEM A	0.162	-1.81	0.951	0.902
MicroPEM B	0.855	-6.67	0.971	0.942
MicroPEM C	0.858	-2.94	0.986	0.972

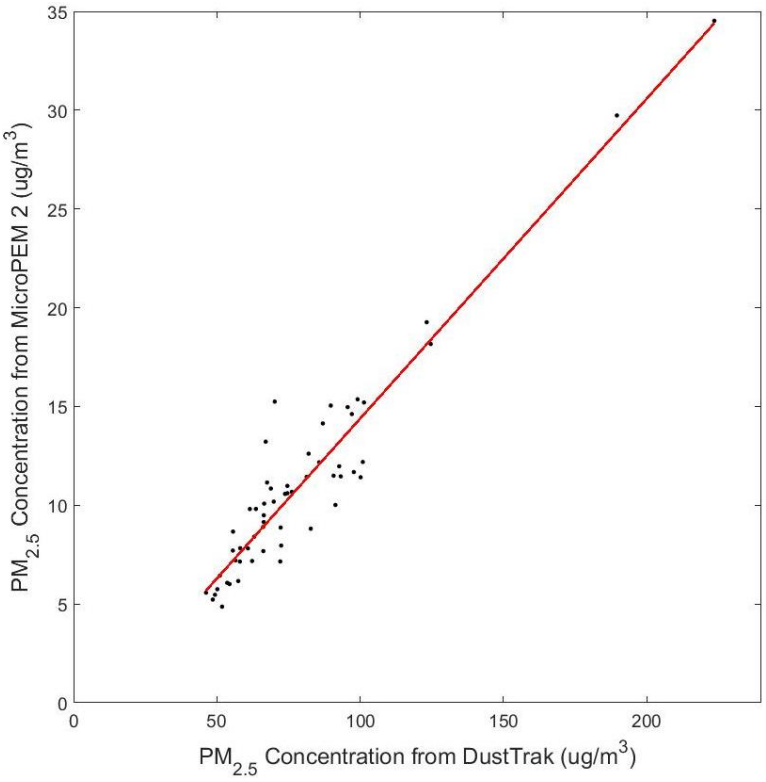


Figure A1. $PM_{2.5}$ concentration from MicroPEM A correlated against the corrected $PM_{2.5}$ data from the DustTrak at the central site on platform 10/11. Co-location occurred for 4 hours and 40 minutes starting at 2145 on 18/01/2017. Red line illustrates the linear regression.

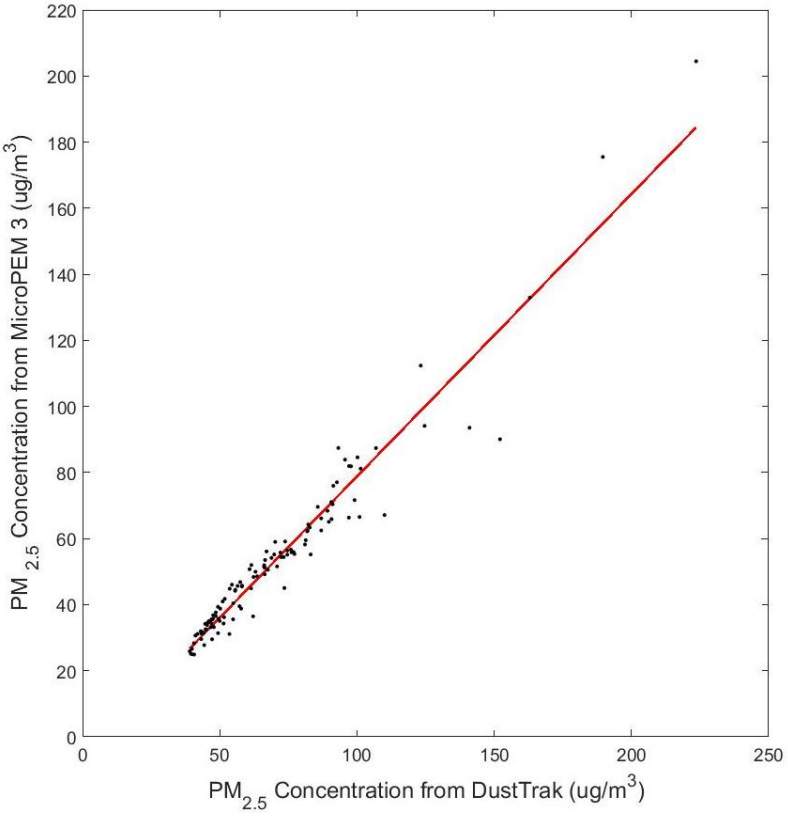


Figure A2. $PM_{2.5}$ concentration from MicroPEM B correlated against the corrected $PM_{2.5}$ data from the dustTrak at the central site on platform 10/11. Co-location occurred for 8 hours starting at 2145 on 18/01/2017. Red line illustrates the linear regression.

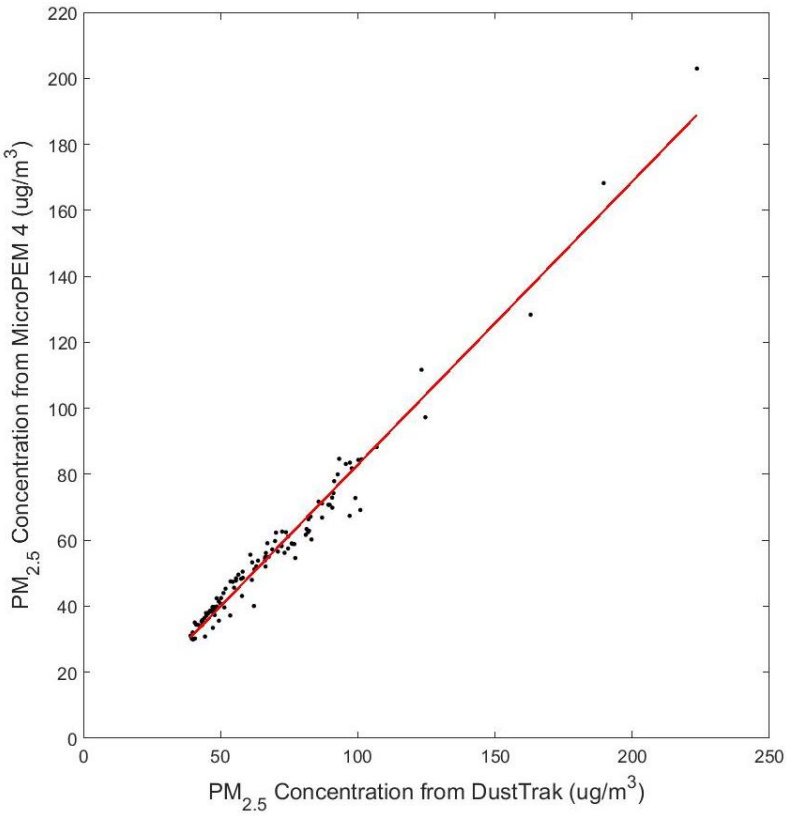


Figure A3. $PM_{2.5}$ concentration from MicroPEM C correlated against the corrected $PM_{2.5}$ data from the dustTrak at the central site on platform 10/11. Co-location occurred for 7 hours and 10 minutes starting at 2145 on 18/01/2017. Red line illustrates the linear regression.

2.4.2. Black Carbon

Three AE51 MicroAeths were co-located against the AE33 at the central site on platform 10/11 from 2150 on 18/01/2017 until 2335 on 19/01/2017.

Prior to co-location analysis error readings, such as negative values and periods where the instrument did not record, were removed from the data set and the corresponding data set. In addition five-minute averages of black carbon concentration were calculated for the three microAeths and the AE33 aethalometer. Five minute averages were chosen to reduce the noise present on the personal monitors.

The microAeth black carbon concentration was plotted against the AE33 black carbon concentration for each of the three microAeth (Figures A4-A6) and linear regression lines were applied to each plot to determine a correction factor (Table A5).

Table A5. Correction factors for MicroAeths A-C, the pearson correlation coefficient, R-squared value and p-value for the correction factor.

Instrument	Gradient	Intercept	Pearson correlation co-efficient	R^2
MicroAeth A	0.675	9.38	0.794	0.629
MicroAeth B	0.737	-59.3	0.776	0.601
MicroAeth C	0.709	323	0.779	0.606

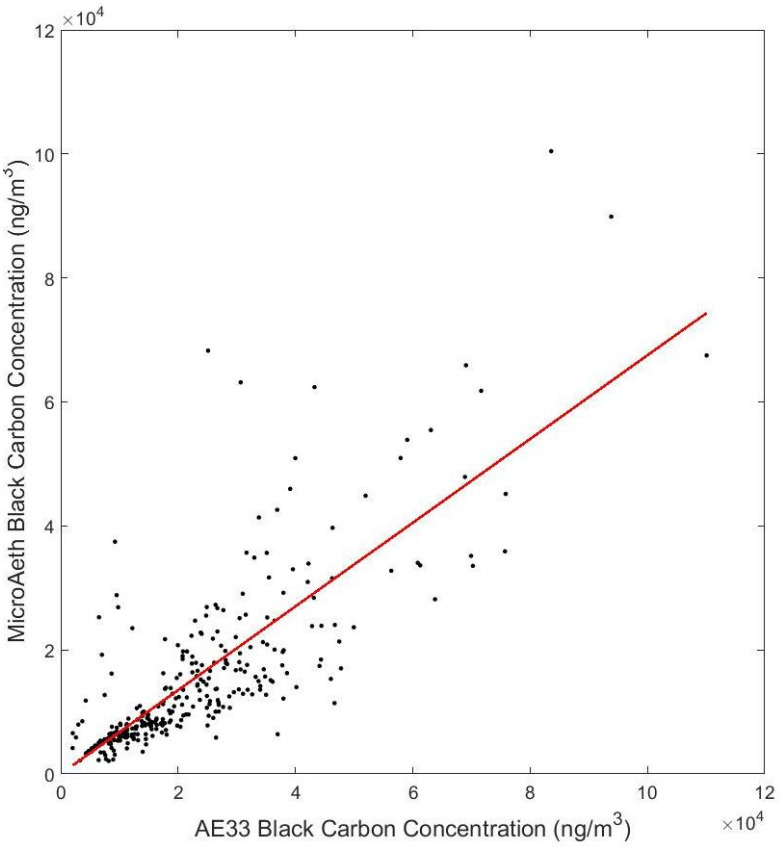


Figure A4. Black carbon concentration from MicroAeth A correlated against black carbon concentration from the AE33 at the central site on platform 10/11. Co-location between 2150 on 18/01/2017 and 2335 on 19/01/2017. Red line illustrates the linear regression.

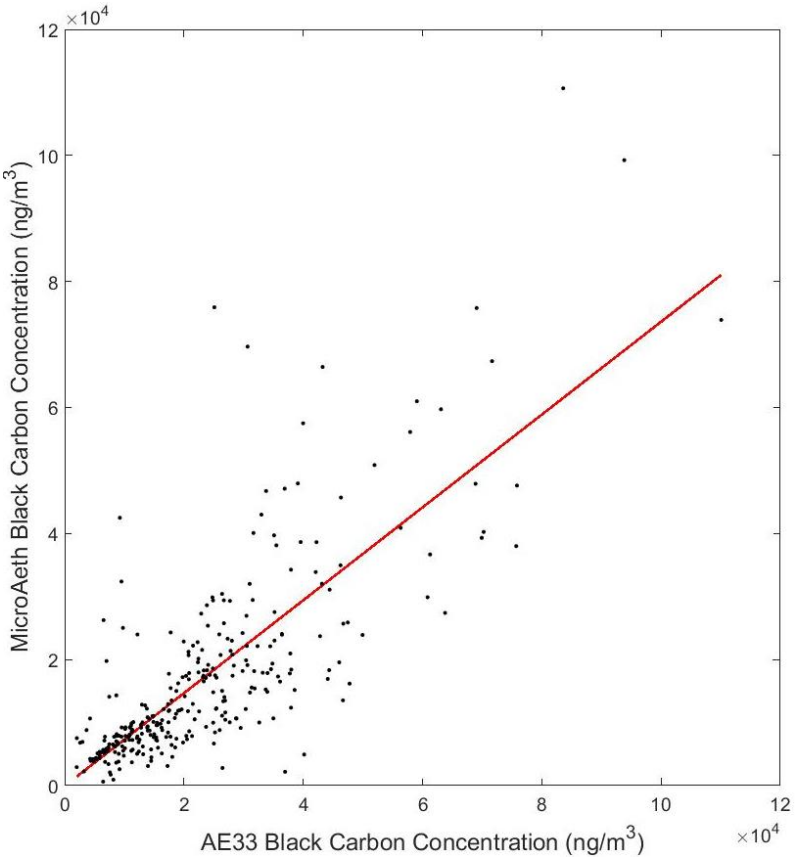


Figure A5. Black carbon concentration from MicroAeth B correlated against black carbon concentration from the AE33 at the central site on platform 10/11. Co-location between 2150 on 18/01/2017 and 2335 on 19/01/2017. Red line illustrates the linear regression.

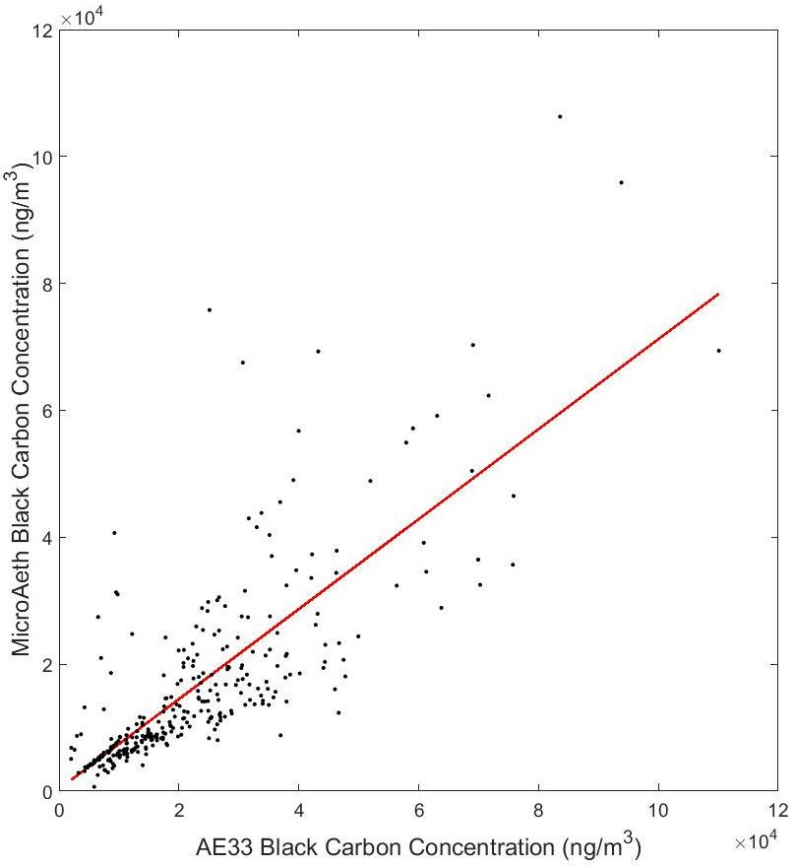


Figure A6. Black carbon concentration from MicroAeth C correlated against black carbon concentration from the AE33 at the central site on platform 10/11. Co-location between 2150 on 18/01/2017 and 2335 on 19/01/2017. Red line illustrates the linear regression

2.5.Data Quality Assurance

After applying the correction factors to the personal monitoring equipment, quality checks of the data highlighted periods where data was incomplete or provided an unrealistic concentration. Such periods may be due to the obstruction of the inlet, as personal monitors were placed inside staffs' pockets with the inlets exposed.

Furthermore, the length of the recording varied for each monitoring period and was not consistent. There are two explanations for the inconsistency, firstly, the daily operation of the station resulted in staff receiving monitoring equipment at different times and secondly, the

instruments are operated by battery, where in some instances, the instrument did not last the entirety of the shift. As a result, it would not be good practice to compare periods where the monitoring length drastically varies.

3. Results

3.1.Particulate Matter

12 out of the 27 shifts monitored exceeded the annual EU air quality limit of 25 μg/m^3; however only one out of the 9 customer service shifts monitored exceeded this limit. It is clear that members of staff who predominately spend their time in the concourse assisting customers are less exposed to the pollutants emitted from the trains.

Table A6 illustrates the average $PM_{2.5}$ concentration for shifts in different locations around the station.

Table A6. Average $PM_{2.5}$ concentration for across all shifts in each location.

Location	Average Concentration ($\mu g/m^3$)	Number of shifts monitored
Concourse[1] (customer service staff)	28.5	9
All platforms	62.2	18
Platform 2/3	88.5	4
Platform 4/5	77.8	3
Platform 6/7	26.7	2
Platform 8/9	37.1	4
Platform 10/11	66.2	5

The highest average $PM_{2.5}$ concentration is on platform 2 and 3, however, the highest exposure during a shift was on platform 10 and 11 on Tuesday morning. These 'islands' are predominantly served by diesel trains.

3.2.Black Carbon

Similarly to $PM_{2.5}$ the train dispatch staff are exposed to a higher concentration of black carbon than the customer service staff (Table A7), as the dispatch team spend a far greater proportion of their shift at platform level.

The 'island' with the highest black carbon concentration is platform 10/11. This platform served only diesel trains of classes HST125, 150, 158, 220 and 221. These trains were built

[1] Customer service staff spend time both at concourse and platform level assisting customers with their needs.

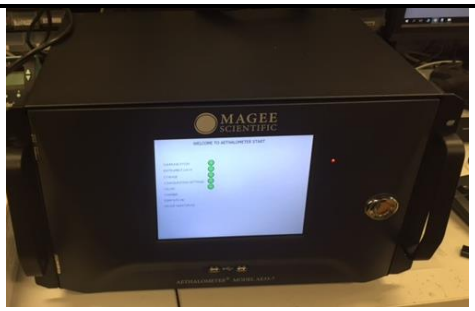
between 1985 and 2002, therefore only have to abide by the air quality regulations at the time of manufacturing, therefore the oldest trains are often the worst offenders for air pollution.

Table A7. Average black carbon concentration for across all shifts in each location.

Location	Average Concentration ($\mu g/m^3$)	Number of shifts monitored
Concourse (customer service staff)	11.1	9
All platforms	18.3	17
Platform 1	20.0	4
Platform 2/3	18.6	2
Platform 4/5	13.4	3
Platform 6/7	15.9	3
Platform 8/9	14.3	3
Platform 10/11	31.3	2

B. SUPPORTING MATERIAL FOR CHAPTER 3

B.1 Images of the Monitoring Equipment

Instrument	Image
AE33 Aethalometer	
AE51 MicroAeth	

AQ Mesh

COZIR CO_2 Sensor

(Gas Sensing, 2016)

Diffusion Tube

(Eleta, 2016)

Horiba APNA-360 NO_x Analyser	
MicroPEM	
TGP-4500 Tinytag	
TSI Dusttrak DRX 8533	

B.2 Diffusion Tube Analysis Calculations

Ambient NO_2 concentration can be measured by the following equation:

$$C = \frac{1}{s} \times \frac{m}{t}$$

where:

C = concentration of NO_2 in the atmosphere in $\mu g/m^3$;

s = sampling rate of NO_2 ($m^3\ h^{-1}$);

m = mass of nitrate in tube (µg);

t = exposure time (h)

The sampling rate depends upon the cross sectional area of the tube, length of tube and diffusion coefficient and can be defined by the following equation:

$$s = \frac{D_{12} a}{l}$$

where:

a = cross sectional area of the tube;

l = length of tube

D_{12} = diffusion coefficient

The diffusion coefficient is reported to be 0.1361 $cm^2\ s^{-1}$ at standard temperature, 273 K, and pressure, 1 atm (1013 hPa) (reference). However, this has been corrected for average temperature in the UK to 0.146 $cm^2\ s^{-1}$, assuming a mean UK temperature of 284 K. For all diffusion tubes exposed in the UK, the sampling rate should be calculated using D = 0.146 cm^2 s^{-1}.

B.3 Instrument Technical Specifications

Instrument	Variable(s)	Unit	Range	Resolution	Accuracy[2]	Size (mm)
AE33 Aethalometer	Black Carbon	ng/m^3	10 – 100,000 ng/m^3	1 ng/m^3	*Not given*	D330xW430xH280
AE51 MicroAeth	Black Carbon	ng/m^3	0 - 1,000,000 ng/m^3	1 ng/m^3	*Not given*	D38xW66xH117
AQ Mesh	Oxides of Nitrogen (NO, NO_2, NO_x)	ppb	NO: 0 – 4000 ppb NO_2: 0 – 4000 ppb NO_x: 0 – 8000 pbb	NO: < 5 ppb NO_2: < 10 ppb NO_x: < 10 ppb	± 5 ppb	D170xW220xH250 (not including antenna – 180)
	Pressure	mb	500 – 1500 mb	1 mb	± 5mb	
COZIR CO_2 Sensor	Carbon Dioxide	ppm	0 – 10,000 ppm	1 ppm	± 50 ppm or ± 3% of reading	Ø50xH17.5
Horiba APNA-360 NO_x analyser	Oxides of Nitrogen (NO, NO_2, NO_x)	ppm	0 – 10 ppm	*Not given*	± 1% of full scale (i.e. 1% of 10 ppm)	D550xW430xH221

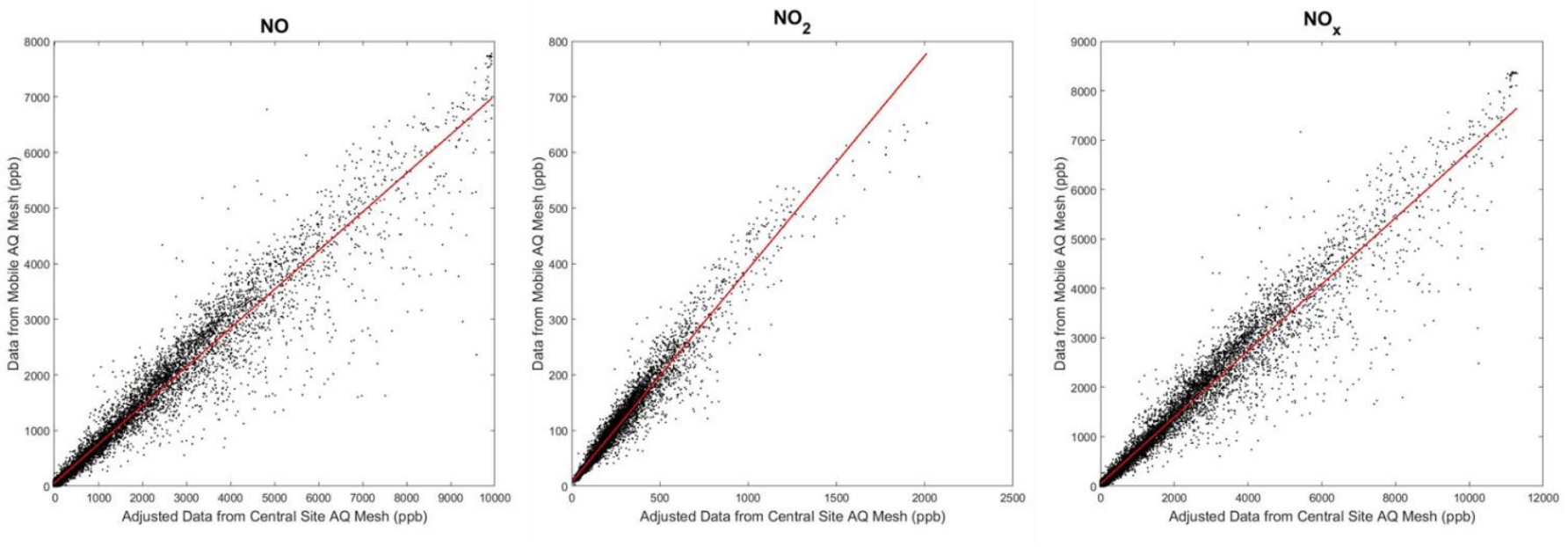
[2] Accuracy is given in standard test conditions, which are 20 °C, 80% relative humidity and with the absence of interfering gases.

MicroPEM	Particulate Matter ($PM_{2.5}$)	$\mu g/m^3$				
TGP-4500 Tingtag	Temperature	°C	-25 - 85 °C	< 0.01 °C	± 0.6 °C	D80xW57xH34
TSI Dusttrak DRX 8533	Paritculate Matter (PM_1, $PM_{2.5}$, $PM_{resp,}$ PM_{10}, PM_{total})	mg/m^3	0.001 to 150 mg/m^3	±0.1% of reading or 0.001 mg/m^3, whichever is greater	*Not given*	D224xW216xH135

(Environmental Instruments Ltd, 2017; Gas Sensing, 2016; Gemini, 2011; Horiba, 2002; Magee Scientific, 2015; TSI Inc, 2014)

B.4 Mobile AQ Mesh Co-Location Plots

Figure B.1. Co-location plots for the mobile AQ Mesh against the corrected central site AQ Mesh, using correction factors in table 1, for the pollutants NO (left), NO2 (middle), NOx (right) between 25/01/2017 and 01/02/2017 with a linear regression line (red line).



B.5 DustTrak Co-Location Figures

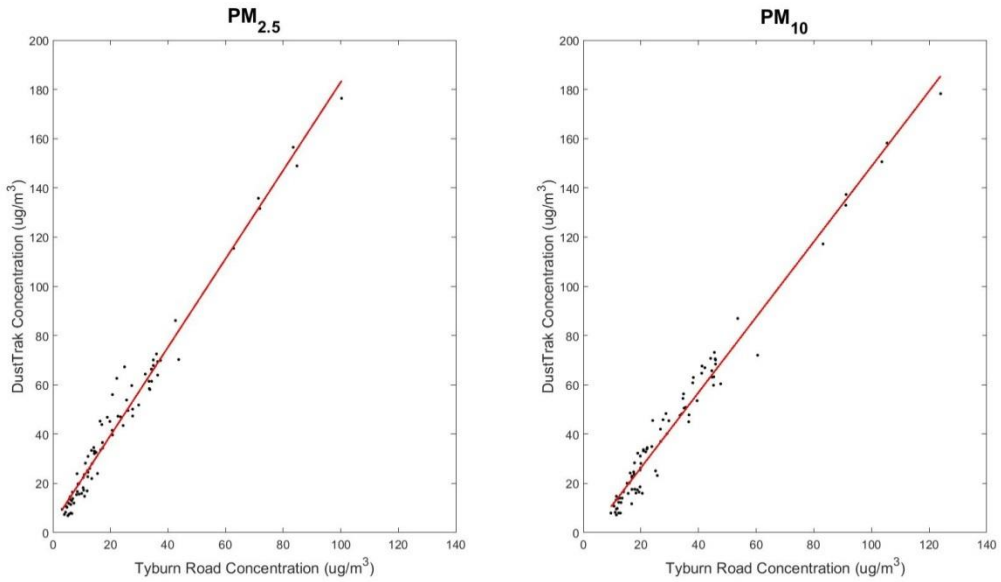


Figure B.2. DustTrak B correlated against Tyburn Road FDMS TEOM for $PM_{2.5}$ (left) and PM_{10} (right). Co-location took place between 1700 on 28/10/2016 and 1000 on 01/11/2016, excluding the data at 0300 on 31/10/2016 and 0300 on 01/11/2016. Red line is linear regression line.

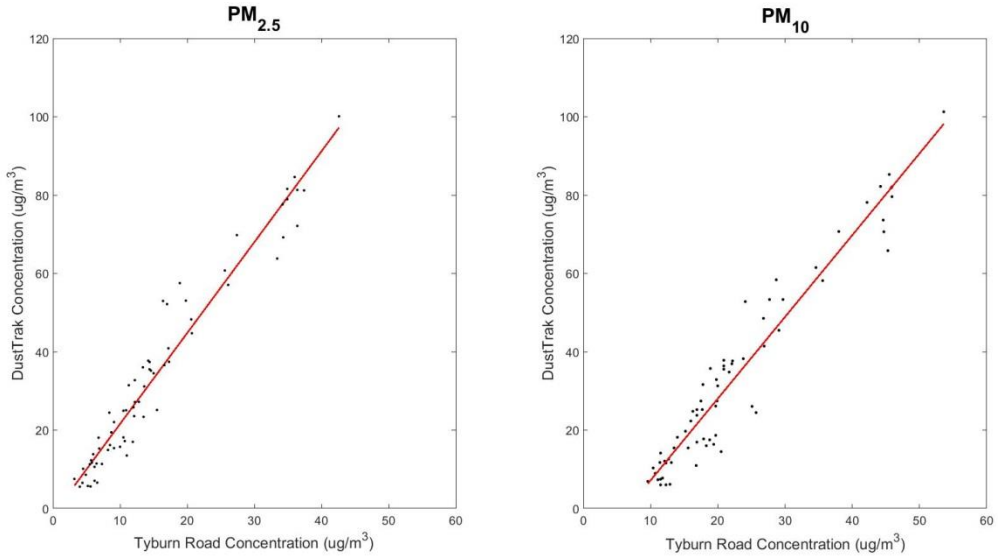


Figure B.3. DustTrak C correlated against Tyburn Road FDMS TEOM for $PM_{2.5}$ (left) and PM_{10} (right). Co-location took place between 1700 on 28/10/2016 and 1400 on 31/10/2016 excluding the data at 0300 on 31/10/2016. Red line is linear regression line.

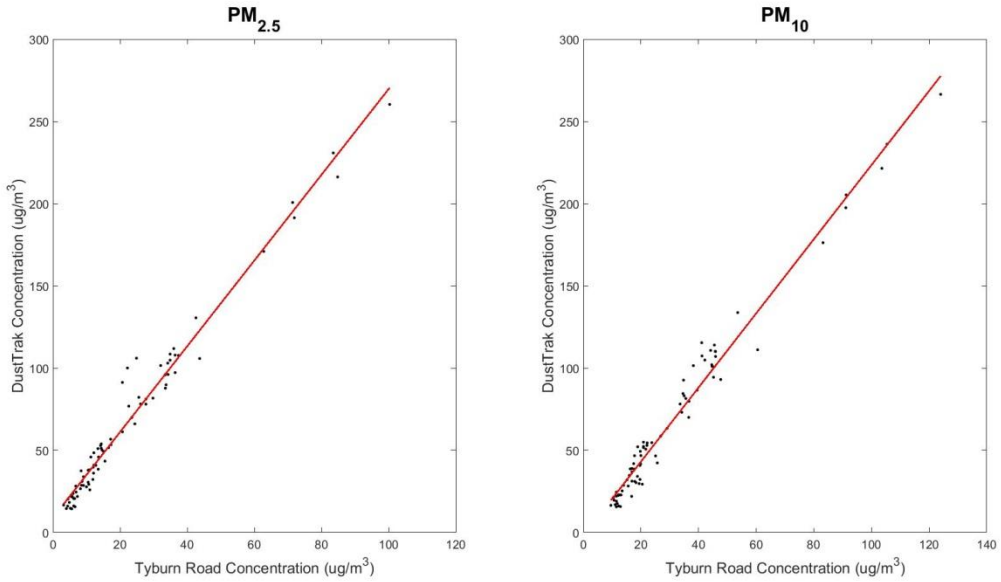


Figure B.4. DustTrak D correlated against Tyburn Road FDMS TEOM for $PM_{2.5}$ (left) and PM_{10} (right). Co-location took place between 1700 on 28/10/2016 and 1000 on 01/11/2016, but data between 0400 and 1000 on 31/10/2016 has been removed due to errors. Red line is linear regression line.

B.6 Idling Time

Mean difference in actual arrival and scheduled arrival, i.e. delay in arrival (column 2), and mean difference in actual departure and scheduled departure, i.e. delay in departure, (column 3) in mm:ss for each day from 17/11/2016 to 23/01/2017. The difference between the delay in arrival and delay in departure (column 4) is positive when delay in departure exceeded the delay in arrival, therefore increasing idling time, and is negative when delay in arrival exceeded the delay in departure, therefore reducing idling time. Note, there is no data for 25/12/2016 and 26/12/2016 as there were no passenger services on this day and the station was closed. In addition, there is no data for 18/01/2017 as there was an error in obtaining the train timetable data for this day.

Date	Arrival (mm:ss)	Departure (mm:ss)	Difference (mm:ss)
17/11/2016	06:58	05:13	-01:45
18/11/2016	02:29	00:24	-02:05
19/11/2016	03:49	03:49	00:00
20/11/2016	04:10	02:43	-01:27
21/11/2016	03:39	03:45	00:06
22/11/2016	03:30	02:26	-01:04
23/11/2016	01:33	02:22	00:49
24/11/2016	04:38	03:42	-00:56
25/11/2016	04:09	03:16	-00:53
26/11/2016	06:12	05:03	-01:09
27/11/2016	02:50	01:56	-00:54
28/11/2016	03:21	04:25	01:04
29/11/2016	04:24	01:46	-02:38
30/11/2016	07:41	08:55	01:14
01/12/2016	07:40	06:21	-01:19
02/12/2016	01:58	03:09	01:11

03/12/2016	01:56	02:53	00:57
04/12/2016	03:12	02:02	-01:10
05/12/2016	03:01	02:09	-00:52
06/12/2016	01:29	02:35	01:06
07/12/2016	02:32	01:59	-00:33
08/12/2016	02:56	03:40	00:44
09/12/2016	02:29	01:36	-00:53
10/12/2016	01:34	03:04	01:30
11/12/2016	01:43	01:07	-00:36
12/12/2016	03:36	06:30	02:54
13/12/2016	02:44	01:58	-00:46
14/12/2016	04:32	02:19	-02:13
15/12/2016	04:45	02:26	-02:19
16/12/2016	02:32	01:47	-00:45
17/12/2016	02:09	01:42	-00:27
18/12/2016	01:19	00:41	-00:38
19/12/2016	03:53	04:55	01:02
20/12/2016	01:33	01:11	-00:22
21/12/2016	02:43	02:12	-00:31
22/12/2016	02:29	03:39	01:10
23/12/2016	04:12	03:12	-01:00
24/12/2016	01:03	00:38	-00:25
25/12/2016	n/a	n/a	n/a
26/12/2016	n/a	n/a	n/a
27/12/2016	04:27	03:38	-00:49
28/12/2016	04:13	05:39	01:26
29/12/2016	01:51	01:18	-00:33
30/12/2016	02:34	02:07	-00:27
31/12/2016	00:56	00:45	-00:11
01/01/2017	00:44	00:49	00:05
02/01/2017	03:27	00:58	-02:29
03/01/2017	01:01	00:47	-00:14

04/01/2017	01:43	01:10	-00:33
05/01/2017	01:22	00:59	-00:23
06/01/2017	03:19	02:58	-00:21
07/01/2017	00:58	00:42	-00:16
08/01/2017	01:05	00:49	-00:16
09/01/2017	02:04	01:22	-00:42
10/01/2017	01:05	00:43	-00:22
11/01/2017	02:04	01:32	-00:32
12/01/2017	02:26	01:31	-00:55
13/01/2017	02:07	01:31	-00:36
14/01/2017	00:50	00:57	00:07
15/01/2017	00:44	00:25	-00:19
16/01/2017	00:43	01:57	01:14
17/01/2017	01:41	01:24	-00:17
18/01/2017	n/a	n/a	n/a
19/01/2017	00:10	01:27	01:17
20/01/2017	02:51	02:28	-00:23
21/01/2017	01:49	01:26	-00:23
22/01/2017	02:57	02:45	-00:12
23/01/2017	04:16	02:02	-02:14
Mean	02:46	02:25	-00:21

B.7 Calculation of Average Delay in Arrivals and Departure Script

- **Import data from spreadsheet**

Script for importing data from the following spreadsheet:

```
  Workbook: P:\Air_Quality_Project\Analysis\Train
Analysis\SelectingDate\Arrival_Departure\data.xlsx

  Worksheet: Sheet1
```

To extend the code for use with different selected data or a different spreadsheet, generate a function instead of a script.

```
% Auto-generated by MATLAB on 2018/02/20 16:04:37
```

- **Import the data**

```
[~, ~, raw] = xlsread('P:\Air_Quality_Project\Analysis\Train
Analysis\SelectingDate\Arrival_Departure\data.xlsx','Sheet1');

raw(cellfun(@(x) ~isempty(x) && isnumeric(x) && isnan(x),raw)) = {''};
```

- **Replace non-numeric cells with NaN**

```
R = cellfun(@(x) ~isnumeric(x) && ~islogical(x),raw); % Find non-numeric cells

raw(R) = (Moreno et al.); % Replace non-numeric cells
```

- **Create output variable**

```
data = reshape([raw{:}],size(raw));
```

- **Allocate imported array to column variable names**

```
Plan_Arr = data(:,1);

Act_Arr = data(:,2);

Plan_Dep = data(:,3);

Act_Dep = data(:,4);
```

- **Clear temporary variables**

```
clearvars data raw R;
```

- Calculate Difference in Arrival and Departure Times

- **load excel file into matlab**

```
run('importdata.m')
```

- **Calculate if trains are early or late**

```
Arrival=Plan_Arr-Act_Arr;

Depature=Act_Dep-Plan_Dep;
```

- **Convert to seconds**

```
Arrival=Arrival/(1/86400);

Depature=Depature/(1/86400);



A=nanmean(Arrival);



if A<0; % negative value shows train arrived late

    x='late';

    Alate=A*-1;

    Alate=Alate/60;

    Amin=floor(Alate);

    Asec=round(((Alate-Amin)*60),0);

    textstatement=['Trains arrived at the station on average ' ,num2str(Amin), '
minutes and ' ,num2str(Asec), ' seconds ' ,x, '.'];
```

```
    disp(textstatement)



elseif A>0; %positive value shows train arrived early

    x='early';

    Aearly=A/60;

    Amin=floor(Aearly);

    Asec=round(((Aearly-Amin)*60),0);

    textstatement=['Trains arrived at the station on average ' ,num2str(Amin), '
minutes and ' ,num2str(Asec), ' seconds ' ,x, '.'];

    disp(textstatement)

end



D=nanmean(Depature);



if D>0; % positive value shows train departed late

    x='late';

    Dlate=D/60;

    Dmin=floor(Dlate);

    Dsec=round(((Dlate-Dmin)*60),0);

    textstatement=['Trains departed at the station on average ' ,num2str(Dmin), '
minutes and ' ,num2str(Dsec), ' seconds ' ,x, '.'];

    disp(textstatement)



elseif D<0; %negative value shows train departed early

    x='early';
```

```
    Dearly=D*-1;

    Dearly=Dearly/60;

    Dmin=floor(Dearly);

    Dsec=round(((Dearly-Dmin)*60),0);

    textstatement=['Trains departed at the station on average ' ,num2str(Dmin), '
minutes and ' ,num2str(Dsec), ' seconds ' ,x, '.'];

    disp(textstatement)

end
```

C. Evaluation of Air Quality at the Birmingham New Street Railway Station

Original Article

Institution of MECHANICAL ENGINEERS
Journal of RAIL AND RAPID TRANSIT

Evaluation of air quality at the Birmingham New Street Railway Station

Proc IMechE Part F: J Rail and Rapid Transit
2018, Vol. 232(6) 1864–1878

DOI: 10.1177/0954409717752180
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SAGE

AL Hickman, CJ Baker, X Cai, JM Delgado-Saborit and JE Thornes

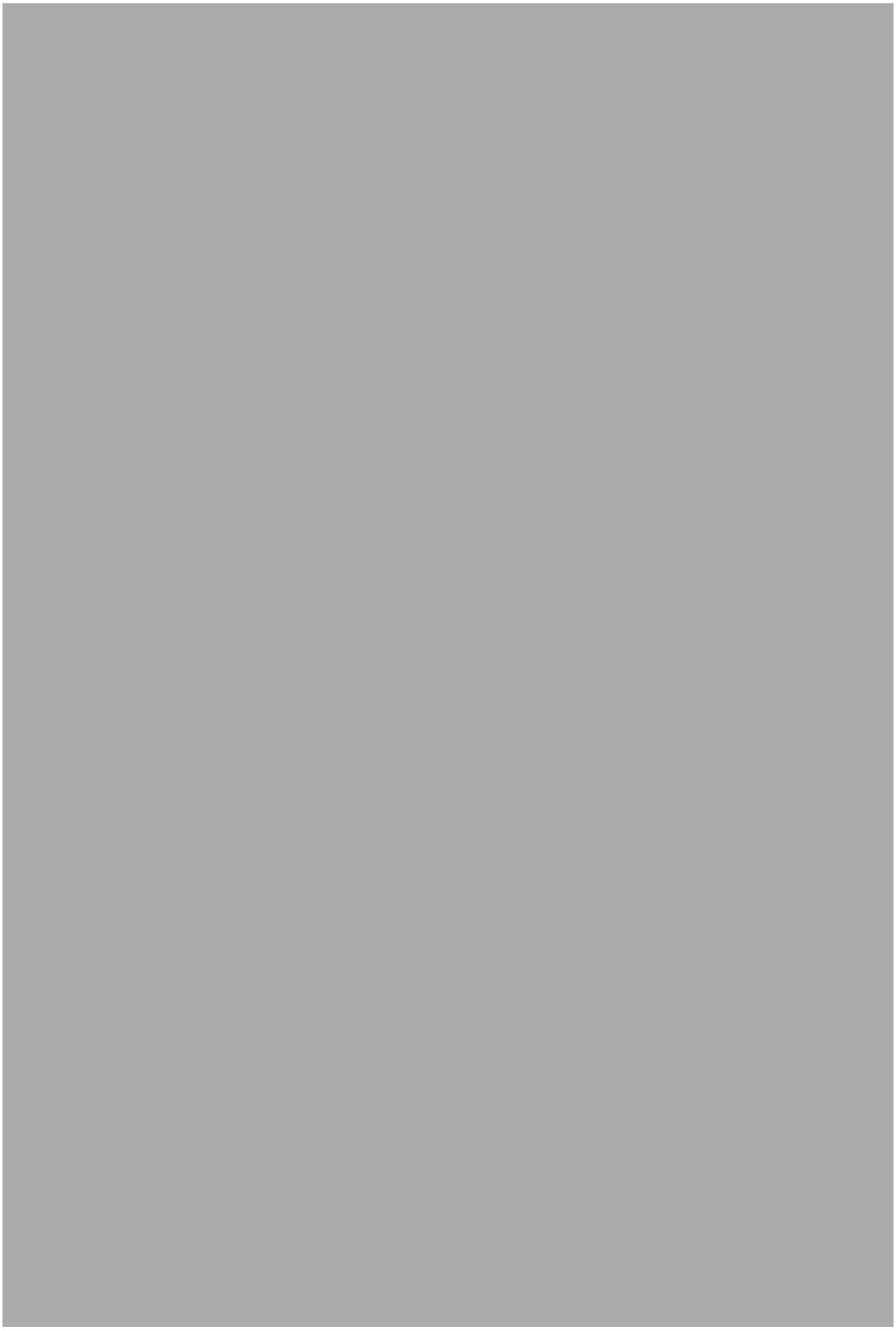
Abstract

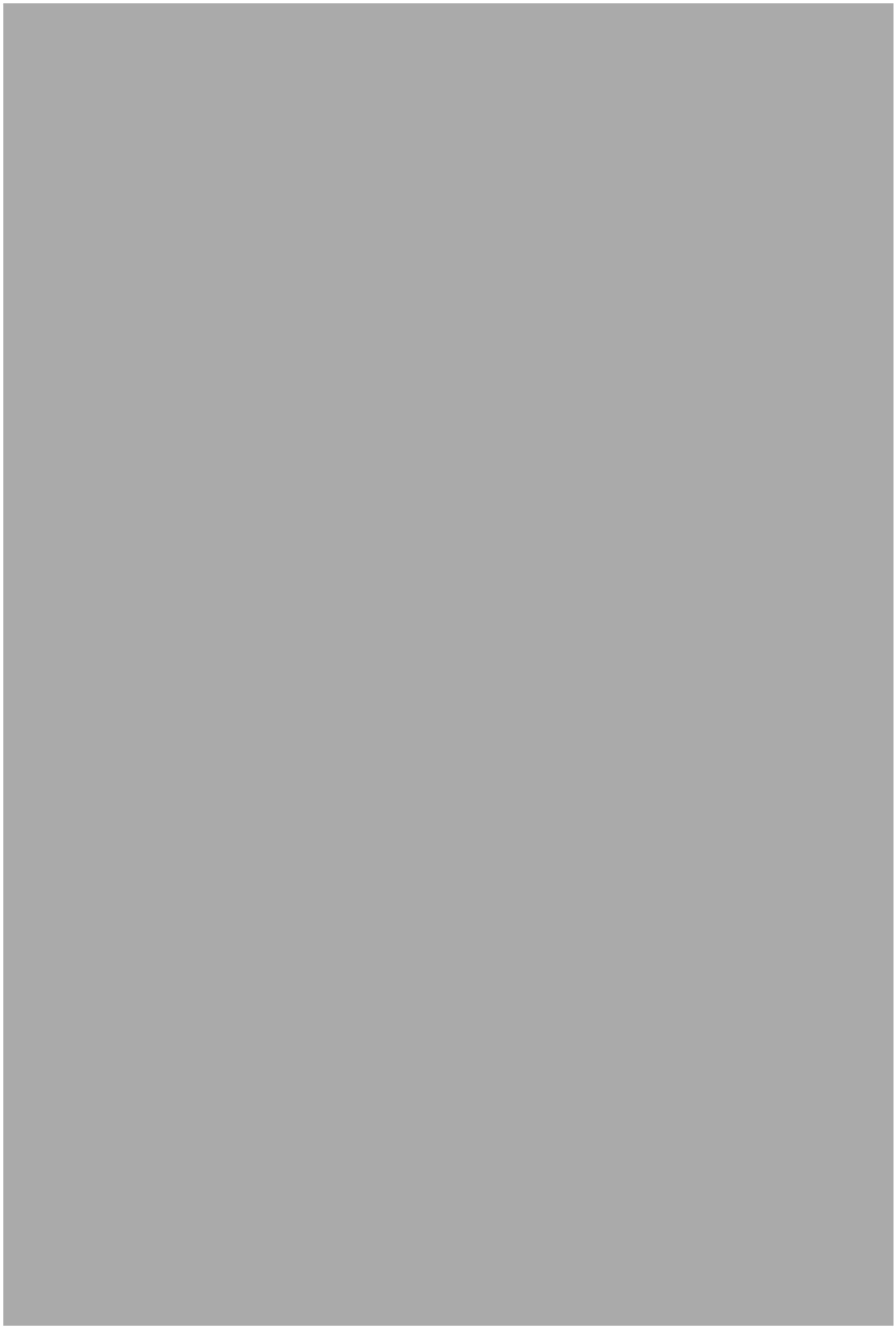
Air pollution from diesel emissions is becoming an increased international concern, and whilst attention has been primarily focused on the automotive industry, concerns have also been raised about emissions from diesel rail vehicles. This paper reports an extensive series of measurements made at the Birmingham New Street station, a major rail interchange in the Midlands of England, with a mix of diesel and electric train movements, which is of particular concern because of the enclosed nature of the platforms. This study was undertaken in collaboration with Network Rail to better understand the environment in and around the station over a longer period to provide a more detailed analysis of the complex environment at the station. The station environment has been considered in terms of the European Union (EU) and Department of Environment, Food and Rural Affairs (DEFRA) limits as part of the monitoring methodology, but it should be noted that these limits do not apply in this environment as the Management of Health and Safety at Work Regulation 1999 and the Control of Substances Hazardous to Health Regulations 2002 are applicable. The monitoring campaign consisted of diffusion tube measurements to measure nitrogen dioxide at a large number of different locations throughout and around the station. These were followed by detailed measurements of oxides of nitrogen, particulate matter, carbon dioxide and black carbon (a diesel tracer) at a smaller number of sites at the platform level. The results are analysed to give concentrations over a wide variety of time scales, and long- and short-term averages. The effects of ambient wind conditions and individual train movements are also considered. Recommendations are made for possible remedial measures and for future work to more fully understand the physical mechanisms involved.

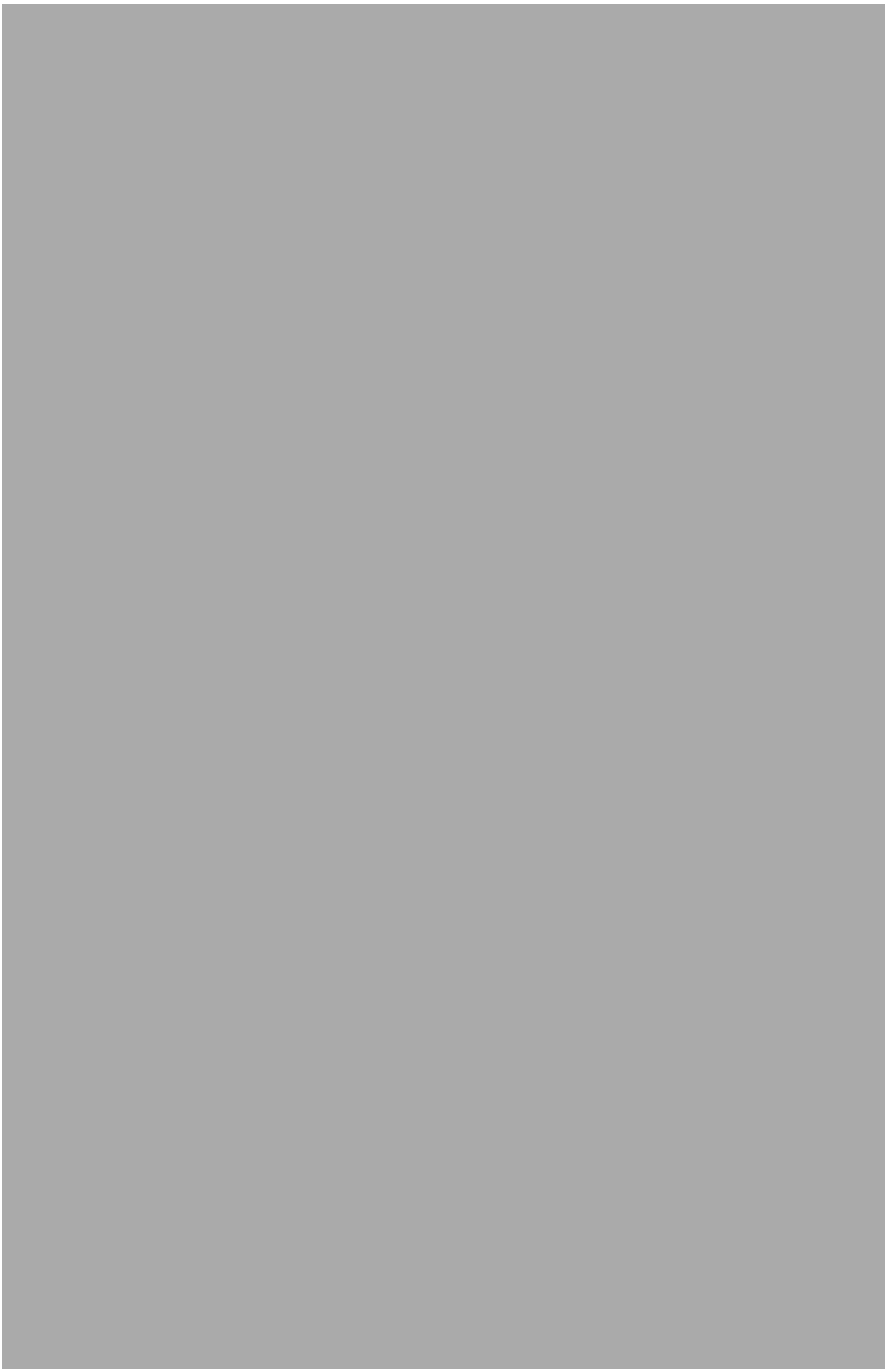
Keywords

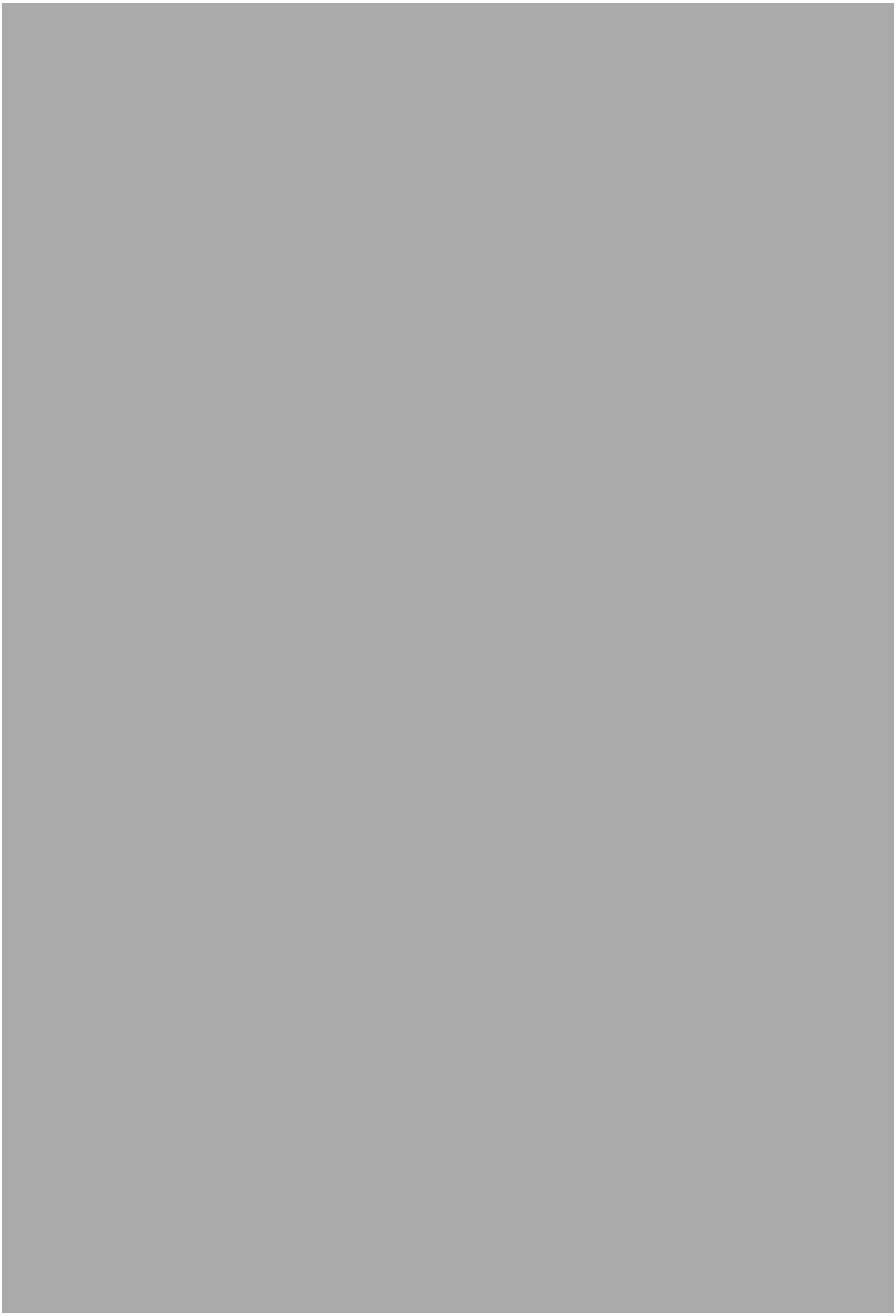
Air pollution, diesel emissions, diesel trains, oxides of nitrogen, particulate matter, railway station

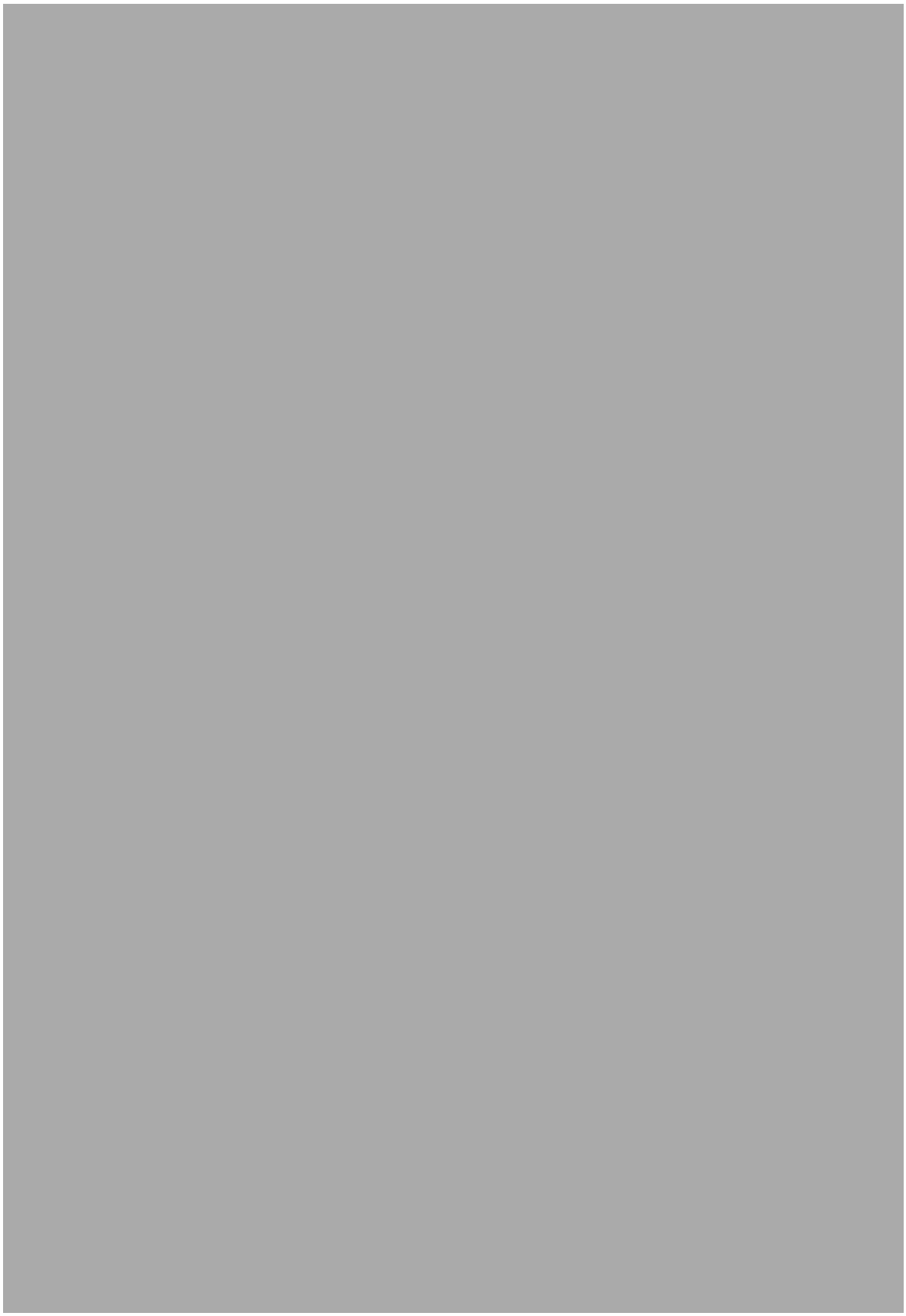
Date received: 29 September 2017; accepted: 11 December 2017

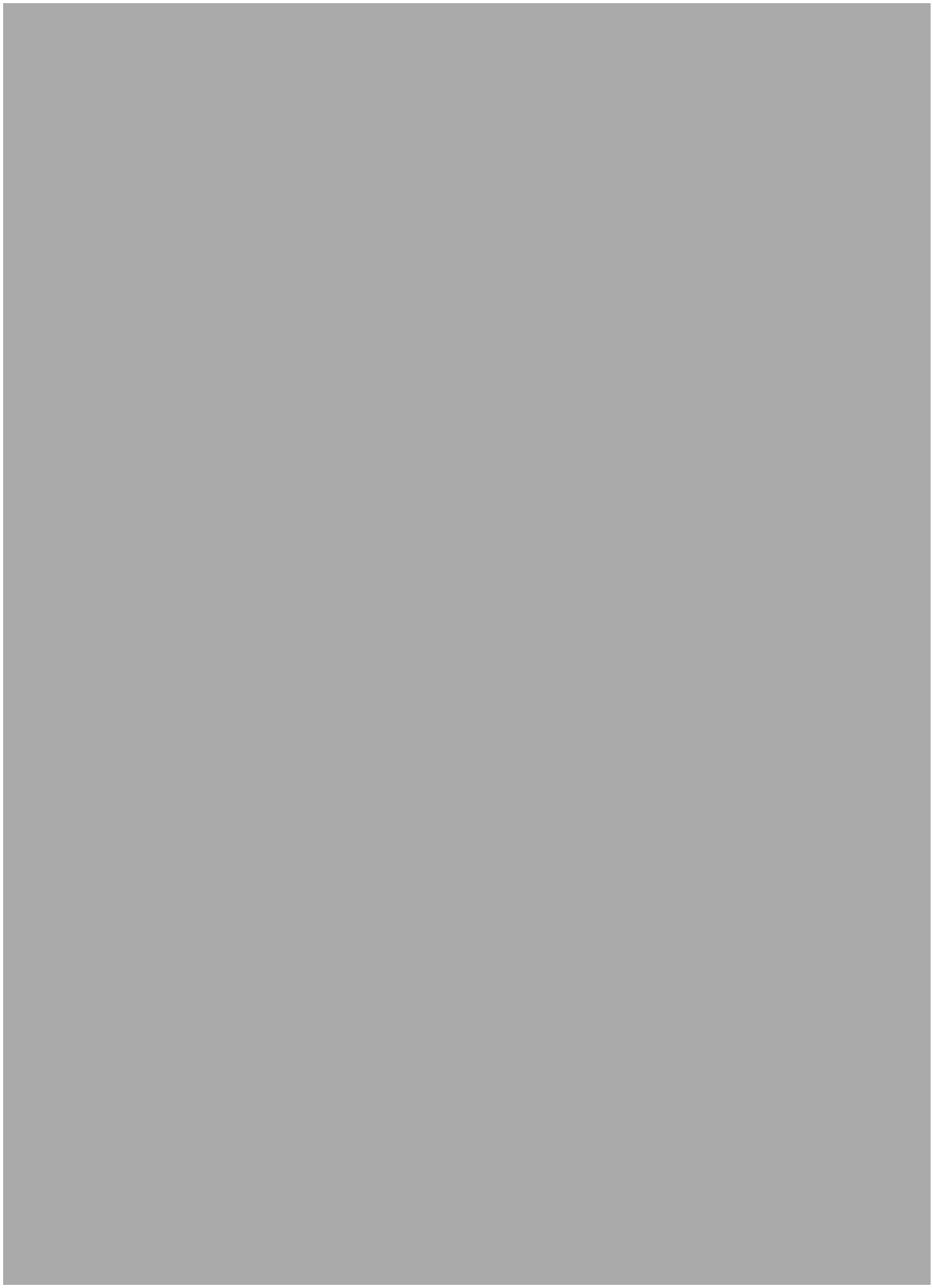


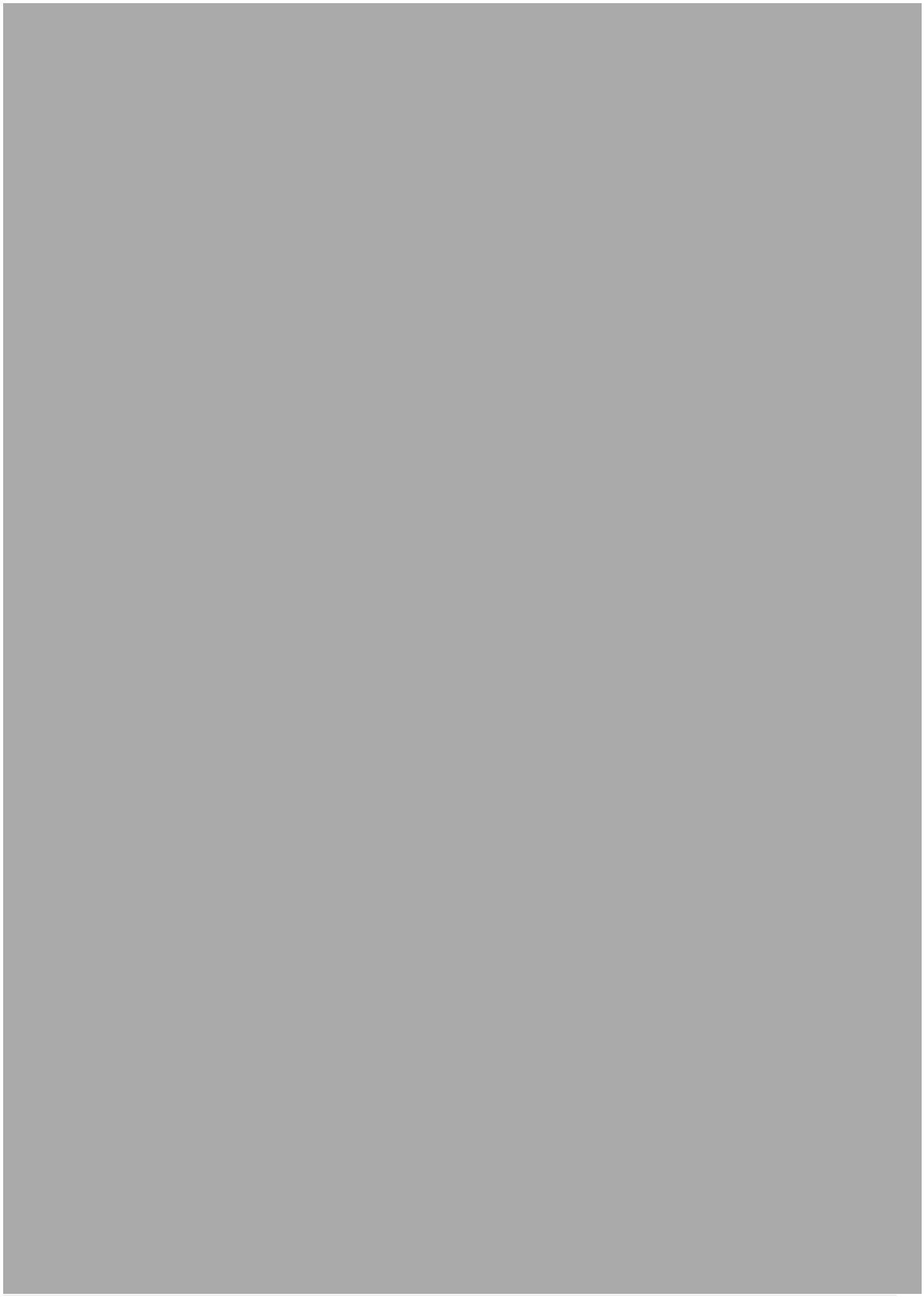


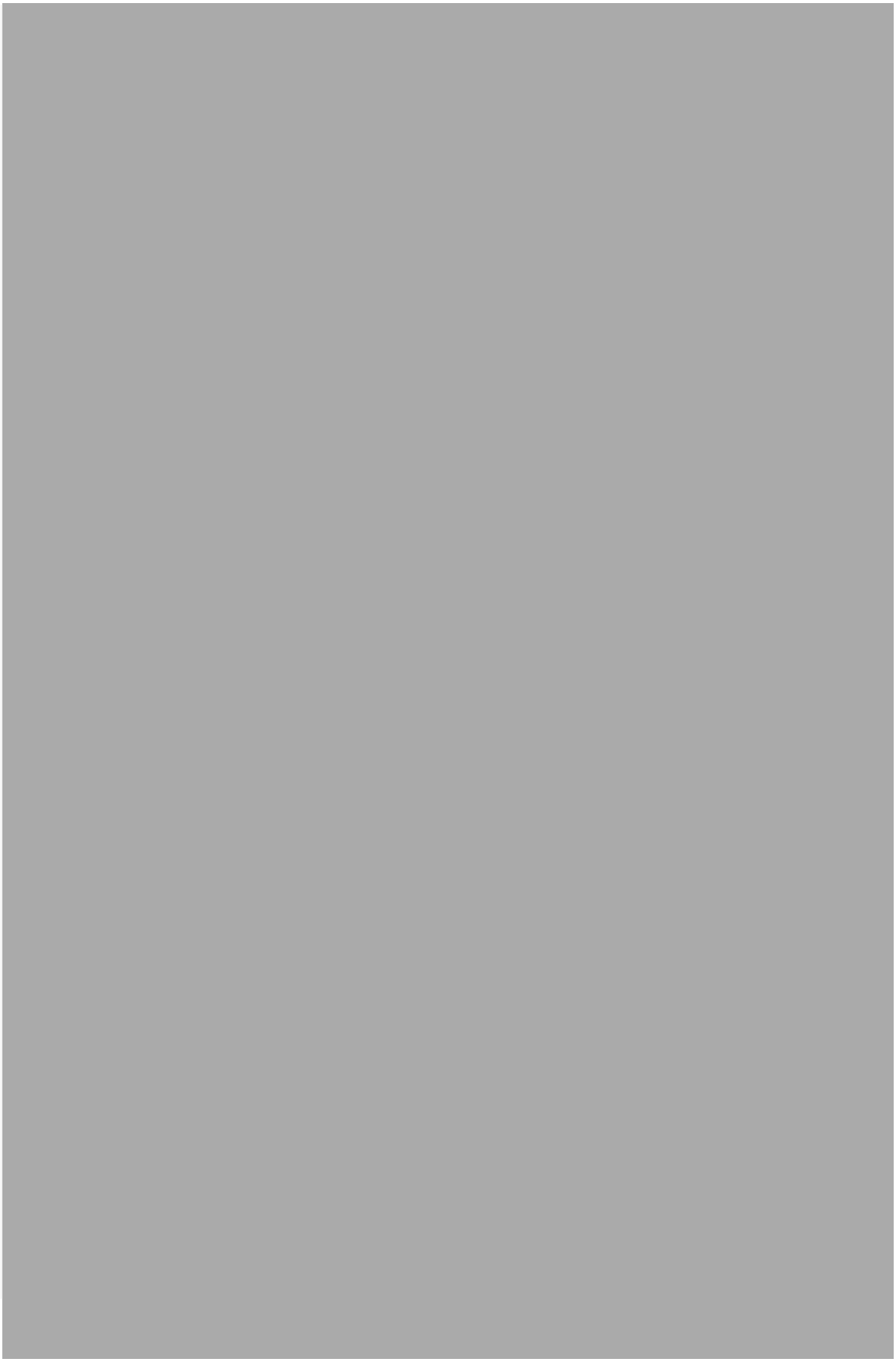


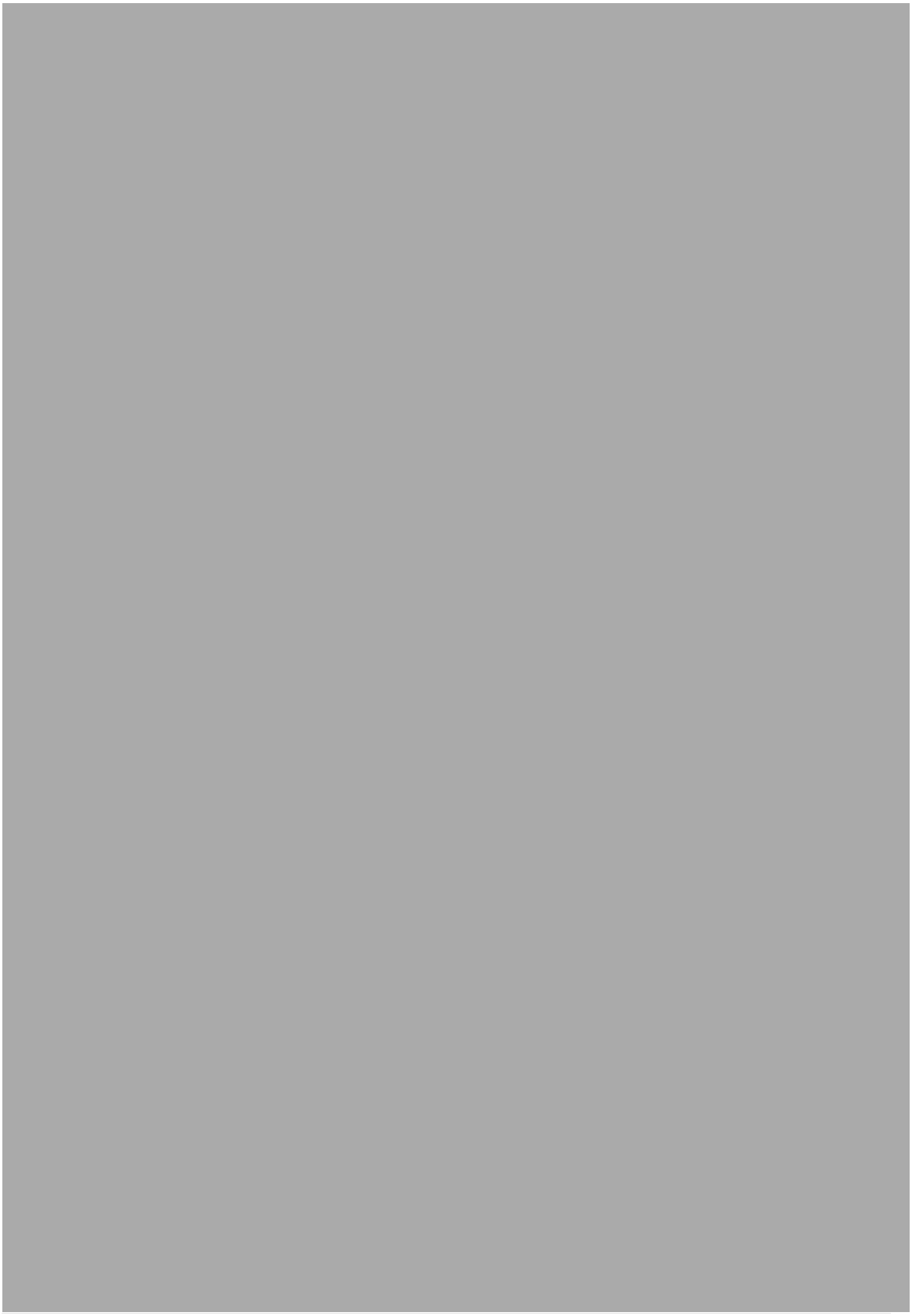


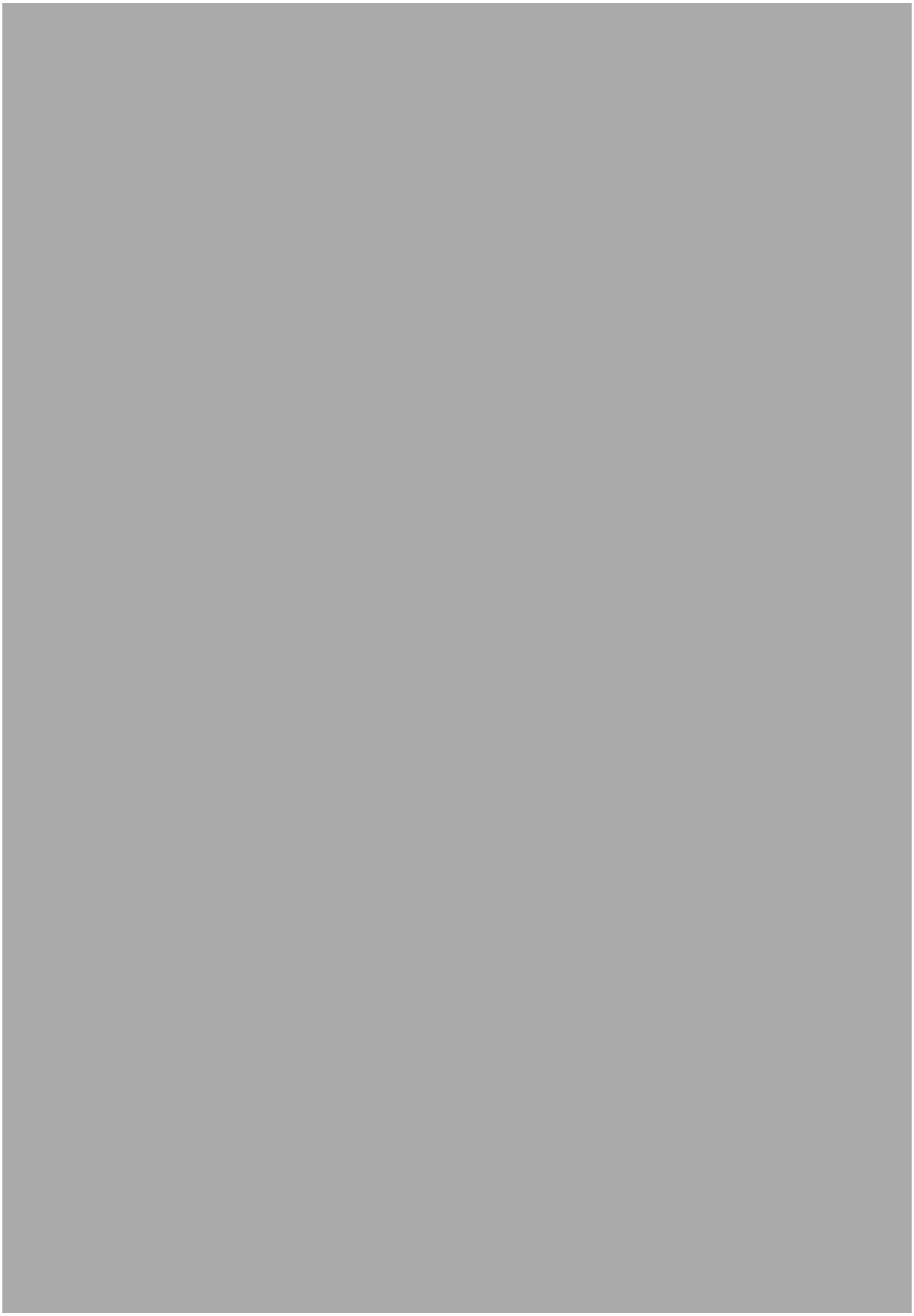


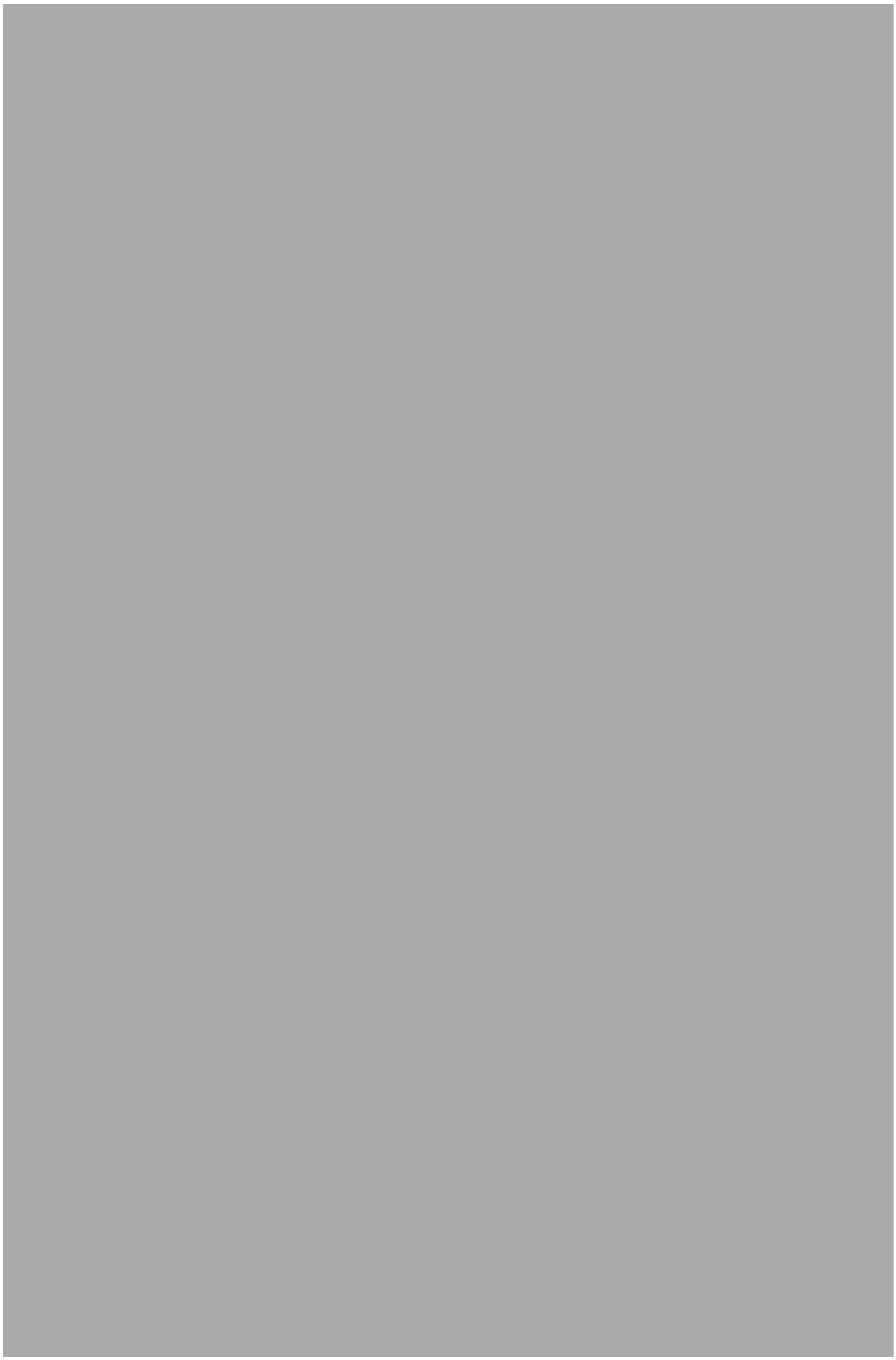


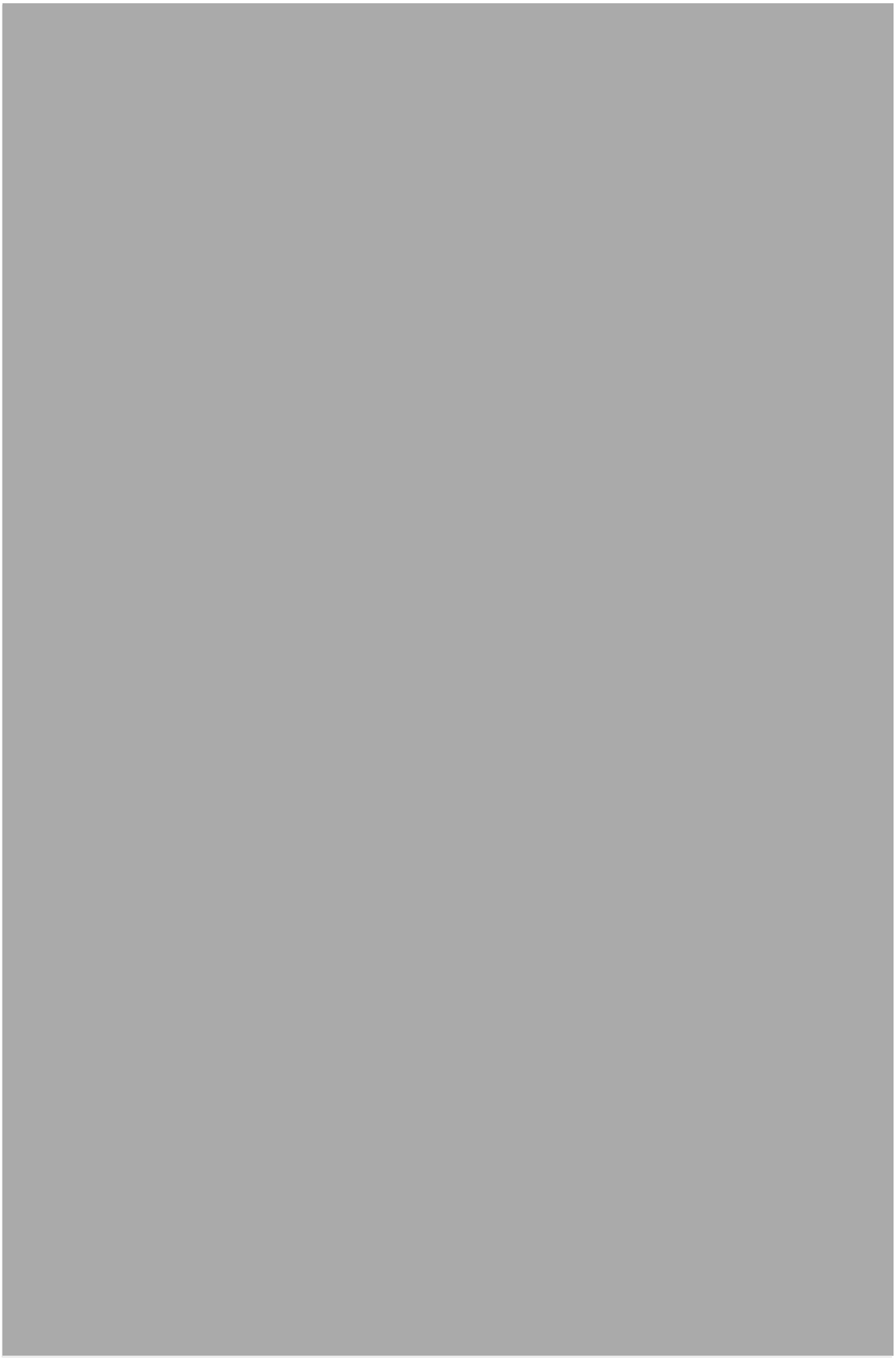


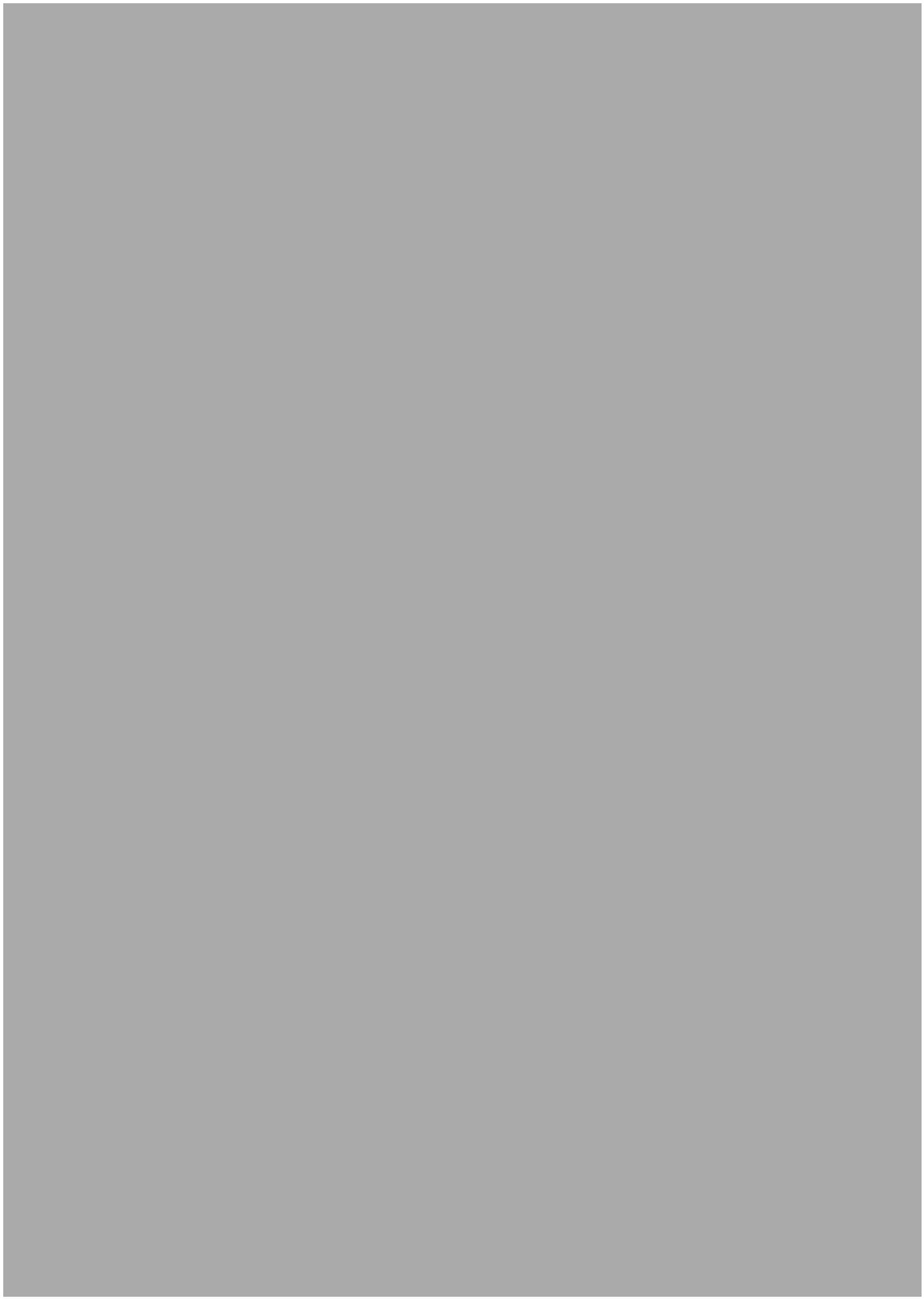


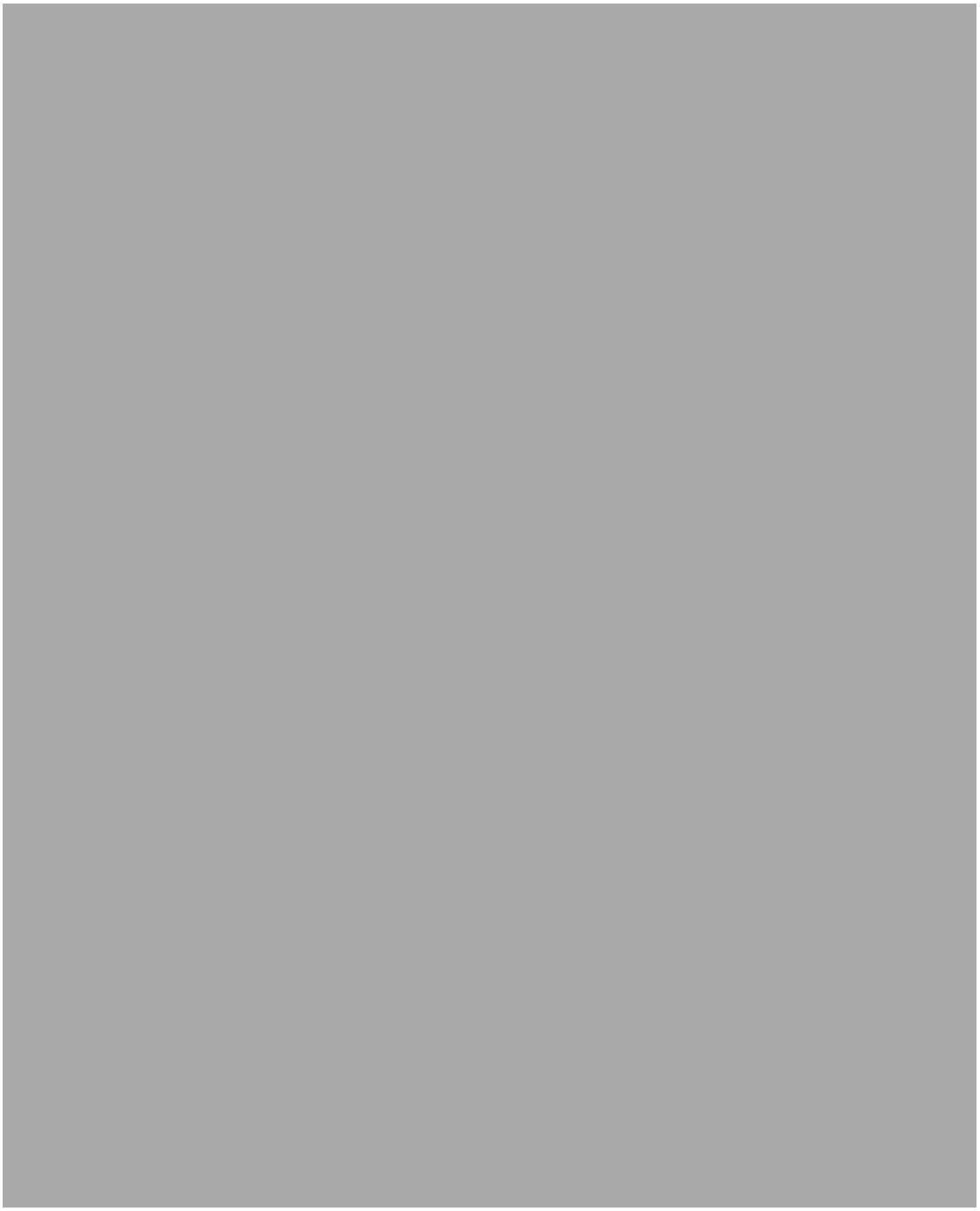












D. Supporting Material for Chapter 6

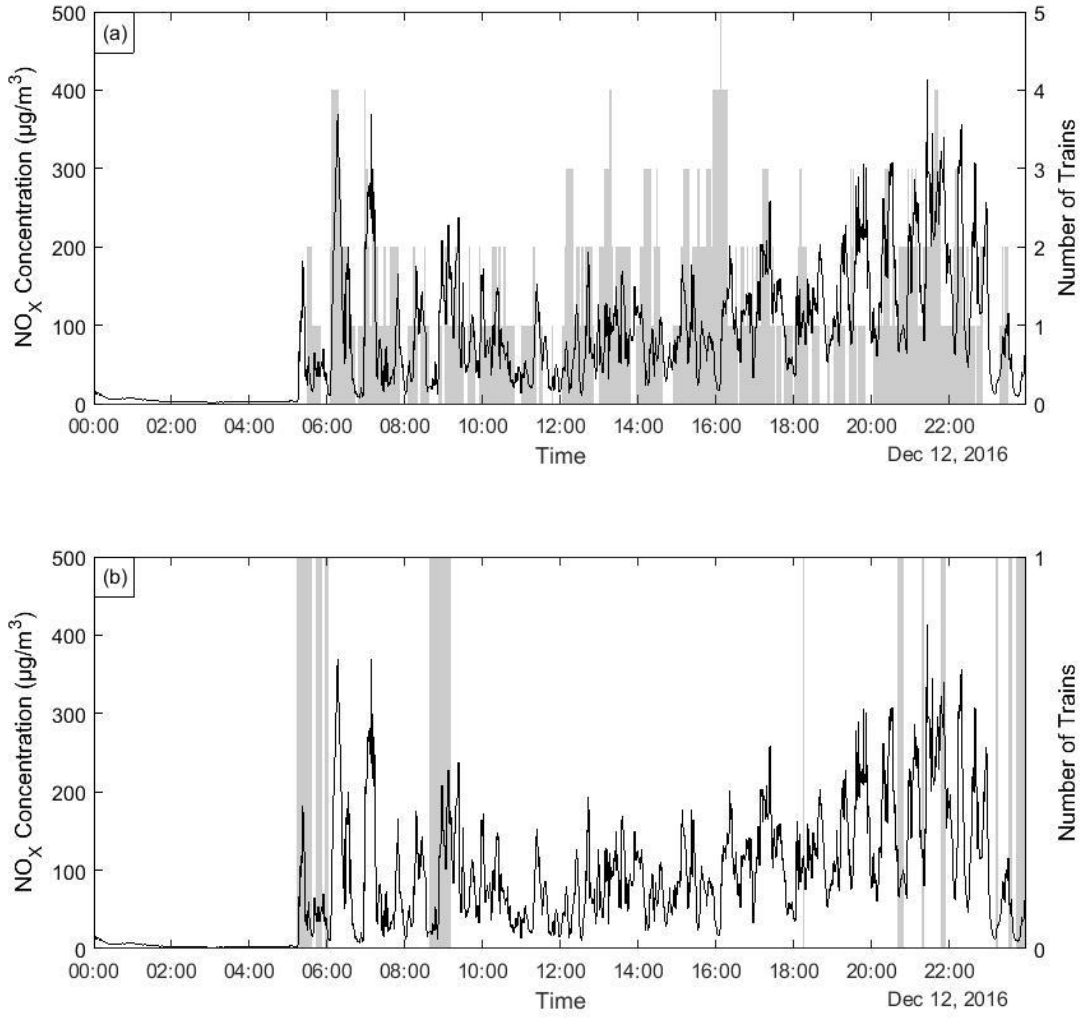


Figure D.1. Minute NO_x concentration (µg/m^3) for 12th December 2016 with shading showing number of (a) diesel trains and (b) electric trains occupying platform 10 and/or 11.

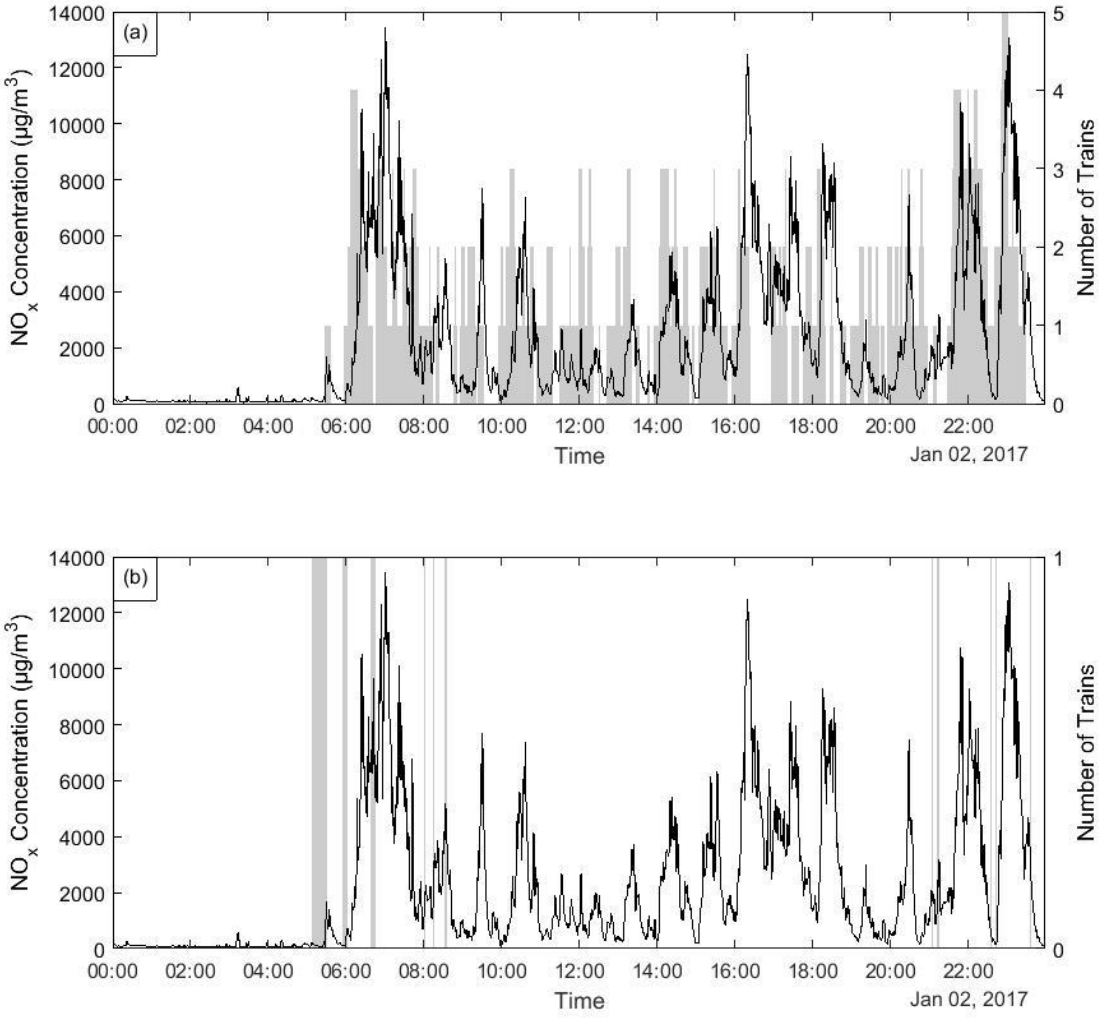


Figure D.2. Minute NO_x concentration (µg/m^3) for 2nd January 2017 with shading showing number of (a) diesel trains and (b) electric trains occupying platform 10 and/or 11.

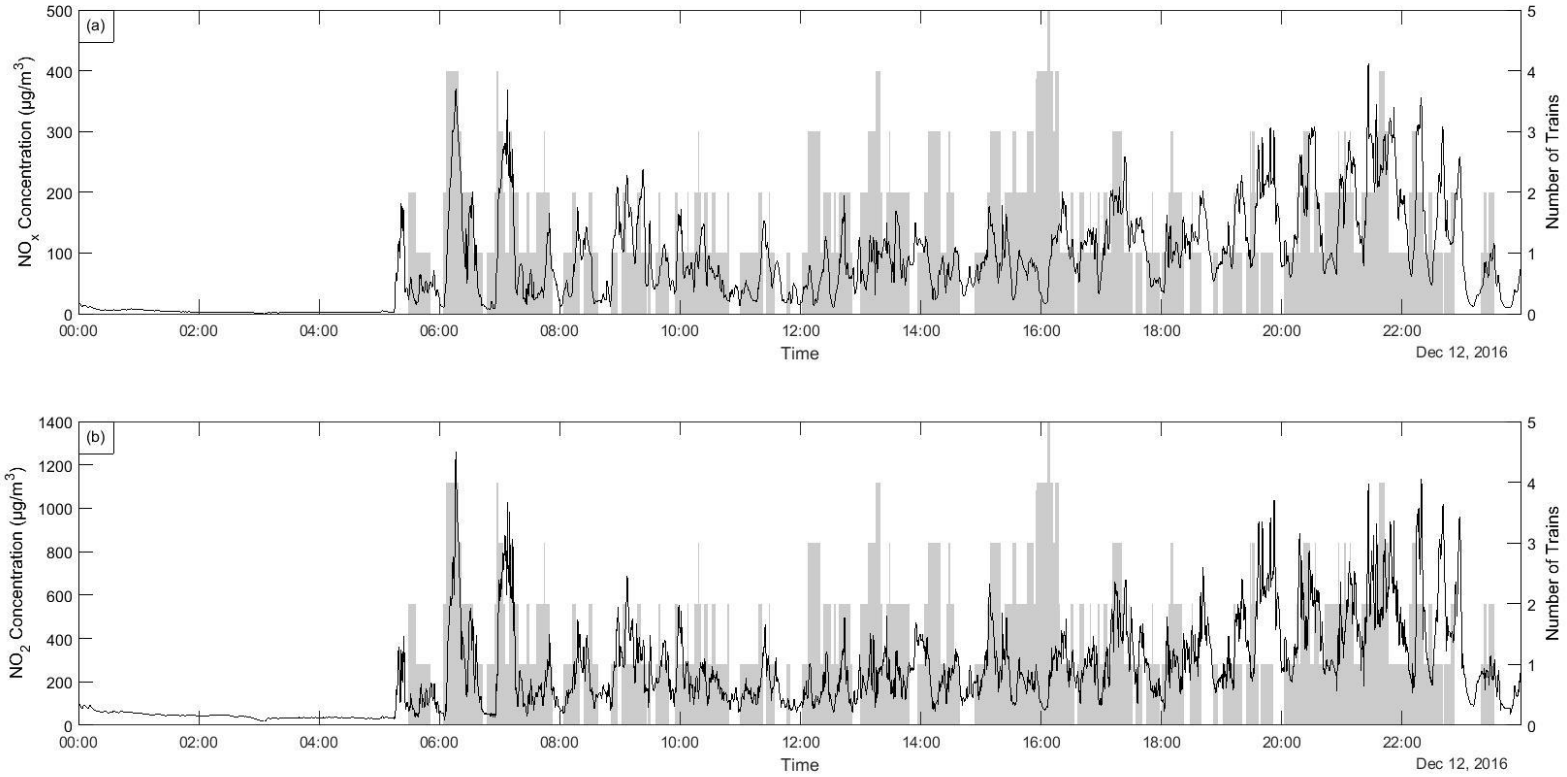


Figure D.3. Minute concentrations of (a) NO_x and (b) NO_2 for 12th December 2016 with shading showing number of diesel trains occupying platform 10 and/or 11.

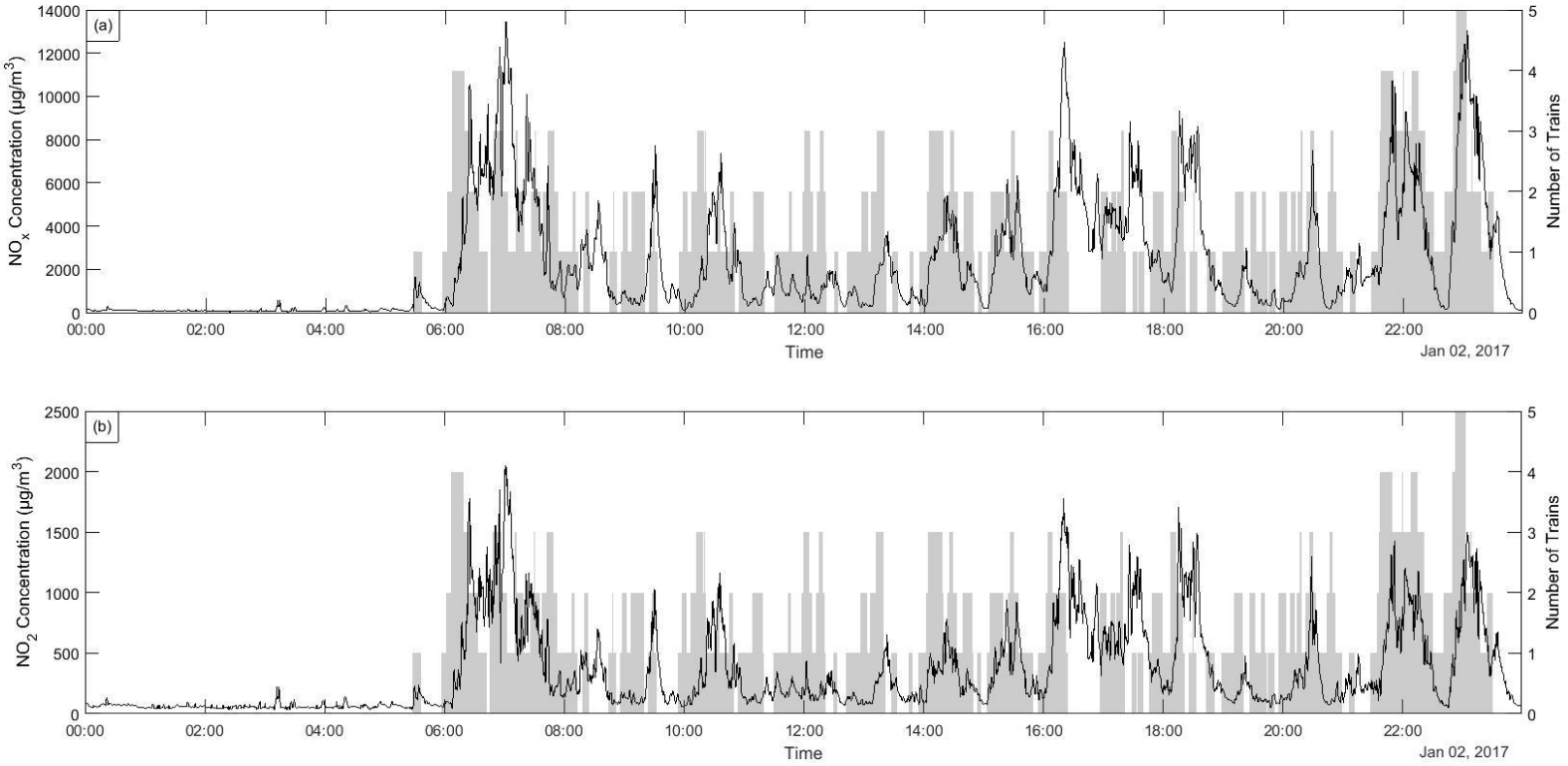


Figure D.4. Minute concentrations of (a) NO_x and (b) NO_2 for 2nd January 2017 with shading showing number of diesel trains occupying platform 10 and/or 11.

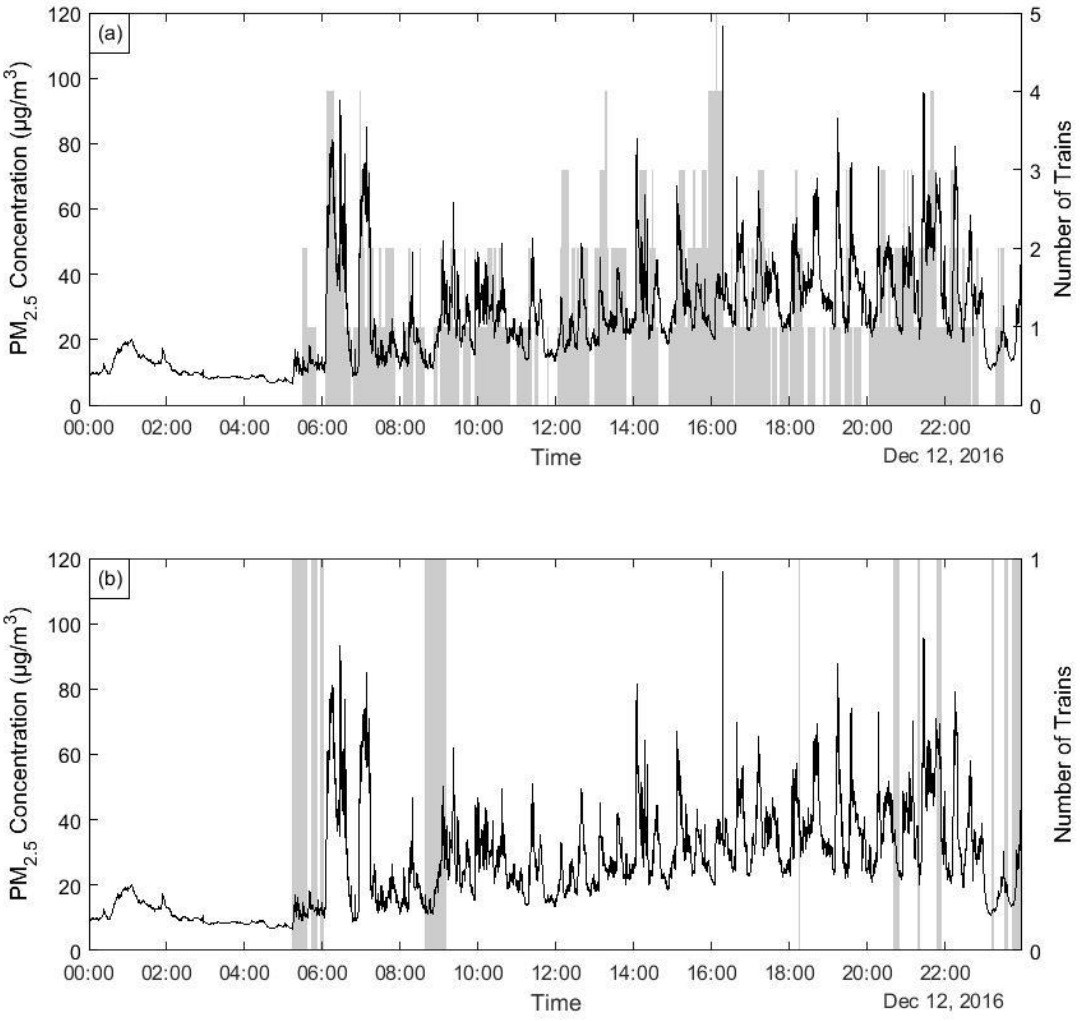


Figure D.5. Minute $PM_{2.5}$ concentration ($\mu g/m^3$) for 12th December 2016 with shading showing number of (a) diesel trains and (b) electric trains occupying platform 10 and/or 11.

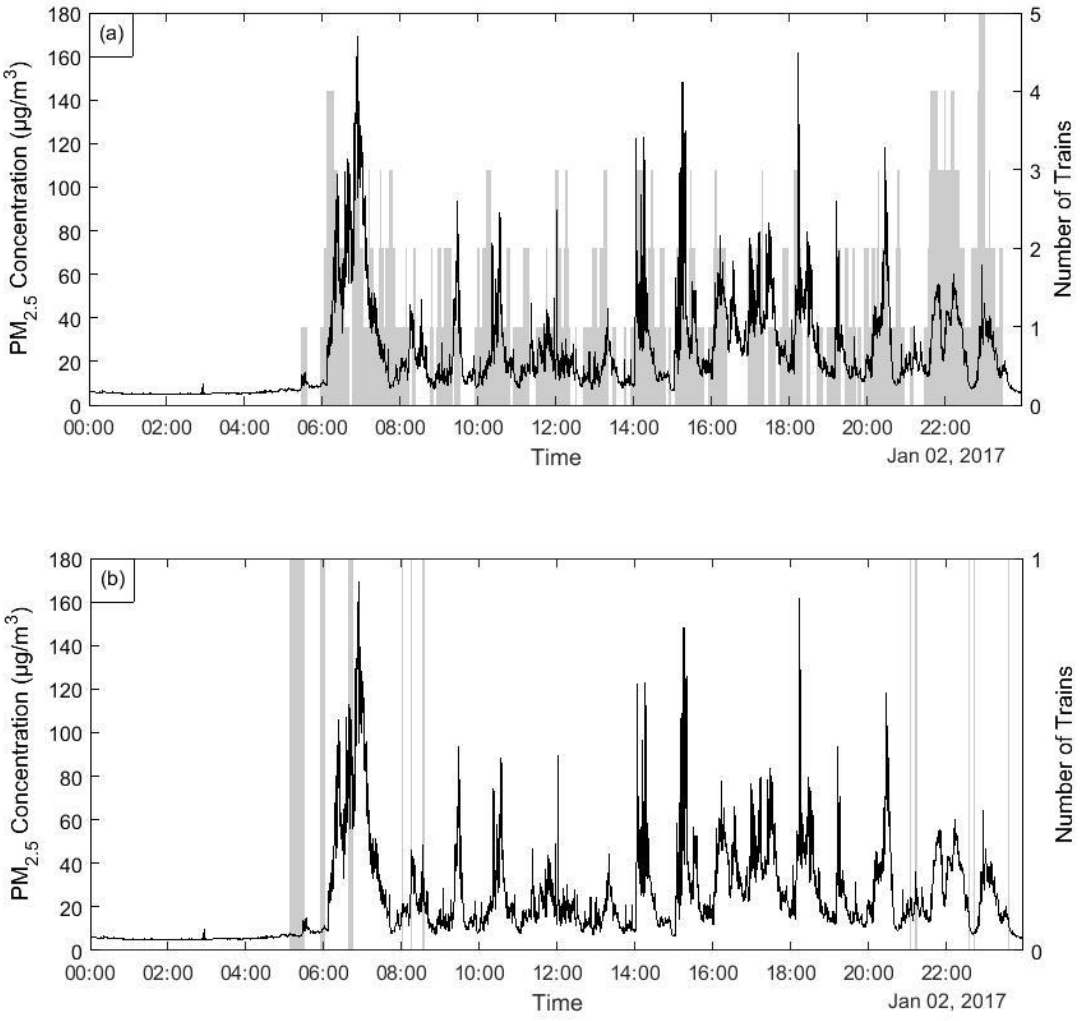


Figure D.6. Minute $PM_{2.5}$ concentration (µg/m^3) for 2nd January 2017 with shading showing number of (a) diesel trains and (b) electric trains occupying platform 10 and/or 11.

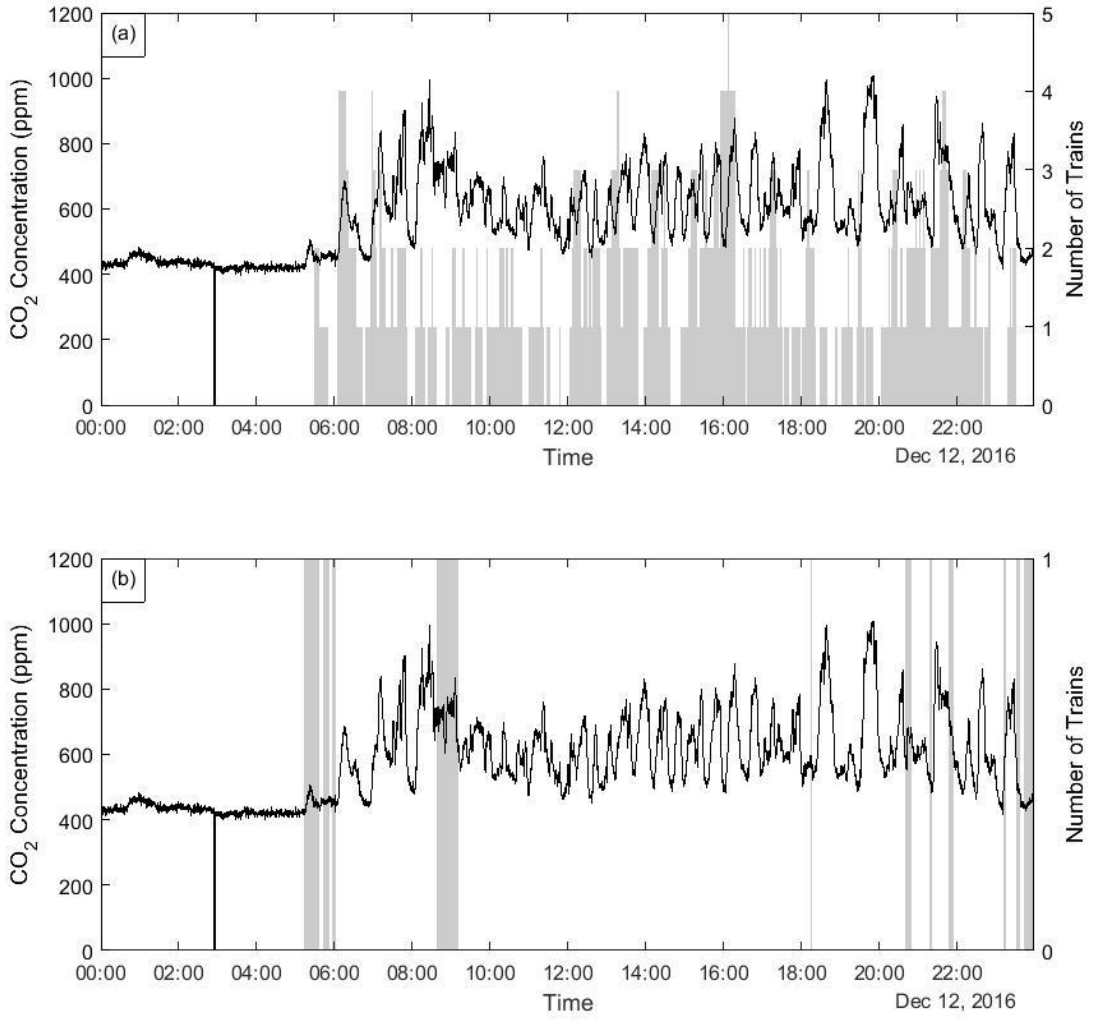


Figure D.7. Minute CO_2 concentration (ppm) for 12th December 2016 with shading showing number of (a) diesel trains and (b) electric trains occupying platform 10 and/or 11.

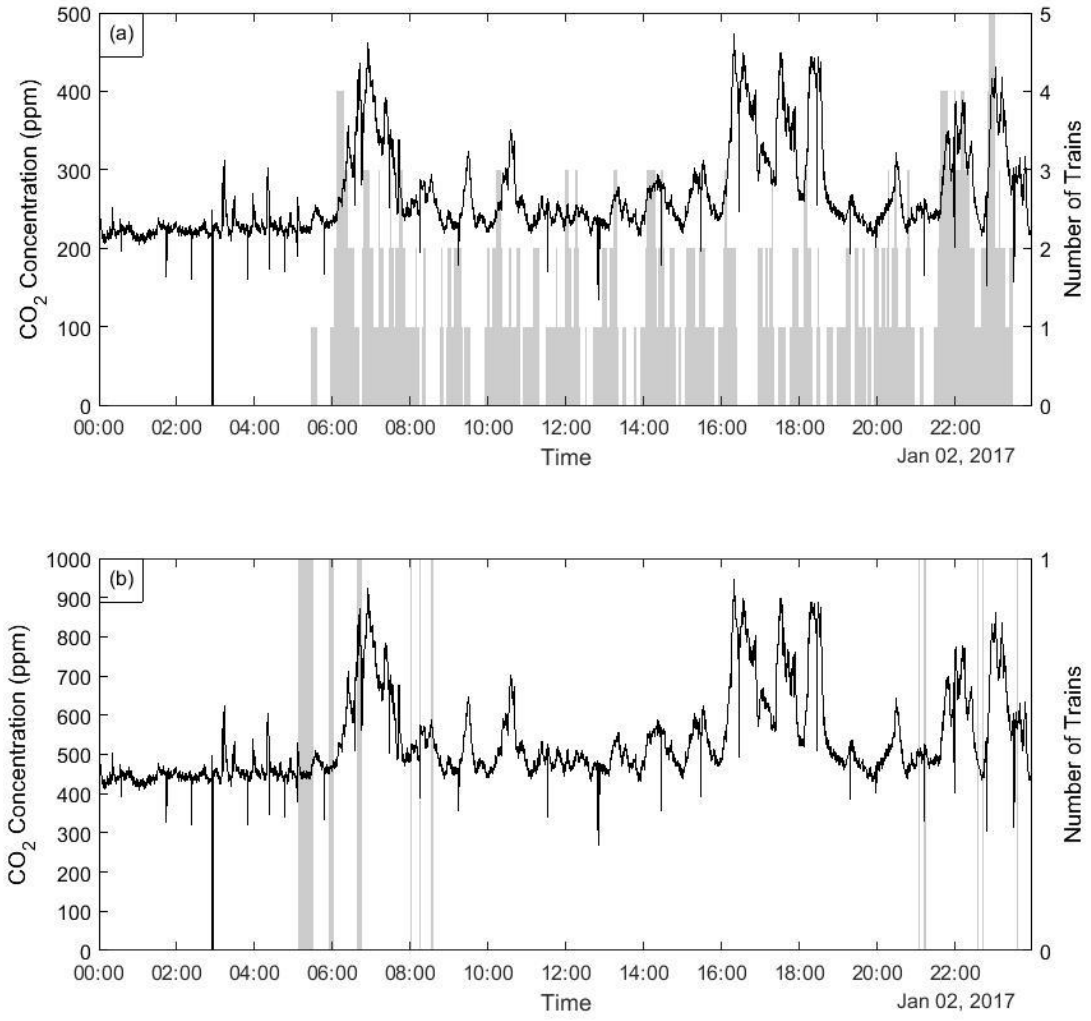


Figure D.8. Minute CO_2 concentration (ppm) for 2nd January 2017 with shading showing number of (a) diesel trains and (b) electric trains occupying platform 10 and/or 11.

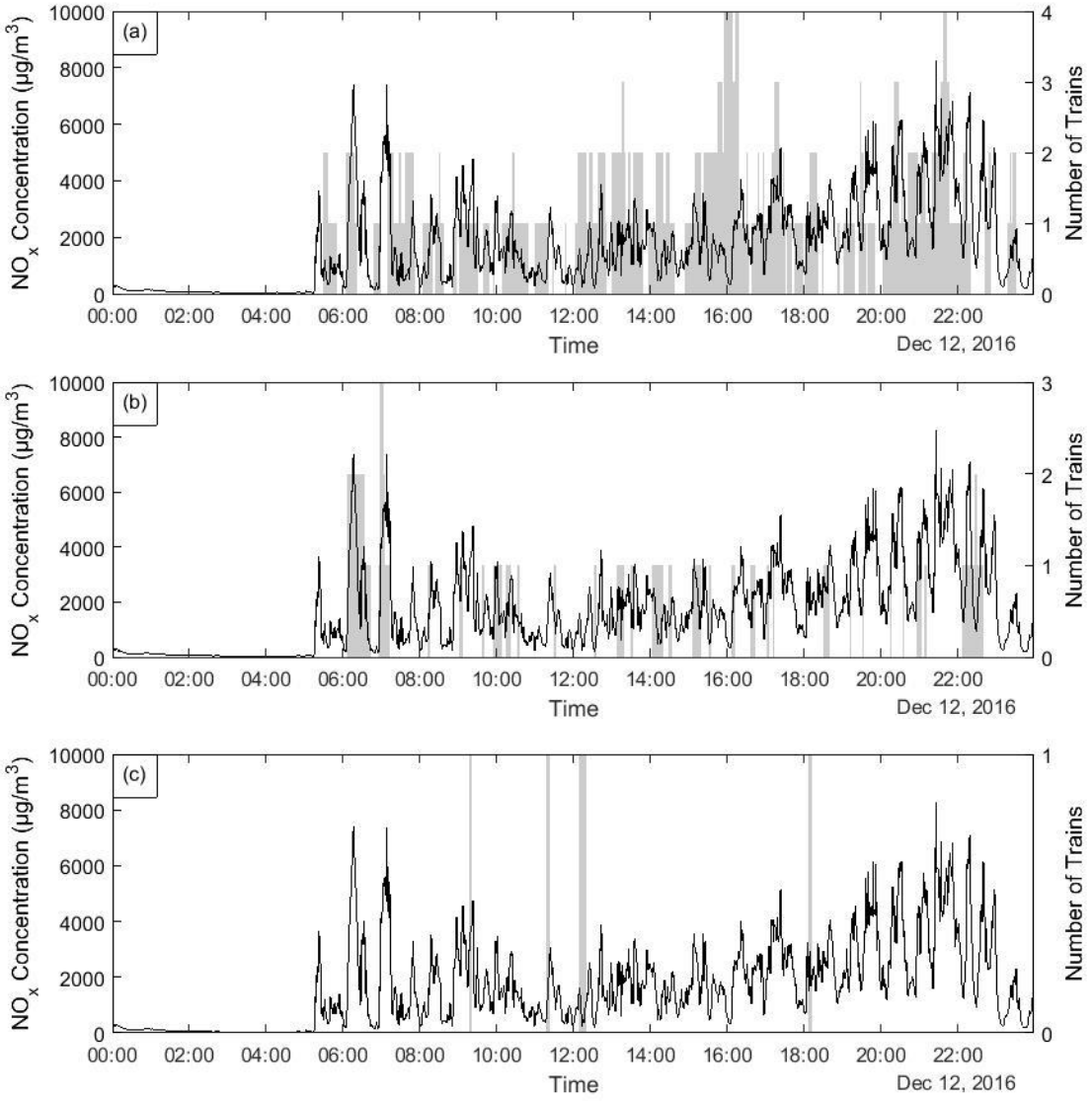


Figure D.9. Minute NO_x concentration (µg/m^3) for 12th December 2016 with shading showing number of (a) class 158/170 (Express Sprinter/Turbostar), (b) class 220/221 (Voyager) and (c) HST (InterCity 125) occupying platform 10 and/or 11.

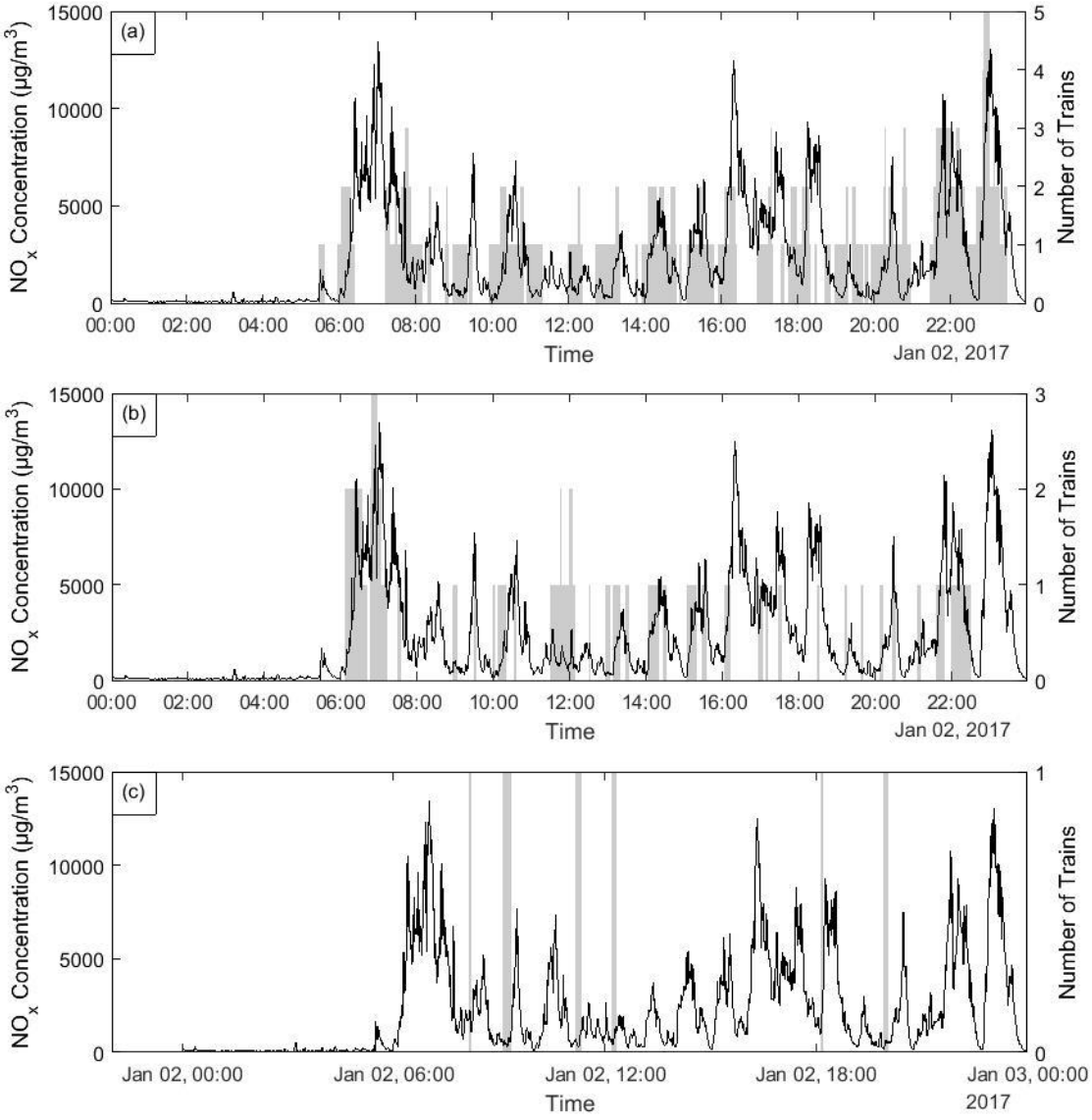


Figure D.10. Minute NO_x concentration (µg/m^3) for 6th January 2017 with shading showing number of (a) class 158/170 (Express Sprinter/Turbostar), (b) class 220/221 (Voyager) and (c) HST (InterCity 125) occupying platform 10 and/or 11.

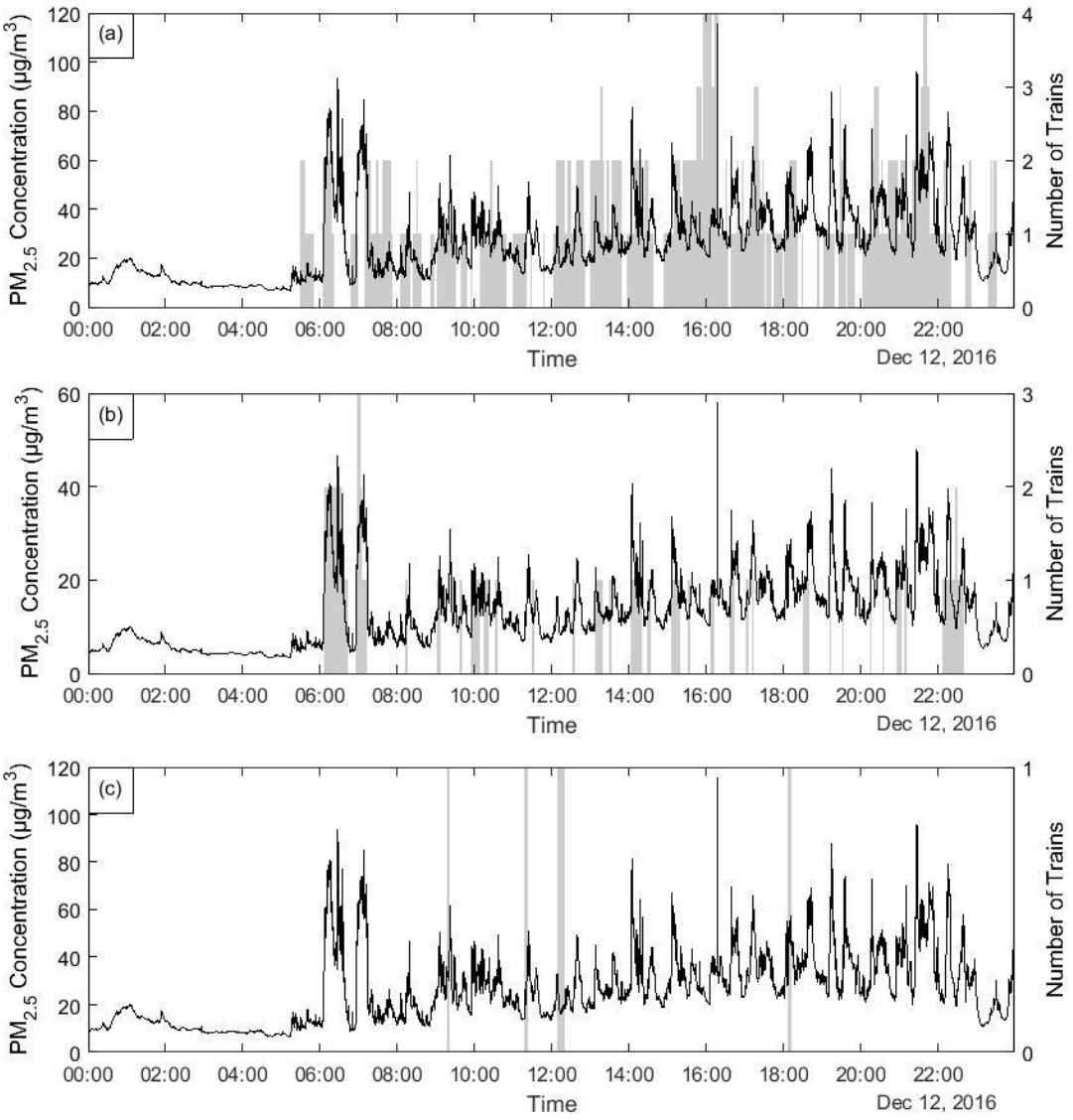


Figure D.11. Minute $PM_{2.5}$ concentration ($\mu g/m^3$) for 12th December 2016 with shading showing number of (a) class 158/170 (Express Sprinter/Turbostar), (b) class 220/221 (Voyager) and (c) HST (InterCity 125) occupying platform 10 and/or 11.

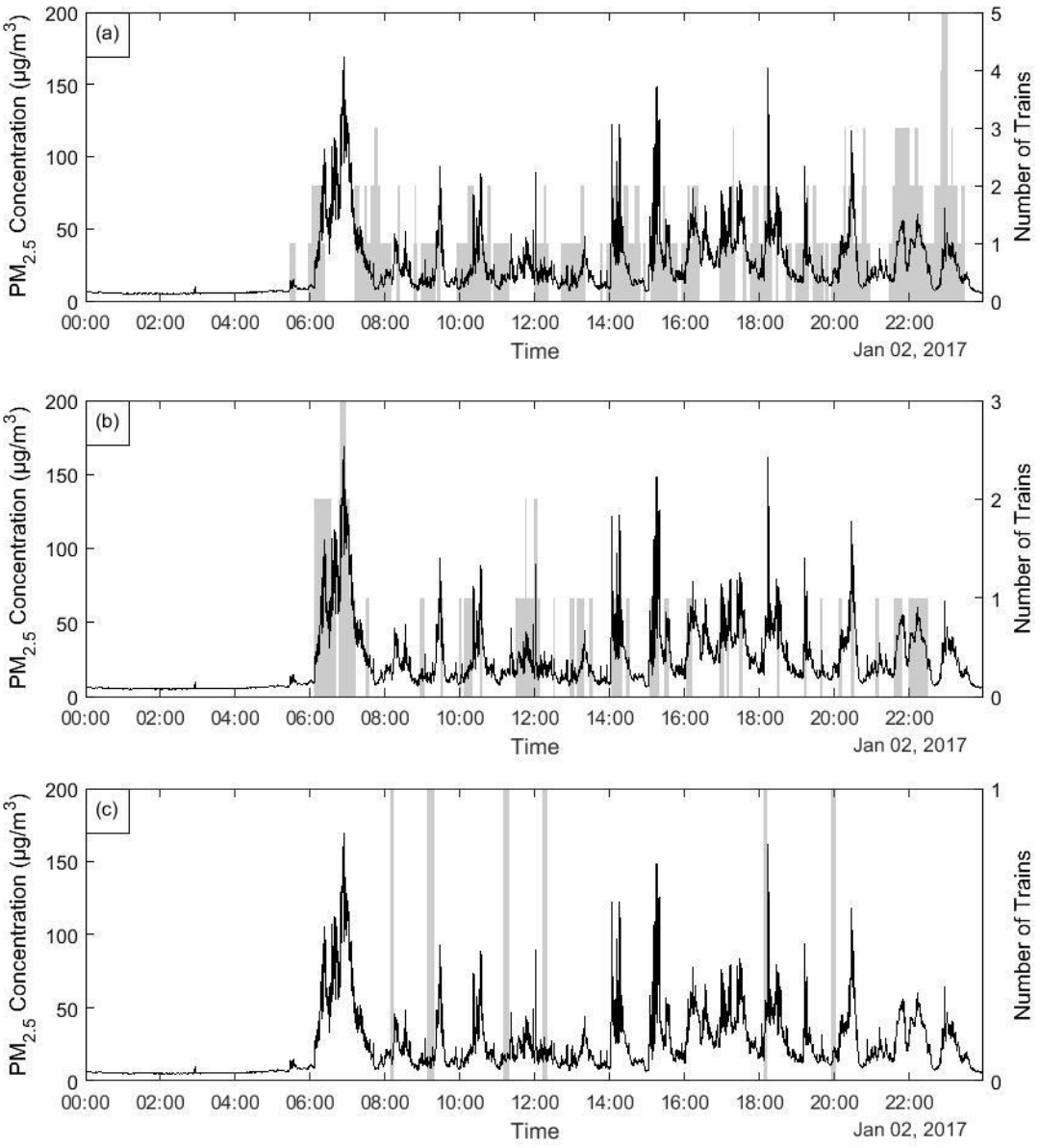


Figure D.12. Minute $PM_{2.5}$ concentration (µg/m^3) for 2nd January 2017 with shading showing number of (a) class 158/170 (Express Sprinter/Turbostar), (b) class 220/221 (Voyager) and (c) HST (InterCity 125) occupying platform 10 and/or 11.

E. Air Quality in Enclosed Railway Stations

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Air quality in enclosed railway stations
Thornes, Hickman, Baker, Cai and Delgado Saborit

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Air quality in enclosed railway stations

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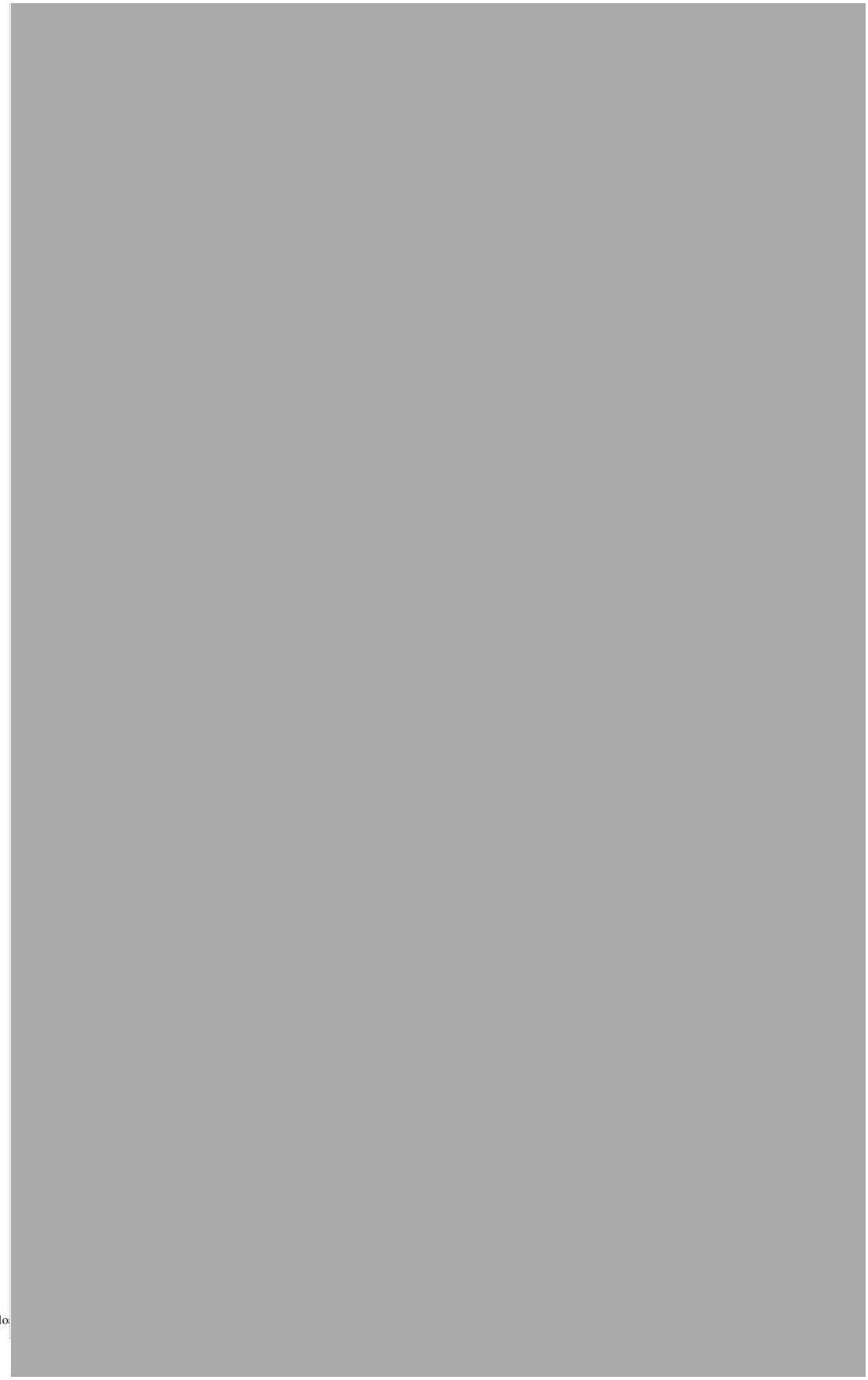
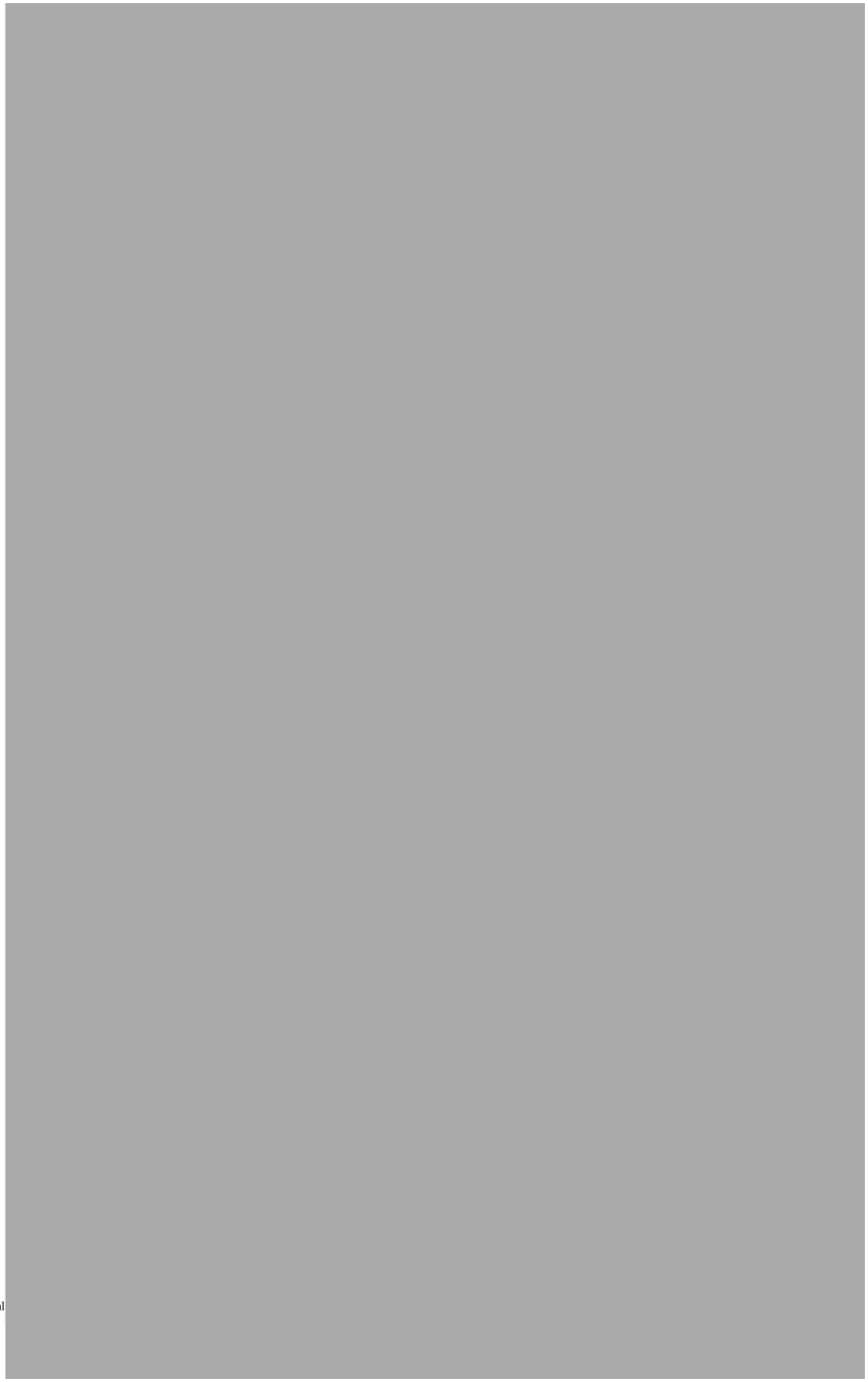
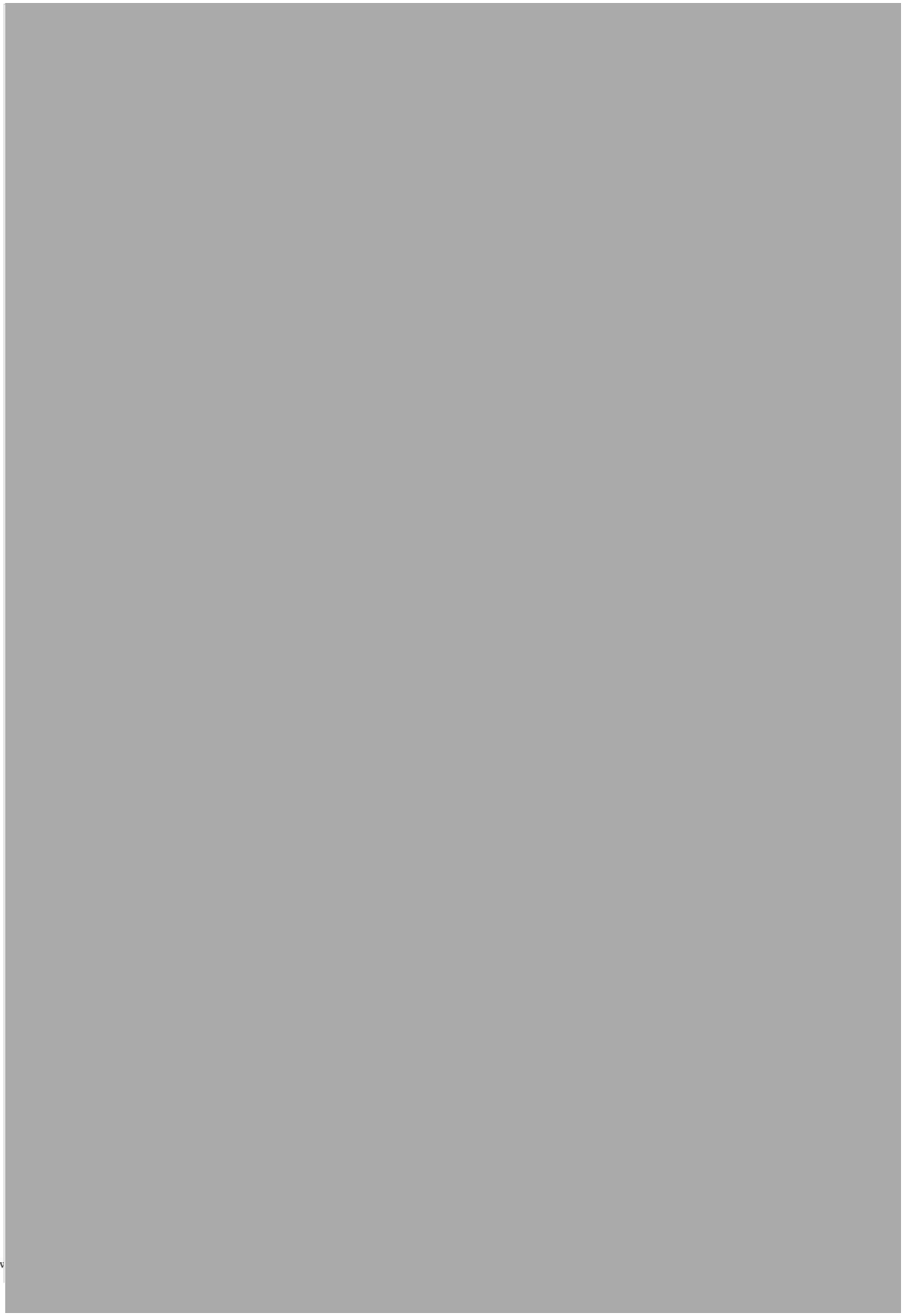
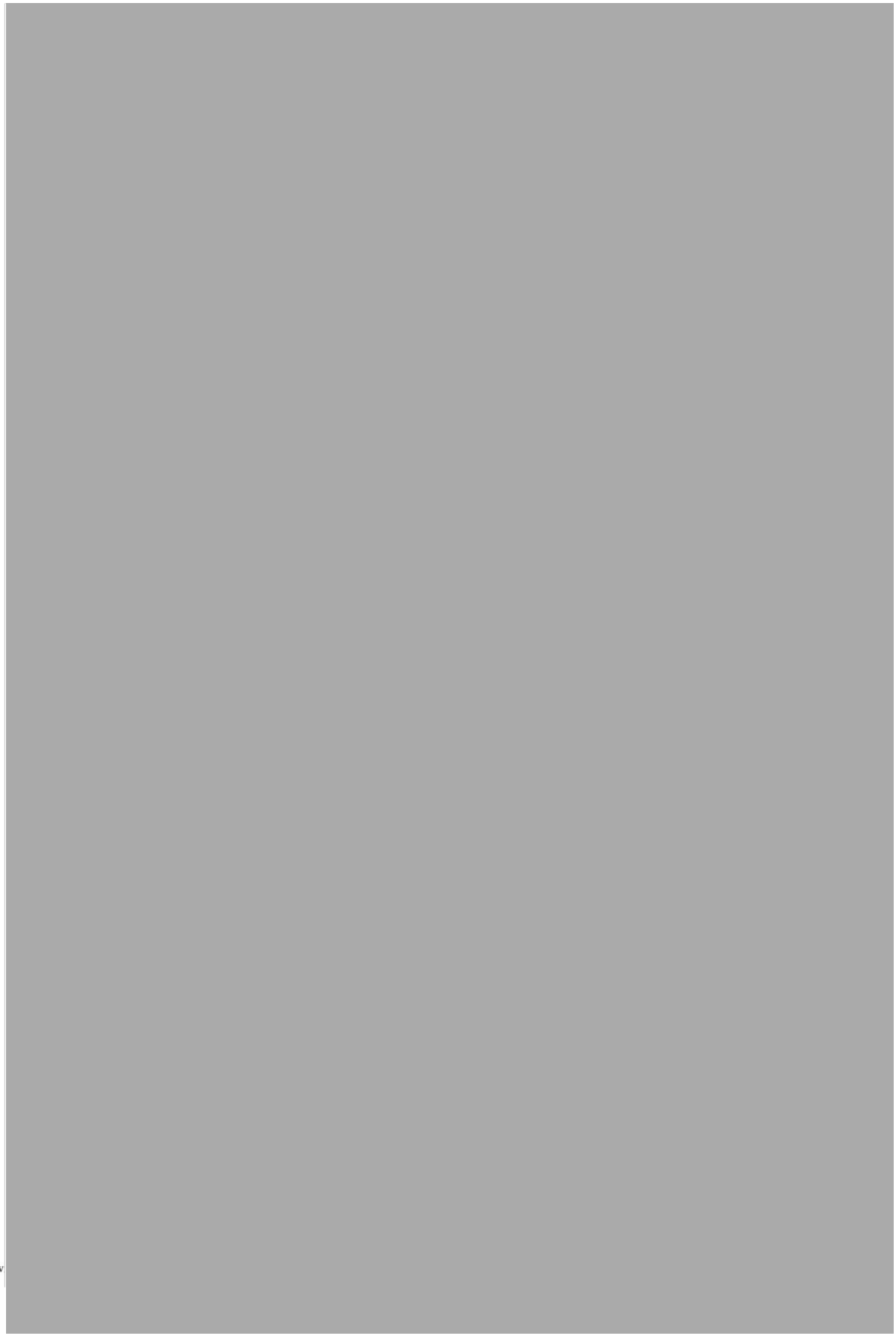
In 2012, the World Health Organization's International Agency for Research on Cancer (IARC) reclassified diesel engine exhaust and related ambient air pollution to be carcinogenic and associated with increased mortality from lung cancer. This could have critical consequences for both public and occupational health in enclosed railway stations where ventilation is often inadequate. Recent policies encouraging a shift to public transport, along with increasing passenger and train numbers, have led to a variety of co-benefits, including improved health and well-being from increased walking and cycling. This paper considers the unintended consequences of a reduction of air quality in crowded enclosed railway stations and concludes with a number of possible interventions to ensure that public health is not affected, especially by air pollution from stationary diesel trains. Pollution from electric trains can also lead to poor air quality due to the production of metal-rich ultrafine particles from brake linings, friction between wheel and rail, and from overhead pantographs. Current occupational health standards are not suitable for enclosed railway stations and need to be reconsidered in the light of the IARC findings. More measurements of the levels of particulates and nitrogen dioxide in enclosed railway stations need to be undertaken and published.









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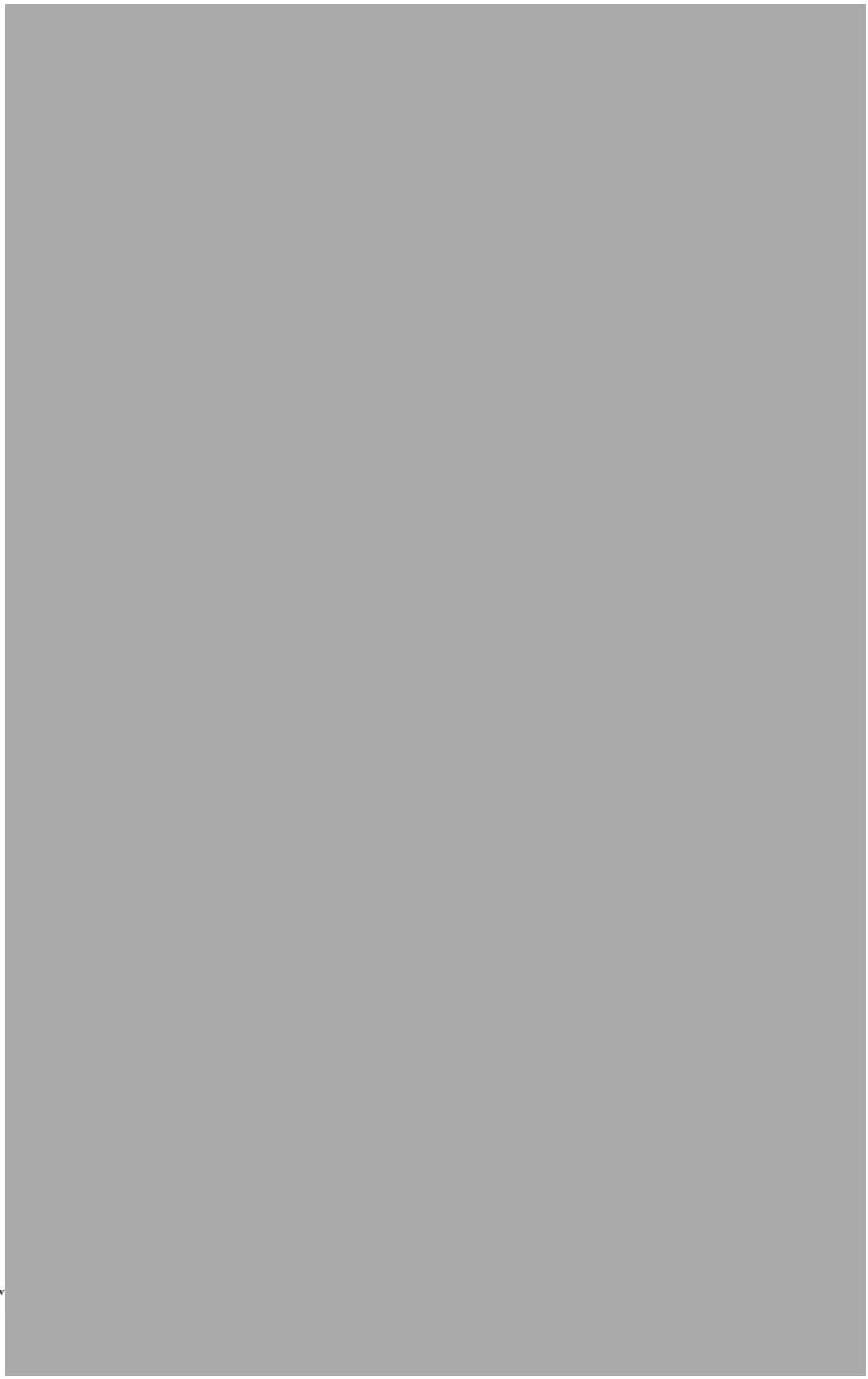

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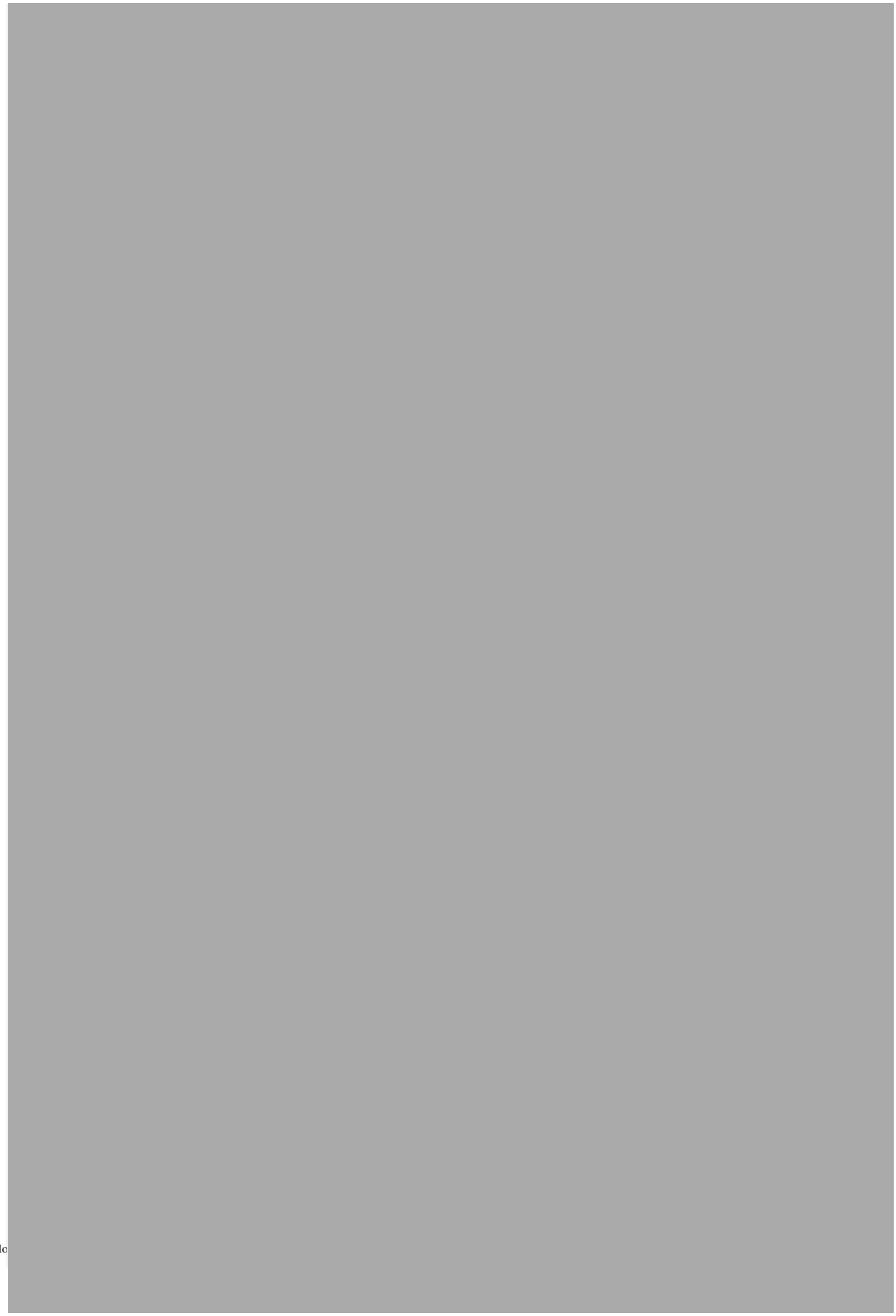

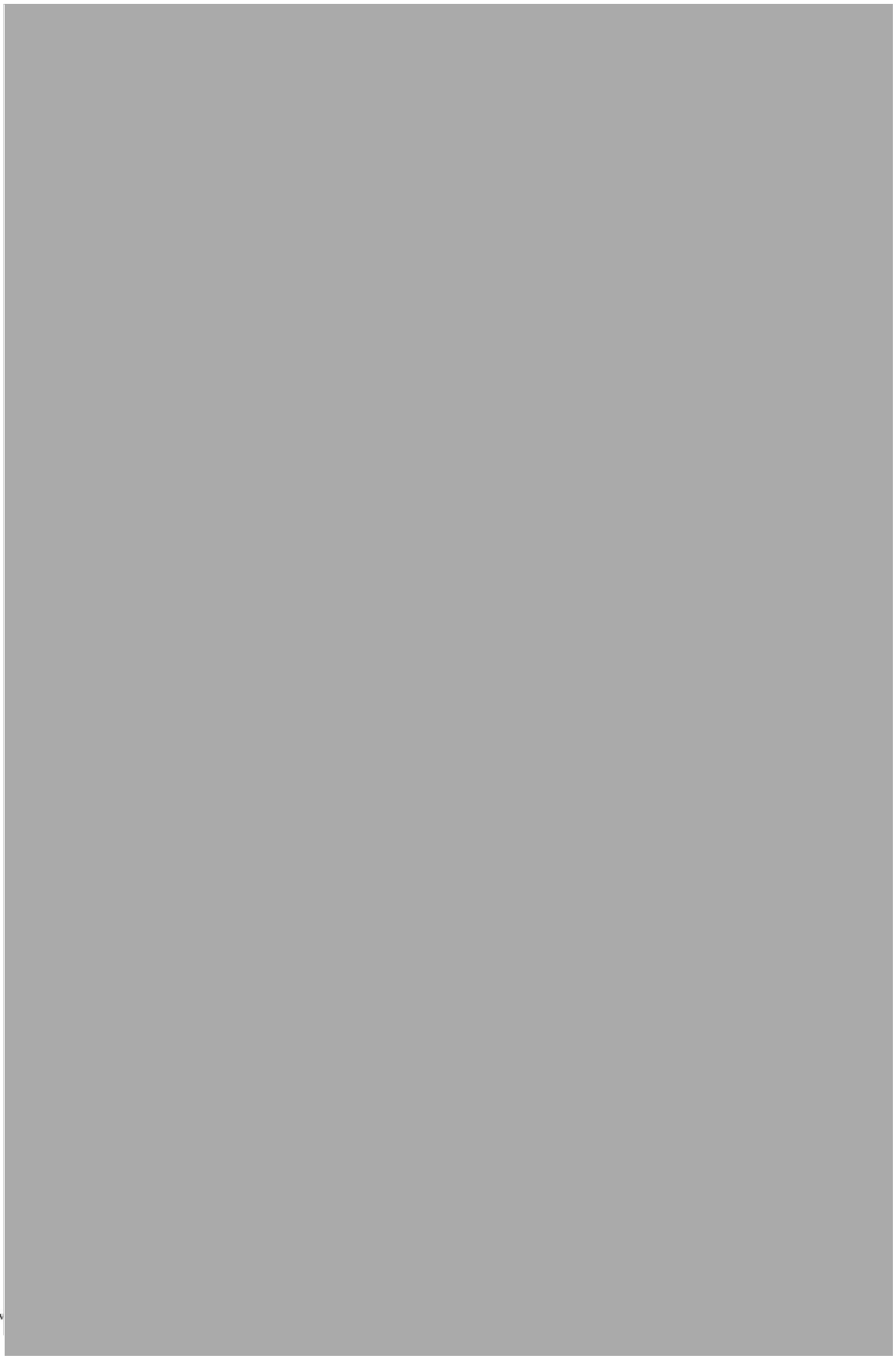

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